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Swiss cable study

Date 3 February 2025

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1.1 Scope of application and objectives

The number of cable projects in the Swiss transmission grid has increased significantly in recent years. In this study, “cables” refer to underground XLPE cables. Therefore, for the readers’ convenience, only the word “cable” will be used hereinafter.

Until now, each new cable project and its impact on the grid has been analysed individually. Studies carried out for cable projects such as the Gotthard route have shown that cables have a considerable impact on network behaviour and grid operations.

The most significant impacts are listed below:

- Voltage rise due to reactive power generated by the cables.
- Resonance phenomena due to the decrease in resonant frequencies brought by cable integration.
- Higher harmonic content in the grid since the cables act as an amplifier.
- As these effects are already observed with the cables currently planned, we can expect the impact of these phenomena to become even more pronounced as the length of cables installed increases. In this situation, it is prudent to express our concerns and to probe further into the impact of a significant rise in the number of cable projects in the grid. This will make it possible to anticipate challenges and to plan projects in a sustainable way.

To this end, Swissgrid has made the decision to carry out a comparative study of three scenarios with different time horizons:

1. The first scenario corresponds to the cables already installed in the grid.
2. The second scenario contains the cables in scenario 1 and those already planned or under construction. Its time horizon has not yet been defined as it remains uncertain, but 2040 has been taken as a rough estimate.
3. The third scenario is a hypothetical scenario with a large number of cables. This is a key scenario in the comparative analysis, as it allows us to evaluate the impact of extensive cabling on the grid and compare it with the two previous scenarios. The locations of the new cables in this scenario have been chosen, taking into account the lines that will be revamped in the sectoral plan in the coming years. The cables from the second scenario have also been included. As this is an entirely hypothetical scenario, no time horizon is specified.

Although the time horizons of the scenarios are different, the same grid topology corresponding to the start grid of the latest SN2040 strategic grid has been used for all three scenarios. This is because in order to analyse the impact of the cables, all the other parameters must remain constant. Otherwise, it would be difficult to identify whether the changes were due to an increase in the number of cables or to a change in grid topology. The grid topology used in the study is shown below.

Figure 1-1: Start grid for the SN2040 strategic grid

The three negative impacts mentioned above were analysed for each of the three scenarios. The results were then compared in order to draw conclusions about the impact of cables on the grid.

The analyses presented in this work package aim to quantify the reactive power compensation requirements in the three scenarios. The impact on resonant frequency and harmonic content will be analysed in dedicated work packages.

1.2 Active and reactive power

Reactive power is an electrical phenomenon which, although not performing useful work like active power, plays a fundamental role in the operation of electrical systems. Unlike active power, which is transformed into light, heat or movement, reactive power is linked to the creation and maintenance of the magnetic fields needed to operate equipment with coils or motors, such as transformers, lifts or household appliances like washing machines or refrigerators. Although reactive power is not consumed in the traditional sense of the term, it is essential for the start-up and smooth operation of these appliances.

The voltage that reaches our homes is an alternating voltage, which means that it oscillates very rapidly over time between two values, as shown in the image.

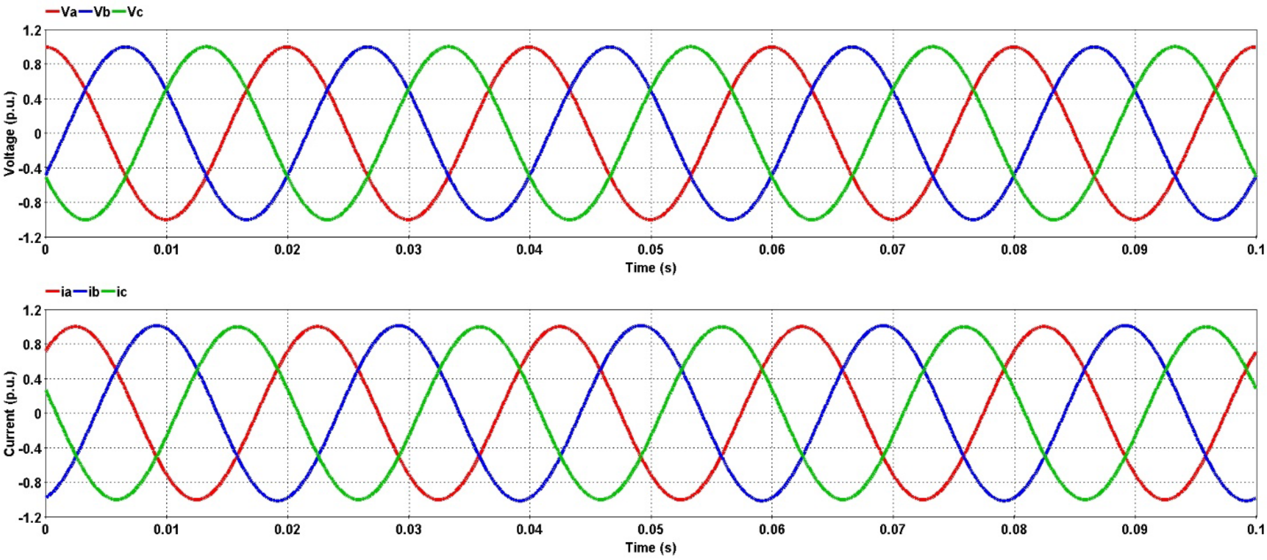


Figure 1-2: Voltage and current

As a result, the current also alternates, but it will be more or less out of phase with the voltage depending on the load connected.

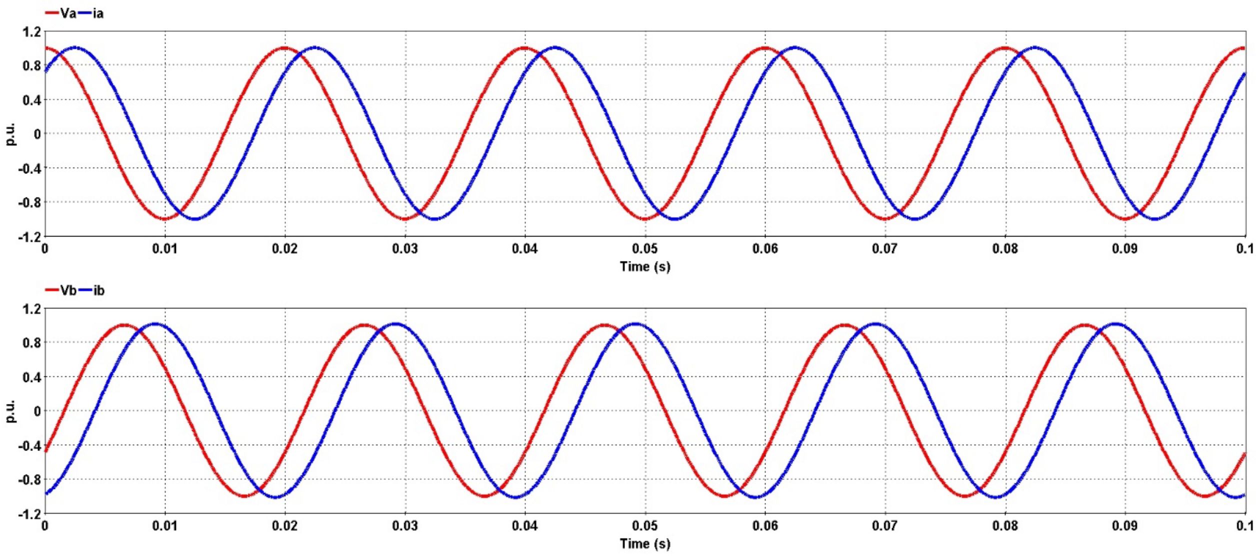


Figure 1-3: Phase lag of current with respect to voltage for an inductive load

Purely resistive loads only consume active power, in which case the voltage and current peaks occur at the same time.

However, most loads have an inductive or capacitive component, which is the source of reactive power. In the presence of reactive power, the current and voltage are out of phase and the peaks do not occur at the same time. Consequently, in the presence of reactive power, the total power flowing along the line is higher. This is why we say that an excess of reactive power overloads the lines.

Another undesirable effect of excess reactive power when it is capacitive is that it increases voltages. The grid operates within a voltage range without any problems. When voltages exceed the maximum permissible values in the voltage range, risks of damage to grid components arise.

Several methods exist for voltage reduction. The most common ones are described below:

- Disconnect lines and/or cables carrying little current momentarily, as lines with a light load produce more reactive power. However, this method is dangerous because it reduces redundancy, meshing and grid security.
- Reduce the voltage setpoint values of generators. The generators then absorb reactive power and reduce it from the grid. The disadvantage of this method is that it may not be effective. Generators can only absorb a very limited amount of reactive power. Beyond a certain level of absorption, changes to the setpoint voltage will have no effect, as the generator will have reached its limits.
- Phase-shifting transformers can also be used to lower the voltage of a given voltage level (with the opposite effect on the other voltage level). However, they have virtually no effect on the amount of reactive power generated or absorbed by the grid.
- Install reactive power compensation devices. Differenty types of reactive power compensation devices are available on the market , such as shunt reactors, SVCs and STATCOMs. Shunt reactors are the simplest of the three and consist of an inductive device that compensates for the capacitive reactive power generated by the grid.

The illustrations below show the two main types of shunt reactors (oil-insulated and air-insulated).

Figure 1-4: Three-phase 420 kV, 50-250 Mvar shunt reactor (length 18.7 m, tank width 4 m, width 7.6 m, tank height 4.5 m, height 11.1 m, transport weight 219,000 kg, operating weight 361,000 kg). Source [1.1]

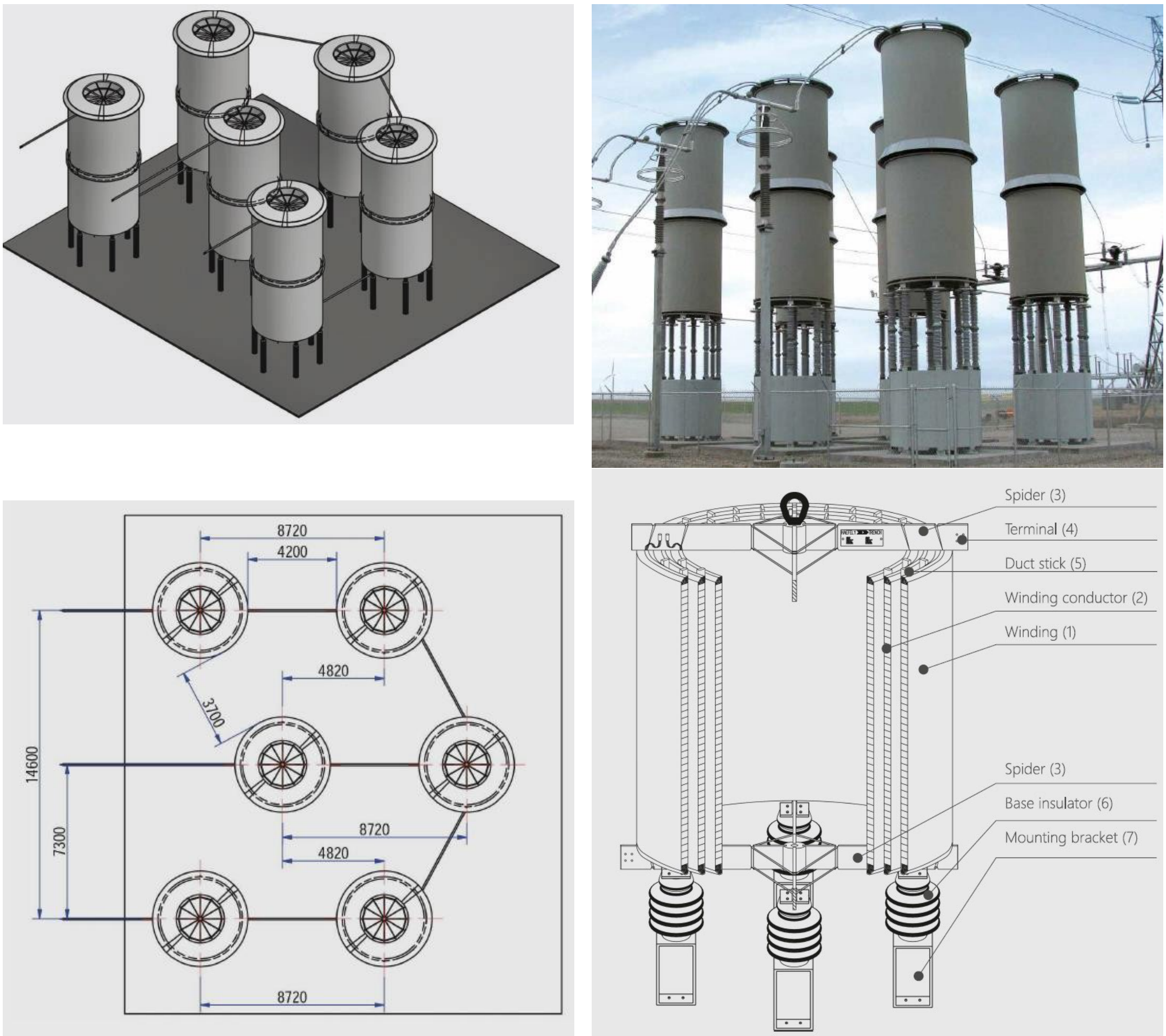


Figure 1-5: Arrangement of a three-phase air-insulated shunt reactor. Top/bottom left: Arrangement of a 420 kV, 120 Mvar reactance coil (approx. 400 m2). Top right: 345 kV, 20 Mvar shunt reactor. Bottom right: Structure of an air-insulated shunt reactor (partial). Source: [1.1]

Undervoltages can also lead to issues in the network, which is discussed in this document. Grids with intensive cable penetration are capacitive, resulting in overvoltages rather than undervoltages.

Currently in Switzerland, with the cables in scenario 1, the situation is already critical in terms of steady-state overvoltages. Operators are often deprived of any effective measures to reduce voltage. Sometimes, even if all the power plants are absorbing reactive power at their maximum capacity, the voltages at various network locations still exceed the permissible limits. This is why, as the number of cables increases, there is no choice but to compensate for 100% of their reactive power production.Reactive power compensation in cable projects

It is well-known fact that the electrical characteristics of AC cables differ considerably from those of overhead lines. One of the main electrical differences is the capacitive charging current, which is much higher in a cable than in an overhead line of the same length and power rating. A cable always retains the behaviour of a capacitor, whereas the properties of an overhead line range from less pronounced capacitive behaviour to inductive behaviour as the load increases, with a neutral point in-between (the surge impedance loading of the line).

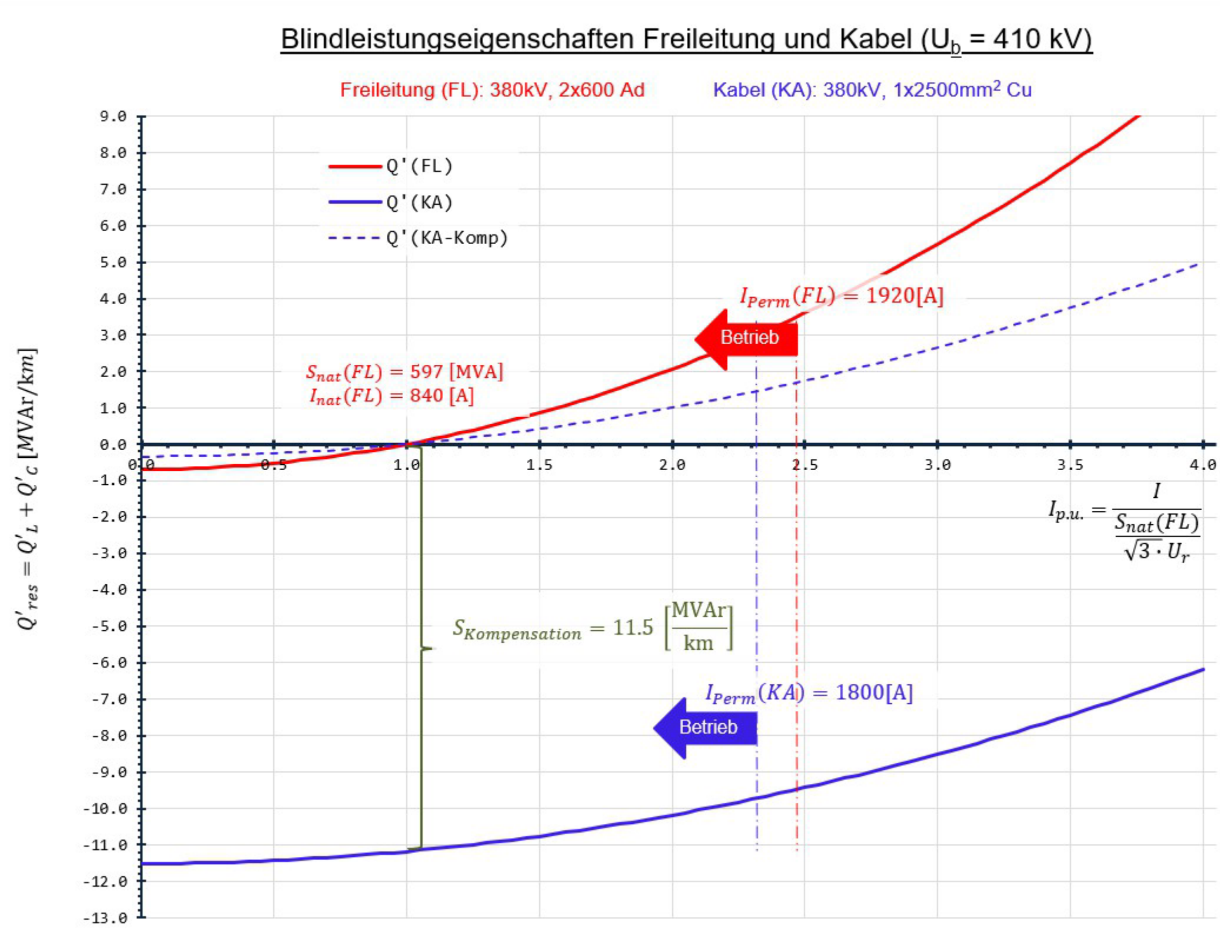


Figure 1-6: Reactive power behaviour of an overhead line (red) and a 380 kV cable (blue)
Source [1.1]

The reactive power generated by the cables causes voltage rise in the grid and exerts extra loading on the conductors. This is why reactive power must be compensated for by connecting shunt reactors to the cable terminals. These elements have a huge impact on losses. At 220 kV, losses can total up to 10 kW per km of cable; at 380 kV, the figure would be three times as high because reactive power increases with the square of the voltage. The space of the substations or transitions between cables and lines must be significantly increased, given that the installation of a shunt reactor takes up an area equivalent to that of a football pitch.

The total Mvar to be compensated is proportional to the length of cable installed. It should be noted that when there are two systems in parallel or two cables per phase, reactive power generation doubles. In some cases, it is necessary to compensate at both cable terminals, either because the length of the cable connection is close to 20 km, or because the size of the compensation required is too large. When the cable is comprised of two systems, and compensation is necessary at one terminal where no substation is connected, a shunt reactor has to be installed in each system. Cables that measure less than 3 km long are not necessarily compensated alongside the cable, but their reactive power generation is taken into account to increase the size of neighbouring compensation systems. These and similar considerations indicate that the total Mvar compensated for does not correspond exactly to the total number of kilometres of cable.

Different compensation solutions may be suitable for the same project. Optimising these solutions depends largely on good planning and thorough knowledge of the planned cable projects. This is the only way to plan compensation requirements on a long-term basis. For example, it would not be desirable to plan a small compensation system at a substation only to discover shortly afterwards that other cable projects are being planned in the vicinity. That is why it is not advised to plan compensation systems for each individual project, but rather for groups of projects.

A compensation solution has been calculated for each of the three scenarios studied. The aim of this analysis is to compare the number of compensation elements needed, as well as their cost and space requirements. Detailed conclusions are given in the following section.

1.3 Compensation elements required in the three scenarios

The compensation requirements were fulfilled by shunt reactors of four different sizes: 50, 100, 120 and 150 Mvar. It is common for operators to define standard sizes of shunt reactors to facilitate processes. In cases where the compensation required is between two values, the higher value is usually chosen. However, in some cases where compensation is carried out directly on the cable, the compensation value has to be reduced to avoid issues of zero-crossing delay. This problem occurs in cables with more than 50% compensation when the compensation element is connected at the same time as the cable. This problem does not apply to compensation systems connected to the substation, as a sequential connection is possible.

1.3.1 Scenario 1

All the cables currently installed are less than 7 km long. They are 380 kV cables to connect the Linth-Limmern and Nant de Drance power plants to 380 kV Swissgrid substations. These cables measure 4.54 km and 5.96 km, respectively. The 220 kV Bavona – Peccia cable connection is 6.1 km, and the cable between Grimsel and Gerstenegg measures 2.5 km. There are two cables in the Zurich region, the Riniken and Spreitenbach cables, which are respectively 1.47 and 2.33 km long.

The reactive power generated by the existing cables has not been compensated for until now. Around 100 Mvar from the Linth-Limmern cables and around 130 Mvar from the Nant de Drance cables are currently absorbed by the respective power plants and neighbouring power plants.

As of now, there is only one shunt reactor in the Swiss transmission network with a power rating of 60 Mvar connected to the tertiary widing (16 kV) of the 380/220 kV transformer at Breite.

As the number of cable projects and their lengths increase, more shunt reactors shall need to be installed to keep the voltages within permissible limits.

Since the goal of this theoretical analysis is to compare the amount of compensation required, the same criteria have been applied for all three scenarios. This is why the Linth-Limmern and Nant de Drance compensation systems have been included in this first scenario, even though they are not currently installed.

For the ease of calculation, the reactive power of each cable has been rounded to the nearest ten. A standard-size shunt reactor has then been chosen to meet all the reactive power requirements.

The cables considered in this first scenario and their reactive power are listed in the table below. Cables of less than 1 km are included in the model, but their reactive power generation is not taken into account in the comparison and thus does not appear in the tables.

Project	Operating voltage (kV)	Cable cross-section (mm²)	Cable length (km)	Parallel systems	Cables per phase	Q_{cable} (Mvar)	Substation
220 kV Niederwil – Regensdorf (Spreitenbach)	235	1,200	2.33	1	2	17.79	
220 kV Beznau – Birr (Riniken – Gäbihübel)	235	2,500	1.47	1	2	15.66	
380 kV Beznau – Mettlen (Riniken – Gäbihübel)	410	2,500	1.47	1	2	37.26	
380 kV Châtelard – Nant de Drance	410	1,600	5.96	1	2	125.90	380 kV Châtelard
380 kV Bâtiaz – Le Verney	410	1,000	1.23	1	2	23.29	
380 kV Limmern – Tierfehd	410	1,600	4.54	1	2	95.90	380 kV Tierfehd
150 kV Manno – Mendrisio (Brusino – Morcote)	150	800	2.85	2	1	8.90	
150 kV Manno – Pian Scairolo	150	800	5.59	2	1	17.46	
Total						**342.17**	

Table 1-1: Compensation solution for scenario 1

To avoid compensation that is too low and unrealistic, compensation has only been considered for the longest cables, i.e., those at Nant de Drance and Limmern. Compensation requirements for other cables will be taken into account in scenario 2. Therefore, total compensation in this scenario is 230 Mvar. In order to compensate for 100% of this reactive power while complying with the size requirements suggested above, shunt reactors of 100 Mvar and 150 Mvar have been chosen for Châtelard and Tierfehd respectively, rendering a total of 250 Mvar of compensation capacity.

The cables and shunt reactors for scenario 1 are shown in Figure 1-7.

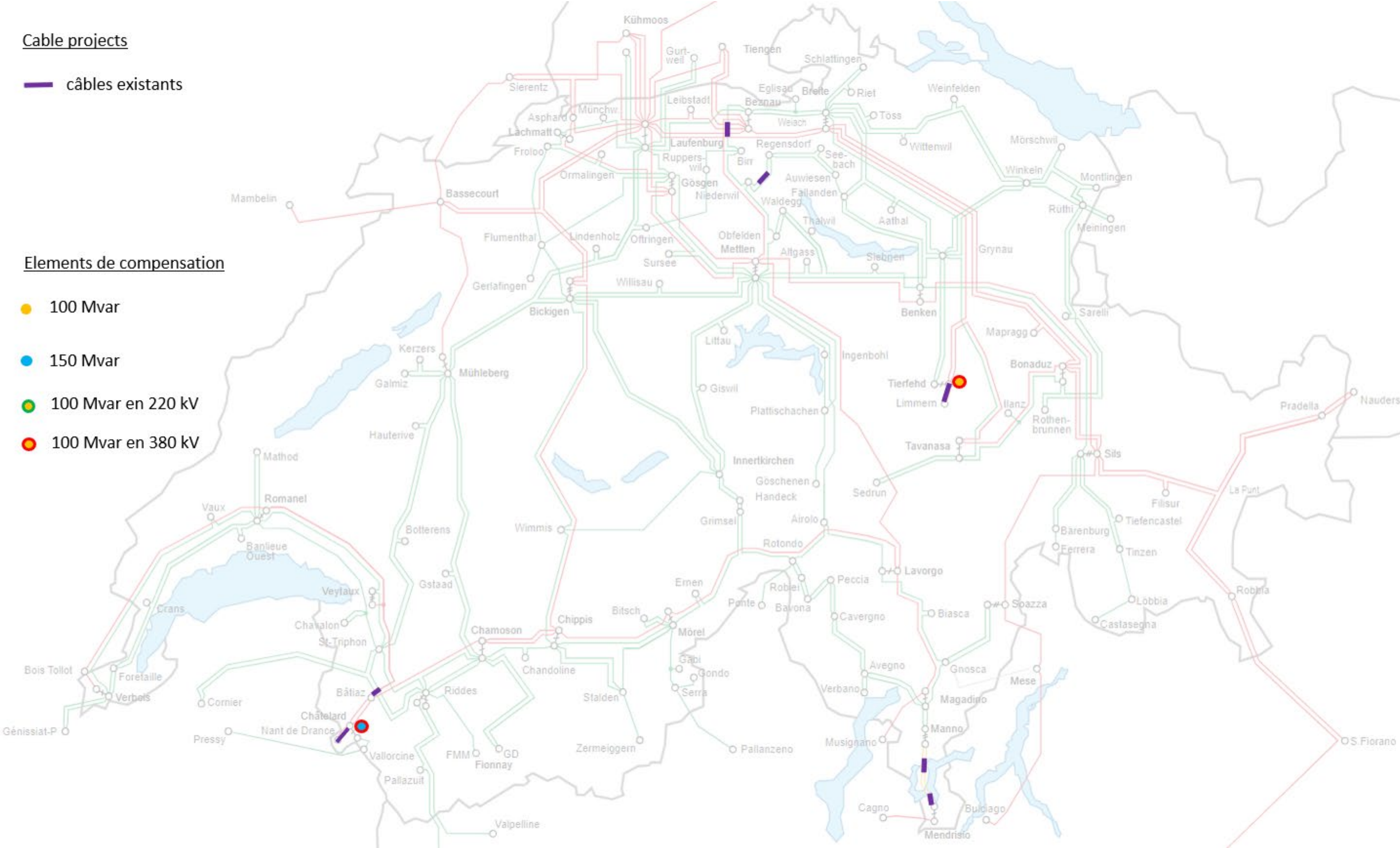


Figure 1-7: Compensation solution for scenario 1

1.3.2 Scenario 2

Scenario 2 includes the cables from scenario 1 with the addition of several new projects that have already been planned, such as Gotthard, Innertkirchen – Ulrichen, Glaubenberg, Maggia Valley and several projects in the Zurich region.

Unlike in the previous scenario, there are some quite long cables measuring around 20 km. As a result, the reactive power compensation requirements are higher, and several shunt reactors are needed for the same project.

In this scenario, the small but significant amount of reactive power generated by the Spreitenbach and Riniken cables in scenario 1 has been taken into account, and 40 Mvar has been added to the 220 kV Niederwil compensation.

The compensation solution suggested for the Innertkirchen – Ulrichen cables is higher than its reactive power generation. This is because two compensations per substation have to be included at Innertkirchen and Seehalten to enable two-node operation. In reality, long cable projects such as this one have to be calculated taking into account a certain margin of redundancy in the event of the unavailability of a shunt reactor. Redundancy requirements have not been taken into account in this analysis to allow a more linear comparison based on the number of kilometres of cable installed.

The location of the compensation is specified in each case. When the word “cable” appears in the place of a substation, this means that a compensation system must be installed along the path of the cable. This table only lists new cables in scenario 2, i.e., the cables to be added to scenario 1 to obtain scenario 2.

Project	Operating voltage (kV)	Cable cross-section (mm^2)	Cable length (km)	Parallel systems	Cables per phase	Q_{cable} (Mvar)	Substation
220 kV Airolo – Mettlen (Gotthard)	235	2,500	18.00	1	1	95.87	220 kV Airolo, cable
220 kV Innertkirchen – Handeck	235	2,500	12.00	2	1	127.83	220 kV Innertkirchen, 220 kV Seehalten
220 kV Handeck – Grimsel	235	2,500	6.50	2	1	69.24	220 kV Innertkirchen, 220 kV Seehalten
220 kV Grimsel – Seehalten	235	2,500	5.30	2	1	56.46	220 kV Innertkirchen, 220 kV Seehalten
220 kV Innertkirchen – Mettlen (and Innertkirchen – Giswil)	235	2,500	5.00	2	1	53.26	220 kV Innertkirchen
220 kV Innertkirchen – Wimmis	235	2,500	5.00	1	1	26.63	220 kV Innertkirchen
220 kV Bickigen – Innertkirchen	235	2,500	5.00	2	1	53.26	220 kV Innertkirchen
220 kV Innertkirchen – Mettlen (and Giswil – Littau)	235	2,500	9.50	2	1	101.20	Cable
220 kV Bavona – Peccia	235	1,400	6.70	1	2	51.15	220 kV Peccia
220 kV Cavergno – Peccia	235	1,400	7.40	1	2	56.49	220 kV Peccia
220 kV Avegno – Cavergno	235	1,400	15.00	1	2	114.51	220 kV Avegno
220 kV Avegno – Magadino	235	1,400	3.30	1	2	25.19	220 kV Avegno
220 kV Foretaille – Verbois	235	2,500	4.80	1	2	51.13	220 kV Verbois
220 kV Niederwil – Obfelden	235	2,500	4.50	1	1	23.97	220 kV Niederwil

380 kV Beznau – Mettlen (parallel to Niederwil – Obfelden)	410	2,500	4.50	1	1	57.03	380 kV Mettlen
220 kV Obfelden – Waldegg	235	2,500	2.00	1	2	21.31	220 kV Waldegg
220 kV Thalwil – Waldegg	235	2,500	10.00	2	1	106.53	220 kV Waldegg
Total						**1,091.06**	

Table 1-2: Compensation solution for scenario 2

According to the information given in the previous table, the planned cables will require a total compensation of 1,091 Mvar. After choosing the standard shunt reactors and adding the compensation from scenario 1, a total of 1,670 Mvar of compensation would be required for scenario 2.

The compensation solution suggested for scenario 2 is shown in Figure 1-8.

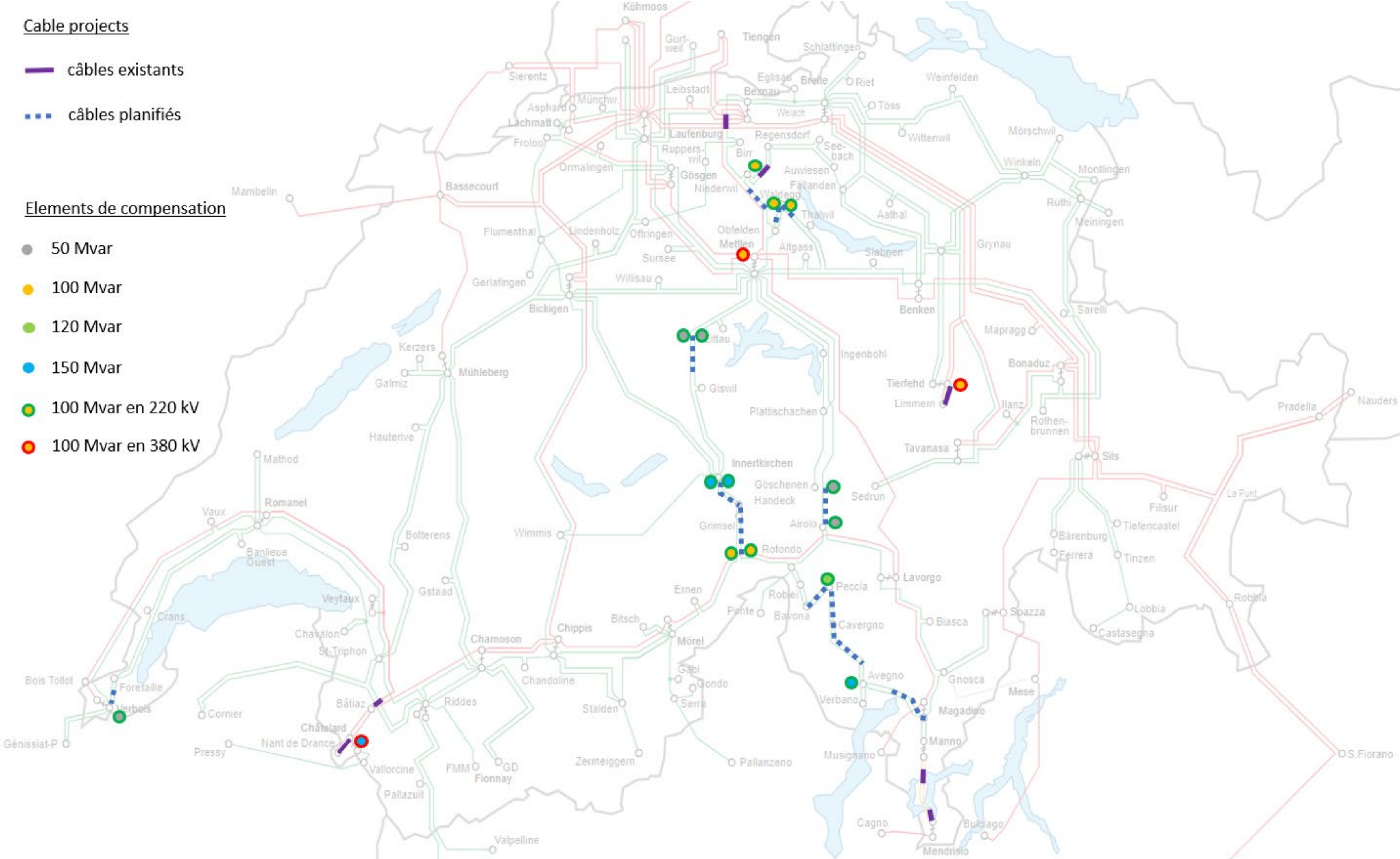


Figure 1-8: Compensation solution for scenario 2

The compensation solution suggested for scenario 2 is comprised of a total of 17 shunt reactors, including 5 of 50 Mvar, 7 of 100 Mvar, 1 of 120 Mvar and 4 of 150 Mvar. The maximum capacity is 1,670 Mvar.

1.3.3 Scenario 3

Scenario 3 includes the cables from scenario 2, with the integration of a large number of new projects. The decision regarding the new cable sections is based on the lines that will be revamped in the coming years. For the purposes of the study, it is assumed that in the course of these line refurbishment projects, these lines shall be partially or entirely converted to cables. The choice of cable cross-sections is based on assumptions. Under no circumstances should these cables be considered as future projects. This scenario has been created for comparative analysis purposes only.

It should be noted that the suggested cable lengths are approximate and are based on current line lengths. Detailed study of the new cable routes has not been carried out.

The following table specifies the location of the compensation scheme for each project. When the word "cable" appears in the place of a substation, this means that a compensation system must be installed along the path of the cable. This table only lists new cables in scenario 3, i.e., the cables to be added to scenario 2 to obtain scenario 3.

Project	Operating voltage (kV)	Cable cross-section (mm^2)	Cable length (km)	Parallel systems	Cables per phase	Q_{cable} (Mvar)	Substation
380 kV Benken – Mettlen (between Mettlen and Samstagern)	410	2,500	20.0	1	1	253.49	380 kV Mettlen, cable
220 kV Altgass – Mettlen (between Mettlen and Samstagern)	235	2,500	17.1	1	1	91.13	220 kV Altgass
220 kV Altgass – Samstagern (between Mettlen and Samstagern)	235	2,500	14.6	1	1	77.55	220 kV Altgass
220 kV Grynau – Mettlen (between Mettlen and Samstagern)	235	2,000	20.0	1	1	97.16	220 kV Mettlen, cable
380 kV Beznau – Breite	410	1,600	17.0	2	2	718.22	380 kV Breite, cable
220 kV Auwiesen – Regensdorf	235	2,000	12.1	2	1	117.56	220 kV Auwiesen
220 kV Auwiesen – Fällanden	235	2,000	6.0	1	1	29.15	220 kV Auwiesen
220 kV Breite – Fällanden and Fällanden – Grynau (Breite – Y/Fehraltorf)	235	2,500	9.0	2	1	95.87	220 kV Fällanden
220 kV Benken – Fällanden	235	2,500	37.0	2	1	394.14	220 kV Benken, 220 Fällanden, cable
220 kV Aathal – Breite and Fällanden – Grynau (Aathal – Y/Fehraltorf)	235	2,500	8.0	2	1	85.22	220 kV Aathal
220 kV Aathal – Grynau	235	2,500	22.0	2	1	234.36	220 kV Aathal, 220 kV Grynau

220 kV Grynau – Samstagern	235	2,000	7.0	1	1	34.00	220 kV Grynau
220 kV Grynau – Winkeln	235	1,600	9.0	2	2	156.15	220 kV Grynau, cable
220 kV Mörschwil – Winkeln (via Y – St.Gallen)	235	2,500	17.0	2	1	181.09	220 kV Mörschwil, 220 kV Winkeln
220 kV Rüthi – Winkeln	235	1,600	12.0	1	2	104.10	220 kV Winkeln
220 kV Bonaduz – Rüthi	235	1,600	15.0	2	2	260.24	220 kV Rüthi, cable
380 kV Bonaduz – Sils	410	1,600	14.0	2	2	591.47	380 kV Bonaduz, 380 kV Sils
220 kV Bonaduz – Rüthi	235	1,600	5.0	2	2	86.75	220 kV Rüthi
380 kV Benken – Sils (West)	410	2,500	13.0	1	1	164.77	380 kV Sils
220 kV Benken – Sils (Ost)	235	2,500	13.0	1	1	69.24	220 kV Sils
380 kV Lavorgo – Mettlen	410	1,600	14.0	1	2	295.74	380 kV Lavorgo, cable
380 kV Sils – Soazza	410	1,600	12.0	1	2	253.49	380 kV Soazza, cable
220 kV Löbbia – Tinzen	235	800	8.0	1	1	27.76	220 kV Tinzen
380 kV Lavorgo – Musignano	410	2,000	13.0	1	2	302.07	380 kV Magadino, cable
Total						**10,590.48**	

Table 1-3: Compensation solution for scenario 3

There is a huge increase in the need for reactive power compensation in this scenario. A total of 10.59 Gvar is required to compensate for the reactive power generated by the new cables in scenario 3. After choosing the necessary standard shunt reactors and adding the compensation from scenario 2, a total of 13.11 Gvar of compensation is required for scenario 3. This compensation need can be fulfilled by 15 shunt reactors of 50 Mvar, 33 of 100 Mvar, 33 of 120 Mvar and 34 of 150 Mvar.

The compensation solution suggested for scenario 3 is shown in Figure 1-9.

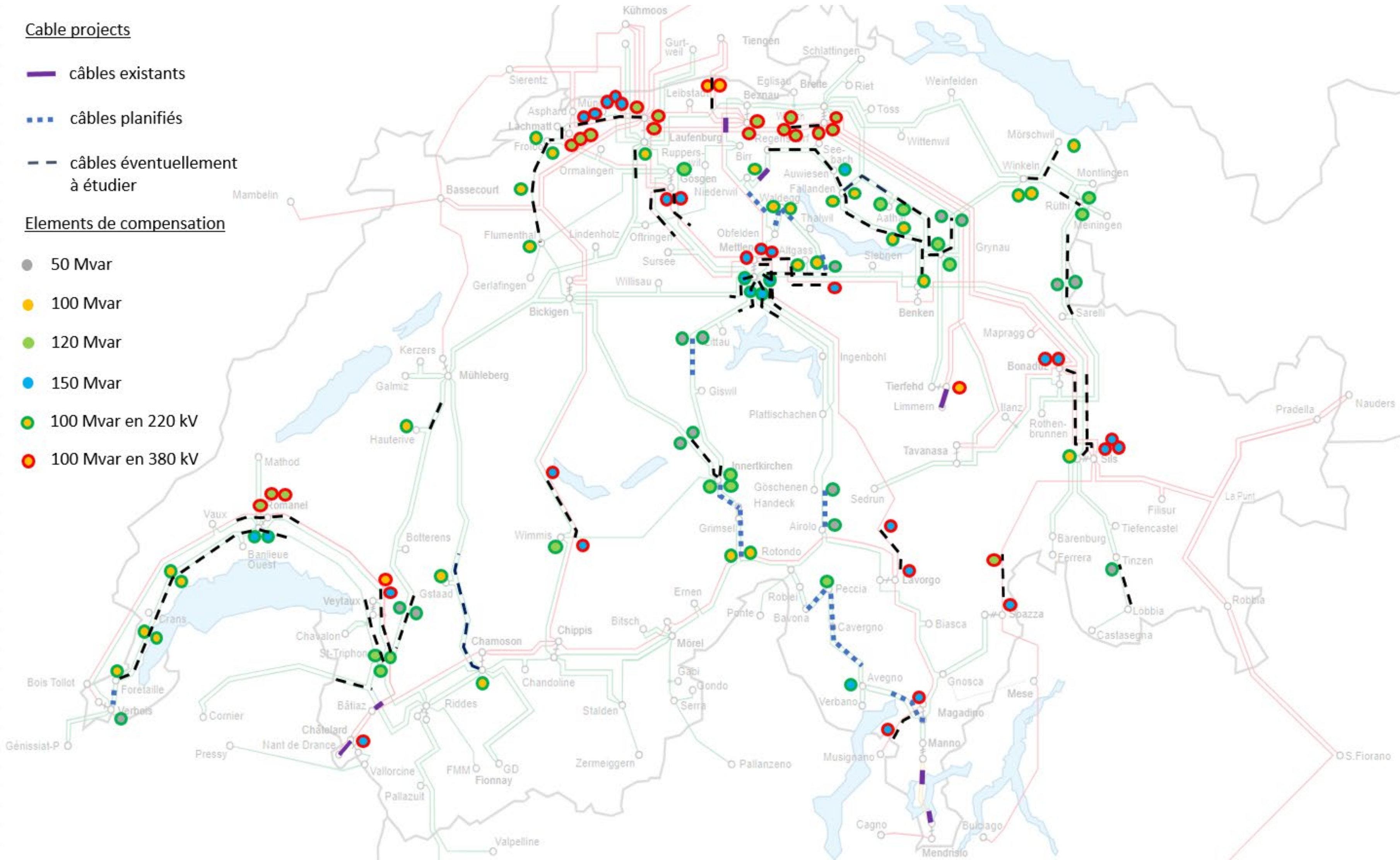


Figure 1-9: Compensation solution for scenario 3

Due to the large number of shunt reactors required in certain areas, the size of some substations would have to be increased considerably. For example, up to 7 shunt reactors would be needed in one substation (Mettlen), and up to 11 shunt reactors would be required along one cable (380 kV Lachmatt – Laufenburg). New substations would then have to be created along the cable route to connect the compensation elements. Intermediate substations would be similar in appearance to the one shown shown in Figure 1-10.

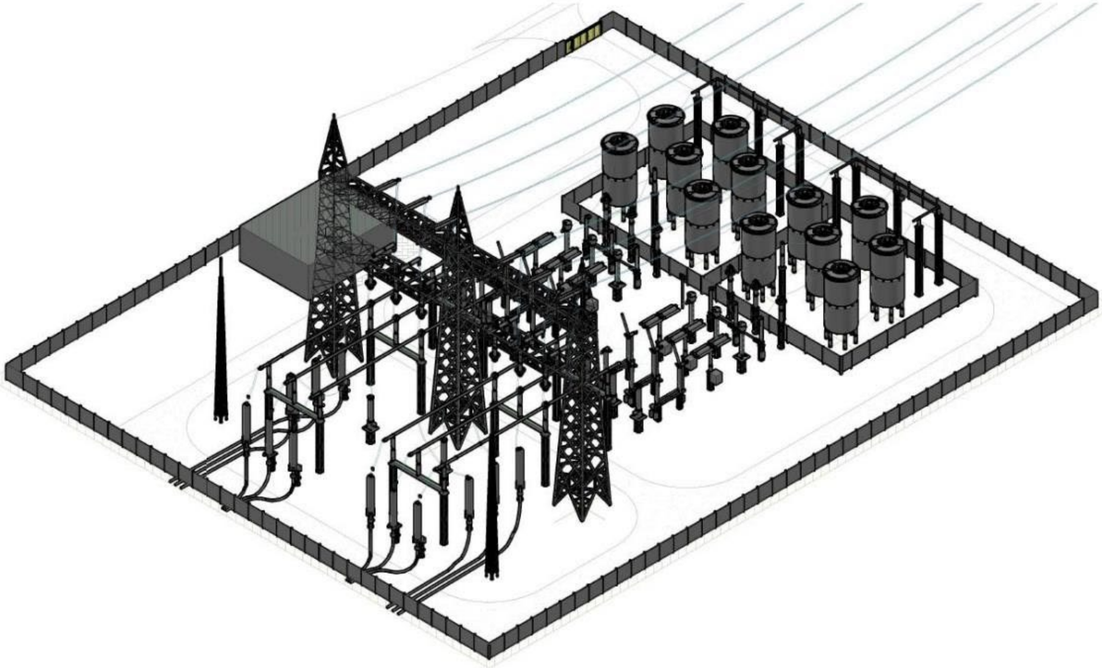


Figure 1-10: Transition substation between a 420 kV overhead line and a cable with a compensation system with ironless air-core reactors (approx. 100 m x 70 m). Source: [1.1]

The Leibstadt nuclear power plant can be taken as a reference to understand these numbers. This power plant can absorb up to 513 Mvar of reactive power with an active power generation of 1,220 MW. Without installing shunt reactors to compensate for the cables, 25 power plants as such would be needed to absorb all the reactive power generated in scenario 3. This comparison merely serves to facilitate understanding of the numbers involved. A solution as such would be neither technically feasible nor sustainable.

One particular characteristic of reactive power is that it must be compensated for where it is generated. Otherwise, it would have to be transported by lines and cables to the point of absorption. This would overload the grid and require oversized lines and cables. For this reason, the space reserved for the installation of the shunt reactors should be next to the cables. This means that the visual impact of an overhead line would not be eliminated but would simply be replaced by shunt reactors.

1.3.4 Summary of reactive power compensation requirements

To facilitate the comparison of the three scenarios, the following table summarises the compensation elements required with the cable lengths taken into account. The type of coil is shown in brackets. The first figure within the brackets indicates the number of air-insulated coils and the second the number of oil-insulated coils. The cable length is calculated according to the number of systems and the number of cables per phase. A cable with 2 systems and 2 cables per phase is counted by multiplying its length by 4.

	Scenario 1	Scenario 2	Scenario 3
Q produced by the cables (Mvar)	342	1,433	12,365
Q compensation (Mvar)	250	1,670	12,960
Number of 50 Mvar shunt reactors	0	5 (3/2)	15 (12/3)
Number of 100 Mvar shunt reactors	1 (0/1)	7 (0/7)	33 (9/24)
Number of 120 Mvar shunt reactors	0	1 (0/1)	33 (0/33)
Number of 150 Mvar shunt reactors	1 (0/1)	4 (0/4)	33 (0/33)
Total number of shunt reactors	2	17	114
Cable length (km)	51	268	1,132

Table 1-4: Number of shunt reactors by type and scenario

1.4 Estimated space required for shunt reactors in scenario 3

The size of a compensation shunt reactor, taking into account the space required for grid connection and isolation, is equivalent to around 3,000 m². This is a mean value for shunt reactors of between 50 and 150 Mvar, which can take up between 2,000 and 5,000 m² depending on their size and voltage level. This figure takes into account the surface area required to connect the shunt reactor to the grid and the insulation space. However, access to the shunt reactor is not considered in the calculation.

114 shunt reactors are required in the compensation solution suggested for scenario 3, which means that these shunt reactors would require a minimum of 342,000.00 m² of extra space. Taking the space required for a football pitch (around 7,200 m²) as a known reference, 48 football pitches would be needed in the immediate vicinity of the new cables to install the necessary reactive compensation elements.

Currently in the Swissgrid network, space is already limited for additional elements at various substations. If a cable project were to be implemented near these substations, , significant grid structure modification would be entailed. New substations would have to be built elsewhere to such that shunt reactors can be connected to cable terminals. Intermediate stations would have to be built to allow compensation elements to be installed along certain cable routes. In addition, substantial changes would have to be made to the current line routes. A large number of planning application procedures would also have to be undertaken, which would extend the total time required to complete the projects.

The Lachmatt substation in scenario 3 is a good example to illustrate such an issue. The available space is already limited, and there are plans to install a new 380/220 kV transformer as well as a feed in/out connection for the 380 kV Asphard – Gösgen line. The installation of a 380 kV Lachmatt – Laufenburg cable with a length of 32 km would require compensation at 380 kV Laufenburg, several shunt reactors along the cable route as well as at 380 kV Lachmatt. In particular, 3 shunt reactors of 120 Mvar would be required at 380 kV Lachmatt. In a substation that is already short of space, an additional 9,000 m² would be needed to accommodate the shunt reactors.

Figure 1-11 illustrates the layout of the Lachmatt substation, taking into account the current project to install a 380 kV GIS, the new 380/220 kV transformer and the feed in/out connection for the 380 kV Asphard – Gösgen line. The estimated surface area required for these new elements is 7,850 m² (in blue).

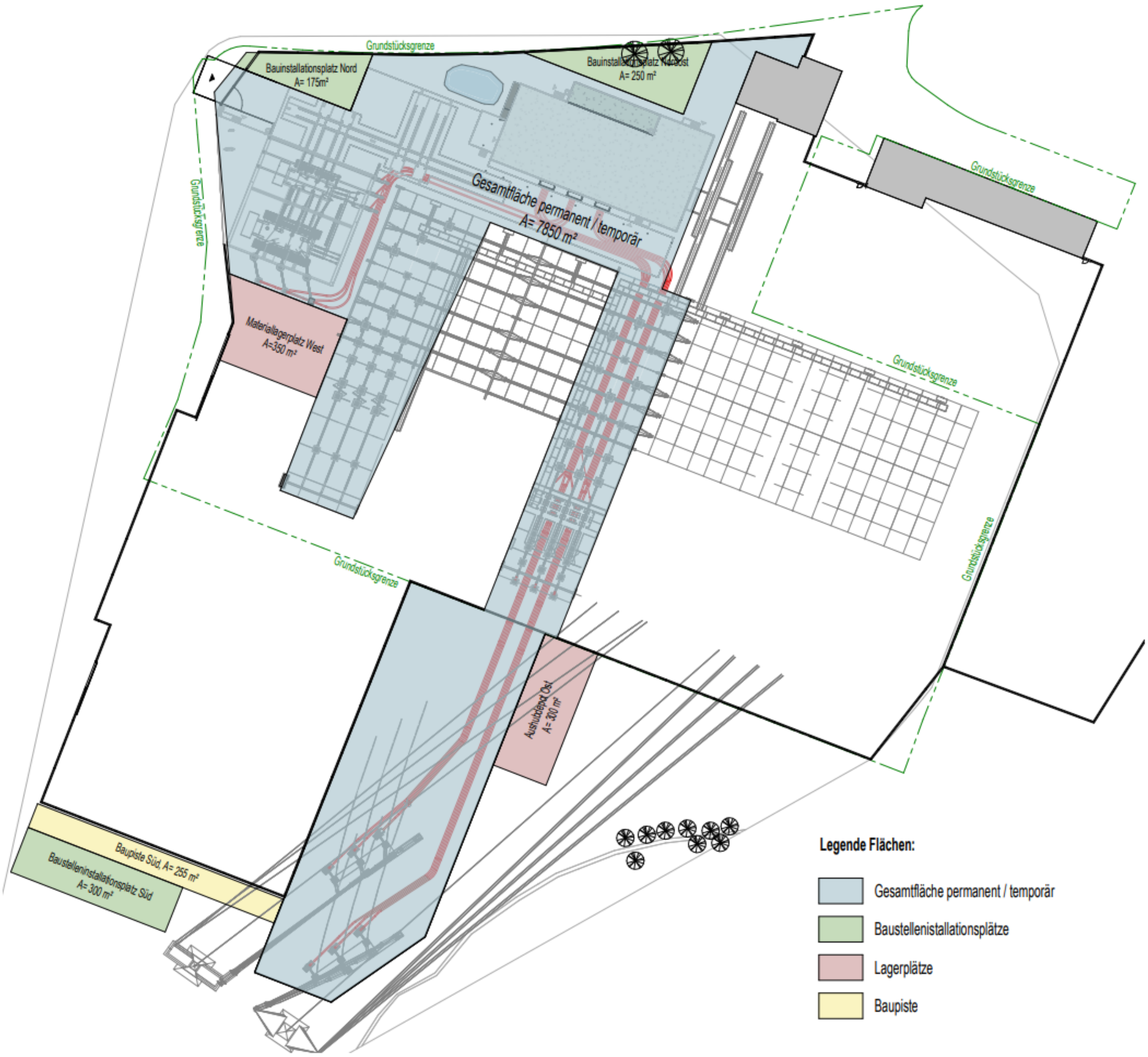


Figure 1-11: Lachmatt substation

If the project of installing a 380 kV cable between Lachmatt and Laufenburg was approved, three 120 Mvar coils would be required at 380 kV Lachmatt. The surface area occupied by these three coils (approximately 9,000 m²) would be greater than the surface area required for the entire substation refurbishment project, including a new GIS, a transformer and a line feed-in/out.

As is shown in Figure 1-12, it is not possible to extend the Lachmatt substation to accommodate the coils.

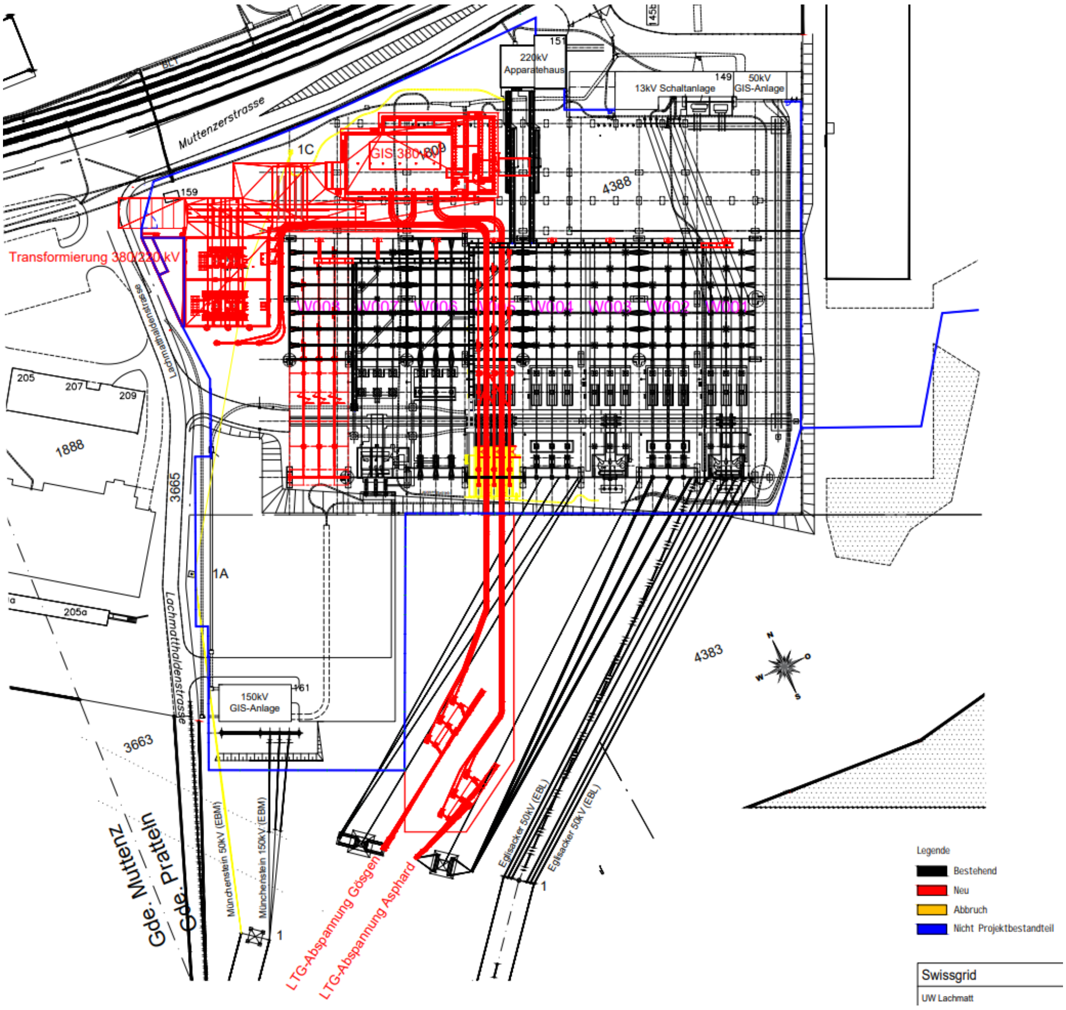


Figure 1-12: Lachmatt substation

The solution would be to find another place for the shunt reactors in the immediate vicinity of the substation and to connect them by cable. Alternatively, a new, larger substation would have to be built elsewhere in Lachmatt.

A zoom of Figure 1-9 is shown below to illustrate the number of shunt reactors required for the Lachmatt – Laufenburg 380 kV cable project.

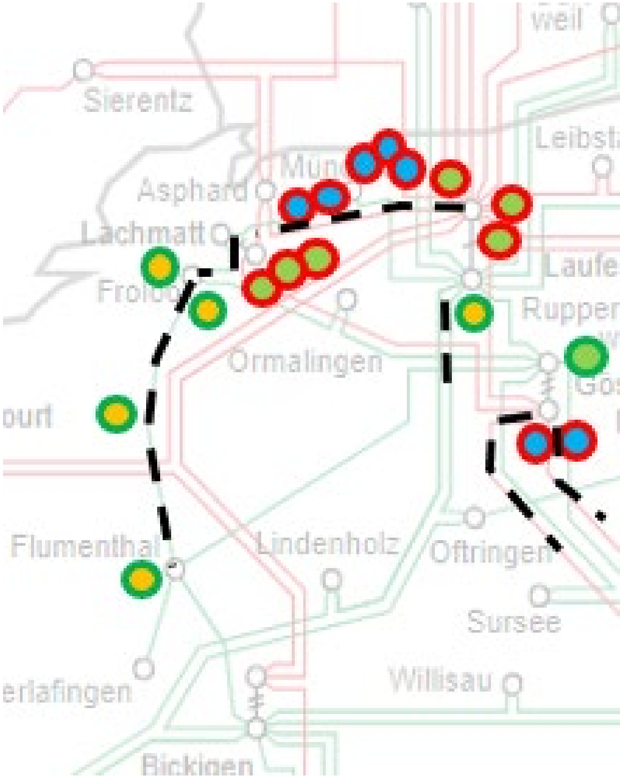


Figure 1-13: Compensation shunt reactors in scenario 3 near Lachmatt

In addition to compensation at Lachmatt, it would also be necessary to connect five 150 Mvar shunt reactors to one or more intermediate stations along the cable route. This would require the construction of intermediate stations like the one shown in Figure 1-11 between Lachmatt and Laufenburg.

Finally, three 120 Mvar shunt reactors would also be required at 380 kV Laufenburg. A total of 11 shunt reactors would take up at least 33,000 m² to absorb the 1,470 Mvar produced by a single cable project.

Following the same reasoning for other grid locations, we would quickly come to the conclusion that existing substations in the vicinity of large numbers of cables would be too small to accommodate the new compensation elements required. The structure of the Swiss transmission network could be considerably affected by the constraints imposed by cable projects.

The size of existing substations in the Swissgrid grid varies from 743 m² in Robbiei to 137,924 m² in Laufenburg, with the average being 19,527 m² and a total surface area of 2,460,435 m². The 114 coils from scenario 3 would require 342,000 m², which corresponds to 14% of the surface area currently occupied in total by all Swissgrid's substations. The surface area required for a single shunt reactor (3,000 m²) is more than three times the size of the smallest existing substation. A single shunt reactor represents 15% of the size of an average substation. As shown in Figure 1-13, multiple substations would require compensation elements in scenario 3. Several substations would need two or even three shunt reactors. Installing a similar number of cables to that envisaged in scenario 3 would increase the surface area taken up by substations by around 14%. This is an optimistic estimate, assumingthat all the necessary substations could be expanded, which, as we have seen, is far from the case.

1.5 Calculation of the cost of compensation elements for the three scenarios

The costs of compensation for each scenario studied were calculated. The unit prices, taking into account according to size, voltage level and type of insulation, are shown in the table below. They include the shunt reactor, foundations, an AIS DSS field, field control technology, station control technology, communication, planning, auxillary services and losses (capitalised at the time of investment) [1.2]. However, the cost does not take into account factors such as space limitation and the need to build new substations. The cables themselves are not included in the cost calculation either. The table shows the cost per scenario, which amounts to CHF 29.9, 182.2 and 1,365.9 million for scenarios 1, 2 and 3 respectively.

		Number of shunt reactors			**Costs of shunt reactors [CHF million]**		
	Unit price [CHF million]	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
50 Mvar air-insulated 220 kV	4	0	3	12	0	12	48
50 Mvar oil-insulated 220 kV	8	0	2	3	0	16	24
100 Mvar air-insulated 220 kV	5	0	0	7	0	0	35
100 Mvar oil-insulated 220 kV	11.3	0	5	22	0	56.5	248.6
120 Mvar oil-insulated 220 kV	12.4	0	1	15	0	12.4	186
150 Mvar oil-insulated 220 kV	14	0	3	8	0	42	112
50 Mvar air-insulated 380 kV	5	0	0	0	0	0	0
50 Mvar oil-insulated 380 kV	9.7	0	0	0	0	0	0
100 Mvar air-insulated 380 kV	6	0	0	2	0	0	12
100 Mvar oil-insulated 380 kV	13.4	1	2	2	13.4	26.8	26.8
120 Mvar oil-insulated 380 kV	14.5	0	0	18	0	0	261
150 Mvar oil-insulated 380 kV	16.5	1	1	25	16.5	16.5	412.5
Total		**2**	**17**	**114**	**29.9**	**182.2**	**1,365.9**

Table 1-5: Cost of compensation shunt reactors by type and scenario

2 WP 2 – EMT studies of systems and equipment

2.1 Executive summary

The analyses presented in this report represent work package 2 of the Swiss cable study and are used for the purpose of EMT simulations for the three study scenarios shown in annex [4.4.1]

In this study, “cables” refer to underground XLPE cables. Therefore, for the readers’ convenience, only the word “cable” will be used hereinafter.Extensive system- and equipment-level EMT studies have been performed in this work package to evaluate the impact of the cable systems proposed in the three scenarios on the behavior and performance of the existing grid in both frequency- and time-domain.

With focus on network resonances and harmonics, the frequency-domain studies were carried out in a two-step manner: frequency screening and harmonic amplification. Frequency screening studies focus on determining the network locations that are sensitive to certain parallel resonances due to cable integration well as well their respective resonant frequencies, which are crucial in identifying potential risks (and severity) of TOVs that may be encountered during network transients such as energization events. Harmonic amplification studies, on the other hand, carry the goal of predicting how much low-order harmonics infiltrating into the network from nonlinear loads and power electronics devices can be amplified in densely cabled areas under certain grid conditions due to resonances, causing power quality issues, stressing and even damaging different kinds of network equipment.

Time-domain studies for an AC network usually cover a large variety of transient events, including but not limited to energization of large transformers/saturable shunt reactors/capacitor banks/overhead lines/cables, faults (e.g., ground faults, transformers, generator, etc.) and clearing, insulation coordination, load rejection, system islanding, circuit breaker auto-reclosing, etc. Considering the specifics of this project, we focus mostly on the energization studies of large transformers at the sensitive network locations identified in the frequency screening studies to assess the risks of excessive TOVs to be expected with the cable projects proposed in the different scenarios.In addition, an analysis is provided to represent the relationship between cable connection and the steady-state voltage rise caused by the cable’s reactive power at its connection point. This relationship helps to determine, on the one hand, the maximum total length of cable allowed to be implemented near a certain node with respect to its short-circuit power, and on the other hand, the maximum size of compensation equipment needed to avoid excessive voltage rise on a node when a compensation element is lost.

The main conclusions drawn from the performed studies are presented as follows:

2.1.1 Frequency scan studies

- Several critical cases of parallel resonance have been identified in Scenario 3 with the most cable projects.

While the frequency response at various network locations under different operating conditions remains rather non-critical for Scenarios 1 and 2, several extremely critical cases of parallel resonances have been identified in Scenario 3. With severe risks of parallel resonance at the 2nd and the 3rd harmonics, these cases would cause highly distorted and poorly damped TOVs during on-site transients, leading to considerable thermal and dielectric stress on network equipment and even equipment failure. These cases are found at 380 kV network locations of Romanel and Magadino.

Furthermore, potential risks of parallel resonance on the 3rd harmonic might arise at other locations, such as 220 kV Wimmis, and 380 kV Lavorgo, if these areas become even more densely cabled than they are in Scenario 3.

- The system frequency response may deteriorate further in scenario 4 with an even higher number of cable projects than in scenario 3.

In an additional scenario 4 where the number of cable projects is higher than in scenario 3, the deterioration in the system frequency response can be confirmed in areas of the grid where the frequency response was not critical in scenarios 1, 2 and 3. At 380 kV Nant de Drance, 380 kV Mörel, 380 kV Lavorgo, 380 kV Tierfehd, 380 kV Filisur and 380 kV Soazza, previously non-critical parallel resonances become critical with even lower frequencies and higher impedance amplitude, while in other cases, new parallel resonance peaks appear at lower-order harmonics, posing risks of critical TOVs during grid transient events.

- The increase in the number of cable projects in the grid (from scenario 1 to scenario 3) shifts the parallel resonant frequencies of the system towards lower harmonics, increasing the risk of TOVs.

Comparison of frequency response at various network locations between Scenarios 1, 2 and 3 shows a noticeable shift of parallel resonance towards low-order harmonics. In particular, the parallel resonant frequencies for Scenario 3 at multiple network locations shifts to under the 4th harmonic (i.e., 200 Hz), which would expose the network to considerable risks of TOVs due to the excitation of low-order harmonic parallel resonance during transients, especially under unfavorable operating conditions such as low short-circuit power and contingencies.

- Cable integration has a higher impact on the 380 kV grid than the 220 kV due to lower system damping in the former.

Compared to the 220 kV grid, the 380 kV is significantly less meshed with fewer generation groups and loads connected to it, which makes it that the network damping on the 380 kV is generally lower as compared to the 220 kV grid, resulting in higher impedance amplitude at resonances. Since a high system damping helps to mitigate TOVs and other transients during on-site operations and events, cable integration on the 380 kV grid is expected to have a larger impact on the overall grid performance and equipment safety than on the 220 kV grid. That is to say, it would be “safer” to consider implementing cable projects on the 220 kV grid than on the 380 kV grid.

2.1.2 Harmonic amplification studies

- The amplification of low-order harmonics worsens as the number of cable projects in the grid increases.

No risks of harmonic amplification should be expected in a network comprised purely of overhead lines. Integrating cable projects into a network introduces capacitive elements into the grid, significantly increasing the risks of amplification on certain low-order harmonics. In general, as the number of cable projects increases, the amplification of low-order harmonics becomes more severe, as can be seen in the comparison between Scenarios 1, 2 and 3. This is the case for the amplification of the 7th harmonic at the 220 kV Crans, 220 kV Banlieue Ouest, 220 kV Romanel and 220 kV Vaux substations. This amplification becomes critical in scenario 3, whereas it is negligible in scenarios 1 and 2. In the vicinity of Nant de Drance, the amplification of the 7th harmonic already exists in the current situation but increases significantly in scenario 3.

However, there are exceptions to this rule, as demonstrated in section 2.3.2.1.3 by the example of the reduction in the amplification of the 5th harmonic at Airolo in scenario 3. For this reason, detailed harmonic amplification studies should be carried out for all new cable projects so that any potential harmonic resonance problems can be anticipated at the planning stage.

- High short-circuit power can alleviate harmonic amplification problems.

Comparisons of amplification of low-order harmonics between low and high short-circuit power conditions at multiple network locations have been made. In general, increasing the network short-circuit power can mitigate issues related to amplification of low-order harmonics by shifting the harmonic resonant frequency towards higher frequencies and damping harmonic resonance on different harmonic travelling paths.This is the case for the amplification of the 5th harmonics at Airolo in scenario 2, where the amplification could be as much as 11 times higher in the low short-circuit power condition. However, exceptions to this rule have once again been discovered. In the vicinity of Nant de Drance, higher amplifications are observed with low short-circuit power in scenario 2. However, in scenario 3, harmonic amplifications are higher with higher short-circuit power. This case is explained in detail in sections 2.3.2.2.2 and 2.3.2.2.3.

- A single cable project in a densely cabled grid can have a significant impact on harmonic amplification in distant locations.

Issues of harmonic amplification become increasingly complex as more and more cables are integrated into the network. In a densely cabled network, the specific implementation scheme of a certain network segment either with overhead lines or with cables would not only have an impact on harmonic amplification in the local area, but it may also have a large impact on the amplification of low-order harmonics in a remote area. For example, the 220 kV section Altgass – Samstagern would have an impact on the amplification factors observed in Ticino. The complexity of this issue demonstrates once again the need of harmonic amplification studies for any new cable project to be integrated into the network while considering possible different implementation schemes (lines or cables) of each project.

Overall, amplification of low-order harmonics during cable integration (especially intensive cable integration) can be a tricky issue, which would absolutely require detailed harmonic amplification studies for the purpose of risk identification, definition of certain operating principles as well as decision-making on filter design and installation.

2.1.3 Time-domain studies (energisation of large transformers)

- Critical TOVs are to be expected during transformer energisation at locations sensitive to parallel resonances in scenario 3 (e.g. 380 kV Romanel and 380 kV Magadino).

In Scenario 3, severe and poorly damped TOVs can be observed when energizing the large transformers at 380 kV Romanel and 380 kV Magadino under certain grid topologies and configurations. With the TOV amplitude exceeding 1.5 pu in certain cases, these TOVs would pose considerable dielectric and thermal stress on the network equipment in proximity, causing equipment premature ageing and even failure.

Nonetheless, it is also observed that for Scenario 2 with much fewer cable projects, the same grid topologies and configurations would result in much mitigated TOVs such that concerns for grid operation stability and security should not be raised.

Overall, it is safe to say that intensive cable integration, such as in Scenario 3, would greatly increase risks of critical TOVs at multiple network locations during on-site transient events.

- The short-circuit power at a given point on the grid plays an important role in the impact of integrating cables in the vicinity. Further studies have been carried out to demonstrate this.

As is already known, cable integration generally tends to decrease the parallel resonance frequencies at various network locations, exposing them to potential risks of critical TOVs during on-site transient events such as energization, fault recover, system islanding, etc. However, the impact of cable integration varies from one node to another, depending on the short-circuit power of the node.

For a weak node such as 380 kV Romanel, increasing the cabling length proposed in Scenario 3 from 40 km to 117.4 km around 380 kV Romanel further shifts the parallel resonance from the 3rd harmonic towards the

2^{nd} harmonic, leading to much more aggravated TOVs (from 1.32 pu to beyond 1.5 pu) for a certain N-1 contingency during the energization of the Romanel transformers.

On the other hand, for a strong node such as 380 kV Laufenburg, almost tripling the cabling length from 64.8 km to 171.74 km would only slightly shift the parallel resonant frequency by less than 10 Hz in a tested N-1 contingency. In addition, the high system damping brought by the high short-circuit power makes it that the network harmonic impedance at 380 kV Laufenburg at low-order harmonics (i.e., 2^{nd}, 3^{rd}, and 4^{th}) is sufficiently low to avoid the excitation of any low-order parallel resonances. Unsurprisingly, no TOVs can be observed during the energization of the Laufenburg transformer for either tested case, even with intensive cabling in proximity to 380 kV Laufenburg.

To sum it up, it would be rather safe to integrate cable projects in the vicinity of a strong node as minimum impact on the existing grid can be expected. However, attention should be paid when integrating cable projects close to a weak node since further detailed investigations or studies might be necessary.

2.1.4 Voltage step due to the connection of cables and/or the loss of a compensation device

The reactive power generated by cables causes an increase in the steady-state voltage of the node to which the cable is connected. This voltage rise is directly proportional to the amount of reactive power generated by the cable and inversely proportional to the short-circuit power of the node. Considering that the reactive power produced by a cable is directly related to its length, we can conclude that a strong node (high short-circuit power) is more capable to withstand the connection of a large number of cables without it having a great influence on its steady-state voltage.

By definition, the maximum permissible voltage step in the Swissgrid network is 2% [2.29]. Given this limit, it is possible to estimate the maximum total length of cables connected to a node based on the short-circuit power for a given operating voltage.

Similarly, when a cable is in operation and its compensating element is lost (e.g., due to a fault or operation failure), the voltage of the corresponding node tends to increase. The power rating of the shunt reactors should, therefore, be limited so that the loss of one of these elements does not cause a steady-state voltage rise exceeding the 2% limit.

In summary, the analyses show that compensation elements with a power rating of less than 200 Mvar should be used for nodes with a minimum short-circuit power of below 10 GVA. These results should always be treated with caution and used as an preliminary evaluation, bearing in mind that more in-depth studies may be necessary, especially for weak nodes.

2.2 Frequency scan studies

A power system network is composed of various electrical equipment and components that are resistive, inductive or capacitive in nature. Some of these inductive and capacitive reactances may become equal to one another at certain frequencies, leading to series or parallel resonances. The number and frequency of these resonant points depend on multiple factors, such as the complexity of the network and the lumped or distributed nature of its components, the parameters of their electrical characteristics, their locations in relation to each other and the point of interest. On the other hand, components of nonlinear nature (e.g., transformer iron core) and certain switching operations (e.g., energization events, power electronic devices in normal operation, ground fault clearing, system islanding, etc.) could generate voltage and current waveforms with components across a wide spectrum of frequencies. These rich harmonic voltage and current components, when certain conditions are met, would cause poorly damped oscillations at system resonant frequencies, leading to excessive harmonic distortion and overvoltages. This can be illustrated using an example where a nonlinear inductance is switched onto a simple RLC network, as is shown in Figure 2-1.

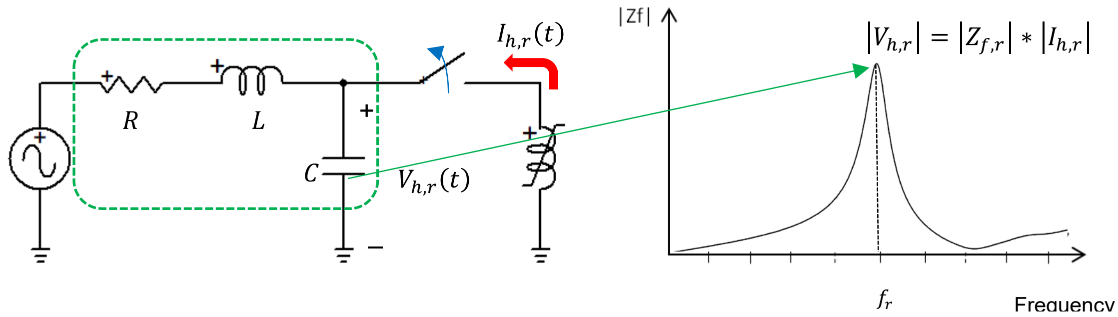


Figure 2-1: Illustration of the connection of a non-linear inductor to an RLC grid

As is shown in Figure 2-1, the RLC network has a parallel resonant frequency at f_r with a relatively high impedance. This resonance is defined by the LC components in the network:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

The nonlinear inductance, such as a saturable transformer or shunt reactor, injects currents containing a wide spectrum of frequency components when switched on. As a result, the current component at f_r, $I_{h,r}$, will be amplified by the large network impedance at resonance $Z_{f,r}$, leading to a relatively high voltage component at f_r seen at the network terminal, represented by $V_{h,r}$. This voltage component, superimposed on the fundamental frequency voltage component $V_{50\ Hz}$, would give rise to higher-than-normal voltages (overvoltages) measured in the network. These overvoltages would cause insulation and equipment premature ageing, deterioration or even failure from excessive dielectric stress and/or heating.

Therefore, it is crucial to perform studies on network harmonics and resonances to evaluate the sensitive points in the network that are prone to resonance and stability issues prior to introducing new electrical components and equipment or to conducting in-depth analyses.

Moreover, underground cables are generally considerably more capacitive compared to overhead lines, potentially driving network resonant frequency points towards lower-rank harmonics, which makes it particularly important to perform studies on network harmonics and resonances in a cable-dense transmission grid.

The studies on network harmonics and resonances are usually performed in a two-step manner, with the first step, namely frequency screening, focusing on determining the network points that are sensitive to resonances (either parallel or series) as well as their respective resonant frequencies and the second step, which is harmonic amplification, aiming to evaluate the system response to certain harmonic frequencies in terms of amplification.

The outcomes of frequency screening studies are presented in this section whereas those of harmonic amplification are presented in section 2.3.

2.2.1 Methodology

In EMTP, frequency screening of the harmonic impedance at a certain network location can be performed by injecting a current of 1 A of a specific frequency within a pre-defined frequency range into the point of interest and measuring the voltage response at this point. The measured voltage across the pre-defined frequency spectrum corresponds to the harmonic impedance seen at the driving point.

In general, frequency screenings are usually carried out up to 2500 Hz (i.e., the 50th harmonic frequency). Considering the specifics of the Swiss transmission grid and the TOVs (temporary overvoltages) excited by certain transient events, we are interested in any parallel resonance up to the 7th harmonic frequency (i.e., 350 Hz). Therefore, it is deemed sufficient to perform frequency screening up to 500 Hz in the scope of this work. Note that among all the possible parallel resonant frequencies under the 7th harmonic, attention shall be directed to resonant frequencies at or close to low-order integer harmonic frequencies (i.e., 100 Hz, 150 Hz, 200 Hz, etc.).

Network short-circuit power plays an important role in the resonance. Generally speaking, a high short-circuit level (SCL) tends to shift the parallel resonance towards higher frequencies, reducing potential risks of TOVs excited by any resonance. On the contrary, a low SCL would further push the grid resonance towards lower frequencies, thus increasing potential risks of resonance excited TOVs during transient events. The short-circuit power at a certain node in the network depends on multiple factors, such as production level if generation groups are present, planned or unplanned contingencies, equipment outages (e.g., transformers, lines/cables, shunt reactors/capacitors, SVCs, filters, etc.).

The network EMT model allows switching between two production levels - optimal and low. The optimal production level (optimal SCL hereinafter) allows to evaluate the network response under optimal operating conditions in terms of production. It is calculated at each node based on internal short-circuit studies. The low SCL condition, on the other hand, is a fictive operating condition, with the objective of studying the system response under non-optimal operating conditions when local generation groups are at 50% of their respective capacity. In frequency screening studies, low SCL, together with various N-1 (and N-2 in certain cases) line/cable contingencies have been considered, aiming to evaluate the frequency response of the network with the planned cable projects under "unfavorable" grid conditions to achieve a conservative overall assessment. The N-1 (and N-2) contingencies are carefully defined to achieve the more "unfavorable" grid conditions (e.g., lower-order resonances, lower SCL, etc.).

Furthermore, apartment from resonant frequencies, the network harmonic impedance amplitude at resonance, which is related to grid damping (i.e., grid configuration, loading conditions, etc.), is also a determining factor of the severity of TOVs that can be excited by certain transient events. Lacking relevant international standards, TSOs across Europe usually employ their own critical threshold values for the harmonic impedance amplitude at resonance. A few examples are given in Table 2-1 [2.1].

TSO	Critical threshold values
Svenska Kraftnät	100 Hz ± 10 Hz: 400 Ohm 150 Hz ± 10 Hz: 800 Ohm
Eirgrid	<150 Hz: 1,000 Ohm
Energinet	100 Hz ± 10 Hz: 400 Ohm 150 Hz ± 10 Hz: 600 Ohm 200 Hz ± 10 Hz: 2,400 Ohm
RTE	Different values for harmonics between 2 and 10

Table 2-1: Critical threshold values for harmonic impedance amplitude used by European TSOs

Note that a margin of ±10 Hz has been adopted by most TSOs when it comes to frequency screening analyses to account for possible deviations between the simulation results and the real network due to inaccuracies in modelling approaches, assumptions, unpredictable grid conditions, etc. According to Table 2-1 and from a conservative perspective, we will focus on parallel resonances at or near harmonic frequencies of up to 200 Hz with a margin of ±10 Hz and the critical threshold values given in Table 2-2.

Resonant frequencies	Critical threshold values
100 Hz ± 10 Hz	400 Ohm
150 Hz ± 10 Hz	600 Ohm
200 Hz ± 10 Hz	2,400 Ohm

Table 2-2: Critical impedance threshold values for harmonics up to the 4th harmonic in this study

Frequency screening has been performed at a total of 28 network locations at either voltage level, as is shown below. These locations are chosen based on the presence of large Swissgrid 220/380 kV transformers and/or their proximity to the planned cable projects.

220 kV Altgass	220 kV Auwiesen	220 kV Benken	220 kV Bickigen
380 kV Bickigen	220 kV Chamoson	380 kV Châtelard	220 kV Fällanden
220 kV Froloo	220 kV Flumenthal	220 kV Gösgen	380 kV Gösgen
220 kV Lachmatt	380 kV Lachmatt	220 kV Laufenburg	380 kV Laufenburg
380 kV Lavorgo	220 kV Magadino	220 kV Mettlen	380 kV Mettlen
220 kV Mühleberg	220 kV Romanel	380 kV Romanel	220 kV Sarelli
380 kV Sils	380 kV Soazza	220 kV Wimmis	220 kV Winkeln

2.2.2 Results and discussion

The following conclusions can be drawn from the performed studies:

- Several critical cases of parallel resonance in terms of resonant frequencies and harmonic impedance amplitude (as per Table 2-2) have been found in Scenario 3 with the most cable projects at 380 kV Romanel and 380 kV Magadino under certain network conditions (see Section 2.2.2.1).
- With an even higher cable content than in scenario 3, a deterioration in the system frequency response in relation to scenario 3 was observed and confirmed in scenario 4. In scenario 4, low-order critical harmonic resonances were observed at several locations in the grid, whereas they had not been observed in the previous scenarios 1, 2 and 3. In some cases, previously non-critical parallel resonances become critical after shifting to lower-order harmonics due to additional cable projects, while in other cases new parallel resonance peaks appear at lower-order harmonic frequencies, with a significant impedance amplitude that would lead to a critical TOV during grid transients (see section 2.2.2.2).
- The increase in the number of cable projects shifts the resonant frequencies of the system towards lower-order harmonics at various grid locations, which, in turn, increases the risk of TOVs and low-order harmonic resonances during grid transients (see section 2.2.2.3).
- Compared to the 380 kV grid, the more meshed 220 kV grid generally ensures higher system damping at various locations on the grid, which reduces the potential risks of TOVs and resonances brought by the integration of cable projects. This implies that it is relatively “safer” to implement cable projects on the 220 kV grid as compared to the 380 kV grid (see section 2.2.2.4).

The four main conclusions above are examined in more detail in the respective sections. The frequency scan studies were first carried out on scenario 3. For ease of reading, the results posing risks of lower-order harmonic resonances are described in section 2.2.2.1, whereas the rest are presented in annex 4.4.3.

In addition, it should be pointed out that although they have not been identified as locations with critical risks of parallel resonance, 220 kV Wimmis and 380 kV Lavorgo deserve the readers' attention, as potential risks of parallel resonance may arise if additional cable projects other than those included in scenario 3 are envisaged in local grid areas (see annex 4.4.3).

2.2.2.1 Critical cases of parallel resonances

Several critical cases of parallel resonance in terms of resonant frequencies and magnitude of harmonic impedance (according to Table 2-2) were found in scenario 3 at 380 kV Romanel and 380 kV Magadino under certain grid conditions.

2.2.2.1.1 380 kV Romanel

Several cable projects are proposed in Scenario 3 in the vicinity of 380 kV Romanel, which are:

- 8 km from 380 kV Romanel towards 380 kV Bois Tollot
- 8 km from 380 kV Romanel towards 380 kV La Bâtiaz
- 12 km around 380 kV Veytaux, ~36 km from 380 kV Romanel

Parallel resonances at low-order harmonics are to be expected at 380 kV Romanel.

The following cases have been considered in the frequency scan studies for 380 kV Romanel:

Case	Description
1	Condition N
2	N-1 on 380 kV Romanel – Bois Tollot
3	N-1 on 380 kV Romanel – La Bâtiaz
4	N-1 on 380 kV Châtelard – La Bâtiaz
5	N-1 on 380 kV Chamoson – La Bâtiaz
6	N-2 on 380 kV Romanel – Bois Tollot and Chamoson – La Bâtiaz

The network impedance with respect to frequency seen at 380 kV Romanel for all 6 cases in Scenario 3 is presented in Figure 2-2.

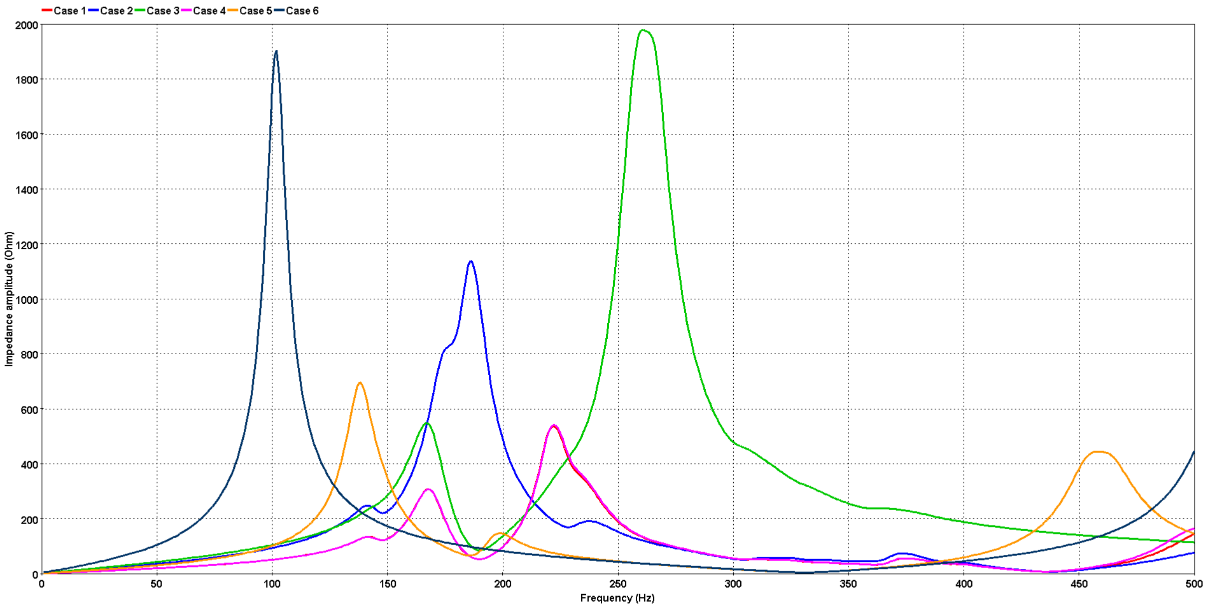


Figure 2-2: Harmonic impedance at 380 kV Romanel for the 6 cases – low SCL, scenario 3

The impedance amplitude close to the 2nd, 3rd and 4th harmonics in all 6 cases for Scenario 3 is presented in Table 2-3.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
100 Hz ±10 Hz	42 – 61	77 – 112	88 – 122	42 – 61	77 – 139	600 – 1,904
150 Hz ±10 Hz	121 – 212	219 – 353	224 – 430	121 – 211	190 – 666	143 – 215
200 Hz ±10 Hz	52 – 217	298 – 988	85 – 217	52 – 215	79 – 146	72 – 92

Table 2-3: Impedance amplitude close to the 2nd , 3rd and 4th harmonics at 380 kV Romanel for the 6 cases – low SCL, scenario 3

Note that two cases are highlighted in Table 2-3 in which the impedance amplitude around a certain harmonic order exceeds the critical threshold values defined in Table 2-2. The following phenomena can be expected in scenario 3:

- Saturation or re-saturation of the transformer at Romanel (e.g., energisation on the 380 kV side, fault clearing at a neighbouring 380 kV line, etc.) under N-1 contingency of 380 kV La Bâtiaz – Chamoson (case 5) and low SCL conditions would potentially lead to TOVs with a significant 3rd harmonic component due to the grid resonance close to the 3rd harmonic with a sufficiently high magnitude.
- Severe TOVs can be expected when the transformer at Romanel is saturated or re-saturated from energization on the 380 kV side, fault clearing at a nearby 380 kV line, etc. under N-2 contigencies of 380 kV La Bâtiaz – Chamoson and Romanel – Bois Tollot (Case 6). This is because this network topology leads to parallel resonance close to the 2nd harmonic with an extremely high impedance amplitude.

As a comparison, the harmonic impedance at 380 kV Romanel for all three scenarios (i.e., Scenarios 1, 2 and 3) for both Cases 5 and 6 is plotted in Figure 2-3 and Figure 2-4. Similarly, the impedance amplitudes close to the 2nd, 3rd and 4th harmonics for all three scenarios in Cases 5 and 6 are presented in Table 2-4 and Table 2-5, respectively.

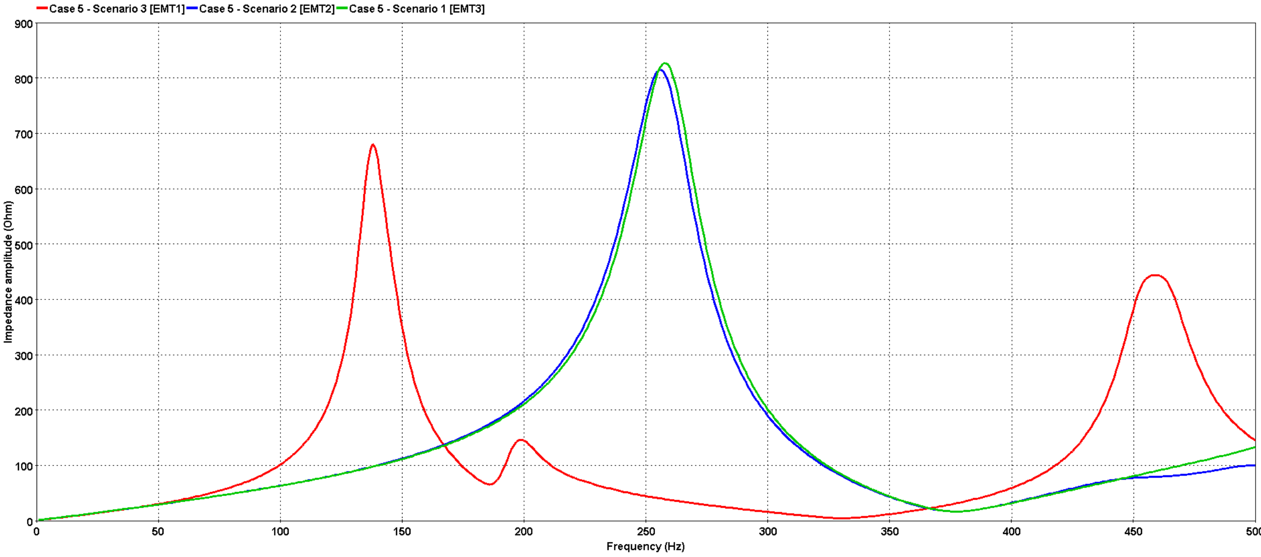


Figure 2-3: Comparison of harmonic impedance at 380 kV Romanel for case 5 in scenarios 1, 2 and 3

	Scenario 1	Scenario 2	Scenario 3
100 Hz ±10 Hz	77 – 139	55 – 71	55 – 71
150 Hz ±10 Hz	190 – 666	100 – 125	99 – 124
200 Hz ±10 Hz	79 – 146	185 – 257	181 – 249

Table 2-4: Impedance amplitude close to the 2nd, 3rd and 4th harmonics at 380 kV Romanel for case 5 – comparison of scenarios 1, 2 and 3

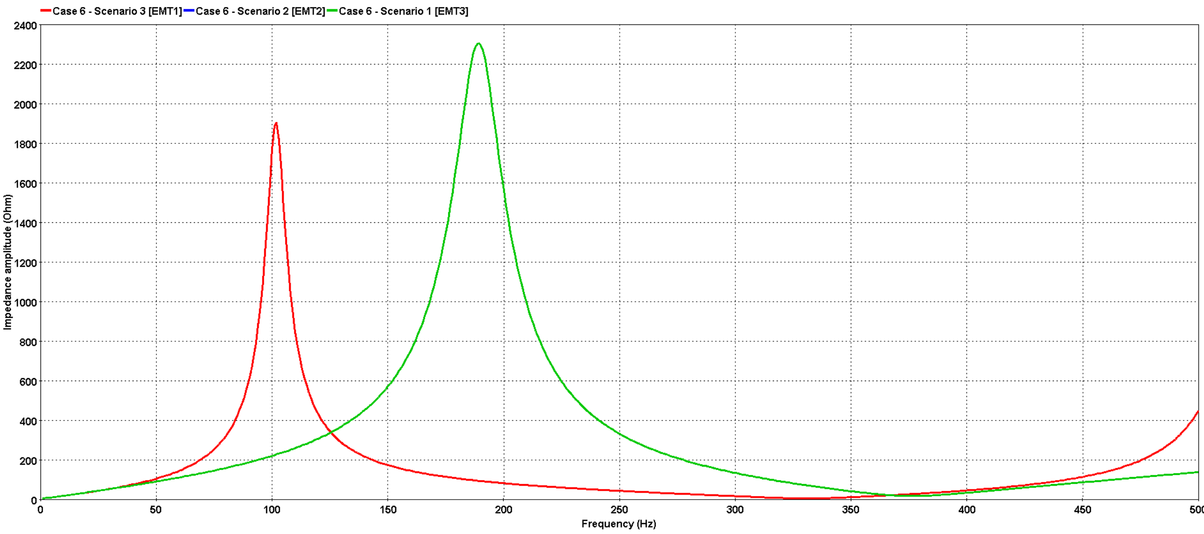


Figure 2-4: Comparison of harmonic impedance at 380 kV Romanel for case 6 in scenarios 1, 2 and 3

	Scenario 1	Scenario 2	Scenario 3
100 Hz ±10 Hz	600 – 1,904	186 – 258	186 – 258
150 Hz ±10 Hz	143 – 215	450 – 753	450 – 753
200 Hz ±10 Hz	72 – 92	988 – 2,298	988 – 2,298

Table 2-5: Impedance amplitude close to the 2nd, 3rd and 4th harmonics at 380 kV Romanel for case 6 – comparison of scenarios 1, 2 and 3

It can be observed in both plots that the parallel resonance shifts towards higher frequencies in Scenarios 1 and 2 with fewer cable projects. In particular:

- **Case 5**

The removal of the two 8 km cables from 380 kV Romanel towards 380 kV La Bâtiaz and towards 380 kV Bois Tollot has the most significant impact on the network resonance shift, which is obvious due to their proximity with the location of frequency screening.

The 4.8 km cable on 220 kV Foretaille – Verbois causes a slight frequency shift in the resonance between Scenarios 1 and 2. Due to its short length and large distance (coupled with the 380 kV grid at Verbois), its impact on the harmonic resonance seen at 380 kV Romanel is insignificant. Other cables included in Scenario 2, such as those at Innertkirchen and Ticino, have minimal impact on the harmonic resonance at 380 kV Romanel because they are electrically two far away. The resonant frequency that is slightly over the 5th harmonic in Scenario 1 and 2 is a result of the 380 kV Nant de Drance cables.

- **Case 6**

The N-2 contingency considered in Case 6 excludes the 8 km cable from 380 kV Romanel towards 380 kV Bois Tollot. Therefore, the frequency shift observed in Scenarios 1 and 2 as compared to Scenario 3 is due to the removal of the 8 km cables from 380 kV Romanel towards 380 kV La Bâtiaz.

No observable difference can be noticed in harmonic resonance between Scenarios 1 and 2. This is because a 380 kV island is created from 380 kV to 380 kV Nant de Drance by the considered N-2 contingency and all cable systems in Scenario 2 are coupled with the 380 kV island at electrically remote points.

Additionally, the exclusion of the 380 kV line Romanel – Bois Tollot in the N-2 contingency further decreases the SCL at 380 kV Romanel, leading to a parallel resonance under the 4th harmonic in Scenarios 1 and 2. Once again, this parallel resonance is a result of the 380 kV Nant de Drance cables.

2.2.2.1.2 380 kV Magadino

A 13 km cable segment is proposed in Scenario 3 from 380 kV Magadino towards 380 kV Musignano in Italy. Since the network around 380 kV Magadino is not meshed, only two cases have been considered in the frequency screening studies for 380 kV Magadino, which are given below:

Case	Description
1	Condition N
2	N-1 on 380 kV Lavorgo – Magadino

The network impedance with respect to frequency seen at 380 kV Magadino for both cases in Scenario 3 is presented in Figure 2-5.

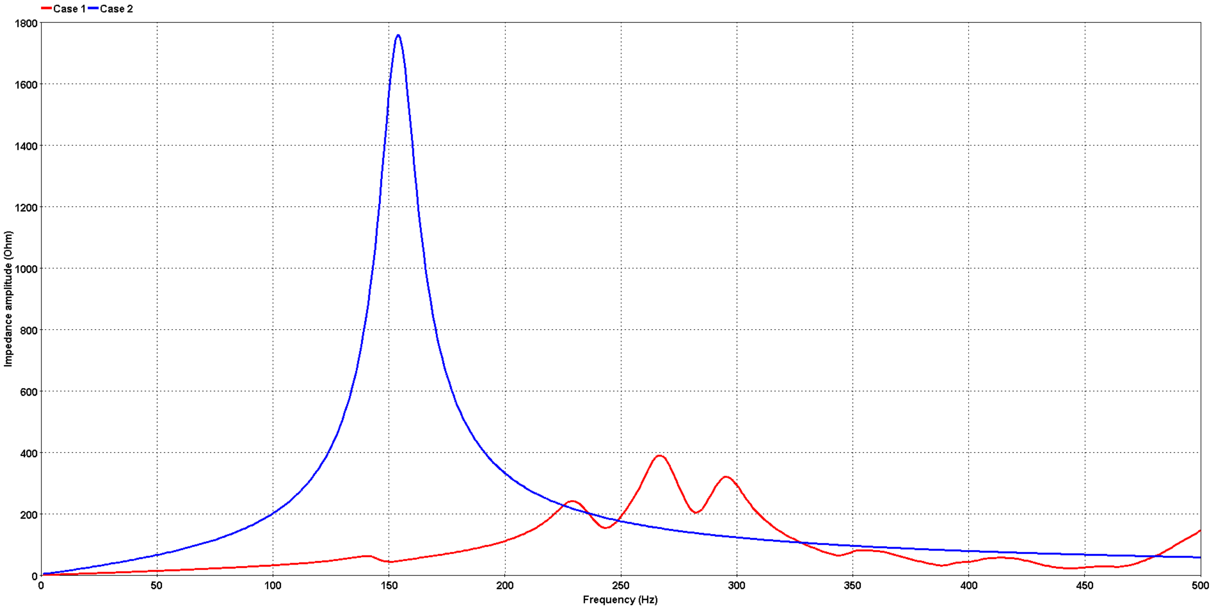


Figure 2-5: Harmonic impedance at 380 kV Magadino for both cases – low SCL, scenario 3

The impedance amplitude close to the 2nd, 3rd and 4th harmonics in both cases for Scenario 3 is presented in Table 2-6.

	Case 1	Case 2
100 Hz ±10 Hz	28 – 37	159 – 260
150 Hz ±10 Hz	44 – 62	829 – 1,760
200 Hz ±10 Hz	90 – 140	280 – 411

Table 2-6: : Impedance amplitude close to the 2nd, 3rd and 4th harmonics at 380 kV Magadino for both cases – low SCL, scenario 3

Note that the case with N-1 on 380 kV Magadino – Lavorgo is highlighted in Table 2-6. The impedance amplitude around the 3rd harmonic considerably exceeds the critical threshold value defined in Therefore, the following phenomenon in Scenario 3 can be predicted:

- Saturation or re-saturation of the transformer at Magadino (e.g., energization on the 380 kV side, fault clearing at a nearby 380 kV line, etc.) under N-1 contingency of 380 kV Magadino - Lavorgo (Case 2) and low SCL conditions would potentially lead to critical TOVs with a significant 3rd harmonc component due to network resonance close to the 3rd harmonic with an extremely high amplitude.

By way of comparison, the harmonic impedance at 380 kV Magadino for all three scenarios (i.e., Scenarios 1, 2 and 3) for Case 2 and plotted in Figure 2-6. Similarly, the impedance amplitudes close to the 2nd, 3rd and 4th harmonics for all three scenarios in Case 2 are presented in Table 2-7.

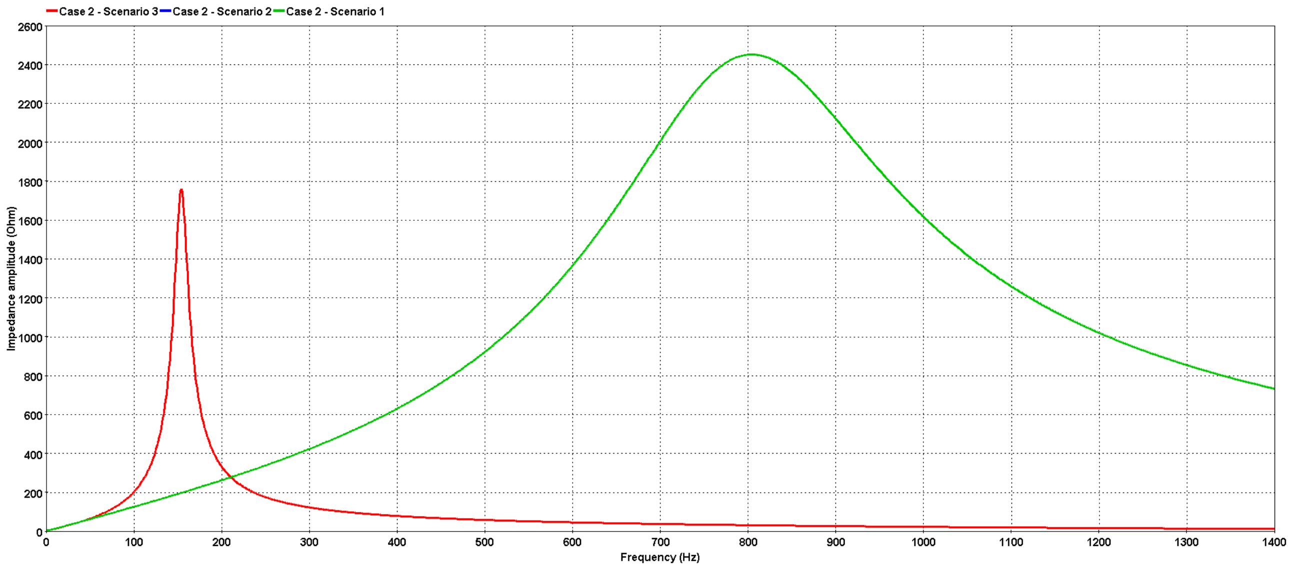


Figure 2-6: Comparison of harmonic impedance at 380 kV Magadino for case 2 in scenarios 1, 2 and 3

	Scenario 1	Scenario 2	Scenario 3
100 Hz ±10 Hz	159 – 260	112 – 138	112 – 138
150 Hz ±10 Hz	829 – 1,760	178 – 205	178 – 205
200 Hz ±10 Hz	280 – 411	247 – 276	247 – 276

Table 2-7 Impedance amplitude close to the 2nd, 3rd and 4th harmonics at 380 kV Magadino for case 2 – comparison of scenarios 1, 2 and 3

It can be observed in the plot that the parallel resonance disappears in Scenarios 1 and 2, after the removal of the 13 km cable from 380 kV Magadino towards 380 kV Musignano.

In particular, the harmonic impedance in Scenarios 1 and 2 showcases typical characteristics of overhead lines within the defined frequency range, having a parallel resonance due to the impedance of the source and the line itself and the line shunt capacitance. This is because the N-1 contingency isolates 380 kV Magadino from the Swissgrid network, and the Italian grid is only represented by a Thevenin equivalent.

Different harmonic impedance seen at 380 kV Magadino is to be expected in reality under the considered N-1 contingency since the actual Italian network should bring about certain dynamics. For further confirmation, it would be necessary to obtain detailed grid information from Terna in order to model a few more lines and substations to the south. However, it is safe to assume critical TOVs due to parallel resonance around the 3rd harmonic can be eliminated with the removal of the 13 km 380 kV Magadino – Musignano cable.

2.2.2.2 Network resonances in a fourth scenario

To make it easier to understand the impact of cables on resonant frequencies, a fourth scenario was created with a higher cable content than in scenario 3. This fourth scenario was only used for the calculation of network harmonic impedance. Its compensation requirements and harmonic amplification were not studied. The new cables in scenario 4 are shown in light blue in Figure 2-7.

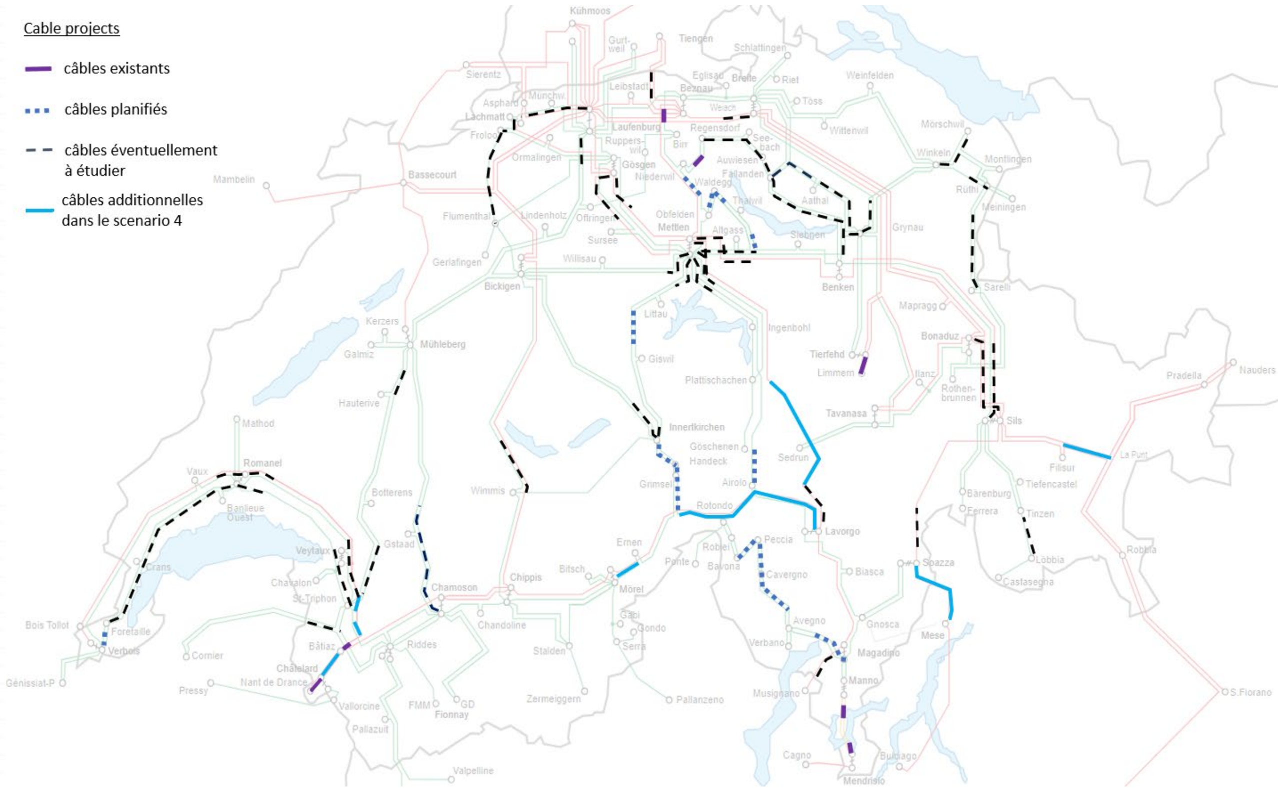


Figure 2-7: Cable connection projects in scenario 4

The resonant frequencies at different grid points were studied in this scenario. Only the critical results are presented below.

2.2.2.2.1 380 kV Châtelard

A comparison of network impedance amplitude with respect to frequency observed at 380 kV Châtelard in scenarios 1, 2, 3 and 4 for N-1 on 380 kV Bâtiaz – Chamoson is shown in Figure 2-8.

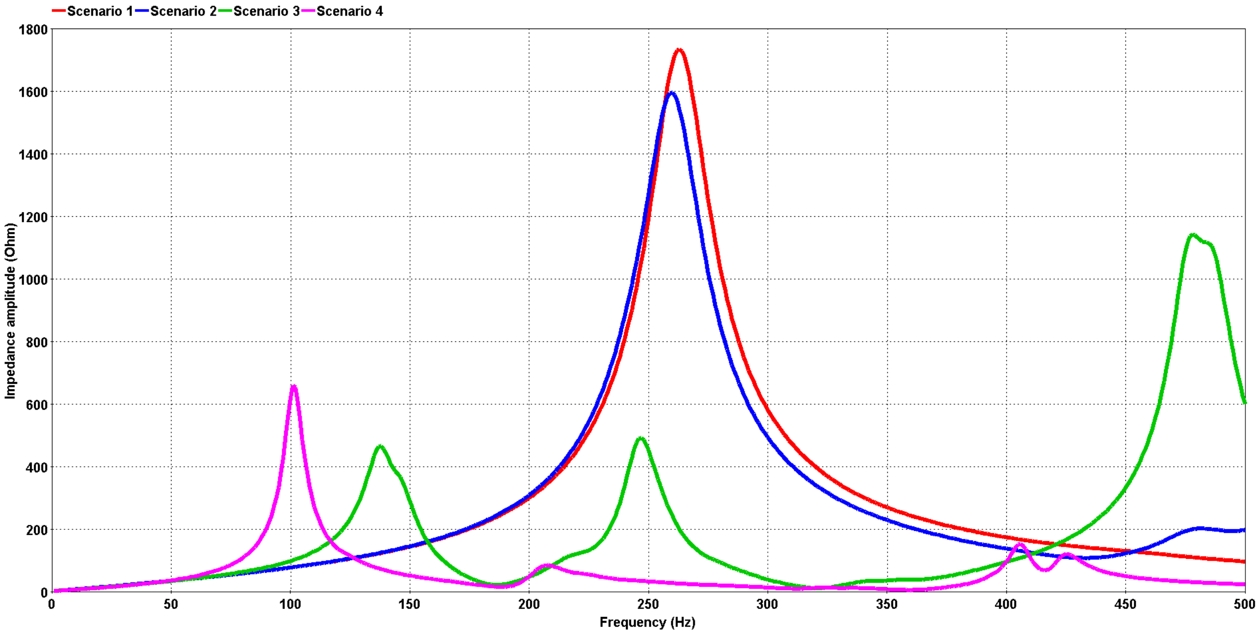


Figure 2-8: Comparison of harmonic impedance at 380 kV Châtelard in scenarios 1, 2, 3 and 4

A comparison of the impedance amplitude close to the 2nd, 3rd , 4th and 5th harmonics in scenarios 1, 2, 3 and 4 is shown in Table 2-8.

Harmonic order	2nd	3rd	4th	5th
Scenario 1 (Ohm)	67 – 87	126 – 163	252 – 362	805 – 1,688
Scenario 2 (Ohm)	67 – 87	127 – 165	258 – 376	879 – 1,595
Scenario 3 (Ohm)	77 – 128	131 – 442	23 – 84	242 – 490
Scenario 4 (Ohm)	203 – 659	39 – 67	15 – 84	27 – 37

Table 2-8: Impedance amplitude close to the 2nd, 3rd, 4th and 5th harmonics at 380 kV Châtelard – comparison of scenarios 1, 2, 3 and 4

Notes: While this contingency leads to a parallel resonance slightly below the 3rd harmonic with a relatively low amplitude in scenario 3, in scenario 4 the parallel resonance shifts to nearly 100 Hz (the 2nd harmonic) with an alarmingly high impedance amplitude. Serious risks of TOVs can be expected.

2.2.2.2.2 380 kV Nant de Drance

A comparison of network impedance amplitude with respect to frequency observed at 380 kV Nant de Drance in scenarios 1, 2, 3 and 4 for N-1 on 380 kV Bâtiaz – Chamoson is shown in Figure 2-9.

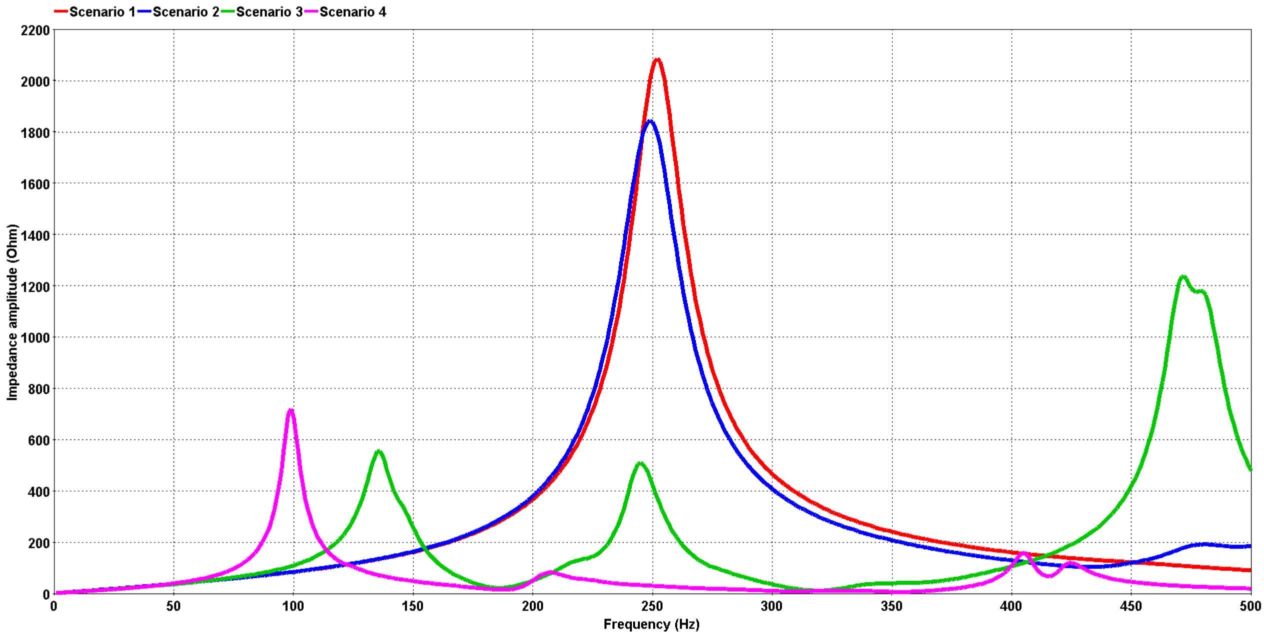


Figure 2-9: Comparison of harmonic impedance at 380 kV Nant de Drance in scenarios 1, 2, 3 and 4

A comparison of the impedance amplitude close to the 2nd, 3rd , 4th and 5th harmonics in scenarios 1, 2, 3 and 4 is shown in Table 2-9.

Harmonic order	2nd	3rd	4th	5th
Scenario 1 (Ohm)	73 – 96	141 – 186	301 – 461	1,346 – 2,084
Scenario 2 (Ohm)	73 – 96	142 – 188	309 – 484	1,338 – 1,844
Scenario 3 (Ohm)	86 – 147	122 – 454	25 – 91	220 – 510
Scenario 4 (Ohm)	224 – 720	37 – 63	15 – 82	24 – 35

Table 2-9: Impedance amplitude close to the 2nd, 3rd, 4th and 5th harmonics at 380 kV Nant de Drance – comparison of scenarios 1, 2, 3 and 4

Note: As in the previous case, the parallel resonance shifts to the 2nd harmonic and the impedance amplitude increases to a significantly high value, posing risks of TOVs during transient events at 380 kV Nant de Drance.

2.2.2.2.3 380 kV Mörel

A comparison of network impedance amplitude with respect to frequency observed at 380 kV Mörel in scenarios 1, 2, 3 and 4 for N-2 on 380 kV Chippis – Mörel and Lavorgo – Magadino is shown in Figure 2-10.

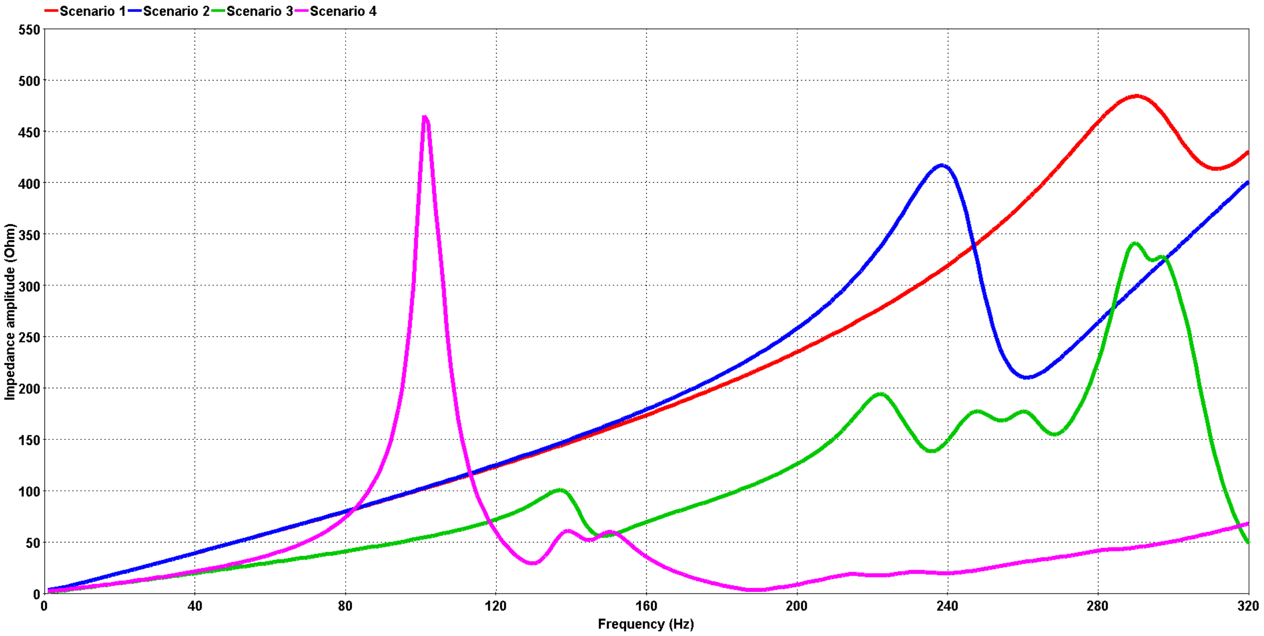


Figure 2-10: Comparison of harmonic impedance at 380 kV Mörel in scenarios 1, 2, 3 and 4

A comparison of the impedance amplitude close to the 2nd, 3rd , 4th and 5th harmonics in scenarios 1, 2, 3 and 4 is shown in Table 2-10.

Harmonic order	2nd	3rd	4th	5th
Scenario 1 (Ohm)	73 – 96	141 – 186	301 – 461	1,346 – 2,084
Scenario 2 (Ohm)	73 – 96	142 – 188	309 – 484	1,338 – 1,844
Scenario 3 (Ohm)	86 – 147	122 – 454	25 – 91	220 – 510
Scenario 4 (Ohm)	224 – 720	37 – 63	15 – 82	24 – 35

Table 2-10: Impedance amplitude close to the 2nd, 3rd, 4th and 5th harmonics at 380 kV Mörel – comparison of scenarios 1, 2, 3 and 4

Note: A parallel resonance appears at the 2nd harmonic with a high amplitude in scenario 4 due to the additional cable projects, which is not the case in scenarios 1, 2 or 3.

2.2.2.2.4 380 kV Lavorgo

A comparison of network impedance amplitude with respect to frequency observed at 380 kV Lavorgo in scenarios 1, 2, 3 and 4 for N-2 on 380 kV Chippis – Mörel and Lavorgo – Magadino is shown in Figure 2-11.

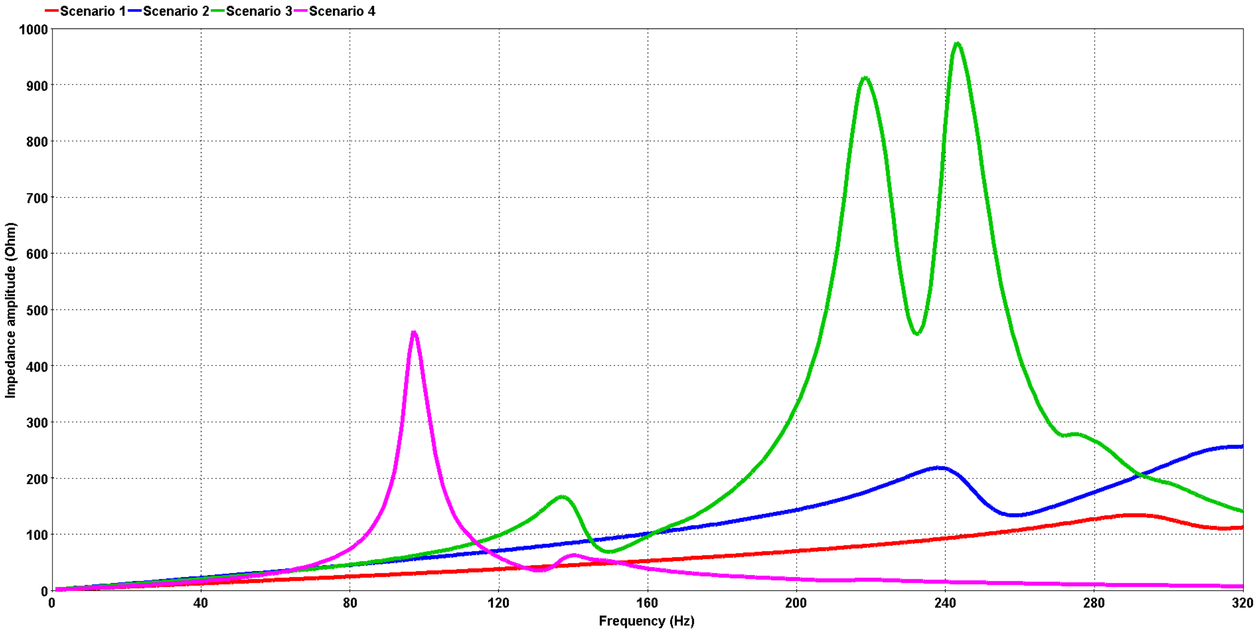


Figure 2-11: Comparison of harmonic impedance at 380 kV Lavorgo in scenarios 1, 2, 3 and 4

A comparison of the impedance amplitude close to the 2nd, 3rd , 4th and 5th harmonics in scenarios 1, 2, 3 and 4 is shown in Table 2-11.

Harmonic order	2nd	3rd	4th	5th
Scenario 1 (Ohm)	27 – 34	45 – 52	65 – 75	92 – 107
Scenario 2 (Ohm)	51 – 63	85 – 101	130 – 158	133 – 217
Scenario 3 (Ohm)	54 – 78	69 – 151	224 – 568	416 – 974
Scenario 4 (Ohm)	113 – 462	39 – 62	17 – 23	12 – 15

Table 2-11: Impedance amplitude close to the 2nd, 3rd, 4th and 5th harmonics at 380 kV Lavorgo – comparison of scenarios 1, 2, 3 and 4

Note: As in the previous case, a new parallel resonance appears at the 2nd harmonic in scenario 4 with a significant magnitude, posing risks of TOVs for transient events at 380 kV Lavorgo.

2.2.2.2.5 380 kV Tierfehd

A comparison of network impedance amplitude with respect to frequency observed at 380 kV Tierfehd in scenarios 1, 2, 3 and 4 for N-1 on 380 kV Tierfehd – Tavanasa is shown in Figure 2-12.

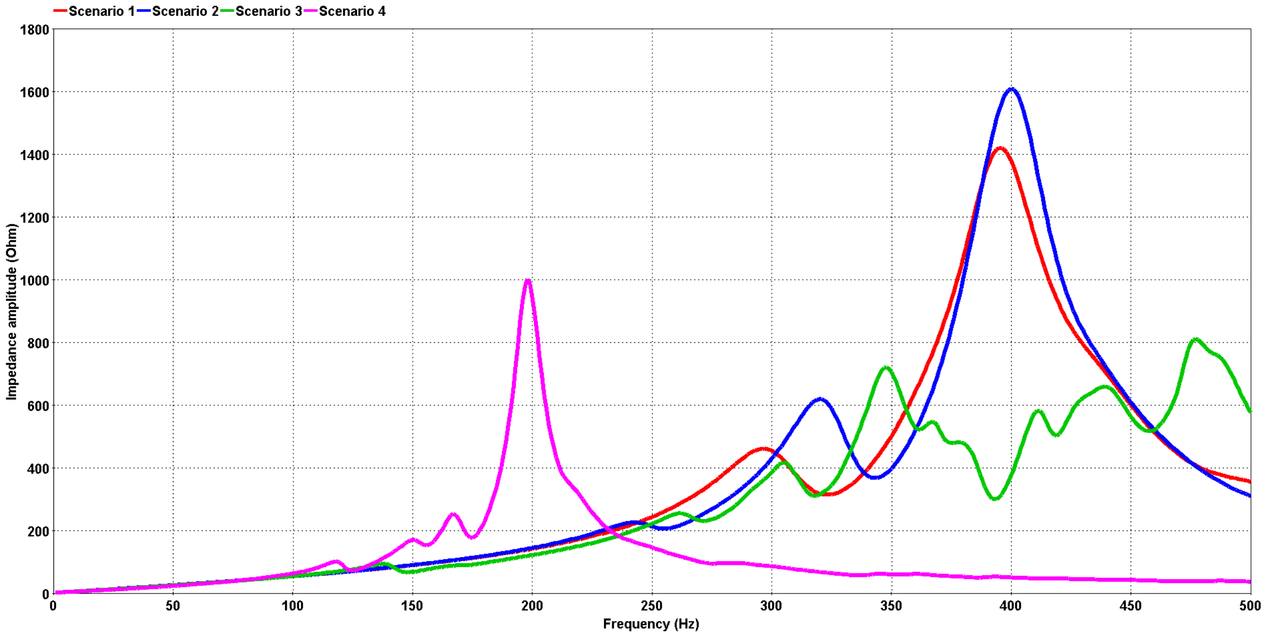


Figure 2-12: Comparison of harmonic impedance at 380 kV Tierfehd in scenarios 1, 2, 3 and 4

A comparison of the impedance amplitude close to the 2nd, 3rd, 4th and 5th harmonics in scenarios 1, 2, 3 and 4 is shown in Table 2-12.

Harmonic order	2nd	3rd	4th	5th
Scenario 1 (Ohm)	46 – 60	81 – 98	129 – 156	215 – 278
Scenario 2 (Ohm)	47 – 60	81 – 98	130 – 160	205 – 225
Scenario 3 (Ohm)	46 – 61	66 – 91	108 – 135	193 – 253
Scenario 4 (Ohm)	50 – 80	121 – 175	434 – 1001	120 – 169

Table 2-12: Impedance amplitude close to the 2nd, 3rd, 4th and 5th harmonics at 380 kV Tierfehd – comparison of scenarios 1, 2, 3 and 4

Notes: A parallel resonance with a high impedance amplitude appears at the 4th harmonic in scenario 4, which is not the case in scenarios 1, 2 or 3. Although this resonance is not high enough to cause a critical TOV, a deterioration in the system frequency response was confirmed with the additional cables in scenario 4, and increased dielectric stress on grid equipment in the area can be expected during transient events at 380 kV Tierfehd.

2.2.2.2.6 380 kV Filisur

A comparison of network impedance amplitude with respect to frequency observed at 380 kV Tierfehd in scenarios 1, 2, 3 and 4 for N-1 on 380 kV Filisur – Sils is shown in Figure 2-13.

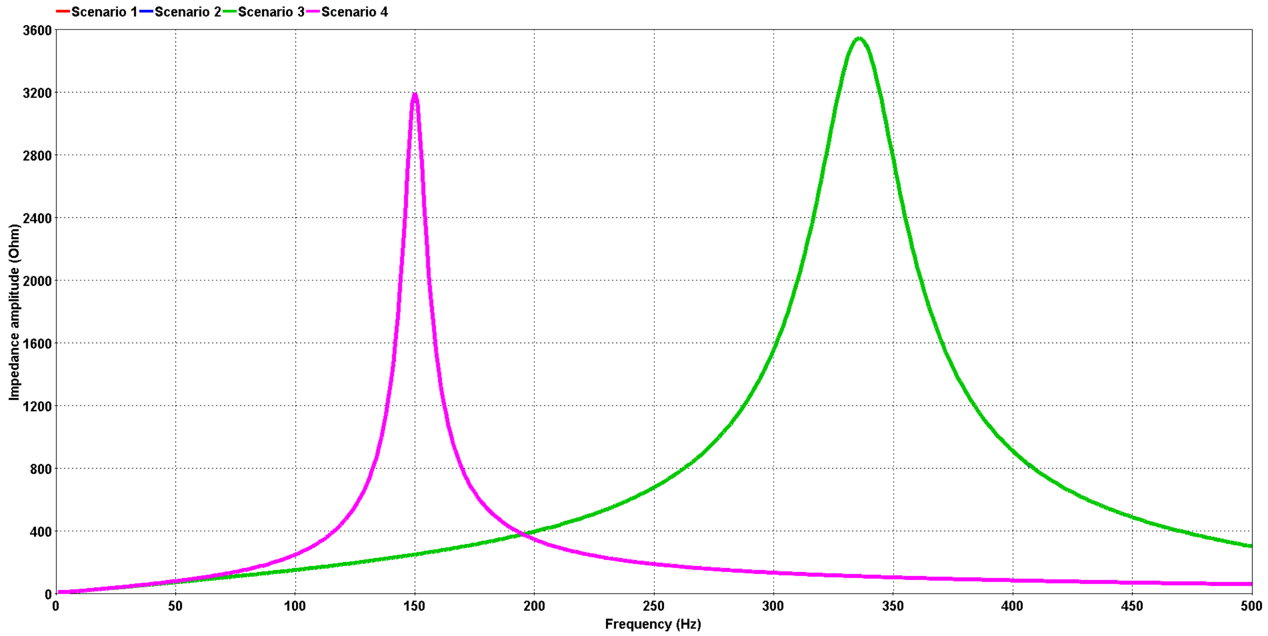


Figure 2-13: Comparison of harmonic impedance at 380 kV Filisur in scenarios 1, 2, 3 and 4

A comparison of the impedance amplitude close to the 2nd, 3rd , 4th and 5th harmonics in scenarios 1, 2, 3 and 4 is shown in Table 2-13.

Harmonic order	2nd	3rd	4th	5th
Scenario 1 (Ohm)	131 – 166	225 – 271	358 – 435	599 – 770
Scenario 2 (Ohm)	131 – 166	225 – 271	358 – 435	599 – 770
Scenario 3 (Ohm)	131 – 166	225 – 271	358 – 435	599 – 770
Scenario 4 (Ohm)	193 – 325	1,345 – 3,196	292 – 421	171 – 204

Table 2-13: Impedance amplitude close to the 2nd, 3rd, 4th and 5th harmonics at 380 kV Filisur – comparison of scenarios 1, 2, 3 and 4

Notes: The previously non-critical resonance between the 5th and 6th harmonics now shifts towards the 3rd harmonic in scenario 4. The extremely high impedance amplitude indicates a serious risk of TOVs during transient events.

2.2.2.2.7 380 kV Soazza

A comparison of network impedance amplitude with respect to frequency observed at 380 kV Tierfehd in scenarios 1, 2, 3 and 4 for N-1 on 380 kV Sils – Soazza is shown in Figure 2-14.

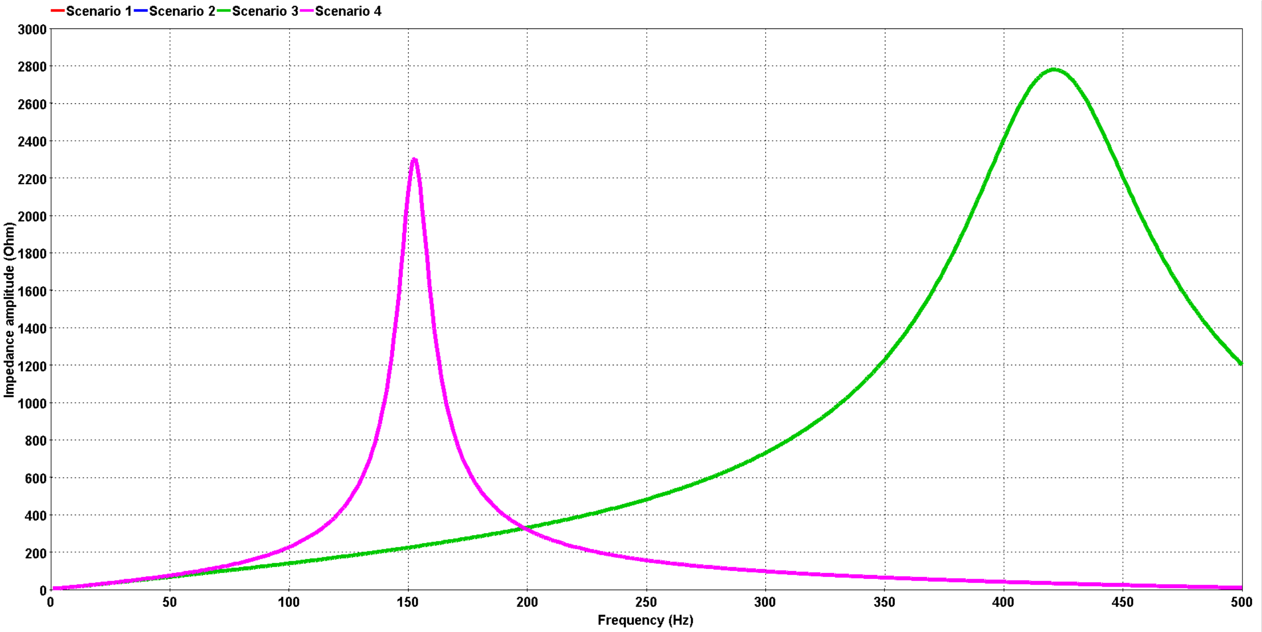


Figure 2-14: Comparison of harmonic impedance at 380 kV Soazza in scenarios 1, 2, 3 and 4

A comparison of the impedance amplitude close to the 2nd, 3rd, 4th and 5th harmonics in scenarios 1, 2, 3 and 4 is shown in Table 2-14.

Harmonic order	2nd	3rd	4th	5th
Scenario 1 (Ohm)	124 – 155	205 – 243	304 – 356	447 – 522
Scenario 2 (Ohm)	124 – 155	205 – 243	304 – 356	447 – 522
Scenario 3 (Ohm)	124 – 155	205 – 243	304 – 356	447 – 522
Scenario 4 (Ohm)	180 – 293	1,000 – 2,304	266 – 412	141 – 175

Table 2-14: Impedance amplitude close to the 2nd, 3rd, 4th and 5th harmonics at 380 kV Soazza – comparison of scenarios 1, 2, 3 and 4

Notes: As in the previous case, the previously non-critical resonance located beyond the 8th harmonic now shifts towards the 3rd harmonic in scenario 4. The extremely high impedance amplitude indicates a serious risk of TOVs during transient events.

2.2.2.3 Shift in resonant frequency of the system as the number of cable projects increases

Increasing the number of cable projects shifts system resonant frequencies towards lower harmonics at various network locations, which, in turn, increases the risks of TOVs and resonances at low-order harmonics during network transients.

This can be demonstrated by comparing the harmonic impedance at different network locations under different network conditions between the three proposed scenarios. Comparisons have been effectuated at 4 non-adjacent network locations: 220 kV Verbois, 380 kV Romanel, 380 kV Mettlen and 220 kV Fällanden, and the focus is the first parallel resonant peak. For each tested network location, two different grid conditions (i.e., N condition and N-1 contigency) have been considered.

2.2.2.3.1 220 kV Verbois

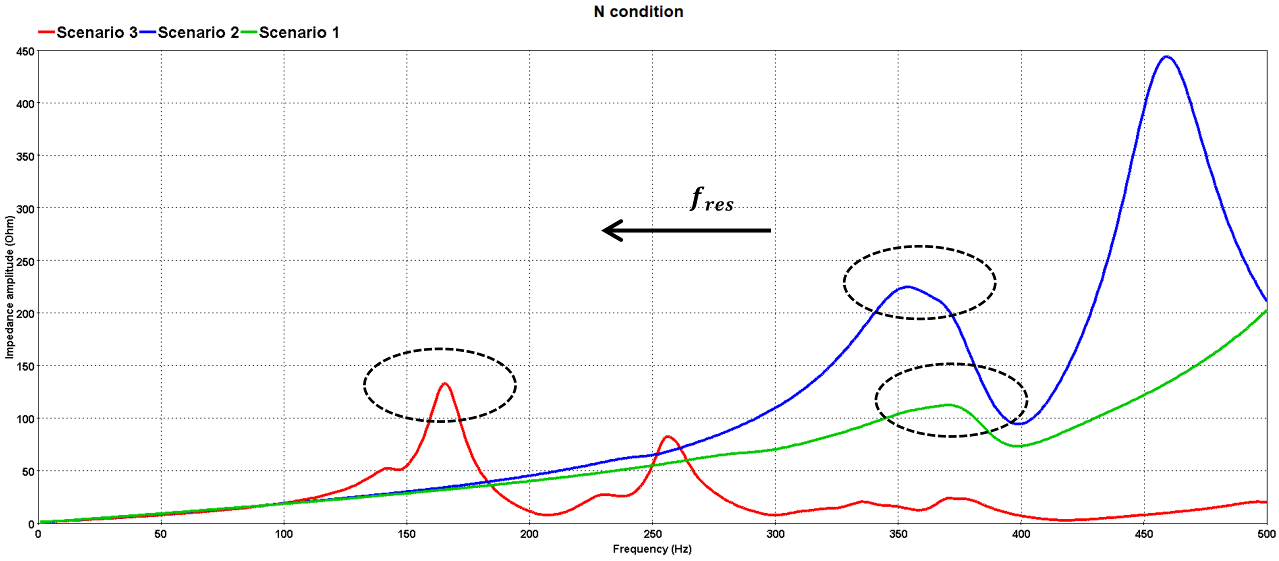


Figure 2-15: Comparison of harmonic impedance at 220 kV Verbois in scenarios 1, 2 and 3 – condition N

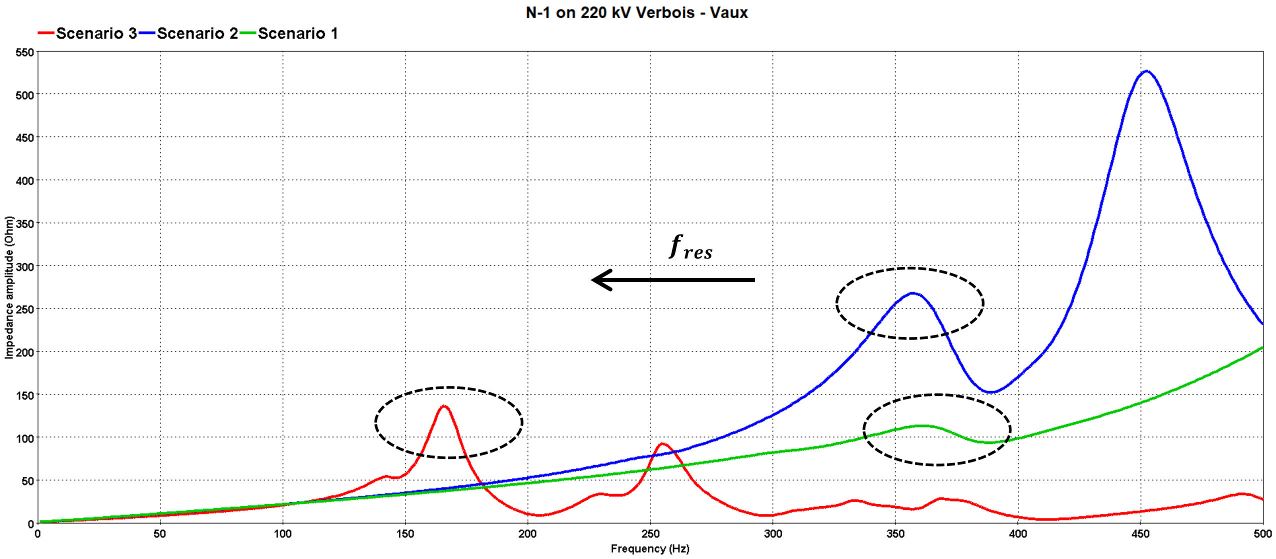


Figure 2-16: Comparison of harmonic impedance at 220 kV Verbois in scenarios 1, 2 and 3 – N-1 contingency

2.2.2.3.2 380 kV Romanel

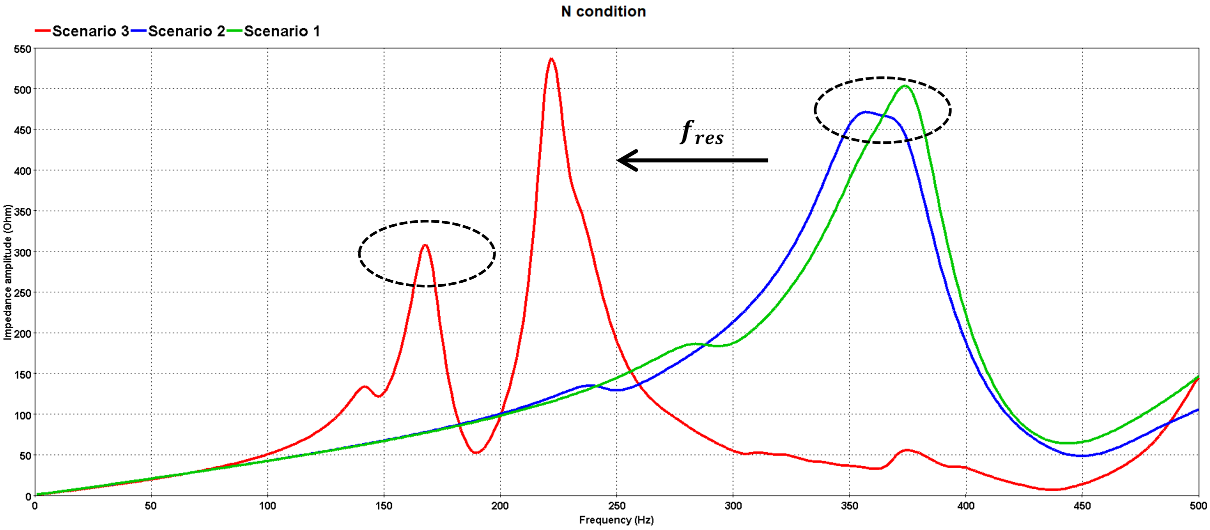


Figure 2-17: Comparison of harmonic impedance at 380 kV Romanel in scenarios 1, 2 and 3 – condition N

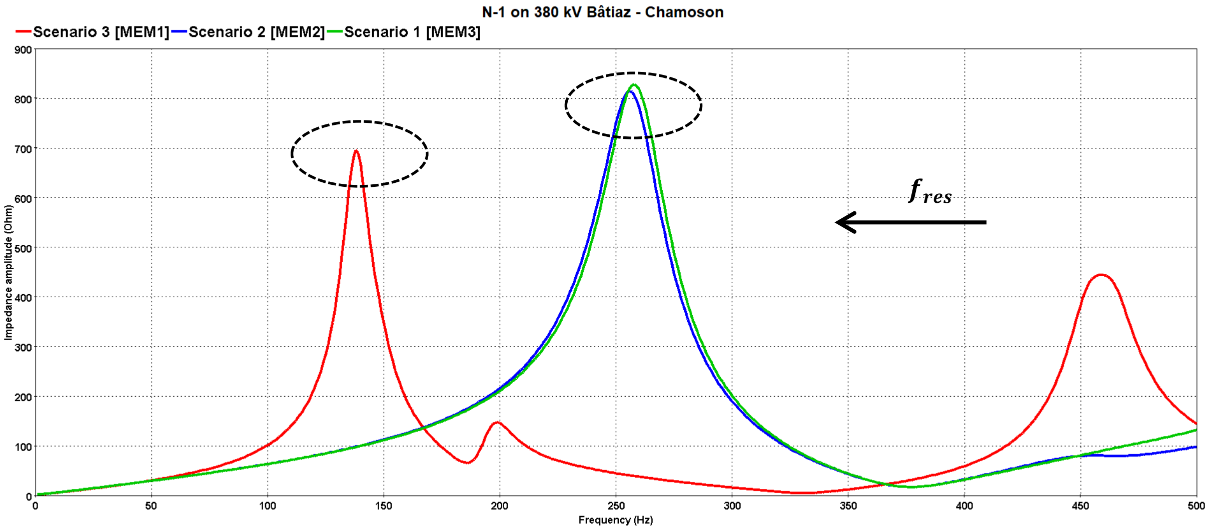


Figure 2-18: Comparison of harmonic impedance at 380 kV Romanel in scenarios 1, 2 and 3 – condition N-1

2.2.2.3.3 380 kV Mettlen

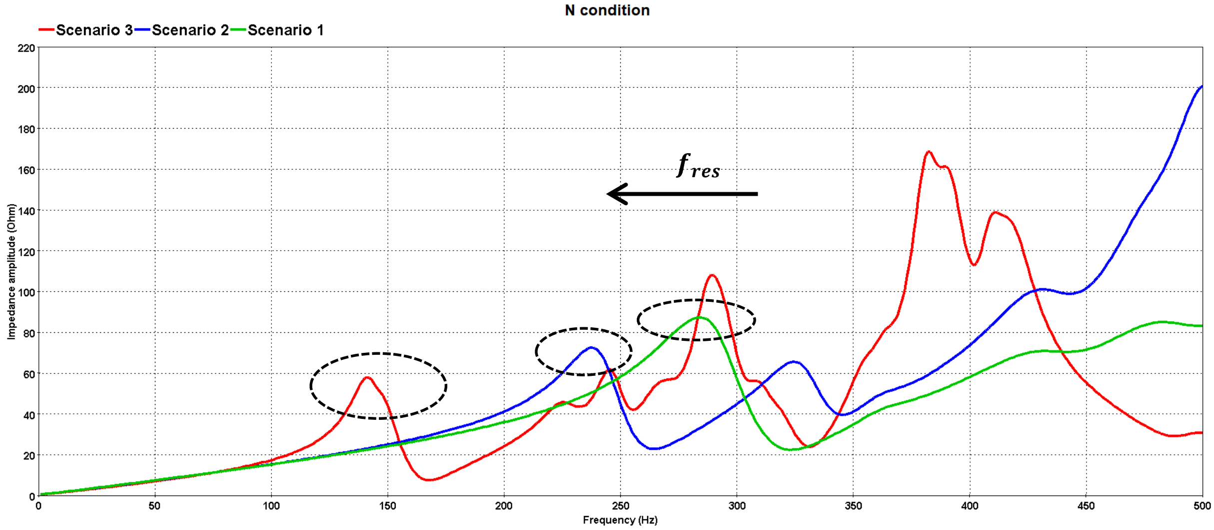


Figure 2-19: Comparison of harmonic impedance at 380 kV Mettlen in scenarios 1, 2 and 3 – condition N

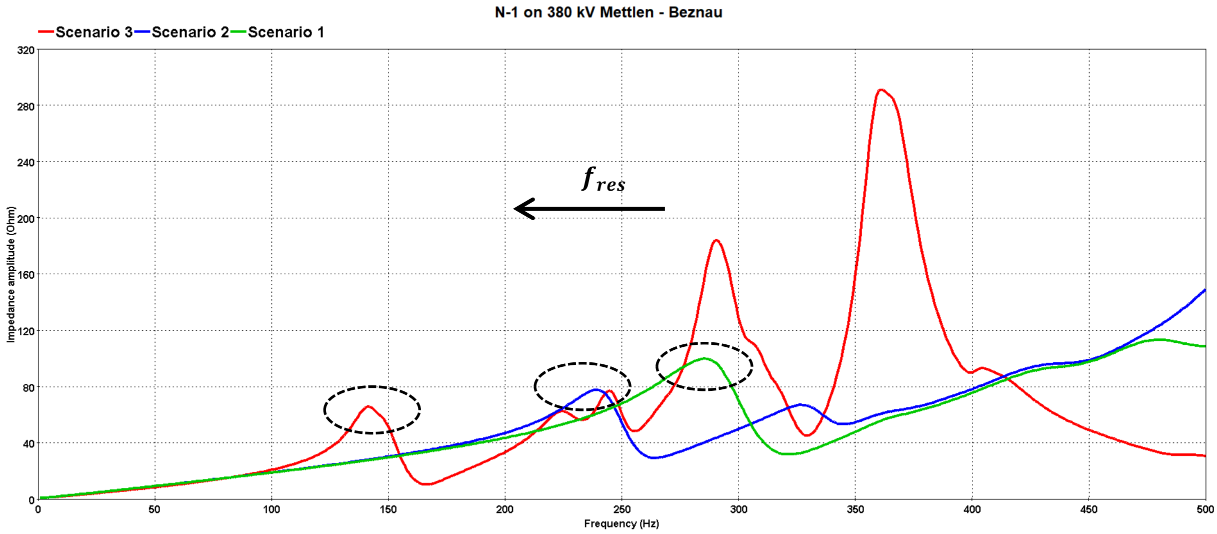


Figure 2-20: Comparison of harmonic impedance at 380 kV Mettlen in scenarios 1, 2 and 3 – condition N-1

2.2.2.3.4 220 kV Fällanden

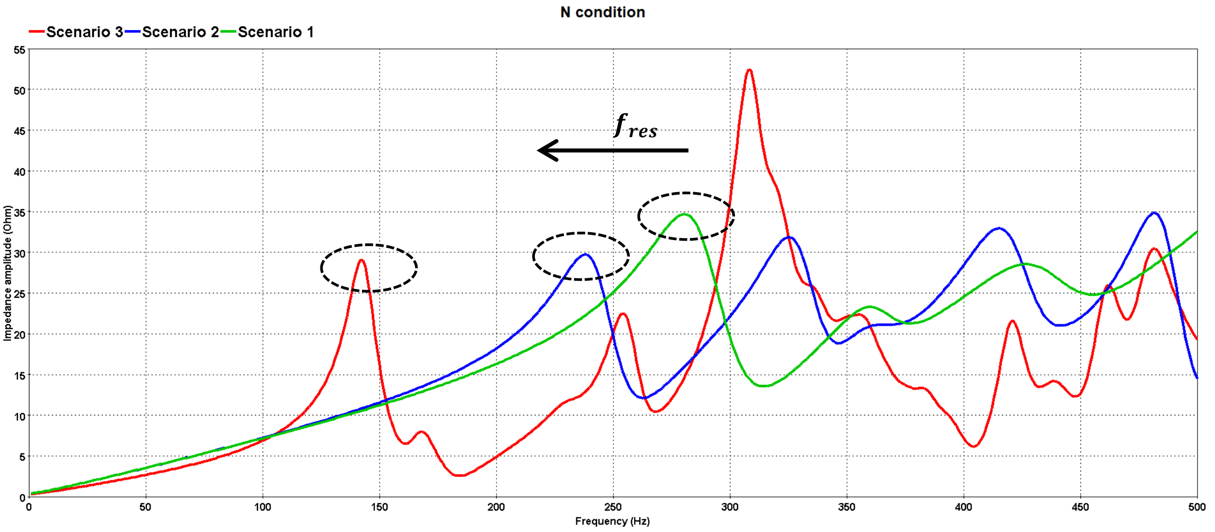


Figure 2-21: Comparison of harmonic impedance at 220 kV Fällanden in scenarios 1, 2 and 3 – condition N

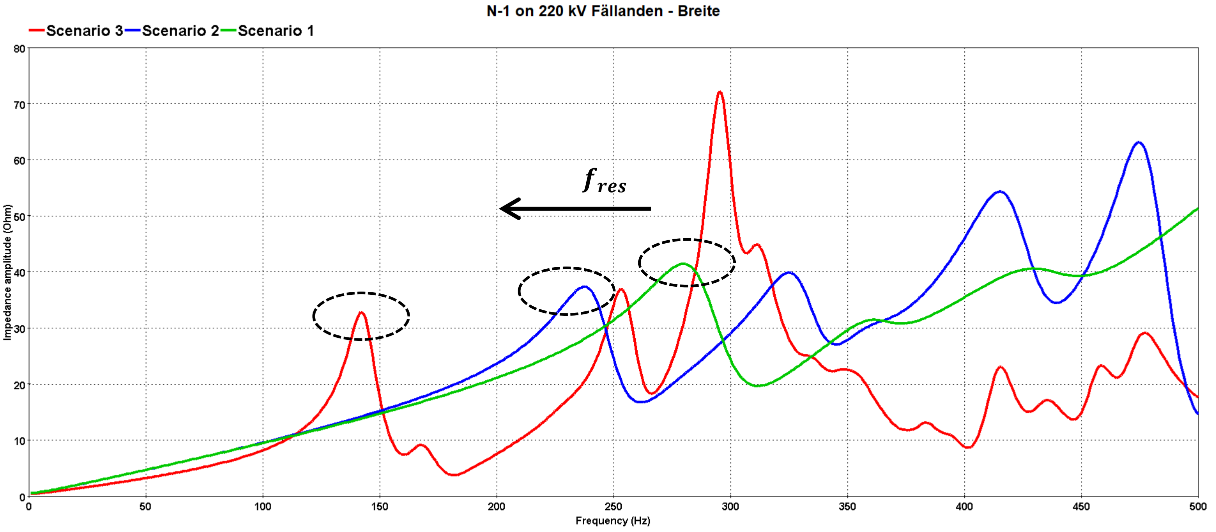


Figure 2-22: Comparison of harmonic impedance at 220 kV Fällanden in scenarios 1, 2 and 3 – condition N-1

2.2.2.3.5 Remarks

Two main observations can be made based on the results presented in the previous sections:

- A noticeable first parallel resonant peak can be observed at all the 4 tested network locations and for all 3 scenarios except for Scenario 1 at 220 kV Verbois where the first peak is rather flat. This is because the existing 220 kV cable projects in Scenario 1 are all extremely far away from 220 kV Verbois (i.e., Spreitenbach cables, Riniken cables, and Bâtiaz – Le Verney cables), thus having limited impact on the harmonic impedance at 220 kV Verbois.
- As the number of cable projects increases from Scenario 1 to Scenario 3, the first parallel resonance at all tested network locations shifts towards much lower frequencies, thus exposing the network location of interest to increased risks of TOVs and resonances during network transients.

2.2.2.4 Comparison of system damping between the 220 kV and 380 kV grids

As was discussed in previous sections, both the two aspects of network resonance, frequency and impedance amplitude, are determinant factors for system performance and behavior during transient events. With the resonant frequency determined by the capacitive and inductance elements at resonance, impedance amplitude is related more to system damping, which is further related to grid configuration and loading conditions.

A low system damping tends to result in higher impedance amplitude at resonance, posing, therefore, more risks of TOVs during transient events. However, a high system damping often mitigates the impact of network resonances and TOVs, thus improving grid performance during transient events. Since the 220 kV grid is a lot more meshed than the 380 kV grid at various network locations, it is believed that the system damping in the 220 kV grid is generally considerably higher than that in the 380 kV grid under similar loading and network conditions. Therefore, it would be generally “safer” to implement cable projects on the 220 kV grid as compared to in the 380 kV grid, as the impact from TOVs and resonances can be better mitigated with more system damping. The harmonic impedance amplitude of both voltage levels at 5 non-adjacent network locations, Romanel, Bickigen, Mettlen, Laufenburg and Bondauz, is presented in the following sections. Note that the simulations were performed for the same minimum loading condition and grid configuration (N condition).

2.2.2.4.1 Romanel

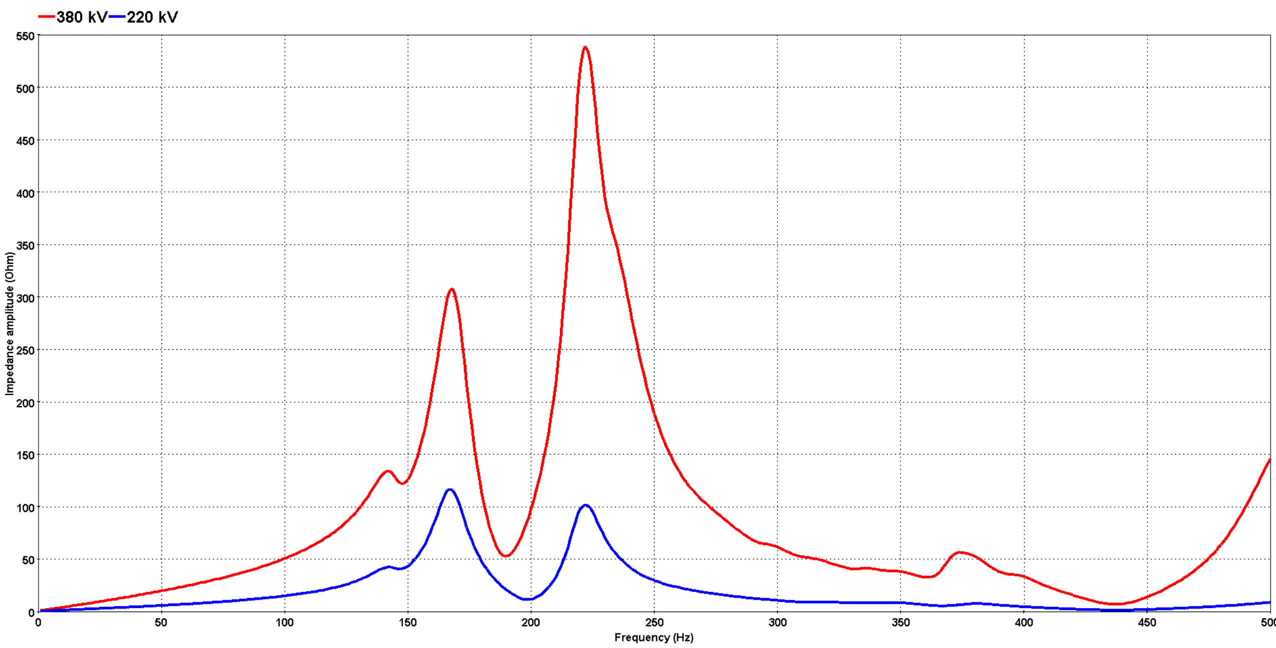


Figure 2-23: Comparison of harmonic impedance between 220 kV and 380 kV Romanel – condition N

2.2.2.4.2 Bickigen

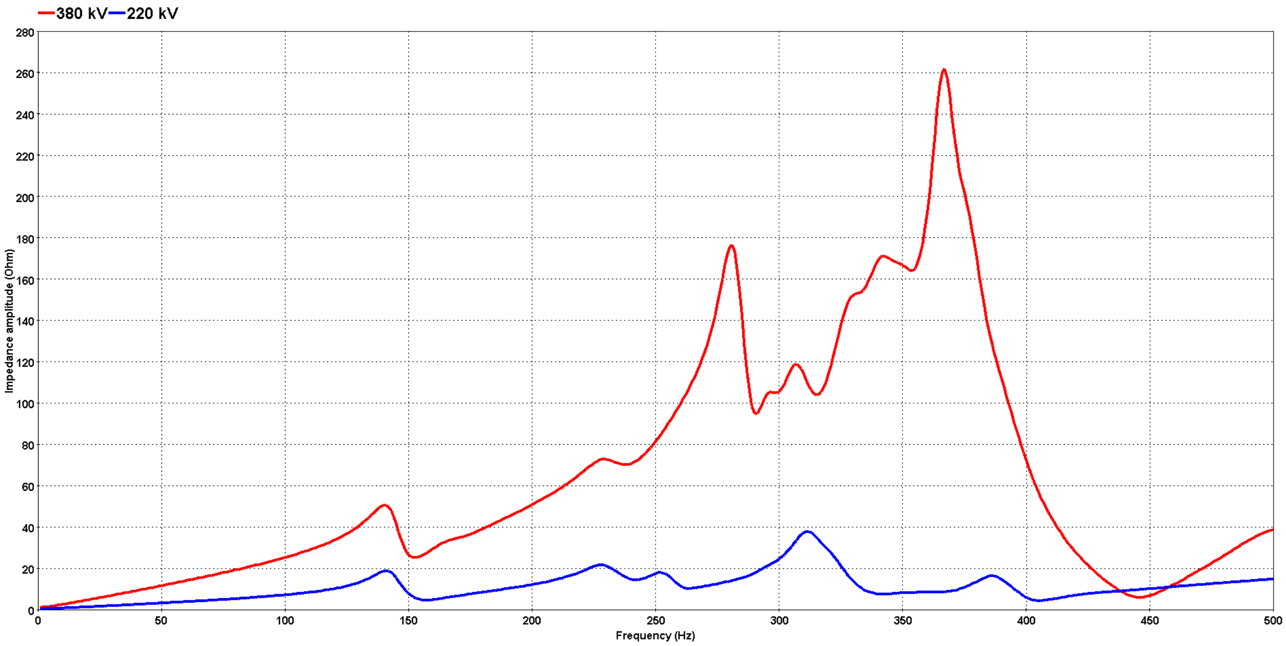


Figure 2-24: Comparison of harmonic impedance between 220 kV and 380 kV Bickigen – condition N

2.2.2.4.3 Mettlen

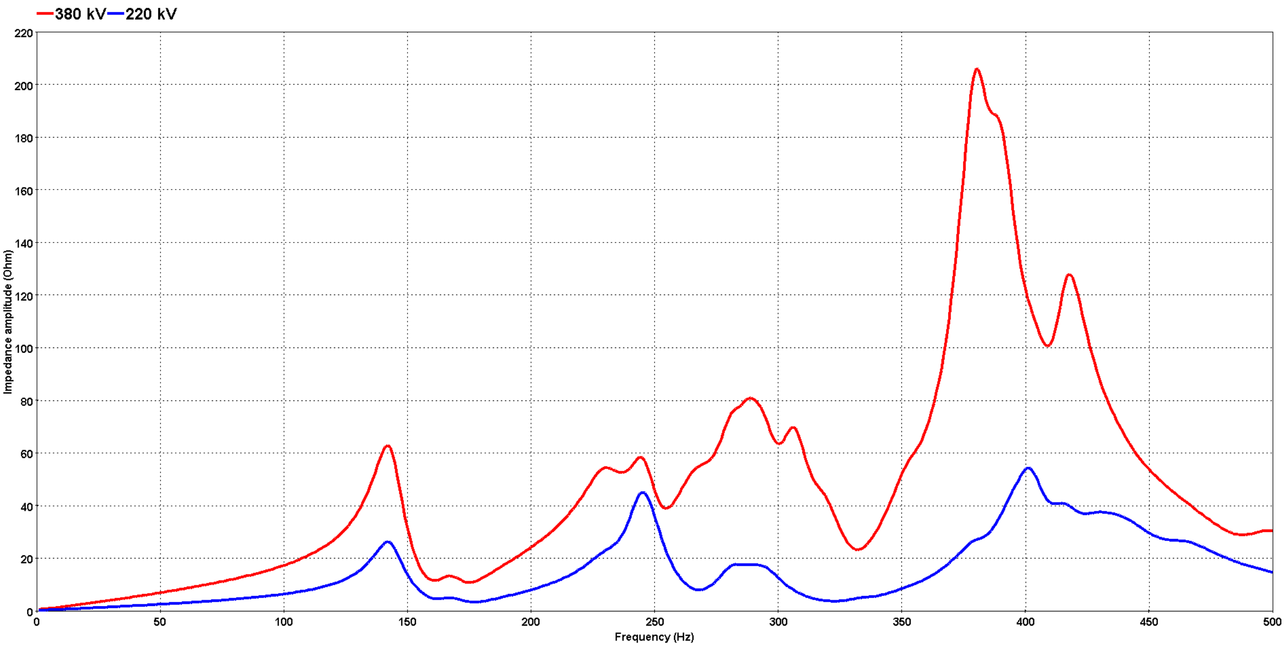


Figure 2-25: Comparison of harmonic impedance between 220 kV and 380 kV Mettlen – condition N

2.2.2.4.4 Laufenburg

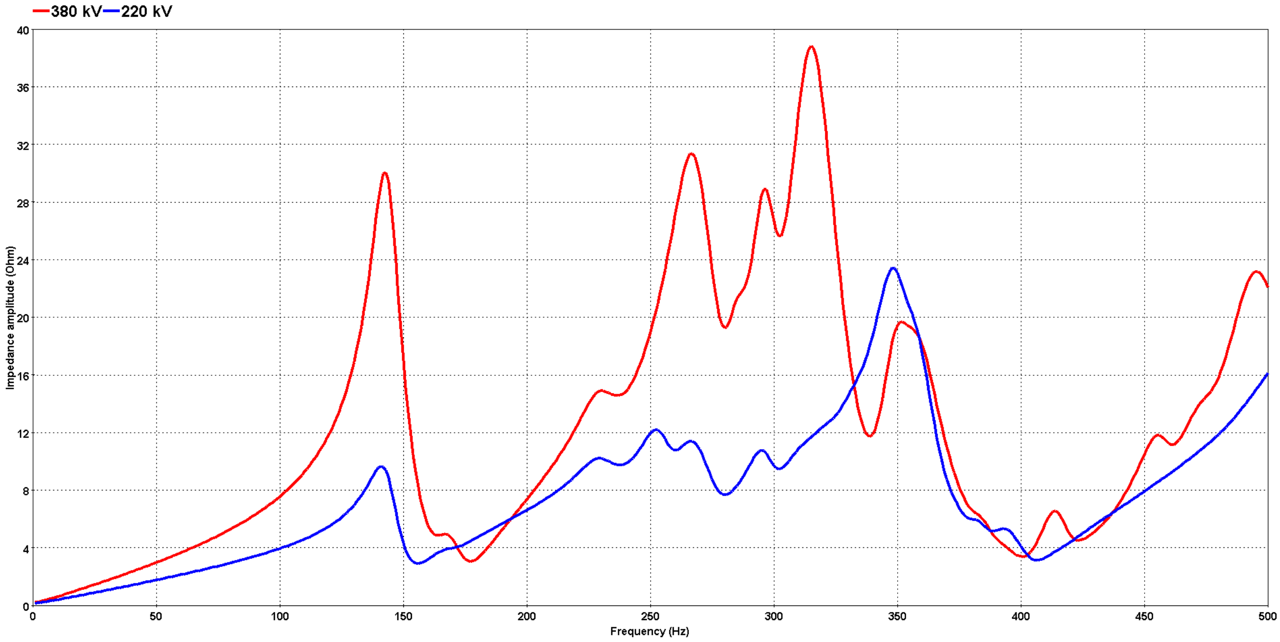


Figure 2-26: Comparison of harmonic impedance between 220 kV and 380 kV Laufenburg – condition N

2.2.2.4.5 Bonaduz

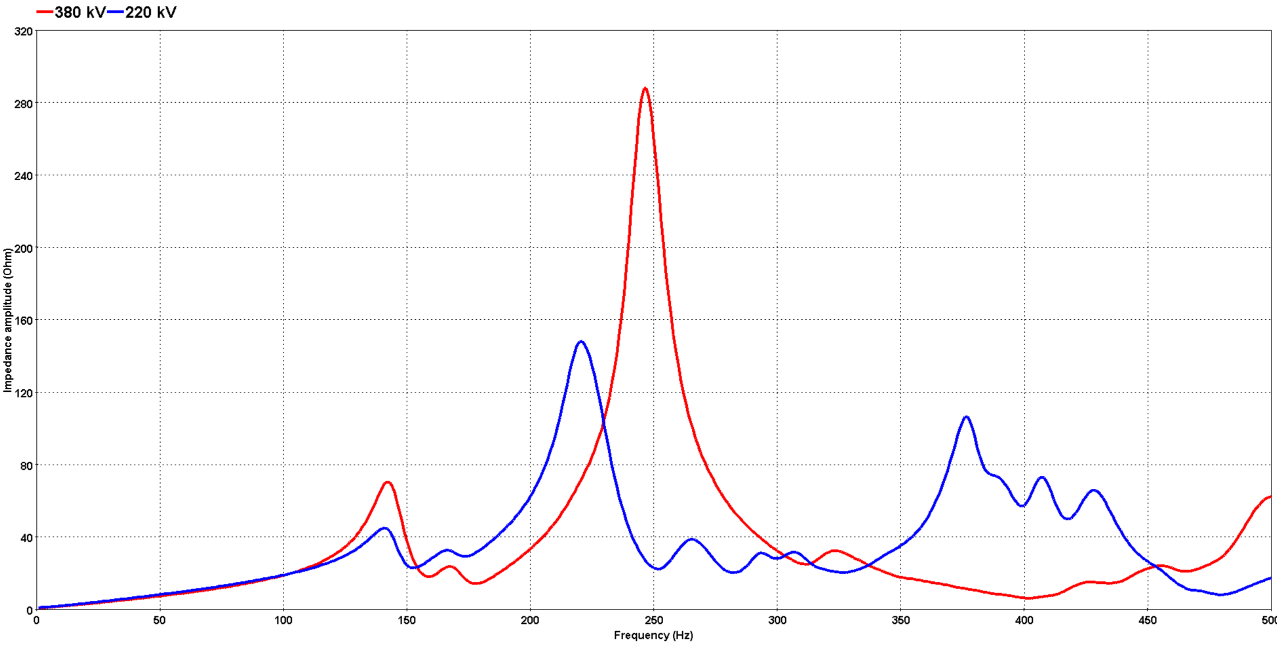


Figure 2-27: Comparison of harmonic impedance between 220 kV and 380 kV Bonaduz – condition N

2.2.2.4.6 Remarks

As was predicted, the harmonic impedance, either at resonances or across the entire frequency spectrum, is generally lower on the 220 kV level as compared to the 380 kV level, indicating that the 220 kV grid offer higher system damping. It can be, hence, predicted that even with more cable projects (thus even lower parallel resonant frequencies), high system damping in the 220 kV grid tends to lower the system impedance such that TOVs resulting from on-site transient events would have a less significant impact on system performance and pose less risks of thermal and dielectric stress on network equipment. That is to say, it would be relatively “safer” in terms of TOVs and resonances to implement more cable projects on the 220 kV grid than on the 380 kV grid.

2.2.3 Conclusion

The network frequency response is directly related to the potential TOVs that can be encountered during network transients from on-site operations and general events such as energization, fault recovery, load rejection, system islanding, etc., which, in turn, would have a considerable impact on grid operation stability and security.

Extensive system-level studies of frequency screening have been performed based on the proposed cable scenarios. The studies were performed at over 20 network locations that could be sensitive to the excitation of certain parallel resonance, while considering unfavorable network configurations in terms of contingencies and short-circuit power, with the goal of identifying the network locations and the corresponding grid configurations that would potentially lead to critical TOVs during network transient events.

Several conclusions can be drawn from the performed studies:

- Critical cases of parallel resonance were identified in scenario 3.

While the frequency response at various network locations under different operating conditions remains rather non-critical for Scenarios 1 and 2 with fewer cable projects, severe extremely critical cases of parallel resonance have been identified in Scenario 3 with the most cable projects. These cases pose severe risks of parallel resonance at low-order harmonics, notably the 2^{nd} and the 3^{rd}, with extremely high impedance amplitude at resonance. Once excited by network transient events such and energization, fault recovery and system islanding, highly distorted and poorly damped TOVs from parallel resonance can be expected, leading to considerable dielectric and thermal stress on network equipment and even equipment failure. The problematic network locations are 380 kV Romanel and 380 kV Magadino, and the associated network contingencies are the following:

- N-1 380 kV La Bâtiaz – Chamoson
- N-2 380 kV La Bâtiaz – Chamoson and Romanel – Bois Tollot
- N-1 380 kV Magadino – Lavorgo

- The system frequency response may deteriorate further in scenario 4 with an even higher number of cable projects than in scenario 3.

The deterioration in the system frequency response is confirmed in scenario 4, where the number of cable projects is even higher than in scenario 3. At 380 kV Nant de Drance, 380 kV Mörel, 380 kV Lavorgo, 380 kV Tierfehd, 380 kV Filisur and 380 kV Soazza, previously non-critical parallel resonances become critical with even lower frequencies and higher impedance amplitude , while in other cases, new parallel resonance peaks appear at lower-order harmonics, posing risks of critical TOVs during grid transient events.

- The increase in the number of cable projects in the grid shifts the parallel frequencies of the system towards lower-order harmonics at various locations.

Comparison of frequency response at various network locations between Scenarios 1, 2 and 3 shows a noticeable shift of parallel resonance towards low-order harmonics. In particular, the parallel resonant frequencies for Scenario 3 at multiple network locations is shifted to under the 4th harmonic (i.e., 200 Hz), which would expose the network to considerable risks of TOVs due to the excitation of low-order harmonic parallel resonance during network transients, especially under unfavorable operating conditions such as low short-circuit power level and contingencies.

- Cable integration has a higher impact on the 380 kV grid than the 220 kV due to lower system damping in the former

The impedance amplitude at resonance, or overall, across a defined frequency spectrum, is related to to system damping and loading conditions. Compared to the 220 kV grid, the 380 kV is significantly less meshed and there are fewer generation groups and loads (from mid- or low-voltage grids) connected to it, which makes it that the network damping on the 380 kV is generally lower as compared to the 220 kV grid, resulting in higher impedance amplitude at resonances. Since a high system damping helps to mitigate TOVs and other transients during on-site operations and events, cable integration on the 380 kV grid is expected to have a larger impact on the overall grid performance and equipment safety than on the 220 kV grid. That is to say, it would be "safer" to consider implementing cable projects on the 220 kV grid than on the 380 kV grid.

2.3 Harmonic amplification studies

Typical sources of harmonics in power systems are nonlinear loads (e.g., certain industrial equipment, Variable Speed Drives for AC/DC motors, battery chargers, etc.) and power electronics devices (e.g., HVDC converters, wind farms, SVC, STATCOM, etc.). The harmonics originated from these sources can propagate through system impedances, become amplified several times in cable-dense areas due to resonances, leading to deteriorated supply voltage. This can be illustrated in a simplified manner, as is shown in Figure 2-28.

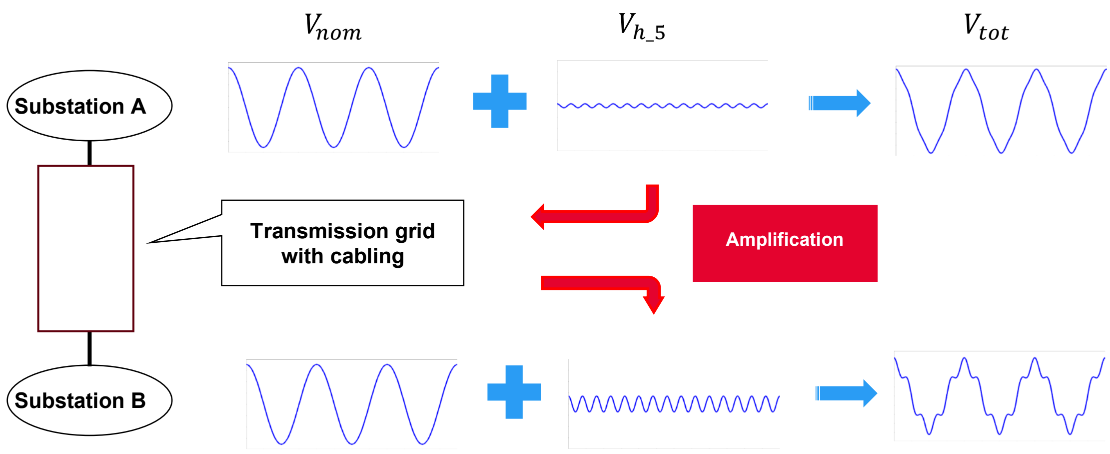
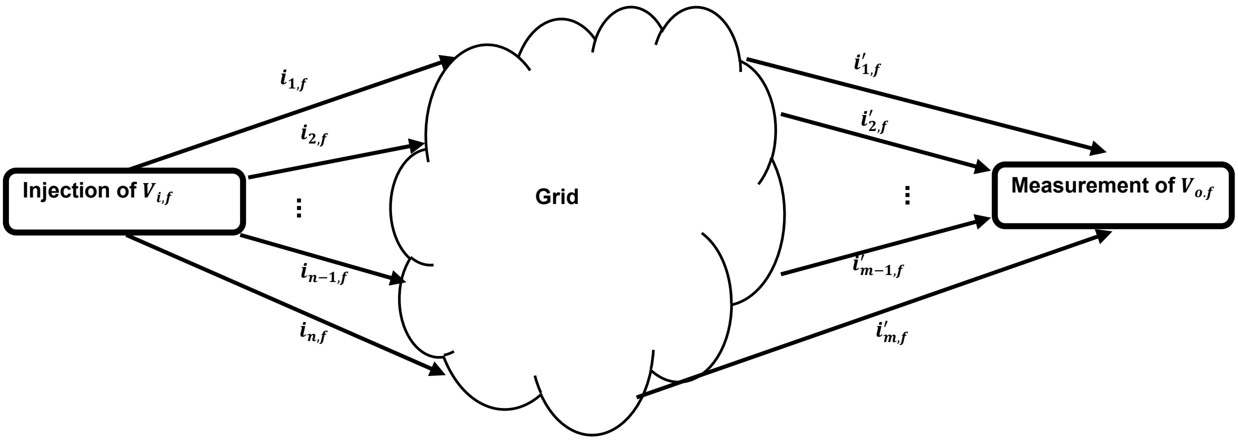


Figure 2-28: Illustration of harmonic amplification

In Figure 2-28, the 5th harmonic with relative amplitude lower than that defined in standard [2.2] propagates into the grid at Poste A from a local nonlinear load. This harmonic creates minor distortion on the voltage measured at Poste A, which is acceptable. When it reaches Poste B after travelling through a transmission path consisting of both lines and cable segments, it gets amplified by the resonance and has a relative amplitude now over the limit defined in standard IEC 61000-3-6 [2.2]. This amplified 5th harmonic is superimposed on the fundamental component of the voltage waveforms, leading to severe voltage distortion.

Although harmonic amplification is a result of network resonance due to the interaction of the inductive and capacitive elements, the degree of amplification depends little on the harmonic impedance seen at the terminal of observation. Instead, the degree of amplification at the terminal of observation is the collective impact of harmonic resonances on all the travelling paths from the injection point to the observation point. This can be understood using the simple illustration given inFigure 2-29.



$$V_{o,f} = Z_{1,f}i'_{1,f} + Z_{2,f}i'_{2,f} + \cdots + Z_{m-1,f}i'_{m-1,f} + Z_{m,f}i'_{m,f}$$

Figure 2-29: Illustration of the propagation and amplification of harmonics

In Figure 2-29, harmonics of a certain amplitude and frequency, $V_{i,f}$, are injected at a certain network location. These harmonics propagate towards other parts of the network via the n departs de ligne at this network location in the form of harmonic currents. After further merging/splitting/etc. in the network, some harmonic currents would reach another network location from the m travelling paths seen at the observation point, resulting in a harmonic voltage of the same frequency. This harmonic voltage is a sum of products of each harmonic current reaching the observation point and the corresponding harmonic impedance of the traveling path:

$$V_{o,f} = Z_{1,f}i'_{1,f} + Z_{2,f}i'_{2,f} + \cdots + Z_{m-1,f}i'_{m-1,f} + Z_{m,f}i'_{m,f}$$

Therefore, it is easy to understand that if resonance is excited on a certain travelling path or several travelling paths at the harmonic frequency, the corresponding harmonic impedance Z would be high, leading to a much higher harmonic voltage at the observation point compared to the injection point.

An increased THD (Total Harmonic Distortion) as a result of harmonic amplification has several repercussions on normal equipment maintenance and system operation by stressing the network and potentially damaging equipment. These impacts include (but not limited to):

- Equipment overheating (e.g., transformers, motors, neutrals, etc.)
- Audible noise in transformers and rotating masses
- Motor vibration
- Increased skin effect in line and cable conductors
- Thermal tripping of protective devices and logic faults of digital devices
- Capacitor bank failure

To prevent unforeseen issues, it is recommended to conduct studies of harmonic amplification in the planning stage of projects of intensive cable integration.

2.3.1 Methodology

Harmonic amplification studies are performed by injecting voltages of different harmonic frequencies (i.e., 250 Hz, 350 Hz, 550 Hz, 650 Hz, 850 Hz, 950 Hz, etc.) with an amplitude of 1 V at a certain location in the network and measuring the voltages at various other locations. The ratio of measured harmonic of a certain rank to the injected harmonic of the same rank defines the amplification factor (AF), indicating the severity of amplification of the harmonic rank in question or the degree of amplification. During this process, all other voltage sources (i.e., Thevenin equivalents) are short-circuited. Since nonlinearity due to harmonic voltage level is not expected, the results would remain consistent even with larger injection values. Note that ratio of voltage transformation needs to be taken into account when the injection and measurement points are on two different voltage levels.

International standards regarding the degree of amplification that should raise concerns among transmission grid operators do not exist. However, from experience ([2.3] and [2.5]), the following guidelines are adopted in this study, as is shown in Table 2-15.

AF<1	No harmonic amplification problems
1<AF<3	Medium harmonic amplification, non-critical
3<AF<10	Moderate to critical harmonic amplification
AF>10	Extremely critical harmonic amplification

Table 2-15: General guidelines on the severity of harmonic amplification

It is noted that it is assumed that all AFs below 3 (marked in green and yellow) should not raise any concerns of severe harmonic amplification, whereas those above 3, especially above 10, should deserve the reader's attention.

From experience, amplification of low-order harmonics, especially the 5^{th} and the 7^{th} (i.e., 250 Hz and 350 Hz) should deserve the most attention in the Swissgrid network due to the following reasons:

- Presence of even harmonics in the harmonic background of transmission networks is usually insignificant.
- High-order odd harmonics are less likely to become problematic due to larger damping at higher frequencies.
- Amplification of interharmonics (i.e., harmonics with values between integer multiples of 50 Hz) is not of concern due to the lack of VSC (Voltage Source Converter)-HVDC directly connected to the transmission network.

Locations of potential harmonic sources need to be carefully determined. Particularly, 220 kV and 380 kV substations connected to mid- to low-voltage levels (with possible connections to nonlinear loads) and to the SBB network should be considered as potential sources of harmonic pollution. In addition, amplification in the areas with intensive cable penetration needs to be evaluated first and foremost. Based on these guidelines, the following 12 locations have been chosen and tested as potential harmonic pollution sources (a selection of the results are presented in annex 4.4.4):

220 kV Verbois	380 kV Bois Tollot	380 kV Romanel	220 kV St. Triphon
220 kV Wimmis	220 kV Mettlen	380 kV Mettlen	220 kV Mühleberg
220 kV Gerlafingen	220 kV Fällanden	220 kV Sils	380 kV Musignano

In general, increasing cable penetration and low SCL can be expected to intensify the amplification of a certain harmonic rank. However, this is not always true, especially when there is intensive cabling in a certain network area, as is shown in Figure 2-30.

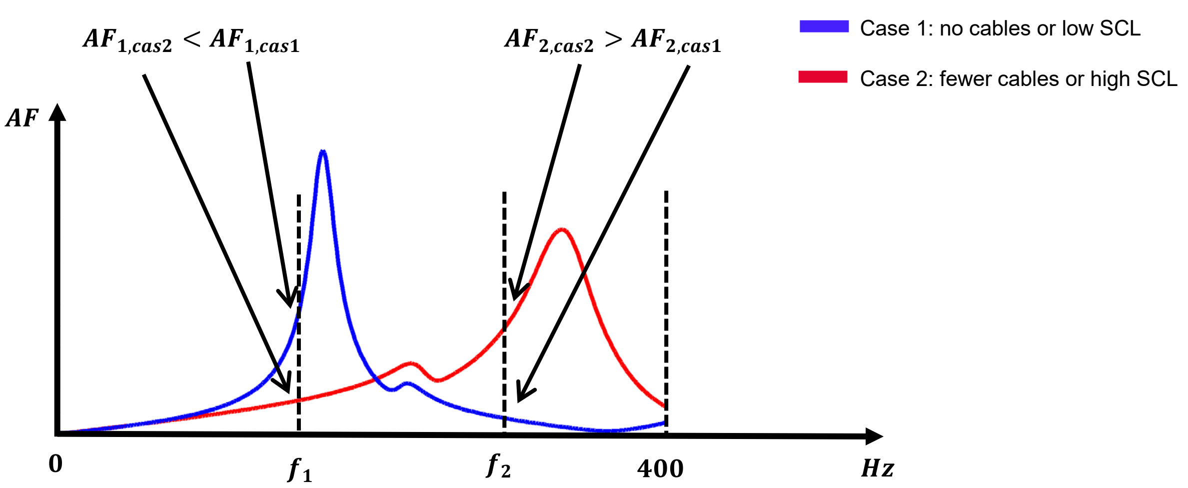


Figure 2-30: Generic explanation of the impact of grid configuration on harmonic resonances

Intensive cabling can shift the network resonance towards lower-order harmonics. Since we are mostly interested in the amplification on the 5th and the 7th harmonics, our focus is the behavior of the impedance of the harmonic travelling path under 400 Hz (i.e., 8th).

Two cases with different harmonic resonant frequencies have been defined:

- Case 1 (blue curve) : lower harmonic resonant frequency due to more cables connected in the vicinity or low short-circuit power
- Case 2 (red curve): higher harmonic resonance frequency due to fewer cables connected in the vicinity or high short-circuit power

For the amplification of a certain harmonic rank f_1, the amplification in Case 1 with more cables or low short-circuit power is higher than in Case 2 with fewer cables or high short-circuit power. However, for the amplification of harmonic rank f_2, it is Case 2 with fewer cables or high short-circuit power that has a higher amplification factor.

As more cables are integrated into the network, depending on the location of the harmonic resonant frequency of the travelling path(s) as well as the harmonic rank of interest, the result can be unpredictable, making it **absolutely necessary** to conduct detailed harmonic amplification studies for multiple grid configurations and operating conditions.

2.3.2 Results and discussion

The following main conclusions can be drawn from the performed studies:

- In general, amplification of low-order harmonics (e.g., the 5th and the 7th) gets aggravated as the number of cable projects in the network increases from Scenario 1, 2 to 3 under the same network conditions. That is to say, the more cables there are in the network, the higher the risks of severe harmonic amplifications are. This phenomenon has been observed at multiple network locations (see section 2.3.2.1).

- Network short-circuit power has a large impact on the amplifcation of harmonics. Generallly speaking, a strong short-circuit power usually damps harmonic resonances, mitigating the amplification of low-order harmonics s (see section 2.3.2.2).
- The phenomenon of harmonic amplification becomes complicated with an increasing degree of cabling in the network. In a densely cabled network, a single cable project would not only have an impact on harmonic amplification in the local area, but also it may impact the amplification of low-order harmonics in remote areas. This phenomenon has been observed during the studies performed for this project (see section 2.3.2.3).

Overall, the amplification of low-order harmonics due to cable integration is a result of harmonic resonance along harmonic travelling path, which makes it a complex issue. **Several exceptions to the first two findings have also been identified. These exceptions, together with the third finding, demonstrate the absolute need of performing detailed harmonic amplification studies for the integration of any new cable projects in the future, taking into account variations of network configurations and conditions.** The above three main findings are further elaborated the respective sections.

2.3.2.1 Impact of the number of cable projects in the grid on harmonic amplification

As was seen at the beginning of this chapter, amplification of harmonics of certain ranks is a result of harmonic resonance along certain harmonic current travelling paths before reaching the observation point. If a network area is purely composed of overhead lines, there should be no risks of amplification of low-order harmonics. However, integrating cable projects into an originally inductive network area composed mostly of overhead lines introduces capacitive elements into the grid, thus posing potential risks of amplification on certain low-order harmonics. Moreover, in general, as the number of cable project increases, the amplification of low-order harmonics becomes more severe.

Harmonic amplification studies for the three scenarios have been conducted at multiple network locations considering variations of network conditions (see annex 4.4.4). Upon comparing the amplification factors for low-order harmonics between Scenarios 1, 2 and 3, a few problematic areas have been identified, notably, the 220 kV path Romanel – Banlieue Ouest – Crans – Foretaille, the 380 kV Romanel – Bâtiaz – Châtelard – Nant de Drance and the 220 kV path Mettlen – Airolo.

The following test cases are presented to demonstrate the impact of the number of cable projects on the amplification of low-order harmonics (i.e., the 5^{th} and the 7^{th}) (comparison between Scenarios 1, 2 and 3):

Injection point	Observation point	SCL	Grid configuration
220 kV Verbois	220 kV Crans	Low	N-1 on 220 kV Romanel – Veytaux
	220 kV Banlieue Ouest		
	220 kV Romanel		
	220 kV Vaux		
380 kV Romanel	380 kV Bâtiaz		N-1 on 380 kV Bâtiaz – Chamoson
	380 kV Châtelard		
	380 kV Nant de Drance		
	220 kV Châtelard		
220 kV Mettlen	220 kV Airolo		N-2 on 220 kV Airolo – Rotondo and Airolo – Lavorgo

2.3.2.1.1 Harmonic amplification at 220 kV Crans, 220 kV Banlieue Ouest, 220 kV Romanel and 220 kV Vaux

The grid configuration near 220 kV Crans, 220 kV Banlieue Ouest, 220 kV Romanel and 220 kV Vaux for Scenarios 1, 2 and 3 for the demonstrative case is illustrated in Figure 2-31.

Note that the entire network area is comprised only of overhead lines in Scenario 1 whereas the only cable segments in Scenario 2 in this area is the 4.8 km double-circuit cable system between 220 kV Foretaille and 220 kV Verbois. However, the entire section of 57 km between 220 kV Foretaille and 220 kV Romanel is implemented by underground cables in Scenario 3. In addition, a cable segment with a total length of 16 km (8 km, two cables per phase) is also implemented in Scenario 3 between 220 kV Romanel and 220 kV Vaux.

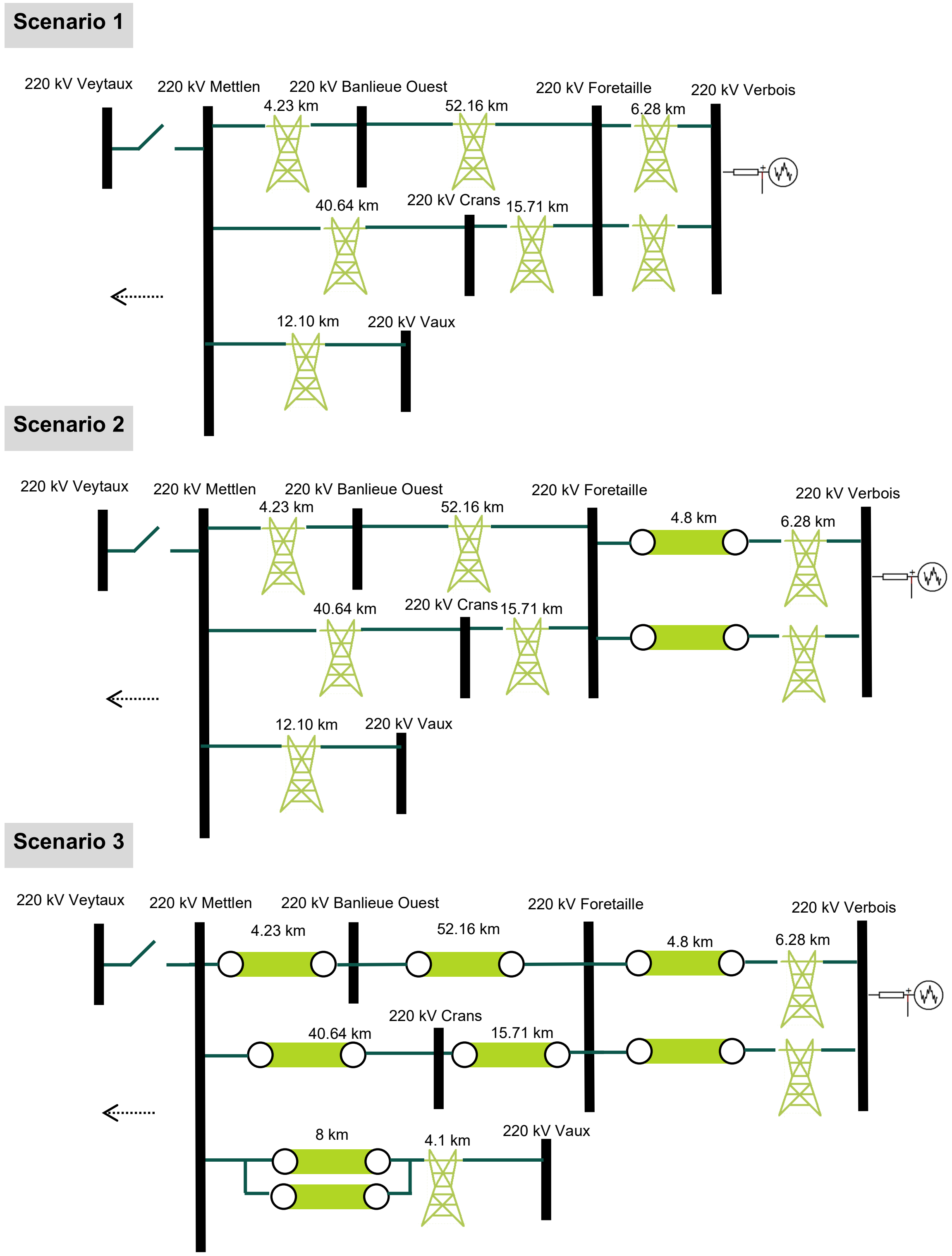


Figure 2-31: Grid configuration near 220 kV Crans, 220 kV Banlieue Ouest, 220 kV Romanel and 220 kV Vaux for the illustrative case – scenarios 1, 2 and 3

The amplification factors observed at 220 kV Crans, 220 kV Banlieue Ouest, 220 kV Romanel and 220 kV Vaux for the illustrative case in scenarios 1, 2 and 3 are shown in Table 2-16.

	AF at the 5th			AF at the 7th		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
220 kV Crans	0.837	0.859	0.635	0.990	0.952	3.532
220 kV Banlieue Ouest	0.664	0.657	0.511	0.786	0.821	4.080
220 kV Romanel	0.642	0.630	0.607	0.773	0.805	3.812
220 kV Vaux	0.694	0.685	0.493	0.806	0.832	3.503

Table 2-16: Comparison of the AF at 220 kV Crans, 220 kV Banlieue Ouest, kV Romanel, and 220 kV Vaux in scenarios 1, 2 and 3 for harmonic injections at 220 kV Verbois – low SCL

Note: While no risks of amplification of low-order harmonics can be identified in Scenarios 1 and 2, critical amplification factors on the 7th harmonic can be observed in Scenario 3 when the area from 220 kV Foretaille to 220 Romanel is intensively cabled.

For further information, the harmonic resonance along the paths 220 kV Verbois – Romanel and 220 kV Romanel - Vaux for both scenarios under the given grid conditions is plotted inFigure 2-32.

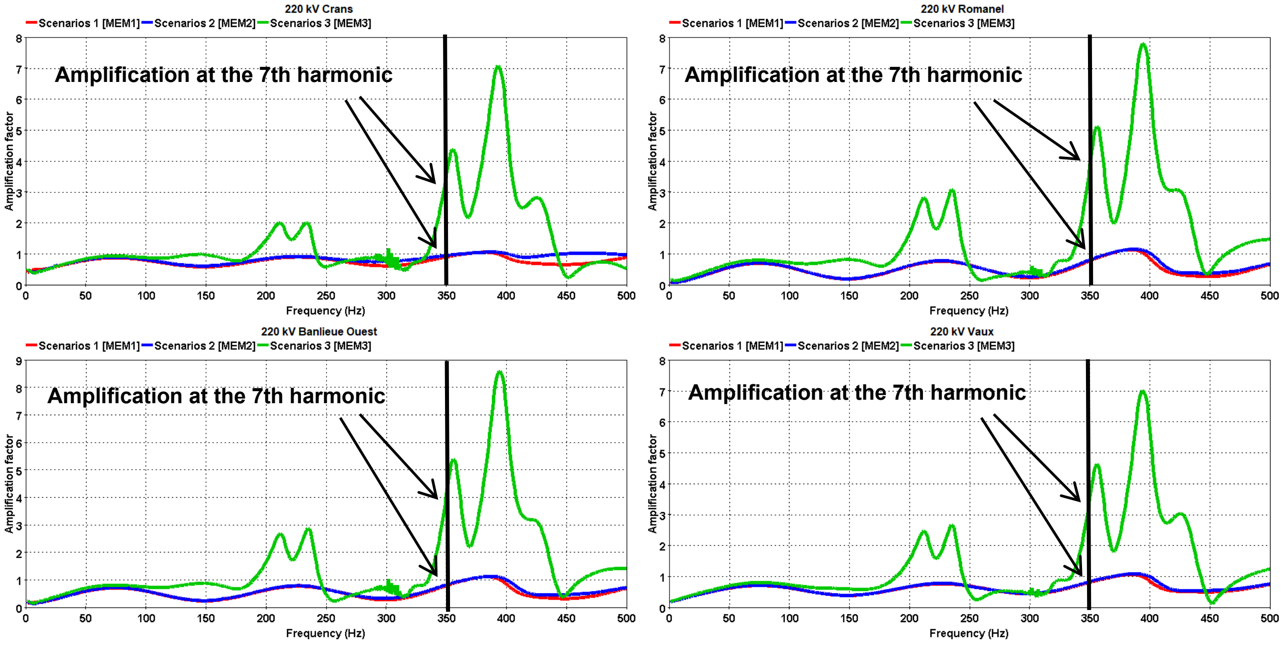


Figure 2-32: Harmonic resonance along 220 kV Verbois – Romanel and 220 kV Romanel – Vaux for scenarios 1, 2 and 3 under the given grid conditions

As shown in Figure 2-32, the introduction of all cable systems in this network area in Scenario 3 results in a harmonic resonance peaking over 350 Hz (the 7th harmonic). Despite the fact that the resonant frequency peak does not fall exactly on the 350 Hz, this harmonic resonance still imposes a large impact on the 7th harmonic, as is seen in the results.

2.3.2.1.2 Harmonic amplification at 380 kV La Bâtiaz, 380 kV Châtelard, 380 kV Nant de Drance and 220 kV Châtelard

The grid configuration near 380 kV Romanel as far as 380 kV Nant de Drance for scenarios 1, 2 and 3 for the illustrative case is shown in Figure 2-33.

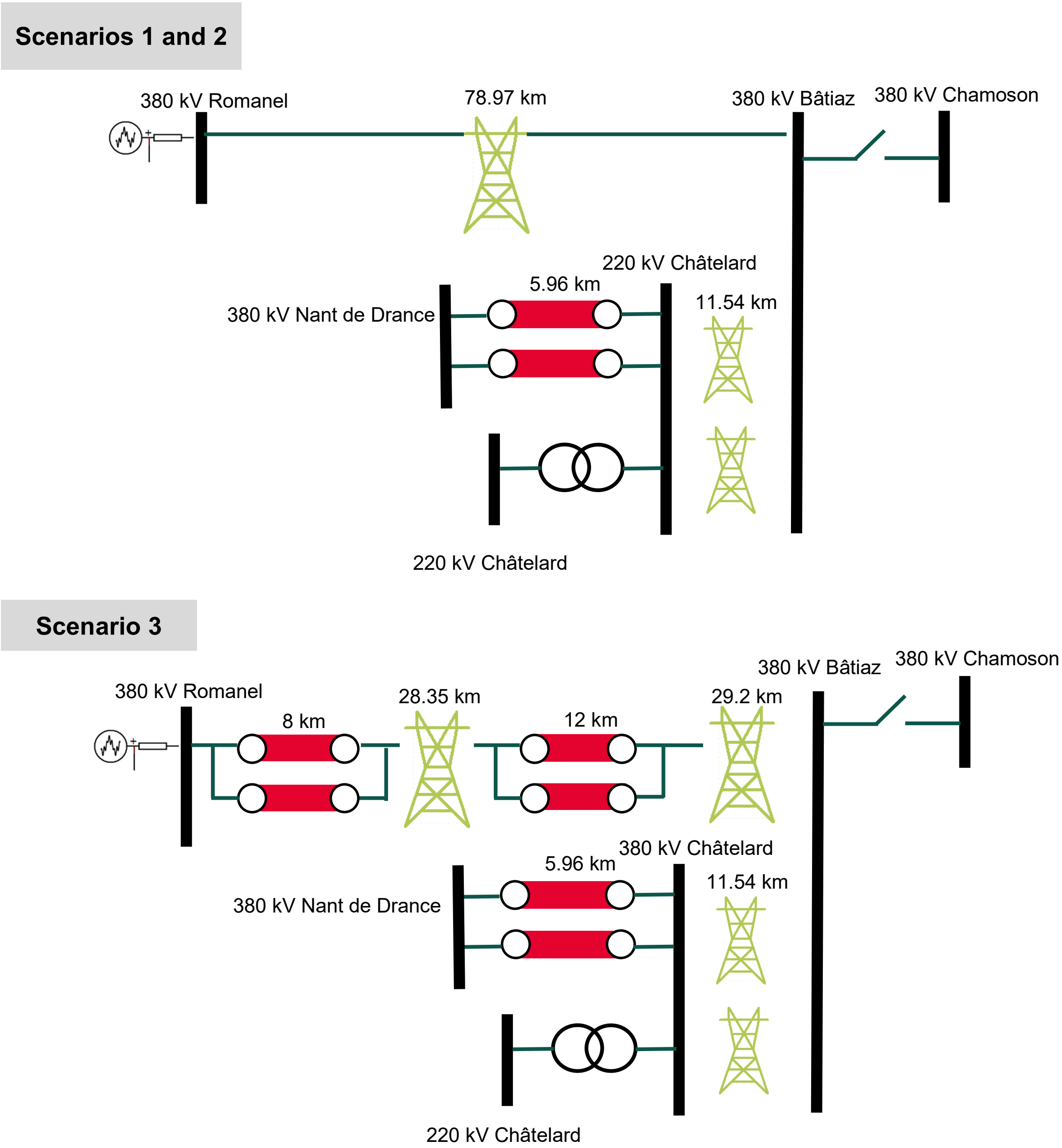


Figure 2-33: Grid configuration near 380 kV Romanel, 380 kV Bâtiaz, 220/380 kV Châtelard and 380 kV Nant de Drance for the illustrative case – scenarios 1, 2 and 3

Note that the only cable segments in Scenarios 1 and 2 in this area is the 5.96 km double-circuit 380 kV Châtelard-Nant de Drance cables. However, the 58.7 km transmission path in Scenario 3 from 380 kV Romanel towards 380 kV La Bâtiaz becomes a mixed line/cable section with a total of 40 km cables (two cables per phase), The amplification factors observed at 380 kV Bâtiaz, 380 kV Châtelard, 380 kV Nant de Drance and 220 kV Châtelard for the demonstrative case for Scenarios 1, 2 and 3 are presented in Table 2-17.

	AF at the 5th			**AF at the 7th**		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
380 kV Bâtiaz	1.262	1.262	2.005	4.542	4.542	7.887
380 kV Châtelard	1.280	1.280	2.033	4.777	4.777	8.287
380 kV Nant de Drance	1.282	1.282	2.036	4.809	4.809	8.337
220 kV Châtelard	0.585	0.585	1.605	2.276	2.276	6.810

Table 2-17: Comparison of AF at 380 kV Bâtiaz, 380 kV Châtelard, 380 kV Nant de Drance and 220 kV Châtelard in scenarios 1, 2 and 3 for harmonic injections at 220 kV Verbois – low SCL

Notes: Critical amplification factors on the 7th harmonics can be observed in the Nant de Drance area of both voltage levels with low SCL conditions when harmonics are injected into the 380 kV grid at 380 kV Romanel for all three scenarios. In particular, it is not surprising that amplification factors in Scenarios 1 and 2 are identical since the local grid has the same configuration in the Nant de Drance area. As more cable projects are integrated into the grid between 380 kV Romanel and 380 kV Bâtiaz such as in Scenario 3, the amplification factors on the 7th harmonic become worse.

Note that the issues of harmonic amplification have also been identified in previous studies performed by RTEi [2.5]. The amplification factors are much higher at the same observation points in the RTEi studies because an even lower short-circuit values were adopted.

For further information, the harmonic resonance along the paths 380 kV Romanel – Bâtiaz – Châtelard – Nant de Drance for Scenarios 1, 2 and 3 under the given grid conditions is plotted in Figure 2-34.

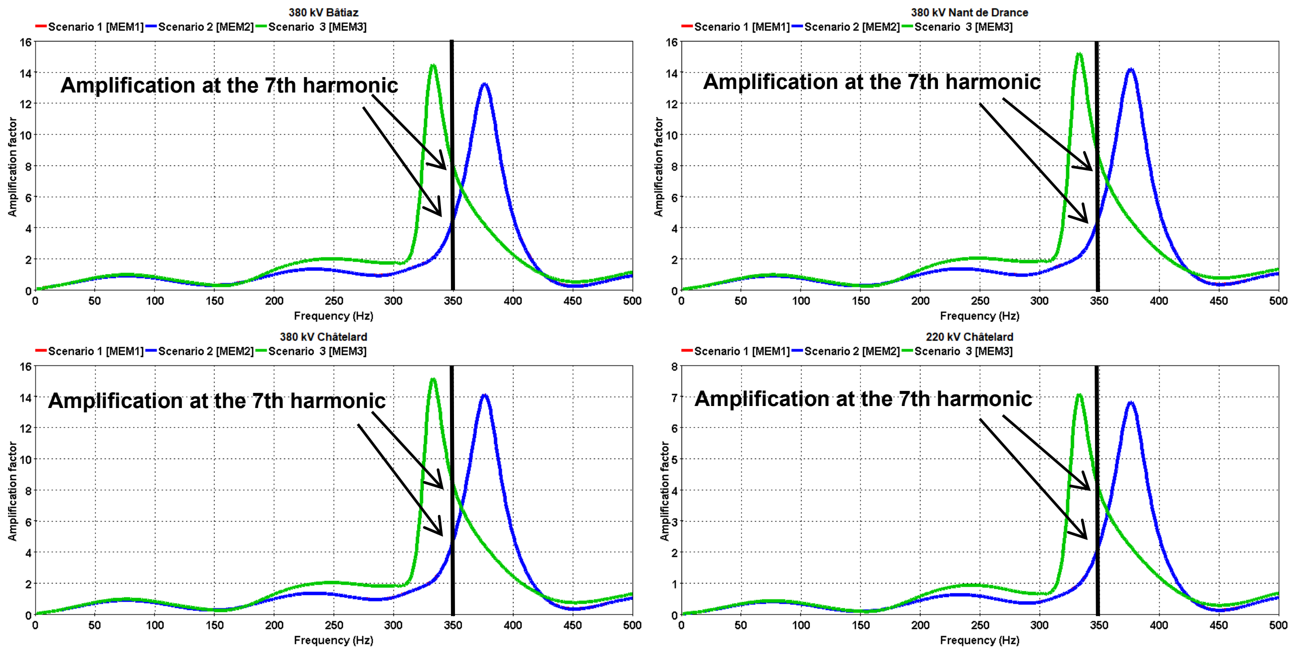


Figure 2-34: Harmonic resonance along the 380 kV Romanel – Bâtiaz – Châtelard – Nant de Drance axis for scenarios 1, 2 and 3 under the given grid conditions.

As shown in Figure 2-34, in Scenarios 1 and 2, the Nant de Drance cables, together with the network topology (N-1 on 380 kV Bâtiaz – Chamoson), results in a harmonic resonance peaking around 375 Hz. This leads to a relatively high amplification on the 7th harmonic (i.e., 350 Hz).

As more cable projects are introduced in Scenario 3, this harmonic resonance peak shifts towards lower frequencies to below 350 Hz. The amplification factors at the 7th harmonic become larger due to a larger harmonic impedance and lower resonant frequency.

According to a recent measurement campaign carried out at 380 kV Romanel [2.30], the 7th harmonic component could even be as high as 4% (see Figure 2-35). This already exceeds the 2% limit defined by the standard [2.2].

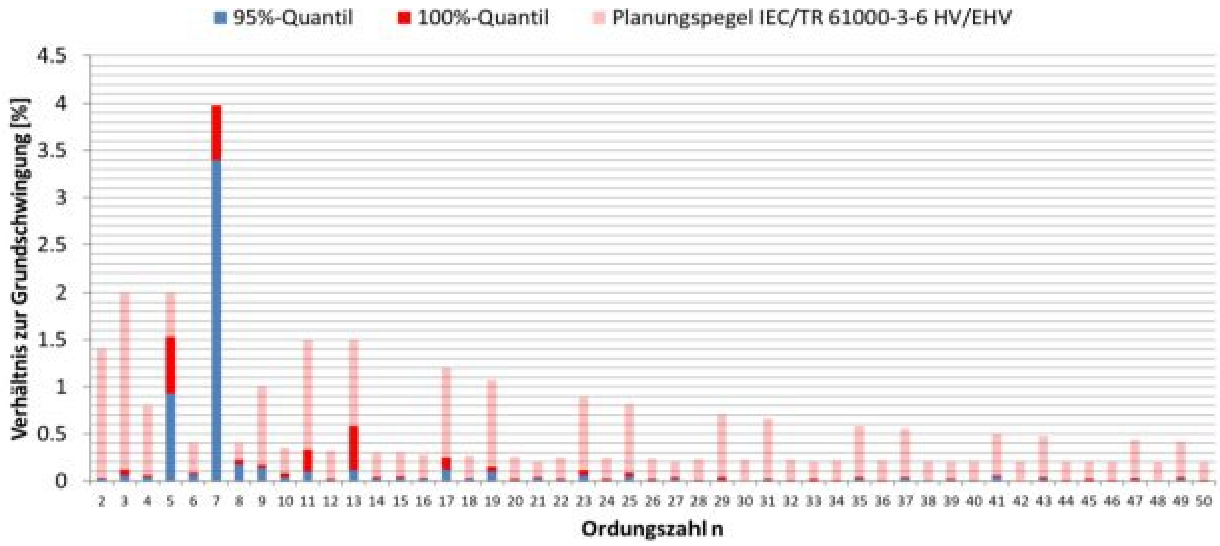


Figure 2-35: Harmonic components in relation to the fundamental component (%) measured at 380 kV Romanel

With an amplification factor of the 7th harmonic reaching 7.887 at 380 kV Bâtiaz, 8.287 at 380 kV Châtelard and 8.337 at 380 kV Nant de Drance in scenario 3 (see Table 2-17, the total distortion of the 7th harmonic at these three locations would be 31.548%, 33.148% and 33.348%, respectively, in the worst-case. Such a significant amplification of the 7th harmonic would have a serious impact on power quality and grid equipment.

2.3.2.1.3 Harmonic amplification at 220 kV Airolo

The grid configuration near 220 kV Airolo for scenarios 1, 2 and 3 of the illustrative case is shown in Figure 2-36.

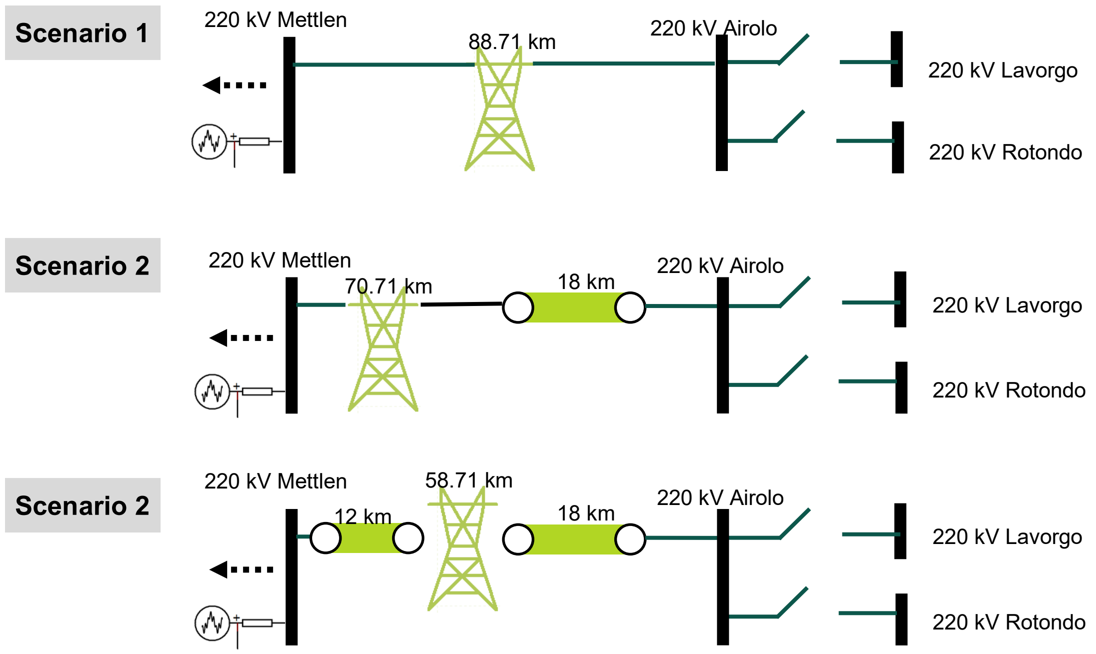


Figure 2-36: Grid configuration near 220 kV Airolo for scenarios 1, 2 and 3 under the given grid conditions

Note that while the 220 kV connection Mettlen – Airolo is purely comprised of overhead lines in Scenario 1, an 18 km Gotthard cable is introduced in Scenarios 2 north of 220 kV Airolo. In Scenario 3, another cable segment of 12 km is integrated south of Mettlen, making the total length of cable connection on the connection 220 kV Mettlen – Airolo 30 km.

The N-2 contingency isolates 220 kV Airolo from 220 kV Rotondo and Lavorgo, leaving the Gotthard cable radially connected to the harmonic source via a long overhead line path.

The amplification factors observed at 220 kV Airolo for the demonstrative case for Scenarios 1, 2 and 3 are presented in Table 2-18.

	AF at the 5th			**AF at the 7th**		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
220 kV Airolo	1.058	11.32	6.143	1.191	1.306	1.913

Table 2-18: Comparison of AF at 220 kV Airolo in scenarios 1, 2 and 3 for harmonic injections at 220 kV Mettlen – low SCL

Notes: No amplification of low-order harmonics can be observed in Scenario 1, which is understandable since the 220 kV Mettlen – Airolo connection does not have any cable implementation.

An extremely high amplification factor of over 10 on the 5th harmonic can be observed in Scenario 2 at 220 kV Airolo due to the introduction of cable projects (18 km Gotthard cable) in the harmonic propagation path. This case has also been identified in previous studies conducted by RTEi [2.3] and Enernex [2.4].

However, with the integration of another 12 km cable project south of Mettlen in Scenario 3, the amplification factor on the 5th harmonic decreases to slightly above 6. This can be understood by looking at the harmonic resonance along the path 220 kV Mettlen – Airolo for the three scenarios, as is shown in Figure 2-37.

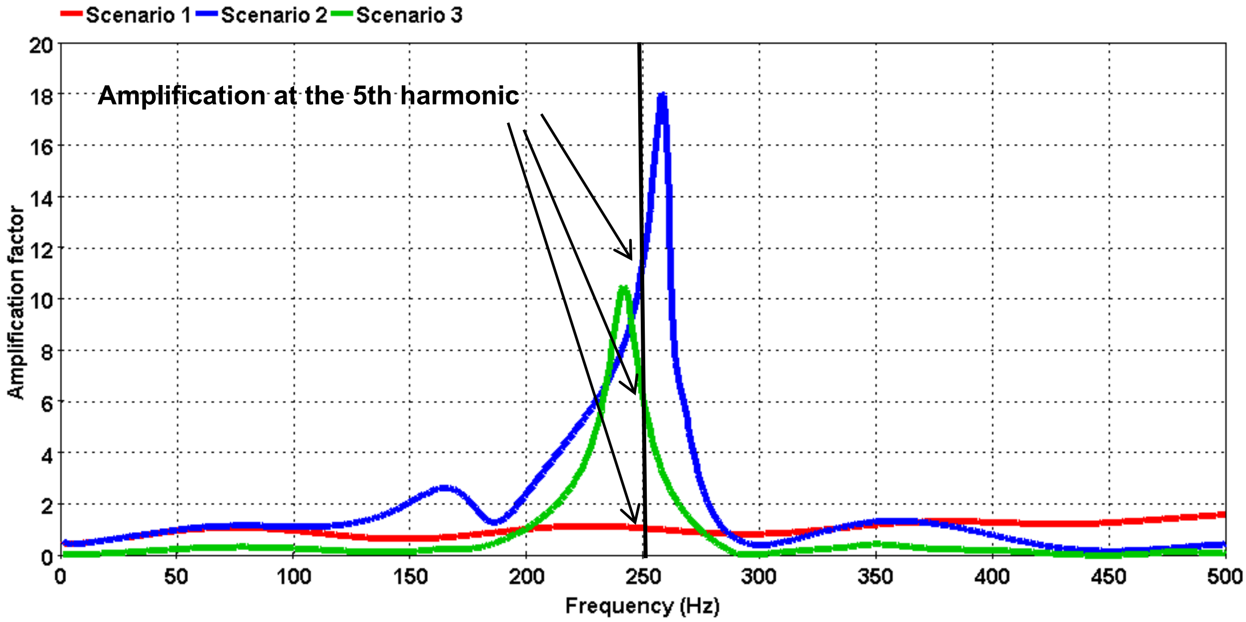


Figure 2-37: Harmonic resonance along 220 kV Mettlen – Airolo for scenarios 1, 2 and 3 under the given grid conditions

As shown in Figure 2-37, the introduction of the 18 km Gotthard cable in Scenario 2 results in a harmonic resonance peaking slightly over 250 Hz (the 5th harmonic), leading to a high amplification factor on the 5th harmonic at 220 kV Airolo. However, although the further integration of another 12 km cable south of Mettlen shifts the harmonic resonance to below 250 Hz, the amplification factor on the 5th harmonic of 250 Hz also decreases as a result.

Overall, it is understood that in general, harmonic amplification is expected to get intensified as more cables are integrated into the network. However, as the harmonic resonance shifts into sufficiently low frequency ranges, the relationship between the amplification factor for a certain harmonic rank and the number of cable projects can become unpredictable. Therefore, it is absolutely necessary to perform detailed harmonic amplification studies considering variations of network configurations and conditions for any new cable project to be integrated into the network.

2.3.2.2 Impact of short-circuit power on harmonic amplification

The network short-circuit strength plays an important role in the amplification of low-order harmonics. In general, amplification of low-order harmonics is usually intensified when the network short-circuit power is low. However, increasing the network short-circuit power is expected to be able to shift the harmonic resonance towards higher frequencies as well as damp the resonant peak, thus mitigating the amplification of low-order harmonics.

The following test cases are presented to demonstrate the impact of the network short-circuit strength on the amplification of low-order harmonics (i.e., the 5th and the 7th) (comparison between low and high SCL):

Injection point	Observation point	Scenario	Grid configuration	Comparison
220 kV Mettlen	220 kV Airolo	2	N-2 on 220 kV Airolo – Rotondo and Airolo – Lavorgo	Low and high SCL
380 kV Romanel	380 kV Bâtiaz	2	N-1 on 220 kV La Bâtiaz – Chamoson	Low and high SCL
	380 kV Châtelard			
	380 kV Nant de Drance			
	220 kV Châtelard			
380 kV Romanel	220 kV Romanel	3	N-1 on 220 kV La Bâtiaz – Chamoson	Low and high SCL
	220 kV Banlieue Ouest			
	220 kV Crans			
	220 kV Foretaille			
	380 kV Bâtiaz			
	380 kV Châtelard			
	380 kV Nant de Drance			
	220 kV Châtelard			

2.3.2.2.1 Amplification of harmonics at 220 kV Airolo

The grid configuration near 220 kV Airolo for scenario 2 of the illustrative case is shown in Figure 2-38.

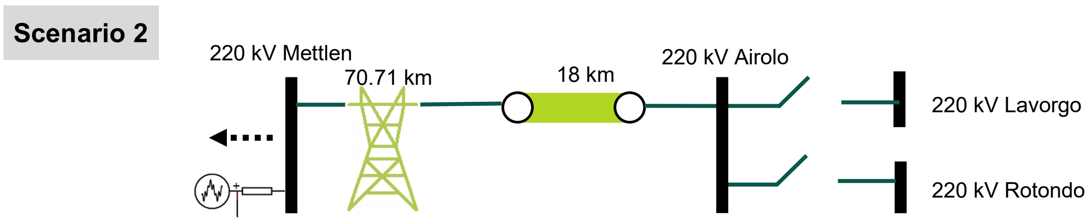


Figure 2-38: Grid configuration near 220 kV Airolo for the illustrative case – scenario 2

Note that an 18 km Gotthard cable is introduced in Scenario 2 north of 220 kV Airolo.

The amplification factors observed at 220 kV Airolo for the demonstrative case with low and high SCL are presented in Table 2-19.

	AF at the 5th		AF at the 7th	
	Low SCL	High SCL	Low SCL	High SCL
220 kV Airolo	11.32	1,306	7,322	1,387

Table 2-19: Comparison of AF at 220 kV Airolo between low SCL and high SCL for harmonic injections at 220 kV Mettlen – scenario 2

Notes: As seen in 2.3.2.1.3, the 5th harmonic can be severely amplified with harmonic injections at 220 kV Mettlen when 220 kV Airolo is isolated from 220 kV Rotondo and Lavorgo under low SCL conditions. However, increasing the network short-circuit power can effectively decrease the amplification factor by almost 40%.

For further information, the harmonic resonance along the path 220 kV Mettlen – Airolo for both low and high SCL under the given grid conditions is plotted in Figure 2-39.

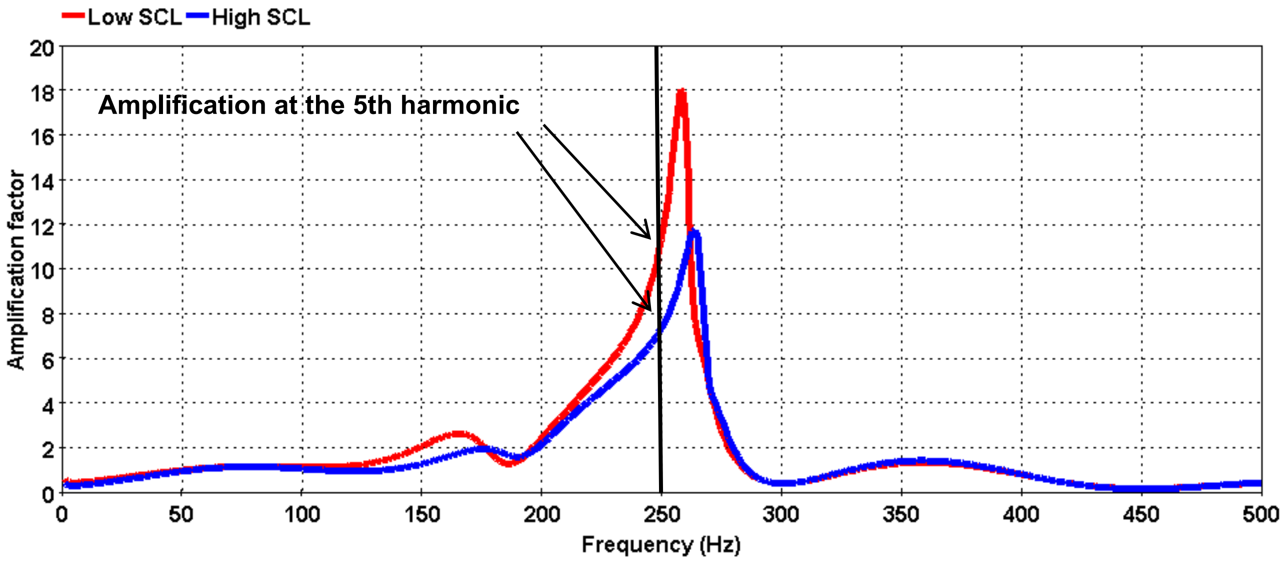


Figure 2-39: Harmonic resonance along 220 kV Mettlen – Airolo for low and high SCL under the given grid conditions

As shown in Figure 2-39, increasing the network short-circuit power not only slightly shifts the harmonic resonance towards higher frequencies, but it also damps the resonant peak along the transmission path 220 kV Mettlen – Airolo. Standing at over 7, although the amplification factor with high SCL is still quite high, it has been effectively decreased from a severely critical value of 11.

2.3.2.2.2 Scenario 2 – amplification of harmonics at 380 kV Bâtiaz, 380 kV Châtelard, 380 kV Nant de Drance and 220 kV Châtelard

The grid configuration near 380 kV Bâtiaz, 380 kV Châtelard, 380 kV Nant de Drance and 220 kV Châtelard for scenario 2 of the illustrative case is shown in Figure 2-40.

Scenario 2

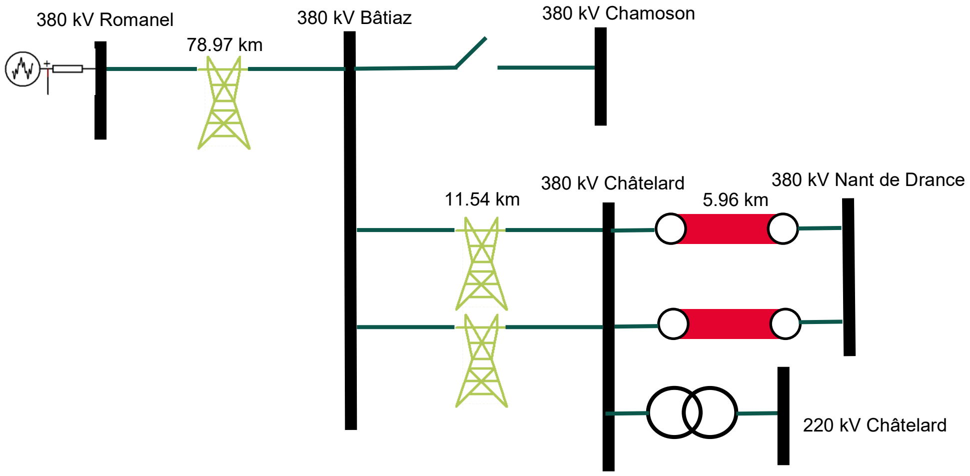


Figure 2-40: Grid configuration near 380 kV Bâtiaz, 380 kV Châtelard, 380 kV Nant de Drance and 220 kV Châtelard for the illustrative case – scenario 2

Note that in Scenario 2, the only cable systems in this network area are the 5.96 km double-circuit 380 kV Châtelard-Nant de Drance cables. Under the given grid configuration, the Nant de Drance cables are radially connected to the harmonic source at 380 kV Romanel.

The amplification factors observed at 380 kV Bâtiaz, 380 kV Châtelard, 380 kV Nant de Drance and 220 kV Châtelard for the demonstrative case with both low and high SCL are presented in Table 2-20.

	AF at the 5th		**AF at the 7th**	
	Low SCL	High SCL	Low SCL	High SCL
380 kV Bâtiaz	1.262	0.877	4.542	1.728
380 kV Châtelard	1.280	0.874	4.777	1.784
380 kV Nant de Drance	1.282	0.871	4.809	1.789
220 kV Châtelard	1.011	0.582	3.894	1.223

Table 2-20: Comparison of AF at 380 kV Bâtiaz, 380 kV Châtelard, 380 kV Nant de Drance and 220 kV Châtelard with low and high SCL for harmonic injections at 380 kV Romanel – scenario 2

Notes: As seen in section 2.3.2.1.2, critical amplification factors on the 7th harmonics can be observed in the Nant de Drance area of both voltage levels with low SCL conditions when harmonics are injected into the 380 kV grid at 380 kV Romanel. Nonetheless, with a high SCL in the network, the amplification factors become non-critical under the same circuit topology.

For further information, the harmonic resonance along the paths 380 kV Romanel – Bâtiaz – Châtelard – Nant de Drance for both low and high SCL under the given grid conditions is plotted in Figure 2-41.

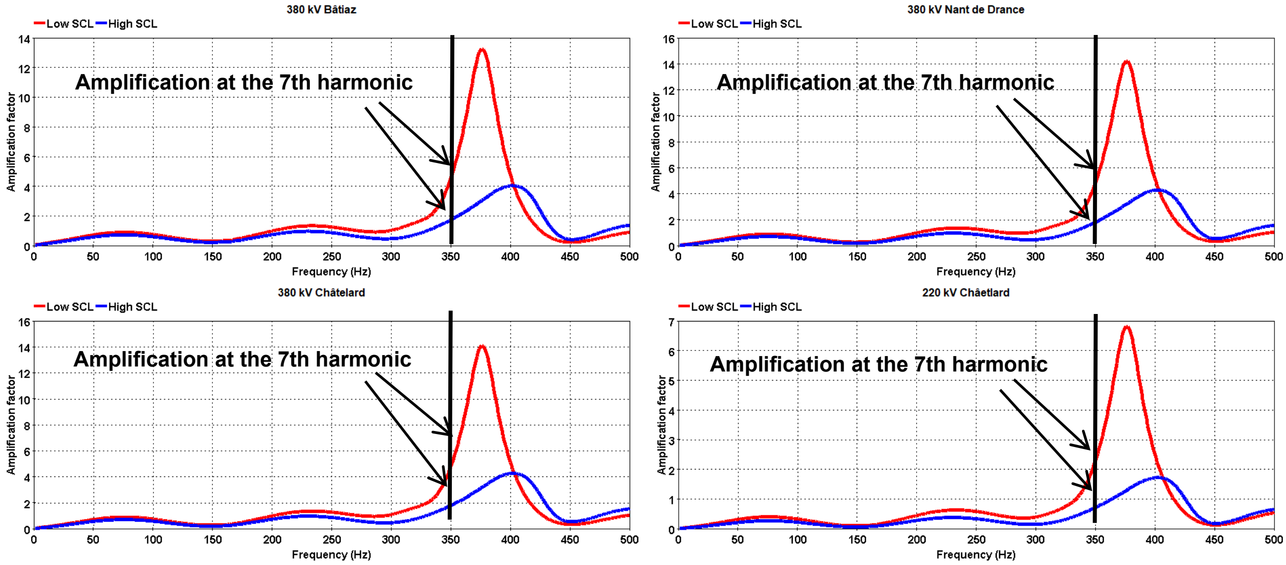


Figure 2-41: Harmonic resonance along the 380 kV Romanel – Bâtiaz – Châtelard – Nant de Drance grid for low and high SCL under the given grid conditions

As shown in Figure 2-41, the Nant de Drance cables, together with the network topology (N-1 on 380 kV Bâtiaz – Chamoson) results in a harmonic resonance peaking around 375 Hz under low SCL condition. This leads to a high amplification on the 7th harmonic (i.e., 350 Hz). However, increasing the SCL not only shifts the harmonic resonance towards even higher frequencies, but also it considerably damps the resonant peak, resulting in much mitigated amplification on the 7th harmonic. Figure 2-41 also indicates that with more cables integrated into this network area, the harmonic resonance peak is likely to further shift towards the 7th harmonic. With its high peak impedance, even more critical issues of harmonic amplification can be expected.

2.3.2.2.3 Scenario 3 – amplification of harmonics along the 380 kV Romanel – Nant de Drance and 220 kV Romanel – Foretaille connections

The grid configuration in scenario 3 near 380 kV Romanel as far as 380 kV Bâtiaz and 220 kV Foretaille is illustrated in Figure 2-42.

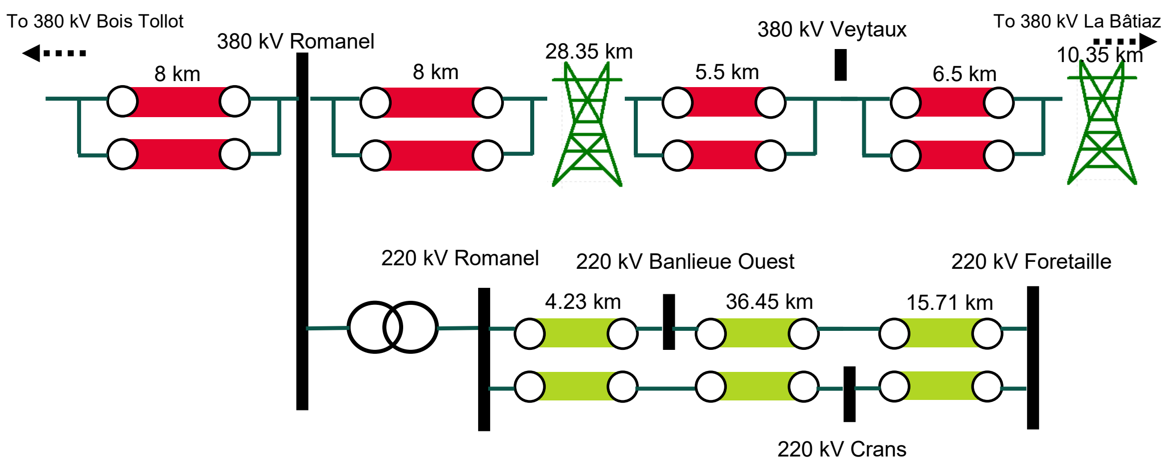


Figure 2-42: Grid configuration near 380 kV Romanel for the illustrative case – scenario 3

The 58.7 km transmission path in Scenario 3 from 380 kV Romanel towards 380 kV La Bâtiaz becomes a mixed line/cable section with a total of 40 km cables (two cables per phase), whereas the 57 km 220 km connection 220 kV Romanel – Foretaille is completely implemented with underground cables.

The amplification factors observed at the observation points for the demonstrative case with both low and high SCL are presented in Table 2-21.

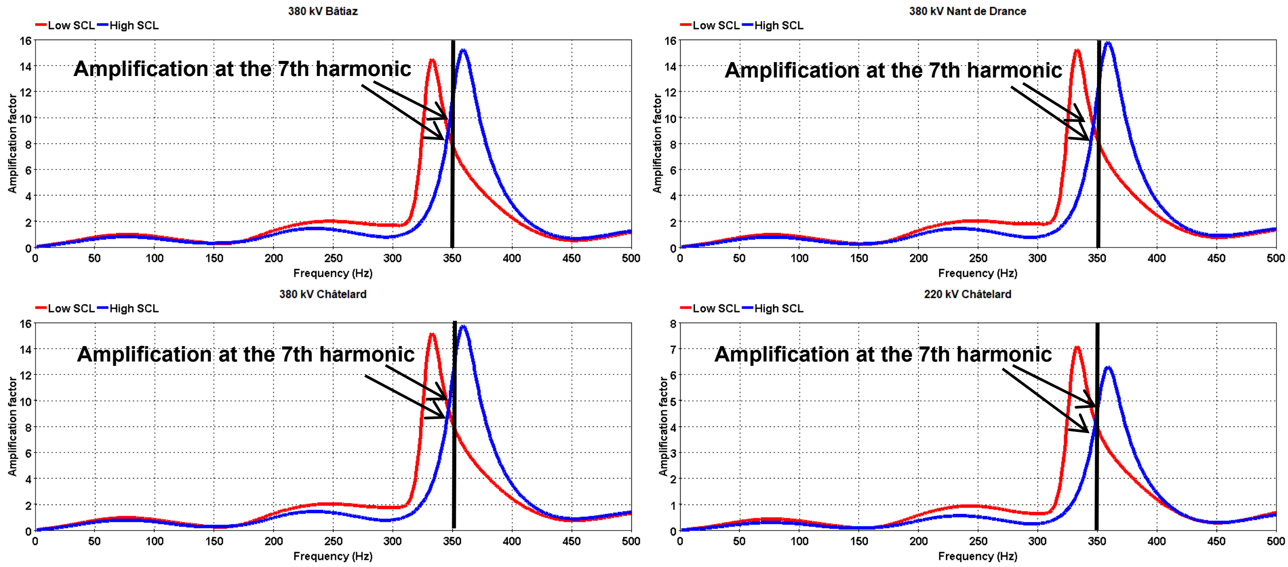
	AF at the 5th		**AF at the 7th**	
	Low SCL	High SCL	Low SCL	High SCL
220 kV Romanel	1.278	3.051	0.335	0.250
220 kV Banlieue Ouest	1.355	3.204	0.408	2.257
220 kV Crans	1.461	3.433	0.529	0.343
220 kV Foretaille	1.368	3.207	0.496	0.306
380 kV Bâtiaz	2.005	1.364	7.887	11.260
380 kV Châtelard	2.033	1.360	8.287	11.627
380 kV Nant de Drance	2.036	1.355	8.337	11.660
220 kV Châtelard	1.605	0.906	6.810	7.972

Table 2-21: Comparison of AF at 220 kV Romanel, 220 kV Banlieue Ouest, 220 kV Crans, 220 kV Foretaille, 380 kV Bâtiaz, 380 kV Châtelard, 380 kV Nant de Drance and 220 kV Châtelard with low and high SCL for harmonic injections at 380 kV Romanel – scenario 3

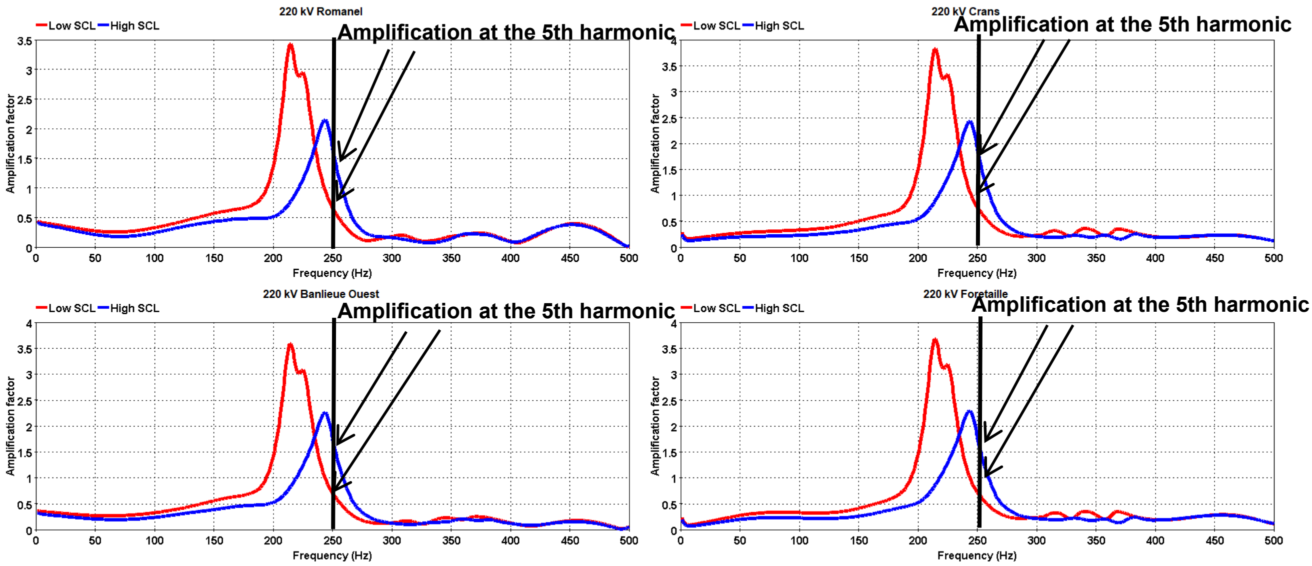
Notes: Under low SCL conditions, no harmonic amplification can be observed on the path 220 kV Romanel – Foretaille, whereas critical amplification factors on the 7^{th} harmonics are observed at various locations in the Nant de Drance region.

Instead of mitigating harmonic resonances, increasing the network short-circuit power in this case actually further increases the amplification factors on the 7^{th} harmonic in the Nant de Drance region to over 10 (extremely critical). Meanwhile, the originally moderate amplification factors on the 5^{th} harmonic along the path 220 kV Romanel – Foretaille also become critical with high network short-circuit strength.

For further information, the harmonic resonance along the paths 380 kV Romanel – Bâtiaz – Châtelard – Nant de Drance and 220 kV Romanel – Banlieue Ouest – Crans - Foretaille for both low and high SCL under the given grid conditions is plotted in Figure 2-43.



(a)



(b)

Figure 2-43: Harmonic resonance along the 380 kV Romanel – Bâtiaz – Châtelard – Nant de Drance and 220 kV Romanel – Banlieue Ouest – Crans – Foretaille paths for low and high SCL under the given grid conditions, (a) 380 kV Romanel – Bâtiaz – Châtelard – Nant de Drance, (b) 220 kV Romanel – Banlieue Ouest – Crans – Foretaille.

As shown in Figure 2-43 (a), the harmonic resonant frequency along the path 380 kV Romanel – Nant de Drance under low SCL conditions at various locations in the Nant de Drance area is below 350 Hz (i.e., the 7th harmonic). With an increased network short-circuit power, this harmonic resonance shifts towards slightly beyond 350 Hz. The harmonic resonance shifts from below the frequency of interested (i.e., 350 Hz, the 7th harmonic) to above it, resulting in the behavior observed in this case.

Similar observations can be made for Figure 2-43 (b), where the harmonic resonant frequency along the path 220 kV Romanel – Foretaille under low SCL conditions is way below 250 Hz (i.e., the 5th harmonic). Increasing the short-circuit power of the network shifts the harmonic resonance closer to 250 Hz, thus leading to a higher amplification on the 5th harmonic.

Overall, it is understood that in general, a high network short-circuit strength is expected to shift the harmonic resonance towards higher frequencies and damp the resonant peak, leading to mitigated amplification factors on low-order harmonics. However, in a densely cable area with the harmonic resonance well within the low frequency range, the actual impact of the network short-circuit power on the amplification of low-order harmonics becomes unpredictable due to the uncertain relationship between the harmonic resonant frequencies and the frequencies of interest (i.e., the 5^{th} and the 7^{th} harmonics). Therefore, once again, it is absolutely necessary to perform detailed harmonic amplification studies considering variations of network configurations and conditions for any new cable project to be integrated into the network.

2.3.2.3 Impact of a cable project on harmonic amplification in distant areas

The phenomenon of harmonic amplification becomes a complex issue with an increasing degree of cable integration in the network. In a densely cabled network, amplification of low-order harmonic in a certain network area not only would depend on the cable projects in the local area, but also it may be impacted by another cable project in an area far way. That is to say, the specific implementation scheme of a certain network segment with overhead lines or cables might have an impact on the amplification of low-order harmonics in a remote area. An example is presented in this section to demonstrate how, in Scenario 3, the implementation of a relatively short network segment of 14.56 km in the Zurich area would have an impact on harmonic amplification in Ticino.

Both areas of Zurich and Ticino in Scenario 3 are densely cabled, as is shown in Figure 2-44. The following test case is presented. It is noted that in this test case, harmonics are injected at 220 kV Mettlen and the amplification factors are observed at various locations in the Zurich and Ticino areas under optimal SCL condition. The considered N-1 contingency 220 kV Airolo – Lavorgo is located in the Ticino region. The impact of the implementation of the 220 kV connection Altgass – Samstagern, as is shown in Figure 2-44, either with overhead lines or cables, is evaluated.

Injection point	Observation point	Scenario	Grid configuration	Comparison
220 kV Mettlen	220 kV Regensdorf	3	N-1 on 220 kV Airolo – Lavorgo	Installation of a cable or line for the 220 kV Altgass – Samstagern section
	220 kV Seebach			
	220 kV Auwiesen			
	220 kV Fällanden			
	220 kV Bavona			
	220 kV Peccia			
	220 kV Cavergno			
	220 kV Avegno			

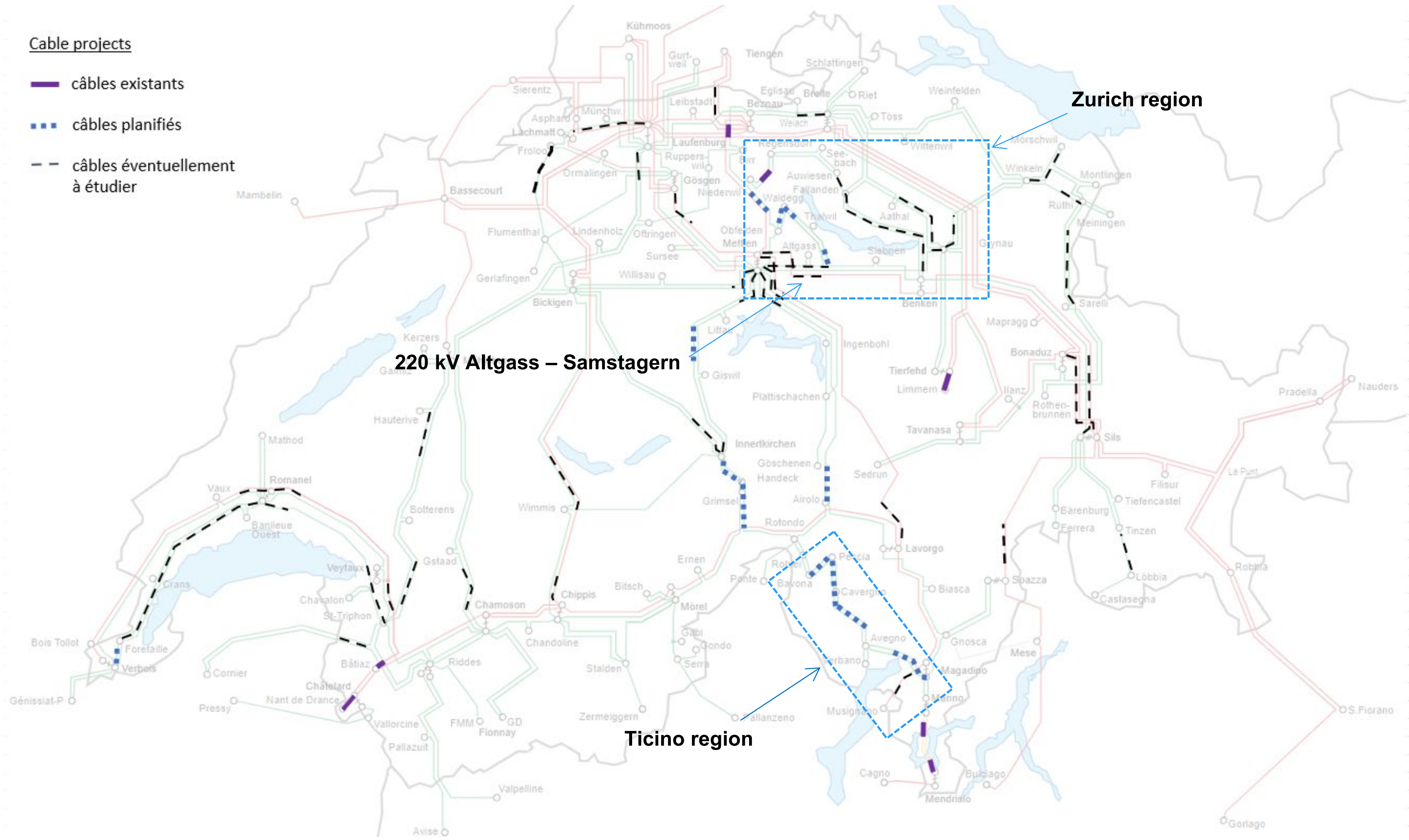


Figure 2-44: Diagrams of the cabling and compensation envisaged in scenario 3

The amplification factors seen at the observation points for the illustrative case using cable and line variants for the 220 kV Altgass – Samstagern section are shown in Table 2-22.

	AF at the 5th		**AF at the 7th**	
	Cable	Line	Cable	Line
220 kV Regensdorf	0.159	0.108	3.013	1.841
220 kV Seebach	0.120	0.085	3.192	1.956
220 kV Auwiesen	0.111	0.084	3.217	1.973
220 kV Fällanden	0.078	0.097	3.289	2.025
220 kV Bavona	0.582	0.670	3.085	2.421
220 kV Peccia	0.567	0.658	3.128	2.455
220 kV Cavergno	0.546	0.639	3.114	2.444
220 kV Avegno	0.391	0.476	2.170	1.698

Table 2-22: Comparison of AF at several locations in the Zurich and Ticino regions with two different designs of the 220 kV Altgass – Samstagern connection for harmonic injections at 220 kV Mettlen – scenario 3

Notes: Table 2-22 shows that when the section 220 kV Altgass – Samstagern is implemented with cables, under the given network conditions, critical amplification factors on the 7^{th} harmonic can be observed at multiple locations in the areas of Zurich and Ticino.

However, if the section 220 kV Altgass – Samstagern remains in the overhead line configuration, the amplification factors on the 7^{th} harmonic in both areas of Zurich and Ticino can be moderately mitigated to below the critical values of 3.

The implementation scheme of a single and relatively short 220 kV segment (Altgass – Samstagern) would have a large impact on the amplification of low-order harmonics in a distant geographical area (Ticino), indicating that issues of harmonic amplification can become quite tricky when the considered network areas are densely cabled. This proves, once again, the absolute need to perform detailed harmonic amplification studies for any new cable project, while taking into account possibly different implementation schemes of each project (with overhead lines or with cables), especially when the degree of cabling in the network increases.

2.3.3 Conclusions

Harmonics are omnipresent in a power system network as they can be emitted from a large number of non-linear loads and power electronics devices. The harmonics originated from these sources can propagate through system impedances and become amplified in cable-dense areas due to resonances, causing power quality issues, stressing and even damaging different kinds of network equipment.

Extensive system-level studies of harmonic amplification have been performed based on the proposed three cable scenarios. The studies were performed at multiple network locations that can be potential points of harmonic pollutions, while considering different network configurations in terms of contingencies and short-circuit power, with focus on the amplification on the 5th and 7th harmonics (the most encountered in transmission grids).

Several conclusions can be drawn from the performed studies:

- The amplification of low-order harmonics worsens as the number of cable projects in the grid increases.

If a network area is purely composed of overhead lines, there should be no risks of harmonic amplification. Integrating cable projects into an originally inductive network area composed mostly of overhead lines introduces capacitive elements into the grid, significantly increasing the risks of amplification on certain low-order harmonics. In general, as the number of cable projects increases, the amplification of low-order harmonics becomes more severe. There exist, however, exceptions to this point when the network area is densely cabled, as is presented in section 2.3.2.1.3, which is the reason why detailed harmonic amplification studies should be performed for any new cable project to foresee any possible issues of harmonic resonance in the planning stage.

- High short-circuit power of the grid can effectively mitigate harmonic amplification problems by damping harmonic resonances in lightly cabled grid areas.

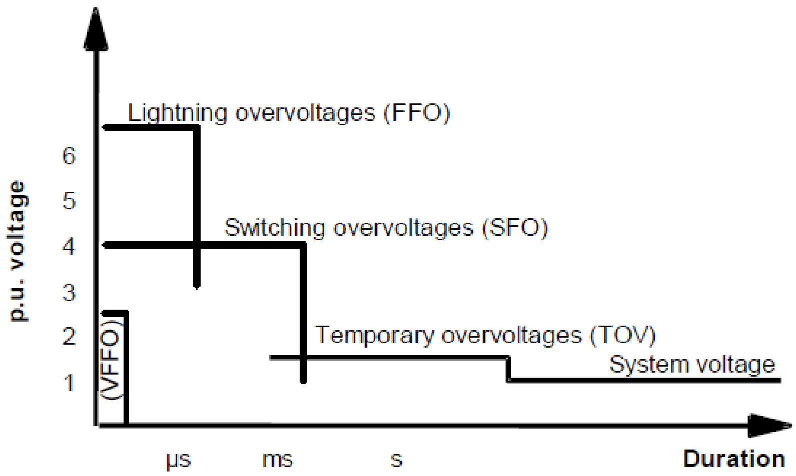
In general, amplification of low-order harmonics is usually intensified when the network short-circuit power is low. However, increasing the network short-circuit power can usually mitigate issues related to amplification of low-order harmonics by shifting the harmonic resonant frequency towards higher frequencies and damping harmonic resonance on different harmonic travelling paths. However, exceptions to this point are once again discovered, as is shown in section 2.3.2.2.3, proving the complexity of the issue of harmonic amplification in densely cabled networks.

- A single cable project in a densely cabled grid can have a significant impact on harmonic amplification in distant locations.

Issues of harmonic amplification become increasingly complex as more and more cables are integrated into the network. In a densely cabled network, the specific implementation scheme of a certain network segment either with overhead lines or with cables would not only have an impact on harmonic amplification in the local area, but it may also have a large impact on the amplification of low-order harmonics in a remote area. The complexity of this issue demonstrates once again the need of harmonic amplification studies for any new cable project to be integrated into the network while considering possible different implementation schemes (lines or cables) of each project.
Overall, amplification of low-order harmonics during cable integration (especially intensive cable integration) can be a tricky issue, which would absolutely require detailed harmonic amplification studies for the purpose of risk identification, definition of certain operating principles as well as decision-making on filter design and installation.

2.4 Time-domain studies

Before delving into the studies presented in this chapter, it is necessary to understand the types of overvoltages encountered in a power grid. Figure 2-45, extracted for IEC standard 60071-4 [2.6], illustrates the types and characteristics of overvoltages often encountered in a power grid.



(a) Types of overvoltages, with the exception of very-fast-front overvoltages

Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz T_t ≥3 600 s	10 Hz < f < 500 Hz 0,03 s ≤ T_t ≤ 3 600 s	20 µs < T_p ≤ 5 000 µs T_2 ≤ 20 ms	0,1 µs < T_1 ≤ 20 µs T_2 ≤ 300 µs	3 ns < T_f ≤ 100 ns 0,3 MHz < f_1 < 100 MHz 30 kHz < f_2 < 300 kHz
Standard voltage shapes	f = 50 Hz or 60 Hz T_t [1]	48 Hz ≤ f ≤ 62 Hz T_t = 60 s	T_p = 250 µs T_2 = 2 500 µs	T_1 = 1,2 µs T_2 = 50 µs	[1]
Standard withstand test	[1]	Short-duration power frequency test	Switching impulse test	Lightning mpulse test	[1]

[1] To be specified by the relevant apparatus committees.

(b) Categories and forms of overvoltage

Figure 2-45: Types and characteristics of the various overvoltages encountered in an electricity grid [2.6]

As explained in previous sections, the low-order harmonic resonances caused by the intensive integration of cables can be excited during certain transient events, leading to the occurrence of TOVs. These TOVs are of a "low frequency (temporary)" nature, as shown in Figure 2-45. TOVs are usually harmonically distorted and lightly damped, thus potentially stressing the high voltage equipment for long durations due to the following two main mechanisms [2.1]:

- Dielectric stress that can lead to insulation failure
- Overheating of equipment and insulation

Since existing international standards related to insulation co-ordination application guidelines do not provide methods to evaluate this type of overvoltages, system operators usually choose to avoid resonance conditions that would lead to excessive TOVs in grid design and operation or to adopt proper mitigation measures to limit the severity of TOVs.

- From experience, the following transient events are likely to generate and inject harmonics into the system thus result in TOVs from resonance excitation:Energisation of large power transformers and saturable shunt reactors
- Energisation of cables and capacitor banks
- Ground fault clearing
- Circuit breaker auto-reclosing
- System islanding

With the goal of demonstrating that high level of cable integration results in low-order harmonic resonances thus leading to excessive TOVs, studies of transformer energization at 380 kV Romanel and 380 kV Magadino for the problematic network topologies/configurations in Scenario 3 identified in Chapter 5 have been performed. Comparisons with Scenarios 1 and 2 under the same grid conditions have been provided in order to verify whether the network performance can be improved with lower degrees of cable integration.

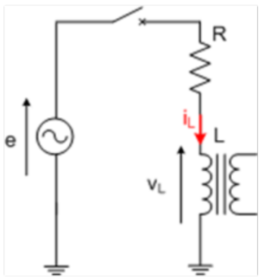
2.4.1 Theoretical background

2.4.1.1 Transformer saturation

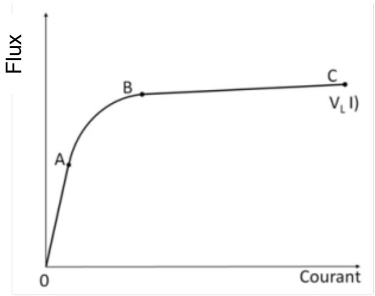
Energization of transformers is a common action that takes place in the operation of electrical power systems on a regular basis. It is generally performed without any adverse consequences to the network since the transient currents and voltages generated during this process can be safely damped within a few seconds in the power network. Nonetheless, in certain situations, the temporary voltage (TOV) that last for an extended period, generated by the low-frequency parallel resonances in the neighboring supply network excited by the rich harmonic contents in the transformer inrush currents, could lead to power quality issues, or even insulation degradation in the transformer.

TOVs caused by parallel resonance during transformer energization originates from the nonlinear properties of the power transformer inductive element (iron core) that can become saturated due to an abrupt change in the voltage (i.e., switching, out-of-phase generator synchronization, external faults and clearing, etc.) applied to it. The resulting severely distorted magnetizing current, namely the inrush current, contains rich harmonic components across a wide range of frequency spectrum which can be amplified by large impedance amplitudes at certain parallel resonant frequency points, leading to TOV at the transformer terminal.

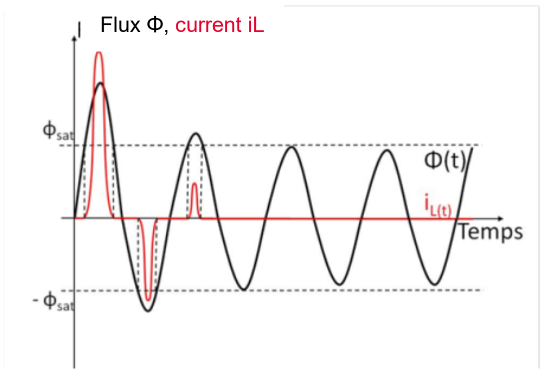
In order to clearly explain the non-linear behavior of the magnetizing branch of a power transformer during energization, the transformer can be simplified to a non-linear inductance L connected in series with a resistance R representing the network series resistance and the transformer winding resistance, supplied by a sinusoidal voltage source represented by e, as is shown in Figure 2-46 (a) [2.7].



a) Energisation of an unloaded transformer



b) Saturation curve tion



c) Flux and current of a non-linear inductor when excited

Figure 2-46: Operating principle of an unloaded transformer

The relationship between the magnetic flux linkage of the non-linear inductor Φ and the magnetising current I (both in rms values) is shown in Figure 2-46 (b). It can be seen that the current I varies non-linearly with respect to the flux Φ. Three different regions can be identified:

- **The linear region 0A:** In this region, as the magnetic flux Φ increases, the current I increases linearly. The corresponding inductance is not saturated and behaves as a constant inductance L_0 equal to the inductance of the transformer winding. Due to its relatively high value L_0, a large increase in magnetic flux Φ causes only a marginal increase in current.
- **The linear region BC:** In this region, the inductance of the transformer's iron core is highly saturated and the core itself, made of ferromagnetic materials, behaves almost like air with a relative permeability close to 1. The value of the corresponding inductance can be represented by a constant L_{sat}. In this region, even a marginal increase in magnetic flux would result in an amplification of the current due to the low value of L_{sat}.
- **The AB non-linear region:** This is the region where the magnetic flux linkage knee-point is situated. It is not possible to define an equivalent constant inductance value because of the non-linear relationship between Φ and I.

When a transformer is operating in steady state, the relationship between the magnetic flux linkage and current is generally located in the linear region 0A with the inductance value L_0 as defined previously. However, during energization, the magnetic flux could reach much higher values, moving the operating point of the inductance beyond region 0A thus causing the transformer to saturate [2.7]. Since the transformer core inductance is different in the different regions distinguished in Figure 2-46 b (e.g., $L_0 \gg L_{sat}$), when the transformer core goes in and out of saturation, which is, in other words, when the operating point moves between different regions in in Figure 2-46 b, the current in the inductance does not remain in a consistent sinusoidal form (in Figure 2-46 c), giving rise to a wide spectrum of harmonics.

2.4.1.2 Factors affecting the saturation level of the transformer

The saturation level of a transformer can be characterized by the magnitudes of the induced inrush currents. The main factors affecting the inrush current magnitudes during energization [2.8] are:

- Transformer design
- Initial conditions
- Grid factors

The design of a transformer determines its steady-state operating point on the saturation curve (Figure 2-46 (b)). As seen above, a transformer can easily be brought to saturation if its operating point is close to the knee-point (region AB in Figure 2-46 (b)).

The initial conditions affecting the inrush current magnitudes are mainly the remanent flux and the point-on-wave (POW) energization. The remanent flux is the flux that remains trapped in the transformer iron core due to a previous de-energization process and determines the initial DC offset of the flux linkage in the core. It would add on top of the flux linkage to further saturate the transformer. On the other hand, the POW at energization determines the maximum amplitude of the inrush current.

Network factors determining the level of saturation are mainly network topology and damping. As was shown in section 2.2, several topologies have been identified for Scenario 3 that would cause parallel resonances at low-order harmonic frequencies. Once excited, severe and poorly damped TOVs are to be expected. As a factor of positive impact, sufficient damping helps attenuate resonances, thus improving the transient behavior of the network and ensuring stable operation.

2.4.2 Methodology

For a given unloaded transformer and grid conditions, the factors determining the exact TOVs to be encountered are restricted to remanent flux and circuit breaker closing instants (POW). In order to find the "worst-case" scenarios in terms of TOVs, it is needed to study different variations of transformer remanent flux and circuit breaker closing instants. Examples of variant sets for transformer remanent flux and circuit breaker closing instants are given in Table 2-23 and Table 2-24, respectively.

Scenario	Φ_{0A}(pu)	Φ_{0B}(pu)	Φ_{0C}(pu)
1	0	0	0
2	0.8	–0.4	–0.4
3	0	0.8	–0.8
4	–0.8	0.4	0.4
5	0	–0.8	0.8
6	0.4	–0.2	–0.2
7	0	0.4	–0.4
8	–0.4	0.2	0.2

9	0	–0.4	0.4

Table 2-23: Example of variation in the residual flux of a transformer

Scenario	t_{close}(s)
1	0.500
2	0.501
3	0.502
4	0.503
5	0.504
6	0.505
7	0.506
8	0.507
9	0.508
10	0.509
11	0.510
12	0.511
13	0.512
14	0.513
15	0.514
16	0.515
17	0.516
18	0.517
19	0.518
20	0.519

Table 2-24: Example of variations in circuit breaker closing times

Table 2-23 lists 9 sets of possible values for the residual flux of the transformer, and Table 2-24 gives 20 possible circuit breaker closing times in a 50 Hz cycle. It should be noted that the example in Table 2-24 assumes that all three phases of the circuit breaker close at the same time and during the interval $[0.50s, 0.52s]$.

Instead of running the 180 simulations to find the worst-case scenario for TOVs, this study focuses more on comparing the transient performance of the grid in the three different cable scenarios when transformers are energised under certain adverse grid conditions. These adverse conditions are as follows:

- Low SCL
- The N-1 (and N-2) contingencies as identified in the critical cases in section 2.2.2.1, leading to lower-order parallel resonances
- The circuit breaker closes when phase a reaches zero, with maximum residual flux on phase a, resulting in deep saturation.

The following values of residual flux were taken into account:

Φ_{0A}(pu)	Φ_{0B}(pu)	Φ_{0C}(pu)
0.8	–0.4	–0.4

Depending on the chosen residual flux, the following circuit breaker closing times are applied so that phase a is closed when the voltage reaches zero:

t_A (s)	t_B (s)	t_C (s)
0.115375	0.115375	0.115375

2.4.3 Results and discussion

The following two main conclusions can be drawn from the performed studies:

- Critical TOVs due to parallel resonance can be expected in scenario 3 when energising transformers at grid locations where potential risks of parallel resonance have been identified in frequency scan studies, such as at 380 kV Romanel and 380 kV Magadino (as seen in section 2.2.2.1). However, reducing the number of cable projects, as in scenario 2, can significantly mitigate the potential problems caused by TOVs (see section 2.4.3.1).
- The short-circuit power of a grid location (node) plays an important role in the impact of integrating cables in its close vicinity. Intensive cabling near a weak node (grid location with low short-circuit power) tends to significantly increase the risk of severe and poorly damped TOVs during grid transients, whereas the impact of intensive cabling around a strong node (grid location with high short-circuit power) is generally attenuated or less pronounced. Consequently, the short-circuit power at a certain grid location could be used as a criterion to determine whether a cable project can be implemented without any problems or whether additional dynamic studies are required. This was demonstrated in the complementary study (see section 2.4.3.2).

The two main conclusions above are examined in more detail in the relevant sections.

2.4.3.1 Critical cases of TOV

According to the results shown in section 2.2.2.1, the following cases of transformer energisation in scenario 3 were implemented, where critical cases of TOV caused by parallel resonance can be expected:

Transformer location	Place of energisation	Contingency	Parallel grid resonance
Romanel	380 kV Romanel	(Case 6) N-2 on 380 kV Romanel – Bois Tollot and La Bâtiaz – Chamoson	2nd harmonic
Romanel	380 kV Romanel	(Case 5) N-1 on 380 kV La Bâtiaz – Chamoson	3rd harmonic
Magadino	380 kV Magadino	(Case 1) N-1 on 380 kV Magadino – Lavorgo	3rd harmonic

Comparisons with Scenario 2 with fewer cable projects are provided to demonstrate the improvement of system performance with lower degrees of cabling.

2.4.3.1.1 Energisation of the transformer at 380 kV Romanel with N-2 contingency (case 6)

2.4.3.1.1.1 Scenario 3

First of all, as a reminder, the harmonic impedance at 380 kV Romanel for the corresponding N-2 contingency (Case 6) as well as the impedance amplitude close to the 2^{nd}, 3^{rd}, and 4^{th} harmonics are presented in Figure 2-47.

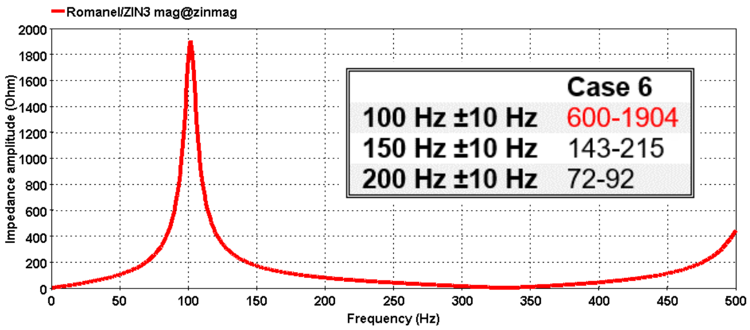
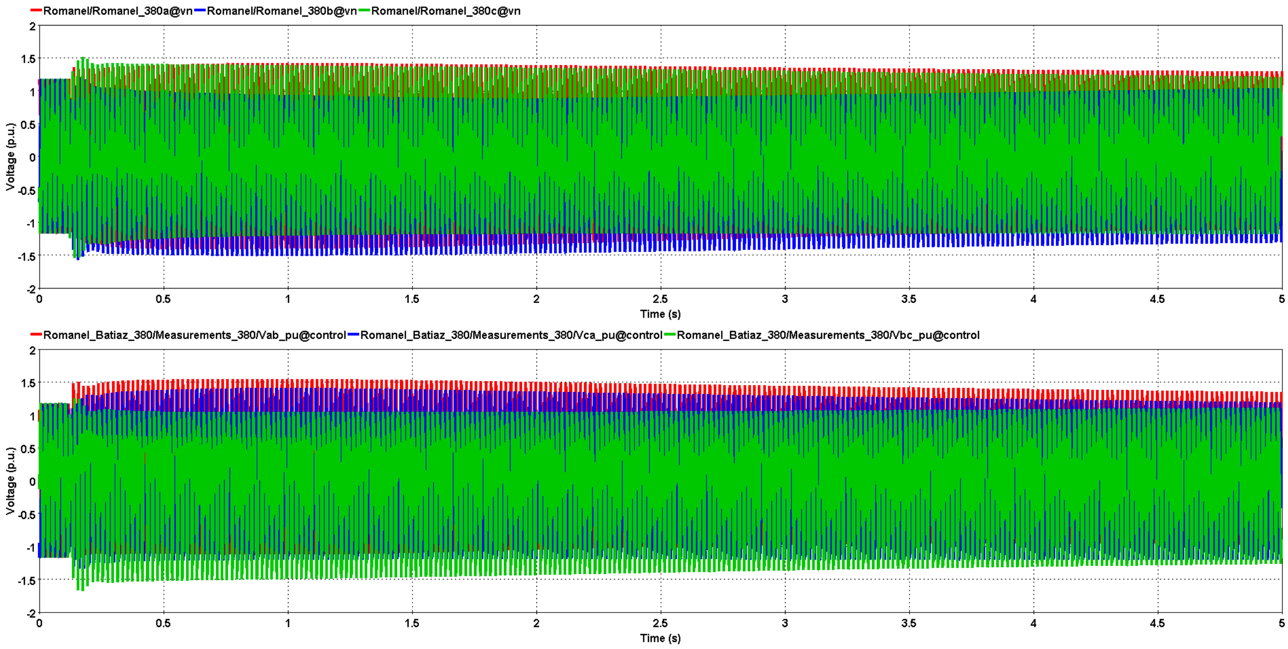


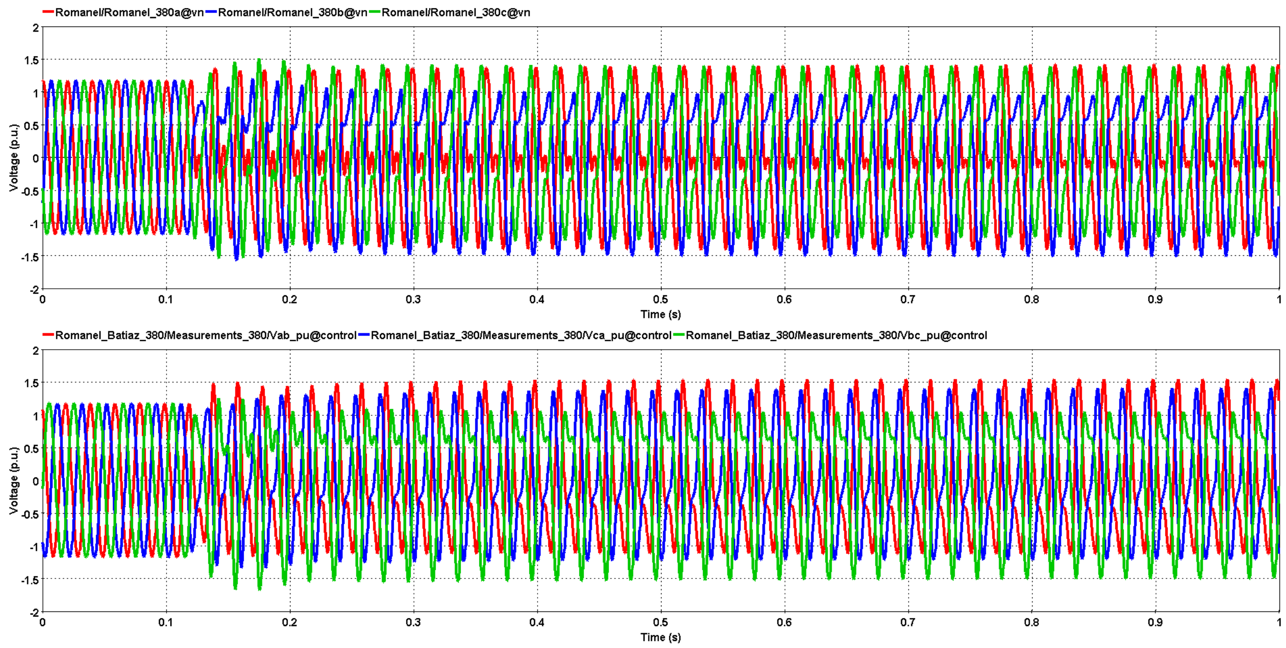
Figure 2-47: Harmonic impedance at 380 kV Romanel for case 6 (N-2 contingency) and the impedance amplitude close to the lower-order harmonics

As explained in 2.2.2.1.1 (section 2), TOVs caused by the excitation of parallel resonance at the 2^{nd} harmonic can be expected during energization of the transformer at 380 kV Romanel under the considered grid conditions.

The three-phase-to-ground voltages (top) and the phase-to-phase voltages (bottom) at 380 kV Romanel for the first 5 s and 1 s of the simulation are presented in Figure 2-48.



(a)



(b)

Figure 2-48: Phase-to-earth voltages and phase-to-phase voltages at 380 kV Romanel – case 6, scenario 3, (a) for the first five seconds of the simulation, (b) for the first second of the simulation

Notes: Severe harmonically distorted TOVs can be observed after circuit breaker closing. Maximum amplitude for both phase-to-ground and phase-to-phase voltages exceeds 1.5 p.u. This case is extremely critical because the high and poorly damped TOVs are expected to exert considerable dielectric and thermal stress on the grid equipment and insulation in the vicinity of 380 kV Romanel.

The transformer inrush current for the first 1 s of simulation as well as its harmonic components (from Fourier analysis) for the interval of $[0.2s, 1.0s]$ are plotted in Figure 2-49.

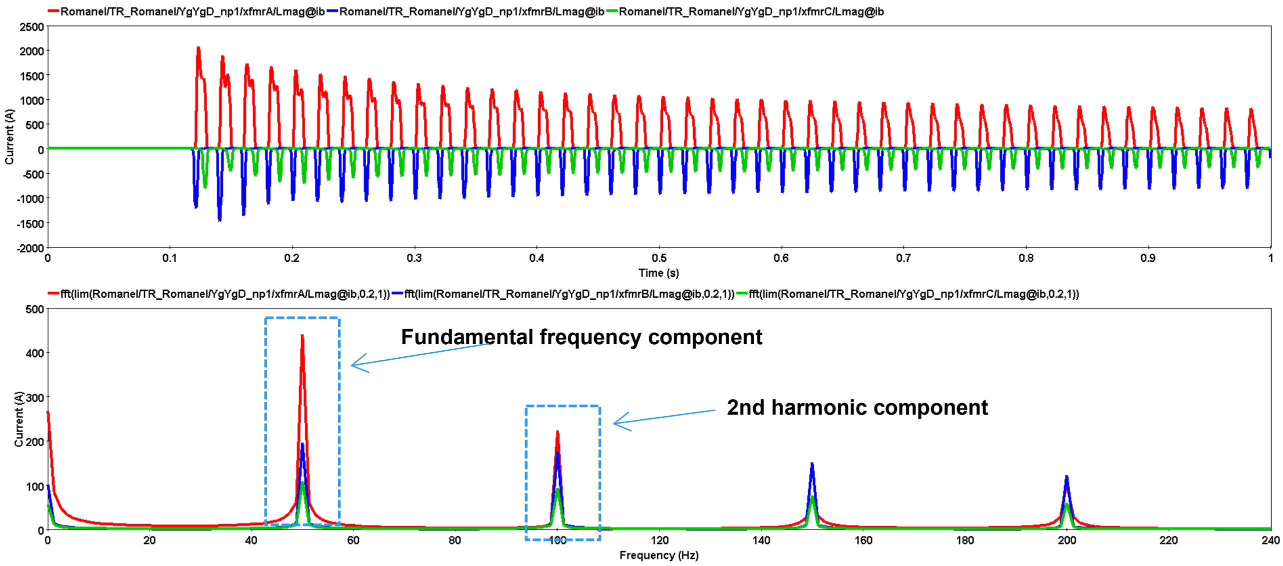


Figure 2-49: Inrush current of the transformer and its harmonic components during the interval $[0.2s, 1.0s]$

Notes: Firstly, as shown in Figure 2-49, the phase a inrush current has the maximum amplitude at the fundamental frequency. This is reasonable since the circuit breaker closing instant is chosen at the zero-crossing of the phase-a-to-ground voltage.

Secondly, the amplitude of the inrush current decreases as the order of harmonic increases (as a general rule, the decrease is proportional to 1/n [1]). This indicates that the significant 2^{nd} harmonic component shall be amplified by the parallel resonance of the grid configuration around the 2^{nd} harmonic, leading to the severe TOVs observed in Figure 2-48. To further validate this point, a Fourier analysis is performed on the three-phase-to-ground voltages at 380 kV Romanel for the interval of $[0.2s, 1.0s]$, as is presented in Figure 2-50.

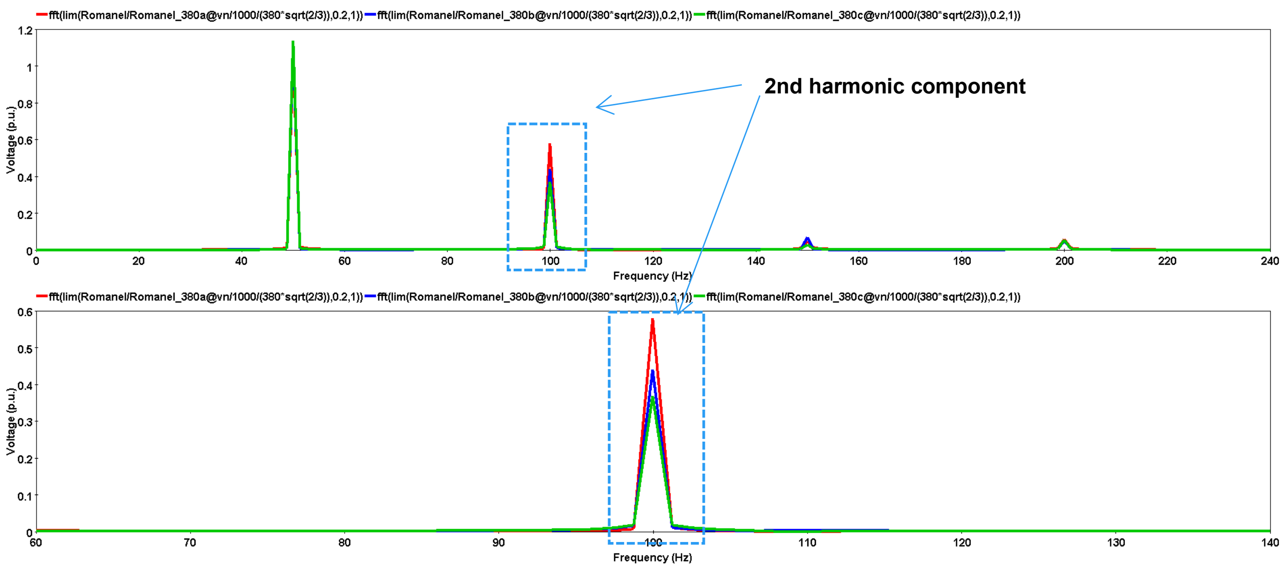


Figure 2-50: Harmonic components of phase-to-earth voltages at 380 kV Romanel for the interval $[0.2s, 1.0s]$

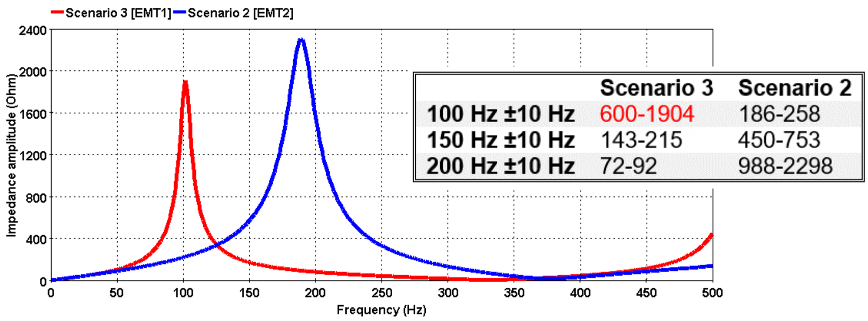
Notes: The top figure in Figure 2-50 shows the harmonic components of the three-phase-to-ground voltages at 380 kV Romanel up to the 4th harmonic whereas the significant 2nd harmonic component is zoomed in the bottom figure.

Among all the harmonic components of the inrush current (despite a decreasing amplitude as the harmonic order increases) shown in Figure 2-49, it is the 2nd harmonic component that gets amplified by the network resonance, resulting in a sufficiently high 2nd harmonic component in the terminal voltage that causes the observed distorted and poorly damped TOVs.

2.4.3.1.1.2 Comparison between scenarios 2 and 3

In order to verify whether the network performance during transient events such as transformer energization can be improved with fewer cables in the area of 380 kV Romanel, time-domain simulations are also performed for Scenario 2 and the results are compared with those in Scenario 3. Note that the comparison is only made between Scenarios 2 and 3 since the harmonic impedance at 380 kV Romanel for the given grid conditions in Scenario 1 is the same as that in Scenario 2.

First of all, the harmonic impedance at 380 kV Romanel for Scenarios 2 and 3 for the corresponding N-2 contingency (Case 6) as well as the impedance amplitude close to the 2nd, 3rd, and 4th harmonics are presented in Figure 2-51.



	Scenario 3	Scenario 2
100 Hz ±10 Hz	600-1904	186-258
150 Hz ±10 Hz	143-215	450-753
200 Hz ±10 Hz	72-92	988-2298

Figure 2-51: Harmonic impedance at 380 kV Romanel for case 6 (N-2 contingency) and the impedance amplitude close to the lower-order harmonics for scenarios 2 and 3

The removal of the two cable projects near 380 kV Romanel in Scenario 2 considerably shifts the parallel resonance towards higher frequencies, resulting in non-critical impedance values around the 2nd, 3rd and the 4th harmonics as compared to Scenario 3. Severe TOVs with the potential to stress and even damage insulation and grid equipment are not to be expected during energization of the transformer at 380 kV under the considered grid conditions.

The three-phase-to-ground voltages at 380 kV Romanel for both Scenarios 3 and 2 for the first 1 s of the simulation are presented in Figure 2-52.

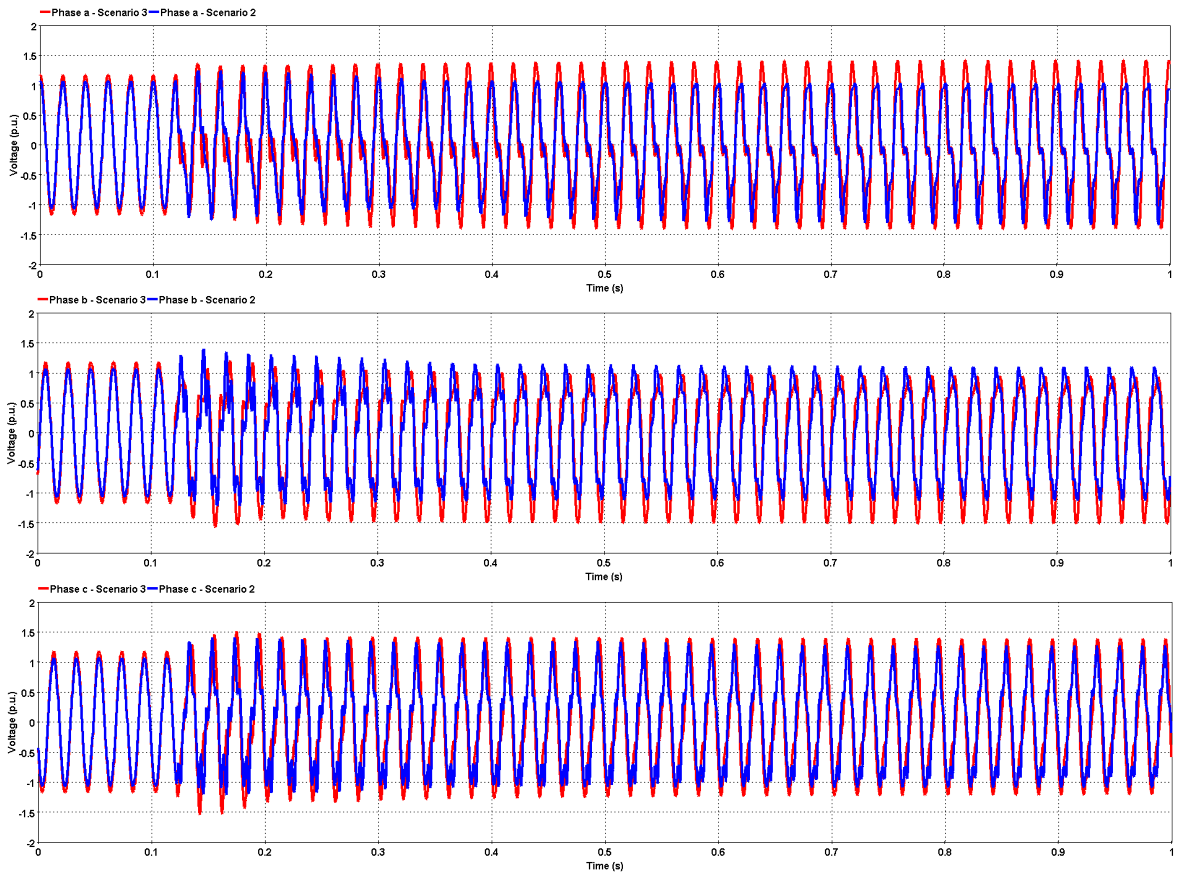


Figure 2-52: Phase-to-earth voltages at 380 kV Romanel – case 6, scenarios 2 and 3 for the first second of the simulation

Notes: As seen in section 2.4.3.1.1.1, highly harmonically distorted and poorly damped TOVs exceeding 1.5 pu can be observed in Scenario 3. However, removing the cable systems in Scenario 2 near 380 kV Romanel results in much mitigated TOVs with the maximum amplitude reaching 1.2 pu and quickly descending, significantly decreasing the risks of dielectric and thermal stress on the grid equipment and insulation.

Furthermore, a comparison of Fourier analysis on the three-phase-to-ground voltages at 380 kV Romanel between Scenarios 2 and 3 is presented inFigure 2-53.

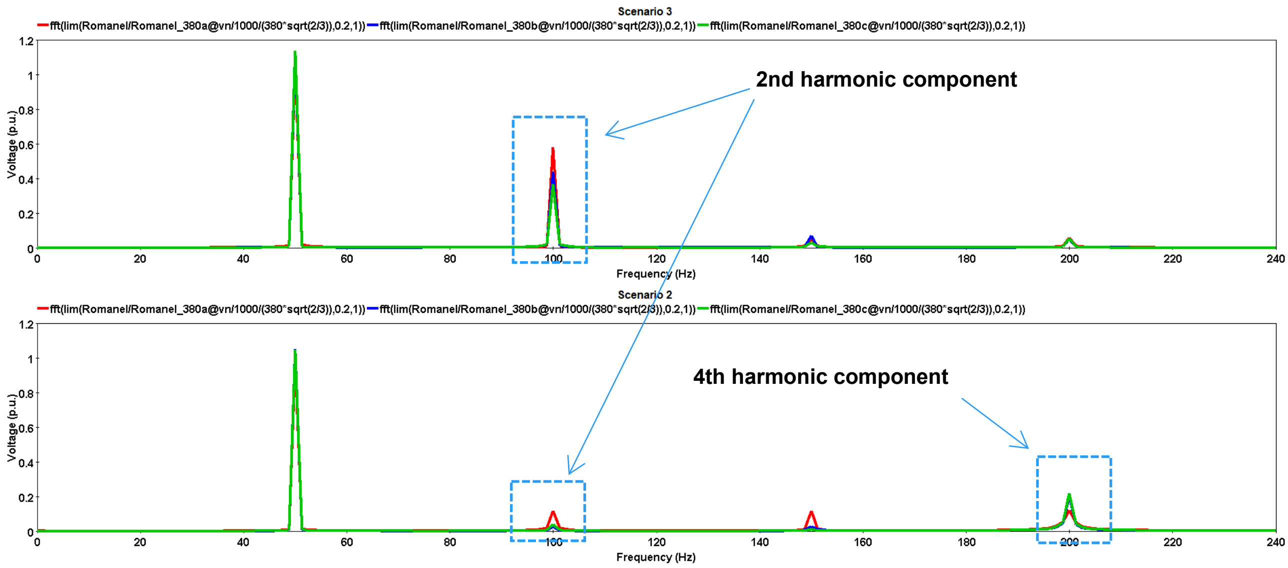


Figure 2-53: Comparison of harmonic components of phase-to-earth voltages at 380 kV Romanel in scenarios 2 and 3

Notes: In comparison to Scenario 3, the 2nd harmonic component of the three-phase-to-ground voltages at 380 kV Romanel in Scenario 2 is greatly reduced, which explains the observed mitigated TOVs in the terminal voltage. However, as the network parallel resonance shifts towards the 4th harmonic, a slightly pronounced 4th harmonic component can be observed in the terminal voltage in Scenario 2. Due to its relatively higher order and insufficient impedance amplitude at the 4th harmonic (please see Figure 2-51), the resulting TOVs are deemed non-critical and thus pose less risks of dielectric and thermal stress on the network equipment and insulation.

2.4.3.1.2 Energisation of the transformer at 380 kV Romanel with N-1 contingency (case 5)

2.4.3.1.2.1 Scenario 3

Similar to the previous case, as a reminder, the harmonic impedance at 380 kV Romanel for the corresponding N-1 contingency (Case 5) as well as the impedance amplitude close to the 2nd, 3rd, and 4th harmonics are presented in Figure 2-54.

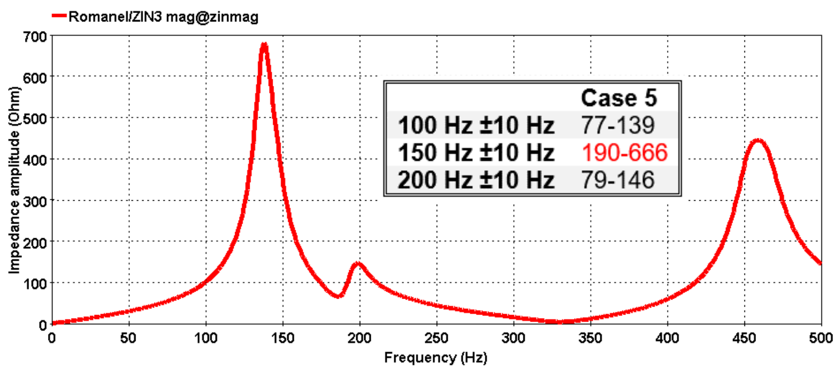
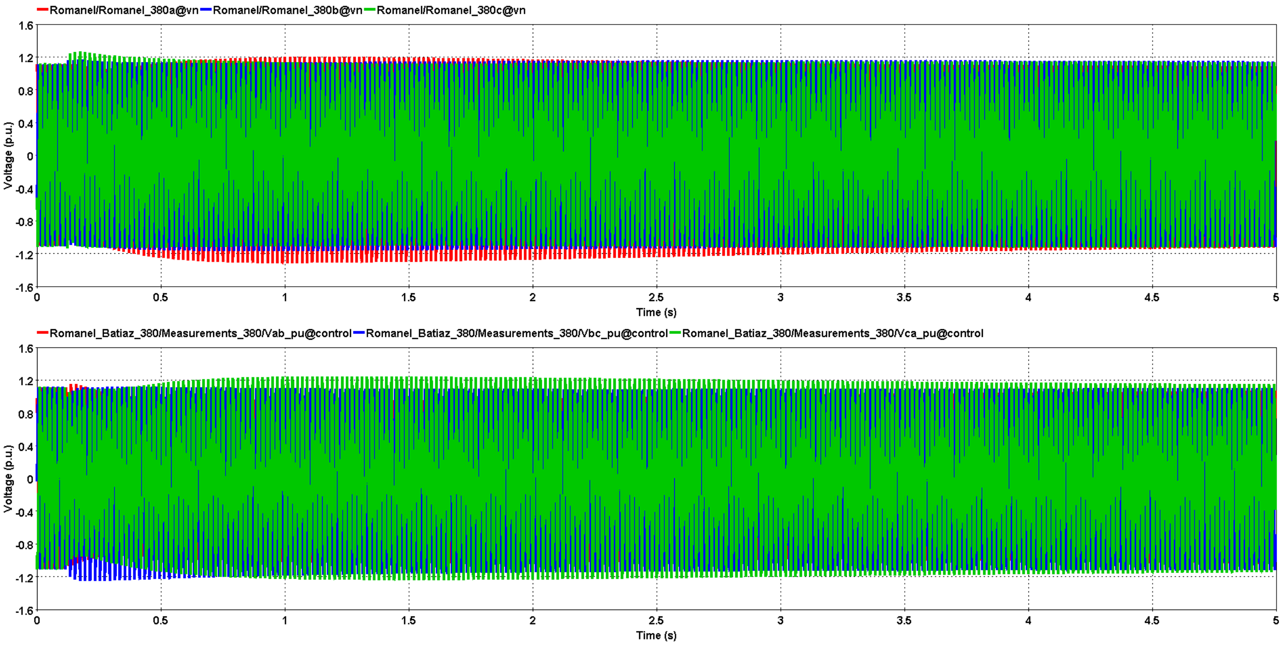


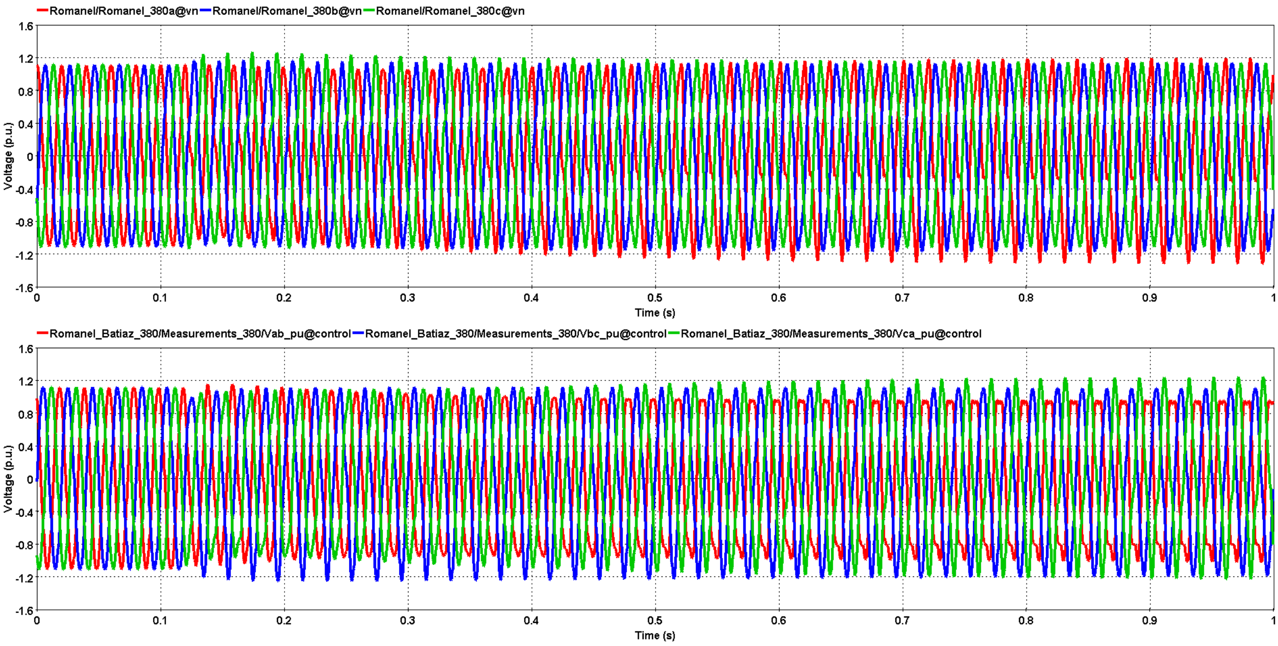
Figure 2-54: Harmonic impedance at 380 kV Romanel for case 5 (N-1 contingency) and the impedance amplitude close to the lower-order harmonics

As explained in section 2.2.2.1.1, TOVs caused by the excitation of parallel resonance at the 3rd harmonic can be expected during energization of the transformer at 380 kV Romanel under the considered grid conditions.

The three-phase-to-ground voltages (top) and the phase-to-phase voltages (bottom) at 380 kV Romanel for the first 5 s and 1 s of the simulation are presented inFigure 2-55.



(a)



(b)

Figure 2-55: Three-phase voltages to earth and voltages between phases at 380 kV Romanel – case 5, scenario 3, (a) for the first five seconds of the simulation, (b) for the first second of the simulation

Notes: Harmonically distorted TOVs can be observed after circuit breaker closing. Maximum amplitude of the phase-to-ground voltage reaches 1.32 p.u. whereas the phase-to-phase voltage has a maximum amplitude of 1.26 p.u. The TOVs are moderately damped, thus posing potential risks of dielectric and thermal stress on the nearby equipment and insulation.

The transformer inrush current for the first 1 s of simulation as well as its harmonic components (from Fourier analysis) for the interval of $[0.2s, 1.0s]$ are plotted in Figure 2-56.

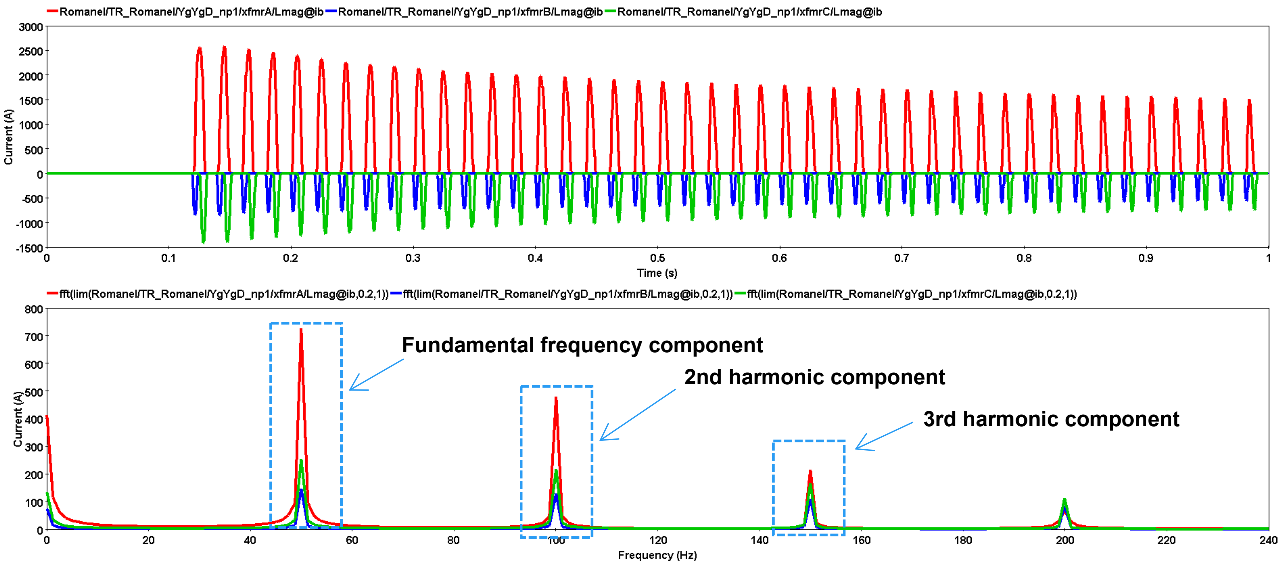


Figure 2-56: Inrush current of the transformer and its harmonic components during the interval $[\mathbf{0.2}s, \mathbf{1.0}s]$

Notes: Similar to the previous case (Scenario 3), the phase a inrush current has the maximum amplitude at the fundamental frequency. This is reasonable since the circuit breaker closing instant is chosen at the zero-crossing of the phase-a-to-ground voltage.

Secondly, as was seen in the previous case, the amplitude of the inrush current decreases as the order of harmonic increases (as a general rule, the decrease is proportional to 1/n [2.1]). In this case, it is the 3rd harmonic component that shall be amplified by the parallel resonance of the grid configuration around the 3rd harmonic, leading to the TOVs observed in Figure 2-55. To further validate this point, a Fourier analysis is performed on the three-phase-to-ground voltages at 380 kV Romanel for the interval of $[0.2s, 1.0s]$, as is presented inFigure 2-57.

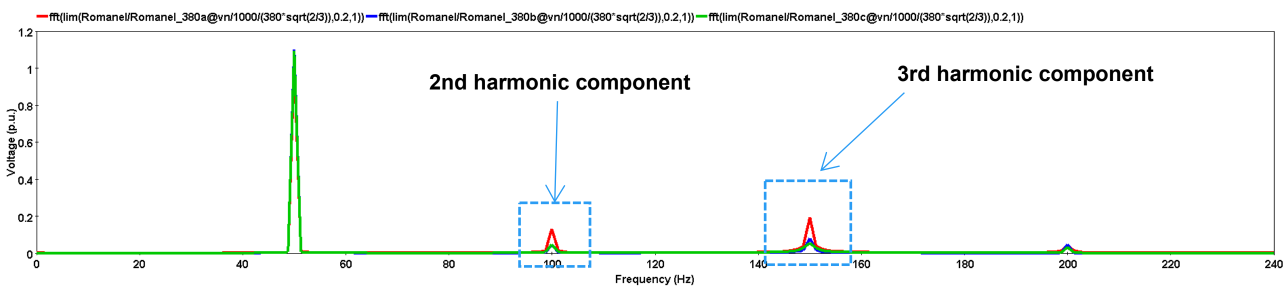


Figure 2-57: Harmonic components of phase-to-earth voltages at 380 kV Romanel for the interval $[\mathbf{0.2}s, \mathbf{1.0}s]$

Note: Although the 2nd harmonic component of the inrush current has a greater amplitude, it is the 3rd harmonic component, amplified by the grid impedance at network resonance, that has a noticeably higher amplitude in the terminal voltage at 380 kV Romanel.

2.4.3.1.2.2 Comparison between scenarios 2 and 3

A comparison is made between Scenarios 2 and 3 to demonstrate the point that network performance during transient events such as transformer energization can be improved with fewer cables in the area. Once again, the comparison is only made between Scenarios 2 and 3 since the harmonic impedance at 380 kV Romanel for the given grid conditions in Scenario 1 is quite similar to that in Scenario 2.

First of all, the harmonic impedance at 380 kV Romanel for Scenarios 2 and 3 for the corresponding N-1 contingency (Case 5) as well as the impedance amplitude close to the 2nd, 3rd, and 4th harmonics are presented in Figure 2-58.

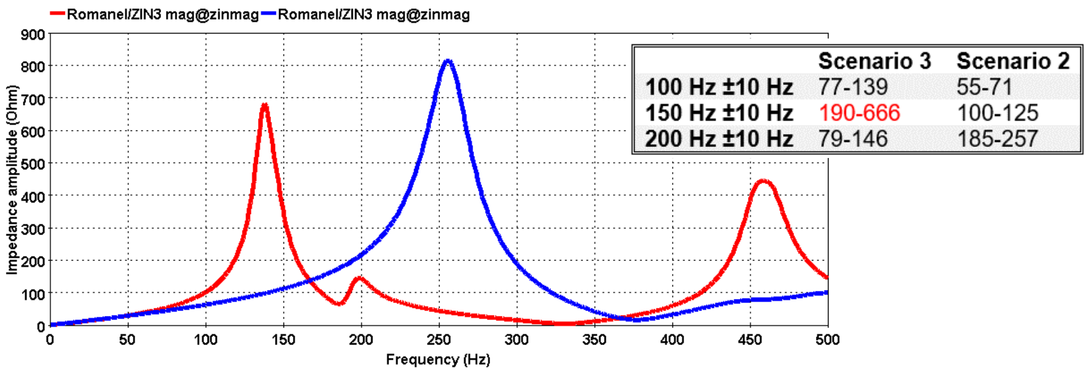


Figure 2-58: Harmonic impedance at 380 kV Romanel for case 5 (N-1 contingency) and the impedance amplitude close to the lower-order harmonics for scenarios 2 and 3.

The removal of the two cable projects near 380 kV Romanel in Scenario 2 considerably shifts the parallel resonance towards higher frequencies, resulting in non-critical impedance values around the 2nd, 3rd and the 4th harmonics as compared to Scenario 3. Severe TOVs with the potential to stress and even damage insulation and grid equipment are not to be expected during energization of the transformer at 380 kV Romanel under the considered grid conditions.

The three-phase-to-ground voltages at 380 kV Romanel for both Scenarios 3 and 2 for the first 1 s of the simulation are presented in Figure 2-59.

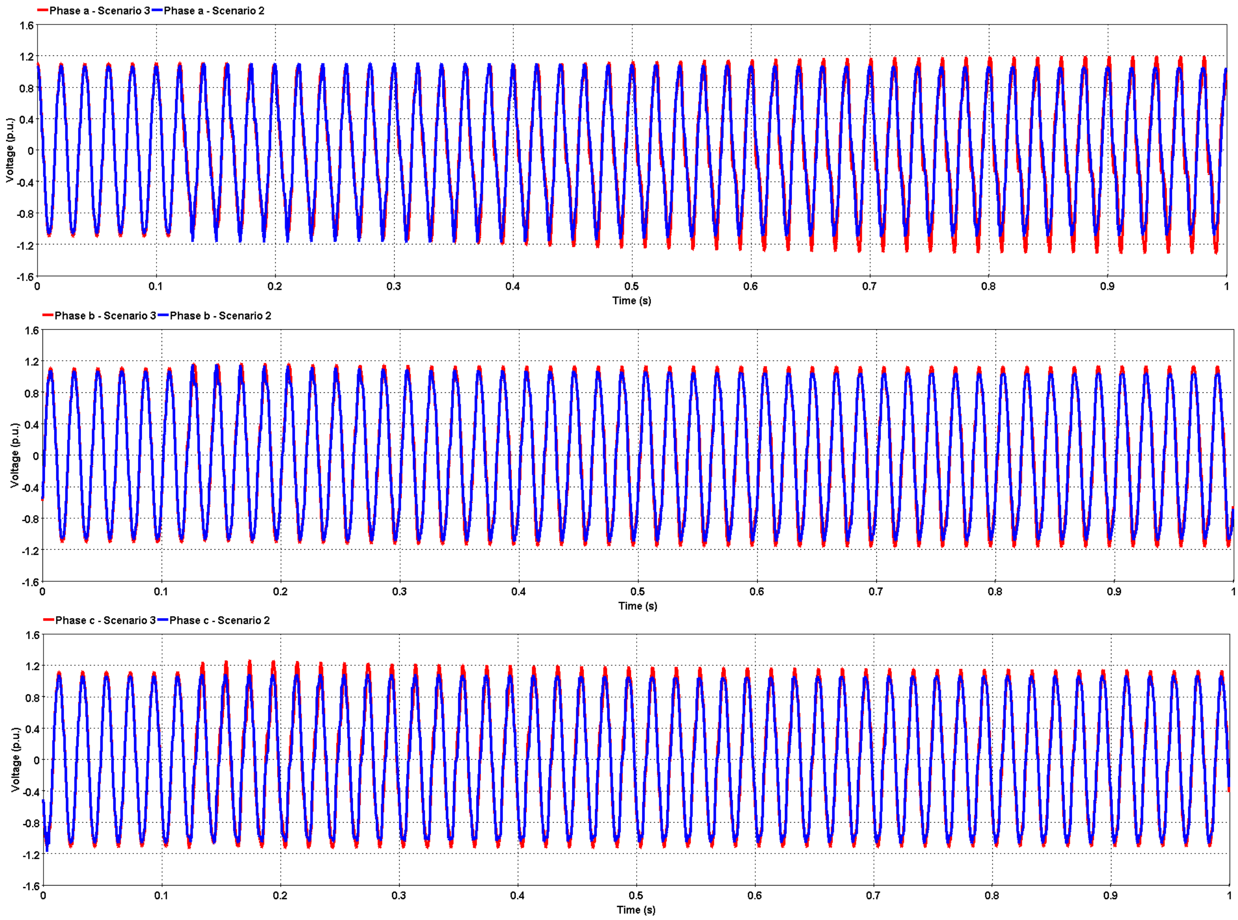


Figure 2-59: Phase-to-earth voltages at 380 kV Romanel – case 5, scenarios 2 and 3 for the first second of the simulation

Notes: As seen in section 2.4.3.1.2.1, harmonically distorted and moderately damped TOVs reaching 1.32 pu can be observed in Scenario 3. However, removing the cable systems in Scenario 2 near 380 kV Romanel results in much mitigated TOVs with the maximum amplitude reaching 1.18 pu and quickly descending, significantly decreasing the risks of dielectric and thermal stress on the grid equipment and insulation.

Furthermore, a comparison of Fourier analysis on the three-phase-to-ground voltages at 380 kV Romanel between Scenarios 2 and 3 is presented in Figure 2-60.

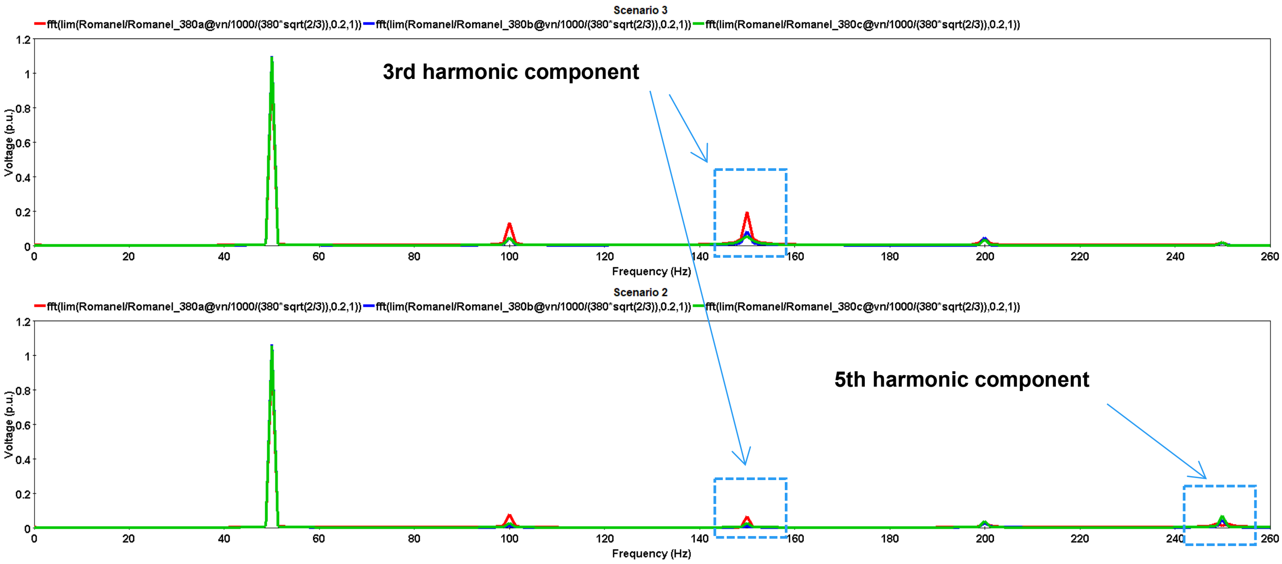


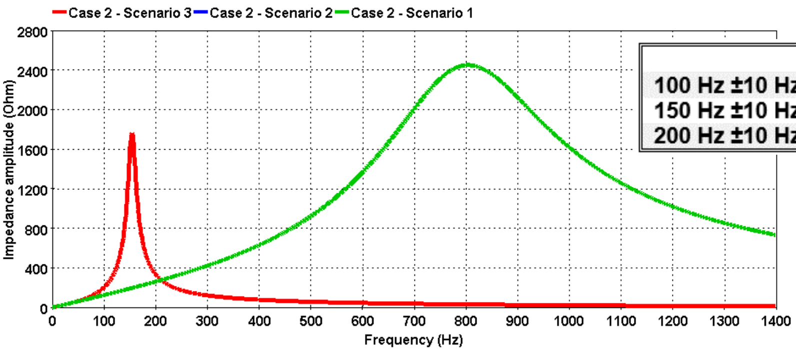
Figure 2-60: Comparison of harmonic components of phase-to-earth voltages at 380 kV Romanel in scenarios 2 and 3

Notes: In comparison to Scenario 3, the 3rd harmonic component of the three-phase-to-ground voltages at 380 kV Romanel in Scenario 2 is greatly reduced, which explains the observed mitigated TOVs in the terminal voltage. However, as the network parallel resonance shifts towards the 5th harmonic, a slightly pronounced 5th harmonic component can be observed in the terminal voltage in Scenario 2. Due to its relatively higher order and insufficient impedance amplitude at the 5th harmonic (please see Figure 2-58), the resulting TOVs are deemed non-critical and thus pose less risks of dielectric and thermal stress on the network equipment and insulation.

2.4.3.1.3 Energisation of the transformer at 380 kV Magadino with N-1 contingency

The N-1 contingency isolates 380 kV Magadino from the Swissgrid network, leaving it only connected to the Italian grid represented by a Thévenin equivalent. Since the Thévenin equivalent lacks sufficient details to represent the actual grid dynamics, only the comparison of the network performance between Scenarios 2 and 3 is made in this section, with the goal of demonstrating that removing the 380 kV Magadino – Musignano cable improves the system performance and ensures stable and secure grid operation.

First of all, the harmonic impedance at 380 kV Magadino for Scenarios 2 and 3 for the corresponding N-1 contingency (Case 2) as well as the impedance amplitude close to the 2nd, 3rd, and 4th harmonics are presented in Figure 2-61.



	Scenario 3	Scenario 2
100 Hz ±10 Hz	159-260	112-138
150 Hz ±10 Hz	829-1760	178-205
200 Hz ±10 Hz	280-411	247-276

Figure 2-61: Harmonic impedance at 380 kV Magadino for case 2 (N-1 contingency) and the impedance amplitude close to the lower-order harmonics for scenarios 2 and 3

With the inclusion of the 13 km cable at 380 kV Magadino towards 380 kV Musignano, the harmonic impedance at 380 kV Magadino has a parallel resonance close to the 3rd harmonic with an alarmingly high impedance amplitude. Such a high amplitude indicates risks of severe TOVs with the potential to stress and even damage insulation and grid equipment in proximity to 380 kV Magadino. However, if the entire 19.29 km transmission path between 380 kV Magadino and 380 kV Musignano is composed of overhead lines, the parallel resonance shifts up close to 800 Hz (i.e., 16th harmonic), the significantly reduced impedance amplitude at or close to low-order harmonics implies much reduced risks of severe TOVs under the same grid conditions.

The three-phase-to-ground voltages at 380 kV Magadino for both Scenarios 3 and 2 for the first 1 s of the simulation are presented in Figure 2-62.

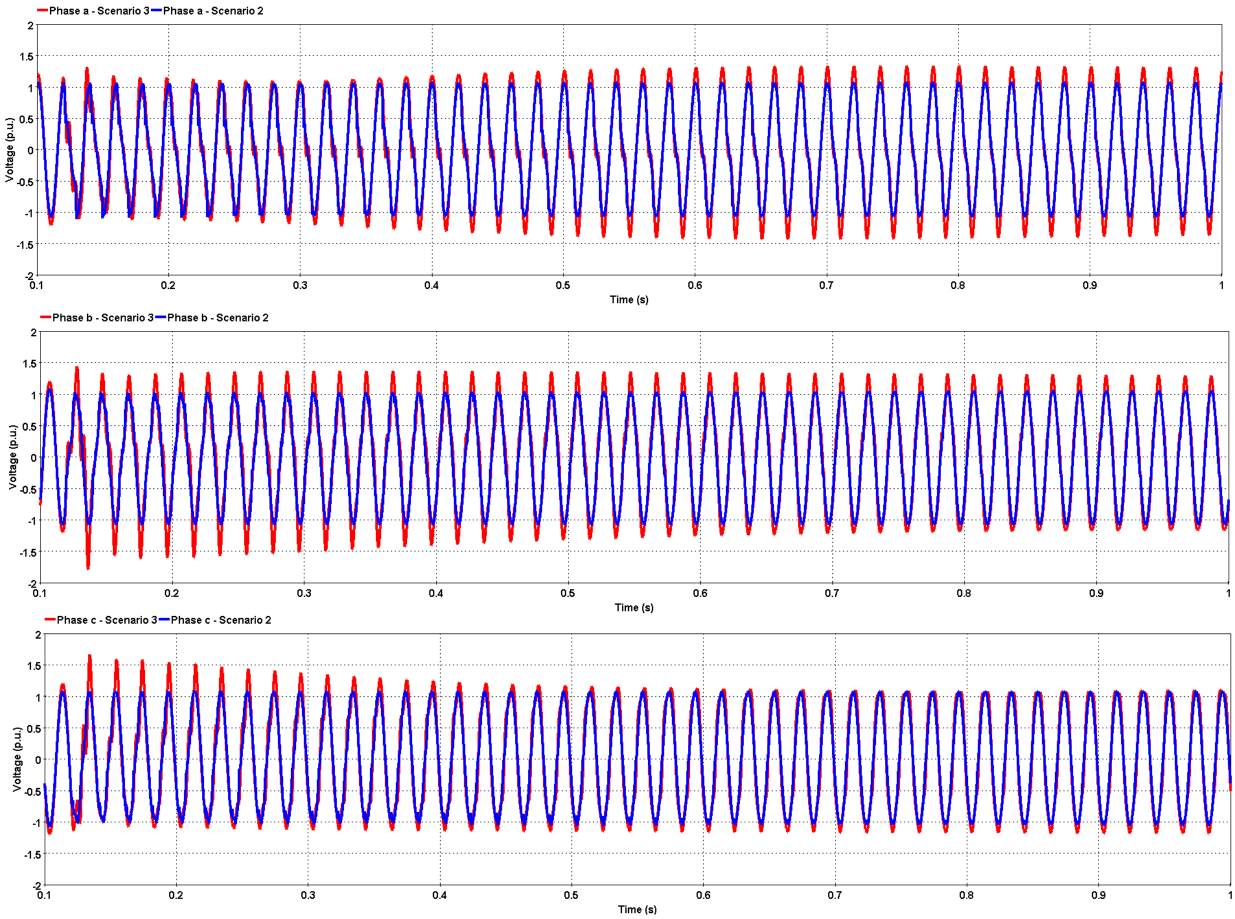


Figure 2-62: Phase-to-earth voltages at 380 kV Magadino – case 2, scenarios 2 and 3 for the first second of the simulation

Notes: As shown in Figure 2-62, harmonically distorted and poorly damped TOVs with a maximum amplitude exceeding 1.5 pu can be observed in Scenario 3. However, removing the 380 kV Magadino – Musignano cable in Scenario 2 near 380 kV Magadino results in much mitigated TOVs with the maximum amplitude reaching merely 1.11 pu and quickly damped, significantly decreasing the risks of dielectric and thermal stress on the grid equipment and insulation.

Furthermore, a comparison of Fourier analysis on the three-phase-to-ground voltages at 380 kV Magadino between Scenarios 2 and 3 is presented in Figure 2-63.

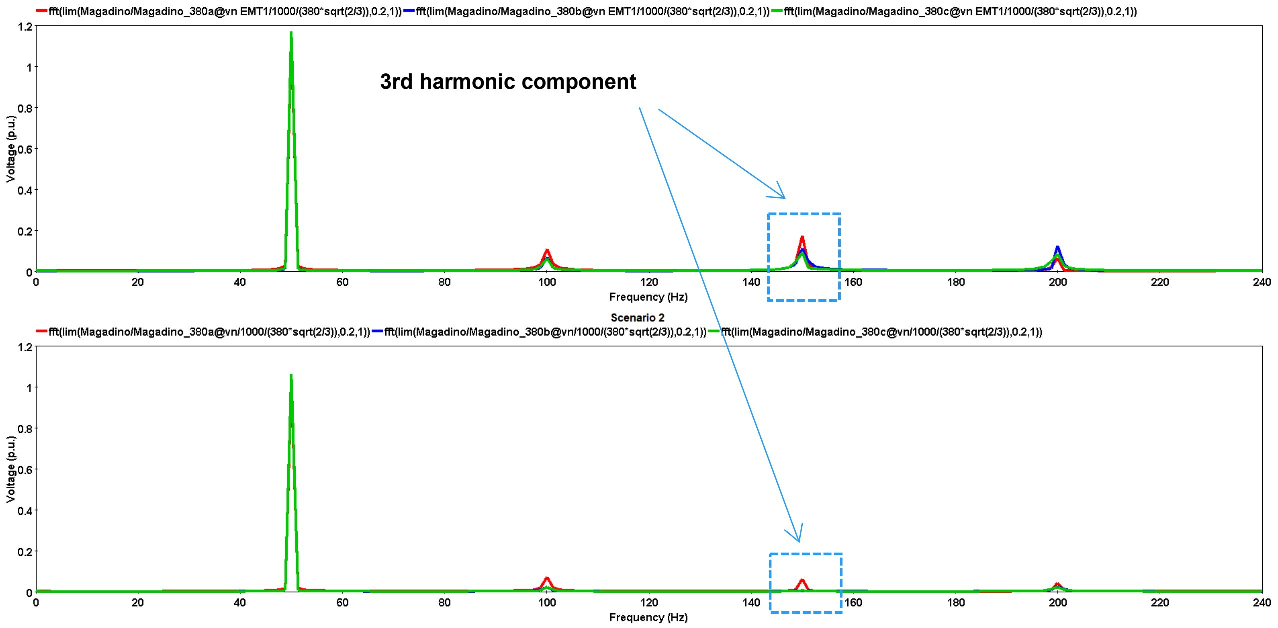


Figure 2-63: Comparison of harmonic components of phase-to-earth voltages at 380 kV Magadino in scenarios 2 and 3

Notes: In comparison to Scenario 3, the 3rd harmonic component of the three-phase-to-ground voltages at 380 kV Magadino in Scenario 2 is greatly reduced, which explains the observed mitigated TOVs in the terminal voltage.

2.4.3.2 Additional studies – impact of intensive cabling near nodes with different short-circuit powers

If the grid can be simplified into an RLC network, its parallel resonant frequency, seen at a certain location, is defined by the LC components in the network:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

in which L is inversely proportional to the grid short-circuit power at the location of interest and C is the total capacitive elements (such as cables) connected in the vicinity.

It is easy to understand that for a given number of cables connected in the vicinity, the higher the short-circuit power is at a certain location, the higher the resonant frequency becomes. Therefore, the impact of intensive cabling on the frequency response of a strong node with high short-circuit power would be less significant as compared to a weak node with low short-circuit power where degraded system performance can be expected.

Moreover, a high short-circuit power indicates higher network damping. A higher network damping is a mitigating factor of negative network phenomena such as TOVs and resonances.

The significant impact of short-circuit power on system response was confirmed in the results of the three scenarios analysed. The decision was therefore made to go even further and to extend the scope of the study by increasing the amount of cabling in two areas that already had a high proportion of cables in scenario 3.380 kV Romanel and 380 kV Laufenburg were chosen to demonstrate this hypothesis. The short-circuit power at 380 kV Romanel is 11 GVA in normal operation, while the short-circuit power at 380 kV Laufenburg is 43 GVA, which is one of the highest of all the substations in the Swissgrid grid.

2.4.3.2.1 Energisation of the transformer at 380 kV Romanel with intensive cabling

The integration of cables near 380 kV Romanel in scenario 3 is illustrated in Figure 2-64.

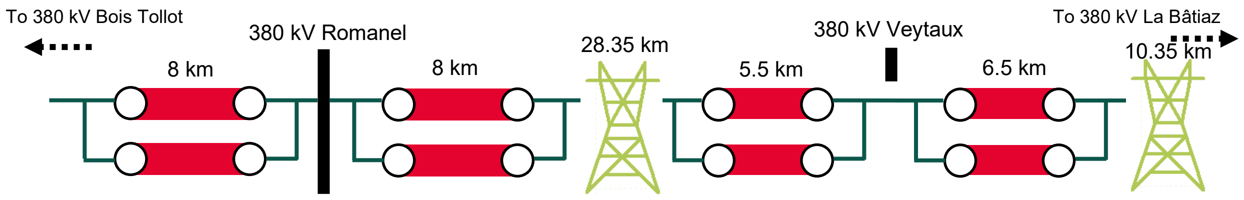


Figure 2-64: Integration of 380 kV cable systems in the vicinity of 380 kV Romanel

The 58.7 km transmission path in Scenario 3 from 380 kV Romanel towards 380 kV La Bâtiaz is a mixed line/cable section with a total of 40 km cables (two cables per phase). Critical TOVs have been observed when energizing the transformer at 380 kV Romanel under N-1 (section 2.4.3.1.2) or N-2 (section 2.4.3.1.1), as explained above.

Now consider a fictive case where the entire 58.7 km transmission path from 380 kV Romanel towards 380 kV La Bâtiaz is implemented with underground cables, with a total cabling length of 117.4 km (two cables per phase), as is seen in Figure 2-65.

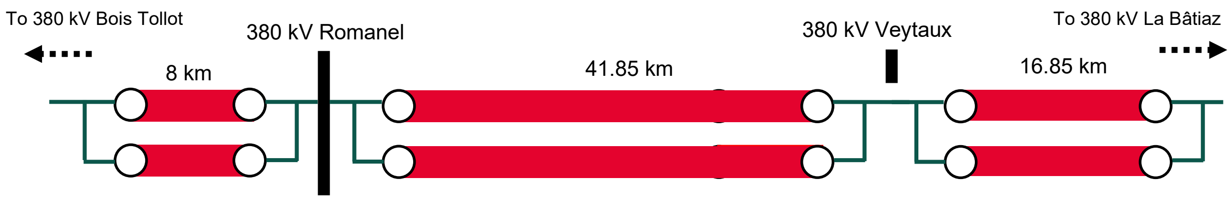


Figure 2-65: 380 kV cable systems in the vicinity of 380 kV Romanel in the fictitious case

The case of N-1 on 380 kV La Bâtiaz – Chamoson, as shown in section 2.4.3.1.2, is used again here to demonstrate the worsening of TOVs in the fictitious case compared to scenario 3.

Once again, the harmonic impedance at 380 kV Romanel for scenario 3 and the fictitious case for the corresponding N-1 contingency (case 5), as well as impedance amplitude close to the 2nd, 3rd, and 4th harmonics are presented in Figure 2-66.

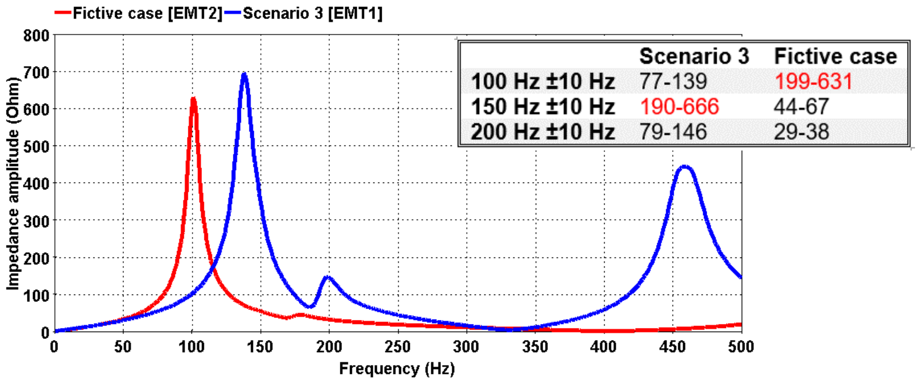


Figure 2-66: Harmonic impedance at 380 kV Romanel for case 5 (N-1 contingency) and the impedance amplitude close to the lower-order harmonics for scenario 3 and the fictitious case

First of all, the short-circuit power at 380 kV Romanel under N condition is approximately 11 GVA. Losing the 380 kV connection Bâtiaz – Chamoson further decreases the short-circuit power at 380 kV Romanel. As shown in Figure 2-66, a total cabling of 117.4 km east of 380 kV Romanel in the fictive case considerably shifts the parallel resonance in this N-1 contingency from around the 3rd harmonic towards around the 2nd harmonic with critical impedance amplitude as defined in Table 2-2. Therefore, even more severe TOVs with the potential to stress and even damage insulation and grid equipment are to be expected during energization of the transformer at 380 kV Romanel under the considered grid conditions.

The three-phase-to-ground voltages at 380 kV Romanel for both Scenarios 3 and the fictive case for the first 1 s of the simulation are presented in Figure 2-67.

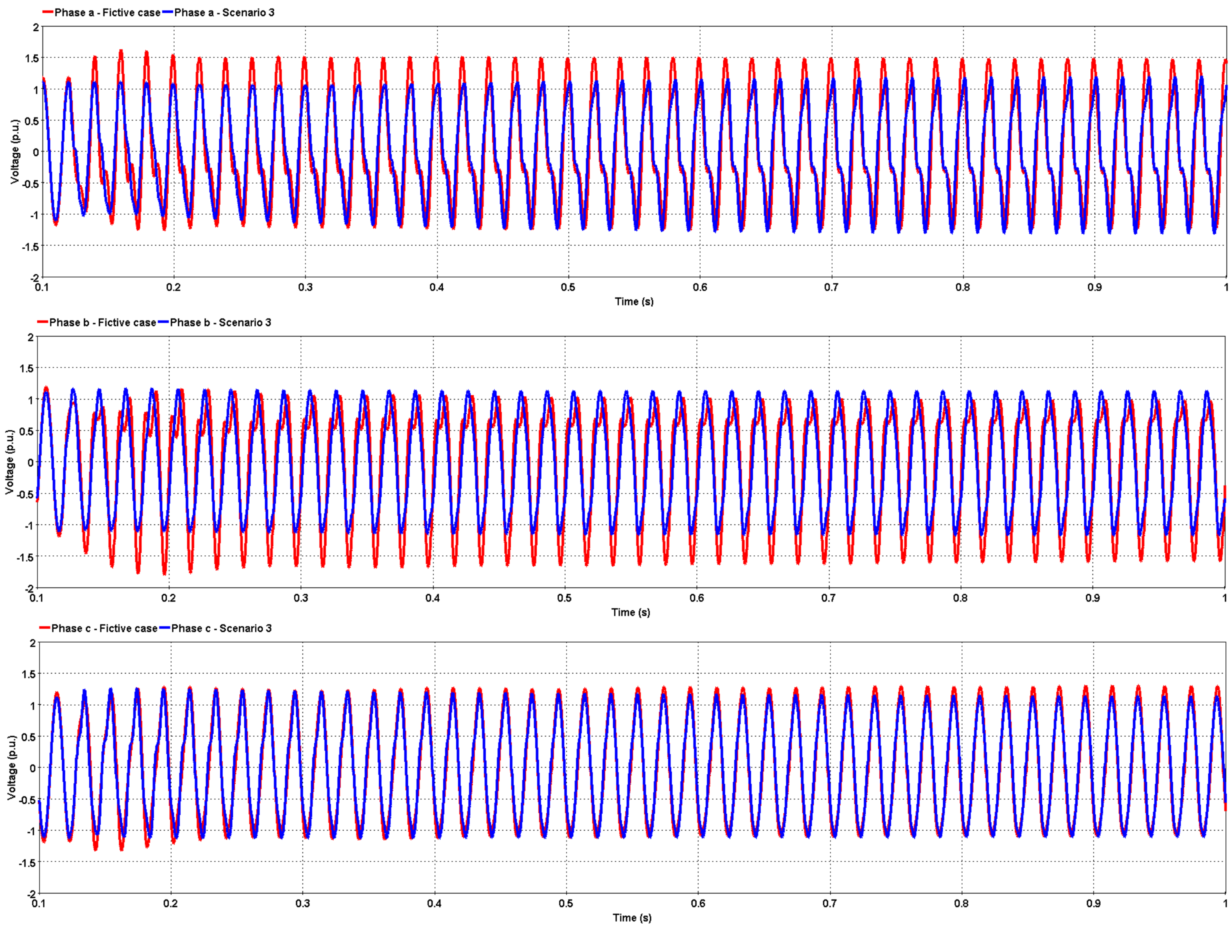


Figure 2-67: Phase-to-earth voltages at 380 kV Romanel – scenario 3 and the fictitious case for the first second of the simulation

Notes: As shown in Figure 2-67, harmonically distorted and poorly damped TOVs exceeding 1.5 pu can be observed in the fictive case whereas the maximum TOV amplitude in Scenario 3 reaches 1.32 pu before descending. This demonstrates that parallel resonance at the 2nd harmonic with a significantly high impedance amplitude due to intensive cabling near 380 kV (the fictive case) leads to more critical TOVs for the given grid configuration as compared to Scenario 3.

Furthermore, a comparison of Fourier analysis on the three-phase-to-ground voltages at 380 kV Romanel between the fictive case and Scenario 3 is presented in Figure 2-68.

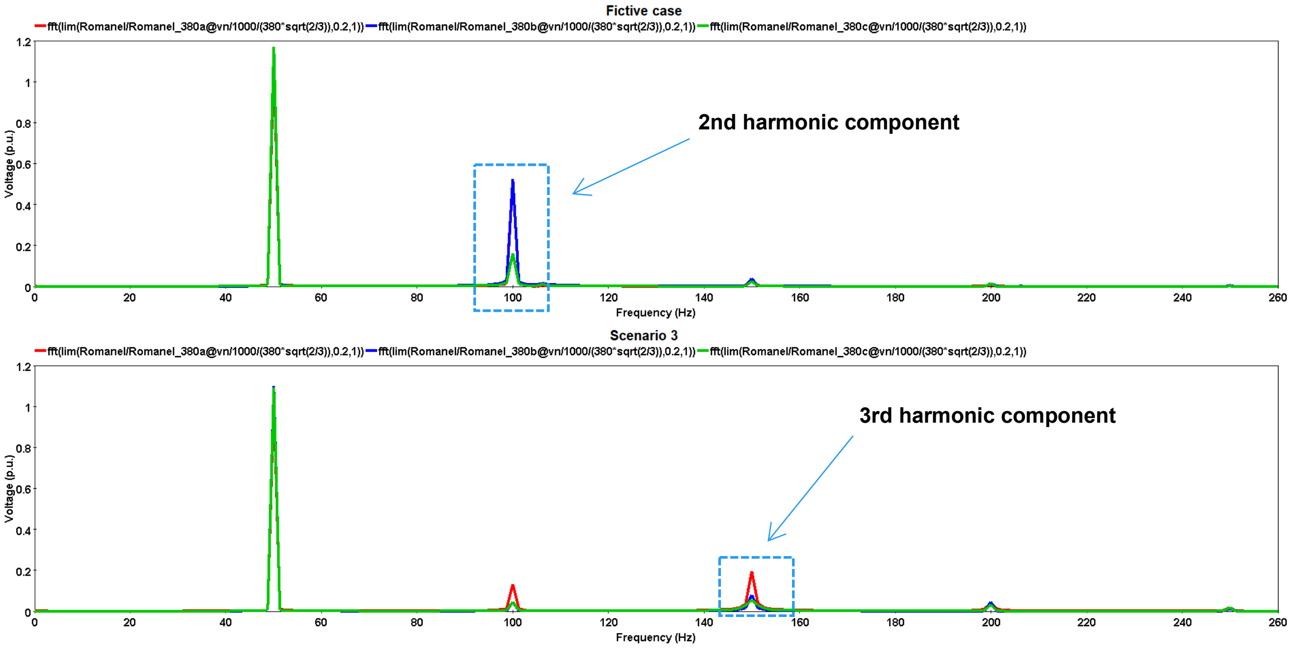


Figure 2-68: Comparison of the harmonic components of phase-to-earth voltages at 380 kV Romanel in the fictitious case and scenario 3

Notes: An increased degree of cabling east of the weak node 380 kV Romanel further shifts the network resonant frequency to around the 2nd harmonic for the given grid configuration in the fictive case, leading to an extremely high 2nd harmonic component almost 50% of the fundamental frequency in the terminal voltages. This explains the observed extremely distorted and severe TOVs in the fictive case. On the other hand, the considered N-1 contingency results in a parallel resonance around the 3rd harmonic in Scenario 3 for the given grid configuration. Although the impedance at resonance in both cases is quite similar, a resonance at a higher harmonic order indicates less severe TOVs, which has been demonstrated in the observed results.

This example demonstrates that extensive cabling close to a weak node (network location with low short-circuit power) tends to have a large impact on the frequency response at this node, which further leads to potential risks of TOVs during transient events.

2.4.3.2.2 Energisation of the transformer at 380 kV Laufenburg with intensive cabling

The integration of the cable systems near 380 kV Laufenburg in scenario 3 is illustrated in Figure 2-69.

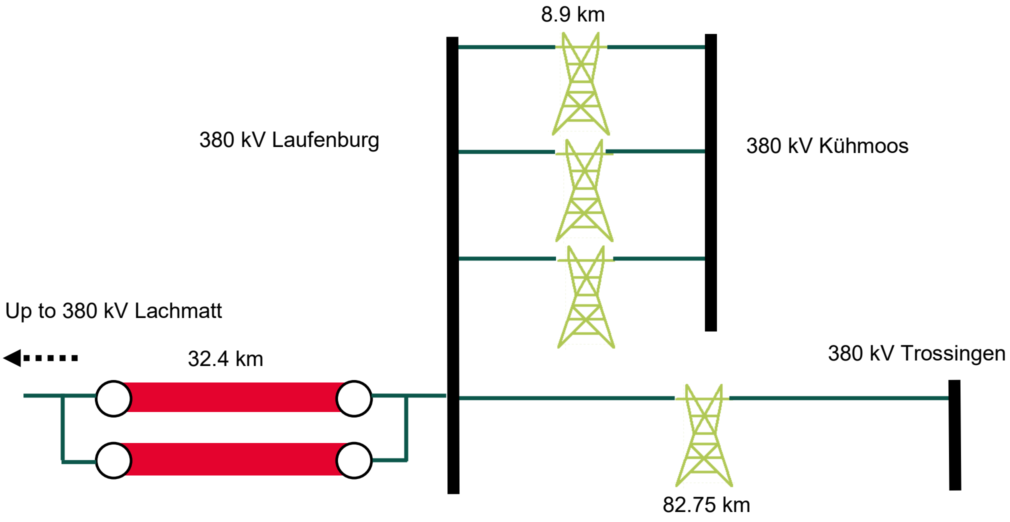


Figure 2-69: Integration of 380 kV cable systems near 380 kV Laufenburg

As shown in Figure 2-69, in Scenario 3, there is only one cable system connected directly at 380 kV Laufenburg, with a total length of 64.8 km (32.4 km, two cables per phase). The three 8.9 km connections between 380 kV Laufenburg and 380 kV Kühmoos, as well as the 82.75 km connection between 380 kV Laufenburg and 380 kV Trossingen are composed purely of overhead lines.

Now consider a fictive case where the three overhead line connections between 380 kV Laufenburg and 380 kV Kühmoos, together with part of the long 82.75 km connection between 380 kV Laufenburg and 380 kV Trossingen, are implemented with underground cables, as is shown in Figure 2-70.

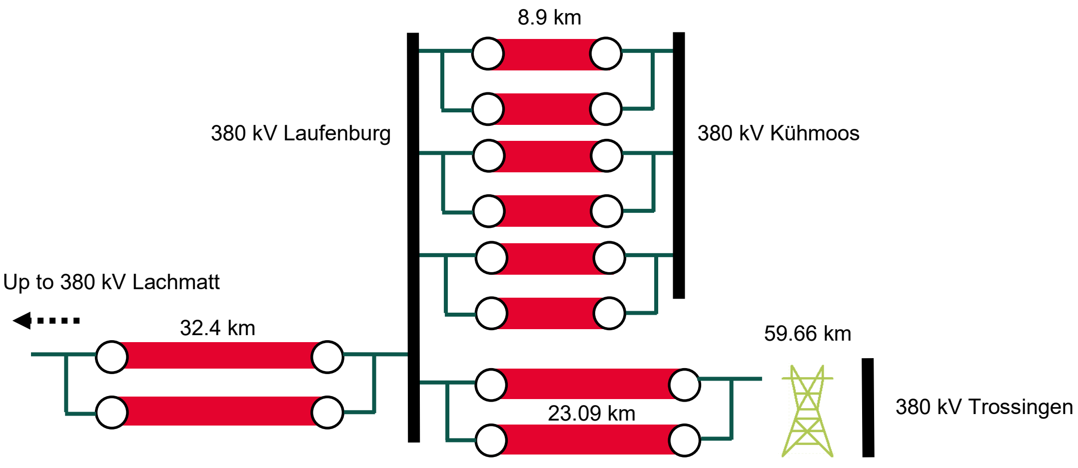
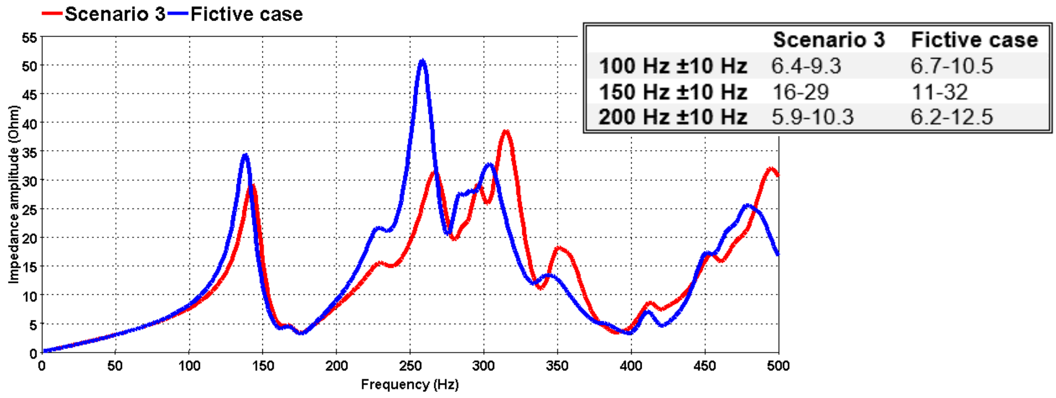


Figure 2-70: 380 kV cable systems near 380 kV Laufenburg in the fictitious case

The additional cable systems contribute to a total length of approximately 106.94 km. Together with the 380 kV Lachmatt – Laufenburg cables, the total length of cables connected directly to 380 kV Laufenburg becomes 171.74 km.

Consider an N-1 contingency on 380 kV Laufenburg – Beznau, the original short-circuit power at 380 kV Laufenburg decreases from 43 GVA to roughly 30 GVA. The harmonic impedance at 380 kV under this N-1 contingency for Scenario 3 and the fictive case as well as the impedance amplitude close to the 2nd, 3rd, and 4th harmonics are presented in Figure 2-71.



	Scenario 3	Fictive case
100 Hz ±10 Hz	6.4-9.3	6.7-10.5
150 Hz ±10 Hz	16-29	11-32
200 Hz ±10 Hz	5.9-10.3	6.2-12.5

Figure 2-71: Harmonic impedance at 380 kV Laufenburg and the impedance amplitude close to the lower-order harmonics for the N-1 contingency for scenario 3 and the fictitious case

As shown in Figure 2-71, the addition of the 106.94 km cable systems does shift the network parallel resonant frequency at 380 kV Laufenburg towards lower harmonic frequencies. However, this shift is much less significant compared to the previous case, despite the long cable length. This demonstrates the statement that strong nodes with a high short-circuit power would have a larger capacity of incorporating more cable projects without degraded performance.

In addition, the impedance amplitude at resonance as well as at low-order harmonic frequencies is quite low, thanks to the high network damping brought by the high short-circuit power. Predictably, severe TOVs during transient events at 380 kV Laufenburg, such as transformer energization, should not be expected in either case.

To confirm, the three-phase-to-ground voltages at 380 kV Laufenburg for both Scenarios 3 and the fictive for the first 1 s of the simulation are presented in Figure 2-72. The curves for the two scenarios are superimposed.

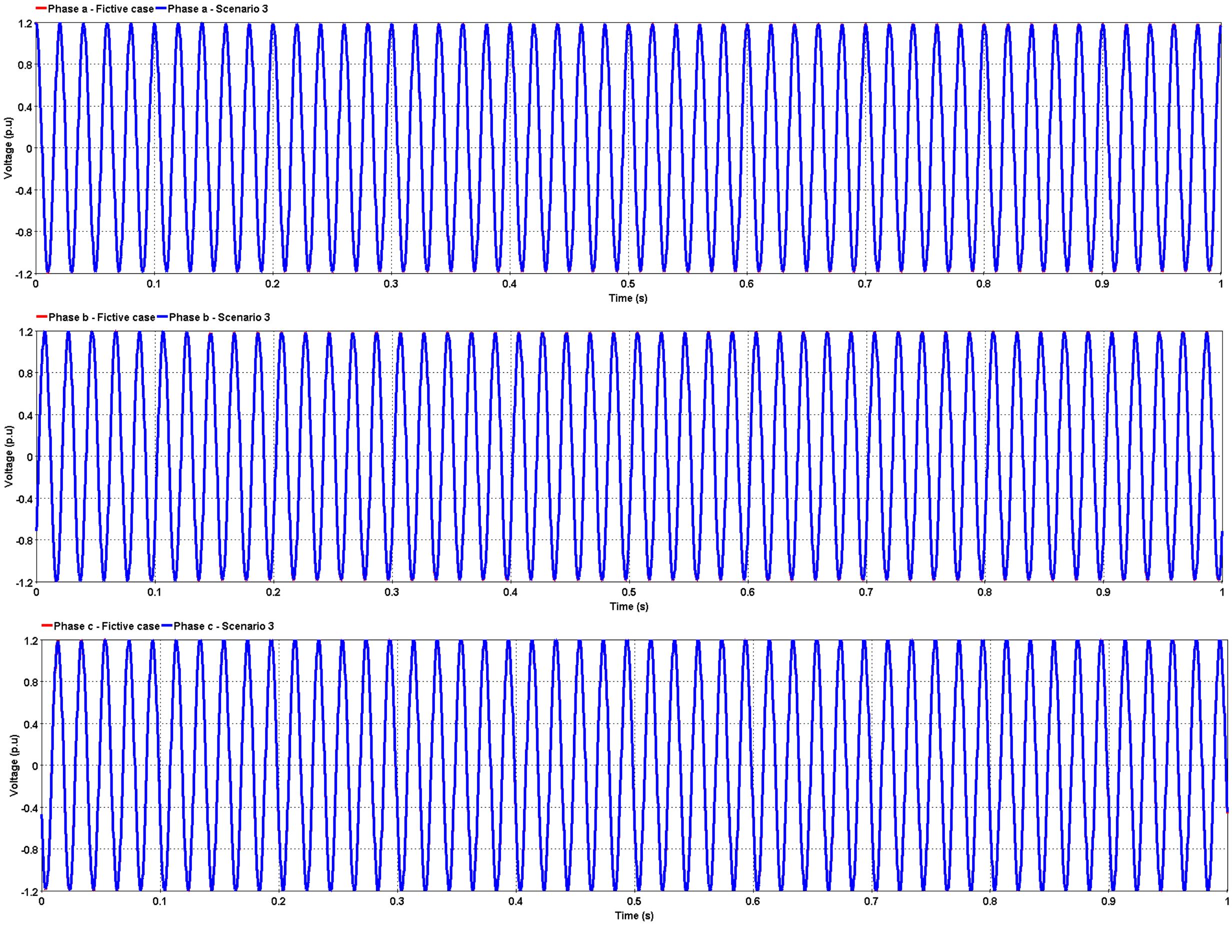


Figure 2-72: Phase-to-earth voltages at 380 kV Laufenburg – scenario 3 and the fictitious case for the first second of the simulation

Notes: First of all, the terminal voltage at 380 kV Laufenburg prior to transformer energization is quite high due to extensive cabling in the vicity (which, in reality, should be lowered with reactive power compensation, etc.). However, despite the high terminal voltage and extensive cabling, almost no TOVs can be observed during transformer energization in both Scenario 3 and the fictive case, confirming that no parallel resonance is excited during the transient event in either case (see Figure 2-71).

This example demonstrates that extensive cabling close to a strong node (network location with high short-circuit power) tends to have a mitigated impact on the frequency response at this node, which should not pose additional concerns for TOVs during transient events.

2.4.4 Conclusion

Time-domain EMT studies can serve as a valuable reference in system planning and operation because they offer visualization of the values and waveforms of various system and equipment parameters (e.g., voltages, currents, active and reactive power, control parameters, references, etc.) in the time-domain either in steady state or during perturbations (e.g, energization of lines/cables/transformers, connection of capacitor banks or shunt reactors, faults and recovery, system islanding, load rejection, protective actions, control step changes of power electronics devices, etc.)

Following the conclusions in section 2, equipment-level time-domain studies have been performed in this chapter to further evaluate the impact of the planned cable projects in all three scenarios on the grid performance and behavior. The time-domain EMT studies performed in this chapter focus on energization of large Swissgrid transformers at the sensitive network locations under the critical grid configurations and conditions that have been identified in section 3.

Several conclusions can be drawn from the performed studies:

- Critical TOVs are to be expected when transformers are energised in the cases identified in section 2.

In section 2, several cases of critical parallel resonance at low-order harmonics, notably the 2nd and the 3rd, have been identified for Scenario 3 with the most cable projects. These cases concern sensitive network locations such as 380 kV Romanel and 380 kV Magadino under certain grid topologies (N-1 and N-2) and conditions (low short-circuit level). Unsurprisingly, severe and poorly damped TOVs can be observed when energizing the large Swissgrid transformers at the said locations under the identified grid topologies and configurations. With the TOV amplitude exceeding 1.5 p.u. in certain cases, these TOVs would pose considerable dielectric and thermal stress on the network equipment in proximity, causing equipment premature ageing and even failure.

Nonetheless, it is also observed that for scenario 2 with much fewer cable projects, the same grid topologies and configurations would result in much mitigated TOVs such that concerns for grid operation stability and security should not be raised.

- Overall, it is safe to say that intensive cable integration, such as in scenario 3, would greatly increase risks of critical TOVs at multiple network locations during on-site transient events. The short-circuit power at a given grid location plays an important role in the impact of integrating cables in the vicinity (additional studies).

As was discussed previously, cable integration generally tends to decrease the parallel resonance frequencies at various network locations, exposing them to potential risks of critical TOVs during on-site transient events such as energization, fault recover, system islanding, etc. However, the impact of cable integration varies from one node to another, depending on the short-circuit power of the node. Two example network locations have been chosen to demonstrate this point with N-1 contingencies, which are 380 kV Romanel and 380 kV Laufenburg.

With a short-circuit power slightly higher than 11 GVA, 380 kV Romanel is a relatively weak node among all 380 kV substations. Increasing the cabling length proposed in Scenario 3 from 40 km to 117.4 km around 380 kV Romanel further shifts the parallel resonance from the 3rd harmonic (in Scenario 3) towards the 2nd harmonic, leading to much more aggravated TOVs (from 1.32 pu to beyond 1.5 pu) for the tested N-1 contingency during the energization of the Romanel transformers.

On the other hand, 380 kV Laufenburg is among the strongest nodes in the 380 kV network. Its short-circuit power stands at over 43 GVA during normal operation. With the N-1 contingency on 380 kV Laufenburg – Beznau, its short-circuit power decreases to around 30 GVA, which is still quite high. Thanks to the strong short-circuit power, almost tripling the cabling length from 64.8 km to 171.74 km would only slightly shift the parallel resonant frequency by less than 10 Hz. In addition, the high system damping brought by the high short-circuit power makes it that the network harmonic impedance at 380 kV Laufenburg at low-order harmonics (i.e., 2nd, 3rd, and 4th) is sufficiently low to avoid the excitation of any low-order parallel resonances. Unsurprisingly, no TOVs can be observed during the energization of the Laufenburg transformer for either tested case, even with intensive cabling in proximity to 380 kV Laufenburg.

To sum it up, it would be rather safe to integrate cable projects in the vicinity of a strong node as minimum impact on the existing grid can be expected. However, attention should be paid when integrating cable projects close to a weak node since further detailed investigations or studies might be necessary.

2.5 Voltage step due to connection or disconnection of cables and compensation devices

Sections 2.2, 2.3 and 2.4 analysed the impact of short-circuit power on resonant frequencies, harmonic amplification and the energisation of large transformers. This section examines the influence of short-circuit power on voltage steps following the connection of cables or the disconnection of shunt reactors. The aim of this analysis is to estimate the maximum cable length values according to the short-circuit power of a node. Similarly, an estimate is given of the maximum compensation that can be lost without leading to an increase in voltage beyond the maximum permissible step. These analyses revolve around the fact that at Swissgrid, the maximum permissible steady-state change in voltage following the connection of a cable or the disconnection of a compensation element is 2% [2.29].

Due to their capacitive characteristics, cables tend to increase the voltage of the node to which they are connected. This increase in voltage can be limited by compensation devices, which absorb some or all of the reactive power generated by the cable. If the compensation device is disconnected (due to a fault or operation failure) while the cable remains live, reactive power flows from the cable to its connection point. This causes a voltage jump to occur at this node, leading to an increase in the steady-state voltage. This increase in voltage depends not only on the amount of compensation lost, but also on the short-circuit power (SCL) of the connection point and the grid meshing around it. In other words, the higher the short-circuit level or the grid meshing, the lower the voltage increase for a given loss in compensation.

2.5.1 Voltage steps caused by the connection/disconnection of a cable

It is possible to roughly estimate the voltage rise on a node caused by a cable when a compensation device is disconnected. In simple terms, an approximation of this case can be given by an LC circuit, where the value of the inductance is inversely proportional to the short-circuit power (L_{sc}) and the value of the capacitance represents the cable capacitance (C_{cable}):

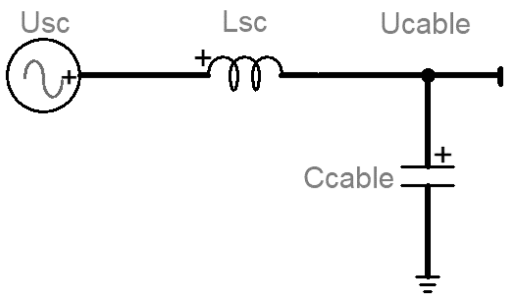


Figure 2-73: Simplified electrical representation of a cable connected to a node

By solving this circuit, it is possible to establish that the voltage rise is directly proportional to the amount of reactive power generated by the cable (Q_{cable}) and inversely proportional to the short-circuit power of the node (S_{sc}):

$$\Delta u_{pu} \propto \frac{Q_{cable}}{S_{sc}}$$

Considering that the reactive power generated by the cable depends on the cable length and the operating voltage, it is possible to estimate the maximum total length of the cables connected to a node *(ℓ_{max})* for a maximum permissible change in voltage (Δu_{max}). This ratio is defined as follows:

$$\ell_{max} = \frac{\Delta u_{max}\,(\Delta u_{max} + 1)}{k_{Q-l}} \cdot S_{sc}$$

where $k_{Q\text{-}l}$ is the reactive power per unit length generated by the cable (in Mvar/km), and Δu_{max} is the maximum permissible change in voltage in *per units (p.u.)*.

For a copper cable system with a nominal voltage of 380 kV, a cross-section of 2,500 mm^2 and an operating voltage of 410 kV, the reactive power per unit length generated by the cable *(k_{Q-l})* is equal to 12.7 Mvar/km [2.22]. Assuming a maximum permissible voltage step of 2% (Δu_{max} = 0.02 p.u.), it is possible to represent the maximum permissible quantity of cable to be installed on a node according to its short-circuit power:

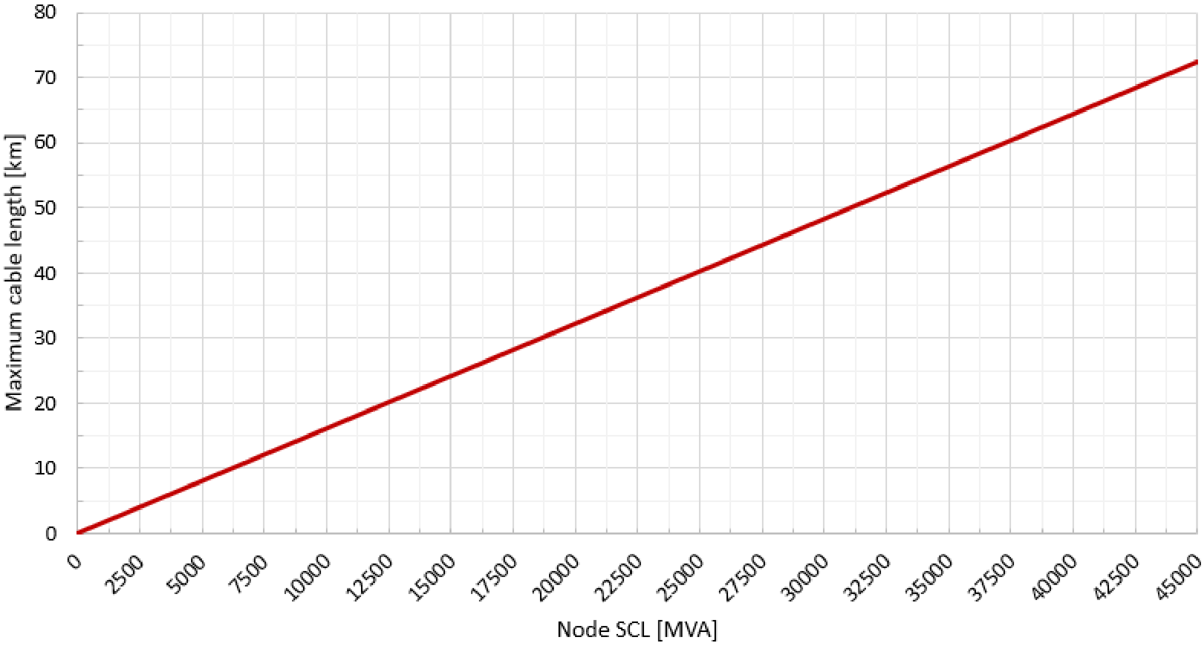


Figure 2-74: Maximum permissible cable length on a 380 kV node for a voltage increase of 2%

This figure shows, for example, that for a 380 kV node with a short-circuit power of 12,500 MVA, a cable (2,500 mm^2) with a length of 20 km would increase the steady-state voltage by 2%. Logically, for a weaker node (lower SCL), the total permissible cable length would be shorter.

If we consider a copper cable system with a nominal voltage of 220 kV, a cross-section of 1,600 mm^2 and an operating voltage of 235 kV, the reactive power per unit length generated by the cable *(k_{Q-l})* is equal to 4.3 Mvar/km [2.22]. Assuming the same maximum permissible voltage step of 2%, the relationship between the short-circuit power of the node and the maximum permissible cable length changes as follows:

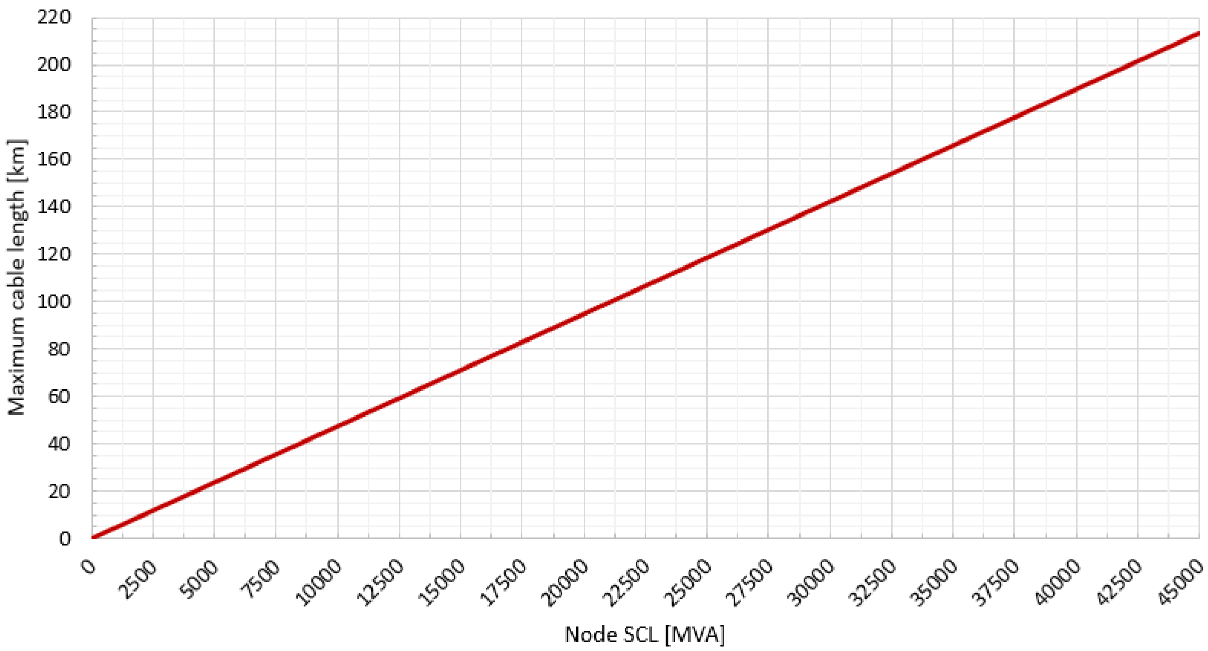


Figure 2-75: Maximum permissible cable length on a 220 kV node for a voltage increase of 2%

Since a 220 kV cable creates a lower feed-in of reactive power into the grid, the maximum permissible cable length on a 220 kV node is much higher than on a 380 kV node.

Equivalent figures can be obtained for other types of cable with different cross-sections and at other voltage operating points.

Based on this relationship between maximum length and short-circuit power, it is possible to identify where the introduction of cables in scenario 3 could cause voltage rises of more than 2%. The Lake Geneva area proves problematic with regard to steady-state voltage rises. In total, 57 km of 220 kV cable is installed between Foretaille and Romanel, and the two longest sections exceed the maximum permissible length, as summarised in the table below:

Line	Planned cable length (km)	Substation 1	Substation 2	Min. SCL between substation 1 and 2 (MVA)	Max. permissible length (km)
220 kV Banlieue Ouest – Foretaille	52.2	B. West	Foretaille	9,500	45.1
220 kV Crans – Romanel	40.7	Crans	Romanel	7,300	34.6

Table 2-25: Comparison of permissible and planned cable lengths in the Lake Geneva region – problematic cases

As far as the 220 kV Banlieue Ouest – Foretaille line is concerned, the 52.2 km of cable could result in a voltage rise exceeding the permitted 2%. Due to the short-circuit power of the nodes, the maximum permissible length would be 45.1 km, 7.1 km less than the planned length.

For the 220 kV Crans – Romanel line, a voltage rise beyond the maximum permissible threshold could occur if the planned 40.7 km of cable are installed. The short-circuit power of the substations would allow a maximum cable length of 34.6 km to be switched on without exceeding the 2% limit, which is 6.1 km less than the length considered in scenario 3.

It is important to note that the cable length limits given above should not be seen as the only limitation to be taken into account. This is an initial restriction, calculated as an approximation. All the necessary EMT studies for resonant frequencies and harmonic amplification must follow, as explained earlier in this report.

2.5.2 Voltage steps caused by the disconnection of a compensation element

Similarly, it is possible to estimate the maximum acceptable reactive compensation loss that would lead to a steady-state voltage rise of no more than 2%. This value can be defined by the following ratio:

$$Q_{comp\ loss} = (\Delta u_{max}^2 + \Delta u_{max}) \cdot S_{sc}$$

where $Q_{comp\ loss}$ represents the reactive compensation loss leading to a voltage rise equal to the maximum permissible value *(Δu_{max})*.

Again, considering the 2% limit *(Δu_{max}* = 0.02 pu), it is possible to plot the maximum permissible reactive compensation loss according to the short-circuit power of the node.

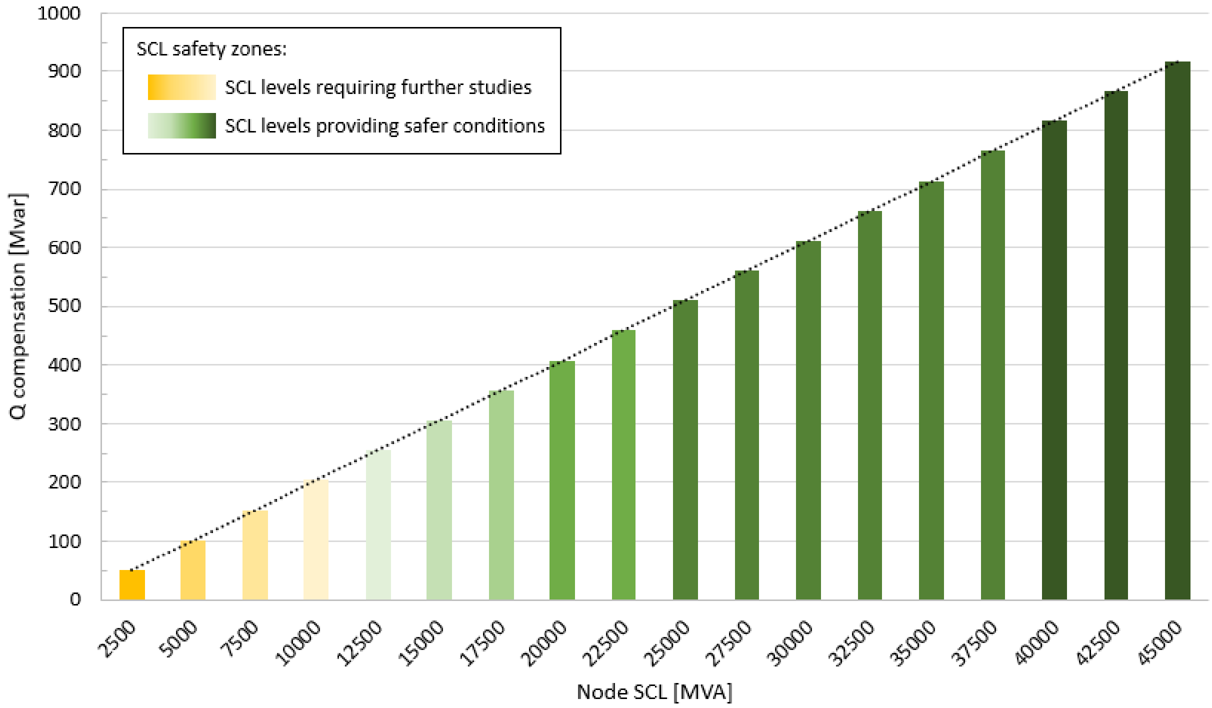


Figure 2-76: Maximum loss of reactive compensation resulting in a voltage jump of 2%

According to the figure above, the maximum possible size of a shunt reactor for a region where the short-circuit power is 10 GVA would be 200 Mvar. As the maximum reasonable capacity envisaged by Swissgrid for its coils is precisely 200 Mvar, it makes sense to limit the capacity of the coils if the short-circuit power at the location of interest is less than 10 GVA.

Finally, it should also be noted that during the EMT studies, it was found that with a short-circuit power greater than 12 GVA, the installation of cables is less likely to create technical problems. However, below this value, further studies are required to assess the situation on a case-by-case basis. This is indicated in the figure above by the short-circuit power safety zones (SCL safety zones).

3 WP 3 – Grid restoration after a blackout

3.1 Introduction

This report is part of the Swiss cable study and constitutes the third and final work package. The aim of this report is to analyse the impact of cables on grid restoration after a blackout.

In this report, “cables” refer to underground XLPE cables. Therefore, for the readers’ convenience, only the word “cable” will be used hereinafter.The current strategy to restore the Swiss transmission grid is based on four restoration cells spread across the country, i.e., the southern, western, central and eastern cells, as is shown in Figure 3-1.

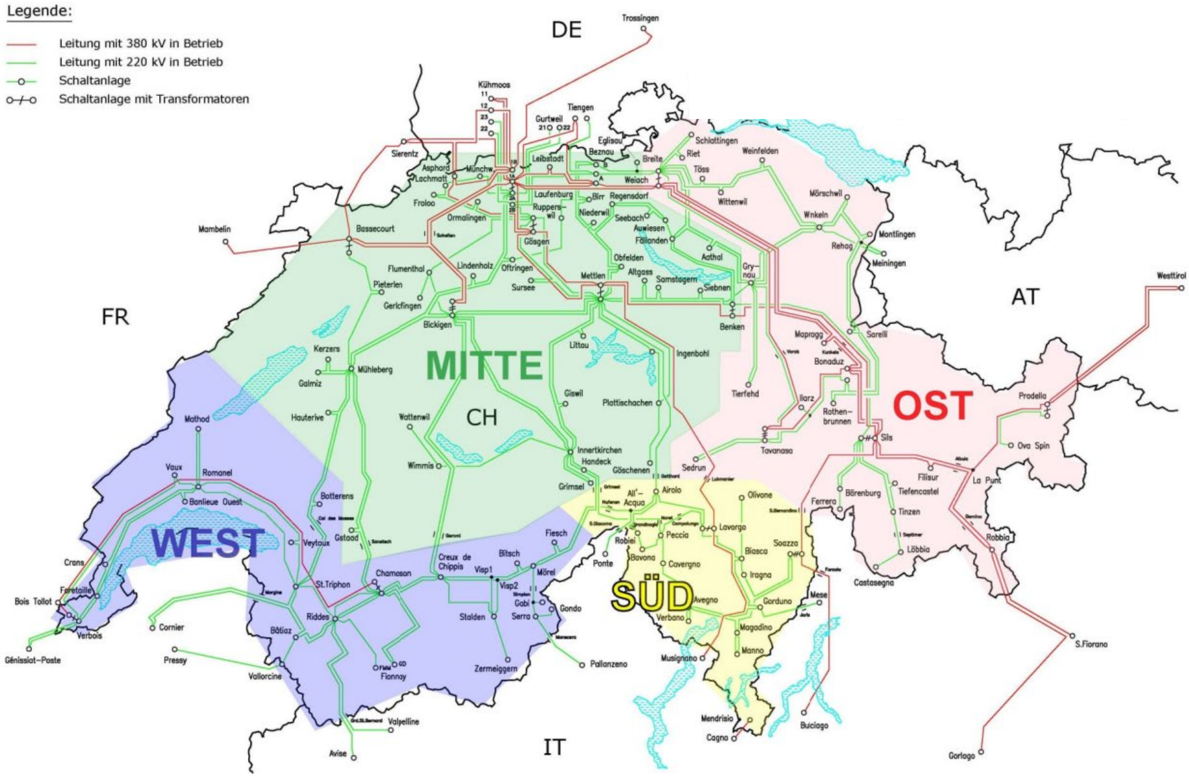


Figure 3-1: Swissgrid restoration cells

In the event of a total failure, the four cells are expected to start the restoration process independently, then connect to each other as part of the synchronisation process. The advantage of having several restoration cells is that the process is faster, and service can be restored within a brief period. Assistance from neighbouring countries would also be very useful in such a situation. However, Switzerland must remain able to restore service independently in the case that assistance from neighbouring countries is not available due to a large-scale blackout.

The best possible scenario for restoration is to have overhead lines of medium lengths. Cable sections make restoration very difficult for a number of reasons described in this report. The increase in cable projects in the transmission grid makes it necessary to re-evaluate the restoration process. Various studies already carried out for current cable projects clearly identify the challenges faced by Swissgrid.

3.2 Restoration of a grid with cables

The restoration process starts with one or more machines with black-start capability (i.e., without the need of external power supply). Gradually, neighbouring lines and transformers are connected until a load, normally a pump, is reached. The load stabilises the restoration cell. After a few minutes of stable operation, other lines can then be connected to expand the cell. During these initial stages, the short-circuit power is very low and the grid is, therefore, very sensitive. The slightest disturbance can lead to the loss of the cell and, consequently, the need to start again from zero.

Connecting long lines is one of the most difficult aspects of grid restoration. These lines require a high capacitive charging current, which causes high generator loading. This effect of charging current becomes intensified as the length of the line increases and is even more pronounced for cables with a very high capacitive current on account of their capacitive nature.

Shunt reactors can be installed to prevent the reactive power produced by the cables from overloading the generators. Their function is to absorb excessive reactive power, giving the generators the possibility to respond to unforeseen load variations. If the shunt reactors are adjustable, they can also be used to maintain voltage levels at appropriate levels during restoration.

However, the problem of the reactive power generated by the cables is not the only thing that hampers restoration. The presence of cables gives rise to excessive overvoltages caused by low-order resonances, which, in turn, would increases the risk of spurious activation of protective devices and damage to grid components.

Swissgrid learned during information exchanges with other European TSOs that so far, there have not been precedents for grid restoration with cables near restoration cells. In general, standard practice is to avoid cables until a sufficiently large and solid cell becomes available. This is possible if the cables are outside the restoration cells or if the grid is sufficiently meshed to avoid the negative impact from them. However, in Switzerland, the machines are usually connected to loads via one route during the restoration process, which leaves little room for flexibility.

According to the current plans, two of the four available cells are affected by cable projects. The cable project in the Maggia Valley has an impact on the southern restoration cell, and the central restoration cell is impacted by the cable projects between Mettlen and Ulrichen.

The consequences are explained in the next two sections.

3.3 Southern restoration cell (OFIMA-OFIBLE)

The southern restoration cell in Ticino relies on generators in Biasca and Olivone, which are connected to the pump at Peccia via the 220 kV Lavorgo – Peccia line.

The 220 kV Lavorgo – Peccia line will be dismantled when the Maggia Valley project is completed. This indicates that the electrical distance between the generators and the pump in the southern cell will be increased by around 27 km, including 6 km of cable between Bavona and Peccia. The current and future restoration route planned for 2022 is shown in yellow in Figure 3-2.

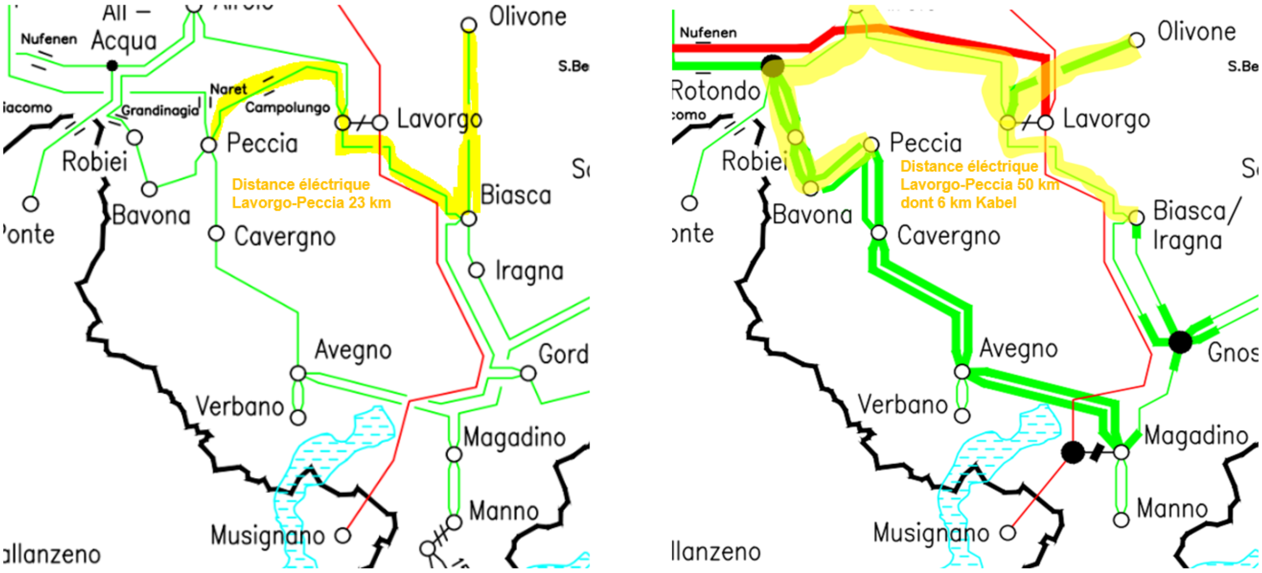


Figure 3-2: Grid restoration path with the current (left) and future (right) grid configuration

It should be noted that since 2022, there have been changes in the planning of the Ticino grid. In particular, there will only be one 220 kV line between Biasca and Gnosca, and the voltage of the Olivone power plant will be 150 kV. However, the difficulties associated with the longer restoration route remain unchanged, and the 150 kV feeder at Olivone could further complicate restoration.

While it is true that the 220 kV Bavona – Peccia connection is already implemented in cable, it is not currently used in the restoration sequence because of the shorter route thanks to the 220 kV Lavorgo – Peccia line.

The cabled sections and the greater length of overhead lines represent a significant variation in the restoration process. This is why a specific study on restoration [3.2] was carried out after the dynamic studies for the cable project [3.1].

The study compares the voltages and reactive power absorption of the generators with the two grid configurations, current and future. The resonant frequencies of the restoration cell are also calculated in both cases.

The results show that there is a clear reduction in resonant frequencies with the future configuration, which causes overvoltages when the Peccia pump transformer is energised. This problem can be solved by installing POW switching in the transformer. Another important conclusion is that more generators will be needed at Biasca and/or Olivone in the future to increase the short-circuit power of the restoration cell. This will make it possible to increase the resonant frequencies as much as possible and to supply the necessary lines, cables and transformers.

Other solutions were considered for the restoration cell, such as using the generators at Verbano. However, this option gave poorer results than the traditional cell because of the low power rating of the generators at Verbano.

The alternative, which could simplify the process, would be to use the Robiei pumps instead of the Peccia pumps. The electrical distance between the generators and the pumps would then be reduced, which would improve results.

To sum up, the results obtained with the future grid configuration are much poorer than the current results. However, the problems encountered can be resolved, and restoration with the southern cell remains possible.

3.4 Central restoration cell (KWO)

As the problem of the central cell is more acute than that of the southern cell, it will be explained in more detail in this report.

Restoration of the central cell starts as normal, with the black start of a 43 MVA generator in Handeck. Innertkirchen also has a 52 MVA generator with black-start capability. Following the resumption of operation of one generator, several others are connected at Innertkirchen and Handeck. The required rotating mass before connecting the Grimsel pump is obtained by assembling approximately 200 MVA of generation. The Grimsel pump is connected via a converter that regulates the load up to a maximum of 100 MVA.

Figure 3-3 shows the grid configuration in the region after the inclusion of the planned cables (dotted lines). The cable length is indicated in km in blue.

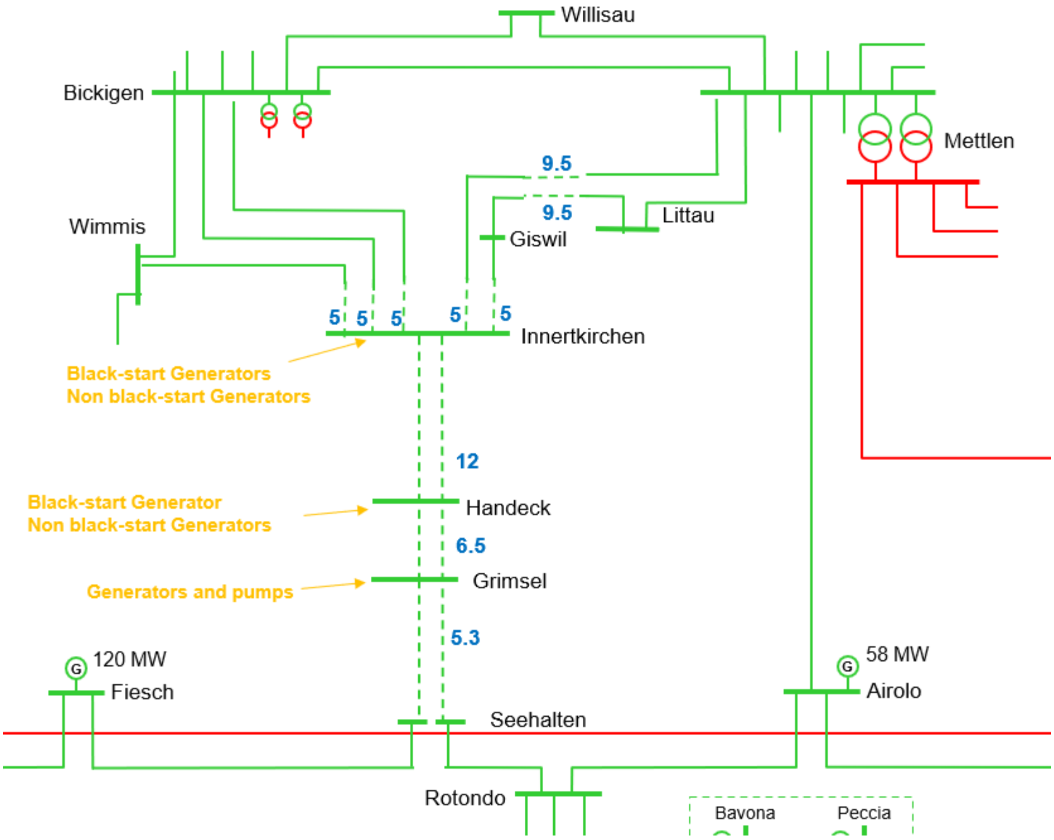


Figure 3-3: Future grid configuration in the Grimsel region

As shown in Figure 3-3, the Handeck and Innertkirchen generators can only be connected to the Grimsel pump using the cables inside the restoration cell. The results below show how this complicates the process significantly.

Several studies have been carried out to simulate different restoration scenarios in order to adapt the current process to the new cable configuration. Firstly, Enernex simulated the current process and three new scenarios envisaged by Swissgrid and KWO to improve the results [3.3]. Then FKH repeated the analyses carried out by Enernex to confirm the obtained results [3.4]. Finally, the simulations were checked internally at Swissgrid, and a new scenario suggested by KWO was simulated [3.5]. Studies carried out by the three different companies [3.3][3.4][3.5] showed that the restoration as currently envisaged will not work with the new cables planned. The problem is caused by the low initial short-circuit power of a single 43 MVA generator. The resonant frequency with long cables and low short-circuit power is close to 50 Hz. This means that very high and sustained overvoltages may be encountered.

Figure 3-4shows the energisation of the 12 km Innertkirchen-Handeck cable at t=1.08s, followed by the energisation of the Innertkirchen transformer at t=3s. Firstly, the transients generated on cable energisation exceed 2 p.u. and take up to one second to decay. Secondly, and more worryingly, energising the Innertkirchen transformer excites low-frequency resonances, resulting in undamped overvoltages.

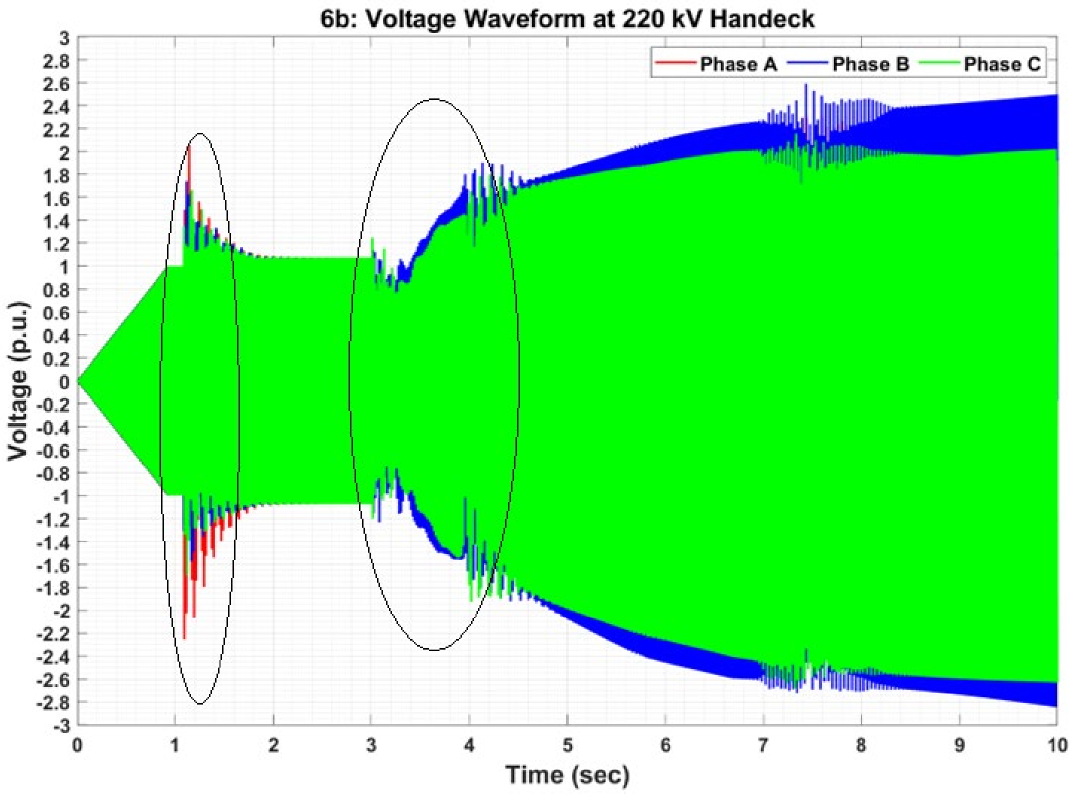


Figure 3-4: Voltage at Handeck during the current restoration process with the future grid configuration

These results clearly show that, as with the southern restoration cell, it is necessary to considerably increase the rotating mass in order to increase the resonant frequency of the system and to be able to energise the cables and transformers without dangerous transients. This means that more generators need to be included in the process.

The voltage must also be increased in the form of a ramp to avoid sudden voltage jumps that can saturate transformers. This method involves interconnecting a group of elements of the restoration cell and gradually increasing the voltage. Three scenarios in line with this methodology were prepared by Swissgrid and KWO and simulated by Enernex [3.3] and FKH [3.4].

The simulations of these three new scenarios show a clear improvement on the current process (which does not work). Transients, although significant, are damped over time. However, there is a voltage imbalance for more than 30 seconds after the load is put into operation.

Figure 3-5 shows the voltage at Handeck according to the process envisaged in one of these three scenarios. The voltage is ramped up with the entire restoration cell (Innertkirchen, Handeck and Grimsel) connected from the start, so that no transients are observed in this phase. However, connecting additional elements outside the restoration cell causes the transients and imbalance illustrated. At t=1.08s, 220 kV Giswil – Innertkirchen is energised, at t=2s the 220/50 kV transformer in Giswil is added, followed by 10 MW of load in Giswil at t=3.5s, 220 kV Giswil – Littau at t=4s, the 220/110 kV transformer in Littau at t=5s, etc.

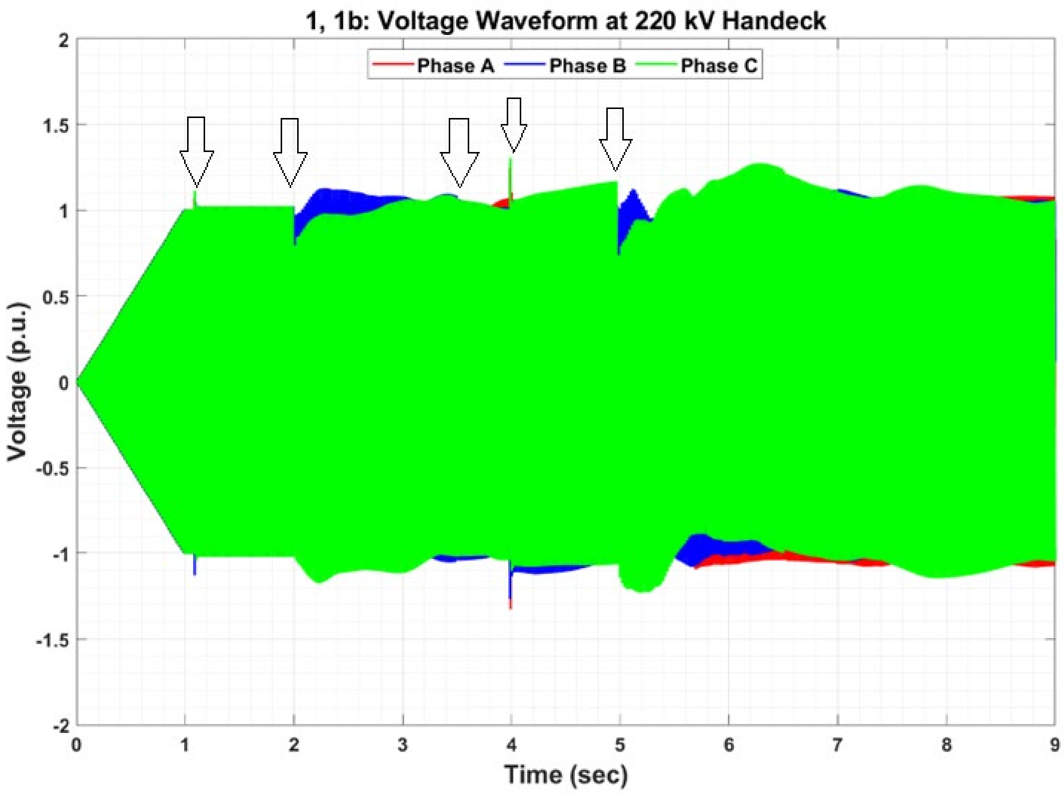


Figure 3-5: Voltage at Handeck during a restoration process adapted to the future grid configuration

The transients produced by the elements connected during the process are damped and are not very high. However, the risk of overvoltage or imbalance protection being activated due to distortion for several seconds cannot be ruled out.

In practice, KWO's specialists consider that these scenarios are extremely difficult to achieve. On the one hand, they would involve using generators that cannot start from scratch and would, therefore, have to be adapted. Additional investments by KWO would be required, which could not be neglected. In addition, a control system would be needed to enable the voltage to increase simultaneously in three substations separated by cables. Hence, it was decided to simulate a fourth scenario in which two islands start up independently and then synchronise.

The results of this fourth scenario, with the black start of two cells and subsequent synchronisation, are described in [3.5]. In summary, the black start of both cells would be possible, although there are significant difficulties in one of the cells that require multiple preconditions to be met, which would be difficult to achieve in practice. Subsequent synchronisation would not be a problem, but the connection of lines, loads and transformers outside the cell is likely to cause imbalance and transients that could trigger protective devices.

Several simulations of load rejection during the restoration process were also carried out [3.6]. The aim was to determine the resilience of the small cell once it is built and the first elements outside the cell are connected. The rejection of a small load is simulated to verify if it would lead to system failure. Depending on the location of the rejected load and its size, there are cases where the system resists the disturbance and others where it does not. As shown below, examples include a loss of just 10 MW at Giswil, causing a system failure.

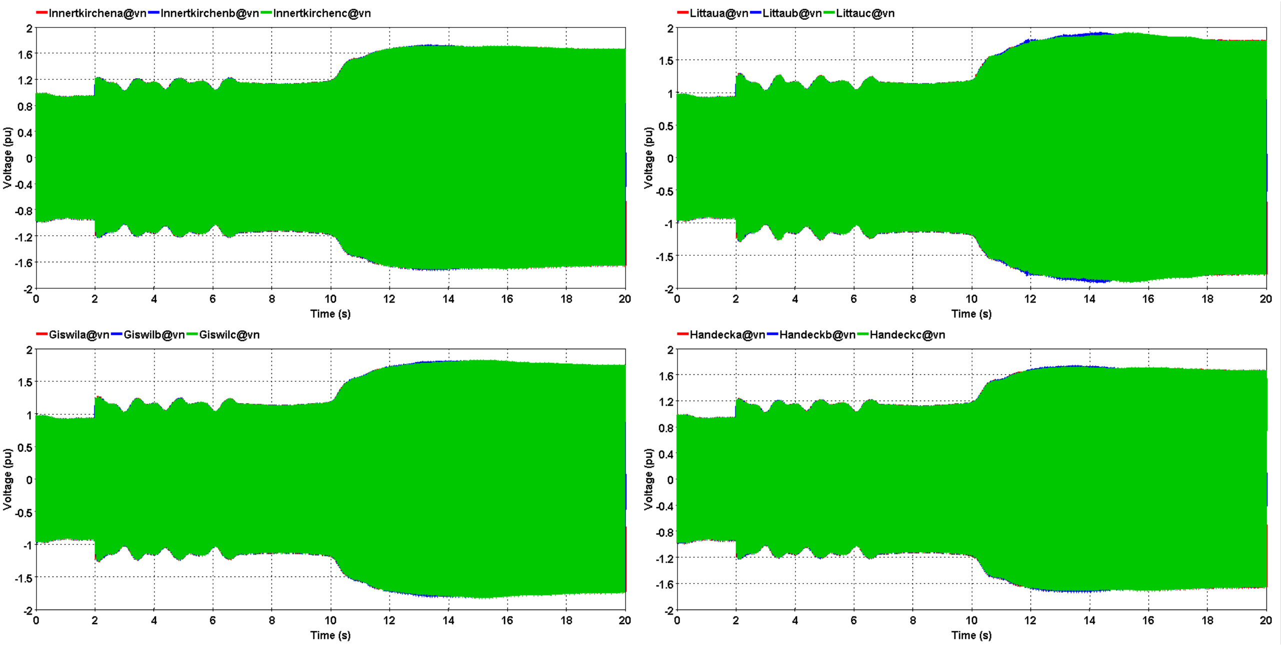


Figure 3-6: Voltage profile at Handeck, Innertkirchen, Giswil and Littau after a 10 MW loss at Giswil (t = 2 s)

To sum up the conclusions of all the analyses carried out, once the planned cable projects have been completed, restoration according to the current plan will no longer be possible. The search for alternative scenarios shows a clear improvement, but the risks are very high, and various adaptations of the Swissgrid grid infrastructure and the KWO power plant would be required. Mandatory adaptations and preconditions that should be met are listed below:

- The new large generators at Innertkirchen and Handeck, of 150 and 90 MW respectively, must have black-start capability (not currently envisaged in the power plant renovation project).
- These generators must be able to maintain the voltage at 0.85 p.u. for several minutes. This has never been done, and the plant specialists do not know if it is possible. The generator undervoltage protectors could trip.
- The pumps connected to Innertkirchen and Grimsel must be able to maintain an imbalance in all three voltage phases for at least 30 seconds.
- It must be ensured that neither undervoltage nor voltage phase imbalances trigger protective devices.
- Shunt compensation reactors would be needed at Innertkirchen and Handeck or Grimsel. This compensation solution is roughly CHF 32 million more expensive than the compensation solution without the possibility of restoration.

- Controlled switching devices (POW switching) would be required in all the transformers in the cell and in those to be connected in the near future.
- It must be possible to demagnetise the transformers and discharge the cables (via and/inductive voltage transformers and/or shunt reactors).

A Swissgrid analysis of the protection parameters at the KWO power plant has already shown that the risk of undesirable protection tripping is very high. Taking all these factors into account, we can conclude that in order to leave the door open to a restoration process in the future, it would be necessary to make numerous investments with no guarantee of success.

Grid restoration is a very exceptional and thus very stressful process. Even if a solution works in theory, there is no guarantee that in this exceptional situation (blackout), all the participants will follow all the steps correctly and without error. In other words, the more complicated the procedure and the more precise the conditions required for a successful black start, the greater the risk of failure in practice.

3.5 Conclusions

The experience of other TSOs and of Swissgrid shows that the presence of cables in or near restoration cells can make restoration after a blackout extremely difficult.

Depending on the technology used to implement the planned developments, new grid restoration strategies may be required. Changes in the location of power plants, the type of generation and its output can greatly alter current restoration concepts and have a direct impact on the time required for restoration. What is more, there is no guarantee that the new concepts will work, since it is impossible to test them in real conditions before the cable projects have been implemented. In this case, decisions must be based on the results of simulations.

As the number of restoration cells available has a direct impact on service restoration time, protecting our restoration cells from cables must be considered a priority.

4 References and annexes

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4.4 WP 2 annexes

4.4.1 Scenarios studied

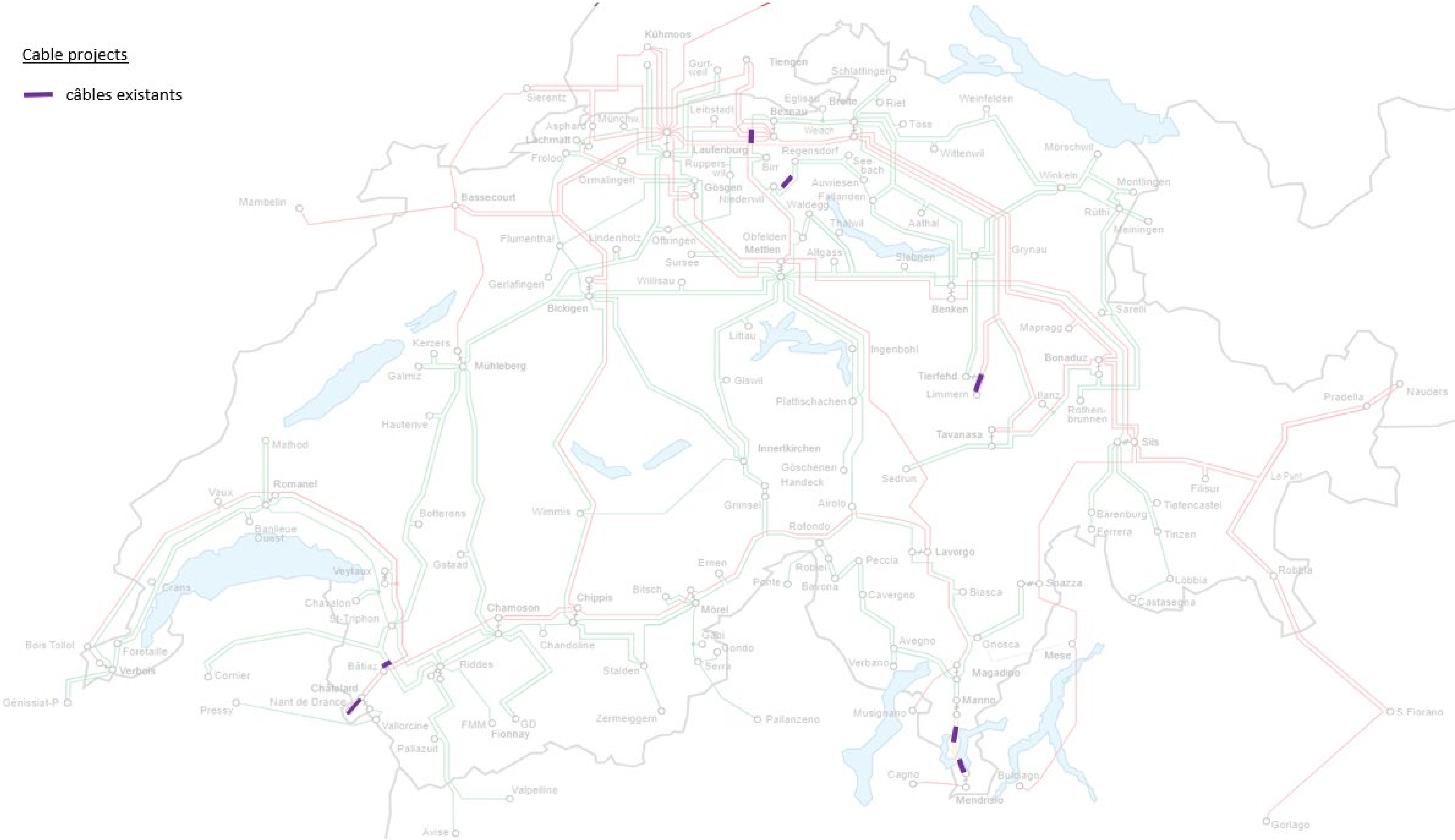


Figure 4-1: Cables considered in scenario 1

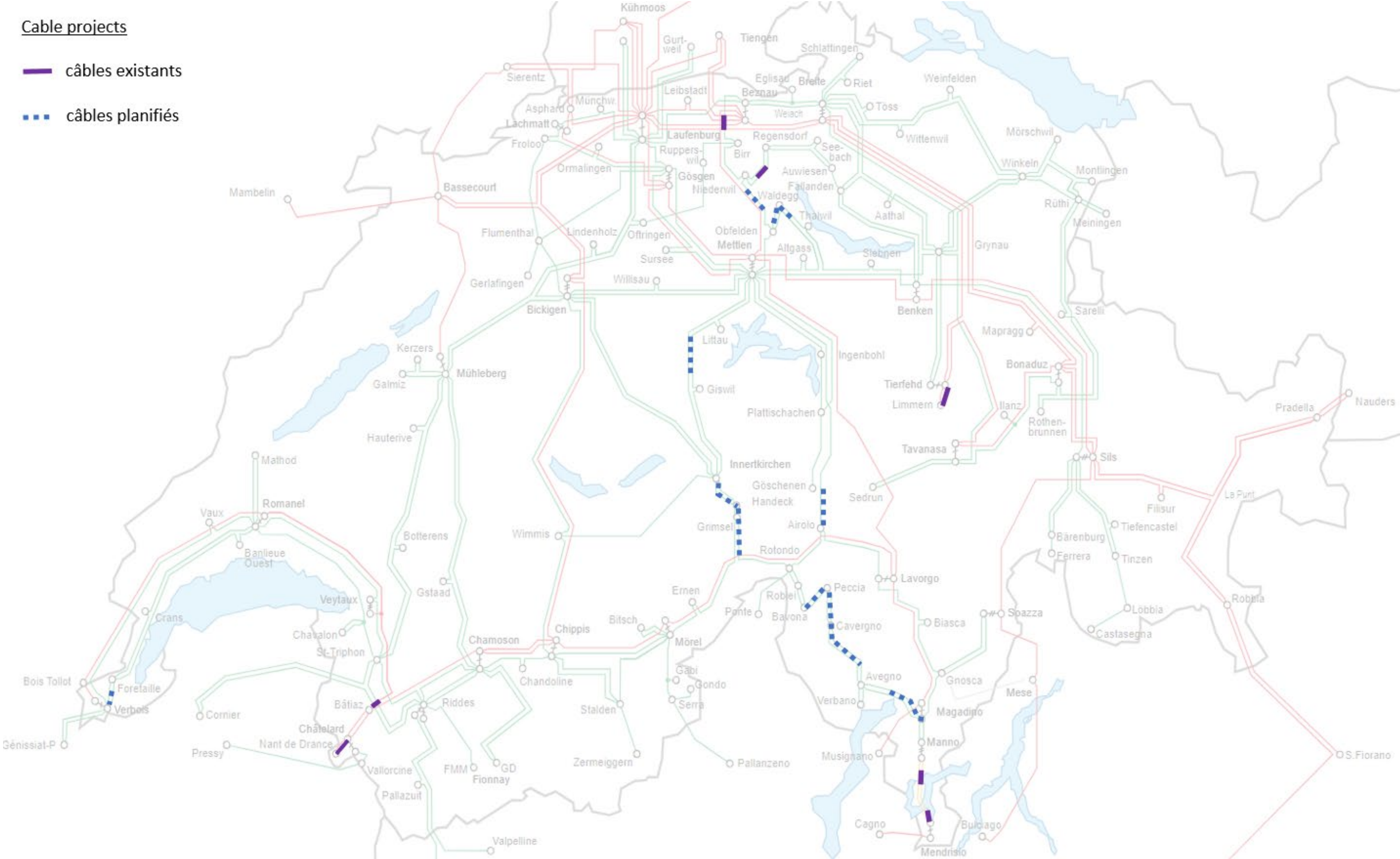


Figure 4-2: Cables considered in scenario 2

swissgrid

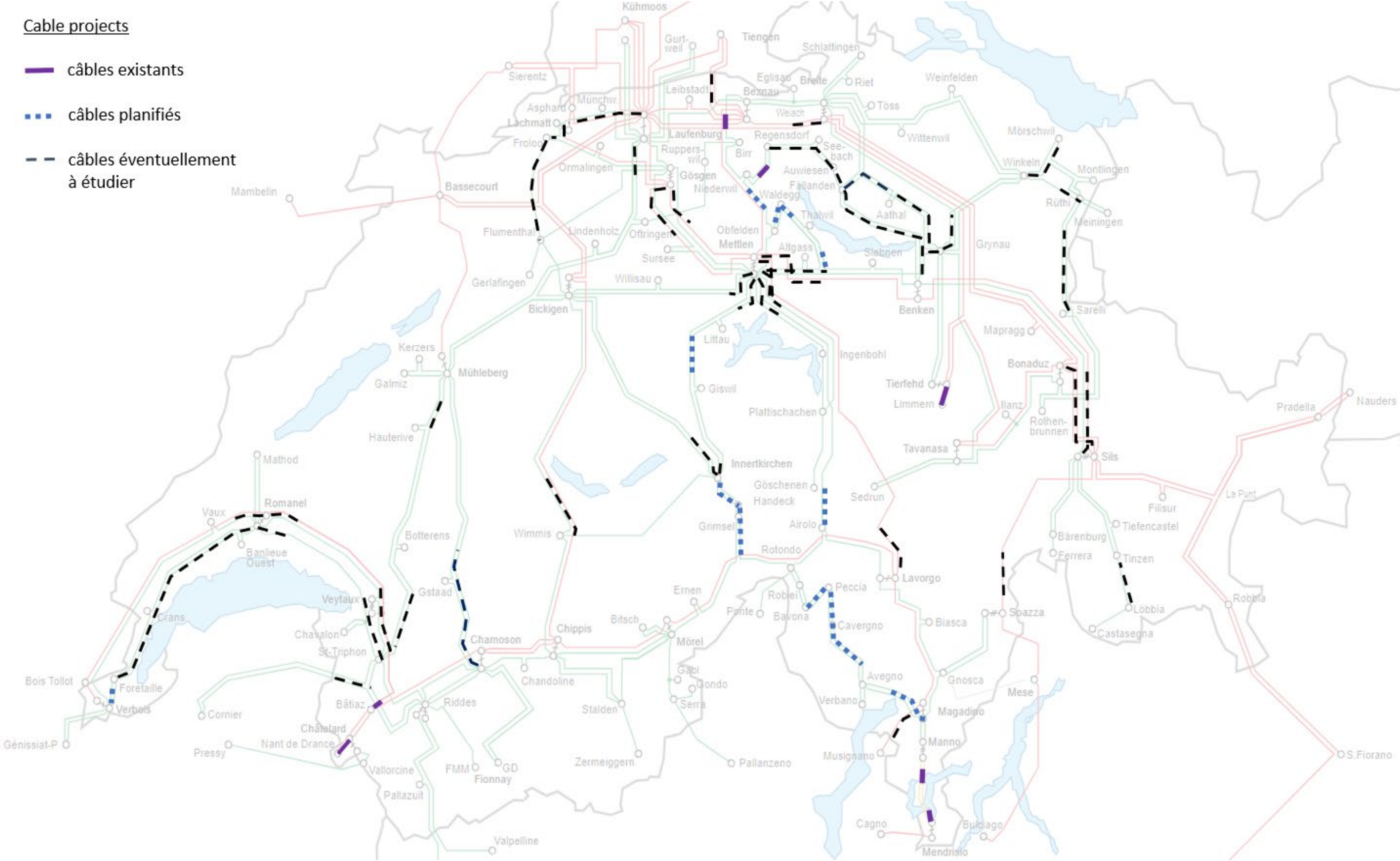


Figure 4-3: Cables considered in scenario 3

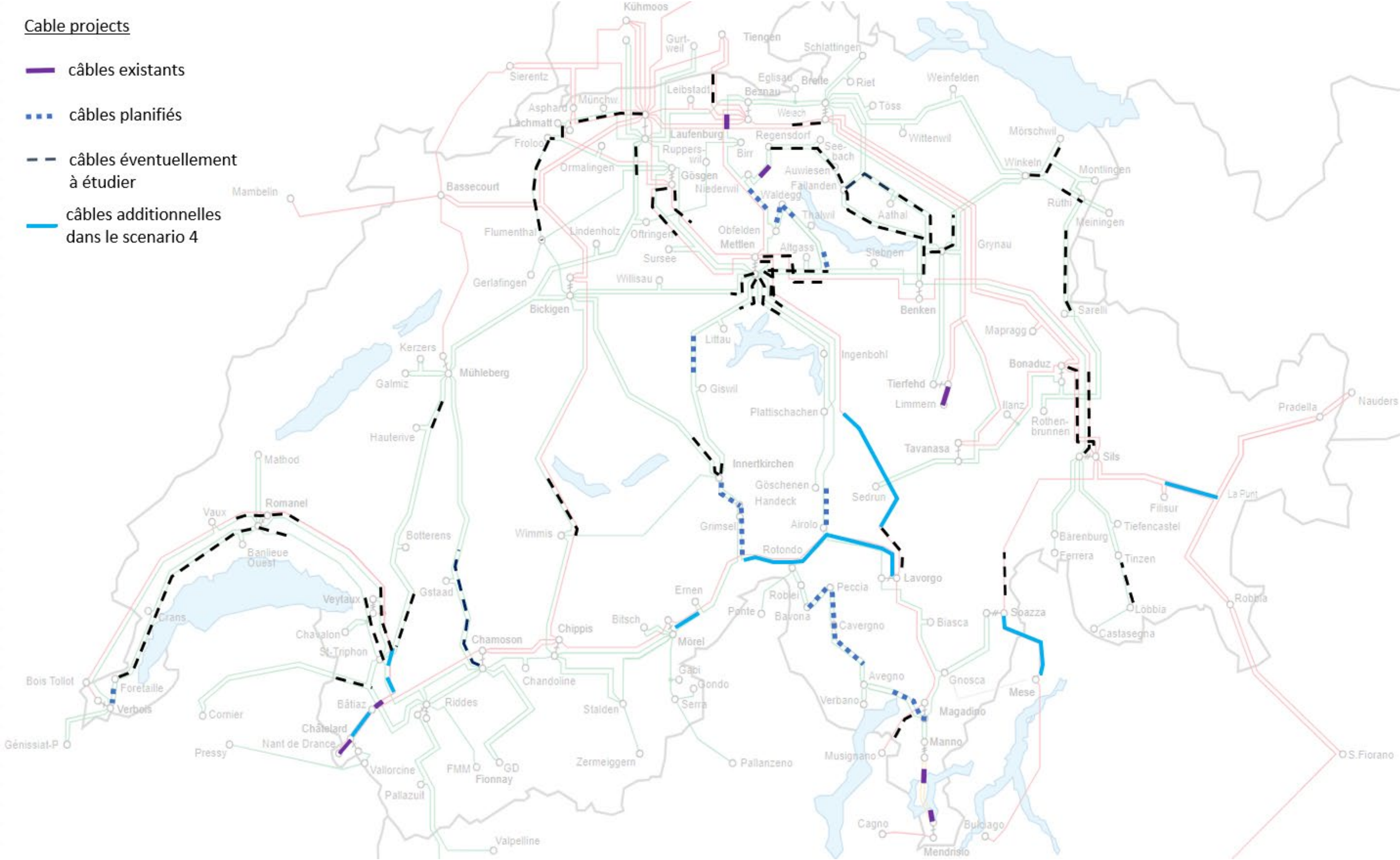


Figure 4-4: Cables considered in scenario 4

4.4.2 Grid modelling in EMTP

4.4.2.1 Advantages of EMT simulations

The increasing complexity of the grid makes it insufficient to merely evaluate the impact of the planned cable systems in the aspects of voltage profile, short-circuit power, and power flow because the transient and dynamic responses of cables for both small and large disturbances differ from overhead lines. Therefore, in order to ensure stable technical performance and secure operation and supply, electromagnetic transients (EMT) studies should also be performed to further assess the system responses towards harmonics and resonances as well as the system behavior under certain on-site transient events.

To demonstrate the advantages of EMT simulations, an overview of three main simulation tools commonly used in power system analysis is presented in Figure 4-5 [2.9].

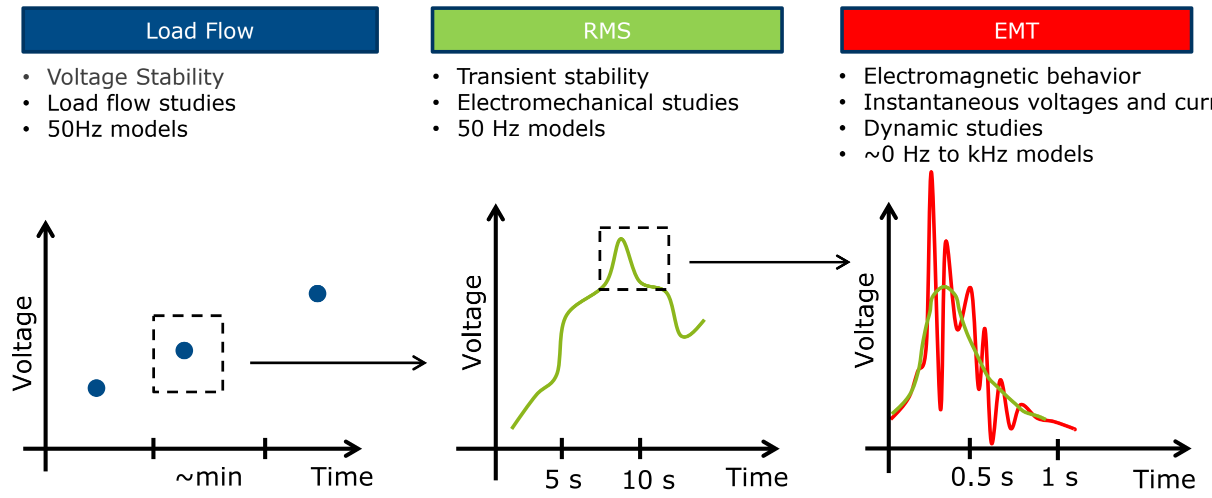


Figure 4-5: Overview of the three types of tools for grid analysis [2.9]

EMT simulations apply to a wide range of frequencies and thus require detailed representations of each network components (i.e., HV equipment, converters, C&P systems, if any, etc.). As can be observed in Figure 4-5, in the time-domain, instead of only showing a single “snapshot” (load-flow) or slow dynamics in a range of several seconds (RMS), EMT simulations offer detailed transient dynamic analysis within microseconds or milliseconds by computing instantaneous waveforms of state variables at an arbitrary time-point in the simulated network, accurately representing the system behavior in a wide range of frequencies. This, however, comes at a price of much longer simulation time as compared to load-flow or RMS tools.

The modelling of several major network components, including modelling approaches and case examples, are presented in the following sections.

4.4.2.2 Introduction of line/cable models in EMTP

4.4.2.2.1 Line/cable models available in EMTP

In power system EMT studies, the modelling of underground cables and overhead lines depends on the phenomena to be studied and a number of other constraints such as the frequency range of interest, the numerical integration time-step with respect to the complexity of the network, etc. Several cable and line models have been proposed in the literature and are currently available in most EMT-type simulation tools. These models can be roughly categorized into two types: lumped parameter models and distributed parameter models.

4.4.2.2.2 Lumped parameter models

Lumped parameter models, alternatively referred to as PI-section models, consider the total length of an underground cable or an overhead line as a single section instead of accounting for an infinite number of incremental cable or line segments. Two types of lumped parameter cable/line models are available in EMTP, as is presented in Table 4-1.

Model name	Characteristics	Applicable basic frequency range
Nominal-PI	R, L, C at fixed rated frequency	50/60
Exact-PI	R, L, C calculated at fixed frequencies and corrected to compensate for the effects of long lines (distributed nature). Only applicable to frequency-domain simulations	DC to kHz

Table 4-1: Cable/line models with lumped parameters available in EMTP

The parameters for the Nominal-PI model are directly derived from the multiplication of the cable/line electrical characteristics R', L' and C'(per unit length resistance, inductance and capacitance, respectively) calculated at power frequency by the total cable/line length, resulting into a model representation with a series impedance $R + j\omega L$ and shunt components of *C* (capacitance) in parallel with *G* (conductance). The equivalent circuit of the three-phase Nominal-PI model in EMTP is presented in Figure 4-6 (neglecting the shunt conductance G).

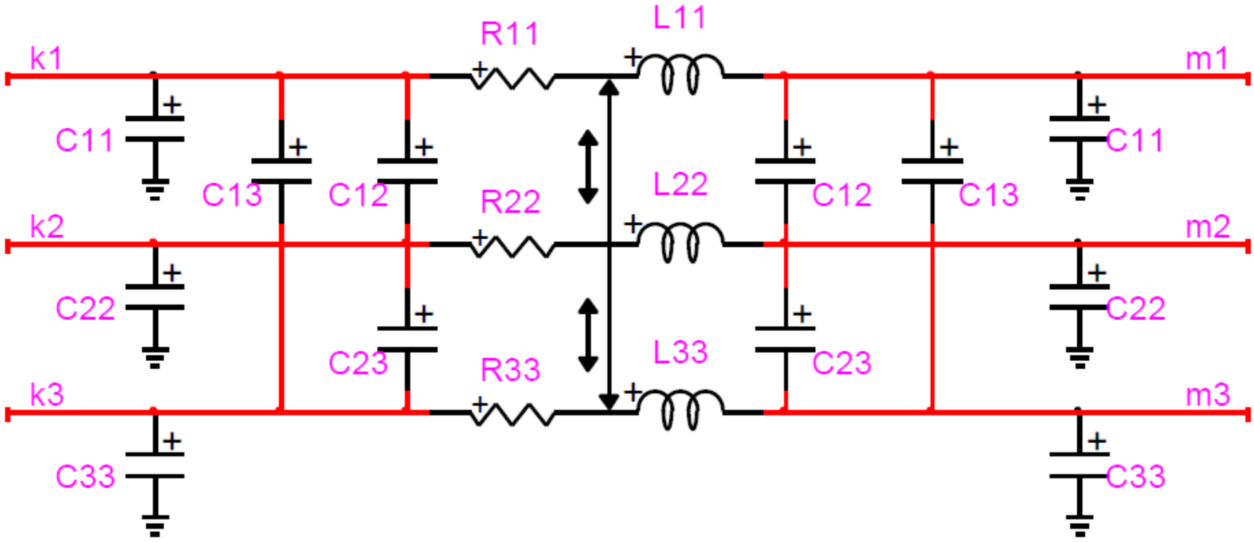


Figure 4-6: Equivalent circuit from the three-phase Nominal-PI model in EMTP (neglecting the shunt conductance G)

The Nominal-PI model can be used with sufficient accuracy for steady-state power frequency phenomena. It is, therefore, employed mostly in studies such as power flow, short circuit, dynamics, etc.

The Exact-PI model, on the other hand, is similar to the Nominal-PI model, with modified lumped R', L' and C' parameters to account for the distributed nature of long cables/lines.

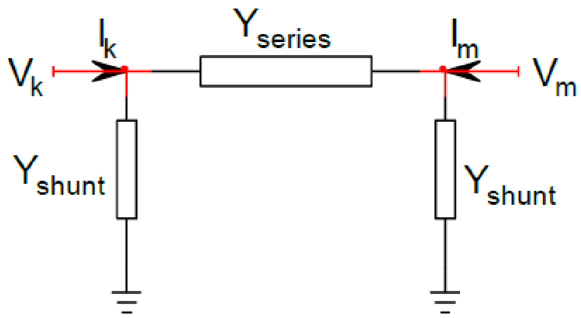


Figure 4-7: Single-phase image of the Exact-PI model in EMTP

For a single-phase cable/line represented using the Exact-PI model, as is shown in Figure 4-7, the relationship between the voltage and current at the sending and receiving ends (k and m, respectively) of the cable/line can be calculated from the following nodal admittance matrix formulation:

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} Y_{series} + Y_{shunt} & -Y_{series} \\ -Y_{series} & Y_{series} + Y_{shunt} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix} \quad (4.1)$$

where V_k, I_k and V_m, I_m denote the sending and receiving end voltages and currents, and the series and shunt admittances are given by:

$$Y_{series} = \frac{1}{Z_c sinh(\gamma l)}$$

$$Y_{shunt} = \frac{1}{Z_c tanh(\gamma l/2)}$$

It is worth mentioning that γ and Z_c are the propagation constant and characteristic impedance, respectively. They can be given by:

$$\gamma = \sqrt{(R' + sL')(G' + sC')} = \underbrace{\alpha \ + j\beta}_{\text{attenuation constant+phase constant}}$$

$$Z_c = \sqrt{\frac{R' + sL'}{G' + sC'}} = \widehat{Z_c} \angle \theta_{Z_c}$$

In EMTP, the Exact-PI model can only be used for steady-state and frequency scan analyses, with the ability of providing accurate simulation results for a specified range of frequencies. Further information on the Exact-PI model can be found in [2.10] – [2.13].

4.4.2.2.3 Distributed parameter models

In reality, an underground cable or an overhead line have a certain length. Their electrical characteristics (R', L' and C') are, therefore, not concentrated and lumped at a certain location of the network but distributed evenly across the entire length of the transmission path. A waveform travelling from one end of a cable/line segment to another could experience amplitude attenuation and phase shift due to such distributed nature of the cable/line electrical characteristics and the limited waveform propagation speed, which needs to be accounted for in detailed transient simulations. Furthermore, transient disturbances in power systems can cause steep voltage wavefronts that contain high frequency components, subsequently leading to overvoltages at bus connections or reflections at open ends. The frequency dependency of cable/line electrical characteristics (i.e., skin effect in the conductors, earth return path, etc.), hence, also need to be accounted for in detailed transient studies. Three types of distributed parameter cable/line models are available in EMTP, as is presented in Table 4-2.

Model name	Characteristics	Applicable basic frequency range
CP (constant parameter)	Shock impedance and propagation speed at a fixed frequency in the modal domain. No frequency dependency. Relatively high computing efficiency.	A fixed frequency at which the shock impedance and propagation speed are evaluated.
FD (frequency dependent)	Frequency dependence in the modal domain. Adoption of certain approximations.	DC to kHz
Wideband	Total frequency dependence in the phase domain. More precise. Heavy calculation load.	DC to kHz

Table 4-2: Distributed parameter cable/line models available in EMTP

Both the CP and FD models are based on the solution of partial differential equations (4.2) and (4.3) (assuming $\Delta x \to 0$) of an infinitesimal lumped-element segment of a single-wire cable/line, as is presented in Figure 4-8.

$$\frac{\partial v(x,t)}{\partial x} = -R' i(x,t) - L' \frac{\partial i(x,t)}{\partial x} \quad (4.2)$$

$$\frac{\partial i(x,t)}{\partial x} = -G' i(x,t) - C' \frac{\partial v(x,t)}{\partial x} \quad (4.3)$$

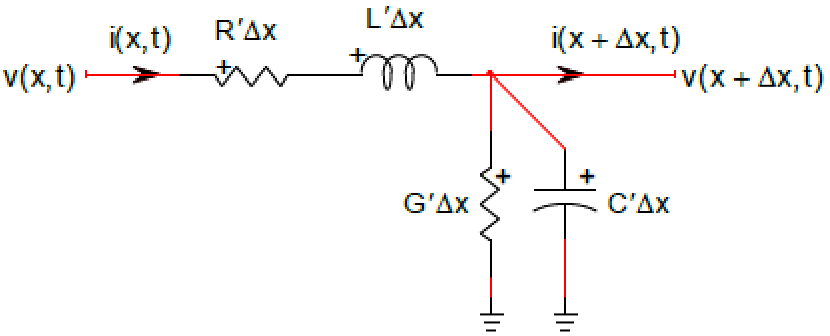


Figure 4-8: Equivalent circuit of an infinitesimal segment of cable/line with a lumped element

Solving equations (4.2) and (4.3) for the entire length l of the cable/line segment (from $x = 0$ to $x = l$), the following two equations can be obtained:

$$I_k = Y_c V_k - H[Y_c V_m + I_m] \quad (4.4)$$

$$I_m = Y_c V_m - H[Y_c V_k + I_k] \quad (4.5)$$

where V_k, I_k and V_m, I_m denote the sending and receiving end voltages and currents, and Y_c, H are given by:

$$Y_c = Z_c^{-1}$$

$$H = e^{-\gamma l}$$

For a multi-conductor system (e.g., three-phase cables/lines), equations (4.2) - (4.5) are in the vector and matrix form.

Subsequently, equations (4.4) and (4.5) shall be further solved in modal domain using a certain modal decomposition technique with transformations and converted back to time-domain for transient studies in EMTP.

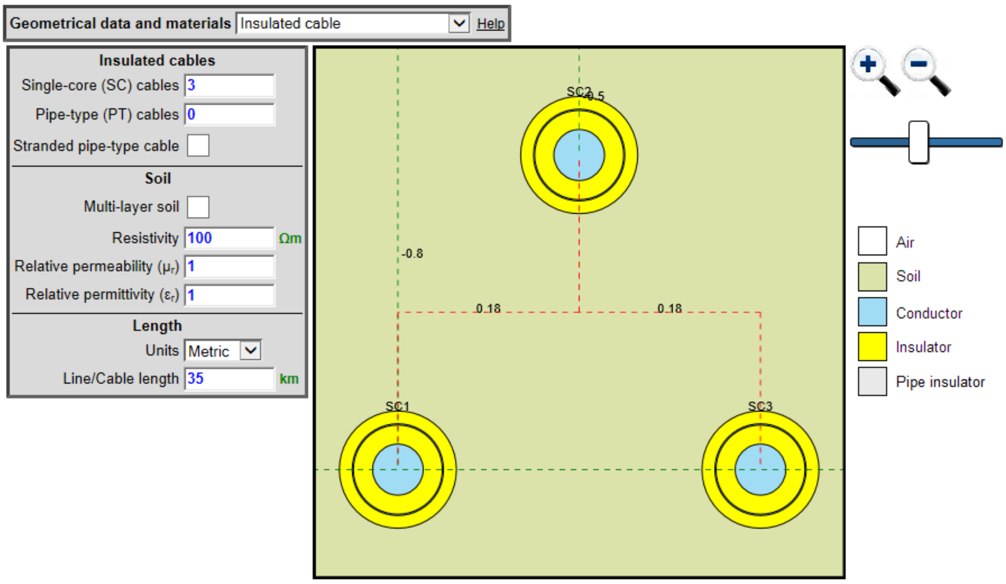
It is noted that for the CP model, Y_c and H are calculated for a single specified frequency whereas they are sampled for a selected frequency range and curve fitted using a Bode-based technique into the equivalent rational functions for the FD model. Detailed information on the CP and FD models can be found in [2.11] and [2.14].

As indicated in Table 4-2, the Wideband model is by far the most accurate model in time-domain simulations with cables and lines for a large band of frequencies. It works in phase domain and accounts for full frequency dependency of cable/line electrical parameters with the least approximations. The theories and algorithms implemented behind the Wideband model in EMTP are, however, quite involved and thus are beyond the scope of this report. Further information on the Wideband model can be found in a number of publications such as [2.15] – [2.20].

Considering the project-specifics, the lumped parameter models are not used to model the cables/lines in the scope of this project due to their limitations as described previously. Among all the distributed parameter models available in EMTP, it is decided that the Wideband model is to be used in modelling all lines/cables in this project since it is by far the most accurate model for time-domain simulations, accounting for full frequency dependency with minimum approximations.

4.4.2.3 Modelling of underground cable segments

In order to derive the cable model data to be used in transient studies, it is necessary to specify their geometrical and material characteristics. Taking the 35 km, 220 kV Froloo – Flumenthal cable in Scenario 3 as an example, the cable geometrical and material data are presented in Figure 4-9. It should be noted that this cable has a cross-section of 1,600 mm^2 based on initial assumptions.



Single-core (SC) cable main data

Cable	Number of conductors	Horizontal position (m)	Ground depth (m)	Radius (cm)
1	2	0	-0.8	5.65
2	2	0.175	-0.49689	5.65
3	2	0.35	-0.8	5.65

Single-core (SC) cable conductors/insulators data

Cable	Conductor	Phase	Inner radius (cm)	Outer radius (cm)	Conductor resistivity (Ohm m)	Conductor relative permeability	Conductor relative permettivity	Insulator relative permittivity	Insulator loss factor
1	1	1	0	2.445	1.76e-8	1	1	2.5318	0.0008
1	2	0	4.295	4.404765	2.84e-8	1	1	2.5	0.001
2	1	2	0	2.445	1.76e-8	1	1	2.5318	0.0008
2	2	0	4.295	4.404765	2.84e-8	1	1	2.5	0.001
3	1	3	0	2.445	1.76e-8	1	1	2.5318	0.0008
3	2	0	4.295	4.404765	2.84e-8	1	1	2.5	0.001

Figure 4-9: Geometric and material data for the 220 kV Froloo – Flumenthal cable in scenario 3 (35 km)

The choice and derivation of certain geometric and material parameters for the cable and the assumptions adopted are highlighted as follows:

4.4.2.3.1 Soil parameters

Not only does earth resistivity play an important role in sheath transient overvoltages, but also it partially contributes to the zero-sequence impedance of the cable system which would impact the system behavior during asymmetric faults. It is decided to use the default value of 100 Ωm proposed by EMTP for the following reasons:

a. earth resistivity is inhomogeneous in nature that varies from one area to another, making it difficult to model cable segments requiring a single fixed earth resistivity value;
b. despite the fact that certain internal documents on this topic are available, accurate on-site measurements are scarce;

c. the default earth resistivity of 100 Ωm provides adequate accuracy in most transient studies, which is sufficient at this stage of the project.

Apart from the earth resistivity, default values proposed by EMTP are also adopted for the soil relative permeability μ_r and permittivity ε_r.

4.4.2.3.2 Single-core (SC) cable main data

In the absence of concrete information regarding cable formation at the current stage of the project, it is assumed that trefoil formation shall be implemented, as is shown in Figure 4-10 [2.21]. Minor differences in the total cable inductance and capacitance due to changes in mutual phase coupling can be expected if another type of formation is implemented on site. However, the current assumptions are pertinent for the purposes of feasibility studies.

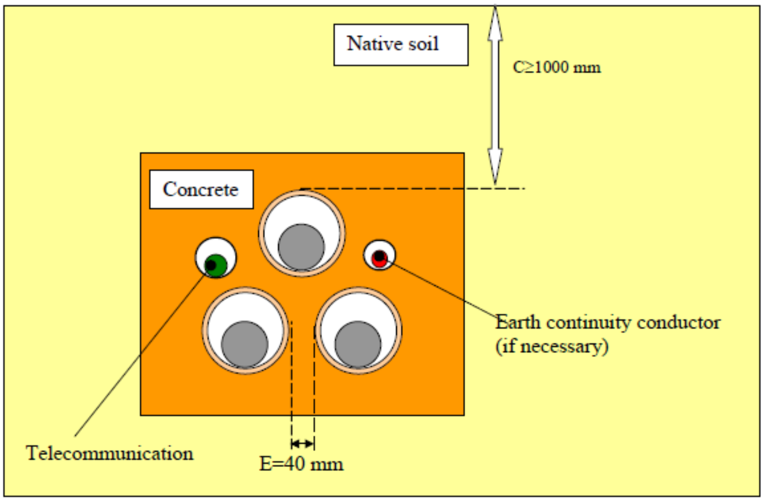


Figure 4-10: Typical diagram of a trefoil cable system [2.21]

The ground depth for underground cable systems is usually under 2 m. A ground depth of over 2 m entails more stringent requirements in civil engineering and thus is quite rare. A ground depth of 0.8 m for phases a and c is taken as an assumption in this project.

4.4.2.3.3 Single-conductor (SC) cable conductors/insulators data

Assuming the Milliken copper conductor core to be solid to simplify parameter derivation, the inner and outer radii of the conductor and metal sheath can be derived from [2.22].

Resistivity of the copper core and the aluminum sheath, as well as the insulator loss factors are obtained from [2.23] [2.24], where field test results of a long cable system of the same type (XLPE) at RTE are presented.

The nominal per-unit length capacitance of such a cable system is 0.25 µF/km according to [2.22]. The relative permittivity of the XLPE insulator can, therefore, be calculated using [2.10].

$$\varepsilon_{r1} = \frac{C\ln(r_2/r_1)}{2\pi\varepsilon_0} \quad (4.6)$$

where:

- C : cable capacitance per unit length (µF/km)
- r_2 : inner radius of the screen
- r_1 : external radius of the conductor
- ε_0 : vacuum permittivity

However, just as for other typical high voltage cables, the copper core in the 220 kV Froloo - Flumenthal cable system is also surrounded by two layers of semiconductor material on the core's outer surface and the sheath's inner surface. The function of these semiconductor layers is to equalize the electric field around the core by reducing electrical stress on the insulation and to prevent electrolytic corrosion of the metallic armor layers. Due to higher resistivity of the semiconductor material, currents tend to flow in the core whereas the charges would pass through the semiconductors. Therefore, the semiconductor layers act as part of the insulation system for the magnetic and current calculations while they act as part of the core for the calculation of cable capacitance. It is, therefore, necessary to modify the relative permittivity of the insulation by treating the semiconductor layers as part of insulation [2.25].

$$\varepsilon_{r1\_mod} = \varepsilon_{r1}\frac{\ln(R_b/R_a)}{\ln(r_b/r_a)} \quad (4.7)$$

where:

- r_b : external radius of the insulation
- r_a : internal radius of the insulation
- R_b : external radius of the second semiconductor layer
- R_a: external radius of the conductor

Therefore, the modified relative permittivity of insulation can be obtained:

$$\varepsilon_{r1\_mod} = 2.5318$$

The outer layers of the cable usually consist of high-density polyethylene materials. They are, however, unknown at the current stage of the project. Considering its much smaller thickness as compared to the insulation layer (thus less impactful on the cable electrical characteristics), a relative permittivity of 2.5 is assumed, as in [2.23].

Apart from the discussions presented previously, several supplementary modelling options also need to be specified in EMTP to improve the overall dynamic performance of the cable model, as is shown in Figure 4-11.

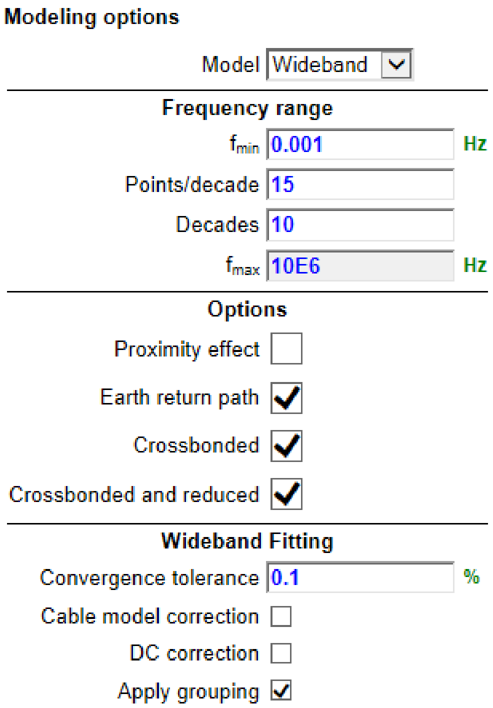


Figure 4-11: Modelling options for Wideband cable models

In Figure 4-11, the option “Earth return path” is important in Wideband models for stability and accurate representation of cable transient behavior (especially the metal sheath) at high frequencies (10 kHz and above). Both options of “Crossbonded” and “Crossbonded and reduced” are chosen to fully account for cross-bonding inside each “major section” and to achieve computational efficiency. Fitting parameters are carefully selected using a trial-and-error approach in “Frequency range” to avoid stability issues caused by passivity violations. Further information on the selection of other modelling options can be found in [2.11].

4.4.2.4 Modelling of overhead line segments

The electrical and physical characteristics of overhead lines in the EMTP Wideband models are derived from conductor and ground wire material and geometrical data as well as geometrical parameters of pylons. Please note that:

- For the existing line segments, all information, including Phasenpläne, is available. Therefore, minimal assumptions are required.
- Major infrastructural upgrade is being planned in certain areas of the network. Therefore, proper assumptions are adopted in modelling these line segments to be implemented in the near future.

For the purpose of demonstration, the derivation of overhead line model parameters in EMTP for the 220 kV 71.1 km double-circuit line Bickigen – Innertkirchen is given in this section as an example. Note that a 15 km cable segment is being planned to replace certain sections of this line, as is included in Scenario 3.

From Phasenplan TR1520, it can be confirmed that the current transmission path Bickigen - Innertkirchen is comprised of a double-circuit overhead line system at 220 kV mounted on the same pylon, with the dominant pylon configuration given in Figure 4-12.

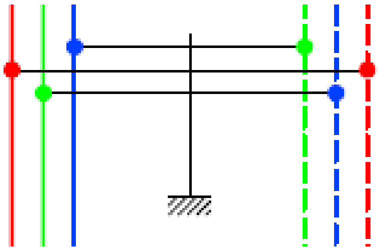


Figure 4-12: Dominant pylon configuration on the Bickigen – Innertkirchen route (both 220 kV lines)

The dimensions of the identified dominant pylon can be obtained from Project A158 Trassendigitalisierung, as shown in Figure 4-13. It is noted that:

- The height of each phase conductor can be identified in the elevation indicator on the right, while the horizontal spacing of each phase conductor is shown directly in the figure (in metres);
- W1 – W6 represent the single-wire phase conductors, and W7 represents the single-wire earth conductor.

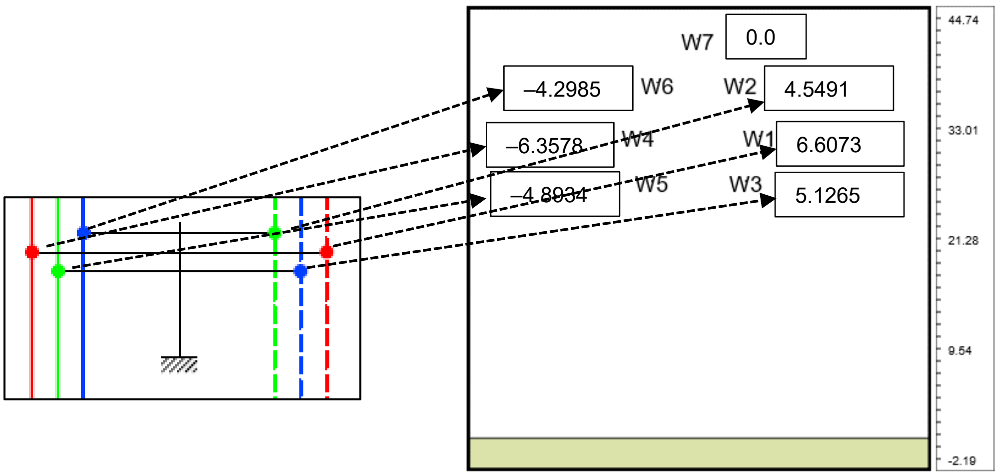


Figure 4-13: 220 kV pylon on the Bickigen – Innertkirchen route

In addition to the geometry data for the pylon, EMTP also requests the following information for the conductors and earth wires:

- type of conductors (single wire or bundled)
- number of conductors per phase if they are bundled
- reference angle of bundling
- bundling radius
- conductor radius
- DC resistance of the conductor

4.4.2.4.1 Phase conductors

The material and geometric data for the 220 kV Bickigen – Innertkirchen line can be found in Table 4-3.

Length (km)	Bundled conductors	Cross-section (mm²)	Type
40.3	1	600	Aldrey
30.8	1	486/+64	ACSR

Table 4-3: Material and geometric data for the 220 kV Bickigen – Innertkirchen line

According to Table 4-3, a 40.3 km section of this connection consists of a single-wire conductor made of Aldrey (AAAC, All Aluminum – Alloy Conductors) for each phase with a cross-section of 600 mm² whereas each phase of the remaining 30.8 km section is comprised of a ACSR (Aluminum Conductors, Steel-Reinforced) single-wire conductor with a cross-section of 486 (aluminum)+64 (steel) mm².

A catalogue of Aldrey and ACSR conductors with similar cross-sections, following IEC 61089 and DIN 48204 Standards, respectively, can be found from a particular manufacturer [2.26]. An excerpt is given in Figure 4-14. The corresponding values are taken as assumptions in this project.

Code Number	Nominal cross sectional area	Conductor construction	Approx. overall diameter	Approx. overall weight	Max. DC Resistance at 20 °C	Rated strength	AES Code
	mm²	No. x Ø (mm)	mm	Kg / km	Ω / km	KN	
500	575.0	37 x 4.45	31.20	1585.5	0.05770	169.76	L02B800370IMX

(a)

Nominal cross sectional area	Nominal cross sectional area		Conductor construction		Approx. overall diameter	Approx. overall weight	Calculated DC Resistance at 20 °C	Ampacity (*)	Rated strength	AES Code
	Al	St	Al	St						
	mm²		No. x Ø (mm)		mm	Kg / km	Ω / km	A	KN	
450 / 40	448.71	39.49	48 x 3.45	7 x 2.68	28.7	1553	0.06440	920	120.19	S02I400550DMX
490 / 65	490.29	63.55	54 x 3.40	7 x 3.40	30.6	1860	0.05900	960	152.85	S02I500610DMX
495 / 35	494.36	34.09	45 x 3.74	7 x 2.49	29.9	1636	0.05840	985	120.31	S02I600520DMX

(b)

Figure 4-14: Excerpt from the Aldrey and ACSR conductor catalogue for 220 kV Bickigen – Innertkirchen (Alfanar [2.26])

The radius of the conductor and the DC resistance can then be obtained:

For the 40.3 km section:

$$r_{c_{220}} = 1.560\ \text{cm}$$

$$R_{DC\_220} = 0.0577\ \Omega/\text{km}$$

For the 30.8 km section:

$$r_{c_{220}} = 1.530 \text{ cm}$$

$$R_{DC\_220} = 0.0590\ \Omega/\text{km}$$

4.4.2.4.2 Ground wire conductors

Information on the materials and geometric data for the ground wire for the 220 kV Bickigen – Innertkirchen connections is given in Table 4-4.

Length (km)	Cross-section (mm²)	Type
71.1	70	ST

Table 4-4: Material and geometric data for the earth wire in the 220 kV Bickigen – Innertkirchen connections

It is easily understood that the two overhead lines mounted on the same pylon share the same ground wire, which is predominantly 70 mm² St. Due to the absence of conductor catalogue, information regarding the DC resistance and conductor radius of the 70 mm² steel ground wire is assumed to be the same as that of a 74.05 mm² steel ground wire from Hind Aluminium Industries Limited , where a snippet is given in Figure 4-15 (in accordance with ASTM B 416).

No and size of wires	Area	Diameter	Stranding and wire diameter		Nominal breakingload	MaximumDCr esistanceat2 0ºC	Standard Weight
	mm²	mm	Nº	Ø(mm)	daN	Ohm/km	kg/km
7No.7AWG	74.05	11.01	7	3.67	8,530	1.1566	492.9

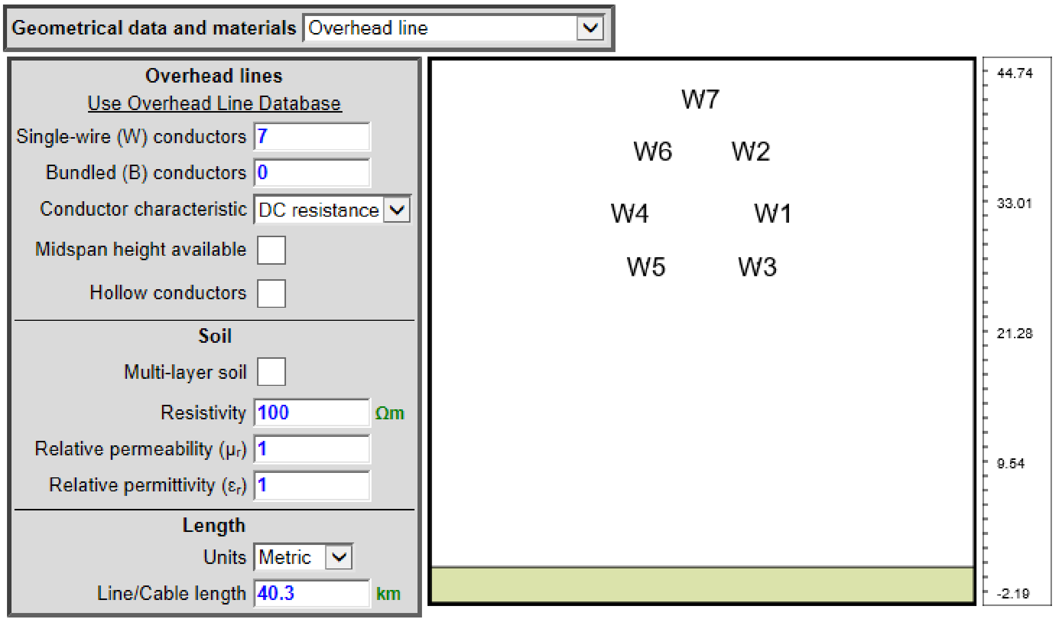
Figure 4-15: Excerpt from the catalogue of conductors for the earth wire on the 220 kV Bickigen – Innertkirchen line (Hind Aluminium Industries Limited)

Therefore:

$$r_{c\_g} = 0.5505 \text{ cm}$$

$$R_{DC_g} = 1.1566\ \Omega/\text{km}$$

Based on the discussions presented above, the geometrical and material data for the 220 kV Bickigen - Innertkirchen overhead lines in the EMTP model can be derived and is presented in Figure 4-16.



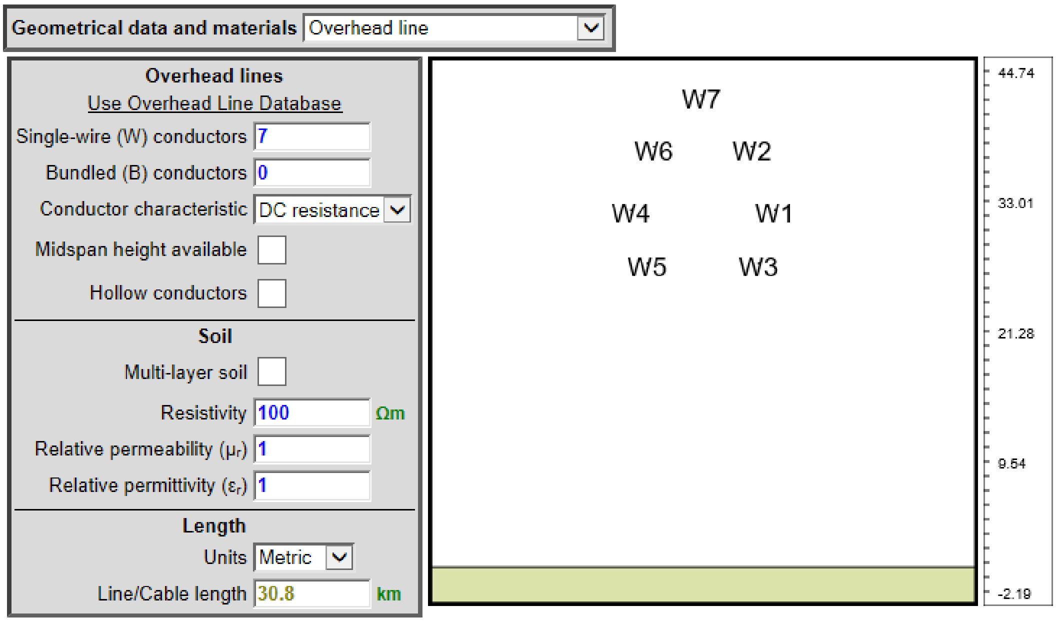
Drawing options

List of tables

Overhead line, Single-wire (W) conductors

Conductor	Phase	Horizontal position (m)	Height (m)	Radius (cm)	DC resistance (Ohm/km)	Conductor relative permeability (μ_r)	Conductor relative permittivity (ε_r)
1	1	6.6073	32.1960	1.56	0.0577	1	1
2	2	4.5491	37.9160	1.56	0.0577	1	1
3	3	5.1265	27.4060	1.56	0.0577	1	1
4	4	-6.3578	32.1960	1.56	0.0577	1	1
5	5	-4.8934	27.4060	1.56	0.0577	1	1
6	6	-4.2985	37.9160	1.56	0.0577	1	1
7	0	0	42.5460	0.5505	1.1566	1	1

(a)



Drawing options

List of tables

Overhead line, Single-wire (W) conductors

Conductor	Phase	Horizontal position (m)	Height (m)	Radius (cm)	DC resistance (Ohm/km)	Conductor relative permeability (μ_r)	Conductor relative permittivity (ε_r)
1	1	6.6073	32.1960	1.53	0.059	1	1
2	2	4.5491	37.9160	1.53	0.059	1	1
3	3	5.1265	27.4060	1.53	0.059	1	1
4	4	-6.3578	32.1960	1.53	0.059	1	1
5	5	-4.8934	27.4060	1.53	0.059	1	1
6	6	-4.2985	37.9160	1.53	0.059	1	1
7	0	0	42.5460	0.5505	1.1566	1	1

(b)

Figure 4-16: Geometric and material data for the 220 kV Bickigen – Innertkirchen lines, a): the 40.3 km section, b): the 30.8 km section

The modelling options for Wideband line models are presented in Figure 4-17.

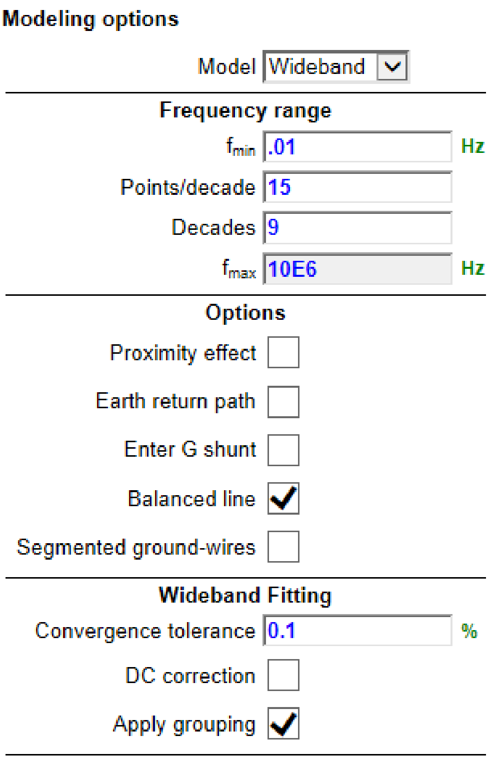


Figure 4-17: Modelling options for Wideband line models

Further information on selecting other modelling options can be found in [2.11].

4.4.2.5 Modelling of Thévenin equivalent network

The network behind each busbar considered as an end point of the studied network has been modelled as a Thevenin equivalent, which is, an ideal voltage source connected to an equivalent Thevenin impedance. The Thevenin impedance is determined by the short-circuit level (SCL), the X/R and the Z_0/Z_1 ratios of the network behind the busbar in question. This approach is valid and is a common practice in transient studies, provided that the required information is available.

Thevenin equivalent parameters at all substations can be derived from the short-circuit contributions provided per line/cable or generation group. It is noted that the short-circuit contributions of lines/cables that are to be included in the EMTP model shall be excluded from the calculation of Thevenin equivalent parameters. The following formula is used to compute the short-circuit contributions of lines/cables and generation groups at each PCC (Point of Common Coupling, a substation connected to generation groups or external systems the modelled network):

$$\mathrm{Icc}(3\mathrm{ph}-\mathrm{fault}) = \mathrm{abs}\left(\sum \mathrm{Icc} * e^{i\theta}\right) \quad (4.8)$$

Assuming a balanced grid ($Z_{aa} = Z_{bb} = Z_{cc}, Z_{ab} = Z_{bc} = Z_{ca}$), the positive, negative and zero sequence impedances at each PCC can be calculated as follows:

$$Z_1 = Z_2 = \frac{U_1}{I_{sc_{3ph}} * \sqrt{3}} \quad (4.9)$$

$$Z_0 = \frac{3 * U_1}{I_{sc_{1ph}} * \sqrt{3}} - Z_1 - Z_2 \quad (4.10)$$

In (4.9) and (4.10), $I_{sc_{3ph}}$ and $I_{sc_{1ph}}$ refer to the three-phase and single-phase fault currents at the PCC being studied. This makes it possible to derive the series resistance and reactance for all the sequences on each busbar.

This classical R-L approach assumes that the Thevenin impedance is comprised of a resistance in series with an inductance, which is only valid for low-frequency applications (i.e., steady-state). As the frequency increases, the Thevenin impedance ($R + j\omega L$) in this approach would almost monotonously increase, thus exhibiting an inductive behavior. However, due to skin effect, a more resistive behavior of the Thevenin equivalent is expected as frequency increases, which renders the classical R-L approach incorrect for high-frequency applications. Another approach, namely the “R-L//R approach”, with an additional resistance in parallel to the inductance, offers an adequate solution to this issue. The Thevenin equivalent representation of the R-L//R approach is given in Figure 4-18 [2.27].

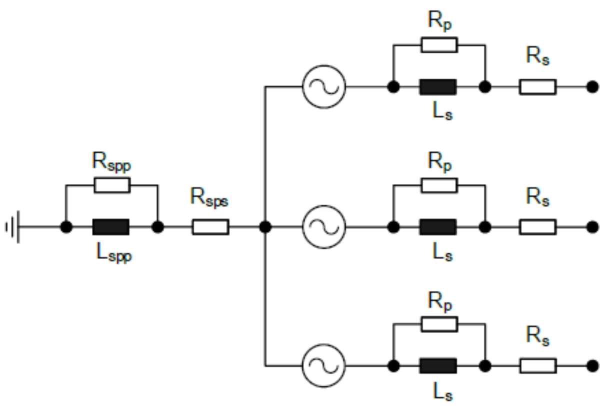


Figure 4-18: Thévenin equivalent according to the R-L//R approach [2.27]

Furthermore, this approach allows for an additional degree of freedom such as to specify the network damping at a frequency other than the fundamental frequency (usually the 3rd harmonic by default if no further information is available). It also includes a star-point impedance that accounts for system performance during unbalanced faults. This star-point impedance comes with a damping, as is shown in Figure 4-18, to obtain realistic results.

The following expressions can be used to compute the Thevenin equivalent using the R-L//R approach, assuming that the X/R ratio is identical for the nominal frequency and the nth harmonic (usually the 3rd harmonic by default). The methodology followed to determine the values of the resistances and the inductances is based on CIGRE brochure B4-832 [2.27].

Input parameters:

- $\mathbf{U_{nom}}$: line-to-line RMS voltage (kV)
- $\boldsymbol{\theta}$: initial angle (degrees)
- $\mathbf{f}$: frequency (Hz)
- $\mathbf{X/R}$: X/R ratio
- $\mathbf{I_{SC3ph}}$: three-phase short-circuit current (kA)
- $\mathbf{I_{SC1ph}}$: single-phase short-circuit current (kA)
- $\mathbf{n}$: tuned for the nth harmonic (generally the 3rd harmonic by default)

Calculations:

$$\omega = 2\pi f$$

$$\varphi = \mathrm{atan}(X/R)$$

$$Z_1 = Z_2 = \frac{U_1}{\sqrt{3} \cdot I_{SC3ph}}$$

$$Z_0 = \frac{3U_1}{\sqrt{3} \cdot I_{sc_{1ph}}} - 2 \cdot Z_1$$

$$A = Z_1 \cdot \sin(\varphi)$$

$$E = \sqrt{A} \cdot n \cdot (n - 1)$$

$$F = A \cdot \tan(\varphi) \cdot (1 - n^2)$$

$$G = A^{\frac{3}{2}} \cdot (n - 1)$$

$$B_1 = \frac{-F + \sqrt{F^2 - 4EG}}{2E}$$

$$B_2 = \frac{-F - \sqrt{F^2 - 4EG}}{2E}$$

$$B_1 > 0 \ \wedge \ B_2 < 0 \ \Rightarrow B = B_1$$

If not, $B = B_2$

$$L_p = \frac{B^2 + A}{\omega}$$

$$R_p = \frac{L_p \cdot \omega \cdot \sqrt{A}}{\sqrt{L_p \cdot \omega - A}}$$

$$R_S = \frac{\frac{\omega \cdot L_p \cdot n}{R_p \cdot \tan(\varphi)} - \left(\frac{\omega \cdot L_p \cdot n}{R_p}\right)^2}{1 + \left(\frac{\omega \cdot L_p \cdot n}{R_p}\right)^2} \cdot R_p$$

$$k = \frac{1}{3}\left(\frac{Z_0}{Z_1} - 1\right)$$

$$L_{spp} = L_p \cdot k$$

$$R_{spp} = R_p \cdot k$$

$$R_{sps} = R_s \cdot k$$

The R-R//L approach requires both single-phase and three-phase short-circuit contributions from each line/cable departure at a substation to accurately define the positive-, negative- and zero-sequence impedance characteristics at each considered busbar in the modelled network.

4.4.2.6 Modelling of transformers

Accurate representation of power transformers in the network is crucial in transient studies. Due to the non-linear nature of their magnetic core, transformers can cause severe overvoltages in the network as a result of their interaction with other capacitive elements. A large number of transformers coupling the 220 kV and 380 kV grids exist in the network, which need to be accurately modelled in this work. Note that step-up transformers connecting generation groups and mid- to low-voltage level grids are not modelled.

The transformers have been modelled based on their test reports, including nameplate data, rated power and voltages, regulation, short-circuit impedance and no-load losses, etc. Proper assumptions have been adopted due to the insufficiency in certain manufacturer no-load test results. The modelling procedure for all transformers is explained in this section, using the one at Mettlen as an example.

The 600 MVA transformer currently hosted at Mettlen shall be replaced by two 800 MVA transformers, with the nameplate data summarized in Table 4-5.

Rated power (MVA)	267/267/51.9
Rated voltage (kV)	$420/\sqrt{3}/247\sqrt{3}/27.05$
Three-phase transformer winding configurations	YNa0d11

Table 4-5: Rated values for a single-phase transformer in Mettlen

The EMTP model of one Mettlen transformer, together with the circuit components inside each phase, are presented in Figure 4-19, in which the magnetizing branches are modelled as nonlinear inductances and the tertiary windings remain open circuit (grounded via a large resistance).

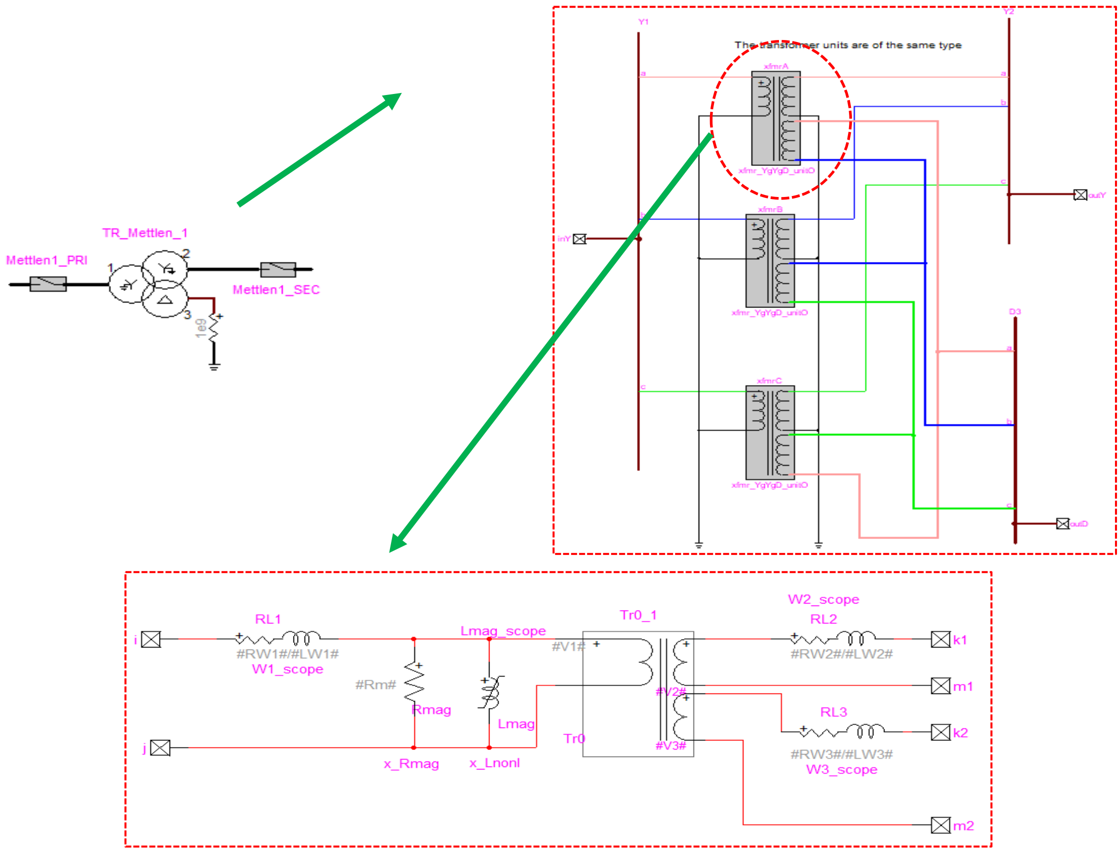


Figure 4-19: EMTP model of a Mettlen transformer and the circuit components in each phase

The copper loss (winding resistance) and leakage flux loss (winding reactance) of each branch, denoted by RL_1, RL_2 and RL_3, are calculated based on results of short-circuit tests while the core losses, including mainly Eddy current loss (denoted by R_m) since hysteresis is not represented, are calculated using results of no-load tests.

4.4.2.6.1 Calculation of winding resistance and leakage reactance

The calculation of winding resistance and leakage reactance of the primary and secondary windings is based on the measurements extracted from a short-circuit test where voltage is applied on the primary winding with the secondary winding short-circuited and the tap changer on secondary winding at its mid-point, using:

$$R_{12} = \frac{P_{sc}}{I_N^2} \quad (4.11)$$

$$Z_{12} = \frac{V_{sc}}{I_N} \quad (4.12)$$

$$X_{12} = \sqrt{Z_{12}^2 - R_{12}^2} \quad (4.13)$$

where:

- R_{12}: total resistance on both windings
- X_{12}: total leakage reactance on both windings
- I_N: nominal current on the primary winding
- P_{sc}: measured active power converted into 75°
- V_{sc}: primary winding voltage applied to the nominal current

Assuming an even split of winding resistance and leakage reactance in pu for both windings, the copper and leakage flux losses for both windings can, therefore, be derived, as is shown in Figure 4-19.

The same methodology can be applied on another short-circuit test where the voltage is applied on the primary winding with the tertiary winding short-circuited to derive the total resistance and leakage reactance on both windings. Since the resistance and leakage reactance of the primary winding have been calculated at the previous step, it suffices to subtract them from the total values to obtain those on tertiary winding, as is presented in Figure 4-19.

4.4.2.6.2 Calculation of core losses and losses of magnetisation inductance

The calculation of the core loss and magnetization inductance can be achieved using measurements extracted from a no-load test where voltage is applied on the tertiary winding with the primary and seconding windings open circuited. The expressions that can be used to obtain these parameters are the following:

$$R_m = \frac{V_{OC}^2}{P_{OC}} \quad (4.14)$$

$$Z_m = |\underline{Z}_m| = \frac{V_{OC}}{I_{OC}} \quad (4.15)$$

$$X_m = \frac{1}{\sqrt{\frac{1}{Z_m^2} - \frac{1}{R_m^2}}} \quad (4.16)$$

where:

- R_m: core loss (resistance on the magnetising arm)
- V_{OC}: rated voltage applied during the no-load test
- I_{OC}: measured no-load current
- P_{OC}: no-load losses
- X_m: magnetisation inductance

The resistance representing the core loss R_m can be easily obtained using the no-load test results from the manufacturer. It is usually an extremely large resistance (i.e., a few hundred to a few thousand pu) thus has little to no impact on transformer transient dynamic behavior. The magnetizing inductance, however, is a nonlinear component dictating the transformer dynamic behavior over the entire operational voltage range. Typical $\phi - I$ characteristics used in EMTP are presented in Figure 4-20.

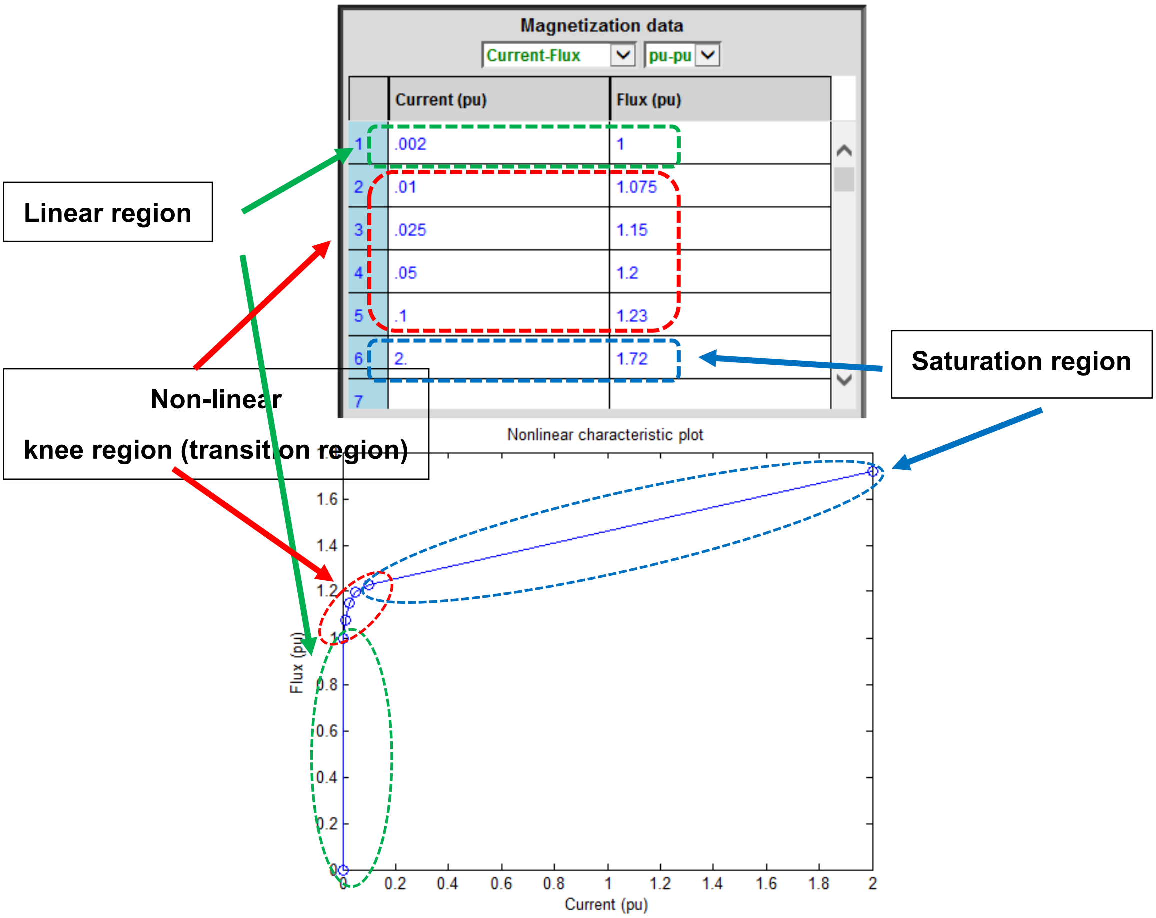


Figure 4-20: Typical ϕ-I characteristics and layout of a non-ideal transformer in EMTP

It should be noted that the characteristics $\phi - I$ shown in Figure 4-20 correspond to the three zones of the transformer iron core characteristics $\phi - I$ of the transformer:

- **Linear region (normal operation)**

In the linear region (flux linkage equal to or less than 1 p.u.), the flux is relatively low, and a large increase in flux would only lead to a small increase in the magnetising current.

- **Non-linear knee region**

The non-linear knee region is an area where a transformer goes from normal operation to saturation, and vice versa. Its correct definition is of vital importance in the study of the transient dynamic behaviour of a transformer.

- **Saturation region**

When the flux exceeds a certain threshold caused by a higher-than-normal applied voltage or residual flux from previous de-energisation, the transformer enters the saturation region, where a small increase in the flux linkage would result in a significant increase in the magnetising current.

According to the characteristics of the transformer $\phi - I$ defined in Figure 4-20, its magnetizing inductance is considered nonlinear as the magnetizing current is not proportional to the flux linkage across different zones of operation. In EMTP, a “piece-wise linear” approach is usually adopted to model a nonlinear component, with its nonlinear characteristics divided into several linear segments. Iterations in time-domain simulations are executed to find the correct operating point during each numerical simulation time-step.

Although ideally, the magnetization curve of a transformer should be derived using manufacturer no-load tests, the applied voltage, usually in the range between 0.9 p.u. and 1.1 p.u., is too narrow to fully represent the entire transformer transient dynamic behavior across the three zones of operation, as was discussed previously. Therefore, it is decided to adopt the default $\phi - I$ characteristics in EMTP in all transformers modelled in the network. It is noted that the magnetizing current in pu is calculated with respect to the nominal current on the tertiary winding, and the flux linkage can be obtained using:

$$\phi = \frac{V_{peak,ph}}{2\pi f} = \sqrt{\frac{2}{3}}\frac{V_{LL}}{2\pi f} \quad (4.17)$$

4.4.3 Frequency scans for scenario 3

4.4.3.1 220 kV Romanel

The following cases were taken into account in the frequency scan studies for 220 kV Romanel:

Case	Description
1	Condition N
2	N-1 on 220 kV Banlieue Ouest – Romanel
3	N-1 on 220 kV Romanel – Vaux
4	N-2 on 220 kV Banlieue Ouest – Romanel and Romanel – Vaux

The impedance amplitude with respect to frequency observed at 220 kV Romanel for the 4 cases in scenario 3 is shown in Figure 4-21.

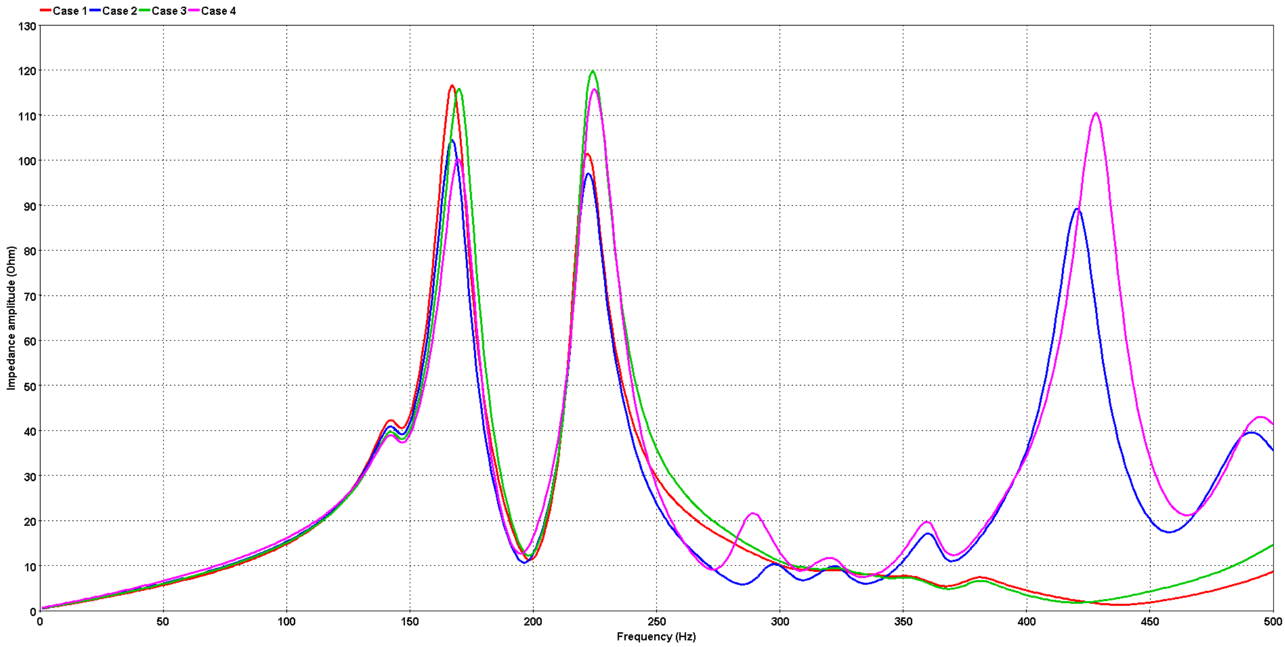


Figure 4-21: Harmonic impedance at 220 kV Romanel for the 4 cases – low SCL, scenario 3

4.4.3.2 380 kV Châtelard

The following cases were taken into account in the frequency scan studies for 380 kV Châtelard:

Case	Description
1	Condition N
2	N-1 on 380 kV Châtelard – La Bâtiaz
3	N-1 on 380 kV Chamoson – La Bâtiaz
4	N-1 on 380 kV Bois Tollot – Romanel
5	N-2 on 380 kV Châtelard – La Bâtiaz and 380 kV Chamoson – La Bâtiaz

The impedance amplitude with respect to frequency observed at 380 kV Châtelard for the 5 cases in scenario 3 is shown in Figure 4-22.

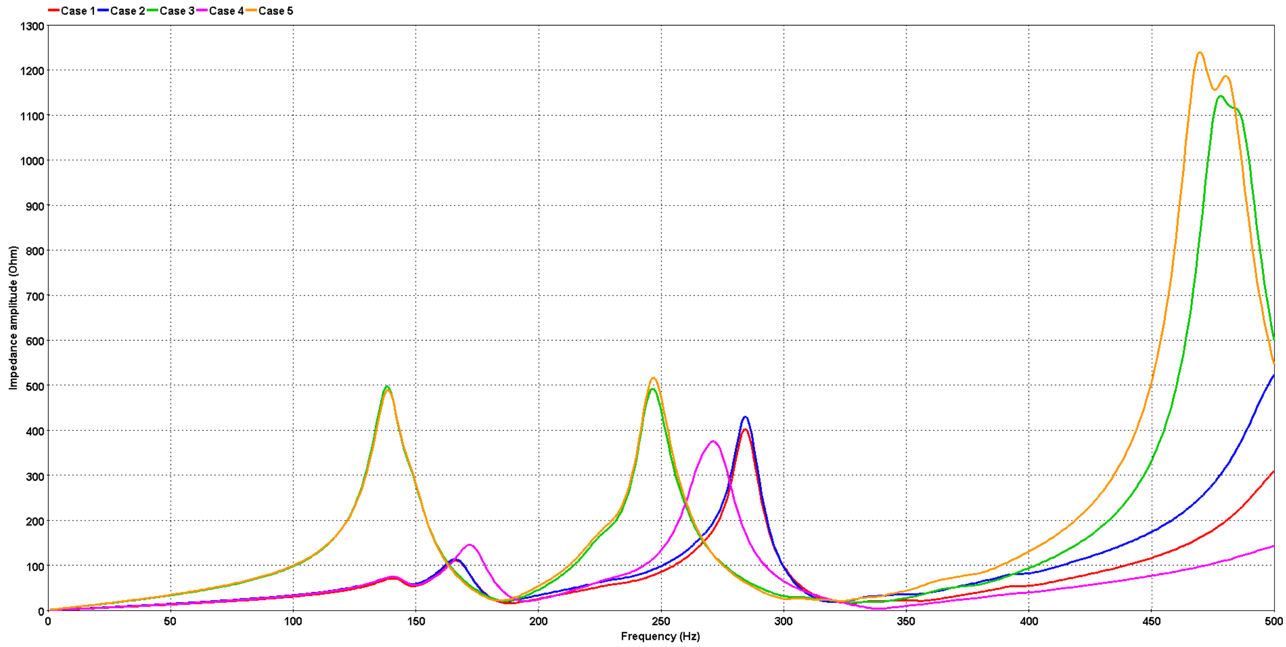


Figure 4-22: Harmonic impedance at 380 kV Châtelard for the 5 cases – low SCL, scenario 3

4.4.3.3 220 kV Chamoson

The following cases were taken into account in the frequency scan studies for 220 kV Chamoson:

Case	Description
1	Condition N
2	N-1 on 220 kV Chamoson – Fionnay GD
3	N-1 on 220 kV Chamoson – Riddes
4	N-2 on 220 kV Chamoson – Fionnay GD

The impedance amplitude with respect to frequency observed at 220 kV Chamoson for the 4 cases in scenario 3 is shown in Figure 4-23.

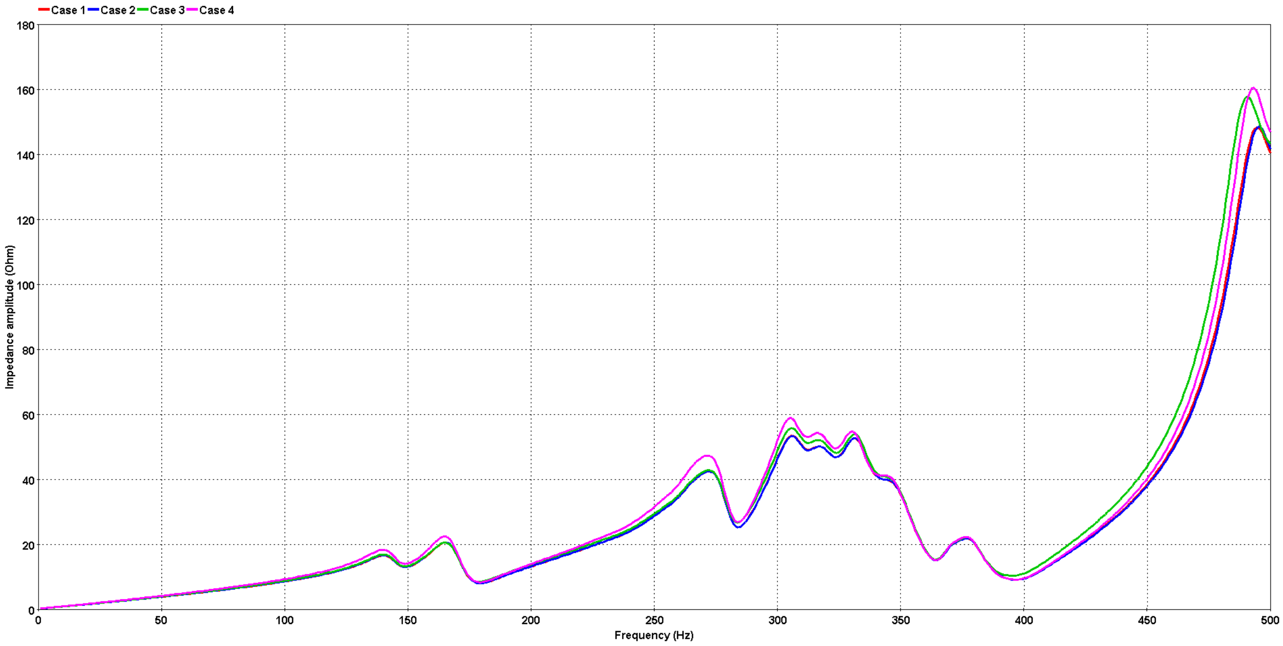


Figure 4-23: Harmonic impedance at 220 kV Chamoson for the 4 cases – low SCL, scenario 3

4.4.3.4 220 kV Mühleberg

The following cases were taken into account in the frequency scan studies for 220 kV Mühleberg:

Case	Description
1	Condition N
2	N-1 on 220 kV Bickigen – Mühleberg
3	N-1 on 220 kV Lindenholz – Mühleberg
4	N-2 on 220 kV Bickigen – Mühleberg and Lindenholz – Mühleberg

The impedance amplitude with respect to frequency observed at 220 kV Mühleberg for the 4 cases in scenario 3 is shown in Figure 4-24.

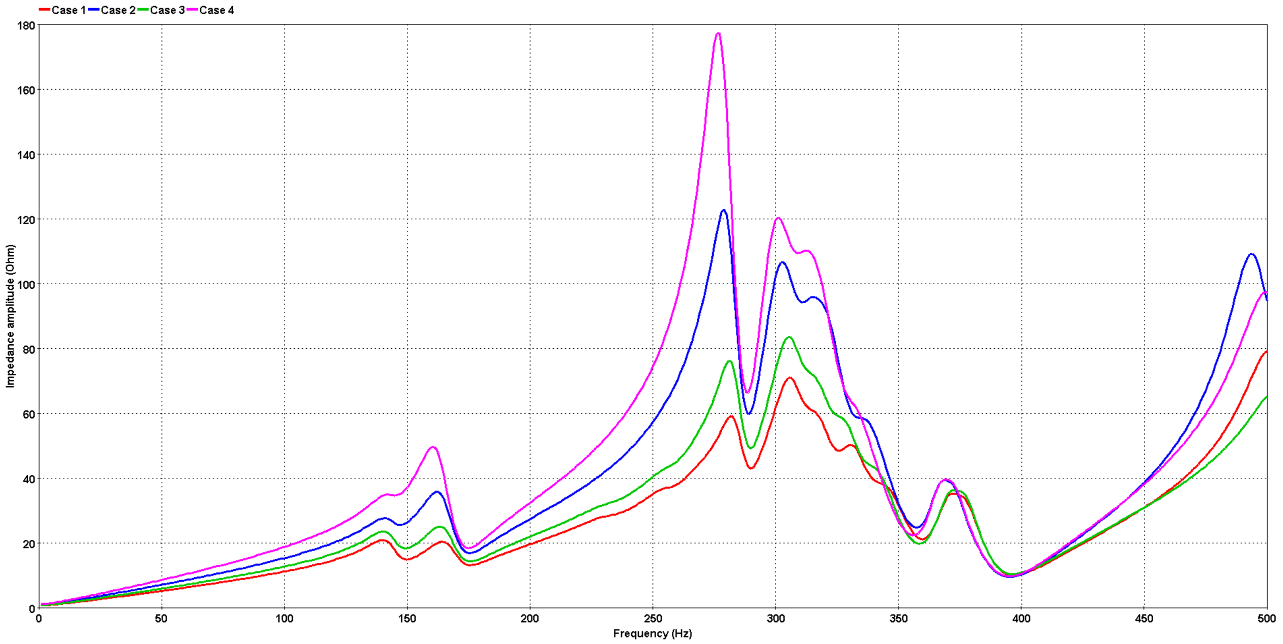


Figure 4-24: Harmonic impedance at 220 kV Mühleberg for the 4 cases – low SCL, scenario 3

4.4.3.5 220 kV Flumenthal

The following cases were taken into account in the frequency scan studies for 220 kV Flumenthal:

Case	Description
1	Condition N
2	N-1 on 220 kV Flumenthal – Bickigen
3	N-1 on 220 kV Flumenthal – Gösgen
4	N-2 on 220 kV Flumenthal – Bickigen and Flumenthal – Gösgen

The impedance amplitude with respect to frequency observed at 220 kV Flumenthal for the 4 cases in scenario 3 is shown in Figure 4-25.

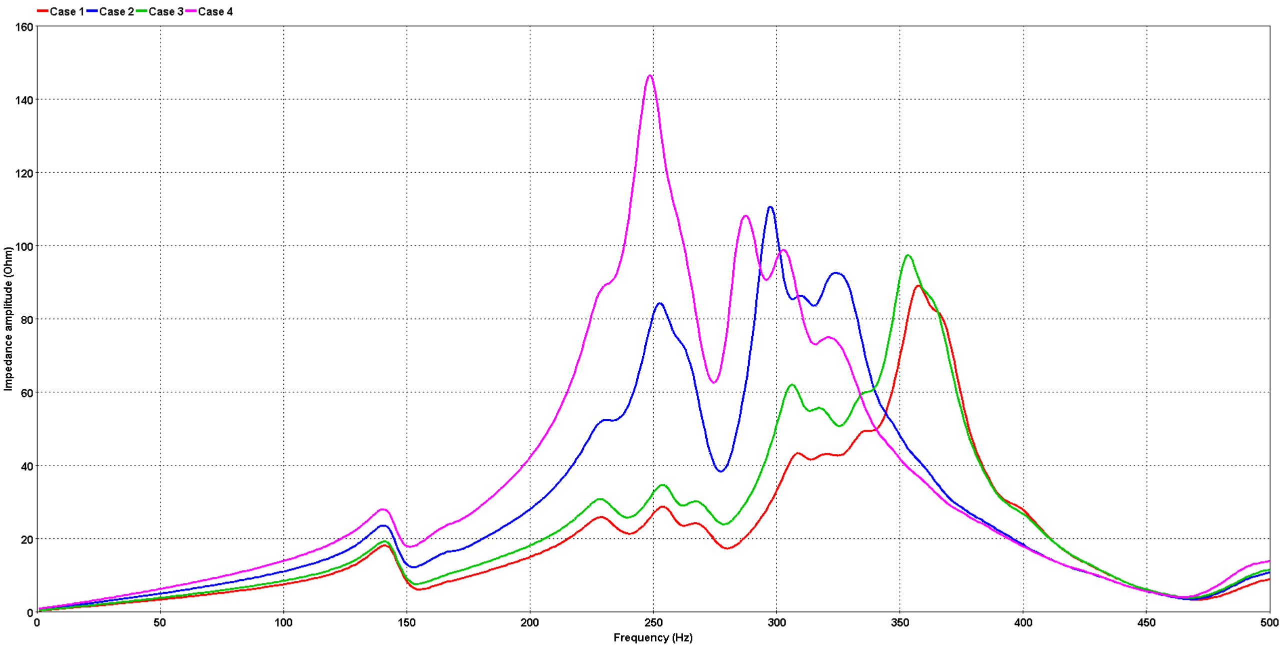


Figure 4-25: Harmonic impedance at 220 kV Flumenthal for the 4 cases – low SCL, scenario 3

4.4.3.6 220 kV Froloo

The following cases were taken into account in the frequency scan studies for 220 kV Froloo:

Case	Description
1	Condition N
2	N-1 on 220 kV Froloo – Lachmatt
3	N-1 on 220 kV Froloo – Flumenthal
4	N-1 on 220 kV Lachmatt – Münchwilen
5	N-2 on 220 kV Froloo – Lachmatt and Lachmatt – Münchwilen

The impedance amplitude with respect to frequency observed at 220 kV Froloo for the 5 cases in scenario 3 is shown in Figure 4-26.

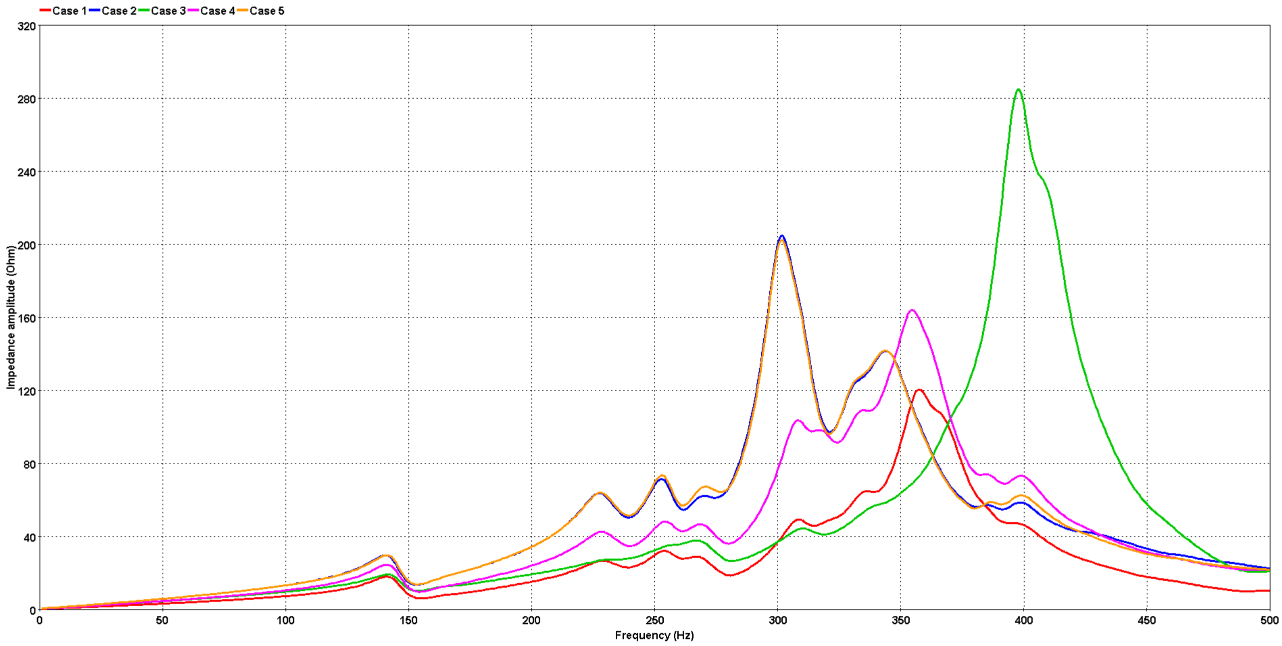


Figure 4-26: Harmonic impedance at 220 kV Froloo for the 5 cases – low SCL, scenario 3

4.4.3.7 220 kV Lachmatt

The following cases were taken into account in the frequency scan studies for 220 kV Lachmatt:

Case	Description
1	Condition N
2	N-1 on 220 kV Lachmatt – Münchwilen
3	N-1 on 220 kV Lachmatt – Froloo

The impedance amplitude with respect to frequency observed at 220 kV Lachmatt for the 3 cases in scenario 3 is shown in Figure 4-27.

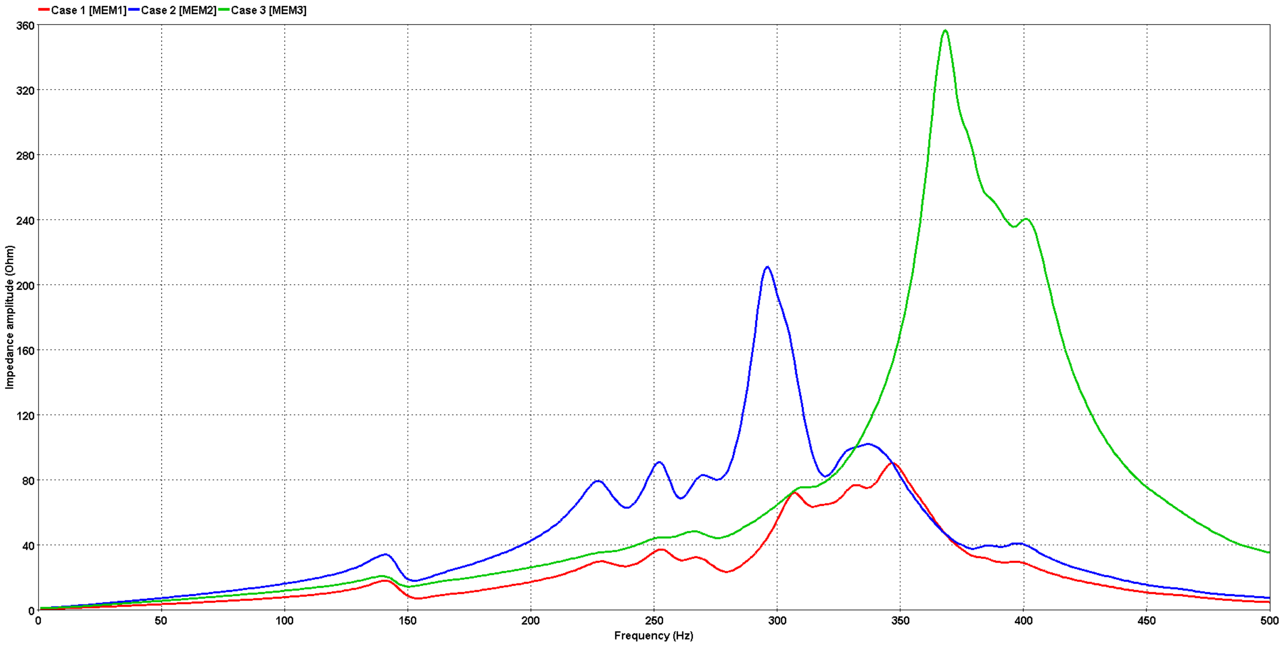


Figure 4-27: Harmonic impedance at 220 kV Lachmatt for the 3 cases – low SCL, scenario 3

4.4.3.8 380 kV Lachmatt

The following cases were taken into account in the frequency scan studies for 380 kV Lachmatt:

Case	Description
1	Condition N
2	N-1 on 380 kV Lachmatt – Gösgen
3	N-1 on 380 kV Asphard – Sierentz
4	N-1 on 380 kV Asphard – Kühmoos
5	N-2 on 380 kV Lachmatt – Gösgen and Asphard – Sierentz

The impedance amplitude with respect to frequency observed at 380 kV Lachmatt for the 5 cases in scenario 3 is shown in Figure 4-28.

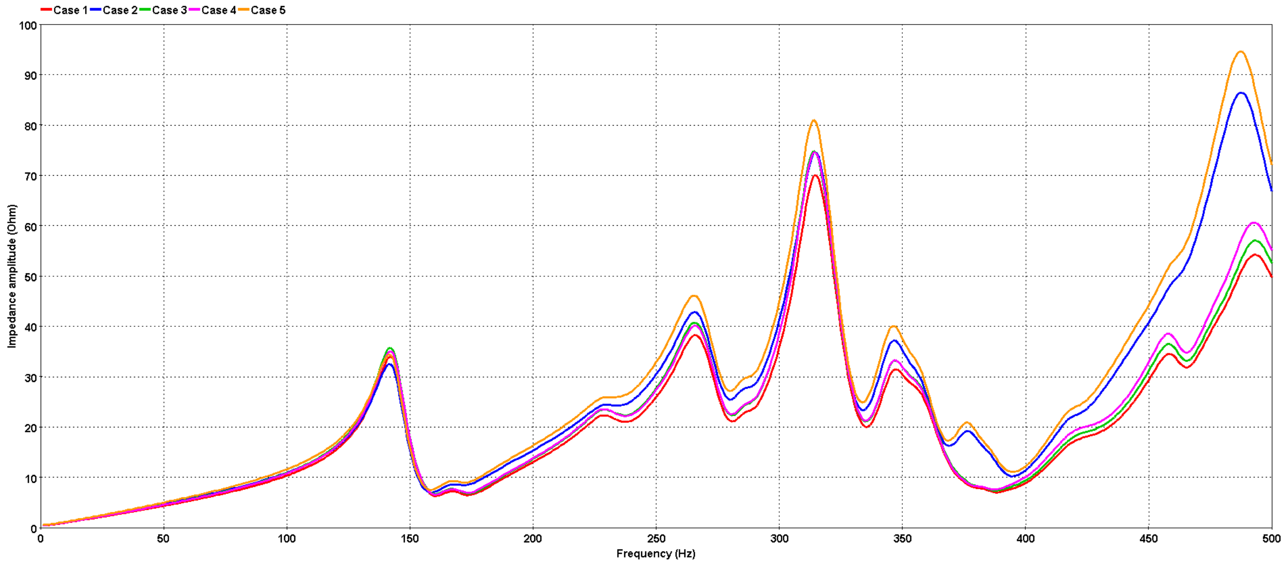


Figure 4-28: Harmonic impedance at 380 kV Lachmatt for the 5 cases – low SCL, scenario 3

4.4.3.9 220 kV Laufenburg

The following cases were taken into account in the frequency scan studies for 220 kV Laufenburg:

Case	Description
1	Condition N
2	N-1 on 220 kV Laufenburg – Gösgen
3	N-2 on 220 kV Laufenburg – Kühmoos
4	N-2 on 220 kV Laufenburg – Gurtweil
5	N-2 on 220 kV Laufenburg – Münchwilen and Laufenburg – Beznau

The impedance amplitude with respect to frequency observed at 220 kV Laufenburg for the 5 cases in scenario 3 is shown in Figure 4-29.

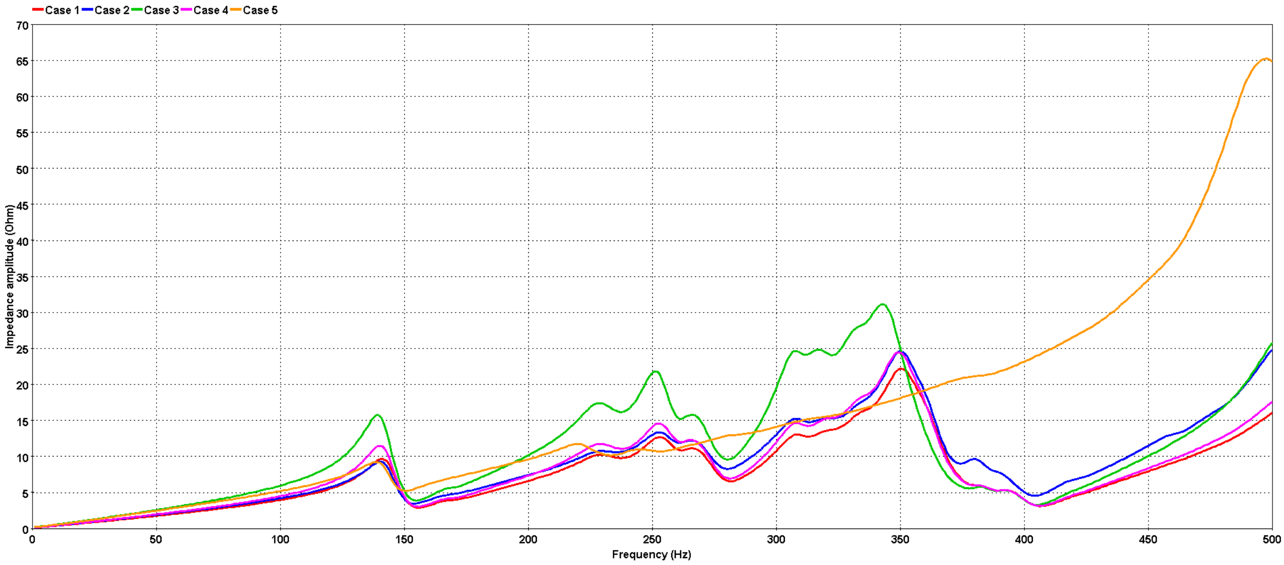


Figure 4-29: Harmonic impedance at 220 kV Laufenburg for the 5 cases – low SCL, scenario 3

4.4.3.10 380 kV Laufenburg

The following cases were taken into account in the frequency scan studies for 380 kV Laufenburg:

Case	Description
1	Condition N
2	N-2 on 380 kV Laufenburg – Kühmoos
3	N-2 on 380 kV Laufenburg – Trossingen and Laufenburg – Tiengen
4	N-2 on 380 kV Laufenburg – Sierentz and Laufenburg – Leibstadt
5	N-2 on 380 kV Laufenburg – Bassecourt and Laufenburg – Bickigen

The impedance amplitude with respect to frequency observed at 380 kV Laufenburg for the 5 cases in scenario 3 is shown in Figure 4-30.

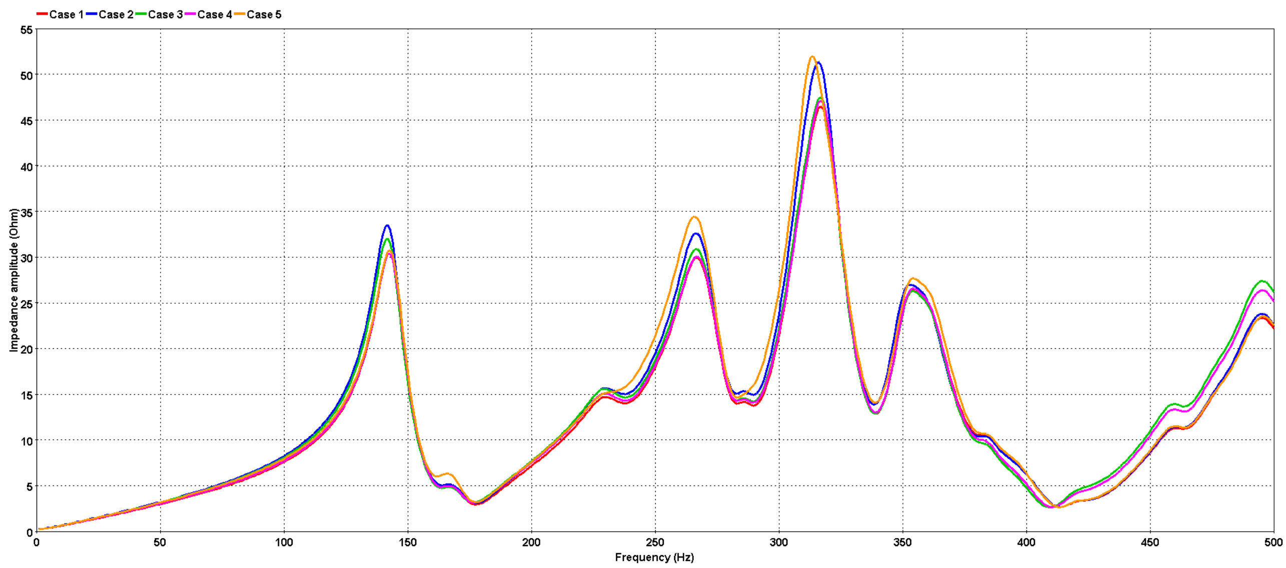


Figure 4-30: Harmonic impedance at 380 kV Laufenburg for the 5 cases – low SCL, scenario 3

4.4.3.11 220 kV Bickigen

The following cases were taken into account in the frequency scan studies for 220 kV Bickigen:

Case	Description
1	Condition N
2	N-1 on 220 kV Bickigen – Mühleberg
3	N-1 on 220 kV Bickigen – Oftringen
4	N-1 on 220 kV Bickigen – Mettlen
5	N-1 on 220 kV Bickigen – Innertkirchen
6	N-2 on 220 kV Bickigen – Mühleberg and Bickigen – Oftringen

The impedance amplitude with respect to frequency observed at 220 kV Bickigen for the 6 cases in scenario 3 is shown in Figure 4-31.

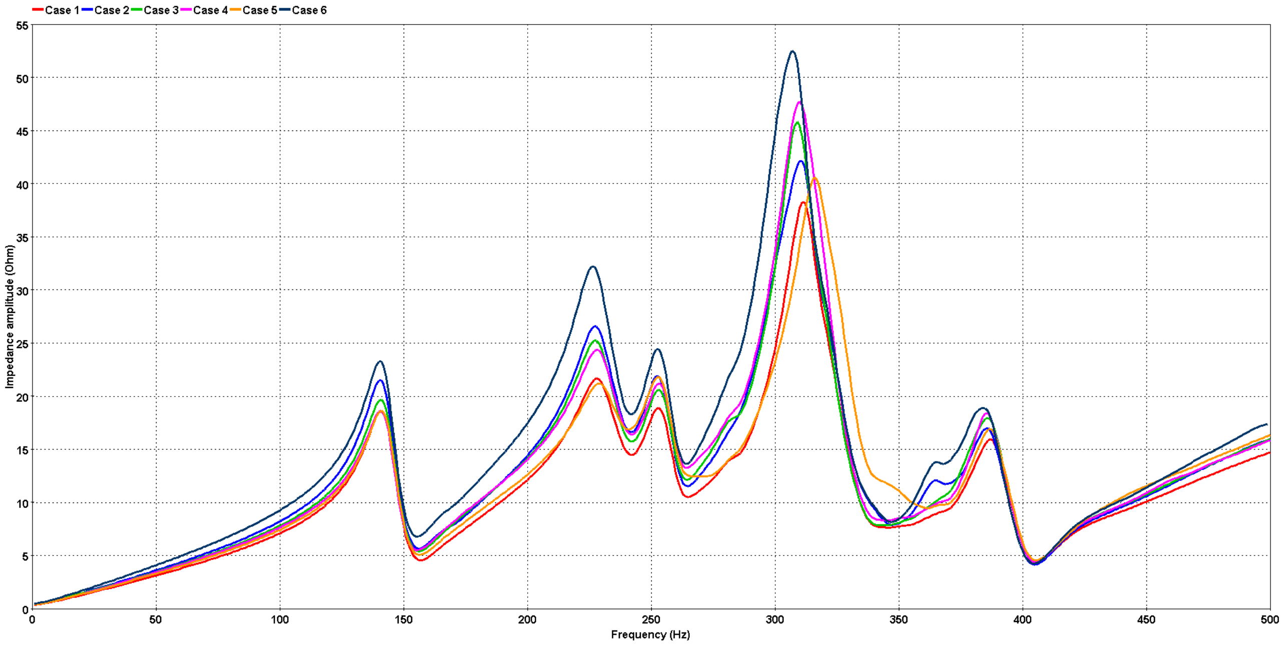


Figure 4-31: Harmonic impedance at 220 kV Bickigen for the 3 cases – low SCL, scenario 3

4.4.3.12 380 kV Bickigen

The following cases were taken into account in the frequency scan studies for 380 kV Bickigen:

Case	Description
1	Condition N
2	N-1 on 380 kV Bickigen – Bassecourt
3	N-1 on 380 kV Bickigen – Laufenburg
4	N-2 on 380 kV Bickigen – Laufenburg and Bassecourt – Laufenburg
5	N-2 on 380 kV Bickigen – Laufenburg and Bassecourt – Mambelin

The impedance amplitude with respect to frequency observed at 380 kV Bickigen for the 5 cases in scenario 3 is shown in Figure 4-32.

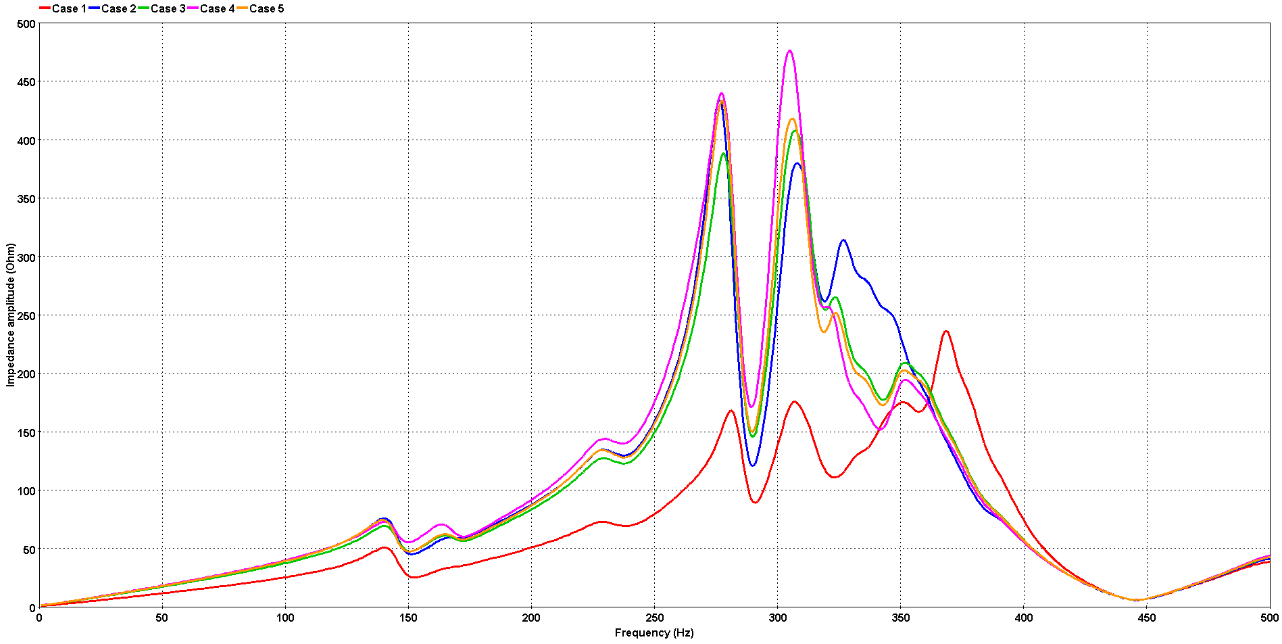


Figure 4-32: Harmonic impedance at 380 kV Bickigen for the 5 cases – low SCL, scenario 3

4.4.3.13 220 kV Wimmis

The following cases were taken into account in the frequency scan studies for 220 kV Wimmis:

Case	Description
1	Condition N
2	N-1 on 220 kV Chippis – Wimmis
3	N-1 on 220 kV Innertkirchen – Wimmis

The impedance amplitude with respect to frequency observed at 220 kV Wimmis for the 3 cases in scenario 3 is shown in Figure 4-33.

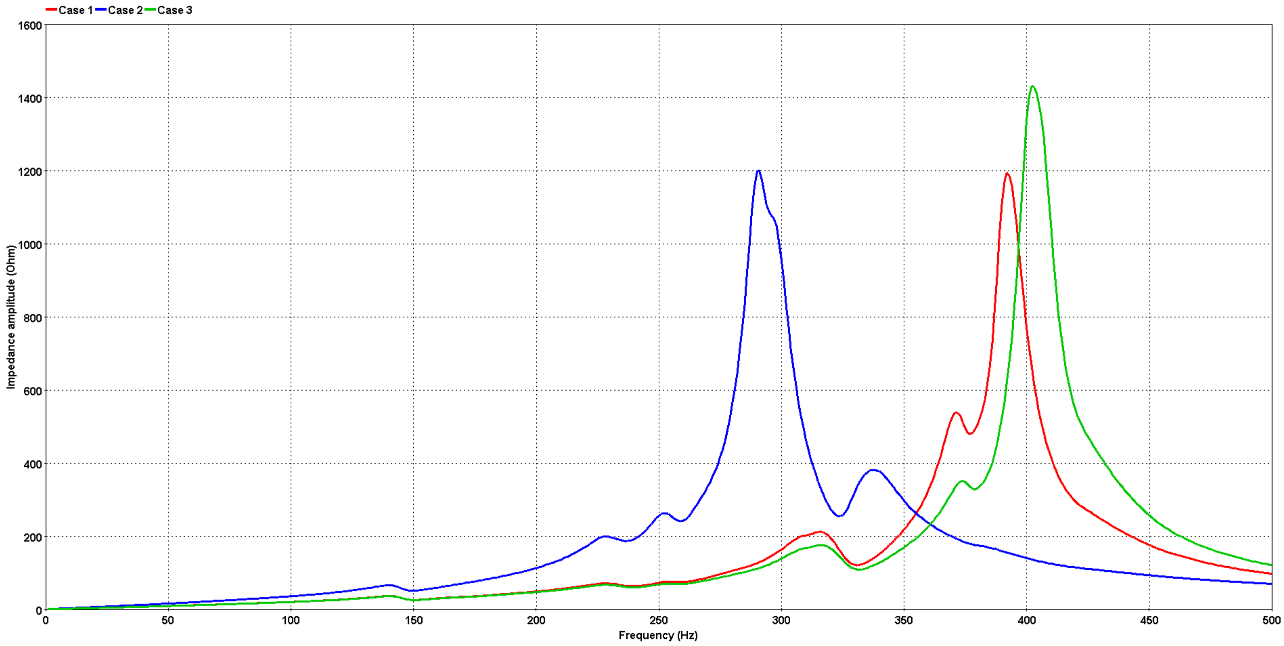


Figure 4-33: Harmonic impedance at 220 kV Wimmis for the 3 cases – low SCL, scenario 3

4.4.3.14 220 kV Mettlen

The following cases were taken into account in the frequency scan studies for 220 kV Mettlen:

Case	Description
1	Condition N
2	N-2 on 220 kV Mettlen – Obfelden and Mettlen – Sursee
3	N-2 on 220 kV Mettlen – Innertkirchen and Mettlen – Littau
4	N-2 on 220 kV Mettlen – Bickigen

The impedance amplitude with respect to frequency observed at 220 kV Mettlen for the 4 cases in scenario 3 is shown in Figure 4-34.

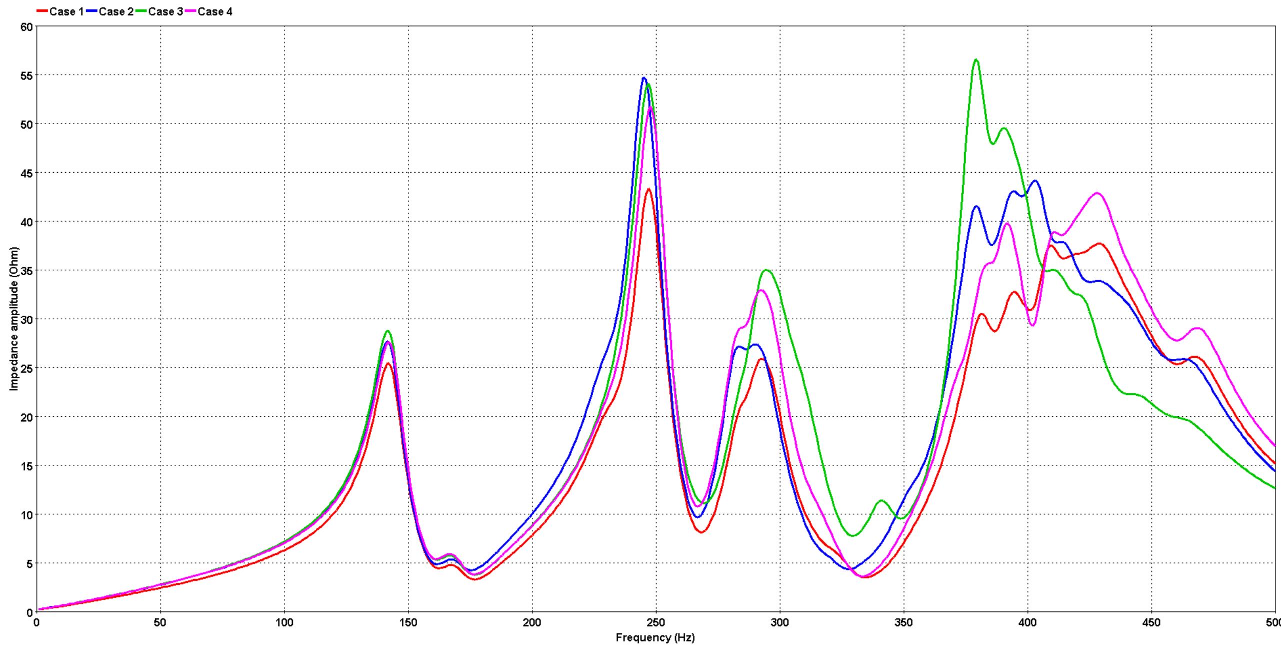


Figure 4-34: Harmonic impedance at 220 kV Mettlen for the 4 cases – low SCL, scenario 3

4.4.3.15 380 kV Mettlen

The following cases were taken into account in the frequency scan studies for 380 kV Mettlen:

Case	Description
1	Condition N
2	N-1 on 380 kV Mettlen – Beznau
3	N-1 on 380 kV Gösgen – Laufenburg
4	N-1 on 380 kV Benken – Sils
5	N-1 on 380 kV Lavorgo – Magadino
6	N-1 on 380 kV Mettlen – Gösgen
7	N-2 on 380 kV Mettlen – Beznau and Gösgen – Laufenburg

The impedance amplitude with respect to frequency observed at 380 kV Mettlen for the 7 cases in scenario 3 is shown in Figure 4-35.

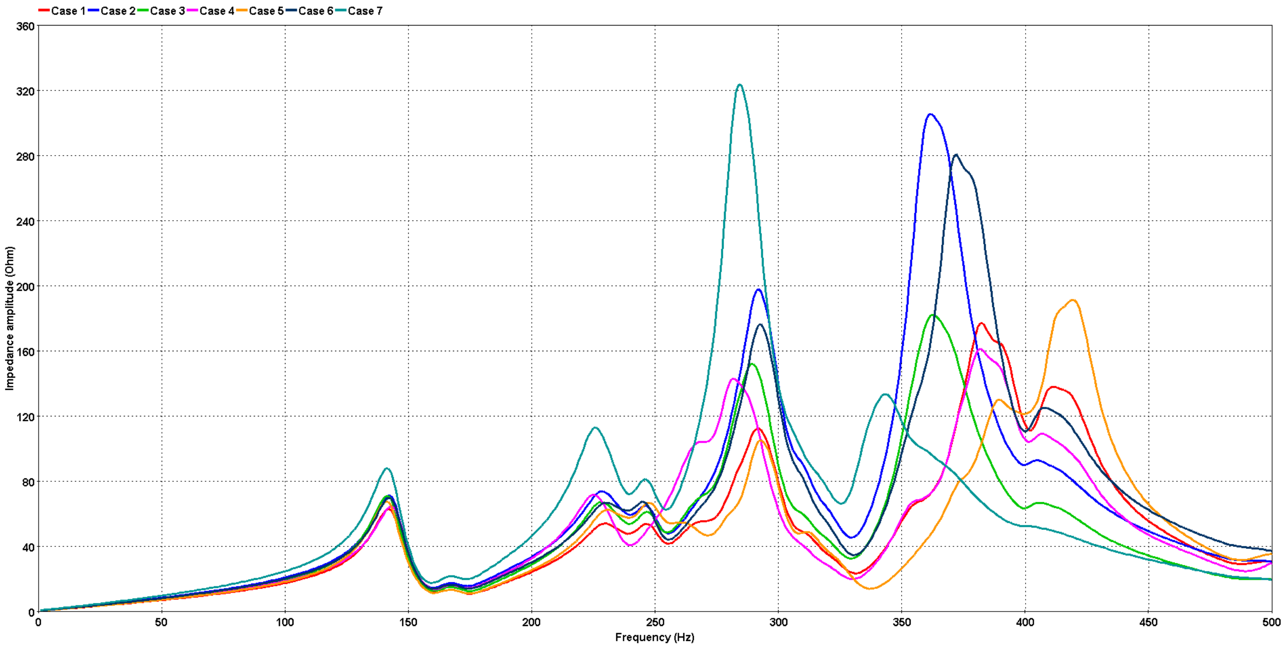


Figure 4-35: Harmonic impedance at 380 kV Mettlen for the 7 cases – low SCL, scenario 3

4.4.3.16 220 kV Gösgen

The following cases were taken into account in the frequency scan studies for 220 kV Gösgen:

Case	Description
1	Condition N
2	N-1 on 220 kV Gösgen – Laufenburg
3	N-1 on 220 kV Gösgen – Ormalingen
4	N-1 on 220 kV Gösgen – Flumenthal
5	N-2 on 220 kV Gösgen – Laufenburg and Gösgen – Ormalingen

The impedance amplitude with respect to frequency at 220 kV Gösgen for the 5 cases in scenario 3 is shown in Figure 4-36.

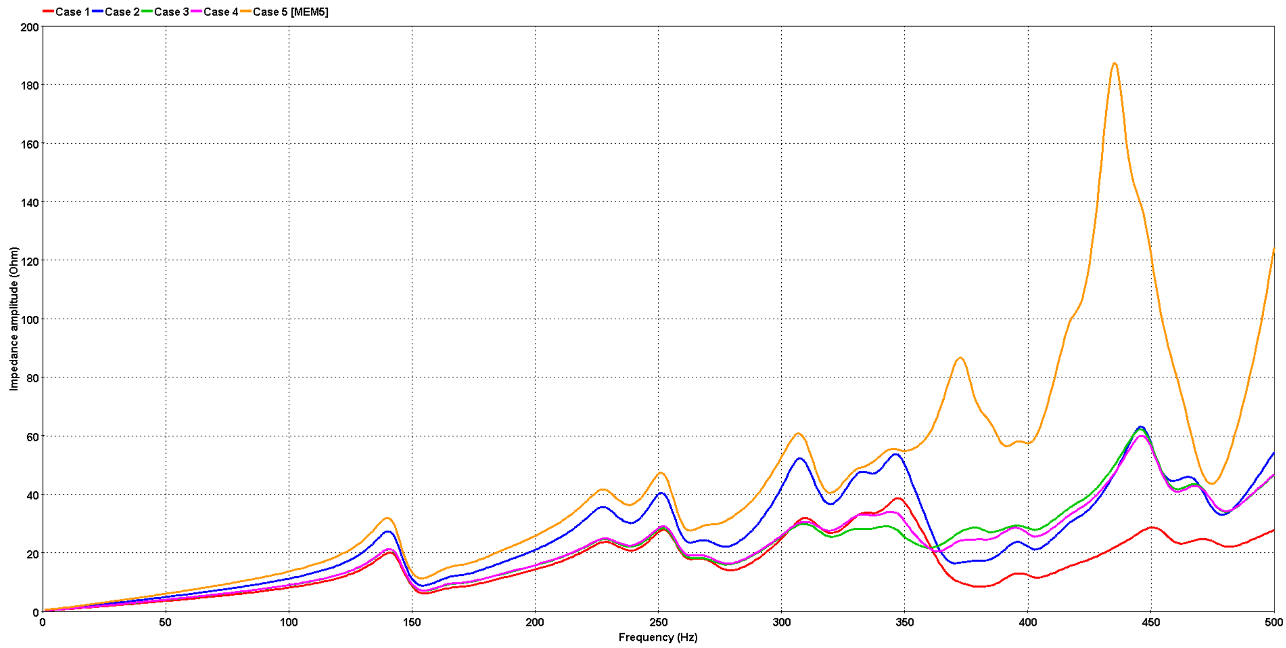


Figure 4-36: Harmonic impedance at 220 kV Gösgen for the 5 cases – low SCL, scenario 3

4.4.3.17 380 kV Gösgen

The following cases were taken into account in the frequency scan studies for 380 kV Gösgen:

Case	Description
1	Condition N
2	N-1 on 380 kV Gösgen – Laufenburg
3	N-1 on 380 kV Gösgen – Lachmatt
4	N-2 on 380 kV Gösgen – Laufenburg and Gösgen – Lachmatt

The impedance amplitude with respect to frequency observed at 380 kV Gösgen for the 4 cases in scenario 3 is shown in Figure 4-37.

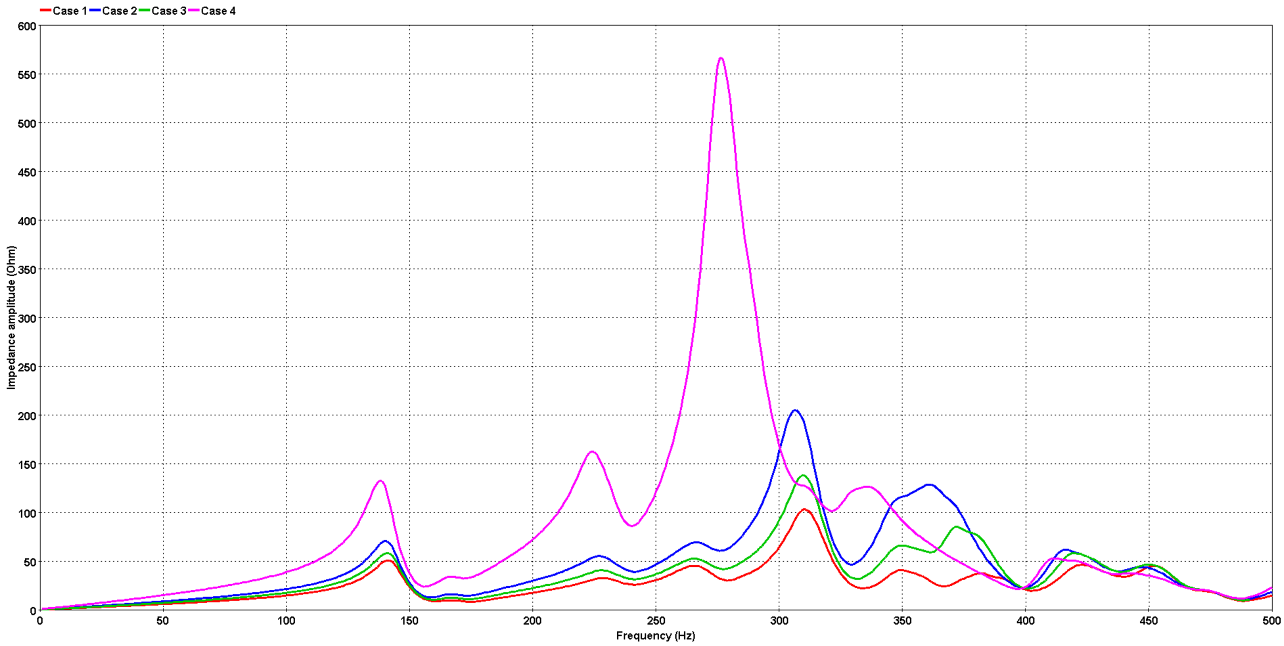


Figure 4-37: Harmonic impedance at 380 kV Gösgen for the 4 cases – low SCL, scenario 3

4.4.3.18 220 kV Altgass

The following cases were taken into account in the frequency scan studies for 220 kV Altgass:

Case	Description
1	Condition N
2	N-1 on 220 kV Altgass – Mettlen
3	N-2 on 220 kV Altgass – Mettlen and Samstagern – Siebnen
4	N-2 on 220 kV Altgass – Mettlen and Obfelden – Mettlen

The impedance amplitude with respect to frequency observed at 220 kV Altgass for the 4 cases in scenario 3 is shown in Figure 4-38.

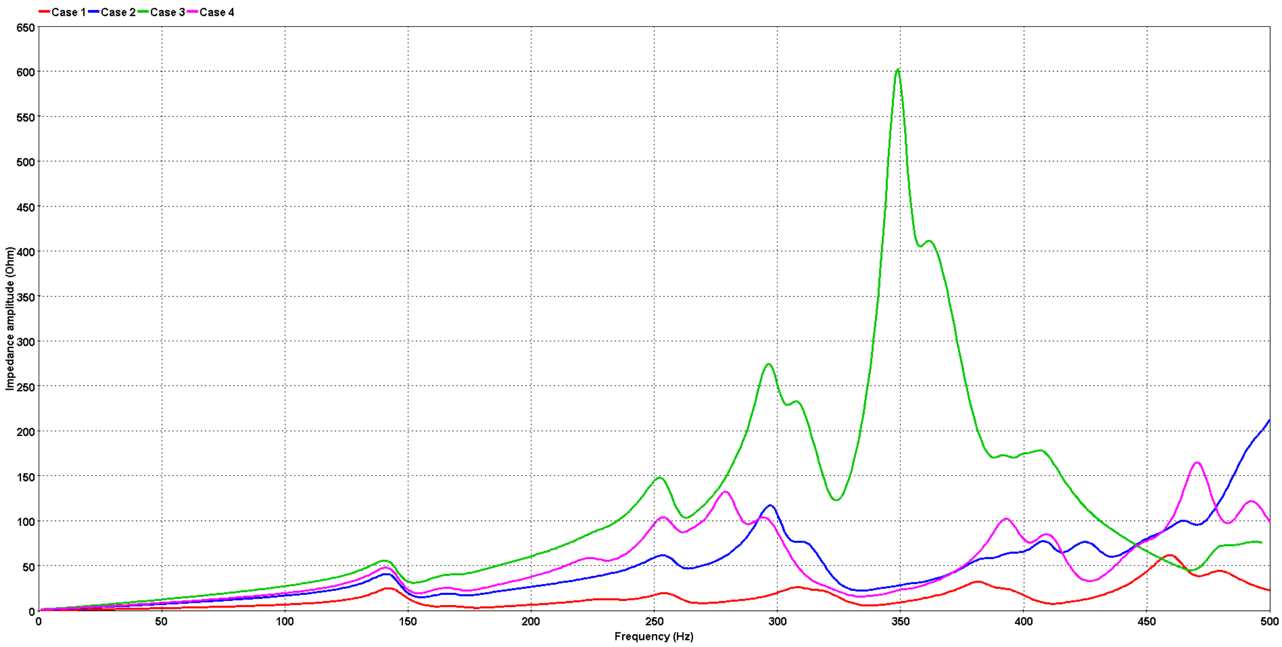


Figure 4-38: Harmonic impedance at 220 kV Altgass for the 4 cases – low SCL, scenario 3

4.4.3.19 380 kV Lavorgo

The following cases were taken into account in the frequency scan studies for 380 kV Lavorgo:

Case	Description
1	Condition N
2	N-1 on 380 kV Lavorgo – Magadino
3	N-1 on 380 kV Lavorgo – Mörel

The impedance amplitude with respect to frequency observed at 380 kV Lavorgo for the 3 cases in scenario 3 is shown in Figure 4-39.

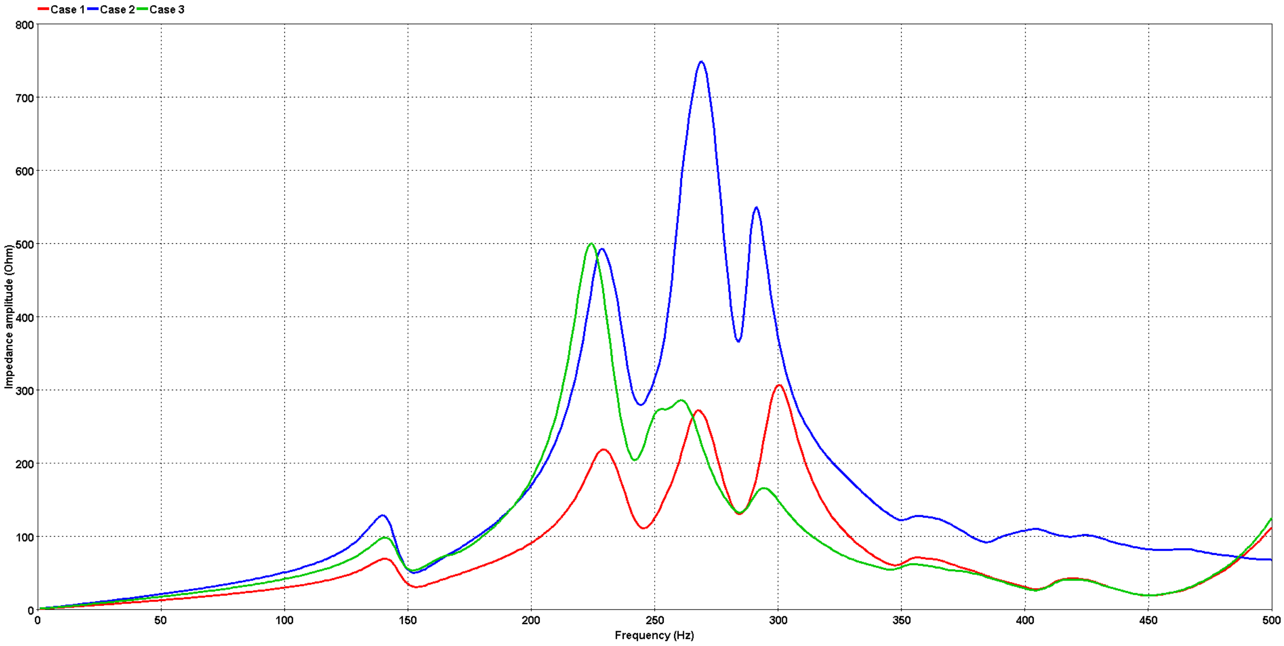


Figure 4-39: Harmonic impedance at 380 kV Lavorgo for the 3 cases – low SCL, scenario 3

4.4.3.20 220 kV Auwiesen

The following cases were taken into account in the frequency scan studies for 220 kV Auwiesen:

Case	Description
1	Condition N
2	N-1 on 220 kV Auwiesen – Seebach
3	N-1 on 220 kV Auwiesen – Fällanden
4	N-1 on 220 kV Niederwil – Regensdorf
5	N-1 on 220 kV Fällanden – Breite
6	N-1 on 220 kV Fällanden – Grynau
7	N-2 on 220 kV Niederwil – Regensdorf
8	N-2 on 220 kV Fällanden – Breite and Fällanden – Grynau

The impedance amplitude with respect to frequency observed at 220 kV Auwiesen for the 8 cases in scenario 3 is shown in Figure 4-40.

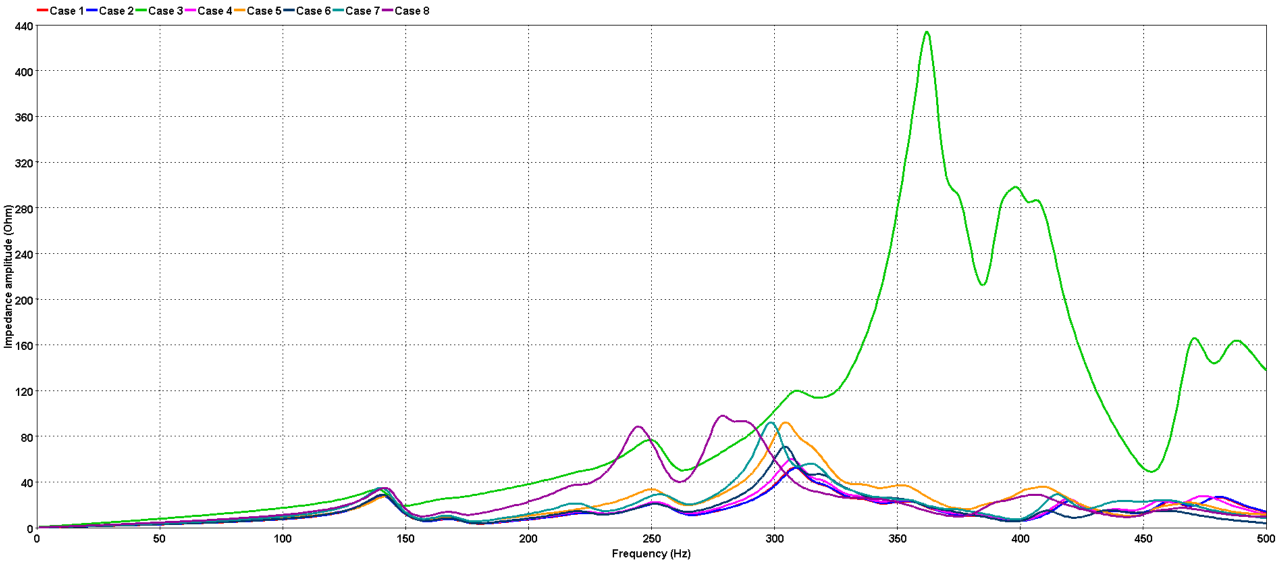


Figure 4-40: Harmonic impedance at 220 kV Auwiesen for the 8 cases – low SCL, scenario 3

4.4.3.21 220 kV Fällanden

The following cases were taken into account in the frequency scan studies for 220 kV Fällanden:

Case	Description
1	Condition N
2	N-1 on 220 kV Fällanden – Auwiesen
3	N-1 on 220 kV Fällanden – Breite
4	N-2 on 220 kV Benken – Siebnen and Benken – Sils
5	N-2 on 220 kV Benken – Siebnen and Grynau – Mettlen

The impedance amplitude with respect to frequency observed at 220 kV Fällanden for the 5 cases in scenario 3 is shown in Figure 4-41.

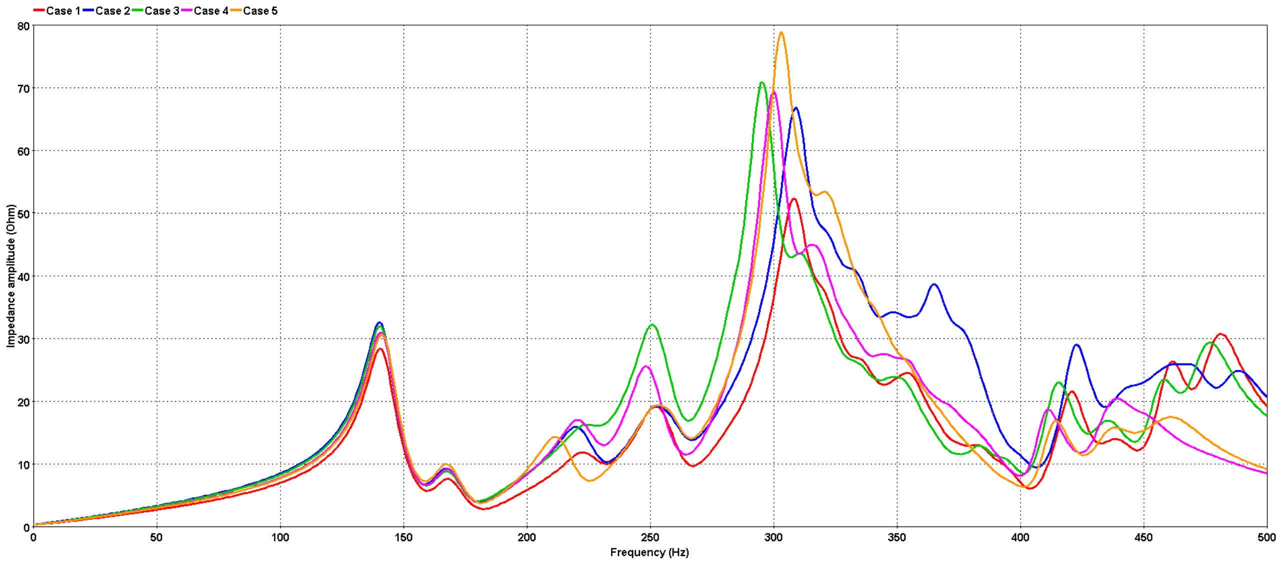


Figure 4-41: Harmonic impedance at 220 kV Fällanden for the 5 cases – low SCL, scenario 3

4.4.3.22 220 kV Benken

The following cases were taken into account in the frequency scan studies for 220 kV Benken:

Case	Description
1	Condition N
2	N-1 on 220 kV Benken – Siebnen
3	N-1 on 220 kV Benken – Sils
4	N-1 on 220 kV Fällanden – Auwiesen
5	N-1 on 220 kV Fällanden – Breite
6	N-2 on 220 kV Benken – Siebnen and Benken – Sils

The impedance amplitude with respect to frequency observed at 220 kV Benken for the 6 cases in scenario 3 is shown in Figure 4-42.

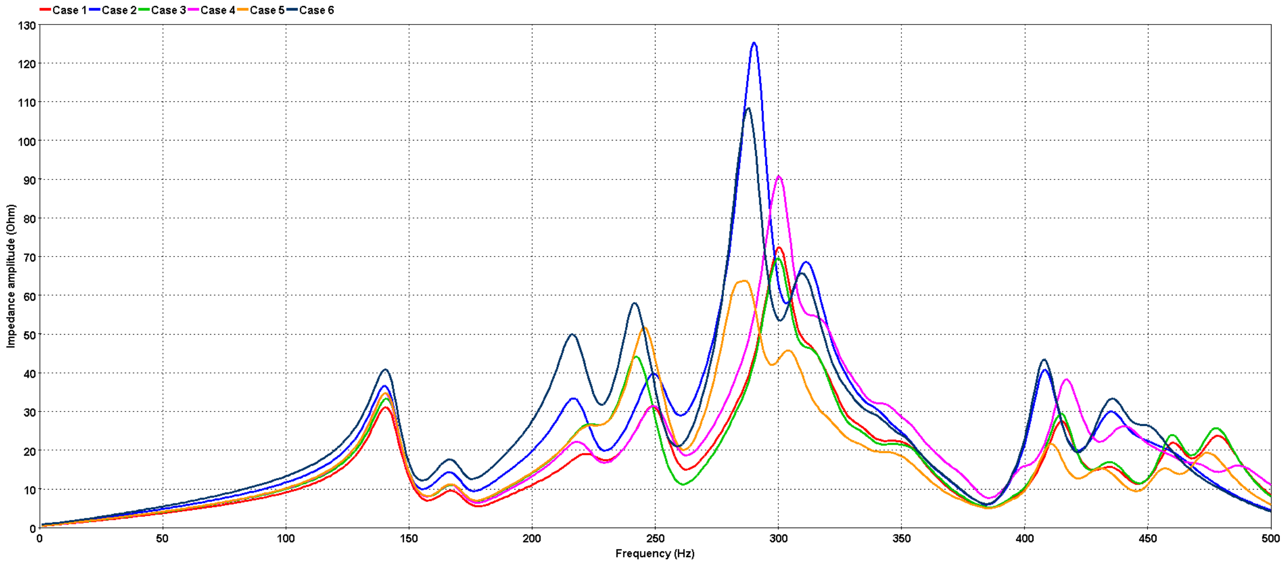


Figure 4-42: Harmonic impedance at 220 kV Benken for the 6 cases – low SCL, scenario 3

4.4.3.23 220 kV Winkeln

The following cases were taken into account in the frequency scan studies for 220 kV Winkeln:

Case	Description
1	Condition N
2	N-1 on 220 kV Winkeln – Weinfelden
3	N-1 on 220 kV Winkeln – Wittenwil
4	N-1 on 220 kV Winkeln – Rüthi
5	N-1 on 220 kV Winkeln – Mörschwil
6	N-2 on 220 kV Winkeln – Weinfelden and Winkeln – Wittenwil

The impedance amplitude with respect to frequency observed at 220 kV Winkeln for the 6 cases in scenario 3 is shown in Figure 4-43.

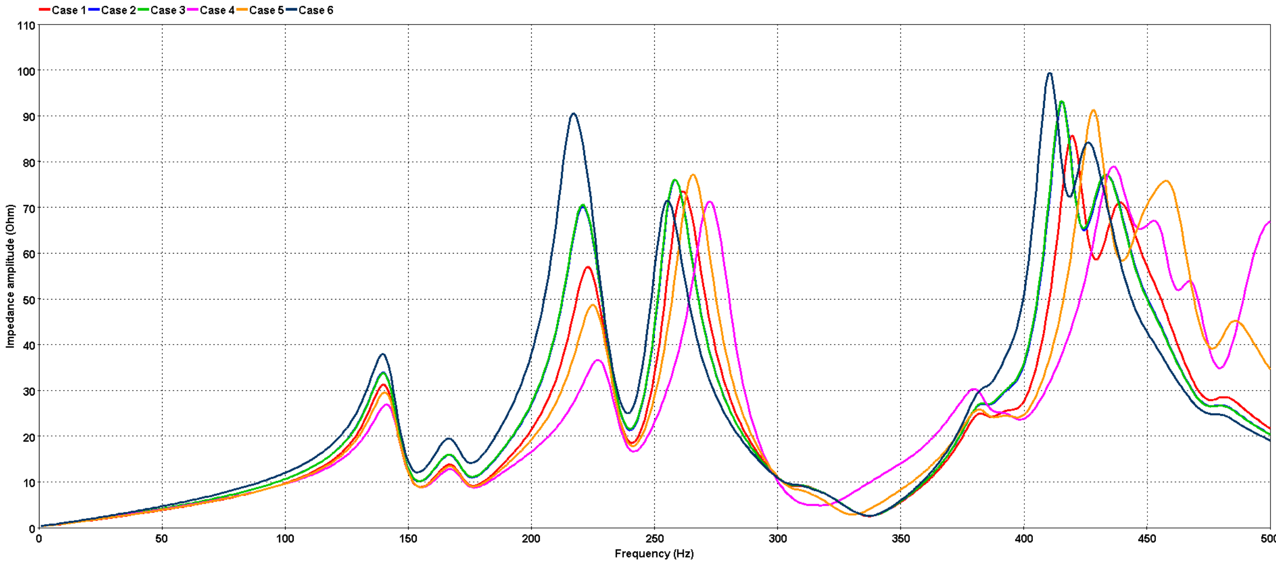


Figure 4-43: Harmonic impedance at 220 kV Winkeln for the 6 cases – low SCL, scenario 3

4.4.3.24 220 kV Sarelli

The following cases were taken into account in the frequency scan studies for 220 kV Sarelli:

Case	Description
1	Condition N
2	N-1 on 220 kV Sarelli – Rothenbrunnen
3	N-2 on 220 kV Sarelli – Rothenbrunnen and Rüthi – Montlingen

The impedance amplitude with respect to frequency observed at 220 kV Sarelli for the 3 cases in scenario 3 is shown in Figure 4-44.

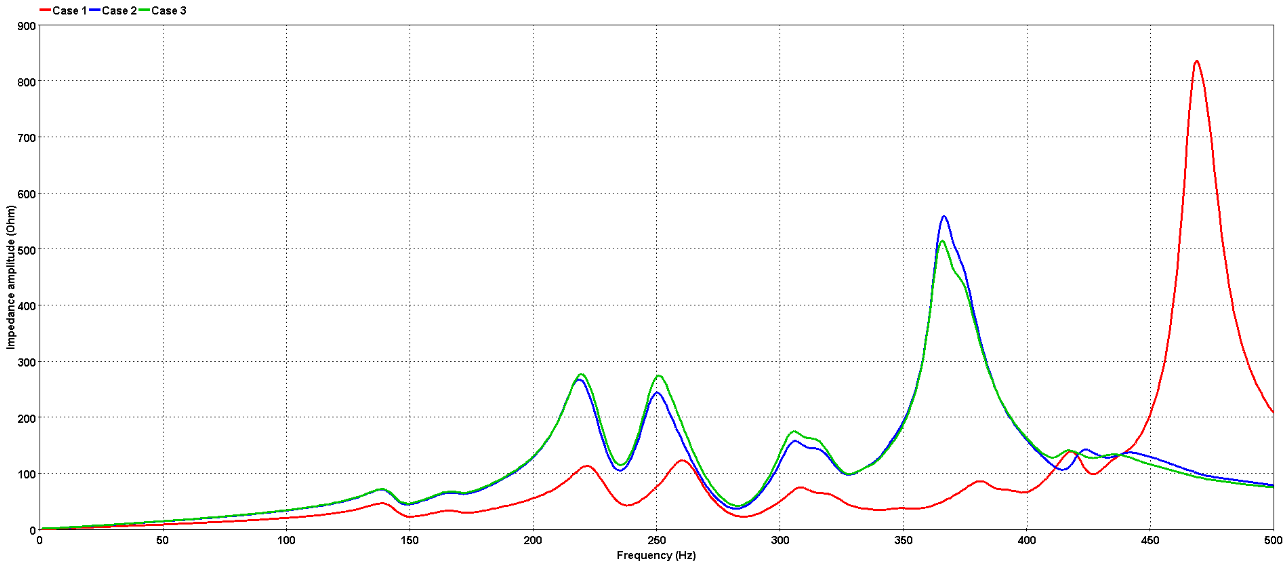


Figure 4-44: Harmonic impedance at 220 kV Sarelli for the 3 cases – low SCL, scenario 3

4.4.3.25 380 kV Sils

The following cases were taken into account in the frequency scan studies for 380 kV Sils:

Case	Description
1	Condition N
2	N-1 on 380 kV Sils – Filisur
3	N-1 on 380 kV Sils – Pradella
4	N-1 on 380 kV Bonaduz – Mapragg
5	N-1 on 380 kV Bonaduz – Breite
6	N-2 on 380 kV Sils – Filisur and Sils – Pradella

The impedance amplitude with respect to frequency observed at 380 kV Sils for the 6 cases in scenario 3 is shown in Figure 4-45.

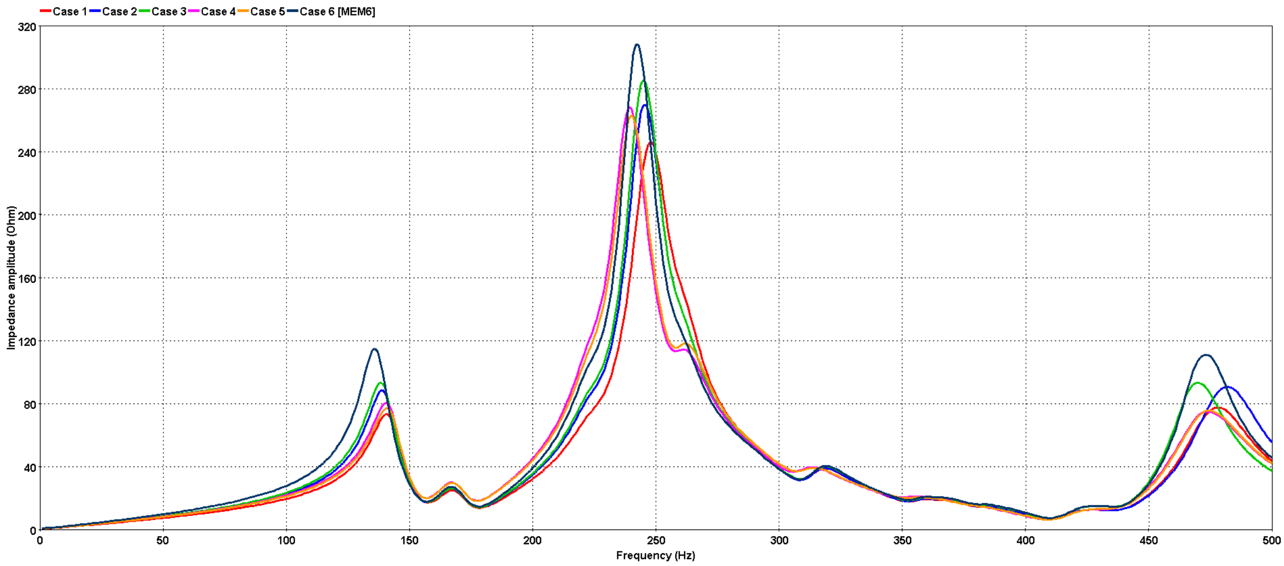


Figure 4-45: Harmonic impedance at 380 kV Sils for the 6 cases – low SCL, scenario 3

4.4.3.26 380 kV Soazza

The following cases were taken into account in the frequency scan studies for 380 kV Soazza:

Case	Description
1	Condition N
2	N-1 on 380 kV Soazza – Mese
3	N-2 on 380 kV Soazza – Mese and Sils – Filisur

The impedance amplitude with respect to frequency observed at 380 kV Soazza for the 3 cases in scenario 3 is shown in Figure 4-46.

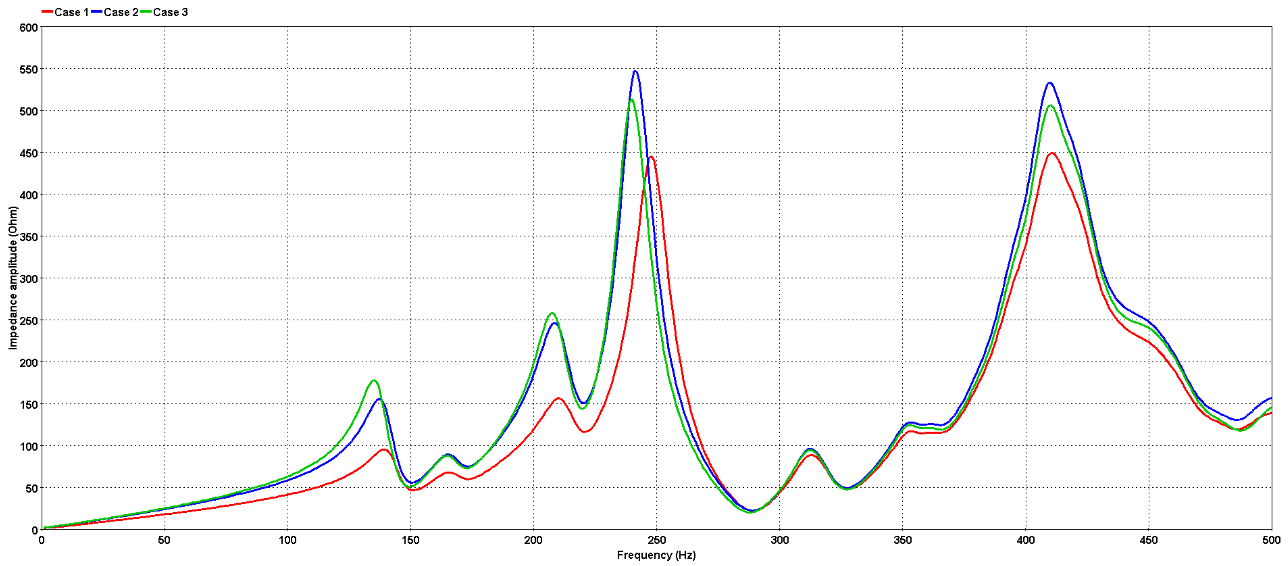


Figure 4-46: Harmonic impedance at 380 kV Soazza for the 3 cases – low SCL, scenario 3

4.4.4 Amplification factors for the three scenarios and different harmonic injection points

4.4.4.1 Scenario 3

4.4.4.1.1 Harmonic injection at 220 kV Fällanden

The following cases were considered for harmonic injection at 220 kV Fällanden:

Case	Description
1	Condition N
2	N-1 on 220 kV Regensdorf – Seebach
3	N-1 on 220 kV Auwiesen – Seebach
4	N-1 on 220 kV Benken – Siebnen
5	N-1 on 220 kV Benken – Sils
6	N-1 on 220 kV Grynau – Mettlen
7	N-2 on 220 kV Benken – Sils and Benken – Siebnen
8	N-2 on 220 kV Grynau – Tierfehd
9	N-2 on 220 kV Grynau – Winkeln
10	N-2 on 220 kV Niederwil – Regensdorf

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV Fällanden under low and optimal SCL conditions are presented in Table 4-6 and Table 4-7, respectively.

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8		Case 9		Case 10	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
220 kV Auwiesen	0.972	1.030	0.963	1.001	0.971	1.021	0.966	1.009	0.976	1.029	0.972	1.025	0.969	1.007	0.978	1.032	0.958	1.034	1.037	1.090
220 kV Seebach	0.965	1.033	0.964	1.003	0.900	1.042	0.957	1.008	0.969	1.033	0.964	1.027	0.960	1.005	0.972	1.036	0.947	1.038	1.045	1.108
220 kV Regensdorf	0.920	1.015	0.856	0.941	0.887	1.015	0.907	0.974	0.928	1.014	0.919	1.004	0.913	0.970	0.932	1.019	0.892	1.022	1.054	1.134
220 kV Aathal	0.512	0.879	0.505	0.875	0.508	0.877	0.470	0.798	0.630	0.885	0.479	0.855	0.584	0.804	0.768	0.948	0.602	1.188	0.449	0.850
220 kV Grynau	0.514	0.845	0.506	0.841	0.510	0.843	0.466	0.766	0.644	0.848	0.475	0.813	0.591	0.768	0.820	0.922	0.619	1.177	0.447	0.814
220 kV Benken	0.791	1.216	0.790	1.208	0.791	1.215	0.860	1.252	0.901	1.263	0.792	1.171	0.985	1.309	0.800	1.239	0.801	1.221	0.784	1.154
380 kV Benken	0.164	0.525	0.159	0.518	0.161	0.524	0.126	0.399	0.171	0.560	0.146	0.430	0.128	0.426	0.235	0.564	0.106	0.544	0.119	0.470
220 kV Benken	0.791	1.216	0.790	1.208	0.791	1.215	0.860	1.252	0.901	1.263	0.792	1.171	0.985	1.309	0.800	1.239	0.801	1.221	0.784	1.154
380 kV Benken	0.164	0.525	0.159	0.518	0.161	0.524	0.126	0.399	0.171	0.560	0.146	0.430	0.128	0.426	0.235	0.564	0.106	0.544	0.119	0.470
220 kV Siebnen	0.732	1.110	0.728	1.098	0.730	1.108	0.476	0.775	0.834	1.147	0.726	1.039	0.536	0.791	0.764	1.135	0.695	1.136	0.696	1.015
220 kV Samstagern	0.613	0.949	0.602	0.929	0.607	0.948	0.482	0.781	0.694	0.972	0.590	0.787	0.542	0.797	0.730	0.980	0.464	1.039	0.503	0.786
220 kV Altgass	0.539	0.881	0.529	0.864	0.533	0.881	0.437	0.727	0.613	0.905	0.513	0.700	0.496	0.745	0.675	0.911	0.364	0.981	0.446	0.739
220 kV Thalwil	0.675	1.082	0.657	1.054	0.665	1.082	0.556	0.876	0.750	1.103	0.652	0.915	0.612	0.886	0.792	1.116	0.518	1.177	0.502	0.834
220 kV Waldegg	0.693	1.104	0.672	1.073	0.682	1.105	0.584	0.884	0.764	1.123	0.671	0.940	0.637	0.892	0.809	1.137	0.537	1.198	0.490	0.832
220 kV Obfelden	0.661	0.964	0.637	0.934	0.648	0.966	0.578	0.769	0.719	0.976	0.643	0.831	0.622	0.772	0.763	0.991	0.517	1.041	0.429	0.687
220 kV Niederwil	0.712	0.766	0.670	0.718	0.691	0.767	0.678	0.681	0.738	0.763	0.707	0.742	0.698	0.672	0.754	0.776	0.644	0.785	0.318	0.323
220 kV Mettlen	0.451	0.789	0.444	0.775	0.447	0.789	0.381	0.639	0.518	0.814	0.423	0.601	0.437	0.658	0.606	0.815	0.255	0.891	0.378	0.669
380 kV Mettlen	0.058	0.628	0.053	0.620	0.055	0.628	0.026	0.545	0.085	0.672	0.053	0.509	0.052	0.588	0.075	0.650	0.157	0.695	0.019	0.563
220 kV Breite	0.357	0.481	0.352	0.480	0.354	0.480	0.338	0.447	0.423	0.491	0.345	0.492	0.403	0.458	0.446	0.490	0.390	0.550	0.315	0.475
380 kV Breite	0.265	0.471	0.264	0.465	0.264	0.468	0.247	0.411	0.251	0.515	0.252	0.404	0.227	0.444	0.331	0.443	0.178	0.501	0.252	0.438

Table 4-6: Amplification factors for harmonic injection at 220 kV Fällanden – low SCL (scenario 3)

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8		Case 9		Case 10	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
220 kV Auwiesen	0.926	1.038	0.921	1.007	0.928	1.028	0.912	1.003	0.932	1.039	0.925	1.029	0.917	1.003	0.929	1.039	0.925	1.044	1.027	1.078
220 kV Seebach	0.908	1.044	0.922	1.009	0.775	1.078	0.890	1.001	0.915	1.046	0.907	1.033	0.897	1.001	0.912	1.046	0.907	1.051	1.033	1.094
220 kV Regensdorf	0.829	1.038	0.737	0.973	0.764	1.050	0.800	0.967	0.841	1.040	0.828	1.018	0.811	0.967	0.836	1.040	0.826	1.050	1.037	1.115
220 kV Aathal	0.356	0.780	0.362	0.774	0.361	0.778	0.382	0.708	0.371	0.779	0.452	0.674	0.404	0.710	0.496	0.862	0.440	1.151	0.414	0.732
220 kV Grynau	0.371	0.779	0.377	0.772	0.375	0.776	0.394	0.691	0.387	0.777	0.481	0.657	0.416	0.691	0.536	0.868	0.468	1.175	0.433	0.723
220 kV Benken	0.692	1.266	0.690	1.254	0.691	1.262	0.847	1.241	0.792	1.325	0.690	1.213	0.955	1.311	0.694	1.283	0.704	1.280	0.680	1.172
380 kV Benken	0.367	0.543	0.360	0.536	0.362	0.544	0.306	0.470	0.333	0.584	0.353	0.490	0.265	0.512	0.372	0.591	0.353	0.553	0.297	0.484
220 kV Benken	0.692	1.266	0.690	1.254	0.691	1.262	0.847	1.241	0.792	1.325	0.690	1.213	0.955	1.311	0.694	1.283	0.704	1.280	0.680	1.172
380 kV Benken	0.367	0.543	0.360	0.536	0.362	0.544	0.306	0.470	0.333	0.584	0.353	0.490	0.265	0.512	0.372	0.591	0.353	0.553	0.297	0.484
220 kV Siebnen	0.541	1.236	0.535	1.217	0.537	1.230	0.136	1.017	0.641	1.288	0.517	1.143	0.063	1.018	0.556	1.257	0.584	1.283	0.478	1.080
220 kV Samstagern	0.232	1.322	0.211	1.289	0.217	1.319	0.140	1.041	0.325	1.358	0.134	1.091	0.064	1.041	0.267	1.365	0.408	1.466	0.026	1.029
220 kV Altgass	0.127	1.276	0.107	1.243	0.113	1.272	0.181	0.982	0.214	1.307	0.060	1.025	0.098	0.982	0.161	1.323	0.346	1.433	0.072	0.989
220 kV Thalwil	0.272	1.487	0.242	1.448	0.251	1.488	0.056	1.141	0.361	1.524	0.187	1.241	0.037	1.142	0.310	1.532	0.432	1.642	0.025	1.129
220 kV Waldegg	0.289	1.512	0.255	1.471	0.265	1.515	0.019	1.145	0.374	1.547	0.209	1.267	0.077	1.145	0.328	1.556	0.441	1.666	0.045	1.142
220 kV Obfelden	0.289	1.298	0.251	1.262	0.262	1.304	0.070	0.970	0.361	1.324	0.228	1.098	0.135	0.971	0.325	1.334	0.410	1.425	0.079	0.967
220 kV Niederwil	0.502	0.875	0.442	0.836	0.460	0.887	0.420	0.715	0.534	0.882	0.485	0.822	0.450	0.715	0.520	0.884	0.530	0.911	0.088	0.551
220 kV Mettlen	0.067	1.187	0.061	1.157	0.063	1.184	0.220	0.883	0.115	1.213	0.141	0.930	0.135	0.883	0.065	1.237	0.308	1.350	0.166	0.917
380 kV Mettlen	0.396	0.639	0.394	0.634	0.395	0.642	0.414	0.682	0.344	0.706	0.392	0.599	0.347	0.763	0.378	0.676	0.458	0.672	0.390	0.609
220 kV Breite	0.225	0.384	0.229	0.383	0.228	0.384	0.256	0.389	0.233	0.382	0.276	0.371	0.269	0.392	0.273	0.404	0.223	0.488	0.263	0.380
380 kV Breite	0.426	0.178	0.417	0.176	0.420	0.174	0.362	0.232	0.411	0.216	0.411	0.181	0.338	0.284	0.451	0.164	0.345	0.132	0.343	0.179

Table 4-7: Amplification factors for harmonic injection at 220 kV Fällanden – optimal SCL (scenario 3)

4.4.4.1.2 Harmonic injection at 220 kV Verbois

The following cases were considered for harmonic injection at 220 kV Verbois:

Case	Description
1	Condition N
2	N-1 on 220 kV Romanel – Veytaux
3	N-1 on 220 kV Romanel – Vaux
4	N-1 on 220 kV Vaux – Verbois
5	N-2 on 220 kV Romanel – Vaux and Vaux – Verbois

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV Verbois under low and optimal SCL conditions are presented in Table 4-8 and Table 4-9,respectively.

	Case 1		Case 2		Case 3		Case 4		Case 5	
	5	7	5	7	5	7	5	7	5	7
380 kV Verbois	0.854	0.853	0.979	0.787	0.638	0.797	0.601	0.835	0.633	0.796
220 kV Foretaille	0.854	1.475	0.858	2.472	0.829	1.398	0.827	1.397	0.829	1.398
220 kV Crans	0.619	1.844	0.635	3.532	0.570	1.694	0.566	1.748	0.570	1.694
220 kV Banlieue Ouest	0.464	1.867	0.511	4.080	0.372	1.643	0.363	1.842	0.367	1.642
220 kV Romanel	0.561	1.685	0.607	3.812	0.482	1.467	0.474	1.695	0.477	1.466
380 kV Romanel	2.379	1.069	2.621	0.925	1.950	0.923	1.878	1.079	1.943	0.924
220 kV Vaux	0.450	1.560	0.493	3.503	0.939	0.938	0.447	1.685	0.000	0.000
220 kV Veytaux	0.755	1.225	0.807	1.192	0.660	1.045	0.652	1.247	0.656	1.046
220 kV St Triphon	0.689	1.715	0.752	1.044	0.597	1.460	0.584	1.728	0.592	1.462
220 kV Riddes	0.678	1.956	0.742	1.609	0.575	1.683	0.559	1.954	0.572	1.683
380 kV Bâtiaz	1.764	1.221	1.934	2.032	1.441	1.079	1.389	1.187	1.436	1.075
380 kV Nant de Drance	1.792	1.295	1.964	2.156	1.463	1.144	1.410	1.259	1.458	1.139
380 kV Châtelard	1.790	1.287	1.962	2.140	1.462	1.137	1.409	1.250	1.457	1.132
220 kV Châtelard	1.414	1.052	1.549	1.758	1.155	0.930	1.113	1.023	1.151	0.926
220 kV Vallorcine	1.399	1.042	1.532	1.741	1.142	0.921	1.100	1.012	1.138	0.917

Table 4-8: Amplification factors for harmonic injection at 220 kV Verbois – low SCL (scenario 3)

	Case 1		Case 2		Case 3		Case 4		Case 5	
	5	7	5	7	5	7	5	7	5	7
380 kV Verbois	1.237	0.467	1.479	0.321	0.931	0.485	0.868	0.481	0.920	0.490
220 kV Foretaille	1.005	0.747	1.052	1.611	0.923	0.730	0.910	0.619	0.920	0.730
220 kV Crans	0.984	0.915	1.120	2.044	0.805	0.823	0.772	0.639	0.799	0.822
220 kV Banlieue Ouest	1.255	1.434	1.454	2.188	1.007	1.263	0.958	1.120	0.996	1.263
220 kV Romanel	1.365	1.531	1.563	2.043	1.125	1.357	1.078	1.246	1.114	1.358
380 kV Romanel	3.335	0.440	3.841	0.333	2.698	0.390	2.563	0.351	2.680	0.394
220 kV Vaux	1.150	1.303	1.321	1.875	0.735	0.792	1.019	1.207	0.000	0.000
220 kV Veytaux	1.340	3.019	1.112	3.055	1.111	2.659	1.076	2.455	1.103	2.663
220 kV St Triphon	1.153	3.066	1.101	2.852	0.947	2.694	0.907	2.493	0.939	2.698
220 kV Riddes	0.888	1.628	0.916	1.562	0.725	1.429	0.693	1.325	0.719	1.430
380 kV Bâtiaz	2.188	0.566	2.481	0.949	1.761	0.503	1.675	0.436	1.750	0.500
380 kV Nant de Drance	2.171	0.588	2.461	0.983	1.748	0.522	1.663	0.452	1.737	0.519
380 kV Châtelard	2.180	0.586	2.471	0.980	1.755	0.521	1.669	0.451	1.744	0.517
220 kV Châtelard	1.452	0.396	1.645	0.672	1.169	0.352	1.112	0.304	1.161	0.350
220 kV Vallorcine	1.422	0.388	1.611	0.659	1.144	0.345	1.089	0.297	1.137	0.343

Table 4-9: Amplification factors for harmonic injection at 220 kV Verbois – optimal SCL (scenario 3)

4.4.4.1.3 Harmonic injection at 380 kV Bois Tollot

The following cases were considered for harmonic injection at 380 kV Bois Tollot:

Case	Description
1	Condition N
2	N-1 on 380 kV Bâtiaz – Romanel
3	N-1 on 380 kV Bâtiaz – Chamoson
4	N-2 on 380 kV Chamoson – Chippis

The amplification factors on the 5th and 7th harmonics for harmonic injection at 380 kV Bois Tollot under low and optimal SCL conditions are presented in Table 4-10 and Table 4-11, respectively.

	Case 1		Case 2		Case 3		Case 4	
	5	7	5	7	5	7	5	7
380 kV Verbois	0.825	0.870	0.825	0.905	0.905	0.901	0.826	0.945
220 kV Foretaille	1.147	1.062	1.217	0.359	0.384	0.263	1.091	0.896
220 kV Crans	1.301	1.127	1.366	0.417	0.468	0.340	1.248	0.882
220 kV Banlieue Ouest	1.347	0.843	1.397	0.402	0.525	0.390	1.306	0.538
220 kV Romanel	1.310	0.692	1.352	0.367	0.516	0.371	1.271	0.414
380 kV Romanel	0.331	0.866	0.351	1.121	1.091	0.071	0.355	0.298
220 kV Vaux	1.229	0.652	1.282	0.340	0.451	0.313	1.188	0.422
220 kV Veytaux	1.319	1.273	1.346	0.893	0.598	0.352	1.295	1.230
220 kV St Triphon	1.150	1.635	1.195	0.901	0.436	0.337	1.128	1.458
220 kV Riddes	0.622	1.377	0.658	0.365	0.250	0.292	0.616	1.028
380 kV Bâtiaz	0.151	0.502	0.246	0.942	2.154	0.569	0.303	0.671
380 kV Nant de Drance	0.154	0.532	0.250	0.997	2.188	0.604	0.308	0.710
380 kV Châtelard	0.153	0.528	0.250	0.990	2.185	0.600	0.307	0.705
220 kV Châtelard	0.120	0.436	0.197	0.813	1.715	0.492	0.241	0.581
220 kV Vallorcine	0.118	0.432	0.195	0.806	1.696	0.488	0.238	0.576

Table 4-10: Amplification factors for harmonic injection at 380 kV Bois Tollot – low SCL (scenario 3)

	Case 1		Case 2		Case 3		Case 4	
	5	7	5	7	5	7	5	7
380 kV Verbois	0.782	0.936	0.805	0.897	0.826	0.919	0.766	0.931
220 kV Foretaille	2.016	0.301	3.159	0.384	1.043	0.158	2.120	0.248
220 kV Crans	2.254	0.238	3.473	0.464	1.232	0.166	2.377	0.174
220 kV Banlieue Ouest	2.318	0.126	3.446	0.455	1.360	0.228	2.446	0.111
220 kV Romanel	2.272	0.154	3.339	0.416	1.353	0.245	2.396	0.155
380 kV Romanel	1.219	0.390	1.446	1.089	1.294	0.065	1.361	0.392
220 kV Vaux	2.088	0.091	3.137	0.386	1.188	0.178	2.200	0.078
220 kV Veytaux	1.937	0.605	2.686	0.787	1.122	0.485	2.016	0.468
220 kV St Triphon	1.639	0.668	2.280	0.797	0.894	0.502	1.686	0.504
220 kV Riddes	0.878	0.514	1.067	0.475	0.430	0.312	0.873	0.352
380 kV Bâtiaz	0.879	0.671	0.448	0.398	1.742	0.635	1.032	0.693
380 kV Nant de Drance	0.873	0.696	0.445	0.413	1.729	0.658	1.025	0.719
380 kV Châtelard	0.876	0.693	0.446	0.412	1.735	0.656	1.028	0.717
220 kV Châtelard	0.583	0.475	0.297	0.282	1.153	0.449	0.684	0.491
220 kV Vallorcine	0.571	0.466	0.291	0.276	1.129	0.440	0.670	0.481

Table 4-11: Amplification factors for harmonic injection at 380 kV Bois Tollot – optimal SCL (scenario 3)

4.4.4.1.4 Harmonic injection at 380 kV Romanel

The following cases were considered for harmonic injection at 380 kV Romanel:

Case	Description
1	Condition N
2	N-1 on 380 kV Bâtiaz – Chamoson
3	N-1 on 380 kV Bois Tollot – Romanel
4	N-2 on 380 kV Chamoson – Chipps

The amplification factors on the 5th and 7th harmonics for harmonic injection at 380 kV Romanel under low and optimal SCL conditions are presented in Table 4-12 and Table 4-13, respectively.

	Case 1		**Case 2**		**Case 3**		**Case 4**	
	5	7	5	7	5	7	5	7
380 kV Verbois	0.183	0.877	0.213	0.361	0.574	0.672	0.197	0.636
220 kV Foretaille	1.538	1.129	1.368	0.496	0.947	1.118	1.620	0.886
220 kV Crans	1.639	1.046	1.461	0.529	0.955	1.054	1.724	0.841
220 kV Banlieue Ouest	1.514	0.485	1.355	0.408	0.788	0.539	1.589	0.468
220 kV Romanel	1.424	0.288	1.278	0.335	0.716	0.348	1.493	0.337
380 kV Romanel	0.197	0.956	0.198	0.550	0.286	0.935	0.079	1.117
220 kV Vaux	1.429	0.368	1.282	0.348	0.724	0.423	1.499	0.399
220 kV Veytaux	1.365	1.927	1.283	0.349	0.659	1.814	1.397	1.298
220 kV St Triphon	1.192	2.242	1.135	0.322	0.565	2.143	1.206	1.513
220 kV Riddes	0.546	1.445	0.622	0.286	0.216	1.451	0.517	1.057
380 kV Bâtiaz	0.553	1.460	2.005	7.887	0.630	1.363	0.757	3.060
380 kV Nant de Drance	0.561	1.550	2.036	8.337	0.640	1.446	0.769	3.238
380 kV Châtelard	0.561	1.538	2.033	8.287	0.639	1.435	0.769	3.216
220 kV Châtelard	0.443	1.265	1.605	6.810	0.505	1.181	0.607	2.649
220 kV Vallorcine	0.438	1.253	1.587	6.745	0.499	1.170	0.600	2.624

Table 4-12: Amplification factors for harmonic injection at 380 kV Romanel – low SCL (scenario 3)

	Case 1		Case 2		Case 3		Case 4	
	5	7	5	7	5	7	5	7
380 kV Verbois	1.109	0.350	1.008	0.358	1.039	0.232	1.101	0.302
220 kV Foretaille	3.645	0.444	3.207	0.306	2.334	0.531	3.534	0.420
220 kV Crans	3.908	0.469	3.433	0.343	2.462	0.521	3.783	0.459
220 kV Banlieue Ouest	3.648	0.347	3.204	0.286	2.257	0.299	3.529	0.368
220 kV Romanel	3.473	0.290	3.051	0.250	2.139	0.214	3.360	0.313
380 kV Romanel	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
220 kV Vaux	3.385	0.309	2.974	0.249	2.080	0.241	3.276	0.325
220 kV Veytaux	2.832	0.509	2.474	0.466	1.741	0.467	2.709	0.309
220 kV St Triphon	2.412	0.554	2.101	0.522	1.487	0.590	2.294	0.252
220 kV Riddes	1.129	0.481	0.996	0.320	0.678	0.616	1.046	0.141
380 kV Bâtiaz	0.549	1.572	1.364	11.260	0.512	1.621	0.657	1.612
380 kV Nant de Drance	0.545	1.627	1.355	11.660	0.509	1.678	0.652	1.670
380 kV Châtelard	0.547	1.623	1.360	11.627	0.511	1.674	0.654	1.665
220 kV Châtelard	0.364	1.112	0.906	7.972	0.340	1.147	0.435	1.141
220 kV Vallorcine	0.356	1.091	0.887	7.819	0.333	1.125	0.426	1.119

Table 4-13: Amplification factors for harmonic injection at 380 kV Romanel – optimal SCL (scenario 3)

4.4.4.1.5 Harmonic injection at 220 kV Mettlen

The following cases were considered for harmonic injection at 220 kV Mettlen:

Case	Description
1	Condition N
2	N-1 on 220 kV Ernen – Seehalten
3	N-1 on 220 kV Airolo – Rotondo
4	N-1 on 220 kV Airolo – Lavorgo
5	N-1 on 220 kV Altgass – Samstagern
6	N-1 on 220 kV Samstagern – Siebnen
7	N-1 on 220 kV Samstagern – Thalwil
8	N-1 on 220 kV Mettlen – Sursee
9	N-1 on 220 kV Gösgen – Laufenburg

10	N-1 on 220 kV Gösgen – Ormalingen
11	N-1 on 220 kV Altgass – Mettlen
12	N-2 on 220 kV Airolo – Rotondo and Airolo – Lavorgo
13	N-2 on 220 kV Obfelden – Waldegg
14	N-2 on 220 kV Birr – Niederwil and Mettlen – Obfelden
15	N-2 on 220 kV Mettlen – Obfelden and Breite – Fällanden

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV Mettlen under low and optimal SCL conditions are presented in Table 4-14 and Table 4-15, respectively.

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	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mettlen	0.349	1.104	0.341	0.695	0.347	0.483	0.333	0.575	0.356	0.849	0.359	0.845	0.349	1.100	0.322	1.177
220 kV Obfelden	0.976	0.409	0.979	0.370	0.975	0.407	0.982	0.359	0.880	0.143	0.985	0.620	0.998	0.470	0.961	0.471
220 kV Waldegg	1.054	0.368	1.058	0.441	1.054	0.526	1.060	0.464	0.916	0.276	1.093	0.914	1.089	0.438	1.042	0.402
220 kV Thalwil	1.047	0.331	1.050	0.449	1.046	0.543	1.051	0.483	0.890	0.333	1.103	0.985	1.109	0.441	1.036	0.340
220 kV Samstagern	0.992	0.357	0.995	0.496	0.992	0.585	0.994	0.539	0.802	0.450	1.082	1.070	0.981	0.359	0.985	0.316
220 kV Altgass	1.008	0.656	1.009	0.737	1.008	0.786	1.009	0.764	1.009	1.023	1.053	1.062	1.002	0.669	1.004	0.622
220 kV Niederwil	0.750	1.497	0.755	1.155	0.750	0.987	0.765	1.028	0.683	0.519	0.698	0.327	0.760	1.490	0.724	1.619
220 kV Regensdorf	0.785	2.426	0.796	1.961	0.784	1.707	0.799	1.769	0.715	0.761	0.685	0.818	0.790	2.359	0.762	2.622
220 kV Seebach	0.789	2.553	0.802	2.080	0.789	1.817	0.802	1.880	0.720	0.796	0.680	0.902	0.794	2.477	0.767	2.759
220 kV Auwiesen	0.786	2.570	0.800	2.097	0.786	1.834	0.799	1.897	0.717	0.799	0.675	0.919	0.790	2.492	0.764	2.777
220 kV Fällanden	0.770	2.611	0.785	2.146	0.770	1.885	0.782	1.946	0.704	0.803	0.651	0.981	0.773	2.527	0.750	2.820
220 kV Aathal	0.683	1.747	0.708	1.522	0.682	1.400	0.688	1.419	0.675	0.332	0.685	0.462	0.683	1.683	0.661	1.830
220 kV Grynau	0.743	1.616	0.771	1.374	0.743	1.244	0.746	1.267	0.739	0.300	0.752	0.425	0.744	1.556	0.724	1.709
220 kV Benken	0.636	2.276	0.645	1.832	0.636	1.588	0.645	1.637	0.548	0.767	0.437	1.062	0.635	2.191	0.628	2.489
220 kV Siebnen	0.739	1.553	0.745	1.223	0.739	1.040	0.745	1.072	0.621	0.671	0.433	1.059	0.735	1.478	0.731	1.722
220 kV Giswil	0.643	1.231	0.736	0.770	0.654	0.497	0.791	0.454	0.645	0.862	0.646	0.867	0.643	1.179	0.644	1.008
220 kV Innertkirchen	0.561	1.909	0.687	1.399	0.585	1.060	0.713	1.012	0.574	1.233	0.584	1.297	0.562	1.843	0.541	1.613
220 kV Handeck	0.497	1.979	0.630	1.502	0.524	1.183	0.643	1.125	0.514	1.279	0.527	1.345	0.497	1.913	0.473	1.684
220 kV Grimsel	0.461	1.973	0.595	1.521	0.490	1.222	0.598	1.160	0.481	1.272	0.496	1.338	0.461	1.908	0.434	1.688
220 kV Seehalten	0.436	1.954	0.568	1.523	0.466	1.244	0.562	1.178	0.457	1.256	0.474	1.322	0.436	1.890	0.405	1.679
220 kV Airolo	0.675	1.406	0.711	0.885	0.636	1.296	0.446	1.786	0.701	0.955	0.733	0.992	0.674	1.367	0.559	1.264
220 kV Sils	1.406	0.653	1.423	0.477	1.405	0.425	1.416	0.400	1.378	0.274	1.380	0.341	1.409	0.630	1.335	0.794

	Case 9		Case 10		Case 11		Case 12		Case 13		Case 14		Case 15	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mettlen	0.352	1.103	0.339	1.197	0.356	0.833	0.309	0.559	0.350	1.110	0.298	0.926	0.348	0.842
220 kV Obfelden	0.973	0.379	0.973	0.454	0.946	0.141	0.977	0.360	0.832	0.600	1.288	0.591	1.120	0.465
220 kV Waldegg	1.052	0.346	1.052	0.348	1.013	0.286	1.053	0.468	1.257	0.811	1.315	0.313	1.188	0.203
220 kV Thalwil	1.045	0.319	1.044	0.268	1.000	0.348	1.044	0.487	1.206	0.752	1.261	0.120	1.167	0.040
220 kV Samstagern	0.991	0.369	0.990	0.231	0.935	0.478	0.987	0.545	1.061	0.565	1.113	0.343	1.082	0.362
220 kV Altgass	1.007	0.667	1.007	0.593	0.943	0.487	1.005	0.767	1.043	0.785	1.068	0.685	1.053	0.698
220 kV Niederwil	0.744	1.452	0.746	1.648	0.729	0.469	0.761	1.023	0.686	1.585	1.179	1.109	0.931	0.958
220 kV Regensdorf	0.781	2.343	0.781	2.687	0.760	0.674	0.776	1.762	0.747	2.438	1.099	1.346	1.050	1.364
220 kV Seebach	0.787	2.464	0.786	2.830	0.764	0.703	0.772	1.873	0.760	2.552	1.063	1.363	1.074	1.409
220 kV Auwiesen	0.784	2.480	0.783	2.850	0.761	0.706	0.768	1.890	0.759	2.565	1.048	1.356	1.075	1.410
220 kV Fällanden	0.769	2.518	0.768	2.896	0.745	0.707	0.743	1.940	0.753	2.590	0.977	1.314	1.074	1.403
220 kV Aathal	0.686	1.701	0.680	1.862	0.674	0.258	0.581	1.427	0.676	1.741	0.661	0.738	0.665	0.534
220 kV Grynau	0.749	1.568	0.742	1.744	0.736	0.230	0.617	1.273	0.738	1.606	0.717	0.678	0.771	0.568
220 kV Benken	0.635	2.180	0.635	2.572	0.605	0.686	0.639	1.631	0.640	2.189	0.821	1.071	0.884	1.179
220 kV Siebnen	0.738	1.478	0.738	1.783	0.700	0.622	0.739	1.066	0.761	1.422	0.904	0.655	0.940	0.725
220 kV Littau	0.862	0.404	0.861	0.665	0.864	0.691	0.883	0.550	0.862	0.413	0.884	0.586	0.867	0.696
220 kV Giswil	0.640	1.254	0.636	0.990	0.648	0.887	0.671	0.478	0.641	1.226	0.688	0.851	0.652	0.865
220 kV Innertkirchen	0.562	1.936	0.552	1.399	0.571	1.245	0.538	1.042	0.562	1.899	0.574	1.339	0.566	1.210
220 kV Handeck	0.498	2.006	0.486	1.462	0.508	1.289	0.450	1.157	0.499	1.970	0.501	1.393	0.499	1.254
220 kV Grimsel	0.464	2.000	0.450	1.460	0.473	1.280	0.398	1.193	0.464	1.964	0.458	1.391	0.462	1.246
220 kV Seehalten	0.439	1.979	0.424	1.447	0.448	1.263	0.358	1.213	0.440	1.945	0.423	1.378	0.435	1.229
220 kV Airolo	0.689	1.427	0.650	1.082	0.681	0.957	6.143	1.912	0.679	1.406	0.469	1.045	0.641	0.924
220 kV Sils	1.405	0.603	1.396	0.866	1.396	0.255	1.303	0.392	1.383	0.626	1.404	0.319	1.350	0.440

Table 4-14: Amplification factors for harmonic injection at 220 kV Mettlen – low SCL (scenario 3)

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mettlen	0.408	1.357	0.413	0.980	0.414	0.752	0.388	0.907	0.448	0.828	0.458	0.883	0.409	1.369	0.423	1.398
220 kV Obfelden	0.691	1.176	0.688	1.012	0.690	0.988	0.700	1.026	0.398	0.327	0.735	0.705	0.692	1.263	0.692	1.197
220 kV Waldegg	0.778	1.296	0.775	1.063	0.776	1.067	0.786	1.074	0.342	0.527	0.886	0.978	0.779	1.437	0.780	1.312
220 kV Thalwil	0.791	1.233	0.788	0.987	0.790	1.007	0.799	0.997	0.289	0.606	0.934	1.032	0.792	1.475	0.794	1.245
220 kV Samstagern	0.786	1.032	0.784	0.788	0.785	0.831	0.793	0.790	0.185	0.730	0.992	1.092	0.784	0.981	0.790	1.035
220 kV Altgass	0.900	0.930	0.899	0.763	0.900	0.814	0.904	0.759	0.185	0.740	1.004	1.070	0.900	0.909	0.903	0.920
220 kV Niederwil	0.285	1.693	0.278	1.882	0.282	1.680	0.299	1.902	0.119	0.550	0.222	0.487	0.286	1.729	0.283	1.769
220 kV Regensdorf	0.144	2.584	0.132	2.956	0.141	2.664	0.159	3.013	0.128	0.817	0.098	0.984	0.145	2.584	0.146	2.716
220 kV Seebach	0.107	2.739	0.095	3.130	0.105	2.829	0.120	3.192	0.158	0.866	0.139	1.091	0.108	2.732	0.108	2.880
220 kV Auwiesen	0.100	2.759	0.087	3.153	0.097	2.851	0.111	3.217	0.167	0.872	0.154	1.112	0.101	2.750	0.099	2.901
220 kV Fällanden	0.079	2.815	0.073	3.221	0.080	2.920	0.078	3.289	0.210	0.891	0.224	1.192	0.080	2.799	0.072	2.962
220 kV Aathal	0.305	1.579	0.320	1.929	0.311	1.748	0.276	1.978	0.343	0.377	0.334	0.558	0.305	1.568	0.288	1.666
220 kV Grynau	0.304	1.480	0.321	1.791	0.311	1.617	0.274	1.837	0.344	0.323	0.337	0.504	0.305	1.469	0.285	1.564
220 kV Benken	0.267	0.451	0.273	0.129	0.143	2.660	0.154	2.992	0.200	0.896	0.287	1.317	0.144	2.554	0.150	2.715
220 kV Siebnen	0.296	1.994	0.287	2.164	0.293	1.985	0.311	2.220	0.121	0.839	0.284	1.304	0.295	1.954	0.307	2.090
220 kV Littau	0.913	1.196	0.948	0.759	0.908	0.840	0.924	0.698	0.924	0.883	0.927	0.946	0.913	1.185	0.909	1.200
220 kV Giswil	0.860	2.376	0.988	2.379	0.840	1.668	0.898	1.726	0.898	1.230	0.907	1.491	0.860	2.358	0.846	2.393
220 kV Innertkirchen	0.779	2.779	0.955	3.169	0.751	2.120	0.828	2.332	0.829	1.415	0.843	1.727	0.779	2.765	0.760	2.801
220 kV Handeck	0.731	2.753	0.926	3.260	0.701	2.182	0.785	2.415	0.785	1.406	0.799	1.712	0.731	2.740	0.714	2.779
220 kV Grimsel	0.679	2.674	0.900	3.237	0.667	2.167	0.754	2.412	0.753	1.369	0.767	1.665	0.698	2.662	0.682	2.702
220 kV Seehalten	0.676	2.605	0.887	3.212	0.644	2.151	0.734	2.423	0.733	1.337	0.747	1.627	0.676	2.594	0.662	2.635
220 kV Airolo	0.570	1.500	0.672	1.624	0.699	0.909	0.757	3.029	0.656	0.719	0.673	0.888	0.570	1.495	0.568	1.509
220 kV Sils	0.898	0.972	1.250	0.306	1.243	0.344	1.235	0.279	0.999	0.204	0.792	0.262	1.241	0.487	1.208	0.478

	Case 9		Case 10		Case 11		Case 12		Case 13		Case 14		Case 15	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mettlen	0.429	0.975	0.410	0.968	0.452	0.972	0.365	0.332	0.414	0.972	0.424	1.062	0.411	0.923
220 kV Obfelden	0.683	0.986	0.688	1.045	0.390	0.316	0.709	0.702	0.539	0.979	0.482	1.064	0.529	0.816
220 kV Waldegg	0.770	1.035	0.775	1.093	0.330	0.571	0.796	0.751	1.048	1.386	0.610	0.786	0.654	0.614
220 kV Thalwil	0.784	0.962	0.788	1.012	0.276	0.665	0.808	0.709	1.003	1.274	0.657	0.550	0.698	0.454
220 kV Samstagern	0.781	0.771	0.784	0.798	0.169	0.823	0.800	0.615	0.879	0.926	0.723	0.287	0.756	0.357
220 kV Altgass	0.898	0.760	0.900	0.750	0.170	0.834	0.908	0.730	0.947	0.876	0.869	0.609	0.885	0.648
220 kV Niederwil	0.269	1.852	0.278	1.957	0.108	0.640	0.316	1.503	0.221	1.917	0.205	1.586	0.268	1.240
220 kV Regensdorf	0.122	2.904	0.132	3.089	0.131	0.937	0.182	2.460	0.111	2.972	0.075	1.828	0.197	1.814
220 kV Seebach	0.087	3.073	0.094	3.273	0.165	0.985	0.142	2.615	0.086	3.141	0.054	1.845	0.174	1.893
220 kV Auwiesen	0.080	3.096	0.086	3.297	0.176	0.991	0.132	2.637	0.083	3.163	0.054	1.833	0.167	1.900
220 kV Fällanden	0.073	3.161	0.071	3.370	0.221	1.005	0.091	2.708	0.081	3.225	0.075	1.776	0.140	1.916
220 kV Aathal	0.331	1.904	0.318	1.991	0.360	0.396	0.239	1.722	0.328	1.934	0.323	0.919	0.313	0.780
220 kV Grynau	0.332	1.763	0.319	1.857	0.362	0.361	0.235	1.567	0.328	1.793	0.324	0.857	0.291	0.790
220 kV Benken	0.128	2.858	0.132	3.070	0.208	1.013	0.171	1.427	0.147	2.884	0.099	1.523	0.208	1.678
220 kV Siebnen	0.281	2.113	0.287	2.280	0.123	0.952	0.330	1.739	0.324	2.114	0.242	1.035	0.340	1.133
220 kV Littau	0.950	0.755	0.947	0.754	0.961	0.609	0.931	0.516	0.948	0.765	0.949	0.561	0.914	0.857
220 kV Giswil	0.994	2.361	0.986	2.164	1.033	1.196	0.923	1.066	0.988	2.375	0.993	1.549	0.862	1.238
220 kV Innertkirchen	0.965	3.146	0.953	2.883	1.015	1.719	0.864	1.650	0.956	3.158	0.962	2.207	0.782	1.474
220 kV Handeck	0.935	3.237	0.923	2.978	0.990	1.772	0.827	1.773	0.927	3.250	0.934	2.268	0.735	1.468
220 kV Grimsel	0.910	3.213	0.898	2.965	0.967	1.761	0.798	1.801	0.901	3.227	0.910	2.254	0.702	1.435
220 kV Seehalten	0.897	3.188	0.885	2.950	0.955	1.748	0.781	1.821	0.888	3.202	0.897	2.237	0.174	1.893
220 kV Airolo	0.684	1.605	0.671	1.593	0.765	0.813	4.198	2.063	0.675	1.623	0.694	1.038	0.578	1.729
220 kV Sils	1.250	0.304	1.247	0.291	1.004	0.051	1.222	0.401	1.234	0.303	1.187	0.114	1.207	0.255

Table 4-15: Amplification factors for harmonic injection at 220 kV Mettlen – optimal SCL (scenario 3)

4.4.4.1.6 Harmonic injection at 220 kV Gerlafingen

The following cases were considered for harmonic injection at 220 kV Gerlafingen:

Case	Description
1	Condition N
2	N-1 on 220 kV Froloo – Lachmatt
3	N-1 on 220 kV Froloo – Ormalingen
4	N-1 on 220 kV Lachmatt – Münchwilen
5	N-1 on 220 kV Laufenburg – Münchwilen

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV Gerfalingen under low SCL conditions are presented in Table 4-16.

	Case 1		Case 2		Case 3		Case 4		Case 5	
	5	7	5	7	5	7	5	7	5	7
220 kV Flumenthal	0.699	0.903	0.829	1.415	0.710	0.958	0.752	1.053	1.053	0.624
220 kV Froloo	0.618	1.028	0.895	1.950	0.657	1.152	0.737	1.279	1.419	1.529
220 kV Lachmatt	0.518	0.888	0.155	0.221	0.545	0.989	0.679	1.165	1.572	1.956
380 kV Lachmatt	0.131	0.347	0.093	0.283	0.127	0.327	0.116	0.317	0.247	0.272
380 kV Asphard	0.125	0.356	0.091	0.286	0.121	0.336	0.109	0.328	0.230	0.278
220 kV Münchwilen	0.328	0.527	0.145	0.142	0.333	0.569	0.122	0.059	1.772	2.346
220 kV Ormalingen	0.447	0.655	0.575	1.169	0.274	0.263	0.488	0.770	0.892	0.874
220 kV Bickigen	0.293	0.139	0.333	0.240	0.292	0.148	0.299	0.176	0.411	0.125
380 kV Bickigen	0.168	0.313	0.161	0.205	0.164	0.300	0.161	0.254	0.248	0.307
220 kV Mühleberg	0.151	0.351	0.140	0.349	0.150	0.327	0.134	0.393	0.203	0.377
380 kV Mühleberg	0.136	0.223	0.114	0.224	0.133	0.222	0.121	0.216	0.203	0.207
220 kV Gösgen	0.331	0.387	0.357	0.594	0.275	0.262	0.319	0.402	0.529	0.391
380 kV Gösgen	0.141	0.337	0.124	0.202	0.132	0.341	0.128	0.310	0.238	0.295
220 kV Sursee	0.265	0.217	0.288	0.329	0.232	0.154	0.254	0.238	0.408	0.230
220 kV Laufenburg	0.242	0.328	0.135	0.100	0.240	0.343	0.122	0.059	0.204	0.061
380 kV Laufenburg	0.102	0.332	0.077	0.257	0.098	0.314	0.085	0.314	0.174	0.271
220 kV Lindenholz	0.230	0.193	0.159	0.168	0.227	0.190	0.148	0.208	0.236	0.194
220 kV Oftringen	0.257	0.207	0.221	0.069	0.250	0.232	0.200	0.067	0.303	0.030
220 kV Innertkirchen	0.259	0.877	0.264	1.063	0.244	0.828	0.258	0.918	0.378	0.568
220 kV Handeck	0.256	0.875	0.251	1.079	0.241	0.824	0.254	0.920	0.384	0.561

220 kV Grimsel	0.254	0.848	0.244	1.055	0.240	0.797	0.251	0.894	0.386	0.547
220 kV Seehalten	0.254	0.817	0.240	1.024	0.240	0.768	0.250	0.863	0.390	0.531

Table 4-16: Amplification factors for harmonic injection at 220 kV Gerlafingen – low SCL (scenario 3)

4.4.4.1.7 Harmonic injection at 220 kV Mühleberg

The following cases were considered for harmonic injection at 220 kV Mühleberg:

Case	Description
1	Condition N
2	N-1 on 220 kV Hauterive – St. Triphon
3	N-1 on 220 kV Botterens – St. Triphon
4	N-1 on 220 kV Chamoson – Gstaad
5	N-1 on 220 kV Chamoson – Riddes
6	N-2 on 220 kV Chamoson – Riddes
7	N-2 on 220 kV Chamoson – Mühleberg and Chamoson – Gstaad
8	N-2 on 220 kV Botterens – St Triphon and Hauterive – St Triphon

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV Mühleberg under low SCL conditions are presented in Table 4-17.

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mühleberg	0.456	0.617	0.457	0.553	0.457	0.553	0.458	0.569	0.456	0.617	0.456	0.616	0.460	0.525	0.457	0.497
220 kV Bickigen	0.216	0.183	0.216	0.116	0.216	0.118	0.214	0.128	0.216	0.182	0.216	0.181	0.211	0.090	0.217	0.072
380 kV Bickigen	0.148	1.263	0.157	0.798	0.158	0.801	0.144	0.882	0.148	1.259	0.148	1.254	0.139	0.607	0.168	0.459
220 kV Lindenholz	0.614	0.514	0.610	0.452	0.610	0.454	0.617	0.449	0.614	0.512	0.614	0.510	0.620	0.458	0.607	0.477
220 kV Flumenthal	0.255	1.188	0.254	0.832	0.254	0.832	0.256	0.881	0.255	1.185	0.255	1.183	0.258	0.656	0.254	0.566
220 kV Gerlafingen	0.240	1.115	0.239	0.780	0.239	0.780	0.241	0.826	0.240	1.112	0.240	1.110	0.242	0.615	0.238	0.531
220 kV Froloo	0.262	1.506	0.260	1.048	0.260	1.048	0.264	1.113	0.262	1.502	0.262	1.499	0.267	0.825	0.259	0.706
220 kV Kerzers	0.982	0.984	0.982	0.984	0.982	0.984	0.982	0.984	0.982	0.984	0.982	0.984	0.982	0.984	0.982	0.984
220 kV Galmiz	0.976	0.978	0.976	0.978	0.976	0.978	0.976	0.978	0.976	0.978	0.976	0.978	0.976	0.978	0.976	0.978
220 kV Wimmis	0.229	2.240	0.231	1.399	0.231	1.408	0.207	1.491	0.229	2.232	0.228	2.223	0.185	0.958	0.234	0.793
220 kV Gstaad	0.606	2.279	0.572	1.632	0.571	1.635	1.176	1.525	0.605	2.272	0.603	2.268	1.180	1.507	0.535	1.155
220 kV Chamoson	0.280	1.989	0.237	1.266	0.236	1.272	0.181	1.257	0.279	1.982	0.277	1.976	0.081	0.746	0.190	0.741
380 kV Chamoson	0.146	1.134	0.102	0.695	0.101	0.699	0.153	0.780	0.147	1.130	0.148	1.127	0.161	0.529	0.063	0.377
220 kV Chandoline	0.187	1.774	0.161	1.121	0.161	1.126	0.114	1.135	0.186	1.767	0.185	1.762	0.048	0.687	0.134	0.647
220 kV Botterens	0.771	2.401	0.683	1.654	0.986	1.145	0.750	1.966	0.771	2.397	0.772	2.393	0.729	1.632	0.990	1.142
220 kV Hauterive	0.860	1.828	0.969	1.098	0.810	1.416	0.849	1.596	0.860	1.826	0.861	1.824	0.837	1.409	0.972	1.095
220 kV Botterens	0.771	2.401	0.683	1.654	0.986	1.145	0.750	1.966	0.771	2.397	0.772	2.393	0.729	1.632	0.990	1.142
220 kV Riddes	0.282	1.984	0.231	1.247	0.230	1.253	0.192	1.277	0.282	1.975	0.284	1.963	0.100	0.781	0.175	0.713
220 kV St Triphon	0.387	2.304	0.244	1.306	0.241	1.316	0.352	1.690	0.387	2.297	0.389	2.289	0.317	1.241	0.088	0.590
220 kV Veytaux	0.294	1.990	0.186	1.135	0.183	1.144	0.275	1.450	0.294	1.984	0.295	1.977	0.255	1.055	0.067	0.526
220 kV Romanel	0.054	0.275	0.047	0.117	0.047	0.118	0.026	0.224	0.054	0.274	0.054	0.272	0.011	0.189	0.048	0.009
380 kV Romanel	0.435	1.058	0.284	0.690	0.279	0.693	0.389	0.690	0.435	1.054	0.436	1.050	0.343	0.429	0.113	0.425

Table 4-17: Amplification factors for harmonic injection at 220 kV Mühleberg – low SCL (scenario 3)

4.4.4.1.8 Harmonic injection at 220 kV Sils

The following cases were considered for harmonic injection at 220 kV Sils:

Case	Description
1	Condition N
2	N-1 on 220 kV Castasegna – Löbbia
3	N-1 on 220 kV Bärenburg – Sils
4	N-1 on 220 kV Sils – Tiefencastel
5	N-1 on 220 kV Sils – Tinzen
6	N-1 on 220 kV Benken – Siebnen
7	N-1 on 220 kV Benken – Sils
8	N-2 on 220 kV Bärenburg – Sils

The amplification factors on the 5^{th} and 7^{th} harmonics for harmonic injection at 220 kV Sils under low SCL conditions are presented in Table 4-18.

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
220 kV Bärenburg	0.962	0.965	0.962	0.965	0.924	0.929	0.962	0.965	0.962	0.965	0.962	0.965	0.962	0.965	0.000	0.000
220 kV Ferrera	0.940	0.944	0.940	0.944	0.903	0.908	0.940	0.944	0.940	0.944	0.940	0.944	0.940	0.944	0.000	0.000
220 kV Tiefencastel	1.003	1.034	1.007	1.038	1.003	1.034	1.012	1.166	1.007	1.070	1.003	1.034	1.003	1.034	1.003	1.034
220 kV Tinzen	1.013	1.085	1.023	1.095	1.013	1.085	1.019	1.173	1.022	1.172	1.013	1.085	1.013	1.085	1.013	1.085
220 kV Löbbia	1.045	1.229	1.075	1.256	1.045	1.229	1.050	1.328	1.054	1.327	1.045	1.229	1.045	1.229	1.045	1.229
220 kV Castasegna	1.029	1.212	0.000	0.000	1.029	1.212	1.034	1.310	1.037	1.310	1.029	1.212	1.029	1.212	1.029	1.212
380 kV Sils	0.798	0.148	0.798	0.148	0.798	0.148	0.798	0.148	0.798	0.148	0.793	0.158	0.942	0.154	0.798	0.148
380 kV Soazza	0.862	0.339	0.862	0.339	0.862	0.339	0.862	0.339	0.862	0.339	0.866	0.364	1.036	0.374	0.862	0.339
220 kV Soazza	0.496	0.174	0.496	0.174	0.496	0.174	0.496	0.174	0.496	0.174	0.514	0.180	0.630	0.206	0.496	0.174
380 kV Tavanasa	0.542	0.159	0.542	0.159	0.542	0.159	0.542	0.159	0.542	0.159	0.532	0.166	0.662	0.153	0.542	0.159
220 kV Tavanasa	0.152	0.029	0.152	0.029	0.152	0.029	0.152	0.029	0.152	0.029	0.144	0.017	0.201	0.058	0.152	0.029
220 kV Benken	0.208	0.173	0.208	0.173	0.208	0.173	0.208	0.173	0.208	0.173	0.176	0.221	0.424	0.081	0.208	0.173
220 kV Siebnen	0.232	0.141	0.232	0.141	0.232	0.141	0.232	0.141	0.232	0.141	0.328	0.120	0.417	0.068	0.232	0.141
220 kV Samstagern	0.299	0.084	0.299	0.084	0.299	0.084	0.299	0.084	0.299	0.084	0.331	0.121	0.405	0.037	0.299	0.084
220 kV Grynau	0.378	0.142	0.378	0.142	0.378	0.142	0.378	0.142	0.378	0.142	0.393	0.174	0.398	0.029	0.378	0.142
220 kV Tierfehd	0.102	0.161	0.102	0.161	0.102	0.161	0.102	0.161	0.102	0.161	0.111	0.191	0.076	0.073	0.102	0.161
380 kV Tierfehd	0.251	0.217	0.251	0.217	0.251	0.217	0.251	0.217	0.251	0.217	0.244	0.235	0.324	0.162	0.251	0.217
380 kV Limmern	0.251	0.218	0.251	0.218	0.251	0.218	0.251	0.218	0.251	0.218	0.244	0.236	0.323	0.162	0.251	0.218
380 kV Bonaduz	0.775	0.155	0.775	0.155	0.775	0.155	0.775	0.155	0.775	0.155	0.769	0.165	0.920	0.161	0.775	0.155
220 kV Rothenbrunnen	0.244	0.168	0.244	0.168	0.244	0.168	0.244	0.168	0.244	0.168	0.268	0.209	0.208	0.040	0.244	0.168
220 kV Sarelli	0.500	0.287	0.500	0.287	0.500	0.287	0.500	0.287	0.500	0.287	0.559	0.350	0.349	0.074	0.500	0.287
220 kV Ilanz	0.176	0.071	0.176	0.071	0.176	0.071	0.176	0.071	0.176	0.071	0.178	0.087	0.205	0.048	0.176	0.071
220 kV Winkeln	0.588	0.045	0.588	0.045	0.588	0.045	0.588	0.045	0.588	0.045	0.635	0.048	0.511	0.066	0.588	0.045

Table 4-18: Amplification factors for harmonic injection at 220 kV Sils – low SCL (scenario 3)

4.4.4.1.9 Harmonic injection at 220 kV St. Triphon

The following cases were considered for harmonic injection at 220 kV St. Triphon:

Case	Description
1	Condition N
2	N-1 on 220 kV Romanel – Vaux
3	N-1 on 220 kV Vaux – Verbois
4	N-1 on 220 kV Crans – Foretaille
5	N-1 on 220 kV Banlieue Ouest – Foretaille
6	N-1 on 220 kV Cornier – Riddes
7	N-1 on 220 kV Botterens – Mühleberg
8	N-1 on 220 kV Hauterive – Mühleberg
9	N-1 on 220 kV Chamoson – Mühleberg
10	N-1 on 220 kV Gstaad – Mühleberg
11	N-2 on 220 kV Riddes – St. Triphon

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV St. Striphon under low SCL conditions are presented in Table 4-19.

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8		Case 9		Case 10		Case 11	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
220 kV Botterens	0.839	1.438	0.838	1.438	0.839	1.437	0.839	1.455	0.837	1.506	0.837	1.428	1.133	1.577	0.770	1.278	0.832	1.313	0.834	1.351	0.786	1.398
220 kV Hauterive	0.654	1.276	0.653	1.275	0.654	1.274	0.654	1.298	0.652	1.362	0.652	1.263	0.547	1.028	0.947	1.329	0.645	1.116	0.648	1.165	0.581	1.229
220 kV Chamoson	0.367	1.062	0.365	1.064	0.367	1.058	0.356	1.119	0.346	1.305	0.354	1.020	0.344	0.965	0.347	0.981	0.326	0.772	0.358	1.023	0.090	1.033
380 kV Chamoson	0.364	0.587	0.373	0.595	0.364	0.581	0.398	0.689	0.433	1.048	0.366	0.575	0.362	0.549	0.362	0.556	0.372	0.495	0.365	0.571	0.465	0.556
220 kV Gstaad	0.453	1.477	0.451	1.478	0.453	1.473	0.444	1.542	0.435	1.750	0.442	1.430	0.378	1.243	0.387	1.283	0.417	1.097	0.405	1.386	0.061	1.412
220 kV Romanel	0.126	0.146	0.124	0.137	0.124	0.112	0.112	0.258	0.124	0.978	0.125	0.152	0.131	0.164	0.131	0.161	0.122	0.191	0.125	0.153	0.132	0.194
380 kV Romanel	1.085	0.578	1.102	0.576	1.084	0.576	1.157	0.612	1.226	0.728	1.084	0.555	1.083	0.511	1.083	0.522	1.081	0.414	1.084	0.548	1.048	0.588
220 kV Mühleberg	0.432	0.959	0.431	0.958	0.431	0.957	0.431	0.984	0.428	1.058	0.429	0.943	0.285	0.664	0.301	0.714	0.418	0.766	0.423	0.826	0.331	0.917
380 kV Mühleberg	0.190	0.547	0.190	0.547	0.190	0.545	0.191	0.580	0.188	0.675	0.189	0.537	0.123	0.413	0.131	0.436	0.185	0.439	0.187	0.486	0.155	0.520
220 kV Riddes	0.418	1.035	0.416	1.036	0.418	1.032	0.408	1.086	0.399	1.252	0.403	0.992	0.397	0.949	0.400	0.964	0.382	0.780	0.409	1.000	0.081	1.009
380 kV Bâtiaz	0.653	0.317	0.666	0.329	0.653	0.310	0.706	0.421	0.757	0.832	0.655	0.316	0.650	0.312	0.651	0.313	0.658	0.306	0.654	0.315	0.730	0.302
380 kV Nant de Drance	0.663	0.333	0.676	0.346	0.663	0.326	0.716	0.444	0.769	0.874	0.664	0.332	0.660	0.328	0.660	0.329	0.668	0.322	0.664	0.332	0.741	0.317
380 kV Châtelard	0.662	0.332	0.675	0.344	0.662	0.325	0.716	0.442	0.768	0.871	0.664	0.330	0.659	0.326	0.660	0.327	0.667	0.320	0.663	0.330	0.740	0.315
220 kV Châtelard	0.521	0.273	0.531	0.283	0.522	0.268	0.564	0.363	0.606	0.714	0.523	0.272	0.519	0.269	0.520	0.270	0.526	0.264	0.522	0.272	0.582	0.261
220 kV Veytaux	0.771	0.851	0.783	0.852	0.780	0.864	0.773	0.820	0.773	0.643	0.772	0.849	0.772	0.844	0.771	0.846	0.774	0.834	0.772	0.849	0.827	0.843

Table 4-19: Amplification factors for harmonic injection at 220 kV St. Triphon – low SCL (scenario 3)

4.4.4.1.10 Harmonic injection at 220 kV Wimmis

The following cases were considered for harmonic injection at 220 kV Wimmis:

Case	Description
1	Condition N
2	N-1 on 220 kV Bickigen – Mühleberg
3	N-1 on 220 kV Bickigen – Oftringen
4	N-1 on 220 kV Bickigen – Flumenthal
5	N-1 on 220 kV Bickigen – Mettlen
6	N-1 on 220 kV Bickigen – Innertkirchen
7	N-2 on 220 kV Airolo – Lavorgo and Airolo – Rotondo
8	N-2 on 220 kV Ernen – Seehalten and Rotondo – Seehalten

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV Wimmis under low SCL conditions are presented in Table 4-20.

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
220 kV Airolo	0.197	0.152	0.203	0.183	0.201	0.154	0.141	0.163	0.200	0.156	0.200	0.176	0.805	0.052	0.060	0.210
220 kV Bickigen	0.171	0.040	0.185	0.061	0.180	0.041	0.189	0.056	0.184	0.045	0.187	0.064	0.126	0.095	0.128	0.117
380 kV Bickigen	0.090	0.085	0.092	0.015	0.092	0.085	0.077	0.131	0.095	0.084	0.100	0.086	0.064	0.094	0.077	0.088
220 kV Chamoson	0.070	0.230	0.058	0.114	0.071	0.231	0.077	0.220	0.073	0.232	0.073	0.238	0.068	0.254	0.070	0.321
380 kV Chamoson	0.046	0.093	0.049	0.025	0.049	0.093	0.065	0.094	0.050	0.093	0.046	0.094	0.050	0.107	0.069	0.120
220 kV Chippis	0.180	0.100	0.176	0.117	0.180	0.100	0.205	0.058	0.182	0.099	0.180	0.089	0.193	0.101	0.225	0.119
380 kV Chippis	0.056	0.095	0.058	0.021	0.059	0.095	0.077	0.098	0.060	0.094	0.057	0.094	0.059	0.110	0.081	0.112
220 kV Giswil	0.142	0.213	0.151	0.243	0.145	0.213	0.125	0.261	0.138	0.221	0.130	0.259	0.136	0.164	0.383	0.119
220 kV Grimsel	0.127	0.240	0.134	0.270	0.131	0.241	0.127	0.298	0.126	0.247	0.120	0.293	0.112	0.218	0.444	0.176
220 kV Gstaad	0.084	0.346	0.058	0.214	0.085	0.347	0.084	0.336	0.089	0.348	0.091	0.358	0.072	0.376	0.067	0.483
220 kV Handeck	0.133	0.245	0.140	0.276	0.137	0.246	0.131	0.304	0.131	0.252	0.124	0.299	0.117	0.218	0.441	0.173
220 kV Innertkirchen	0.141	0.242	0.149	0.273	0.144	0.243	0.138	0.302	0.138	0.250	0.128	0.297	0.123	0.206	0.427	0.160
220 kV Lavorgo	0.222	0.019	0.230	0.021	0.227	0.020	0.152	0.019	0.224	0.018	0.223	0.016	0.117	0.070	0.061	0.038
380 kV Lavorgo	0.264	0.157	0.274	0.179	0.271	0.158	0.193	0.191	0.266	0.163	0.256	0.190	0.149	0.144	0.033	0.193
220 kV Littau	0.123	0.095	0.131	0.114	0.123	0.095	0.088	0.109	0.117	0.102	0.117	0.113	0.145	0.047	0.250	0.026
220 kV Magadino	0.234	0.062	0.242	0.079	0.237	0.064	0.149	0.052	0.234	0.060	0.240	0.063	0.101	0.089	0.091	0.122
220 kV Mettlen	0.117	0.042	0.124	0.055	0.115	0.042	0.077	0.040	0.110	0.047	0.114	0.047	0.153	0.027	0.198	0.043
380 kV Mettlen	0.126	0.057	0.131	0.039	0.128	0.056	0.118	0.021	0.126	0.058	0.116	0.067	0.125	0.075	0.123	0.172
220 kV Mörel	0.079	0.042	0.078	0.011	0.081	0.043	0.114	0.063	0.081	0.043	0.070	0.050	0.089	0.038	0.145	0.071
380 kV Mörel	0.083	0.053	0.086	0.059	0.087	0.053	0.082	0.014	0.085	0.053	0.076	0.051	0.048	0.066	0.068	0.013
220 kV Plattischachen	0.115	0.044	0.122	0.058	0.113	0.043	0.075	0.042	0.108	0.049	0.112	0.049	0.150	0.027	0.192	0.045
220 kV Rotondo	0.183	0.193	0.190	0.230	0.188	0.196	0.132	0.214	0.186	0.198	0.189	0.227	0.103	0.267	0.074	0.260
220 kV Seehalten	0.123	0.234	0.129	0.264	0.127	0.235	0.123	0.290	0.122	0.241	0.118	0.285	0.109	0.217	0.446	0.177
220 kV Stalden	0.131	0.065	0.128	0.069	0.133	0.064	0.163	0.033	0.134	0.063	0.129	0.053	0.146	0.065	0.191	0.101

Table 4-20: Amplification factors for harmonic injection at 220 kV Wimmis – low SCL (scenario 3)

swissgrid

4.4.4.1.11 Harmonic injection at 380 kV Musignano

The following cases were considered for harmonic injection at 380 kV Musignano:

Case	Description
1	Condition N
2	N-1 on 380 kV Lavorgo – Magadino
3	N-1 on 380 kV Lavorgo – Mettlen
4	N-1 on 380 kV Lavorgo – Mörel
5	N-2 on 380 kV Lavorgo – Mörel and Lavorgo – Mettlen

The amplification factors on the 5th and 7th harmonics for harmonic injection at 380 kV Musignano under low SCL conditions are presented in Table 4-21.

	Case 1		Case 2		Case 3		Case 4		Case 5	
	5	7	5	7	5	7	5	7	5	7
380 kV Lavorgo	0.786	2.043	0.227	0.378	0.795	0.815	1.079	2.127	0.997	0.977
220 kV Lavorgo	0.641	1.373	0.312	0.051	0.692	0.576	0.806	1.392	0.818	0.644
380 kV Magadino	1.018	1.078	1.067	1.189	1.034	1.131	1.081	0.939	1.081	1.165
220 kV Magadino	0.729	1.074	0.605	0.517	0.797	0.729	0.822	1.001	0.874	0.759
220 kV Manno	0.712	1.094	0.590	0.527	0.778	0.743	0.802	1.019	0.854	0.773
220 kV Avegno	0.708	1.559	0.557	0.474	0.797	0.819	0.796	1.551	0.875	0.860
220 kV Bavona	0.625	2.008	0.451	0.385	0.736	0.876	0.699	2.062	0.812	0.936
220 kV Verbano	0.701	1.546	0.552	0.471	0.790	0.812	0.789	1.539	0.867	0.853
220 kV Robiei	0.583	1.872	0.408	0.325	0.689	0.791	0.649	1.935	0.760	0.849
220 kV Cavergno	0.681	2.063	0.503	0.439	0.790	0.937	0.762	2.107	0.869	0.995
220 kV Rotondo	0.516	1.650	0.338	0.234	0.614	0.653	0.570	1.726	0.674	0.710
220 kV Peccia	0.655	2.055	0.478	0.414	0.766	0.915	0.733	2.105	0.844	0.975
220 kV Airolo	0.525	1.580	0.309	0.173	0.611	0.612	0.609	1.646	0.693	0.668
220 kV Seehalten	0.352	1.264	0.133	0.325	0.369	0.624	0.321	1.343	0.345	0.720
380 kV Soazza	0.510	0.785	0.411	0.109	0.498	0.346	0.625	0.740	0.593	0.330
220 kV Soazza	0.596	0.257	0.447	0.129	0.622	0.195	0.708	0.244	0.707	0.224
220 kV Gnosca	0.650	0.754	0.476	0.245	0.695	0.461	0.763	0.721	0.783	0.497
220 kV Biasca	0.629	0.984	0.395	0.130	0.676	0.496	0.760	0.970	0.776	0.544

Table 4-21: Amplification factors for harmonic injection at 380 kV Musignano – low SCL (scenario 3)

4.4.4.1.12 Harmonic injection at 380 kV Mettlen

The following cases were considered for harmonic injection at 380 kV Mettlen:

Case	Description
1	Condition N
2	N-1 on 380 kV Lavorgo – Mörel
3	N-1 on 380 kV Lavorgo – Magadino
4	N-1 on 380 kV Gösgen – Laufenburg
5	N-1 on 380 kV Gösgen – Lachmatt
6	N-1 on 380 kV Benken – Sils
7	N-2 on 380 kV Lavorgo – Mörel and Lavorgo – Magadino

The amplification factors on the 5^{th} and 7^{th} harmonics for harmonic injection at 380 kV Mettlen under low and optimal SCL conditions are presented in Table 4-22 and Table 4-23, respectively.

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7
220 kV Mettlen	0.745	0.459	0.885	0.350	0.924	0.653	0.741	0.427	0.718	0.433	1.297	0.441	0.931	0.333
380 kV Lavorgo	1.729	0.852	1.909	0.697	1.223	3.736	1.688	0.530	1.672	0.670	1.589	0.972	1.678	1.532
220 kV Lavorgo	1.823	0.275	1.822	0.144	1.526	1.484	1.777	0.280	1.765	0.277	1.701	0.271	1.815	0.439
380 kV Mörel	1.214	0.163	0.722	0.232	1.039	1.227	1.200	0.113	1.185	0.128	1.228	0.195	0.825	0.232
220 kV Mörel	1.162	0.374	0.911	0.399	1.136	0.340	1.145	0.264	1.134	0.299	1.268	0.399	1.064	0.399
220 kV Gösgen	0.697	0.399	0.903	0.492	0.888	0.436	0.693	0.234	0.667	0.227	1.128	0.428	0.889	0.503
380 kV Breite	0.136	0.542	0.208	0.364	0.150	1.035	0.065	0.645	0.099	0.538	0.156	0.515	0.139	0.341
380 kV Sils	0.663	0.125	0.960	0.097	0.846	0.272	0.726	0.138	0.658	0.118	2.124	0.185	0.941	0.098
380 kV Bonaduz	0.649	0.107	0.941	0.080	0.832	0.243	0.712	0.120	0.645	0.103	2.076	0.172	0.922	0.082
380 kV Mapragg	0.525	0.034	0.762	0.057	0.677	0.044	0.591	0.026	0.527	0.028	1.769	0.058	0.755	0.065
380 kV Benken	0.519	0.577	0.532	0.556	0.524	0.616	0.521	0.632	0.522	0.595	0.861	0.699	0.514	0.553
380 kV Tavanasa	0.536	0.050	0.752	0.067	0.685	0.059	0.582	0.044	0.532	0.045	1.572	0.047	0.746	0.074
380 kV Pradella	0.427	0.143	0.623	0.113	0.547	0.311	0.468	0.158	0.424	0.135	1.380	0.212	0.610	0.113
380 kV Filisur	0.630	0.127	0.914	0.099	0.804	0.276	0.690	0.140	0.625	0.120	2.021	0.188	0.895	0.100
220 kV Tinzen	0.541	0.313	0.746	0.355	0.671	0.436	0.588	0.200	0.536	0.238	1.649	0.323	0.752	0.364
220 kV Obfelden	0.652	0.163	0.842	0.144	0.839	0.290	0.650	0.134	0.627	0.127	1.315	0.178	0.846	0.143
220 kV Waldegg	0.709	0.198	0.909	0.138	0.907	0.379	0.707	0.195	0.682	0.167	1.420	0.190	0.916	0.132
220 kV Giswil	1.640	1.155	1.534	1.000	1.767	1.463	1.605	0.660	1.590	0.891	2.033	1.244	1.789	1.000
220 kV Innertkirchen	1.913	1.206	1.741	1.070	2.008	1.491	1.876	0.612	1.859	0.893	2.241	1.324	2.045	1.079
220 kV Handeck	1.944	1.182	1.738	1.069	2.013	1.422	1.904	0.579	1.889	0.864	2.213	1.303	2.054	1.080

220 kV Grimsel	1.934	1.138	1.715	1.039	1.989	1.350	1.894	0.547	1.879	0.826	2.168	1.257	2.033	1.051
220 kV Seehalten	1.926	1.092	1.697	1.005	1.967	1.280	1.885	0.516	1.871	0.788	2.131	1.209	2.015	1.018
220 kV Rotondo	2.167	0.476	1.981	0.576	2.114	0.364	2.114	0.055	2.102	0.245	2.152	0.576	2.295	0.605
220 kV Ernen	1.376	0.572	1.130	0.571	1.368	0.542	1.352	0.326	1.340	0.430	1.509	0.623	1.331	0.574
220 kV Wimmis	1.453	0.592	1.402	0.330	1.625	1.447	1.443	0.493	1.425	0.531	1.871	0.622	1.550	0.319
220 kV Ingenbohl	0.744	0.476	0.884	0.364	0.922	0.676	0.740	0.442	0.717	0.449	1.293	0.457	0.933	0.345
220 kV Plattischachen	0.739	0.474	0.876	0.363	0.912	0.674	0.735	0.441	0.713	0.448	1.277	0.455	0.929	0.344

Table 4-22: Amplification factors for harmonic injection at 380 kV Mettlen – low SCL (scenario 3)

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7
220 kV Mettlen	0.485	0.615	0.478	0.712	0.521	0.472	0.521	0.489	0.491	0.549	0.705	0.720	0.562	0.308
380 kV Lavorgo	0.819	1.780	1.253	1.870	1.416	3.229	0.833	1.489	0.822	1.626	0.824	1.946	4.053	1.708
220 kV Lavorgo	0.557	0.371	0.819	0.332	0.804	0.833	0.573	0.336	0.561	0.365	0.548	0.397	2.227	0.402
380 kV Mörel	0.444	0.566	0.191	0.361	0.694	1.473	0.448	0.468	0.442	0.516	0.477	0.649	0.259	0.247
220 kV Mörel	0.325	0.463	0.257	0.775	0.426	0.544	0.333	0.435	0.323	0.429	0.382	0.473	0.380	0.319
220 kV Gösgen	0.459	0.072	0.442	0.423	0.486	0.424	0.516	0.190	0.466	0.122	0.576	0.099	0.480	0.283
380 kV Breite	0.222	1.124	0.234	1.320	0.234	0.900	0.263	0.911	0.238	1.004	0.238	1.215	0.300	0.585
380 kV Sils	0.775	0.463	0.767	0.398	0.811	0.291	0.775	0.372	0.765	0.414	1.231	0.476	0.838	0.201
380 kV Bonaduz	0.785	0.426	0.778	0.358	0.821	0.265	0.786	0.343	0.775	0.381	1.228	0.436	0.852	0.188
380 kV Mapragg	0.683	0.185	0.680	0.110	0.715	0.161	0.692	0.155	0.678	0.167	1.054	0.160	0.754	0.166
380 kV Benken	0.374	0.514	0.371	0.531	0.363	0.422	0.383	0.531	0.381	0.521	0.819	0.751	0.333	0.494

380 kV Tavanasa	0.748	0.189	0.748	0.125	0.781	0.165	0.747	0.159	0.738	0.172	1.046	0.167	0.836	0.156
380 kV Pradella	0.334	0.269	0.331	0.231	0.350	0.169	0.335	0.216	0.330	0.240	0.533	0.277	0.362	0.117
380 kV Filisur	0.713	0.449	0.706	0.386	0.746	0.282	0.713	0.361	0.704	0.401	1.134	0.462	0.772	0.195
220 kV Tinzen	0.612	0.492	0.614	0.442	0.639	0.502	0.602	0.413	0.600	0.446	0.849	0.485	0.685	0.391
220 kV Obfelden	0.332	0.414	0.318	0.440	0.357	0.347	0.349	0.348	0.331	0.374	0.550	0.525	0.355	0.269
220 kV Waldegg	0.360	0.497	0.345	0.538	0.388	0.351	0.383	0.408	0.361	0.442	0.608	0.622	0.385	0.270
220 kV Giswil	0.575	1.768	0.539	2.044	0.643	1.524	0.604	1.452	0.576	1.589	0.754	1.962	0.843	0.872
220 kV Innertkirchen	0.586	1.948	0.615	2.249	0.663	1.702	0.612	1.614	0.586	1.756	0.742	2.142	0.921	0.959
220 kV Handeck	0.573	1.883	0.608	2.212	0.653	1.664	0.598	1.563	0.573	1.697	0.714	2.070	0.936	0.963
220 kV Grimsel	0.561	1.802	0.598	2.134	0.641	1.604	0.584	1.498	0.561	1.624	0.692	1.980	0.935	0.942
220 kV Seehalten	0.555	1.732	0.595	2.076	0.636	1.553	0.578	1.442	0.555	1.562	0.679	1.902	0.943	0.923
220 kV Rotondo	0.544	0.963	0.683	1.367	0.618	1.135	0.564	0.818	0.546	0.874	0.600	1.056	1.272	0.805
220 kV Ernen	0.387	0.811	0.350	1.140	0.480	0.682	0.399	0.707	0.386	0.739	0.462	0.867	0.535	0.471
220 kV Wimmis	0.496	1.629	0.442	1.218	0.581	1.433	0.508	1.437	0.488	1.484	0.633	1.645	0.559	0.761
220 kV Ingenbohl	0.458	0.605	0.451	0.700	0.493	0.466	0.492	0.481	0.464	0.540	0.667	0.707	0.536	0.302
220 kV Plattischachen	0.434	0.584	0.428	0.675	0.469	0.449	0.466	0.464	0.440	0.520	0.632	0.681	0.518	0.291
220 kV Airolo	0.588	0.679	0.761	1.052	0.717	0.678	0.611	0.579	0.591	0.618	0.647	0.753	1.604	0.568

Table 4-23: Amplification factors for harmonic injection at 380 kV Mettlen – optimal SCL (scenario 3)

4.4.4.2 Scenario 2

4.4.4.2.1 Harmonic injection at 220 kV Fällanden

The following cases were considered for harmonic injection at 220 kV Fällanden:

Case	Description
1	Condition N
2	N-1 on 220 kV Regensdorf – Seebach
3	N-1 on 220 kV Auwiesen – Seebach
4	N-1 on 220 kV Benken – Siebnen
5	N-1 on 220 kV Benken – Sils
6	N-1 on 220 kV Grynau – Mettlen
7	N-2 on 220 kV Benken – Sils and Benken – Siebnen
8	N-2 on 220 kV Grynau – Tierfehd
9	N-2 on 220 kV Grynau – Winkeln
10	N-2 on 220 kV Niederwil – Regensdorf

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV Fällanden under low and optimal SCL conditions are presented in Table 4-24 and Table 4-25, respectively.

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8		Case 9		Case 10	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
220 kV Auwiesen	0.929	0.837	0.931	0.855	0.931	0.856	0.906	0.815	0.930	0.840	0.917	0.834	0.904	0.819	0.928	0.840	0.930	0.838	0.984	0.989
220 kV Seebach	0.919	0.805	0.931	0.855	0.861	0.596	0.893	0.778	0.919	0.809	0.904	0.802	0.890	0.783	0.918	0.808	0.920	0.806	0.982	0.988
220 kV Regensdorf	0.887	0.682	0.857	0.590	0.860	0.593	0.852	0.638	0.887	0.689	0.864	0.677	0.846	0.646	0.884	0.688	0.889	0.684	0.974	0.980
220 kV Aathal	0.729	0.497	0.714	0.497	0.715	0.497	0.682	0.524	0.719	0.471	0.642	0.569	0.667	0.491	0.718	0.454	0.753	0.495	0.597	0.506
220 kV Grynau	0.777	0.553	0.761	0.554	0.761	0.553	0.727	0.582	0.765	0.522	0.662	0.645	0.710	0.543	0.764	0.502	0.824	0.559	0.635	0.564
220 kV Benken	0.927	0.628	0.909	0.622	0.910	0.622	0.842	0.767	0.935	0.632	0.892	0.631	0.863	0.767	0.919	0.613	0.930	0.630	0.771	0.579
380 kV Benken	0.935	0.412	0.915	0.407	0.916	0.407	0.841	0.459	0.916	0.375	0.889	0.442	0.815	0.407	0.920	0.383	0.939	0.406	0.744	0.386
220 kV Benken	0.927	0.628	0.909	0.622	0.910	0.622	0.842	0.767	0.935	0.632	0.892	0.631	0.863	0.767	0.919	0.613	0.930	0.630	0.771	0.579
380 kV Benken	0.935	0.412	0.915	0.407	0.916	0.407	0.841	0.459	0.916	0.375	0.889	0.442	0.815	0.407	0.920	0.383	0.939	0.406	0.744	0.386
220 kV Siebnen	0.962	0.568	0.943	0.555	0.944	0.556	1.192	0.207	0.965	0.572	0.926	0.560	1.161	0.216	0.954	0.557	0.967	0.570	0.783	0.477
220 kV Samstagern	1.086	0.430	1.065	0.406	1.066	0.407	1.206	0.209	1.077	0.436	1.052	0.397	1.175	0.218	1.073	0.429	1.093	0.435	0.884	0.252
220 kV Altgass	1.095	0.244	1.074	0.229	1.075	0.230	1.163	0.159	1.081	0.246	1.073	0.201	1.132	0.155	1.079	0.242	1.104	0.249	0.894	0.139
220 kV Thalwil	1.150	0.467	1.130	0.433	1.132	0.434	1.229	0.248	1.141	0.475	1.115	0.428	1.199	0.263	1.137	0.469	1.158	0.472	0.953	0.227
220 kV Waldegg	1.161	0.468	1.141	0.432	1.143	0.433	1.222	0.258	1.151	0.478	1.126	0.427	1.192	0.274	1.147	0.471	1.169	0.474	0.966	0.217
220 kV Obfelden	1.079	0.390	1.063	0.354	1.064	0.356	1.101	0.237	1.070	0.400	1.047	0.353	1.075	0.252	1.067	0.395	1.087	0.396	0.913	0.169
220 kV Niederwil	0.863	0.454	0.847	0.397	0.849	0.399	0.830	0.378	0.859	0.463	0.830	0.443	0.817	0.391	0.856	0.461	0.866	0.457	0.748	0.148
220 kV Mettlen	1.148	0.155	1.127	0.151	1.128	0.151	1.141	0.173	1.130	0.140	1.145	0.155	1.109	0.156	1.129	0.129	1.159	0.154	0.940	0.135
380 kV Mettlen	0.940	0.252	0.921	0.241	0.922	0.241	0.895	0.230	0.923	0.242	0.910	0.247	0.869	0.217	0.924	0.241	0.946	0.249	0.758	0.172
220 kV Breite	0.695	0.437	0.681	0.437	0.681	0.437	0.650	0.462	0.686	0.416	0.638	0.486	0.636	0.435	0.685	0.404	0.690	0.426	0.570	0.443
380 kV Breite	0.738	0.411	0.722	0.405	0.722	0.405	0.686	0.437	0.722	0.386	0.679	0.458	0.665	0.398	0.723	0.394	0.739	0.400	0.586	0.386

Table 4-24: Amplification factors for harmonic injection at 220 kV Fällanden – low SCL (scenario 2)

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8		Case 9		Case 10	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
220 kV Auwiesen	0.866	0.883	0.881	0.893	0.881	0.894	0.857	0.868	0.867	0.884	0.864	0.880	0.857	0.869	0.866	0.883	0.867	0.883	0.965	0.969
220 kV Seebach	0.841	0.862	0.881	0.893	0.681	0.724	0.831	0.845	0.843	0.864	0.839	0.859	0.830	0.845	0.842	0.862	0.842	0.863	0.960	0.965
220 kV Regensdorf	0.747	0.781	0.678	0.717	0.680	0.721	0.729	0.753	0.749	0.784	0.743	0.776	0.728	0.754	0.747	0.781	0.748	0.782	0.943	0.949
220 kV Aathal	0.411	0.489	0.408	0.484	0.408	0.484	0.406	0.484	0.408	0.480	0.408	0.495	0.402	0.473	0.431	0.489	0.443	0.517	0.384	0.452
220 kV Grynau	0.436	0.520	0.432	0.515	0.432	0.515	0.430	0.514	0.432	0.510	0.433	0.529	0.425	0.502	0.469	0.526	0.495	0.574	0.409	0.484
220 kV Benken	0.683	0.723	0.675	0.713	0.675	0.714	0.749	0.783	0.720	0.747	0.677	0.716	0.804	0.817	0.681	0.718	0.685	0.724	0.626	0.649
380 kV Benken	0.377	0.442	0.370	0.434	0.370	0.434	0.390	0.447	0.378	0.430	0.369	0.436	0.394	0.435	0.371	0.428	0.380	0.444	0.328	0.380
220 kV Benken	0.683	0.723	0.675	0.713	0.675	0.714	0.749	0.783	0.720	0.747	0.677	0.716	0.804	0.817	0.681	0.718	0.685	0.724	0.626	0.649
380 kV Benken	0.377	0.442	0.370	0.434	0.370	0.434	0.390	0.447	0.378	0.430	0.369	0.436	0.394	0.435	0.371	0.428	0.380	0.444	0.328	0.380
220 kV Siebnen	0.644	0.691	0.633	0.678	0.633	0.679	0.425	0.512	0.675	0.713	0.636	0.680	0.423	0.514	0.643	0.688	0.647	0.694	0.563	0.585
220 kV Samstagern	0.567	0.637	0.548	0.614	0.548	0.616	0.436	0.524	0.585	0.651	0.554	0.614	0.434	0.526	0.567	0.635	0.573	0.641	0.427	0.457
220 kV Altgass	0.446	0.439	0.430	0.423	0.431	0.424	0.361	0.377	0.457	0.448	0.430	0.413	0.359	0.379	0.447	0.438	0.452	0.443	0.332	0.313
220 kV Thalwil	0.591	0.716	0.566	0.686	0.567	0.688	0.481	0.606	0.606	0.730	0.577	0.690	0.479	0.609	0.592	0.715	0.597	0.721	0.407	0.477
220 kV Waldegg	0.593	0.730	0.565	0.698	0.565	0.700	0.495	0.624	0.605	0.743	0.578	0.703	0.493	0.626	0.593	0.729	0.599	0.735	0.389	0.475
220 kV Obfelden	0.544	0.628	0.514	0.598	0.515	0.599	0.474	0.549	0.552	0.638	0.531	0.604	0.473	0.552	0.545	0.627	0.549	0.633	0.327	0.387
220 kV Niederwil	0.582	0.644	0.536	0.601	0.537	0.603	0.551	0.599	0.585	0.648	0.575	0.633	0.549	0.600	0.582	0.643	0.584	0.646	0.251	0.320
220 kV Mettlen	0.326	0.256	0.314	0.247	0.314	0.248	0.291	0.237	0.329	0.258	0.307	0.230	0.289	0.236	0.328	0.254	0.334	0.261	0.238	0.185
380 kV Mettlen	0.248	0.280	0.241	0.272	0.241	0.272	0.238	0.264	0.249	0.276	0.239	0.266	0.236	0.258	0.247	0.273	0.253	0.282	0.197	0.216
220 kV Breite	0.415	0.483	0.411	0.477	0.411	0.477	0.411	0.478	0.411	0.474	0.412	0.486	0.406	0.468	0.419	0.476	0.416	0.481	0.385	0.442
380 kV Breite	0.262	0.388	0.258	0.381	0.258	0.382	0.259	0.382	0.254	0.370	0.259	0.386	0.250	0.362	0.251	0.365	0.266	0.390	0.232	0.337

Table 4-25: Amplification factors for harmonic injection at 220 kV Fällanden – optimal SCL (scenario 2)

4.4.4.2.2 Harmonic injection at 220 kV Verbois

The following cases were considered for harmonic injection at 220 kV Verbois:

Case	Description
1	Condition N
2	N-1 on 220 kV Romanel – Veytaux
3	N-1 on 220 kV Romanel – Vaux
4	N-1 on 220 kV Vaux – Verbois
5	N-2 on 220 kV Romanel – Vaux and Vaux – Verbois

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV Verbois under low and optimal SCL conditions are presented in Table 4-26 and Table 4-27, respectively.

	Case 1		Case 2		Case 3		Case 4		Case 5	
	5	7	5	7	5	7	5	7	5	7
380 kV Verbois	0.606	0.767	0.616	0.774	0.593	0.751	0.589	0.741	0.593	0.748
220 kV Foretaille	0.960	1.013	0.967	1.019	0.951	1.006	0.949	1.003	0.951	1.006
220 kV Crans	0.839	0.934	0.859	0.952	0.812	0.914	0.806	0.904	0.812	0.913
220 kV Banlieue Ouest	0.608	0.779	0.657	0.821	0.541	0.731	0.525	0.706	0.540	0.728
220 kV Romanel	0.576	0.758	0.630	0.805	0.502	0.705	0.484	0.678	0.501	0.703
380 kV Romanel	0.484	0.801	0.505	0.816	0.449	0.764	0.439	0.741	0.447	0.757
220 kV Vaux	0.642	0.794	0.685	0.832	0.900	0.932	0.470	0.658	0.000	0.000
220 kV Veytaux	0.319	0.497	0.164	0.315	0.279	0.464	0.269	0.447	0.278	0.462
220 kV St Triphon	0.239	0.419	0.177	0.337	0.209	0.392	0.202	0.377	0.208	0.390
220 kV Riddes	0.138	0.325	0.114	0.285	0.123	0.306	0.119	0.296	0.122	0.304
380 kV Bâtiaz	0.232	0.682	0.234	0.674	0.214	0.648	0.209	0.629	0.213	0.643
380 kV Nant de Drance	0.235	0.722	0.238	0.713	0.217	0.687	0.212	0.666	0.216	0.681
380 kV Châtelard	0.235	0.717	0.237	0.709	0.217	0.682	0.212	0.661	0.216	0.677
220 kV Châtelard	0.186	0.590	0.187	0.583	0.171	0.561	0.167	0.544	0.170	0.556
220 kV Vallorcine	0.184	0.584	0.185	0.577	0.169	0.555	0.165	0.538	0.168	0.551

Table 4-26: Amplification factors for harmonic injection at 220 kV Verbois – low SCL (scenario 2)

	Case 1		Case 2		Case 3		Case 4		Case 5	
	5	7	5	7	5	7	5	7	5	7
380 kV Verbois	0.481	0.525	0.488	0.533	0.473	0.515	0.469	0.509	0.473	0.514
220 kV Foretaille	0.934	0.971	0.940	0.977	0.926	0.963	0.923	0.959	0.926	0.963
220 kV Crans	0.775	0.824	0.792	0.842	0.752	0.801	0.743	0.790	0.751	0.800
220 kV Banlieue Ouest	0.512	0.574	0.554	0.619	0.452	0.517	0.430	0.490	0.451	0.515
220 kV Romanel	0.479	0.543	0.527	0.594	0.412	0.479	0.387	0.448	0.411	0.477
380 kV Romanel	0.377	0.471	0.394	0.491	0.348	0.438	0.334	0.418	0.345	0.432
220 kV Vaux	0.547	0.604	0.584	0.643	0.782	0.806	0.361	0.420	0.000	0.000
220 kV Veytaux	0.240	0.285	0.112	0.139	0.207	0.251	0.194	0.236	0.206	0.250
220 kV St Triphon	0.176	0.215	0.129	0.159	0.152	0.190	0.143	0.178	0.151	0.189
220 kV Riddes	0.087	0.116	0.070	0.095	0.076	0.104	0.072	0.098	0.076	0.103
380 kV Bâtiaz	0.157	0.256	0.160	0.260	0.144	0.237	0.138	0.225	0.143	0.233
380 kV Nant de Drance	0.156	0.265	0.159	0.269	0.143	0.245	0.137	0.233	0.142	0.242
380 kV Châtelard	0.157	0.264	0.160	0.269	0.144	0.244	0.138	0.233	0.142	0.241
220 kV Châtelard	0.104	0.181	0.106	0.184	0.096	0.167	0.092	0.159	0.095	0.165
220 kV Vallorcine	0.102	0.177	0.104	0.180	0.094	0.164	0.090	0.156	0.093	0.162

Table 4-27: Amplification factors for harmonic injection at 220 kV Verbois – optimal SCL (scenario 2)

4.4.4.2.3 Harmonic injection at 380 kV Bois Tollot

The following cases were considered for harmonic injection at 380 kV Bois Tollot:

Case	Description
1	Condition N
2	N-1 on 380 kV Bâtiaz – Romanel
3	N-1 on 380 kV Bâtiaz – Chamoson
4	N-2 on 380 kV Chamoson – Chippis

The amplification factors on the 5th and 7th harmonics for harmonic injection at 380 kV Bois Tollot under low and optimal SCL conditions are presented in Table 4-28 and Table 4-29, respectively.

	Case 1		Case 2		Case 3		Case 4	
	5	7	5	7	5	7	5	7
380 kV Verbois	0.971	1.000	0.975	0.998	0.980	0.956	0.974	1.007
220 kV Foretaille	0.689	1.028	0.732	0.995	0.787	0.546	0.718	1.114

220 kV Crans	0.632	0.968	0.681	0.930	0.743	0.452	0.665	1.064
220 kV Banlieue Ouest	0.532	0.853	0.595	0.803	0.678	0.287	0.575	0.970
220 kV Romanel	0.521	0.839	0.587	0.787	0.674	0.270	0.566	0.961
380 kV Romanel	0.682	0.983	0.863	0.971	1.078	0.545	0.763	1.203
220 kV Vaux	0.553	0.864	0.607	0.816	0.678	0.330	0.591	0.970
220 kV Veytaux	0.296	0.560	0.317	0.467	0.364	0.159	0.335	0.657
220 kV St Triphon	0.227	0.477	0.228	0.361	0.264	0.127	0.264	0.568
220 kV Riddes	0.149	0.381	0.100	0.204	0.116	0.067	0.180	0.482
380 kV Bâtiaz	0.312	0.827	0.050	0.199	1.361	2.598	0.503	1.379
380 kV Nant de Drance	0.317	0.875	0.051	0.211	1.382	2.756	0.511	1.460
380 kV Châtelard	0.317	0.869	0.051	0.210	1.380	2.736	0.510	1.450
220 kV Châtelard	0.250	0.715	0.040	0.172	1.089	2.248	0.402	1.193
220 kV Vallorcine	0.247	0.708	0.040	0.171	1.077	2.227	0.398	1.182

Table 4-28: Amplification factors for harmonic injection at 380 kV Bois Tollot – low SCL (scenario 2)

	Case 1		**Case 2**		**Case 3**		**Case 4**	
	5	7	5	7	5	7	5	7
380 kV Verbois	0.957	0.970	0.960	0.972	0.960	0.980	0.958	0.971
220 kV Foretaille	0.534	0.675	0.563	0.701	0.560	0.820	0.537	0.687
220 kV Crans	0.476	0.608	0.510	0.636	0.507	0.780	0.479	0.621
220 kV Banlieue Ouest	0.398	0.511	0.448	0.547	0.443	0.755	0.404	0.528
220 kV Romanel	0.396	0.505	0.449	0.544	0.443	0.767	0.401	0.524
380 kV Romanel	0.631	0.738	0.807	0.871	0.791	1.512	0.648	0.783
220 kV Vaux	0.414	0.525	0.455	0.555	0.450	0.735	0.418	0.540
220 kV Veytaux	0.204	0.272	0.218	0.274	0.215	0.388	0.206	0.285
220 kV St Triphon	0.154	0.212	0.154	0.198	0.152	0.278	0.155	0.222
220 kV Riddes	0.091	0.132	0.060	0.081	0.060	0.113	0.091	0.143
380 kV Bâtiaz	0.250	0.387	0.019	0.033	0.693	2.634	0.297	0.503
380 kV Nant de Drance	0.249	0.401	0.019	0.034	0.688	2.726	0.295	0.521
380 kV Châtelard	0.249	0.399	0.019	0.034	0.690	2.718	0.296	0.519
220 kV Châtelard	0.166	0.274	0.013	0.023	0.459	1.866	0.197	0.356
220 kV Vallorcine	0.162	0.268	0.013	0.023	0.449	1.831	0.193	0.349

Table 4-29: Amplification factors for harmonic injection at 380 kV Bois Tollot – optimal SCL (scenario 2)

4.4.4.2.4 Harmonic injection at 380 kV Romanel

The following cases were considered for harmonic injection at 380 kV Romanel:

Case	Description
1	Condition N
2	N-1 on 380 kV Bâtiaz – Chamoson
3	N-1 on 380 kV Bois Tollot – Romanel
4	N-2 on 380 kV Chamoson – Chipps

The amplification factors on the 5th and 7th harmonics for harmonic injection at 380 kV Romanel under low and optimal SCL conditions are presented in Table 4-30 and Table 4-31, respectively.

	Case 1		Case 2		Case 3		Case 4	
	5	7	5	7	5	7	5	7
380 kV Verbois	0.684	0.810	0.681	0.793	0.227	0.383	0.688	0.813
220 kV Foretaille	0.616	0.911	0.607	0.865	0.364	0.609	0.625	0.917
220 kV Crans	0.597	0.870	0.587	0.821	0.388	0.614	0.607	0.876
220 kV Banlieue Ouest	0.580	0.793	0.567	0.739	0.456	0.635	0.592	0.800
220 kV Romanel	0.583	0.786	0.569	0.731	0.472	0.643	0.596	0.793
380 kV Chippis	0.268	0.534	0.048	0.077	0.262	0.520	0.082	0.122
220 kV Vaux	0.565	0.792	0.553	0.739	0.440	0.627	0.577	0.799
220 kV Veytaux	0.339	0.531	0.308	0.427	0.280	0.449	0.360	0.544
220 kV St Triphon	0.267	0.456	0.223	0.322	0.225	0.393	0.289	0.470
220 kV Riddes	0.192	0.371	0.098	0.167	0.174	0.339	0.211	0.398
380 kV Bâtiaz	0.452	0.831	1.262	4.542	0.448	0.817	0.653	1.139
380 kV Nant de Drance	0.459	0.880	1.282	4.809	0.455	0.865	0.664	1.206
380 kV Châtelard	0.458	0.874	1.280	4.777	0.455	0.860	0.663	1.197
220 kV Châtelard	0.362	0.719	1.011	3.931	0.359	0.707	0.523	0.985
220 kV Vallorcine	0.358	0.712	0.999	3.894	0.355	0.700	0.518	0.976

Table 4-30: Amplification factors for harmonic injection at 380 kV Romanel – low SCL (scenario 2)

	Case 1		Case 2		Case 3		Case 4	
	5	7	5	7	5	7	5	7
380 kV Verbois	0.506	0.554	0.504	0.551	0.104	0.137	0.506	0.554
220 kV Foretaille	0.406	0.522	0.399	0.512	0.225	0.296	0.405	0.523
220 kV Crans	0.400	0.503	0.393	0.492	0.256	0.321	0.399	0.504
220 kV Banlieue Ouest	0.427	0.501	0.417	0.487	0.349	0.399	0.427	0.502
220 kV Romanel	0.444	0.512	0.432	0.497	0.374	0.421	0.443	0.513

380 kV Chippis	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
220 kV Vaux	0.399	0.478	0.389	0.464	0.327	0.379	0.398	0.480
220 kV Veytaux	0.235	0.282	0.210	0.249	0.201	0.237	0.233	0.285
220 kV St Triphon	0.183	0.225	0.149	0.179	0.159	0.192	0.180	0.228
220 kV Riddes	0.121	0.154	0.059	0.072	0.112	0.141	0.118	0.160
380 kV Bâtiaz	0.394	0.519	0.877	1.728	0.392	0.516	0.456	0.637
380 kV Nant de Drance	0.391	0.537	0.871	1.789	0.389	0.534	0.453	0.659
380 kV Châtelard	0.392	0.536	0.874	1.784	0.390	0.533	0.455	0.657
220 kV Châtelard	0.261	0.367	0.582	1.223	0.260	0.365	0.303	0.450
220 kV Vallorcine	0.256	0.360	0.570	1.200	0.254	0.358	0.296	0.442

Table 4-31: Amplification factors for harmonic injection at 380 kV Romanel – optimal SCL (scenario 2)

4.4.4.2.5 Harmonic injection at 220 kV Mettlen

The following cases were considered for harmonic injection at 220 kV Mettlen:

Case	Description
1	Condition N
2	N-1 on 220 kV Ernen – Seehalten
3	N-1 on 220 kV Airolo – Rotondo
4	N-1 on 220 kV Airolo – Lavorgo
5	N-1 on 220 kV Altgass – Samstagern
6	N-1 on 220 kV Samstagern – Siebnen
7	N-1 on 220 kV Samstagern – Thalwil
8	N-1 on 220 kV Mettlen – Sursee
9	N-1 on 220 kV Gösgen – Laufenburg
10	N-1 on 220 kV Gösgen – Ormalingen
11	N-1 on 220 kV Altgass – Mettlen
12	N-2 on 220 kV Airolo – Rotondo and Airolo – Lavorgo
13	N-2 on 220 kV Obfelden – Waldegg

Case	Description

14	N-2 on 220 kV Birr – Niederwil and Mettlen – Obfelden
15	N-2 on 220 kV Mettlen – Obfelden and Breite – Fällanden

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV Mettlen under low and optimal SCL conditions are presented in Table 4-32 and Table 4-33, respectively.

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mettlen	0.811	0.617	0.846	0.527	0.807	0.638	0.877	0.336	0.889	0.297	0.867	0.314	0.884	0.354	0.872	0.244
220 kV Obfelden	1.000	0.988	1.011	0.942	1.001	0.915	1.041	0.661	1.067	0.454	1.072	0.910	1.061	0.702	1.035	0.737
220 kV Waldegg	1.080	1.134	1.091	1.077	1.079	1.049	1.120	0.744	1.159	0.485	1.178	1.148	1.152	0.812	1.115	0.838
220 kV Thalwil	1.071	1.108	1.083	1.050	1.070	1.025	1.110	0.718	1.154	0.471	1.182	1.169	1.172	0.839	1.104	0.813
220 kV Samstagern	1.013	0.970	1.026	0.915	1.012	0.898	1.049	0.611	1.103	0.412	1.144	1.139	1.023	0.571	1.044	0.703
220 kV Altgass	0.997	0.909	1.003	0.897	0.996	0.861	1.015	0.769	0.978	0.982	1.067	1.067	1.002	0.743	1.013	0.825
220 kV Niederwil	0.794	0.804	0.806	0.709	0.793	0.755	0.855	0.351	0.875	0.344	0.851	0.354	0.865	0.381	0.847	0.354
220 kV Regensdorf	0.776	0.841	0.792	0.726	0.774	0.808	0.836	0.338	0.856	0.377	0.814	0.287	0.842	0.368	0.828	0.314
220 kV Seebach	0.768	0.863	0.785	0.739	0.766	0.838	0.827	0.343	0.847	0.403	0.797	0.306	0.831	0.374	0.819	0.299
220 kV Auwiesen	0.765	0.869	0.784	0.742	0.764	0.847	0.825	0.346	0.845	0.411	0.792	0.317	0.828	0.377	0.816	0.296
220 kV Fällanden	0.758	0.910	0.779	0.772	0.756	0.901	0.817	0.374	0.838	0.455	0.774	0.403	0.818	0.407	0.809	0.293
220 kV Aathal	0.660	1.023	0.685	0.865	0.659	1.048	0.720	0.532	0.731	0.565	0.696	0.593	0.721	0.569	0.711	0.373
220 kV Grynau	0.697	1.064	0.723	0.900	0.696	1.087	0.752	0.515	0.764	0.549	0.728	0.524	0.753	0.552	0.745	0.355
220 kV Benken	0.866	0.936	0.894	0.802	0.864	0.920	0.920	0.335	0.952	0.463	0.817	0.569	0.913	0.360	0.913	0.310
220 kV Siebnen	0.906	0.899	0.929	0.787	0.904	0.859	0.954	0.331	0.993	0.412	0.812	0.565	0.941	0.335	0.948	0.384
220 kV Littau	1.169	0.888	1.384	0.915	1.179	0.918	1.238	0.919	1.181	0.940	1.178	0.944	0.181	0.946	1.179	0.907
220 kV Giswil	1.628	0.695	2.407	0.725	1.674	0.806	1.881	0.693	1.675	0.761	1.663	0.774	1.674	0.780	1.666	0.654
220 kV Innertkirchen	1.759	0.569	2.814	0.519	1.826	0.696	2.104	0.391	1.842	0.474	1.809	0.491	1.822	0.504	1.812	0.344
220 kV Handeck	1.767	0.520	2.886	0.444	1.838	0.640	2.132	0.296	1.836	0.381	1.819	0.397	1.834	0.409	1.823	0.249
220 kV Grimsel	1.747	0.485	2.887	0.395	1.820	0.596	2.119	0.235	1.818	0.318	1.801	0.334	1.815	0.346	1.804	1.190
220 kV Seehalten	1.730	0.457	2.885	0.355	1.803	0.559	2.107	0.184	1.801	0.265	1.784	0.280	1.799	0.291	1.788	0.141
220 kV Airolo	1.734	0.703	2.480	0.731	1.541	0.653	2.440	0.232	1.815	0.325	1.793	0.314	1.811	0.291	1.799	0.395
220 kV Sils	0.764	1.766	0.848	1.560	0.762	1.882	0.834	1.143	0.845	1.170	0.803	1.193	0.832	1.167	0.823	0.825

	Case 9		Case 10		Case 11		Case 12		Case 13		Case 14		Case 15	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mettlen	0.892	0.347	0.891	0.255	0.886	0.297	0.837	0.351	0.895	0.377	0.906	0.208	0.889	0.236
220 kV Obfelden	1.036	0.629	1.047	0.916	1.053	0.500	1.026	0.643	0.903	0.491	1.471	0.741	1.138	0.548
220 kV Waldegg	1.116	0.707	1.126	1.053	1.138	0.478	1.103	0.724	1.554	1.823	1.520	0.712	1.214	0.551
220 kV Thalwil	1.106	0.683	1.116	1.030	1.130	0.463	1.093	0.699	1.490	1.678	1.471	0.621	1.197	0.497
220 kV Samstagern	1.047	0.582	1.055	0.903	1.075	0.403	1.032	0.595	1.307	1.263	1.315	0.403	1.167	0.377
220 kV Altgass	1.014	0.754	1.019	0.932	1.055	0.396	1.007	0.758	1.153	1.060	1.154	0.381	1.049	0.519
220 kV Niederwil	0.846	0.325	0.864	0.519	0.865	0.341	0.835	0.350	0..803	0.351	1.302	0.731	0.930	0.509
220 kV Regensdorf	0.828	0.322	0.845	0.490	0.846	0.375	0.813	0.347	0.815	0.413	1.185	0.695	0.919	0.503
220 kV Seebach	0.820	0.333	0.836	0.474	0.837	0.400	0.803	0.357	0.822	0.448	1.125	0.671	0.915	0.496
220 kV Auwiesen	0.818	0.337	0.833	0.470	0.835	0.408	0.800	0.361	0.824	0.457	1.109	0.664	0.913	0.494
220 kV Fällanden	0.812	0.371	0.826	0.455	0.828	0.453	0.790	0.393	0.837	0.509	1.037	0.636	0.912	0.489
220 kV Aathal	0.714	0.543	0.728	0.470	0.725	0.563	0.691	0.559	0.731	0.651	0.799	0.594	0.713	0.574
220 kV Grynau	0.748	0.522	0.760	0.440	0.758	0.547	0.724	0.541	0.765	0.642	0.839	0.584	0.760	0.546
220 kV Benken	0.919	0.319	0.928	0.544	0.937	0.460	0.890	0.346	1.022	0.619	1.119	0.581	0.988	0.456
220 kV Siebnen	0.952	0.303	0.962	0.632	0.974	0.407	0.928	0.329	1.102	0.747	1.173	0.515	1.022	0.399
220 kV Littau	1.182	0.948	1.182	0.852	1.181	0.940	1.160	0.982	1.182	0.953	1.183	0.927	1.180	0.930
220 kV Giswil	1.677	0.786	1.680	0.478	1.673	0.760	1.609	0.895	1.678	0.806	1.681	0.721	1.673	0.731
220 kV Innertkirchen	1.826	0.508	1.831	0.134	1.822	0.473	1.741	0.641	1.829	0.537	1.833	0.423	1.822	0.435
220 kV Handeck	1.838	0.413	1.843	0.037	1.834	0.379	1.748	0.548	1.841	0.442	1.846	0.334	1.834	0.344
220 kV Grimsel	1.820	0.350	1.824	0.026	1.815	0.317	1.728	0.482	1.822	0.378	1.828	0.277	1.815	0.285
220 kV Seehalten	1.804	0.295	1.808	0.068	1.799	0.264	1.711	0.422	1.806	0.322	1.812	0.229	1.799	0.235
220 kV Airolo	1.816	0.270	1.821	0.567	1.812	0.326	11.32	1.306	1.821	0.278	1.832	0.392	1.813	0.366
220 kV Sils	0.832	1.132	0.842	0.695	0.839	1.167	0.771	1.163	0.855	1.291	0.898	1.163	0.842	1.130

Table 4-32: Amplification factors for harmonic injection at 220 kV Mettlen – low SCL (scenario 2)

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mettlen	0.532	0.658	0.533	0.785	0.534	0.767	0.524	0.786	0.525	0.676	0.513	0.619	0.531	0.660	0.517	0.631
220 kV Obfelden	0.814	1.178	0.814	1.263	0.814	1.228	0.813	1.260	0.764	1.289	0.881	1.308	0.829	1.260	0.808	1.144
220 kV Waldegg	0.874	1.351	0.874	1.453	0.874	1.413	0.872	1.450	0.799	1.525	0.990	1.572	0.899	1.478	0.868	1.313
220 kV Thalwil	0.864	1.317	0.865	1.418	0.865	1.379	0.863	1.416	0.778	1.515	1.006	1.567	0.914	1.526	0.859	1.280
220 kV Samstagern	0.814	1.152	0.815	1.243	0.814	1.209	0.812	1.243	0.709	1.378	0.999	1.451	0.792	1.102	0.809	1.119
220 kV Altgass	0.881	1.053	0.882	1.101	0.882	1.082	0.881	1.101	0.953	0.957	0.979	1.218	0.870	1.026	0.879	1.034
220 kV Niederwil	0.538	0.871	0.538	0.974	0.538	0.934	0.536	0.968	0.507	0.956	0.545	0.885	0.544	0.912	0.530	0.834
220 kV Regensdorf	0.489	0.804	0.490	0.910	0.490	0.871	0.488	0.905	0.461	0.889	0.468	0.771	0.493	0.832	0.482	0.769
220 kV Seebach	0.470	0.770	0.471	0.877	0.471	0.840	0.469	0.873	0.442	0.855	0.433	0.715	0.472	0.791	0.463	0.736
220 kV Auwiesen	0.465	0.761	0.465	0.868	0.466	0.831	0.463	0.864	0.437	0.846	0.423	0.700	0.466	0.780	0.458	0.727
220 kV Fällanden	0.446	0.727	0.446	0.836	0.446	0.801	0.444	0.833	0.418	0.812	0.383	0.639	0.445	0.737	0.438	0.694
220 kV Aathal	0.321	0.555	0.322	0.655	0.322	0.626	0.319	0.652	0.310	0.598	0.297	0.506	0.321	0.560	0.315	0.528
220 kV Grynau	0.360	0.581	0.361	0.683	0.361	0.655	0.358	0.681	0.349	0.623	0.335	0.529	0.360	0.587	0.354	0.554
220 kV Benken	0.562	0.843	0.534	0.966	0.563	0.930	0.559	0.966	0.513	0.980	0.382	0.630	0.554	0.831	0.555	0.807
220 kV Siebnen	0.631	0.922	0.632	1.036	0.632	1.000	0.628	1.036	0.566	1.087	0.377	0.623	0.619	0.899	0.624	0.886
220 kV Littau	0.919	0.467	0.966	0.458	0.911	0.437	0.932	0.523	0.918	0.459	0.918	0.478	0.919	0.466	0.918	0.474
220 kV Giswil	0.867	1.015	1.037	0.772	0.839	0.998	0.913	0.596	0.866	0.996	0.865	0.972	0.867	1.015	0.865	0.958
220 kV Innertkirchen	0.775	1.638	1.007	1.395	0.737	1.644	0.838	1.151	0.774	1.625	0.772	1.851	0.775	1.639	0.772	1.570
220 kV Handeck	0.742	1.778	0.991	1.529	0.701	1.786	0.809	1.279	0.741	1.764	0.738	1.718	0.742	1.778	0.739	1.708
220 kV Grimsel	0.717	1.810	0.973	1.566	0.675	1.819	0.786	1.319	0.716	1.798	0.713	1.752	0.717	1.811	0.714	1.741
220 kV Seehalten	0.702	1.833	0.966	1.593	0.659	1.843	0.773	1.348	0.701	1.821	0.698	1.775	0.702	1.833	0.699	1.765
220 kV Airolo	0.678	2.340	0.804	1.613	0.830	1.043	0.891	2.259	0.675	2.336	0.671	2.282	0.678	2.341	0.674	2.269
220 kV Sils	0.289	0.600	0.296	0.689	0.291	0.701	0.284	0.691	0.279	0.670	0.258	0.562	0.288	0.602	0.282	0.587

	Case 9		Case 10		Case 11		Case 12		Case 13		Case 14		Case 15	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mettlen	0.525	0.682	0.517	0.448	0.523	0.665	0.515	0.764	0.537	0.769	0.527	0.793	0.522	0.695
220 kV Obfelden	0.806	1.130	0.809	0.923	0.746	1.231	0.810	1.236	0.710	0.934	0.818	3.903	0.638	1.803
220 kV Waldegg	0.866	1.298	0.868	1.061	0.772	1.441	0.869	1.421	1.186	4.090	0.881	4.092	0.717	1.978
220 kV Thalwil	0.857	1.266	0.859	1.035	0.747	1.425	0.860	1.387	1.137	3.767	0.873	3.782	0.728	1.878
220 kV Samstagern	0.808	1.108	0.809	0.907	0.671	1.280	0.809	1.217	0.997	2.835	0.824	2.890	0.722	1.550
220 kV Altgass	0.878	1.025	0.879	0.920	0.644	1.231	0.879	1.086	0.978	1.915	0.886	1.787	0.833	1.211
220 kV Niederwil	0.526	0.829	0.530	0.585	0.496	0.917	0.533	0.941	0.498	0.874	0.670	3.190	0.460	1.291
220 kV Regensdorf	0.479	0.766	0.483	0.534	0.450	0.852	0.485	0.879	0.472	0.932	0.582	2.660	0.446	1.212
220 kV Seebach	0.460	0.735	0.463	0.508	0.432	0.819	0.465	0.847	0.463	0.964	0.543	2.386	0.444	1.157
220 kV Auwiesen	0.455	0.727	0.458	0.501	0.426	0.810	0.460	0.838	0.461	0.972	0.532	2.312	0.443	1.144
220 kV Fällanden	0.436	0.696	0.439	0.474	0.408	0.777	0.443	0.808	0.456	1.025	0.488	1.980	0.445	1.098
220 kV Aathal	0.313	0.537	0.315	0.360	0.306	0.580	0.316	0.630	0.325	0.713	0.323	1.061	0.282	0.625
220 kV Grynau	0.353	0.559	0.355	0.372	0.345	0.604	0.355	0.660	0.365	0.745	0.366	1.101	0.334	0.676
220 kV Benken	0.555	0.809	0.555	0.568	0.495	0.927	0.554	0.937	0.630	1.602	0.583	2.110	0.528	1.180
220 kV Siebnen	0.624	0.883	0.625	0.650	0.542	1.021	0.624	1.007	0.732	1.948	0.649	2.321	0.580	1.277
220 kV Littau	0.919	0.459	0.918	0.543	0.919	0.463	0.903	0.500	0.919	0.429	0.919	0.430	0.919	0.452
220 kV Giswil	0.866	0.934	0.865	0.609	0.866	0.990	0.813	0.878	0.868	1.068	0.866	0.879	0.865	0.960
220 kV Innertkirchen	0.774	1.558	0.773	1.137	0.773	1.615	0.701	1.459	0.776	1.727	0.774	1.527	0.773	1.592
220 kV Handeck	0.741	1.696	0.739	1.262	0.740	1.754	0.663	1.593	0.743	1.870	0.741	1.665	0.740	1.731
220 kV Grimsel	0.715	1.731	0.714	1.301	0.715	1.787	0.635	1.627	0.718	1.903	0.715	1.701	0.715	1.765
220 kV Seehalten	0.700	1.755	0.699	1.329	0.700	1.810	0.618	1.652	0.703	1.925	0.700	1.726	0.699	1.789
220 kV Airolo	0.675	2.270	0.674	1.793	0.675	2.324	7.322	1.387	0.670	2.448	0.676	2.289	0.674	2.315
220 kV Sils	0.283	0.629	0.699	1.330	0.275	0.650	0.271	0.694	0.299	0.828	0.289	1.180	0.272	0.746

Table 4-33: Amplification factors for harmonic injection at 220 kV Mettlen – optimal SCL (scenario 2)

4.4.4.3 Scenario 1

4.4.4.3.1 Harmonic injection at 220 kV Fällanden

The following cases were considered for harmonic injection at 220 kV Fällanden:

Case	Description
1	Condition N
2	N-1 on 220 kV Regensdorf – Seebach
3	N-1 on 220 kV Auwiesen – Seebach
4	N-1 on 220 kV Benken – Siebnen
5	N-1 on 220 kV Benken – Sils
6	N-1 on 220 kV Grynau – Mettlen
7	N-2 on 220 kV Benken – Sils and Benken – Siebnen
8	N-2 on 220 kV Grynau – Tierfehd
9	N-2 on 220 kV Grynau – Winkeln
10	N-2 on 220 kV Niederwil – Regensdorf

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV Fällanden under low and optimal SCL conditions are presented in Table 4-34 and Table 4-35, respectively.

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8		Case 9		Case 10	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
220 kV Auwiesen	0.894	0.823	0.906	0.844	0.906	0.845	0.886	0.811	0.894	0.825	0.891	0.822	0.885	0.814	0.894	0.825	0.895	0.823	0.984	0.989
220 kV Seebach	0.874	0.788	0.906	0.844	0.740	0.560	0.865	0.773	0.874	0.791	0.871	0.787	0.863	0.777	0.873	0.791	0.874	0.788	0.982	0.988
220 kV Regensdorf	0.796	0.653	0.737	0.555	0.739	0.558	0.781	0.629	0.796	0.658	0.790	0.651	0.778	0.635	0.795	0.658	0.797	0.654	0.974	0.980
220 kV Aathal	0.591	0.448	0.585	0.450	0.585	0.450	0.583	0.477	0.582	0.428	0.585	0.538	0.572	0.452	0.593	0.426	0.609	0.448	0.545	0.467
220 kV Grynau	0.619	0.491	0.613	0.494	0.613	0.494	0.611	0.523	0.609	0.468	0.613	0.608	0.599	0.494	0.626	0.468	0.658	0.500	0.574	0.517
220 kV Benken	0.748	0.548	0.742	0.547	0.742	0.547	0.824	0.741	0.765	0.559	0.738	0.555	0.853	0.755	0.743	0.539	0.749	0.549	0.696	0.541
380 kV Benken	0.536	0.282	0.528	0.282	0.529	0.282	0.550	0.353	0.526	0.256	0.521	0.314	0.541	0.314	0.525	0.260	0.536	0.277	0.474	0.292
220 kV Benken	0.748	0.548	0.742	0.547	0.742	0.547	0.824	0.741	0.765	0.559	0.738	0.555	0.853	0.755	0.743	0.539	0.749	0.549	0.696	0.541
380 kV Benken	0.536	0.282	0.528	0.282	0.529	0.282	0.550	0.353	0.526	0.256	0.521	0.314	0.541	0.314	0.525	0.260	0.536	0.277	0.474	0.292
220 kV Siebnen	0.704	0.457	0.696	0.453	0.696	0.453	0.460	0.089	0.718	0.467	0.691	0.456	0.453	0.076	0.700	0.452	0.705	0.458	0.635	0.430
220 kV Samstagern	0.606	0.243	0.592	0.233	0.592	0.233	0.465	0.089	0.611	0.252	0.585	0.221	0.459	0.077	0.601	0.247	0.608	0.246	0.494	0.169
220 kV Altgass	0.526	0.107	0.513	0.102	0.514	0.102	0.434	0.141	0.527	0.106	0.500	0.078	0.427	0.122	0.522	0.106	0.529	0.110	0.425	0.069
220 kV Thalwil	0.596	0.223	0.578	0.207	0.579	0.208	0.482	0.071	0.599	0.232	0.575	0.199	0.476	0.066	0.591	0.228	0.598	0.226	0.458	0.114
220 kV Waldegg	0.584	0.204	0.564	0.184	0.565	0.185	0.493	0.067	0.585	0.213	0.563	0.178	0.487	0.071	0.580	0.211	0.586	0.207	0.425	0.077
220 kV Obfelden	0.568	0.181	0.545	0.158	0.546	0.159	0.502	0.078	0.568	0.191	0.547	0.154	0.496	0.087	0.564	0.189	0.570	0.185	0.389	0.068
220 kV Niederwil	0.649	0.392	0.609	0.332	0.610	0.334	0.622	0.351	0.648	0.400	0.639	0.389	0.618	0.361	0.647	0.400	0.650	0.394	0.333	0.080
220 kV Mettlen	0.444	0.178	0.433	0.175	0.433	0.175	0.406	0.212	0.441	0.160	0.411	0.210	0.398	0.191	0.440	0.153	0.449	0.174	0.353	0.158
380 kV Mettlen	0.401	0.193	0.393	0.185	0.393	0.185	0.388	0.175	0.395	0.184	0.383	0.185	0.379	0.162	0.394	0.183	0.403	0.191	0.334	0.136
220 kV Breite	0.575	0.402	0.569	0.403	0.569	0.403	0.569	0.429	0.567	0.387	0.569	0.462	0.559	0.409	0.571	0.382	0.569	0.391	0.528	0.414
380 kV Breite	0.465	0.292	0.458	0.293	0.459	0.293	0.459	0.332	0.451	0.271	0.455	0.349	0.442	0.298	0.448	0.271	0.464	0.284	0.411	0.303

Table 4-34: Amplification factors for harmonic injection at 220 kV Fällanden – low SCL (scenario 1)

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8		Case 9		Case 10	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
220 kV Auwiesen	0.848	0.878	0.866	0.890	0.866	0.890	0.840	0.868	0.848	0.879	0.846	0.875	0.840	0.867	0.848	0.878	0.848	0.880	0.965	0.969
220 kV Seebach	0.820	0.857	0.866	0.890	0.636	0.719	0.810	0.844	0.820	0.857	0.818	0.853	0.810	0.843	0.820	0.856	0.820	0.858	0.960	0.965
220 kV Regensdorf	0.711	0.775	0.634	0.713	0.635	0.717	0.695	0.755	0.712	0.775	0.708	0.768	0.694	0.753	0.711	0.774	0.712	0.778	0.943	0.949
220 kV Aathal	0.391	0.592	0.387	0.584	0.387	0.584	0.387	0.580	0.387	0.581	0.396	0.554	0.382	0.565	0.410	0.580	0.420	0.628	0.368	0.529
220 kV Grynau	0.412	0.641	0.409	0.632	0.409	0.633	0.407	0.627	0.409	0.628	0.422	0.589	0.402	0.610	0.445	0.628	0.468	0.709	0.390	0.574
220 kV Benken	0.629	0.776	0.623	0.767	0.623	0.767	0.735	0.852	0.663	0.783	0.623	0.761	0.790	0.871	0.627	0.768	0.631	0.781	0.589	0.703
380 kV Benken	0.322	0.679	0.317	0.665	0.317	0.665	0.349	0.672	0.323	0.655	0.315	0.647	0.354	0.645	0.317	0.658	0.324	0.687	0.288	0.571
220 kV Benken	0.629	0.776	0.623	0.767	0.623	0.767	0.735	0.852	0.663	0.783	0.623	0.761	0.790	0.871	0.627	0.768	0.631	0.781	0.589	0.703
380 kV Benken	0.322	0.679	0.317	0.665	0.317	0.665	0.349	0.672	0.323	0.655	0.315	0.647	0.354	0.645	0.317	0.658	0.324	0.687	0.288	0.571
220 kV Siebnen	0.568	0.734	0.560	0.722	0.560	0.723	0.257	0.539	0.597	0.738	0.560	0.715	0.256	0.526	0.567	0.726	0.571	0.740	0.512	0.641
220 kV Samstagern	0.437	0.659	0.423	0.642	0.424	0.643	0.264	0.552	0.453	0.655	0.424	0.631	0.263	0.539	0.437	0.649	0.441	0.668	0.339	0.525
220 kV Altgass	0.335	0.605	0.323	0.589	0.324	0.590	0.227	0.539	0.344	0.597	0.317	0.573	0.226	0.525	0.336	0.594	0.340	0.616	0.254	0.479
220 kV Thalwil	0.424	0.650	0.406	0.631	0.406	0.632	0.286	0.559	0.436	0.646	0.411	0.622	0.285	0.546	0.424	0.641	0.428	0.659	0.296	0.498
220 kV Waldegg	0.411	0.636	0.389	0.615	0.390	0.616	0.303	0.559	0.420	0.631	0.397	0.608	0.302	0.547	0.411	0.627	0.415	0.645	0.258	0.473
220 kV Obfelden	0.394	0.614	0.369	0.591	0.370	0.593	0.320	0.554	0.401	0.609	0.381	0.586	0.319	0.543	0.395	0.605	0.398	0.623	0.217	0.443
220 kV Niederwil	0.518	0.642	0.468	0.603	0.469	0.606	0.490	0.609	0.520	0.640	0.512	0.628	0.489	0.604	0.518	0.638	0.520	0.647	0.166	0.374
220 kV Mettlen	0.231	0.585	0.222	0.569	0.223	0.570	0.194	0.548	0.234	0.573	0.208	0.548	0.193	0.532	0.233	0.570	0.238	0.599	0.168	0.462
380 kV Mettlen	0.186	0.538	0.180	0.525	0.181	0.525	0.179	0.512	0.186	0.523	0.176	0.507	0.178	0.494	0.184	0.522	0.189	0.547	0.149	0.433
220 kV Breite	0.396	0.571	0.392	0.563	0.392	0.563	0.393	0.560	0.393	0.561	0.398	0.548	0.389	0.546	0.401	0.558	0.397	0.571	0.370	0.508
380 kV Breite	0.235	0.571	0.231	0.559	0.231	0.559	0.234	0.554	0.227	0.549	0.234	0.537	0.225	0.527	0.224	0.544	0.238	0.577	0.210	0.481

Table 4-35: Amplification factors for harmonic injection at 220 kV Fällanden – optimal SCL (scenario 1)

4.4.4.3.2 Harmonic injection at 220 kV Verbois

The following cases were considered for harmonic injection at 220 kV Verbois:

Case	Description
1	Condition N
2	N-1 on 220 kV Romanel – Veytaux
3	N-1 on 220 kV Romanel – Vaux
4	N-1 on 220 kV Vaux – Verbois
5	N-2 on 220 kV Romanel – Vaux and Vaux – Verbois

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV Verbois under low and optimal SCL conditions are presented in Table 4-36 and Table 4-37, respectively.

	Case 1		Case 2		Case 3		Case 4		Case 5	
	5	7	5	7	5	7	5	7	5	7
380 kV Verbois	0.628	0.754	0.636	0.763	0.614	0.737	0.609	0.727	0.613	0.734
220 kV Foretaille	0.924	0.951	0.931	0.959	0.912	0.941	0.909	0.936	0.912	0.940
220 kV Crans	0.819	0.881	0.837	0.900	0.790	0.855	0.782	0.845	0.789	0.854
220 kV Banlieue Ouest	0.621	0.743	0.664	0.786	0.554	0.686	0.537	0.662	0.553	0.684
220 kV Romanel	0.595	0.725	0.642	0.773	0.521	0.663	0.501	0.637	0.519	0.660
380 kV Romanel	0.531	0.775	0.546	0.791	0.492	0.732	0.481	0.710	0.490	0.725
220 kV Vaux	0.657	0.767	0.695	0.806	0.899	0.934	0.485	0.618	0.000	0.000
220 kV Veytaux	0.358	0.470	0.207	0.293	0.315	0.431	0.303	0.415	0.314	0.429
220 kV St Triphon	0.286	0.392	0.223	0.314	0.252	0.361	0.243	0.347	0.252	0.359
220 kV Riddes	0.189	0.303	0.160	0.266	0.169	0.281	0.164	0.272	0.168	0.280
380 kV Bâtiaz	0.312	0.654	0.310	0.649	0.287	0.616	0.280	0.597	0.286	0.611
380 kV Nant de Drance	0.317	0.693	0.314	0.688	0.292	0.652	0.284	0.632	0.290	0.647
380 kV Châtelard	0.316	0.688	0.314	0.683	0.291	0.648	0.284	0.628	0.290	0.642
220 kV Châtelard	0.250	0.566	0.248	0.562	0.230	0.532	0.224	0.516	0.229	0.528
220 kV Vallorcine	0.247	0.561	0.245	0.556	0.227	0.527	0.221	0.511	0.226	0.523

Table 4-36: Amplification factors for harmonic injection at 220 kV Verbois – low SCL (scenario 1)

	Case 1		Case 2		Case 3		Case 4		Case 5	
	5	7	5	7	5	7	5	7	5	7
380 kV Verbois	0.479	0.521	0.485	0.529	0.469	0.509	0.466	0.503	0.469	0.508
220 kV Foretaille	0.885	0.900	0.892	0.908	0.875	0.889	0.871	0.885	0.875	0.889
220 kV Crans	0.737	0.768	0.755	0.787	0.711	0.741	0.702	0.730	0.710	0.740
220 kV Banlieue Ouest	0.493	0.546	0.535	0.589	0.430	0.483	0.408	0.456	0.429	0.481
220 kV Romanel	0.464	0.519	0.511	0.568	0.393	0.448	0.368	0.419	0.391	0.446
380 kV Romanel	0.370	0.461	0.387	0.481	0.339	0.425	0.326	0.405	0.335	0.418
220 kV Vaux	0.535	0.584	0.572	0.623	0.782	0.807	0.344	0.393	0.000	0.000
220 kV Veytaux	0.232	0.272	0.108	0.134	0.196	0.236	0.184	0.220	0.196	0.234
220 kV St Triphon	0.169	0.206	0.124	0.153	0.144	0.179	0.135	0.168	0.143	0.178
220 kV Riddes	0.083	0.117	0.066	0.097	0.071	0.103	0.067	0.097	0.071	0.102
380 kV Batiaz	0.152	0.261	0.155	0.264	0.138	0.238	0.132	0.227	0.137	0.235
380 kV Nant de Drance	0.151	0.270	0.154	0.274	0.137	0.247	0.132	0.235	0.136	0.243
380 kV Châtelard	0.151	0.269	0.154	0.273	0.138	0.246	0.132	0.234	0.136	0.242
220 kV Châtelard	0.101	0.184	0.103	0.187	0.092	0.169	0.088	0.161	0.091	0.166
220 kV Vallorcine	0.099	0.181	0.101	0.183	0.090	0.165	0.086	0.157	0.089	0.163

Table 4-37: Amplification factors for harmonic injection at 220 kV Verbois – optimal SCL (scenario 1)

4.4.4.3.3 Harmonic injection at 380 kV Bois Tollot

The following cases were considered for harmonic injection at 380 kV Bois Tollot:

Case	Description
1	Condition N
2	N-1 on 380 kV Bâtiaz – Romanel
3	N-1 on 380 kV Bâtiaz – Chamoson
4	N-2 on 380 kV Chamoson – Chippis

The amplification factors on the 5th and 7th harmonics for harmonic injection at 380 kV Bois Tollot under low and optimal SCL conditions are presented in Table 4-38 and Table 4-39, respectively.

	Case 1		Case 2		Case 3		Case 4	
	5	7	5	7	5	7	5	7
380 kV Verbois	0.967	0.979	0.969	0.978	0.973	0.947	0.968	0.985
220 kV Foretaille	0.629	0.764	0.649	0.743	0.698	0.411	0.638	0.829

220 kV Crans	0.590	0.739	0.613	0.714	0.671	0.340	0.601	0.815
220 kV Banlieue Ouest	0.529	0.695	0.560	0.659	0.639	0.230	0.543	0.798
220 kV Romanel	0.525	0.693	0.557	0.655	0.640	0.223	0.539	0.801
380 kV Chippis	0.717	0.916	0.850	0.916	1.061	0.528	0.757	1.121
220 kV Vaux	0.546	0.706	0.571	0.672	0.638	0.268	0.558	0.798
220 kV Veytaux	0.328	0.463	0.314	0.385	0.360	0.131	0.334	0.553
220 kV St Triphon	0.270	0.394	0.236	0.296	0.271	0.105	0.273	0.482
220 kV Riddes	0.198	0.324	0.121	0.163	0.138	0.055	0.201	0.419
380 kV Bâtiaz	0.401	0.757	0.071	0.153	1.339	2.520	0.508	1.270
380 kV Nant de Drance	0.407	0.802	0.072	0.162	1.360	2.674	0.516	1.345
380 kV Châtelard	0.406	0.796	0.072	0.161	1.358	2.655	0.515	1.336
220 kV Châtelard	0.321	0.654	0.057	0.133	1.072	2.181	0.406	1.099
220 kV Vallorcine	0.317	0.648	0.056	0.131	1.060	2.161	0.402	1.088

Table 4-38: Amplification factors for harmonic injection at 380 kV Bois Tollot – low SCL (scenario 1)

	Case 1		Case 2		Case 3		Case 4	
	5	7	5	7	5	7	5	7
380 kV Verbois	0.782	0.936	0.956	0.962	0.956	0.968	0.954	0.960
220 kV Foretaille	2.016	0.301	0.503	0.556	0.501	0.653	0.479	0.544
220 kV Crans	2.254	0.238	0.463	0.518	0.459	0.641	0.433	0.505
220 kV Banlieue Ouest	2.318	0.126	0.421	0.477	0.416	0.668	0.378	0.459
220 kV Romanel	2.272	0.154	0.425	0.480	0.419	0.688	0.378	0.461
380 kV Chippis	1.219	0.390	0.797	0.844	0.781	1.462	0.640	0.758
220 kV Vaux	2.088	0.091	0.429	0.485	0.425	0.649	0.394	0.471
220 kV Veytaux	1.937	0.605	0.206	0.241	0.203	0.347	0.194	0.251
220 kV St Triphon	1.639	0.668	0.145	0.174	0.144	0.249	0.147	0.197
220 kV Riddes	0.878	0.514	0.056	0.071	0.056	0.102	0.087	0.131
380 kV Bâtiaz	0.879	0.671	0.017	0.038	0.684	2.546	0.293	0.484
380 kV Nant de Drance	0.873	0.696	0.017	0.039	0.679	2.635	0.291	0.501
380 kV Châtelard	0.876	0.693	0.017	0.039	0.681	2.627	0.292	0.500
220 kV Châtelard	0.583	0.475	0.011	0.027	0.453	1.804	0.194	0.342
220 kV Vallorcine	0.571	0.466	0.011	0.026	0.444	1.769	0.190	0.336

Table 4-39: Amplification factors for harmonic injection at 380 kV Bois Tollot – optimal SCL (scenario 1)

4.4.4.3.4 Harmonic injection at 220 kV Mettlen

The following cases were considered for harmonic injection at 220 kV Mettlen:

Case	Description
1	Condition N
2	N-1 on 220 kV Ernen – Seehalten
3	N-1 on 220 kV Airolo – Rotondo
4	N-1 on 220 kV Airolo – Lavorgo
5	N-1 on 220 kV Altgass – Samstagern
6	N-1 on 220 kV Samstagern – Siebnen
7	N-1 on 220 kV Samstagern – Thalwil
8	N-1 on 220 kV Mettlen – Sursee
9	N-1 on 220 kV Gösgen – Laufenburg
10	N-1 on 220 kV Gösgen – Ormalingen
11	N-1 on 220 kV Altgass – Mettlen
12	N-2 on 220 kV Airolo – Rotondo and Airolo – Lavorgo
13	N-2 on 220 kV Obfelden – Waldegg
14	N-2 on 220 kV Birr – Niederwil and Mettlen – Obfelden
15	N-2 on 220 kV Mettlen – Obfelden and Breite – Fällanden

The amplification factors on the 5th and 7th harmonics for harmonic injection at 220 kV Mettlen under low and optimal SCL conditions are presented in Table 4-40 and Table 4-41, respectively.

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mettlen	0.668	0.304	0.665	0.291	0.670	0.304	0.664	0.298	0.658	0.274	0.651	0.268	0.667	0.303	0.651	0.205
220 kV Obfelden	0.811	0.435	0.810	0.464	0.811	0.434	0.810	0.437	0.766	0.290	0.833	0.544	0.808	0.440	0.804	0.489
220 kV Waldegg	0.820	0.424	0.818	0.455	0.820	0.423	0.818	0.426	0.753	0.222	0.864	0.618	0.816	0.432	0.813	0.487
220 kV Thalwil	0.824	0.410	0.822	0.444	0.824	0.409	0.822	0.411	0.738	0.185	0.888	0.682	0.818	0.435	0.817	0.480
220 kV Samstagern	0.823	0.387	0.822	0.424	0.823	0.387	0.821	0.388	0.714	0.198	0.911	0.750	0.818	0.373	0.816	0.465
220 kV Altgass	0.897	0.657	0.896	0.675	0.897	0.657	0.896	0.658	0.978	0.981	0.944	0.861	0.895	0.649	0.893	0.704
220 kV Niederwil	0.634	0.259	0.632	0.261	0.634	0.259	0.632	0.248	0.603	0.285	0.622	0.209	0.632	0.257	0.621	0.186
220 kV Regensdorf	0.623	0.307	0.621	0.300	0.624	0.307	0.621	0.293	0.592	0.350	0.596	0.301	0.622	0.305	0.611	0.202
220 kV Seebach	0.619	0.335	0.617	0.324	0.620	0.336	0.617	0.321	0.587	0.386	0.584	0.363	0.617	0.334	0.606	0.214
220 kV Auwiesen	0.618	0.343	0.615	0.331	0.618	0.344	0.616	0.329	0.586	0.396	0.581	0.380	0.614	0.342	0.605	0.218
220 kV Fällanden	0.615	0.386	0.613	0.368	0.616	0.387	0.612	0.372	0.583	0.447	0.568	0.471	0.613	0.386	0.602	0.240
220 kV Aathal	0.551	0.554	0.549	0.518	0.552	0.556	0.548	0.540	0.532	0.565	0.525	0.570	0.549	0.554	0.538	0.354
220 kV Grynau	0.586	0.531	0.584	0.496	0.587	0.532	0.583	0.516	0.568	0.544	0.560	0.553	0.585	0.530	0.574	0.324
220 kV Benken	0.694	0.299	0.692	0.299	0.695	0.300	0.691	0.287	0.640	0.432	0.586	0.609	0.691	0.301	0.682	0.200
220 kV Siebnen	0.730	0.213	0.728	0.244	0.730	0.214	0.727	0.203	0.659	0.349	0.583	0.606	0.726	0.212	0.719	0.219
220 kV Littau	0.896	0.852	0.902	0.888	0.891	0.850	0.897	0.861	0.896	0.856	0.896	0.856	0.896	0.852	0.895	0.863
220 kV Giswil	0.699	0.504	0.725	0.646	0.680	0.494	0.703	0.537	0.697	0.517	0.697	0.521	0.699	0.504	0.696	0.547
220 kV Innertkirchen	0.594	0.310	0.630	0.500	0.568	0.297	0.600	0.353	0.592	0.328	0.592	0.334	0.594	0.310	0.591	0.365
220 kV Handeck	0.523	0.218	0.569	0.393	0.491	0.151	0.351	0.215	0.521	0.188	0.520	0.195	0.523	0.168	0.519	0.226
220 kV Grimsel	0.491	0.112	0.541	0.340	0.454	0.097	0.499	0.149	0.488	0.127	0.487	0.135	0.490	0.113	0.486	0.155
220 kV Seehalten	0.476	0.104	0.532	0.304	0.435	0.098	0.484	0.110	0.473	0.104	0.472	0.111	0.475	0.104	0.471	0.105
220 kV Airolo	0.498	0.134	0.518	0.128	0.625	0.142	0.532	0.181	0.495	0.115	0.492	0.112	0.498	0.135	0.453	0.100
220 kV Sils	0.540	1.098	0.539	1.016	0.543	1.099	0.535	1.094	0.522	1.111	0.509	1.156	0.539	1.098	0.527	0.723

	Case 9		Case 10		Case 11		Case 12		Case 13		Case 14		Case 15	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mettlen	0.674	0.296	0.670	0.289	0.656	0.274	0.658	0.291	0.667	0.303	0.653	0.255	0.653	0.255
220 kV Obfelden	0.806	0.426	0.813	0.618	0.759	0.289	0.808	0.445	0.792	0.448	0.703	0.168	0.703	0.168
220 kV Waldegg	0.815	0.415	0.822	0.632	0.744	0.221	0.816	0.433	0.848	0.362	0.730	0.156	0.730	0.256
220 kV Thalwil	0.820	0.401	0.825	0.639	0.725	0.183	0.820	0.418	0.846	0.360	0.751	0.166	0.751	0.166
220 kV Samstagern	0.819	0.378	0.824	0.639	0.697	0.195	0.819	0.395	0.838	0.353	0.771	0.199	0.771	0.199
220 kV Altgass	0.895	0.655	0.897	0.794	0.684	0.191	0.895	0.662	0.904	0.636	0.869	0.544	0.869	0.544
220 kV Niederwil	0.623	0.233	0.638	0.304	0.599	0.284	0.629	0.243	0.626	0.252	0.650	0.272	0.650	0.272
220 kV Regensdorf	0.614	0.281	0.627	0.336	0.587	0.350	0.618	0.284	0.619	0.302	0.628	0.329	0.628	0.329
220 kV Seebach	0.610	0.309	0.623	0.352	0.582	0.386	0.613	0.310	0.615	0.333	0.616	0.358	0.616	0.358
220 kV Auwiesen	0.609	0.317	0.621	0.356	0.581	0.395	0.612	0.318	0.614	0.341	0.613	0.365	0.613	0.365
220 kV Fällanden	0.607	0.361	0.618	0.380	0.577	0.477	0.609	0.359	0.614	0.387	0.602	0.404	0.602	0.533
220 kV Aathal	0.543	0.531	0.554	0.410	0.530	0.565	0.544	0.523	0.550	0.554	0.529	0.533	0.529	0.404
220 kV Grynau	0.580	0.504	0.589	0.453	0.565	0.543	0.579	0.500	0.585	0.531	0.568	0.504	0.568	0.504
220 kV Benken	0.675	0.535	0.697	0.459	0.631	0.431	0.687	0.278	0.698	0.310	0.667	0.328	0.667	0.328
220 kV Siebnen	0.725	0.179	0.732	0.493	0.649	0.348	0.723	0.201	0.737	0.219	0.695	0.226	0.695	0.226
220 kV Littau	0.851	0.851	0.896	0.881	0.895	0.856	0.889	0.846	0.896	0.852	0.895	0.857	0.895	0.857
220 kV Giswil	0.699	0.499	0.700	0.618	0.697	0.517	0.673	0.479	0.699	0.504	0.696	0.524	0.696	0.524
220 kV Innertkirchen	0.595	0.303	0.596	0.462	0.592	0.328	0.558	0.275	0.594	0.311	0.591	0.337	0.591	0.337
220 kV Handeck	0.524	0.156	0.525	0.345	0.521	0.188	0.478	0.124	0.523	0.169	0.520	0.196	0.520	0.196
220 kV Grimsel	0.492	0.098	0.493	0.286	0.488	0.127	0.440	0.077	0.490	0.113	0.486	0.133	0.486	0.133
220 kV Seehalten	0.477	0.092	0.478	0.245	0.473	0.104	0.419	0.101	0.476	0.104	0.471	0.103	0.471	0.103
220 kV Airolo	0.500	0.121	0.501	0.281	0.454	0.115	1.058	1.191	0.498	0.134	0.493	0.104	0.493	0.104
220 kV Sils	0.538	1.064	0.544	0.709	0.519	1.111	0.499	0.855	0.511	0.880	0.491	0.833	0.491	0.833

Table 4-40: Amplification factors for harmonic injection at 220 kV Mettlen – low SCL (scenario 1)

	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6		Case 7		Case 8	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mettlen	0.476	0.836	0.476	0.833	0.480	0.844	0.473	0.834	0.467	0.817	0.461	0.819	0.476	0.835	0.463	0.816
220 kV Obfelden	0.686	0.854	0.686	0.852	0.686	0.855	0.686	0.853	0.620	0.829	0.729	0.862	0.685	0.848	0.210	0.838
220 kV Waldegg	0.691	0.874	0.691	0.873	0.691	0.876	0.690	0.873	0.589	0.841	0.769	0.895	0.690	0.866	0.687	0.858
220 kV Thalwil	0.692	0.884	0.692	0.883	0.692	0.886	0.691	0.883	0.557	0.845	0.803	0.918	0.692	0.870	0.688	0.868
220 kV Samstagern	0.688	0.885	0.688	0.884	0.689	0.887	0.688	0.884	0.515	0.840	0.839	0.934	0.684	0.878	0.684	0.869
220 kV Altgass	0.815	0.917	0.815	0.916	0.816	0.918	0.815	0.916	0.953	0.957	0.894	0.947	0.813	0.913	0.813	0.907
220 kV Niederwil	0.425	0.731	0.425	0.729	0.426	0.734	0.425	0.729	0.386	0.718	0.419	0.715	0.425	0.727	0.471	0.712
220 kV Regensdorf	0.396	0.725	0.395	0.722	0.396	0.728	0.395	0.723	0.356	0.712	0.368	0.703	0.395	0.722	0.388	0.706
220 kV Seebach	0.384	0.723	0.384	0.721	0.385	0.727	0.384	0.721	0.344	0.711	0.345	0.699	0.384	0.720	0.377	0.704
220 kV Auwiesen	0.381	0.722	0.381	0.720	0.382	0.725	0.380	0.720	0.341	0.710	0.339	0.697	0.381	0.719	0.374	0.703
220 kV Fällanden	0.372	0.727	0.372	0.725	0.373	0.731	0.371	0.726	0.331	0.715	0.314	0.701	0.371	0.725	0.365	0.708
220 kV Aathal	0.282	0.654	0.282	0.652	0.283	0.658	0.281	0.652	0.266	0.644	0.260	0.635	0.282	0.652	0.276	0.636
220 kV Grynau	0.322	0.690	0.322	0.687	0.323	0.694	0.321	0.688	0.306	0.679	0.299	0.669	0.322	0.688	0.317	0.670
220 kV Benken	0.475	0.831	0.474	0.829	0.476	0.836	0.473	0.829	0.396	0.813	0.319	0.781	0.473	0.827	0.468	0.809
220 kV Siebnen	0.533	0.838	0.533	0.836	0.534	0.842	0.532	0.836	0.428	0.815	0.315	0.772	0.531	0.833	0.527	0.817
220 kV Littau	0.831	0.852	0.830	0.854	0.828	0.847	0.832	0.852	0.831	0.851	0.831	0.851	0.831	0.852	0.831	0.850
220 kV Giswil	0.557	0.627	0.579	0.625	0.543	0.606	0.562	0.626	0.557	0.625	0.556	0.625	0.557	0.627	0.556	0.621
220 kV Innertkirchen	0.427	0.509	0.459	0.518	0.407	0.480	0.434	0.508	0.427	0.507	0.426	0.506	0.427	0.509	0.426	0.509
220 kV Handeck	0.340	0.439	0.380	0.448	0.313	0.401	0.349	0.437	0.339	0.437	0.338	0.435	0.340	0.439	0.338	0.430
220 kV Grimsel	0.300	0.412	0.347	0.420	0.269	0.369	0.310	0.408	0.299	0.409	0.298	0.408	0.300	0.412	0.298	0.402
220 kV Seehalten	0.282	0.410	0.336	0.417	0.246	0.361	0.294	0.405	0.281	0.407	0.280	0.405	0.282	0.410	0.280	0.400
220 kV Airolo	0.310	0.476	0.328	0.477	0.460	0.686	0.361	0.462	0.308	0.472	0.307	0.469	0.310	0.476	0.308	0.464
220 kV Sils	0.219	0.676	0.219	0.674	0.221	0.683	0.217	0.675	0.197	0.668	0.178	0.655	0.219	0.675	0.214	0.659

	Case 9		Case 10		Case 11		Case 12		Case 13		Case 14		Case 15	
	5	7	5	7	5	7	5	7	5	7	5	7	5	7
380 kV Mettlen	0.484	0.890	0.476	0.647	0.466	0.823	0.471	0.828	0.476	0.837	0.466	0.817	0.465	0.815
220 kV Obfelden	0.683	0.856	0.686	0.704	0.610	0.813	0.685	0.851	0.675	0.813	0.474	0.784	0.420	0.741
220 kV Waldegg	0.689	0.877	0.691	0.719	0.574	0.818	0.690	0.871	0.704	0.947	0.514	0.813	0.470	0.776
220 kV Thalwil	0.690	0.888	0.692	0.726	0.538	0.814	0.691	0.881	0.702	0.943	0.550	0.832	0.515	0.802
220 kV Samstagern	0.687	0.890	0.688	0.724	0.490	0.801	0.687	0.881	0.695	0.924	0.590	0.845	0.566	0.824
220 kV Altgass	0.815	0.918	0.815	0.822	0.470	0.770	0.815	0.915	0.819	0.936	0.763	0.891	0.0751	0.879
220 kV Niederwil	0.419	0.739	0.425	0.575	0.380	0.707	0.424	0.726	0.421	0.715	0.395	0.746	0.314	0.689
220 kV Regensdorf	0.391	0.735	0.396	0.565	0.350	0.701	0.394	0.720	0.393	0.716	0.365	0.730	0.319	0.696
220 kV Seebach	0.380	0.735	0.384	0.561	0.339	0.699	0.383	0.718	0.383	0.718	0.353	0.723	0.325	0.701
220 kV Auwiesen	0.377	0.734	0.381	0.560	0.335	0.698	0.380	0.716	0.380	0.717	0.350	0.721	0.327	0.701
220 kV Fällanden	0.368	0.742	0.372	0.560	0.325	0.704	0.370	0.722	0.371	0.727	0.340	0.719	0.339	0.716
220 kV Aathal	0.279	0.670	0.282	0.510	0.264	0.938	0.281	0.648	0.282	0.654	0.262	0.636	0.243	0.614
220 kV Grynau	0.320	0.704	0.322	0.522	0.303	0.673	0.321	0.684	0.322	0.690	0.304	0.673	0.292	0.656
220 kV Benken	0.473	0.849	0.475	0.627	0.384	0.793	0.472	0.824	0.477	0.845	0.425	0.811	0.415	0.801
220 kV Siebnen	0.532	0.852	0.533	0.638	0.412	0.790	0.531	0.833	0.537	0.860	0.469	0.814	0.456	0.801
220 kV Littau	0.831	0.852	0.831	0.837	0.831	0.851	0.827	0.846	0.831	0.852	0.831	0.851	0.831	0.851
220 kV Giswil	0.557	0.629	0.557	0.570	0.557	0.625	0.539	0.601	0.557	0.627	0.556	0.624	0.556	0.624
220 kV Innertkirchen	0.428	0.513	0.427	0.435	0.427	0.506	0.402	0.473	0.427	0.509	0.426	0.505	0.426	0.505
220 kV Handeck	0.340	0.446	0.340	0.352	0.339	0.436	0.306	0.392	0.340	0.439	0.338	0.434	0.338	0.434
220 kV Grimsel	0.300	0.420	0.300	0.320	0.299	0.408	0.261	0.358	0.300	0.412	0.298	0.407	0.298	0.407
220 kV Seehalten	0.283	0.421	0.282	0.312	0.281	0.406	0.237	0.349	0.282	0.410	0.280	0.404	0.280	0.404
220 kV Airolo	0.311	0.489	0.310	0.359	0.308	0.471	0.999	1.118	0.310	0.477	0.308	0.469	0.307	0.468
220 kV Sils	0.219	0.703	0.219	0.527	0.194	0.659	0.215	0.668	0.220	0.681	0.202	0.659	0.197	0.649

Table 4-41: Amplification factors for harmonic injection at 220 kV Mettlen – optimal SCL (scenario 1)