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Swiss cable study
Summarised version

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Contents

1 Background 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.

Cables are known to have a considerable impact on grid operations, particularly because they can lead to steady-state voltage rises, various resonance phenomena and amplification of harmonics, etc.

As such phenomena have already been observed with the cables currently planned, we can expect them to become even more pronounced as the total length of cables installed increases. In this situation, it is prudent to express our concerns and to probe further into the impact of such 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.

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

The analyses carried out in this study are based on publications from academia and industry, as documented in the references in this summary, notably [4] - [24] .

The analyses presented in WP1 aim to quantify the reactive power compensation requirements in the three scenarios. WP2 focuses on the impact of cabling on network resonances and harmonics. The impact of cabling on grid restoration after a blackout is examined in WP3.

2 Work package 1: Reactive power compensation

It is well-known 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.

Excessive reactive power overloads lines, leading to voltage rise. 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.

Different types of equipment are available on the market for reactive power compensation, such as shunt reactors, SVCs, STATCOMs, etc., of which shunt reactors are the simplest solution. They mainly consist of an inductor that absorbs the reactive power generated by other elements in the grid. Shunt reactors come in two main types: oil-insulated and air-insulated shunt reactors.

The compensation requirements for the three scenarios have been calculated and are fulfilled by shunt reactors of four different sizes: 50, 100, 120 and 150 Mvar.

The following table summarises the required number of shunt reactors of different sizes in each scenario, with the cable lengths taken into account. The number of shunt reactors with different coil arrangement is shown in brackets, with the first figure indicating the number of air-insulated coils and the second for 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 then 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: Number of shunt reactors by type and scenario

Figures of the locations of the cables and shunt reactors in the three scenarios are presented in the report for WP1. Only the figure for scenario 3, the most restrictive scenario, is included in this summary, as is illustrated in Figure 1.

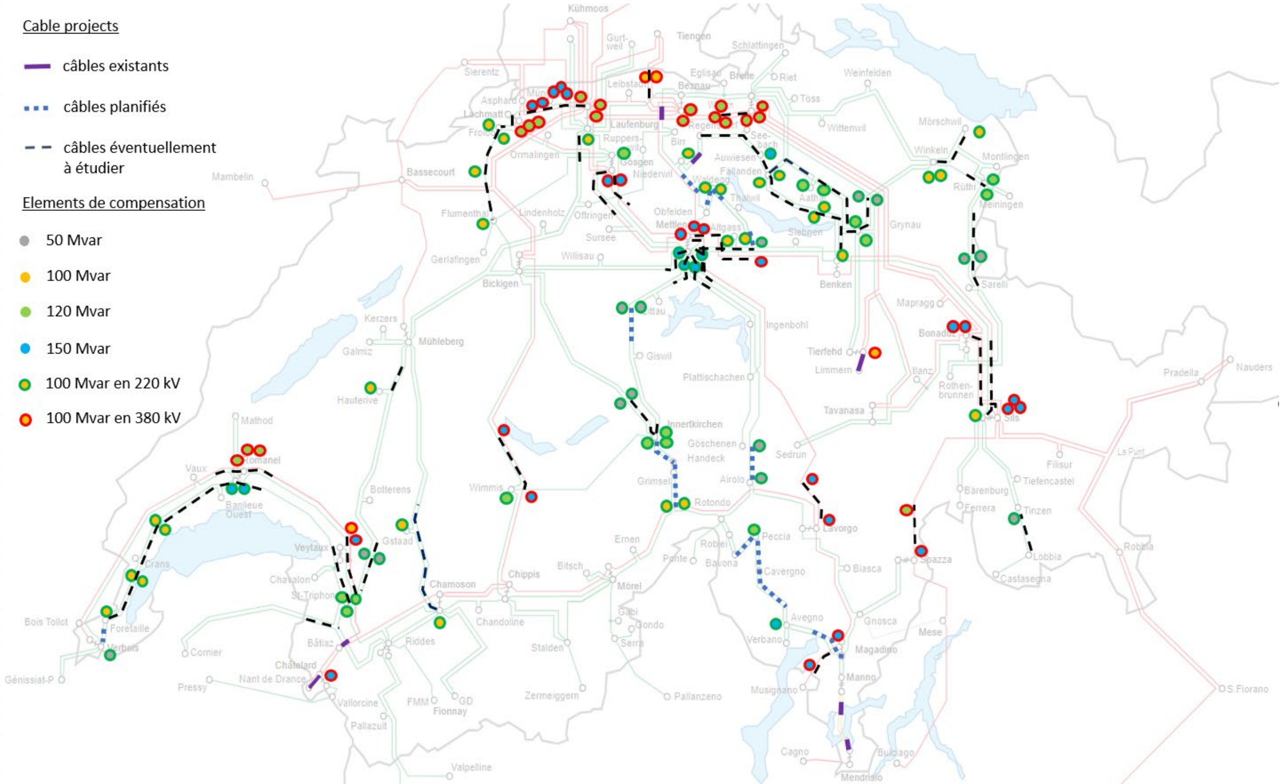

Figure 1: Compensation solution for scenario 3

In total, 114 shunt reactors would be needed to compensate for 12.9 Gvar of reactive power generated by the cables in scenario 3. 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, an equivalent of 25 power plants, as the one in Leibstadt, 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.

Due to the large number of shunt reactors required in certain areas, some substations would need to be expanded considerably. For example, up to 7 shunt reactors would be needed at substation Mettlen, and up to 11 shunt reactors would be required along the cable 380 kV Lachmatt – Laufenburg. 114 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.

The estimated cost of the compensation elements for the three scenarios are CHF 29.9 million for scenario 1, CHF 182.2 million for scenario 2 and CHF 1,365.9 million for scenario 3, respectively [25].

3 Work package 2: Electromagnetic transient studies (EMT studies)

3.1 Frequency scan studies

An electrical network is comprised of various types of electrical equipment and components of resistive, inductive or capacitive nature. Some of these inductive and capacitive reactances can become equal to each other in value at certain frequencies, resulting in series or parallel resonances. What is more, certain switching operations can generate voltage and current waveforms with a high harmonic content. These harmonicrich components can excite existing resonances and cause poorly damped oscillations, leading to excessive harmonic distortion and overvoltages.

In EMTP, frequency scans can be performed by feeding in a 1 A current of a specific frequency at the point of interest and measuring the voltage response at that point. The voltage measured in the predefined frequency spectrum corresponds to the harmonic impedance observed at the point of interest.

There are two important parameters in frequency scans:

1. The resonant frequency, which can be more problematic at lower frequencies. It should be noted that it is resonant frequencies closer to low-order integer harmonics that are likely to cause problems in an AC grid.
2. The second parameter is the impedance of the resonance peak. For resonances close to low-order integer harmonics, the higher the impedance, the greater the risk of overvoltage.

Frequency scans were carried out at various network locations and under different network conditions for the three scenarios. Several aspects of the results were then compared and analysed.

The first conclusion that can be immediately drawn after comparing the **resonant frequencies** in the three scenarios is that they shift towards lower-order harmonic values with increasing penetration of cables. In other words, resonant frequencies at the same network point would decrease from scenario 1 to scenario 2 and from scenario 2 to scenario 3. The example of Verbois is shown below in Figure 2, where the resonant frequencies in scenarios 1 and 2 are both above 350 Hz and very similar, since the only difference is the 4.5 km cable between the 220 kV Foretaille and 220 kV Verbois substations. However, cabling a large part of network in the Lake Geneva region in scenario 3 results in a reduction of almost 200 Hz in the resonant frequency.

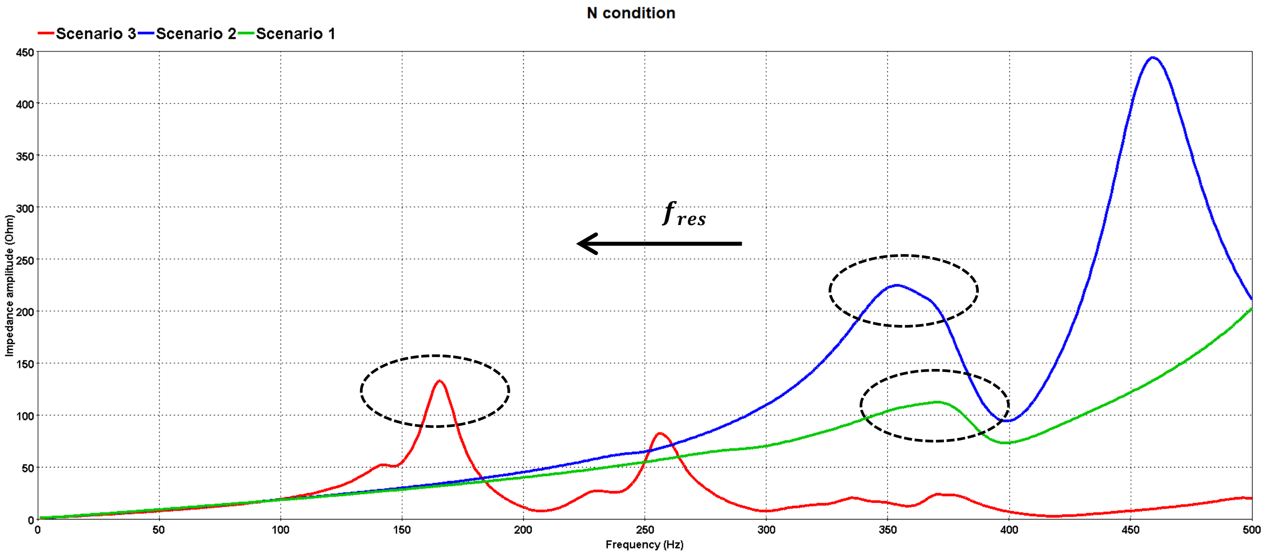

Figure 2: Comparison of harmonic impedance at 220 kV Verbois in scenarios 1, 2 and 3. N Condition

Another interesting conclusion of this study is that **the impedance of the resonant frequency** is much higher in the 380 kV grid than in the 220 kV grid. This phenomenon is a result of different damping in the grid of the two voltage levels. Since the 220 kV grid is more densely meshed than the 380 kV grid, its damping is higher, resonance impedances are thus lower. Comparisons were carried out at various substations where the two voltage levels are coupled, and the results clearly demonstrate this phenomenon. The example of Romanel is shown below in Figure 3.

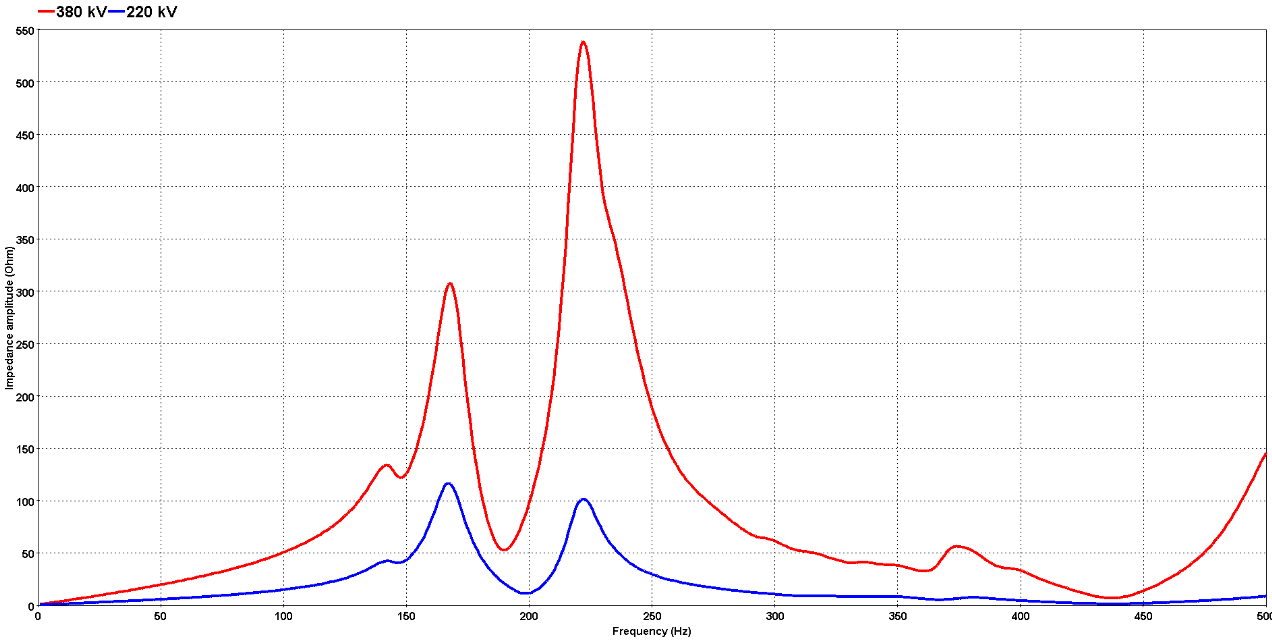

Figure 3: Comparison of harmonic impedance between 220 kV and 380 kV at 380 kV Romanel. N Condition

Regarding the **criticality of the results in different scenarios**, the results show that under normal operating conditions (N, N-1, N-2), no problematic resonances should be expected, either in scenario 1 or in scenario 2. However, two substations were identified with critical risks of resonances in scenario 3: 380 kV Romanel and 380 kV Magadino. These critical cases would occur in the following grid configurations:

- At 380 kV Romanel following an N-1 on the 380 kV Bâtiaz – Chamoson line: potentially problematic due to resonances at the 3rd harmonic.
- At 380 kV Romanel following an N-2 on the 380 kV Bâtiaz – Chamoson and 380 kV Bois Tollot – Romanel lines: potentially problematic at the 2nd harmonic.
- At 380 kV Magadino following an N-1 on 380 kV Lavorgo – Magadino: potentially problematic at the 3rd harmonic.

As an example, the harmonic impedance at 380 kV Romanel is shown in the figure below for various operating conditions (cases 1 – 6), in which cases 5 and 6 would be most likely prone to critical resonances.

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

Table 1: Simulated cases for a frequency sweep at 380 kV Romanel in scenario 3

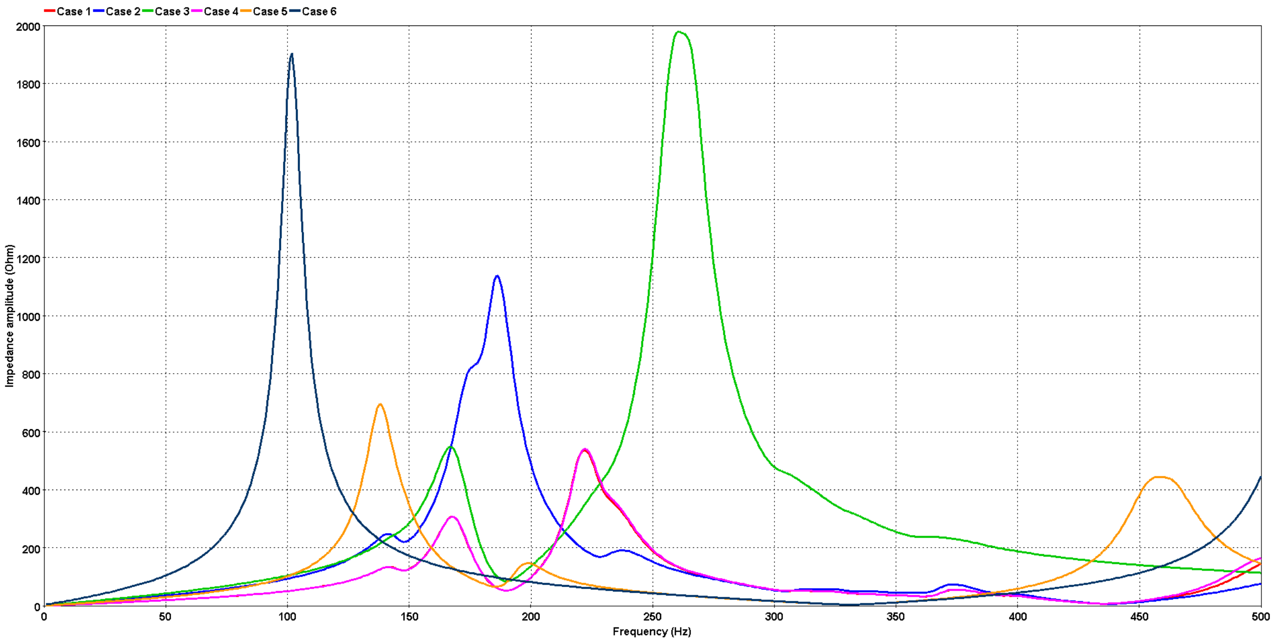

Figure 4: Harmonic impedance at Romanel for the 6 operating cases specified in Table 1 in scenario 3

To make it easier to understand the impact of cables on network resonances, a fourth scenario was created with an even higher cable density than in scenario 3. The deterioration in the system frequency response was confirmed in grid areas where it was previously not critical in scenarios 1, 2 and 3. For example, 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.

3.2 Harmonic amplification studies

Typical sources of harmonics in an electrical network are non-linear loads (e.g. some industrial equipment, variable-speed drives for AC/DC motors, battery chargers, etc.) and power electronics devices (e.g. HVDC converters, wind farms, SVCs, STATCOMs, etc.). Harmonics from these sources can propagate through the system impedances and be amplified several times in areas of high cable density due to resonances, resulting in a deterioration of the supply voltage.

The degree of amplification depends little on the harmonic impedance at the point of observation. In contrast, the degree of amplification at the observation point is the collective impact of the harmonic resonances on all the paths between the feed-in point and the observation point. Consequently, if the resonance is excited on one or more transmission paths, the corresponding harmonic impedance Z will be high, resulting in a much higher harmonic voltage at the observation point than at the feed-in point.

An increase in THD (Total Harmonic Distortion) resulting from harmonic amplification has several repercussions on equipment maintenance and system operation, with additional stress exerted on the grid that can potentially lead to equipment premature ageing and even damage. These repercussions include, but are not limited to:

- Overheating of equipment (e.g., transformers, motors, earthing, etc.)
- Audible noise in transformers and rotating masses

- Motor vibrations
- Increased skin effect in line and cable conductors
- Thermal tripping of protective devices and logic failure in digital devices
- Capacitor bank failure.

To avoid unforeseen problems, it is advised to carry out harmonic amplification studies at the planning stage before integrating cable projects into the grid. Since the phenomenon of harmonic amplification is highly dependent on the harmonic resonances on all the transmission corridors between the feed-in point and the measurement point, it would be impossible to predict such risks without simulations.

Harmonic amplification studies are carried out by feeding in voltages of different harmonic frequencies with an amplitude of 1 V at a certain grid point and measuring the voltages at various other locations. The ratio of the measured harmonic of a given order to the harmonic of the same order fed into the grid defines the amplification factor (AF), which indicates the severity of amplification of the harmonic in question.

A comparison of the harmonic amplification results between the three scenarios shows that **the amplification of low-order harmonics worsens as the number of cable projects in the grid increases**. This is the case for harmonic amplification in the Châtelard region, where critical amplification of the 7th harmonic at both 380 kV and 220 kV can already be seen in the current configuration (scenario 1). The results become even more critical in scenario 3. In the Lake Geneva region, no harmonic amplification can be observed in scenarios 1 and 2. However, due to the installation of a large number of cables in scenario 3 in this area, critical amplification of the 7th harmonic then arises. A comparison of harmonic amplification in the three scenarios at 220 kV Crans, 220 kV Romanel, 220 kV Banlieue Ouest and 220 kV Vaux is shown in the figure below.

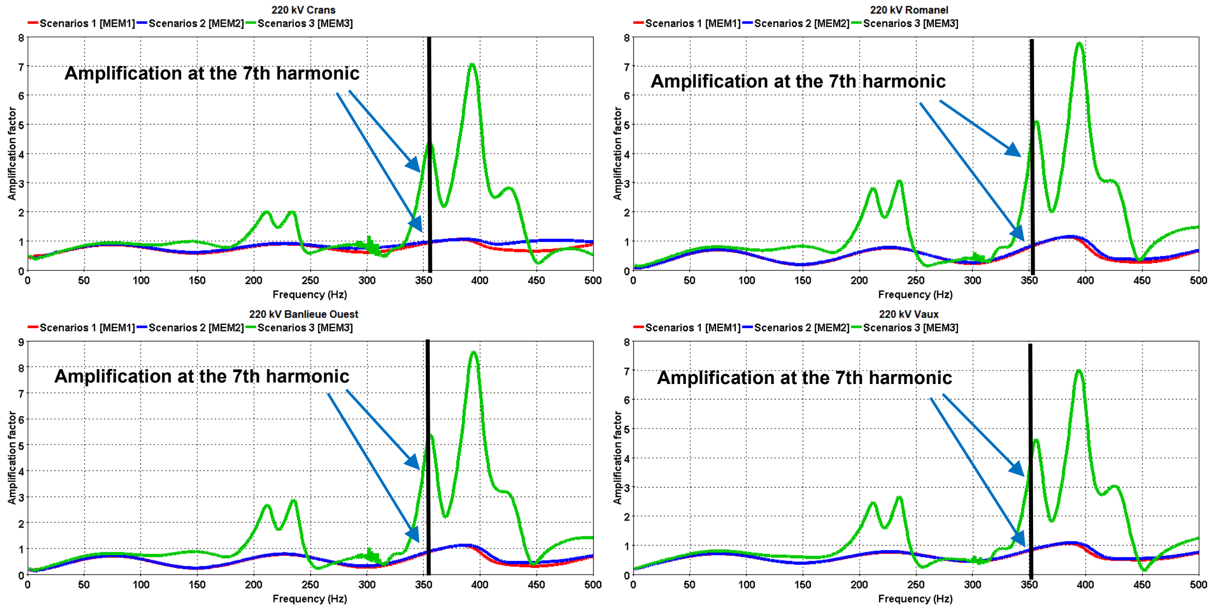

Figure 5: Harmonic resonance along 220 kV Verbois – Romanel and 220 kV Romanel – Vaux for scenarios 1, 2 and 3

While harmonic amplification tends to increase as the number of cables rises, there are exceptions, as in the case of Airolo. Critical amplification of the 5th harmonic is observed in both scenarios 2 and 3, but the amplification factor is even higher in scenario 2 despite fewer cables installed in this scenario near Airolo. The amplification factor measured at Airolo for the three scenarios is illustrated in the figure below.

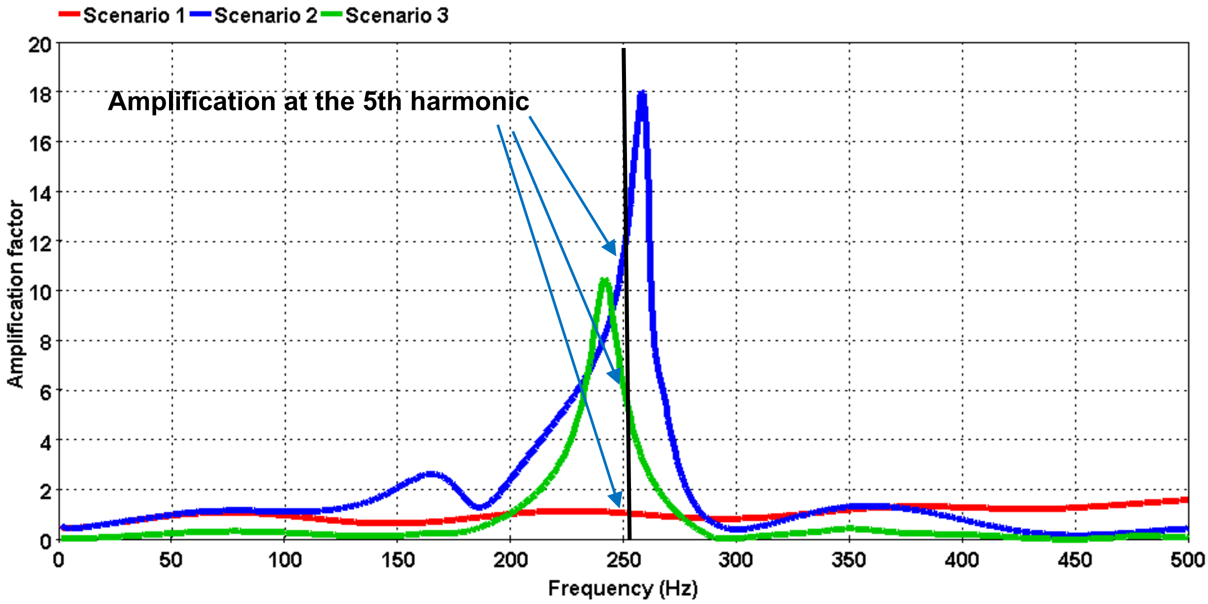

Figure 6: Harmonic amplification at 220 kV Airolo with feed-in at 220 kV Mettlen

As expected, the harmonic resonance frequency at Airolo in scenario 3 is lower than that in scenario 2, with the harmonic impedance at the 5th harmonic (250 Hz) in scenario 2 being higher. For this reason, the amplification of the 5th harmonic at Airolo following a feed-in at Mettlen would be lower in scenario 3 than in scenario 2.

The **short-circuit power of the grid** plays an important role in the amplification of low-order harmonics. In general, the amplification of low-order harmonics increases when the short-circuit power of the local grid is low. This is the case for amplification at 220 kV Airolo in scenario 2, where amplification of the 5th harmonic becomes critical for low short-circuit power conditions. Similar observations can also be made for the Châtelard region in scenario 2, where the amplification of the 7th harmonic becomes critical under low short-circuit power conditions of the local grid. The impact of short-circuit power in scenario 2 at 380 kV Bâtiaz, 380 kV Nant de Drance, 380 kV Châtelard and 220 kV Châtelard is shown in the figure below.

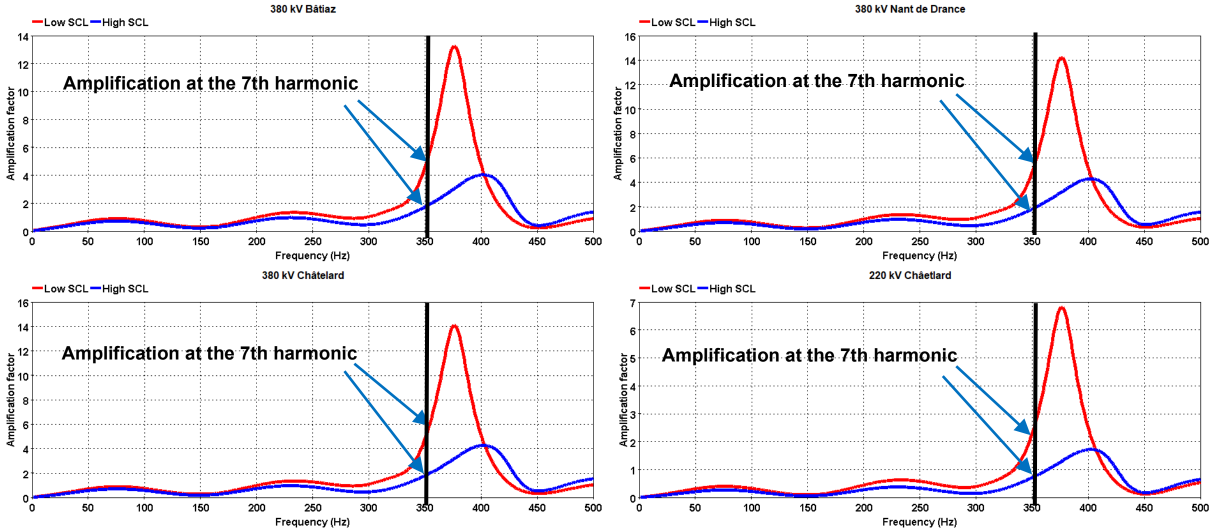

Figure 7: Harmonic amplification at 380 kV Bâtiaz, 380 kV Nant de Drance, 380 kV Châtelard and 220 kV Châtelard in scenario 2 for low and high short-circuit power conditions

According to a recent measurement campaign carried out at 380 kV Romanel [26], the 7th harmonic component could be as high as 4%, which exceeds the limit defined in [2]. With an amplification factor of 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, the distortion of the 7th harmonic at these three locations would be as high as 31.548%, 33.148% and 33.348% in the worst-case scenarios, respectively. Such a high amplification of the 7th harmonic would have a serious impact on power quality and grid equipment.

However, depending on the shape of the harmonic amplification curves, exceptions may occur where amplification of a certain harmonic rank may be higher under high short-circuit power conditions. This is the case, for example, for the 220 kV Romanel, 220 kV Banlieue Ouest, 220 kV Foretaille and 380 kV Bâtiaz substations in scenario 3, where the amplification of the 5th harmonic is higher under high short-circuit power condition. The figure below illustrates this case.

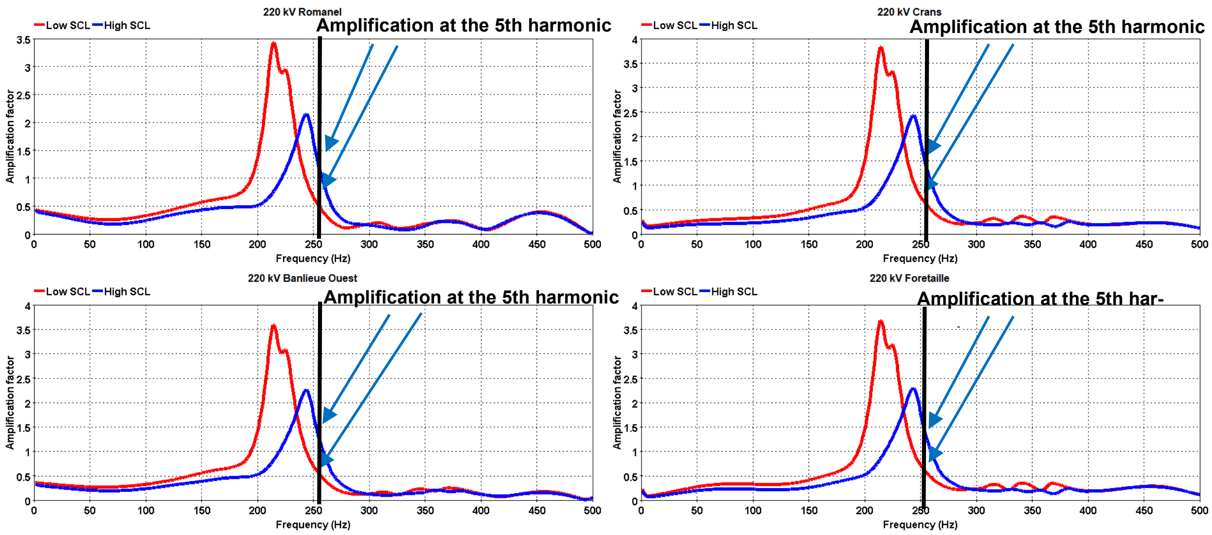

Figure 8: Harmonic amplification in scenario 3 at 220 kV Romanel, 220 kV Crans, 220 kV Banlieue-Ouest and 220 kV Foretaille

The analyses carried out to date demonstrate that it is not possible to predict in advance the impact of a given cable project in terms of harmonic amplification. As the results are often unpredictable, it is absolutely essential to carry out detailed studies on harmonic amplification, taking into account variations in grid configurations and conditions, for any new cable projects to be integrated into the grid.

Another argument that demonstrates the need to carry out harmonic studies for every cable project is **the impact of a cable on the amplification of harmonics in distant areas**. Studies have shown that the 220 kV Altgass – Samstagern cable would have an impact on harmonic amplification in Ticino. Amplification of the 7th harmonic at 220 kV Bavona, Peccia and Cavergno with a feed-in at 220 kV Mettlen becomes critical if a cable is installed between Altgass and Samstagern in scenario 3, whereas it remains moderate for an overhead line.

3.3 Transformer energisation studies

Transformer energisation is a routine operation in electrical networks. It is generally carried out without any negative consequences for the grid, as the transient currents and voltages generated during this process can be safely damped within seconds. However, in certain situations when there are cables in the vicinity, the resonances excited by the transformer inrush currents cause temporary overvoltages (TOV), which may considerably stress network equipment, leading to premature ageing and even permanent damage.

As explained in section 3.1, three critical cases of network resonances were identified with frequency scan studies in scenario 3. Unsurprisingly, the same cases were found to pose great risks of TOV during transformer energisation. These three cases are presented below as a reminder:

- At 380 kV Romanel following an N-1 on the 380 kV Bâtiaz – Chamoson line: potentially problematic due to resonances at the 3rd harmonic.
- At 380 kV Romanel following an N-2 on the 380 kV Bâtiaz – Chamoson and 380 kV Bois Tollot – Romanel lines: potentially problematic at the 2nd harmonic.
- At 380 kV Magadino following an N-1 at 380 kV Lavorgo – Magadino: potentially problematic at the 3rd harmonic.

Detailed simulation results of transformer energization at 380 kV Romanel and Magadino can be found in the report for WP2. This summary only includes the example of transformer energisation at 380 kV Romanel for an N-2 contingency of the 380 kV Bâtiaz – Chamoson and 380 kV Bois Tollot – Romanel lines. In this case, critical and poorly damped TOVs with high 2nd harmonic component can be observed after circuit breaker closing, with the maximum amplitude of the phase-to-ground and phase-to-phase voltages exceeding 1.5 p.u. This case is extremely critical because such TOVs can exert significant dielectric and thermal stress on the equipment and insulation of the grid near 380 kV Romanel. The comparison of the phase-to-ground voltage at 380 kV Romanel between scenarios 2 and 3 for the energisation of the 380/220 kV transformer at 380 kV Romanel is presented in the figure below.

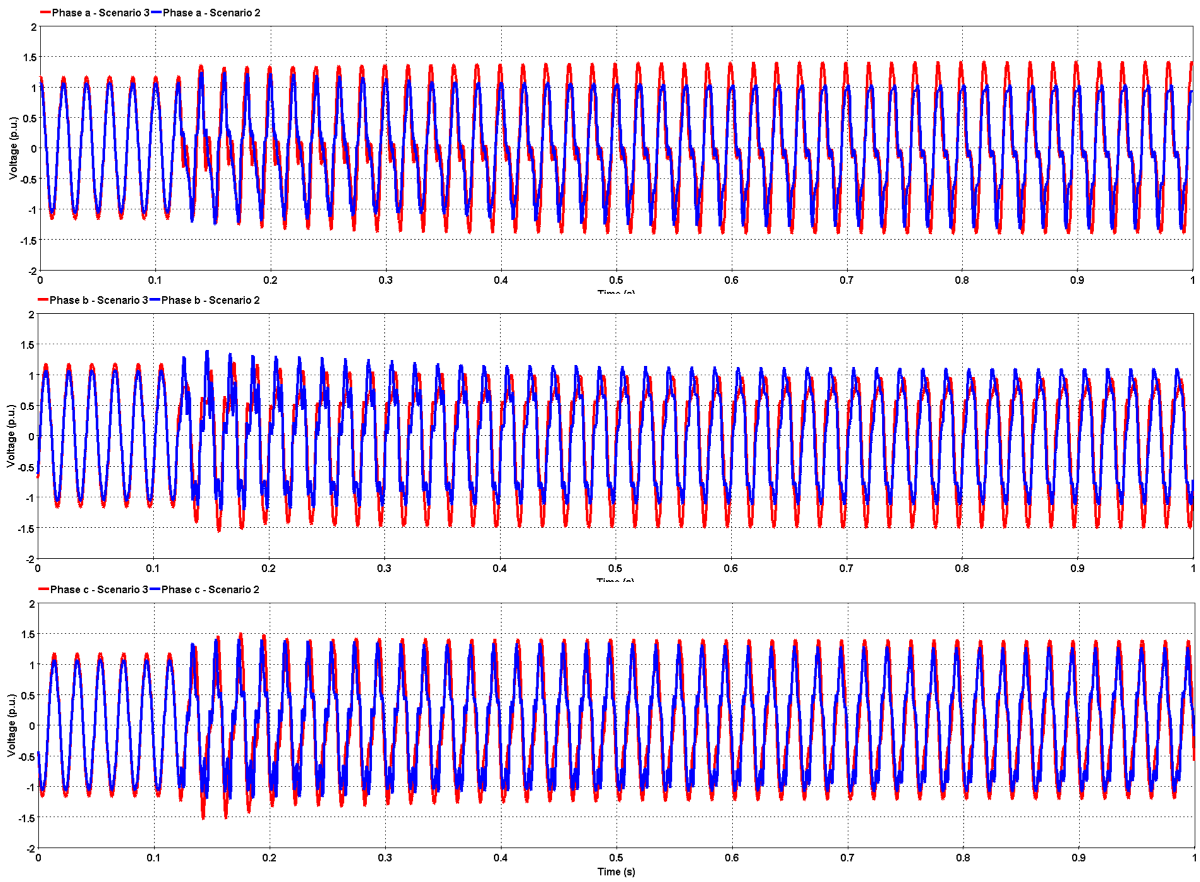

Figure 9: Phase-to-ground voltages at Romanel following the energisation of the 380/220 kV transformer at Romanel. Scenario 2 is in blue and scenario 3 in red

In the figure above, poorly damped TOVs heavily distorted by harmonics and exceeding 1.5 p.u. can be seen in scenario 3 (red). However, in scenario 2 where the total cable length near 380 kV Romanel is significantly reduced, the TOVs resulting from transformer energisation become considerably attenuated, with the maximum amplitude peaking at 1.2 p.u. and decreasing rapidly, significantly reducing the risk of dielectric and thermal stress on equipment and grid insulation (blue).

Moreover, it is known that the **short-circuit power** at the substation where a transformer is energised also has a remarkable impact on post-connection transients. In order to evaluate such impact of short-circuit power, it was decided to extend the scope of the study by further increasing the level of cabling in two already densely cabled areas in scenario 3. 380 kV Romanel and 380 kV Laufenburg were chosen to for this analysis. The short-circuit power at 380 kV Romanel is 11 GVA in normal operation, that at 380 kV Laufenburg is 43 GVA, which is among the highest of all substations in the Swissgrid network. Starting from scenario 3, an additional 77 km of cables were inserted in the vicinity of 380 kV Romanel and around 107 km of extra cables were added near 380 kV Laufenburg. Thanks to the high short-circuit power at 380 kV Laufenburg, almost tripling the length of the cabling from 64.8 km to 171.74 km only slightly shifts the parallel resonant frequency by less than 10 Hz. In addition, the high damping of the system due to the high short-circuit power indicates that the harmonic impedance of the grid at 380 kV Laufenburg is low enough to avoid excitation of any low-order parallel resonance. Unsurprisingly, no TOVs are observed during transformer energisation at 380 kV Laufenburg in the two cases tested, even with intensive cabling in the vicinity of 380 kV Laufenburg.

On the contrary, the impact of increasing the cable length near Romanel by 77 km can be devastating, as shown in red in the figure below.

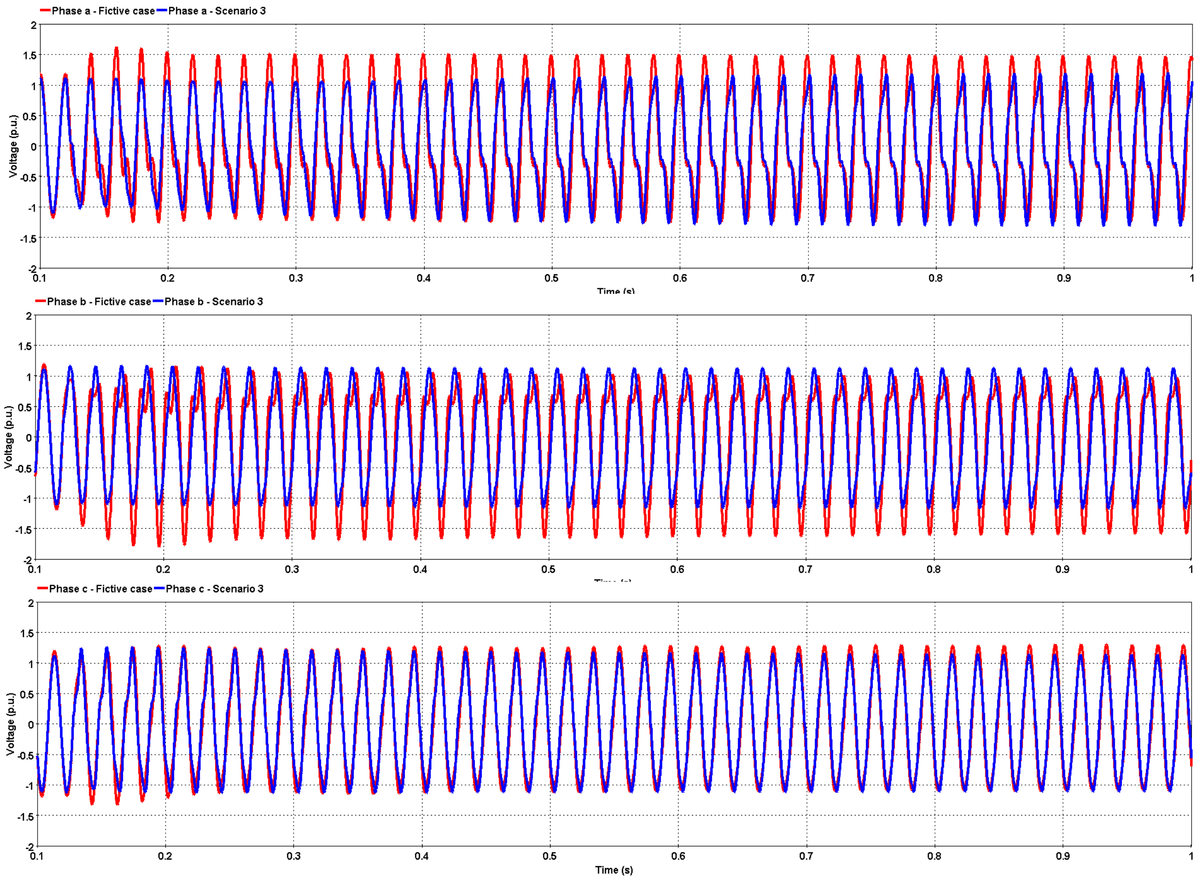

Figure 10: Phase-to-ground voltages at 380 kV Romanel – scenario 3 and the fictitious case for the first second of the simulation

To sum it up, as far as network resonances are concerned, it would be safer to integrate cable projects close to a strong node, as minimal impact can be expected on the existing grid. However, other constraints such as harmonic amplification or the lack of space for compensation devices would have to be studied separately.

3.4 Voltage steps due to connection/disconnection of cables and reactive power compensation devices

This section analyses the influence of short-circuit power on voltage steps following the connection/disconnection of cables and/or shunt reactors. The aim of this analysis is to establish maximum values for cable length and compensation size in order to avoid voltage steps beyond the admissible values. Voltage steps up to 2% are permitted at substations in connection to distribution grids [22].

Ratios of short-circuit power to maximum cable length have been established for 220 and 380 kV connections to avoid exceeding a 2% voltage step. Such a ratio for a 380 kV node (substation) is shown in the following figure.

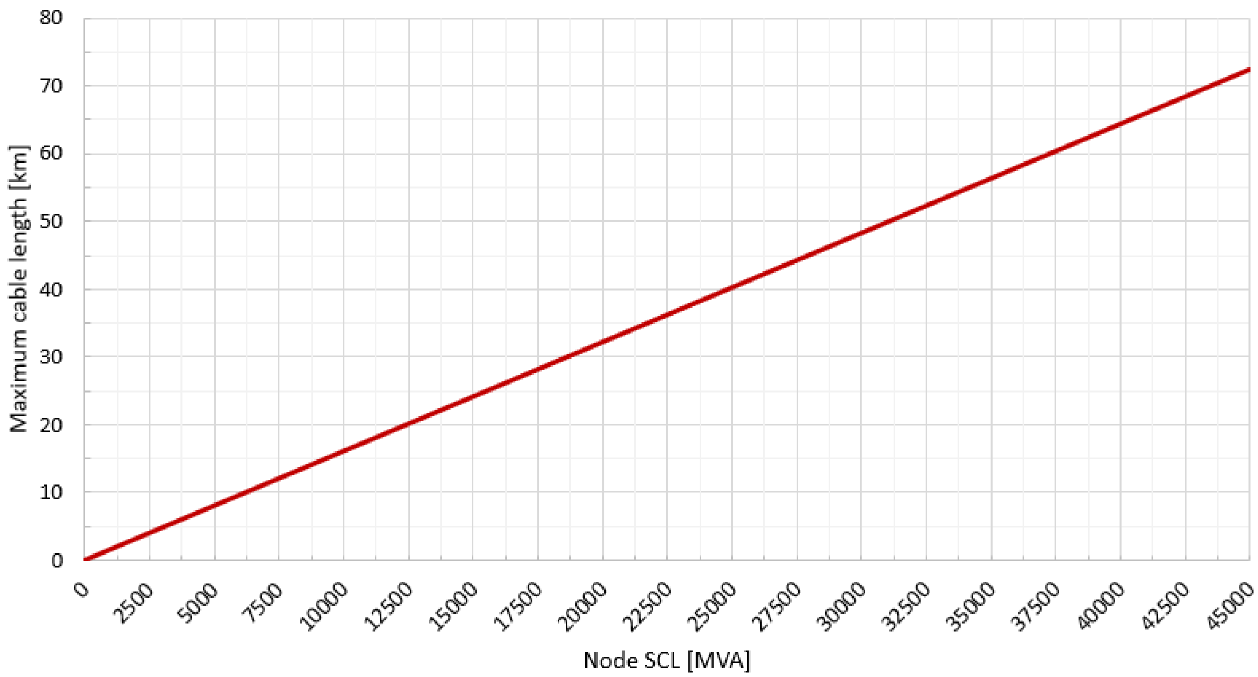

Figure 11: Theoretical maximum permissible total cable length at a given node for a voltage increase of 2%

This figure shows, for example, that for a node with an SCL (short-circuit level) of 12,500 MVA, the connection of a total cable length of 20 km would result in a 2% increase in the steady-state voltage. Logically, for a weaker node (lower SCL), the total permissible cable length would be shorter.

This limitation on cable length should not be seen as the only necessary limitation. It is merely an initial restriction on length. EMT studies evaluating network resonances and harmonics must also be carried out for a more definitive decision.

An estimate of the maximum loss of reactive compensation resulting in a voltage jump of 2% was also calculated according to the same principle, as is shown in the figure below.

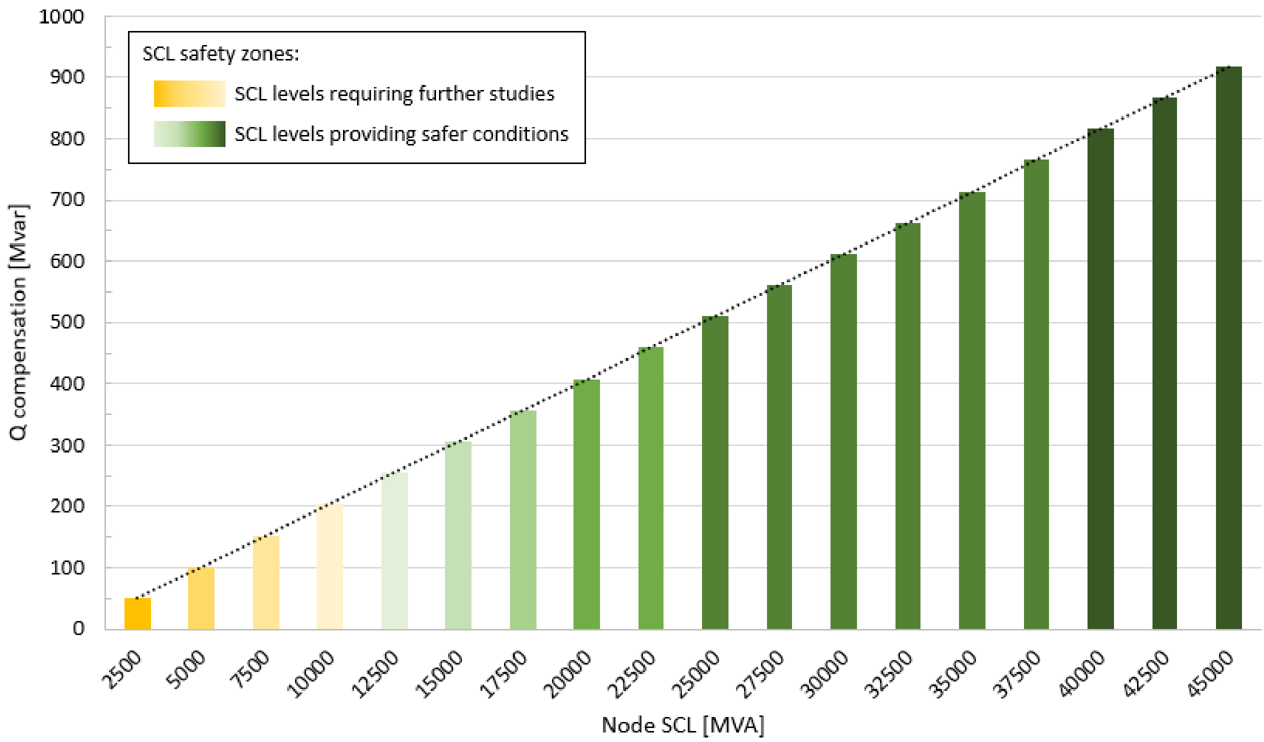

Figure 12: Estimation of the maximum loss of reactive power compensation resulting in a voltage jump of 2%

According to the figure above, the maximum possible loss of a shunt compensation for a node with an SCL of 10 GVA would be 200 Mvar while respecting the limit of voltage step. In areas where the short-circuit power is less than 10 GVA, the coil size should be limited.

4 Work package 3: Grid restoration

The current concept for restoring the Swiss transmission grid is based on four restoration cells spread across the country, i.e., the southern, western, central and eastern cells.

In the event of a total blackout, 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.

Connecting long lines is one of the most difficult aspects of grid restoration. These lines generate a high capacitive charging current, leading to high generator load. This effect becomes more significant 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 excess reactive power, allowing the generators 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 impeding factor 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 simulation results for the Ticino restoration cell demonstrate network transient behaviour deterioration with the future grid configuration, as compared to the current. However, the problems encountered can be mitigated or resolved, and restoration with the southern cell remains possible.

Analyses for the central restoration cell indicate that restoration according to the current plan will no longer be possible. Although investigation into alternative scenarios shows clear improvement in grid transient behaviour during restoration, the prospects remain bleak due to higher risks and needs of extensive revamping and refurbishment of Swissgrid grid infrastructure and the KWO power plant. As a result, the restoration cell with KWO will no longer be available after the installation of the Innertkirchen – Ulrichen cable project.

5 Interpretation of results and regional considerations

The analyses carried out in this study have highlighted technical issues of extensive cable integration in grid operation, as well as other issues, such as those of an economical or ecological nature, due to the need to install compensation devices. The criticality of the various problems encountered is assessed on the basis of scenario 3.

The technical issues include, but are not limited to, network resonance, harmonic amplification, voltage variations and restoration after a blackout.

Risks of low-order **resonances** were identified at 380 kV Romanel and 380 kV Magadino. These resonances would cause critically high TOVs following the energisation of the 380/220 kV transformers at Romanel and Magadino in N-1 contingency. These two transformers would have to be energised exclusively via the grid without contingencies, which is not acceptable. Consequently, the length of the cables in the vicinity of these two nodes should be reduced.

Harmonic amplification in the Lake Geneva region would become critical in scenario 3. For the Châtelard region, the amplification is already critical in scenarios 1 and 2 but worsens considerably in scenario 3. These critical amplifications occur even under contingency-free grid conditions, which is why the system cannot operate without filters. Installing and operating filters would lead to new problems, uncertainties and complexities.

The connection and disconnection of some of the cables planned in scenario 3 would cause **voltage steps** of more than 2%, which necessitates limitation on their length. This is the case for the 57 km cable system along Lake Geneva, with its two longest sections exceeding the maximum permissible length. The specific sections concerned are the 220 kV Banlieue Ouest – Foretaille line (52 km, i.e. 7 km longer than the maximum permissible length) and the 220 kV Crans – Romanel line (40 km, i.e. 6 km longer than the maximum permissible length).

Restoration after a blackout is one of the most critical considerations in relation to the implementation of cables. The results show difficulties in restoring the southern cell, while analyses for the central cell are still underway.

In terms of economic and ecological concerns, the **surface area dedicated to substations** would have to be increased by around 13% to be able to accommodate all the shunt reactors required for scenario 3. This implies the need of expanding existing substations or building new ones at several locations in the network such as Lachmatt, Laufenburg and Romanel.

Certainly, these conclusions were drawn from scenario 3. Any other cable layout would lead to different results.

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