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Assessment of the Swissgrid study on the impacts of underground cabling in EHV networks on the grid operation:

“étude de câblage Suisse”

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Content

List of abbreviations

NL	Network level (i.e., Netzebene in German)
EHV	Extra-high voltage (i.e., 220 kV and above)
EMT	Electromagnetic transients
EMTDC	Electromagnetic transients program[1]
EMTP	Electromagnetic transients program[2]
EMTP-ATP	Alternative Transients Program[3]
EMTP-RV	Electromagnetic transients program[4]
ENTSO-E	European Network of Transmission System Operators for Electricity
FEN	Forschungsstelle Energienetze (Research Center for Energy Networks ETH Zürich)
FSA	Frequency scan analysis
IEEE	Institute of Electrical and Electronics Engineers
MOV	Metal Oxide Varistor
OHL	Overhead transmission lines
PCC	Point of Common Coupling
p.u.	per unit
RMA	Resonance mode analysis
SFOE	Swiss Federal Office of Energy
SVC	Static VAR compensator
TOV	Transient overvoltage
VSD	Variable Speed Drive
XLPE	Cross-linked polyethylene cable

[1] Commercial software developed and maintained by Manitoba HVDC Research Center
[2] First EMT software developed by Dr. Hermann Dommel and Dr. Scott Meyer at BPA in the timeframe of 1966-1983
[3] Free software, developed by Dr. Scott Meyer and maintained by an international group of academics
[4] Commercial software, controlled by EDF, Hydro-Quebec and RTE, developed and maintained by Prof. J. Mahseredjian at PGSTech

1 Introduction

1.1 Background

The potential of using underground cables (instead of overhead lines) in the Swiss transmission grid (NL1; 380 kV and 220 kV) is discussed and investigated each time a new transmission project is planned or when a renovation/conversion/retrofitting of an existing transmission line is considered. The interest in constructing the new transmission lines as underground cables has increased recently. Although this solution offers certain advantages, an increase in the number of underground cables in Switzerland could potentially lead to restrictions in operation of the transmission grid.

In order to analyze, identify and quantify these restrictions, Swissgrid recently performed a study entitled "Cabling Study Switzerland", officially known as étude de câblage Suisse.

It consists of 3 work packages (WP):

- WP1: Study on reactive power compensation (Compensation de la puissance réactive)
- WP2: EMT studies at system and equipment level (Études EMT au niveau des systèmes et des équipements)
- WP3: Study on grid blackstart (Reconstruction du réseau après black-out)

Swissgrid has analyzed three scenarios of increasing cable share in its EHV grid for each WP, which are described in the relevant reports. The SFOE has carried out an initial analysis of this study and is interested in receiving a critical analysis of these documents from FEN.

The final version of the Swissgrid study can be found at www.swissgrid.ch

1.2 Objective and Requirements

The analysis will enable the SFOE to check the plausibility of Swissgrid's analyses and proposals. In addition to a general statement on the study, the analysis will also propose ways of finding solutions to the problems mentioned in this study, in particular:

WP 1. Reactive power compensation

a. Quantification of the reactive power to be compensated. Plausibility of Swissgrid's calculations
b. Location of the reactive power compensation systems: critical analysis of the proposals made by Swissgrid
c. Alternative solutions (Statcom, larger inductors, etc.): FEN proposal with pros and cons (costs, space requirements, flexibility, etc.)

WP 2. EMT studies

a. Plausibility of the calculations and the critical values defined by Swissgrid
b. Are the selected cases realistic (e.g. N-2 case, selected substations)?

c. Investigation of the amplification of harmonics: are alternative solutions possible? (filters, etc.)

WP 3. Restoration / blackstart

a. Plausibility of Swissgrid's calculations

b. General alternative solutions for the problems arising from the “South” and “Center” reconstruction cells (from the grid reconstruction concepts). If possible, assessment of the potential problems in the “East” and “West” restoration cells.

2 Methodology and the assessment

The topic of increasing the share of cabling in transmission networks has been receiving attention, especially since 1990s in an increased manner. [1] and [2], published by the IEEE Task Force on Harmonics Modeling and Simulation, address the challenges and provides guidelines in a holistic manner. The ongoing energy transition, started in early 2000s, integrating large-scale renewable energy resources that are not always located close to the consumption centers, lead to reinforcements in the transmission networks as well as expansion. A well-functioning and well-connected European transmission system is also an enabler for seamless energy transition by exploiting the complimentarities in various regions in terms of generation and demand. In the meantime, due to increased public resistance to constructing new overhead lines, utilization of underground cables are receiving an increasing attention.

A review has been performed on the publicly reported state-of-the-art practices and discussions, covering

– the academic literature [3-7],
– the industrial reports and publications [8-23], and
– the regulatory discussions [24]

on the impacts of increasing share of underground cables in EHV transmission networks on

– the requirements of reactive power compensation,
– the harmonic resonances,
– the switching transients resulting in overvoltages, and
– the restoration (black-start) processes.

The review demonstrates the status of state-of-the-art as well as the industrial experiences in other countries such as Denmark, Germany, Netherlands, Canada, Bulgaria and the UK. In the meantime, the reports by Swissgrid are critically and qualitatively assessed.

The following documents are shared by the SFOE for review:

a. Étude de câblage Suisse, summary, September 4, 2004 (Report, French, 6 pages)

b. Étude de câblage Suisse, WP1 – reactive compensation studies, August 20, 2024 (Report, French, 31 pages)

c. Étude de câblage Suisse, WP2 – EMT studies at the systems and equipment level, September 4, 2024 (Report, French, 207 pages)
d. Étude de câblage Suisse, WP3 – Restoration of the network after a blackout, August 20, 2024 (Report, French, 12 pages)

The following documents, providing insight into the detailed simulations for the restoration analyses, are shared by Swissgrid per request by FEN for review:

e. Black-start scenario 1 (Slides, English, 141 pages)
f. Black-start scenario 2 (Slides, English, 57 pages)
g. Black-start scenario 3 (Slides, English, 55 pages)
h. Black-start scenario 4 (Slides, English, 54 pages)
i. Black-start scenario 5 & 6 (Slides, English, 63 pages)
j. Black-start KWO: Load rejection (Report, English, 13 pages)
k. Black-start KWO: Two cell synchronization (Report, English, 43 pages)

2.1 Guidelines and industrial experiences

ENTSO-E guidelines in 2010 [8], and the reports by **National Grid** (UK) in 2015 [9], **EirGrid** (IR) in 2017 [13] for partial undergrounding[5] of EHV transmission lines provide insight into the aspects such as life expectancy, design, joint bays, cable terminations, time to install / test / commission, reliability of links, environmental aspects, and costs; however, they do not describe any guidelines for technical analysis. The technical brochure published by **Cigre** in 2019 [19] provides guidelines and recommendations on the modeling (i.e., cable layout and characteristics, network modeling, load modeling, converter modeling for wind and solar farms) and analysis only for harmonic studies.

A selected set of publicly available European experiences are summarized below with the key messages:

Denmark 2007: investigated TOVs[6] due to the sending-end switching of combined overhead lines (OHL) and underground cables with shunt reactors using EMT analysis [8].

Highlights: *This article presents a detailed technical analysis of a 400 kV transmission corridor consisting of a combined OHL and underground cable configuration, compensated by a shunt reactor, following a sending-end switching event. The analysis focuses on the occurrence and behaviour of potentially long-duration switching overvoltages. These overvoltages are associated with the slowly decaying post-switching voltage, which may persist for several seconds. Simulation results for the 400 kV transmission system indicate that overvoltage amplitudes can reach up to 132% of the steady-state voltage prior to switching. The root cause of these overvoltages is identified as the resonant characteristics of the network, exacerbated by asymmetries in system components, i.e., including*

[5] ***Partial undergrounding*** is the term used to describe the undergrounding of a short section or short sections of a long transmission circuit that is comprised predominantly of OHL.

[6] ***TOV*** stands for transient overvoltage occurring during switching transients (e.g., short-circuits, outage of lines/cables, energization of lines/cables and transformers, etc.), which can lead to equipment failures due to insulation breakdown.

variations in phase self-impedances, mutual coupling between phases, and asymmetrical capacitive effects introduced by the combination of the OHL, cable and the reactor. Due to the complex nature of the switching dynamics, generalized mitigation strategies cannot be readily defined. However, these findings highlight the necessity of incorporating detailed time-domain simulations into the design and planning processes of such hybrid transmission systems to ensure operational reliability and compliance with insulation coordination standards under switching scenarios.

Denmark 2023: doctoral thesis in collaboration with Energinet (Danish TSO) focusing on propagation of harmonic voltage in a meshed transmission system with a large proportion of underground cables. The impetus for this research stems from specific issues encountered following the integration of underground cables into the Danish transmission system. The installation of these cables has led to unexplained increases in measured harmonic distortion levels, as well as unexpected harmonic propagation and dispersion across the meshed transmission grid. This study commenced with an investigation of the harmonic distortion phenomena within the context of a meshed network, followed by propagation analyses of standing harmonic voltage waves. Subsequently, efforts were directed toward identifying optimal locations within the grid for implementing effective mitigation measures [23].

Highlights: ***Energinet*** *has proposed four distinct methodologies for identifying potential primary locations for harmonic filter installation within a meshed 400-kV transmission grid. A simplified sensitivity index is employed to identify supplementary candidate substations for filter placement, in addition to the initially proposed primary locations. This results in a defined set of substations considered for evaluation as potential filter sites.*

A standardized passive filter, specifically, a second-order high-pass filter tuned to the 11th harmonic with a quality factor of 2, is applied uniformly across all candidate substations. This consistent configuration enables direct comparison of the filter performance under each of the four proposed methodologies.

The comparative analysis assesses the strengths and limitations of each approach, culminating in a ranked evaluation based on the effectiveness of harmonic mitigation. The analytical results obtained align with the findings from extensive simulation studies previously conducted by Energinet as part of this mitigation strategy assessment.

Switzerland 2015: performed harmonic resonance analysis using frequency scans (or sweep) for high and low load scenarios for Swiss EHV grid [11].

Highlights: *In this study, a frequency-dependent model of a power transmission system was developed and implemented. Two analytical methods were employed to evaluate the system's dynamic behavior: (i) frequency scan analysis (FSA) and (ii) resonance mode analysis (RMA). The model was validated using two case studies: a benchmark ten-node network and the Swiss high-voltage transmission system. For each case, four simulation scenarios were conducted: one representing the existing network configuration composed exclusively of overhead lines, and three representing hybrid configurations incorporating underground cables.*

The results demonstrate that the integration of underground cables into a transmission network can significantly lower the system's resonance frequencies. Node participation factors were computed, as part of RMA, to assess the influence of individual nodes on system resonances. The analysis revealed that undergrounding transmission lines between nodes with high participation factors results in a substantial reduction of resonance frequencies. Conversely, replacing overhead lines with underground cables between nodes exhibiting negligible participation factors yields minimal impact on the system's frequency response.

Furthermore, the interdependence between voltage levels was investigated. It was observed that current injections at a node at one voltage level can substantially affect the nodes at a different voltage level, particularly at frequencies corresponding to resonance peaks introduced by the latter.

In conclusion, the frequency-domain analysis presented herein facilitates the identification of resonance-prone nodes within the transmission network and offers critical insight for mitigating adverse impacts when transitioning from overhead to underground transmission. For improved model fidelity and simulation accuracy, future work should incorporate enhanced modeling of frequency-dependent components and the inclusion of non-linear elements such as harmonic sources and AC/DC converters.

Netherlands 2016: investigated resonance frequencies below 1 kHz by frequency scans [12].

Highlights: *This study investigates the impact of long 380 kV underground cables on the resonance behavior of the Dutch transmission grid. A frequency scan analysis (FSA) was performed using a distributed, frequency-dependent parameter model representing the entire 380 kV Dutch transmission network, both with and without the inclusion of cables associated with an 80 km case study project.*

The FSA was conducted under various cabling scenarios within the case study, complemented by a series of sensitivity analyses. These included assessments of the effects of shunt compensation size, compensation location, and different mixed-line configurations on the grid's frequency response.

Simulation results indicate that increasing the cable length in the case study leads to a reduction in the first resonance frequency, reaching a minimum of approximately 190 Hz (between the 3rd and 4th harmonic) under a fully cabled configuration. Additionally, the presence of cables in the case study area increases the number of resonance frequencies below 1 kHz by up to a factor of ten compared to scenarios excluding the case study, and up to seven times compared to configurations with only overhead lines. These findings underscore the elevated risk of resonance associated with extensive underground cabling and emphasize the strong influence of cable length on the system's resonant behavior. While the first resonance frequency remains largely unaffected by variations in shunt compensation size and location, these parameters do alter the total number of resonance frequencies observed. Significant differences were also noted among various mixed-line configurations.

In conclusion, from a resonance mitigation perspective, it is recommended that all feasible combinations of cable and overhead line (OHL) segments, along with the size and placement of shunt reactors, be thoroughly evaluated during the planning phase of future cable integration projects. Such analysis will support the selection of mixed-line and compensation topologies that yield higher first resonance frequencies and a reduced number of low-frequency resonances, thereby enhancing the overall stability and performance of the transmission system.

Bulgaria 2018: analyzing the theory behind the series and parallel resonances, switching transients resulting in TOV using EMT analysis with frequency-dependent models [14].

Highlights: *The study underscores the necessity of conducting a comprehensive investigation into the phenomena described. A review of existing literature reveals that overvoltages of this nature are commonly associated with the operation of power equipment. However, it is evident that there is a lack of dedicated studies and research on this issue within Bulgaria. Additionally, the direct application of solutions and methodologies developed for overvoltage mitigation in other power systems is not feasible under Bulgarian conditions. Therefore, it is imperative to bring this issue to the attention of the scientific community, emphasizing the need for the development of preventive strategies that will not only reduce maintenance costs but also enhance the operational flexibility of power facilities.*

Canada 2019: analyzing the impacts of shunt capacitor banks for a project for N and N-1 states using frequency scans [18].

Highlights: *This study presents a set of guidelines and methodologies for assessing the impact of underground cables on harmonic voltage distortion levels within a power system. A detailed procedure is outlined, incorporating study methodologies and relevant utility standards and criteria. The procedure encompasses several stages, including system modelling, scenario identification, frequency scan analysis, power quality measurements, and voltage distortion level estimation. A real-world project is utilized to demonstrate the application of the proposed procedure. This project involves replacing portions of one 240 kV and three 138 kV overhead transmission lines with underground cables as part of a major road development in Calgary.*

Using the prescribed procedure, FSA studies were conducted to evaluate the impact of the project on the system's frequency response. The results indicated that the introduction of underground cables would increase the impedance of characteristic harmonics at the 138 kV bus. This effect was minimal for lower-order harmonics, such as the 5th harmonic, but became more pronounced for higher-order harmonics, such as the 11th and 13th. Moderate parallel resonance phenomena were observed under certain contingency conditions. The increased harmonic impedance was found to contribute to higher voltage distortion levels. However, impedance scan results alone were insufficient for determining voltage distortion levels and for identifying whether voltage distortion limits were exceeded. The harmonic currents entering the substation also play a critical role in this assessment.

Germany 2019/2020: providing guidelines [6], analyzing the impacts of shunt compensation levels, and the TOVs due to the switching transients using EMT analysis with constant parameter distributed line model, modeling surge arresters (MOVs), analyzing resonance with loads such as induction motors, investigating energization of transformers, combined with frequency scans, for various levels of cabling in selected parts of the grid: 0%, 25%, 50%, 100%, investigating steady-state reactive compensation levels for selected parts of the grid [15-17, 22].

Highlights [6]: *This study addresses critical considerations regarding mixed transmission lines comprising multiple OHL and underground cable sections. Due to the relatively longer lengths of cable sections, reactive power compensation is necessary, typically achieved through the installation of shunt reactors connected to each circuit of the line, which operate with variable power. Additionally, to protect the cable sections from lightning-induced overvoltages, surge arresters should be installed at each OHL-cable junction. The planned double-circuit 380 kV mixed transmission line has been modeled in detail using the EMTP-ATP. The focus of this study is on the switching and fault transients associated with this mixed-line configuration, particularly considering the interaction between the shunt reactors and the line.*

Simulation results of line energization indicate no critical overvoltages or significant stress on the closing circuit breaker. Controlled switching at the voltage zero-crossing is not required. However, the use of circuit breakers with pre-insertion resistors significantly mitigates overvoltage stress on the equipment. Due to the line-side connected shunt reactor, the secondary arc duration is anticipated to be longer compared to configurations without shunt compensation. The de-energization process is not explored in detail within this paper, but several factors such as line loading and compensation degree may impose considerable stress on the opening circuit breaker at both ends due to recovery voltage. Furthermore, inductive voltage transformers (VTs) are also subjected to increased stress during line de-energization.

Highlights [15-17, 22]: *The transmission system expansion plan in Germany includes the construction of several new Extra High Voltage (EHV) transmission lines to transport bulk power generated by wind farms in northern Germany to the southern regions. Some of these EHV lines will be designed as "mixed lines" (also referred to as hybrid lines), comprising both underground cable and overhead line sections. The high charging current associated with XLPE cables requires compensation through the installation of shunt reactors. However, higher degrees of compensation may result in delayed current zero* *crossings after switching operations, necessitating careful determination of the compensation level. From a technical perspective, mixed lines with shunt reactors present several complex transient phenomena that pose challenges for equipment design, protection schemes, and grid operation.*

Various EMT phenomena (e.g., resonant and inrush phenomena due to transformer energization which can result in high voltage stresses on equipment) arising from the operation of compensated mixed lines, based on a planned pilot project consisting of a double-circuit mixed line with a total length of 180 km are analyzed. Upon switching off the mixed line (via three-phase de-energization and single-phase auto-reclosure), critical transient recovery voltages may arise across the open circuit-breaker poles. This phenomenon occurs due to the resonant circuit formed by the cable capacitance and the shunt reactor inductance.

An additional concern is the shift of grid resonant frequencies into the low-order harmonic range, a result of the cable capacitances. Transformer energization within such a grid may trigger low-frequency resonances, leading to sustained voltage oscillations. The effectiveness of potential countermeasures, such as circuit-breakers with pre-insertion resistors, should be evaluated on a case-by-case basis.

Moreover, high capacitances within the transmission system can also impact downstream industrial grids under specific contingencies. A resonant phenomenon involving asynchronous motors is provided as an example. The examples presented demonstrate that the widespread integration of mixed lines into the transmission network requires comprehensive analysis. Electromagnetic interaction phenomena involving different mixed lines or nearby converter stations remain inadequately explored. Depending on grid conditions (such as short-circuit power and grid topology), the grid resonance frequencies may shift into the critical low-order harmonic range, potentially stimulating resonances. The extensive implementation of mixed 380 kV lines in a specific grid area could also lead to significant reactive power imbalances in the event of system splits, hindering both the control of such events and the subsequent grid restoration process. Until open questions are thoroughly researched and sufficient operational experience is gained, the large-scale integration of mixed lines into the transmission network should be avoided from a technical standpoint.

Network restoration becomes significantly more difficult and prone to failure with a high degree of AC cabling (avoidance of resonances, ensuring the reactive power balance at high charging capacities in the start-up network). The current concepts must be adapted and tested. In this regard, further research is needed.

2.2 FEN’s assessment of the methodology and the approach

Three scenarios are defined by Swissgrid (+1 scenario for the FSA) to assess the grid behavior for various operational conditions today and in the future with increasing shares of planned as well as unplanned cabling. The fictitious scenarios serve as a sensitivity analysis covering extreme cases of cabling.

In addition to normal operation conditions (N); the **contingency conditions** N-1 and N-2 are tested for selected scenarios and operational conditions.

All relevant types of analysis employed in reviewed studies are investigated by Swissgrid: (i**) steady-state reactive compensation analysis**, (ii) **frequency scan for harmonics (resonance) analysis**, (iii) **EMT analysis to quantify the TOVs** following switching operations such as energization of transformers

Even though it is classified as switching due to energization of lines/cables, **restoration** (i.e., black start) analysis is given separate focus, which is very important, and was not reported with supported analysis in the reviewed studies as well as in the literature.

The most accurate representation of **frequency-dependent cable and OHL modeling**, Wideband [25, 26], is chosen in EMT analysis in order to accurately capture the grid response during high-frequency transients.

Sensitivity analysis for nodal voltage increase based on **varying short circuit power of a node** is very important, and insightful.

2.3 Questions raised by FEN

1. **Are different grid loading conditions (low load vs. high load) already considered as part of cabling scenario and contingency combinations**?

Response by Swissgrid: As we consider unfavorable network conditions in our studies to study the different phenomena, especially Temporary Overvoltages (TOV), in the possibly worst-case scenarios, light loading condition is considered.

Assessment by FEN: The answer by Swissgrid is acceptable and sound, and FEN suggests that this aspect is clearly stated in the report.

2. **Are the impacts of increasing converter-interfaced systems (i.e., PVs and wind farms, VSD-driven pump-hydro) considered for harmonic resonances in all studies (including restoration)**? The current results may be influenced by increased numbers and types of converters in the system. Even though these devices will be dominantly connected to lower grids (except in some cases for wind farms), their aggregated behavior can be sufficient to model. Since the cable projects considered are in planning for the next decade, it might be important to account for increasing shares of converter-interfaced systems in the grid modeling.

Response by Swissgrid: When it comes to harmonic resonances in the integration of renewable energy resources and VSD-driven pumps/generation units, we can see two main issues:

The presence of converters interfacing the renewable energy resources and the AC network, especially those from previous generations (e.g., LCC, 2-level VSC, etc.) would emit harmonics into the grid and become potential sources of harmonic pollution.

Harmonic resonances may arise due to converter control interactions with the AC network. This would happen mostly with VSC.

For the first issue, in fact, in the harmonic studies performed in the scope of this work, we only considered connection points, or PCC (Point of Common Coupling), to existing large industrial load centers, renewable energy resources and the SBB network as potential sources of harmonic pollution. We are happy to receive this question as it also confirms our concern. Since EMT studies on massive cable integration as well as other issues of network transients are currently on-going at Swissgrid, while being aware of the impact of renewable energy integration in the future, we will surely take it into consideration in the future work as more information becomes available.

For the second issue, which is trickier, we understand that harmonic resonances from converter control interactions with the AC grid are mostly due to non-passivity of converter impedance, which is highly dependent on the control implementation (e.g., certain parameter settings inside converter control loops, etc.) (please see [1]). This means that the problem is vendor-specific. In fact, we are aware that such issues have been encountered and studied by our European partners. One example is the issue of harmonic resonances on the INELFE HVDC link between France and Spain in 2015 (please see Section 7.3 in [2]). And we also understand the challenges to reproduce and investigate such a phenomenon using available offline converter C&P models because:

Generic offline models are usually developed based on available information in the literature and their implementation may differ from the actual control loop implementation by a specific vendor.

Vendor-specific black-boxed offline models might contain simplification on certain C&P functions for reasons of relevancy and simulation efficiency. This could make it impossible to reproduce such a phenomenon encountered on site. Based on the above statements, for the moment, we believe that collective efforts with the converter vendors would be required to investigate and resolve such an issue if it occurs.

However, since we are aware of the impact of renewable energy integration and the technical challenges that come with it, continued effort shall be dedicated to these aspects in future studies at Swissgrid.

[1] H. Saad, et al., "On Resonances and Harmonics in HVDC-MMC Station Connected to AC Grid," IEEE Transactions on Power Delivery, Vol. 32, No. 3, June 2017.

[2] "Composite Testing of HVDC-connected Offshore Wind Farms," available online: https://www.hvdccentre.com/innovation-projects/composite/

Assessment by FEN: Various studies show that the converters (i) can affect the resonant frequency, either exacerbating or alleviating the problems, and (ii) can resonate with each other, introducing new problems. FEN agrees with Swissgrid's assessment on the lack of reliable and realistic converter models due to intellectual property rights. Any attempt of encouraging, urging and/or pressuring the vendors to share the converter models, accurately representing the behavior of the converters deployed in the grids has tremendous value. FEN suggests that Swissgrid is actively engaged with leading vendors, for example by means of dedicated projects, so that the vendors provide such models, which may not be publicly available and might be shared with Swissgrid under special NDA but will help Swissgrid to integrate these models into their studies.

3. **Are network equivalents used in EMT analyses?** In EMT analysis, in order to reduce the size of the system due to computational complexity, the focus is given to a selected part of the grid, and the rest of the network(s) is represented by Thévenin equivalents. If such equivalents are employed, the reduced Thévenin impedances will play an important role in the results of EMT analysis. The reduction process and the robustness of reduction, and at which frequency the reduction is performed is crucial, since the Thévenin impedances will have an impact on harmonic resonances.

Response by Swissgrid: In fact, the entire transmission network model of Swissgrid has been used in all studies performed in the scope of this work. Thévenin equivalents are only used to represent generation units and PCCs with neighbouring countries whose modelling requires detailed information that is not available to Swissgrid. The Thevenin equivalents have been modelled based on Cigré recommendations (please see Appendix B in [3]), with their positive- and zero-sequence impedances obtained from internal short-circuit studies. Considering the relatively large scale of the model, the studied phenomena, and the location of the studied transient phenomena, we believe that issues due to network reduction/equivalencing should not be expected in the obtained results.

[3] "Guide for electromagnetic transient studies involving VSC converters," CIGRÉ technical brochure, WG B4. 70, Ref. 832, 2021.

Assessment by FEN: The answer by Swissgrid is acceptable and sound.

4. **Are the impacts of surge arresters (such as MOVs) modeled in EMT analysis?**

Response by Swissgrid: Indeed, surge arrester models of different voltage levels have been developed based on available manufacturer catalogues at Swissgrid. They have been included in the model and the performed studies. However, we believe that they are irrelevant to the studied phenomena for the following reasons:

Surge arresters are modelled as nonlinear resistances in EMTP using an approach called "piece-wise linearization". During steady-state normal grid operation, the resistance value is large enough such that they can be considered as "open circuit". Therefore, they have no impact on the obtained results for steady state.

As far as we understand, surge arresters generally start to discharge when the voltage is above 2 p.u., which corresponds to overvoltages in switching transients and above. TOVs studies in this work are way below this value. We have indeed considered the inclusion of surge arresters in the tests and compared the results with cases without surge arresters. Minimum differences have been observed, which confirmed our opinion.

Since cable energization is a type of study specific to the equipment itself, it was not performed in the scope of the work whose main objective is to study the impact of massive cabling on the scale of the entire Swiss transmission network. However, we agree that surge arresters should be considered for such events, which would also include back-to-back switch-on of cables and capacitor banks, circuit breaker auto-reclosing, circuit breaker TRV, etc. Apart from that, issues of surge arrester thermal runaway should also be studied.

Assessment by FEN: The answer by Swissgrid is acceptable and sound.

5. **Are harmonic resonances due to heavy industrial load centers equipped dominantly with induction motors (or other non-linear loads) investigated or are there plans to consider such cases?** The properties of the selected nodes in the harmonics analysis are not provided but obviously there is reasoning in the selection of those nodes.

Response by Swissgrid: Indeed, potential harmonic pollution sources in the harmonic studies have been carefully selected, considering the location of (potentially) nonlinear industrial loads as well as connection points to renewable energy resources and to the SBB network with converters that might emit harmonics into the Swissgrid network.

Assessment by FEN: The answer by Swissgrid is acceptable and sound, and FEN suggests that this aspect is clearly stated in the report.

6. **Are there any risks for series resonances in Swissgrid system?** The issues considered and analyses performed demonstrate the problems mainly with parallel resonances.

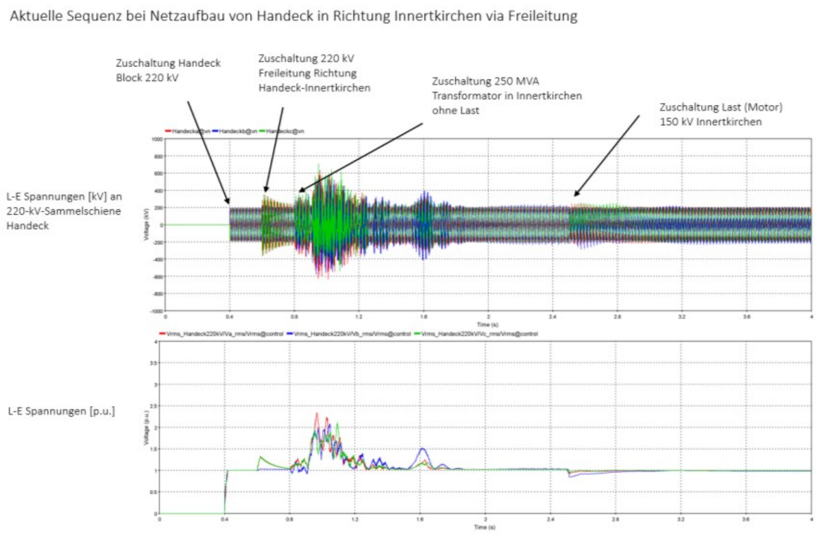
Response by Swissgrid: In fact, our attention was directed to both parallel and series resonances in the frequency scan studies, both in this work and in previous internal cable feasibility studies, as we understand the potential negative impact of both phenomena on the grid.

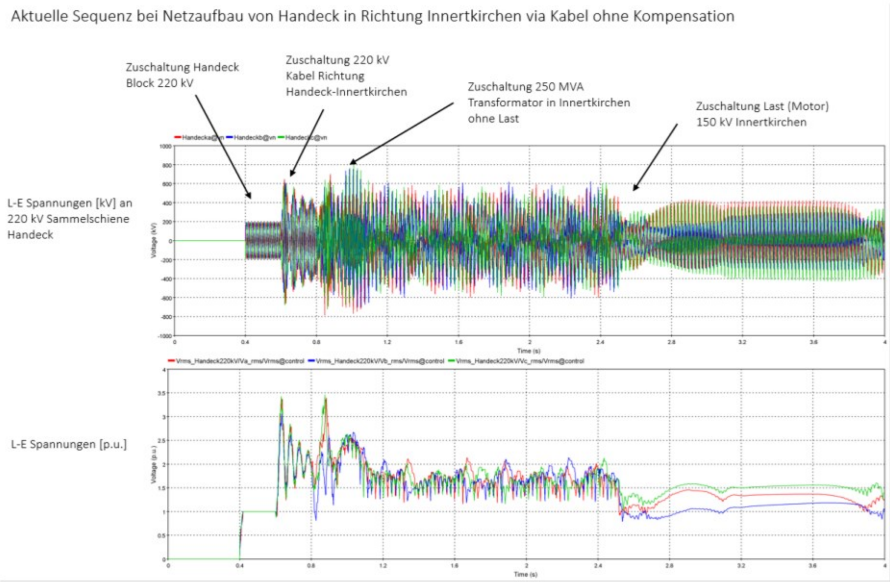
Up to now, only risks of parallel resonance have been detected from previous and on-going studies. However, we shall continue with this approach and pay particular attention to cases prone to series resonance, such as energization of a cable at a transformer terminal while the secondary winding of the transformer is further connected to cable systems.

Assessment by FEN: The answer by Swissgrid is acceptable and sound, and FEN suggests that this aspect is clearly stated in the report.

7. It would be beneficial that regarding restoration in the central cell (in Section 4 of WP3 report), the causality of overvoltages due to cabling is demonstrated by a **comparative figure with the current grid status** (only the results with the proposed grid installations is shown). As a concrete example, in Figure 5, how high the overvoltage peak at t=4s would be with the current grid (without cabling). Access to the cited studies in the report (e.g., [3-5]) would be helpful.

Response by Swissgrid: There's a comparison current – future process in the FKH study. However, in the WP3 we have included just a summary of the most important figures. Please see the comparison below.





Assessment by FEN: The answer by Swissgrid is acceptable and sound. In addition, the following documents, providing insight into the detailed simulations for the restoration analyses, are shared by

Swissgrid per request by FEN for review. In the first five documents, which contain the analysis of an external consulting company, the black start scenarios are simulated by following the existing sequences. Each sequence includes either one of the following: switching on a generator, energizing a transformer, energizing transmission lines or underground cables, energizing distribution transformers. For each black-start scenario, one or more underground cabling variants (1.5 km vs 4.5 km cabling – north-Innertkirchen) are tested. For each cabling variant, EMTP simulations are performed with and without point-on-wave switching breakers.

In the "Two-cell synchronization" report the new black-start strategy of the network nearby Innertkirchen (with cable implementation) proposed by KWO is tested and the conclusion in the reports by the external consulting company are validated.

In the "Load rejection" report prepared by Swissgrid, three load rejection studies and two shunt reactor switchings are analyzed. Load rejection events can occur after successful black-starts. The system behavior is tested for two cases: with and without field current regulator of a synchronous generator. This analysis was performed only for the current configuration (without underground cabling scenarios).

The results of the simulations support the conclusion in WP3 document. As stated in the KWO report on two-cell synchronization, critical installation of new compensation devices that can provide reactive support to maintain the voltage is important to mention.

a. Black-start scenario 1 – Black island Handeck-Innertkirchen-Grimsel (Slides, English, 141 pages)
b. Black-start scenario 2 – Black island Handeck-Grimsel (Slides, English, 57 pages)
c. Black-start scenario 3 – Cell Grimsel (Slides, English, 55 pages)
d. Black-start scenario 4 – Black island Handeck-Innertkirchen-Grimsel with lower generation amount compared to Scenario 1 (Slides, English, 54 pages)
e. Black-start scenario 5 – Black island Handeck-Innertkirchen with pumping motor not included compared to Scenario 1 & Scenario 6 – Cell Handeck (Slides, English, 63 pages)
f. Black-start KWO: Two cell synchronization (Swissgrid Report, English, 43 pages)
g. Black-start KWO: Load rejection (Swissgrid Report, English, 13 pages)

8. As a mitigation measure for the reactive compensation, combinations of 50 MVAr, 100 MVAr, 120 MVAr, 150 MVAr reactors are selected as standard reactor sizes. The combination of these for each scenario may not be unique and how the combinations are achieved is not provided, although most likely they are the optimal combinations for Swissgrid. However**, for a selected set of critical substations (from grid operation perspective) where large amounts of compensation with many reactors are needed, SVCs may also be candidates**: Even though they are more expensive in unit price, the space requirements may be less (for those units with higher than 100 MVAr in capacities), and the new generation SVCs (compact and with grid-forming capabilities) will have additional benefits in future grid operation (e.g., restoration, active filters, etc.).

Response by Swissgrid: Yes, we agree that SVC can add value when there are harmonics problems and reactive power compensation needs at the same time. However, as it is much more expensive, we limit its implementation to special cases where harmonics are present. So far, we have not seen the need to use active filtering.

Assessment by FEN: The answer by Swissgrid is acceptable.

2.4 Overall assessment of the results

The reports contain the most detailed investigations compared to the publicly available reports and articles published by the transmission system operators.

The adopted approaches and modeling types are state-of-the-art and rigorous.

WP1: reactive compensation analysis

- *Quantification of the reactive power to be compensated. Plausibility of Swissgrid's calculations*: The results of the reactive compensation analysis are in line with the expectations and the results of reviewed studies investigating the impacts of partial undergrounding in similar voltage levels in similar sizes and lengths performed by various system operators.
- *Location of the reactive power compensation systems: critical analysis of the proposals made by Swissgrid*. The reactive compensation devices for underground cables are often place at sending -and receiving-end of the transmission system. The identified locations by Swissgrid are sound and reasonable.
- *Alternative solutions (Statcom, larger inductors, etc.): FEN proposal with pros and cons (costs, space requirements, flexibility, etc.)* While the proposed shunt reactor combinations sound and reasonable, increased amount and number of shunt reactors in the system will impact resonant frequencies. Even though deploying SVCs are much more costly, can generate harmonics and may require additional filtering, they can provide advantages such as requiring less space, providing a versatile operation range when voltage fluctuations occur, helping with restoration especially when combined with BESS. The techno-economic assessment of the optimal solution will be based on thorough analysis and simulations on a case-by-case basis. Estimation of the required additional space for reactive compensation (i.e., shunt reactors) is reasonable and in line with what is reported in the industry.

WP2: Resonance and EMT studies

- *Plausibility of the calculations and the critical values defined by Swissgrid*: The results presented in WP2 for the EMT analysis regarding the TOVs due to harmonic resonance are as expected and in line with the results of the reported experiences. The results of the harmonic resonance analysis using frequency scans (FSA) in WP2 are as expected and in line with the results of similar studies in literature.
- *Are the selected cases realistic (e.g., N-2 case, selected substations)*? While the scenarios 1 & 2 are realistic, scenarios 3 & 4 are hypothetical, created to demonstrate the impact of higher cabling share. The selected contingency cases with N-1 and N-2 cases are realistic and selected by Swissgrid based on their operational experience. The substations and nodes where the resonance frequencies are calculated, seem to have been carefully selected by Swissgrid based on the type of load connected to the downstream of the substations. The tested scenarios and cases are sound and reasonable.
- Investigation of the amplification of harmonics: are alternative solutions possible? (filters, etc.) The identification of the location of harmonic filters can be based on [23]: (i) Location at emission source, (ii) Location at point of high distortion level, (iii) Location at point of highest impedance, and (iv) Location at resonance point. Different types (active vs. passive filters) of filters are candidates, however, the specific type and location shall be identified on a case-by-case basis

with detailed analysis. It is important to note that introducing a section of underground cable with an associated reactive compensation system is already increasing the complexity of the system. In addition, introducing harmonic filters have to be carefully analysed with simulation using detailed models of nearby loads as well so that unwanted and unforeseen phenomena can be avoided. The report by Swissgrid does not contain detailed simulations on harmonic filter implementations, while emphasizes the need of such solutions.

WP3: Restoration analysis

– *Plausibility of Swissgrid's calculations:* The results of the restoration analysis are sound and comprehensive; especially for the southern cell the issue with cables is very specific due to layout of the generators, pump station and network (i.e., increased restoration route). The inherently low short circuit power during restoration process exacerbates the problem with increased shares of cabling, which is demonstrated in the analysis for the central cell. Severe problems (overvoltage) during energization of transformers and cables are also observed during restoration analysis, which were also demonstrated in the EMT analysis.

– *General alternative solutions for the problems arising from the "South" and "Center" reconstruction cells (from the grid reconstruction concepts). If possible, assessment of the potential problems in the "East" and "West" restoration cells*. Due to the combinations of three inherent problems (i.e., low grid strength, reduced harmonic resonance and high need for reactive power by the cable), restoration of small cells (within a large cell) is extremely complex in the presence of high shares of underground cables. There is not enough experience reported by industry (globally) for such cases. Meticulous attention has to be paid while updating and/or changing existing restoration practices and adopting new sequences with new technologies which are not yet tested. In addition to the restoration practices analysed and assessed, deployment of SVCs in combination with large-scale BESS, both equipped with grid-forming converters, critically located in the cells, can be candidates to test in the planning stage.

The results of the three groups of analysis (i.e., EMT, harmonic resonance analysis, restoration) demonstrate the problem of reduction in grid resonance frequencies due to future configurations with increased underground cabling, resulting in overvoltages in the network.

The analyses are well designed following the state-of-the-art practices, the reports are well written and have a good technical level regarding breadth and depth. The review of the theory in the Annex of WP2 is commended, provided that EMT, especially modeling and analysis of switching transients in meshed networks, is one of the most complex topics in power system engineering and is seldom taught in European undergraduate and graduate programs (e.g., Prof. Mario Paolone at EPFL, Prof. Xavier Guillaud at Ecole Centrale de Lille, Prof. Carlo Alberto Nucci at University of Bologna).

References

[1] IEEE Task Force on Harmonics Modeling and Simulation, "*Modeling and simulation of the propagation of harmonics in electric power networks: Part 1: concepts, models, and simulation techniques*", IEEE Transactions on Power Delivery, vol. 11, no. 1, January 1996.

[2] IEEE Task Force on Harmonics Modeling and Simulation, "*Modeling and simulation of the propagation of harmonics in electric power networks: Part 2: sample systems and examples*", IEEE Transactions on Power Delivery, vol. 11, no. 1, January 1996.

[3] Johan Engström, "*Underground cables in transmission networks*", MS Thesis, Lund University, 2007.

[4] M.H.J. Bollen, S. Mousavi-Gargari, S. Bahramirad, "*Harmonics resonances due to transmission-system cables*", International Conference on Renewable Energies and Power Quality, April 2014.

[5] U. Karki, D. Gunasekaran and Fang Zheng Peng, "*Reactive compensation of overhead AC transmission lines using underground power cables*," in the Proc. of IEEE Power & Energy Society General Meeting, Denver, CO, USA, 2015.

[6] M. Kizilcay, P. Malicki, S. Papenheim, "*Analysis of Switching Transients of an EHV Transmission Line Consisting of Mixed Power Cable and Overhead Line Sections*", in the Proc. of International Power System Transients (IPST), Seoul, Republic of Korea, 2017.

[7] A. Pouriman, "*Harmonics in transmission lines*", MS Thesis, TU Graz, 2021.

[8] C. L. Bak and W. Wiechowski, "*Analysis and simulation of switching surge generation when disconnecting a combined 400 kV cable/overhead line with shunt reactor*," in the Proc. of International Power System Transients (IPST), Lyon, France, 2007.

[9] ENTSO-E, "*Feasibility and technical aspects of partial undergrounding of extra high voltage power transmission lines*", December 2010.

[10] National Grid, "*Undergrounding high voltage electricity transmission lines*", 2015.

[11] O. Galland, D. Leu, V. Berner, and P. Favre-Perrod, "*Resonance Analysis of a Transmission Power System and Possible Consequences of its Undergrounding*", Periodica Polytechnica Electrical Engineering and Computer Science, vol 59, no. 3, p. 88-93, 2015.

[12] H. Khalilnezhad, M. Popov, L. van der Sluis, J. A. Bos and J. P. W. de Jong, "*Influence of long EHV AC underground cables on the resonance behavior of the Dutch transmission system*," in the Proc. of IEEE Power and Energy Society General Meeting, Boston, MA, USA, 2016.

[13] EirGrid, "North-south 400kv interconnection development: outline and update of eirgrid's consideration of the transmission technology options as presented to the independent expert group", December 2107.

[14] P. Stanchev, D. Georgiev and Y. Kamenov, "*Influence of underground cable lines for high voltage on the behavior of electric power system*," in the Proc. of 20th International Symposium on Electrical Apparatus and Technologies (SIELA), Bourgas, Bulgaria, 2018.

[15] M. Lösing, K. Vennemann, "*Technische Herausforderungen bei der 380-kV-Teilverkabelung im Höchstspannungsnetz*," in the Proc. of 13. ETG/GMA-Fachtagung Netzregelung und Systemführung Energiewende in der Stromversorgung – Systemstabilität und -sicherheit, Berlin 2019.

[16] A. Neufeld, N. Schäkel, L. Hofmann, M. Lösing, "*Probabilistic Calculation of Harmonic Voltages in Transmission Grids with Varying Shares of Underground Cables*," in the Proc. of Cigré Symposium Aalborg, 2019.

[17] M. Kizilcay, P. Malicki, S. Papenheim, M. Lösing and K. Vennemann, "Influence of shunt compensated EHV transmission lines consisting of several overhead line and XLPE cable sections on system performance," in the Proc. of Cigré Symposium Aalborg, 2019.

[18] I. R. Pordanjani, C. Wang, A. Nassif, R. Cui, L. Jiao, "Impacts of Underground Cables on Power System Harmonics – A real case study using simulations and field measurements," in the Proc. of Cigré Symposium Aalborg, 2019.

[19] CIGRE C4/B4 Technical Brochure, "*Network modeling for harmonic studies,*" 766, April 2019.

[20] O. Lennerhag and M. Bollen, "*A power system model for resonance studies,*" in the Proc. of CIRED International Conference on Electricity Distribution, Madrid, Spain, June 2019.

[21] Renewable Grid Initiative, "*Partial undergrounding for extra-high voltage ac connections Understanding the option of 380 kV AC underground cables complementing overhead lines,*" Discussion Paper, 2019.

[22] 50hertz, Amprion, Tennet, Transnet BW, "*Erfahrungsbericht zum Einsatz von Erdkabeln im Höchstspannungs-Drehstrombereich*," October 2020.

[23] B. Søndergaard Bukh, *„On the Propagation of Harmonics in Meshed Transmission Power Systems with a Large Number of Underground Cables*", PhD Thesis, Aalborg University, Denmark, 2023.

[24] H. Evennett, "*Undergrounding electrical transmission cables,*" UK House of Lords Library, February 2024. Available online on February 21, 2025: https://lordslibrary.parliament.uk/undergrounding-electrical-transmission-cables/

[25] O. Ramos-Leanos, J. L. Naredo, J. Mahseredjian, C. Dufour, J. A. Gutierrez-Robles and I. Kocar, "*A Wideband Line/Cable Model for Real-Time Simulations of Power System Transients*," *IEEE Transactions on Power Delivery*, vol. 27, no. 4, pp. 2211-2218, October 2012.

[26] I. Kocar and J. Mahseredjian, "*Accurate Frequency Dependent Cable Model for Electromagnetic Transients*," IEEE Transactions on Power Delivery, vol. 31, no. 3, pp. 1281-1288, June 2016.