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Propagation of Harmonics in Electrical Grids: A Review of Selected Issues

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***Abstract*—Recent years saw increasing of harmonic distortion at transmission grids caused partly by a growing system undergrounding, leading to resonances at lower frequencies. Presently, the estimation of the harmonic distortion through simulations after significant grid changes is not sufficiently accurate and the understanding of harmonics propagation is a topic under research. This hinders grid development by system operators, as it is not possible to assess fully the impact of new lines.**

This paper presents and analyses four harmonic-related phenomena: 1-Impact of line asymmetry in long HVAC cables; 2-Harmonic peak voltage/current along a line; 3-Harmonic propagation between voltage levels; 4-Fillter location. The paper summarizes the root causes and consequences of each phenomenon, together with tools and recommendations that can ease the assessment of harmonic propagation.

***Index Terms*—Harmonics, Harmonic propagation, Line asymmetry, Passive Filters.**

I. Introduction

Historically, harmonic distortion at transmission levels has been mostly restricted to a selected number of situations as the connection to HVDC links and arcing devices, with the installation of passive filters at those locations sufficing as mitigating solution. Currently, there is a trend of increasing harmonic distortion in transmission grids, which is expected to continue with the growing penetration of green energy generation [1]. This is due to a rising number of harmonic sources composed of power electronic devices, the construction of new HVDC links, the increase in harmonic propagation from lower to higher voltage levels, and the increasing kilometres of installed cables that lead to a decrease in the resonance frequencies.

Resonances at low frequencies are a serious challenge for keeping the harmonic voltages below planning levels. Small changes in system parameters can have a large impact on the magnitude of the impedance at harmonic frequencies [2] complicating both the estimation of the harmonic distortion and the design of mitigation solutions. The usage of underground cables at transmission levels has been minor until recently and the resonances were mostly at high frequencies where harmonic injection is small and the damping is high. More recently, the connection of offshore wind farms via radial HVAC cables lead to potential problems with temporary overvoltages (TOVs) and low order resonances [3], [4]. Later studies and measurements have also showed problems with low order resonances for meshed areas of the grid [5], [6].

The operation and design of the Danish transmission grid is already facing several harmonic related challenges. In one case, the partial replacement of two parallel 400 kV overhead lines (OHL) by cables in a section of 8 km leads to a substantial increase of the harmonic voltage levels at two 400 kV substations separated by 170 km [5]. This indicates that changing short sections can have a noticeable impact over a large area of the grid. In another case, the public expressed a desire to implement a new 400 kV line as an underground cable. However, due to high risks and uncertainties related to the harmonic distortion introduced by a new underground cable, the system operator stated that a maximum of 15% of the line could be implemented as an underground cable [7].

In face of the increasing challenges introduced by harmonics distortion caused by system undergrounding, a cooperation between Aalborg University and the Danish TSO Energinet was initiated. This paper presents some of the initial results in a document that can be used for future research on harmonic propagation, modelling and mitigation.

The paper covers four main topics, with more details available in each of the references:

- Impact of line asymmetry in long HVAC cables [8];
- Harmonic peak voltage/current along a line [9];
- Harmonic propagation between voltage levels [10];
- Filter location [11];

II. Impact of Line Asymmetry

HVAC cables in flat formation are installed in an unbalanced layout that leads to inter-sequence coupling between the

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symmetrical impedances. As a result, harmonics are no longer associated with one single sequence (e.g., 2nd harmonic with negative-sequence, 3rd harmonic with zero-sequence, …). Therefore, when studying harmonic propagation in flat formation layouts, the use of decoupled sequences leads to inaccurate results, which has been confirmed by system measurements [12], [13].

Mathematical analysis shows that the impact of the coupling is significant only at frequency ranges where the series resonances of the different decoupled sequences are close [8]. Typically, this means that the coupling between positive and negative sequences impacts the harmonic impedance, whereas couplings with the zero-sequence do not, because the resonance frequencies of the latter are not close to the resonance frequencies of the positive and negative sequences, normally.

Figure 1 shows the positive-sequence impedance of a cable connecting an offshore wind-farm, where the land cable is in flat formation with a distance of 0.4 m between phases. For confidential reasons, some cable parameters are changed and the frequency spectrum of the reference cable is different. The plots show that all curves are virtually identical for frequencies lower than 250 Hz and higher than 450 Hz. In-between these two frequencies, the reference model and the model neglecting coupling with zero-sequence show practically the same impedance magnitude, but to neglect the coupling with negative sequence leads to large differences. Mainly:

- Only one peak, instead of two;
- The single peak is at a different frequency than any of the two peaks;
- A larger resonance peak magnitude and a lower valley when neglecting all couplings;

Typically, the series resonance frequency in a negative-sequence circuit is close to the series resonance frequency in the positive-sequence circuit, but both are far from the series resonance in the zero-sequence circuit. Most power system elements have equal or almost equal positive and negative sequence impedances, mainly rotating machines have different positive and negative sequence impedances, with the zero-sequence impedance different in general. This makes the likelihood of frequencies with coinciding series resonances in the zero sequence circuit and the other sequences less likely. As a result, the current flowing in the negative-sequence is large enough to induce a voltage in the positive-sequence in frequencies close to the resonance of the latter, but the same is unlikely for the current flowing in the zero-sequence.

Furthermore, the resistance in a zero-sequence circuit is larger than the resistance in the negative-sequence circuit, typically. This provides a larger impedance at the series resonance point where the lowest impedance is present, where there could be concerns about the inter-sequence couplings. As a result, the impact of the zero-sequence current in the positive and negative sequences impedances is smaller. It is important to notice that this relation between impedances depends strongly on the earth characteristics, the cable sheath parameters and the respective grounding [14].

Finally, the couplings of the positive and negative sequence circuits with the zero sequence circuit are half of the coupling between the positive and the negative sequence circuits, as seen in (1)-(2), with the position 1x1 corresponding to the positive-sequence impedance.

For all these reasons, coupling with the zero-sequence impedance can normally be neglected for non-triplen harmonics, but coupling between positive and negative sequences impedances should not. Zero-sequence impedances are often difficult to estimate since the earth and grounding electrical parameters might be unknown or lack precision, because they are affected by the geology along the link, weather conditions, soil ionisation and frequency dependence (the latter two should be negligible for power-system harmonic studies), per example. As the coupling with the zero-sequence impedance does not impact the simulation results for non-triplen harmonic, one can have higher confidence in these simulation results and to do them without having precise information on grounding parameters.

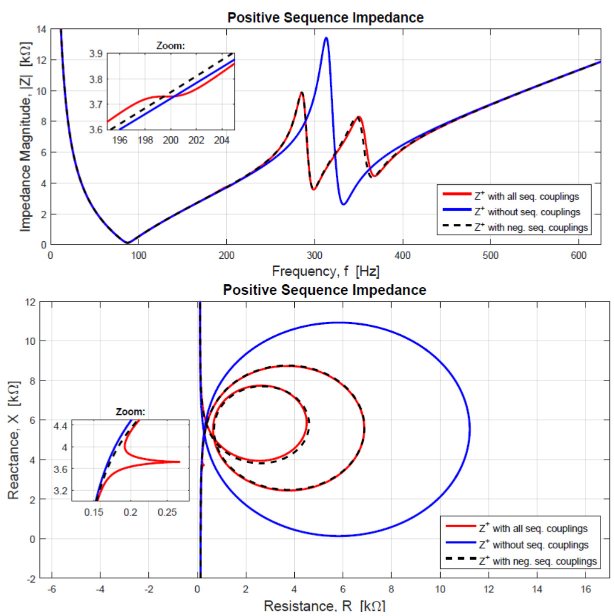

Figure 1 – Positive sequence impedance spectrums (up) and RX plot (down) considering all couplings (red), no couplings (blue) and coupling only with negative-sequence (black-dashed)

$$Z_{ABC} = \begin{pmatrix} Z_S & Z_{m1} & Z_{m2} \\ Z_{m1} & Z_S & Z_{m1} \\ Z_{m2} & Z_{m1} & Z_S \end{pmatrix} \quad (1)$$

$$Z_{+-0} = \begin{bmatrix} Z_S - Z_{m1} + \frac{\Delta Z_m}{3} & -\frac{2\alpha^2}{3}\Delta Z_m & \frac{\alpha}{3}\Delta Z_m \\ -\frac{2\alpha}{3}\Delta Z_m & Z_S - Z_{m1} + \frac{\Delta Z_m}{3} & \frac{\alpha^2}{3}\Delta Z_m \\ \frac{\alpha^2}{3}\Delta Z_m & \frac{\alpha}{3}\Delta Z_m & Z_S + 2Z_{m1} - \frac{2}{3}\Delta Z_m \end{bmatrix} \quad (2)$$

where, Z_S is the self-impedance, Z_{m1} is the mutual coupling between adjacent phases and Z_{m2} is the mutual coupling between the two outer phases, ΔZ_m is the difference between the two mutual couplings when in flat formation ($\Delta Z_m = Z_{m1} - Z_{m2}$) and α is the phasor rotation operator. Figure 2 shows the coupling between phases.

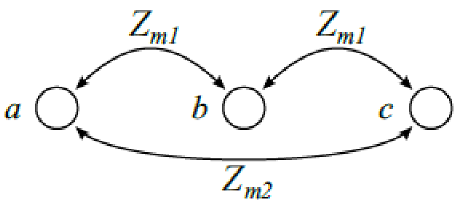

Figure 2 – Example of three conductors in flat formation and the mutual coupling between them

III. Harmonic peak voltage/current along a line

Harmonic calculations estimate the magnitudes of harmonic voltages and currents at the busbars. Decisions on mitigation solutions are then based on these estimations. However, the peak of a harmonic voltage or current might not be at a busbar, but along a line. This is alike very long lines, where it is well known that the peak of voltage/current at power frequency might be along the line [15],[16], but occurring for harmonics in short-medium length lines, because the frequency is higher.

The propagation of harmonics in a line, as well as their voltage and current phase shifts, can be seen as following the circumference of a (I,V) circle in an anticlockwise direction w.r.t. the increasing distance from the ending terminal of line (Figure 3). The magnitudes of the voltage and current along the line changes similar to a sinusoidal (Figure 4), leading to a possible peak voltage or current along the line. Furthermore, Figure 3 shows that:

- Voltage decreases when the power factor of harmonics is inductive, while the current increases. The opposite if the power factor of harmonics is capacitive.
- Power factor changes from inductive to capacitive when voltage is low. The opposite when the current is low.

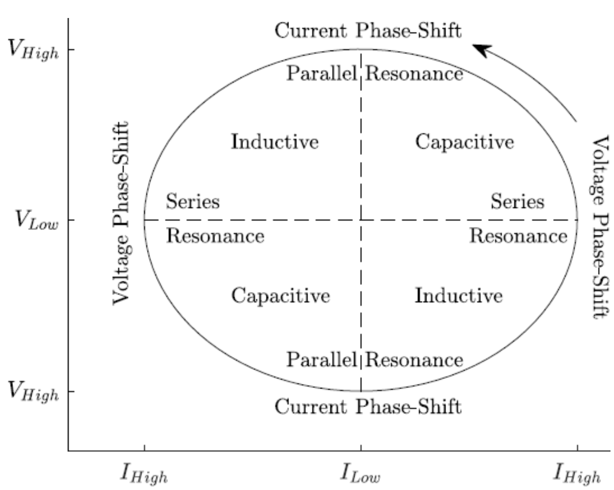

Figure 3 – Harmonic propagation through a line [9]

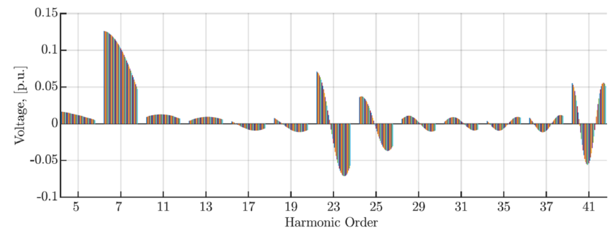

Figure 4 – Voltage through a line for odd order harmonic non-multiple of three. An ideal current source injects the same current magnitude at each harmonic order. Negative voltage indicates a voltage phase-shift and a change in slope indicates a current phase-shift. Each bar is a measurement 3.75 km apart for a 150 km long OHL

As the highest voltage might be along a line and not at its terminals, the lines can be exposed to higher steady-state stresses than estimated from harmonic load-flows, which can result in partial discharges, insulation degradation, flashover or excessive sagging. This is of more concern for cables, because the higher voltages and the higher frequencies can lead to electrical treeing from partial discharges [17], [18].

The probability of having a maximum voltage or current between the terminals increases with the frequency. The magnitude of the harmonics tends to decrease as the frequency increases reducing the likelihood of this being a problem for the installed equipment. To the authors best knowledge, this has never been an issue for present power systems, but this might change in the future with an increase in harmonic injection and in the length of many lines.

A screening method to evaluate if highest stress is along a line is by doing the following comparison: If the value of L_{Max_V} (3) is negative or bigger than the line length (L), it means that the maximum voltage is at one of the busbars. The same for the current, but using the variable L_{Max_I} (4).

$$L_{Max\_V} = (90^\circ - \alpha)\frac{L}{\beta \cdot h} \tag{3}$$

$$L_{Max\_I} = -\alpha \frac{L}{\beta \cdot h} \tag{4}$$

Where, h is the harmonic order and β is the phase displacement between the two busbars at power frequency. α is given by (5), where V_1 and V_2 are the voltages at the busbars for the harmonic h that can be obtained from the harmonic load flow calculations.

$$\alpha = \operatorname{atan}\left(\frac{V_2 \sin(\beta \cdot h)}{V_1 - V_2 \cos(\beta \cdot h)}\right) \tag{5}$$

The screening method can be implemented as an addition to load-flow studies, with the latter estimating V_1 and V_2 and β for different loading conditions. More details on this assessment are available in section 5.3 of [9].

IV. Harmonic Propagation between Voltage Levels

The propagation of harmonics between voltage levels should be assessed when upgrading a grid. A large change in one voltage level might affect the harmonic distortion in other voltage levels and existing mitigation solutions, typically passive filters, might become less efficient.

Assuming as a simplification that harmonic generation is independent of the existing harmonic distortion, the propagation of harmonics can be solved via a direct solution of the admittance matrix [19], [20]. The entire grid impedance is normalised into per units and the impedance seen by a harmonic current depends on its location. Seen from a higher-voltage level, the impedance of a lower-voltage level multiplies by a conversion factor (6), with the opposite happening when seeing the impedance from a lower-voltage level.

$$a = \frac{V_{HV}^2}{V_{LV}^2} \tag{6}$$

The conversion factor can be used to assess radial connections. Figure 5 compares frequency scans for three variations of Figure 6 seen from Bus 7. All parameters are equal for the three cases, except the turn-ratio of the transformer.

Comparing the blue and red lines, it is seen that to have a transformer ratio of 1:1 reduces the frequency of the first resonance point. This happens because of the series inductance from the transformer. However, for the case with the 410/150 kV transformer, the opposite happens with the first resonance point happening at a higher frequency. This is because seen from Bus 7, the series impedances of OHL 1 and of the Thévenin equivalent (Figure 6) reduce by the conversion factor, which is 8 in this particular example. It is shown in [10] that to divide the series impedances of the 410 kV side by the conversion factor and to multiply the shunt capacitances by it results in an overlap of the two frequency scans (i.e., the red and green lines in Figure 5).

Therefore, in this particular case, replacing OHL1 by a cable would lead to a strong decrease of the frequency of the resonance seen from Bus 7, which is in a different voltage level, because the larger capacitance of the cable would be seen as multiplying by the conversion factor.

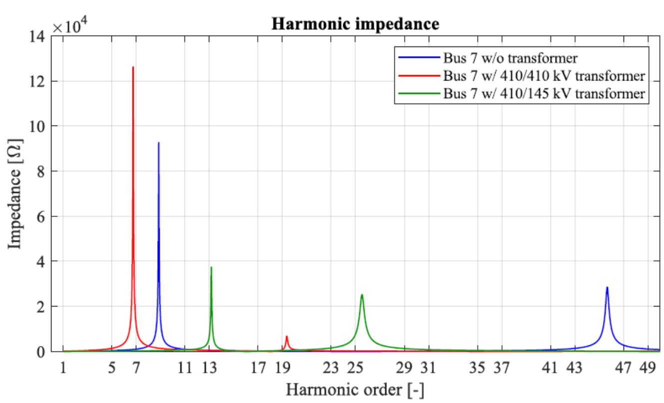

Figure 5 – Comparison of impedance from frequency scans seen from Bus 7 in Figure 6 for a 410 kV system without a transformer (blue), with a 410/410 kV transformer (red) and with a 410/145 kV transformer (green)

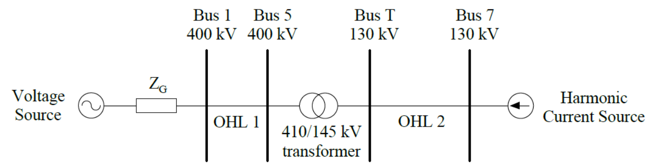

Figure 6 – Single-line diagram of the test circuit for the case with a 410kV/145 kV transformer

The propagation of harmonics in a meshed grid depends on the grid configuration and different grid layouts lead to different phenomena. The assessment of harmonic propagation is not as direct as for the radial line in the previous example, but two tendencies are observed:

- Changes made in the system primarily affect the harmonic impedance at the voltage level where the changes are made;
- Changes made at higher voltage levels have a larger effect on the harmonic impedance at lower voltage levels than the opposite, both for the frequency and magnitude of the resonances. The bigger the difference between the voltage levels, i.e. the transformer ratio, the more this phenomenon is observed.

The first bullet point is expected due to the electric distance introduced by the transformer, which impedes the propagation of harmonics between different voltage levels. The second point relates with the conversion factor: to a decrease in the harmonic propagation from the higher voltage to the lower voltage, the impedance in the latter must increase. The impedance of the lower voltage level multiplies by the conversion factor and so, changes in a lower voltage level have a smaller impact on the harmonic propagation and the distortion at the higher voltage level. In contrast, changes at the higher voltage level have a larger impact on the lower voltage level, because the impedance of the former divides by the conversion factor, which might result in an easier harmonic flow from the lower voltage level to the higher.

The conversion factor helps understanding the tendencies, but it is not enough by itself for assessing meshed grids, where different routes exist for the harmonic flow. In order to know if the voltage harmonic increases or decreases, and to have a more direct overview of harmonic propagation in a meshed system, the off-diagonal impedances for that frequency can be utilised. Considering a harmonic injection in a generic bus A, the harmonic voltages in bus B (7) and bus C (8) are estimated using the off-diagonal impedance of bus A to these two buses.

$$V_{B,h} = Z_{AB,h} I_h \tag{7}$$

$$V_{C,h} = Z_{AC,h} I_h \tag{8}$$

The voltage increase/decrease between the two generic buses (9) is given by dividing (7) and (8).

$$V_{B/C,h} = \frac{Z_{AB,h}}{Z_{AC,h}} \quad (9)$$

Where, $V_{B/C,h}$ is the voltage relation between busbars *B* and *C* and $Z_{XY,h}$ is the off-diagonal impedance between the two busbars, both for a harmonic order *h*. Figure 7 shows a generic example for a harmonic injection at point A, and a comparison between points B and C located at different voltage levels.

The test system from Figure 7, which is based on [21], is used to simulate the propagation of harmonic voltages. Two voltage levels are modelled using frequency-dependent models: 400 kV between Bus 1 and Bus 12 and 130 kV between Bus 21 and Bus 29. Figure 8 shows two cases, one for a harmonic injection at Bus 21 (130 kV) and another for an injection at Bus 1 (400 kV). The harmonic injection consists in repeating the injection of a harmonic with the same magnitude for all harmonic orders. Figure 8 is for a simulation via a harmonic-flow software, but some cases were calculated manually using the off-diagonal impedances and they matched with the simulations.

The comparison of the two cases indicates two interesting behaviours:

- The harmonic voltage can be larger in other busses than the injection bus (this is discussed in the next section);
- The injections in the 130 kV bus barely affect the harmonic voltages in the 400 kV grid, but injections in the 400 kV bus have a noticeable impact in the harmonic voltages in the 130 kV grid, because of the reason previously explained.

Additionally, the simulations were redone by replacing all OHLs by cables and also by replacing all cables by OHLs, with the behaviour described in the last bullet point observed for both cases.

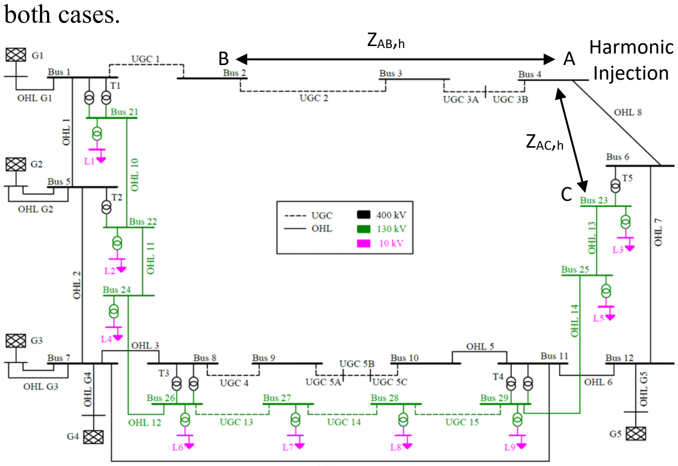

Figure 7 – Test system for propagation of harmonic in a meshed grid. Based on and using data from [21]

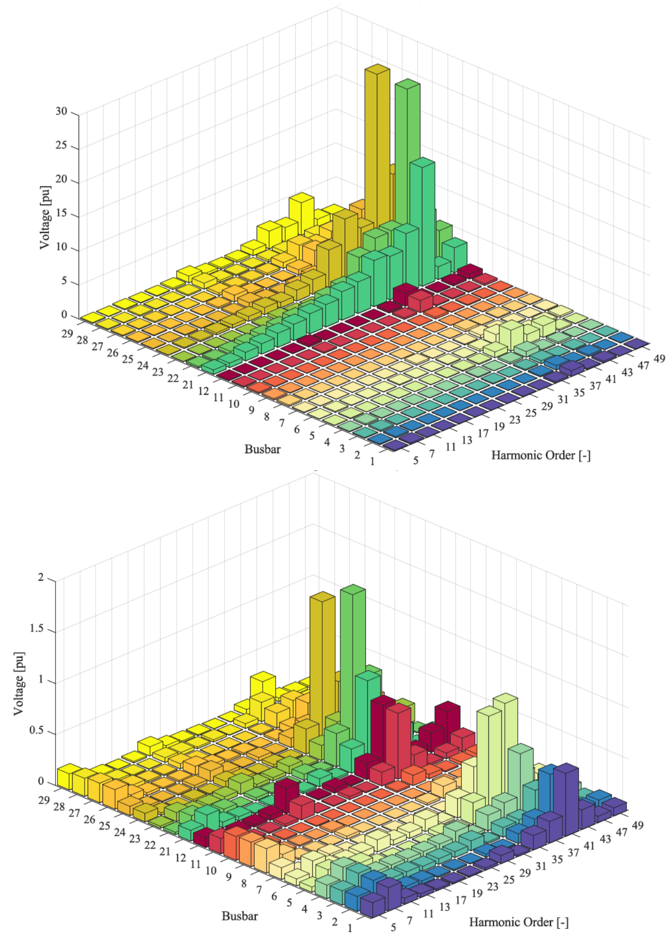

Figure 8 – Harmonic voltages for each bus in the meshed system for the harmonic orders of interest with the harmonic currents injected in Bus 21 (up) or Bus 1 (down). Note: The vertical scales are different

V. Filter Location

A. sdfsdf

The typical solution for reducing excessive harmonic at transmission grid has been the installation of passive filters at the source of the harmonics [2]. This approach is relatively easy and efficient for large harmonics sources as HVDC links [19], but less if multiple unknown sources are present. Furthermore, recent measurements in Denmark show that even for injections from HVDC converters, the use of passive filters at the converters locations is not so straightforward, as changes in the grid might require changes in the filters, due to changes in the resonance frequencies [5].

Another solution to handle an increase of the harmonic levels in a specific location of the grid could be the installation of a filter at that location. However, the installation of the filter changes the grid impedance and it might simply transfer the problem to another location that did not observe high harmonic levels prior to the filter installation [7]. Additionally, the filter can become useless at the next grid upgrading.

An alternative approach that could be considered is to do a semi-optimal filter location. The concept is that some locations have a bigger impact on harmonic propagation. A filter in such location could remove or severely dampen the resonance condition causing the harmonic issues and reduce the need for mitigation in other locations.

To assess the potential of this solution, the homotopy analysis method (see chapter 5 of [22]) is used to find the most impactful filter locations without having to specify filter parameters. The method cannot provide the final harmonic voltage distortions in the system after an actual filter is implemented, as the voltages depend on the filter's parameters. Instead, it ranks the different potential filter locations using only the admittance matrix as input. Therefore, the method can be used as a screening tool by indicating the locations more suitable to reduce harmonic issues and if they are to remain as such for future expansions and/or system changes. Furthermore, in a case of multiple sources, this method can be more quickly done by a combined overall assessment considering multiple selected sources.

For this study, simulations with a generic filter were performed to evaluate the precision of the method. To verify the effectiveness, the frequency-scan with exhaustive screening of filter location is carried out to assess the effectiveness of filter locations.

A simplified model of the Western Denmark transmission grid consisting of 15 nodes is used to validate the usefulness of the method. The homotopy analysis method ranks the different busses according to its first order coefficient (elements in vector $\mathbf{V}[1]$ in (10)) in a descending order (blue bars). Then, complete frequency-scans are performed with a generic C-type filter added to one bus each time (orange bars). Figure 9 compares the results obtained with the method (values of the first coefficient as expressed in (10)) with the impedance at the resonance frequency with a filter in that location. The scale is logarithmic, the results for the homotopy analysis method are unit-less and for the impedance in Ω.

$$\mathbf{V}[1] = -\left[\mathbf{Y}(h)\right]^{-1} diag(0,\cdots,\underset{\text{filter location}}{1},\cdots,0)\left(\left[\mathbf{Y}(h)\right]^{-1}\left[\mathbf{I}(h)\right]\right) \quad (10)$$

where $\mathbf{Y}(h)$ is the admittance matrix for the h-th order frequency, and $\mathbf{I}(h)$ is the vector of h-th order harmonic current injection. The diagonal matrix is an $n\times n$ matrix with the filter location assigned as 1

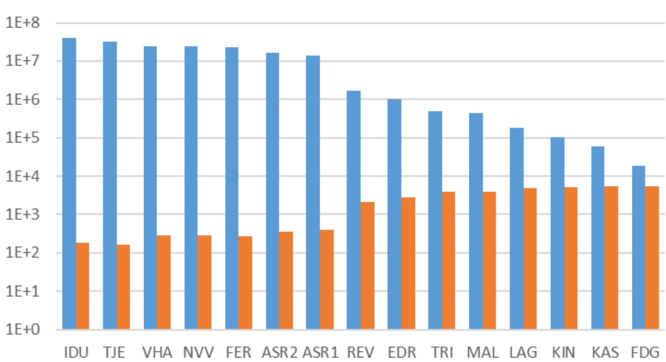

Figure 9 – The optimality rank for the filter locations, and the most left is the optimal location. Comparison of the homotopy analysis method (Blue and in a descending order) with impedance at resonance frequency (Orange and in an ascending order). The names of different busbars are given by the three initials.

The figure shows a very good match. The locations with a large coefficient for the method are also the ones where a filter is more efficient. As a result:

- The method is able to give valuable indication of how different resonance frequencies, seen from a specific busbar and for a specific current injection, are affected by different filter locations. As shown in (10), the resonance frequency is defined by the harmonic order h. The current injection is determined by the vector $\mathbf{I}(h)$, and the filter location is determined by the diagonal matrix. Finally, the ranking of busbar is decided by the ranking of elements in vector $\mathbf{V}(h)$.
- The method is able to give relative information on which filter location has the most effect on each resonance peak.
- To install the filter in the busbar of the injection has a tendency to perform better when the actual filter is implemented than what the method indicates.
- The method cannot give precise indications of the final impedance value after an actual filter is implemented, due to the lack of actual filter values in the method. This means the indications of the method are not fully precise.
- The method is good as an early screening, because it does not require filter parameters. Multiple operational scenarios and grid expansions plans can be accounted in a simple manner for finding the most effective locations for filter placement. Likewise, it can be used to see if some filter locations become redundant in some grid expansion scenarios.
- It is not shown in this paper, but the imaginary part of the coefficient can be used to predict the risk of anti-resonances, i.e. if the installation of a filter at location A leads to an increase in harmonic distortion at location B. For more details, refer to [11].

One important aspect that was easier to notice using the method is that the most impactful filter location is not necessarily at the location of the harmonic injection. If another filter location can effectively remove or severely dampen the resonance condition causing the harmonic issues, this location might be more effective compared to placing a filter at an emission source that does not remove the resonance condition. However, there is a risk that the chosen filter position, which is considered the one with the most impact from a "global" perspective, it is not necessarily giving the best mitigation at a busbar with a harmonic source.

If the number of emission sources increases, e.g. emissions from lower voltage levels, it might be no longer feasible or economical to eliminate the harmonics at the source. A semi-optimisation global solution consisting in installing filters at key location(s) that remove certain resonance conditions from the system could be more suitable. However, this topic requires more research.

VI. Conclusions

The paper reviews some of the main issues related with the impacts of system undergrounding on harmonic distortion. Four different topics were presented and the following main conclusions are made:

- The installation of cables in flat formation results in coupling between symmetrical components. Coupling with the zero-sequence component can normally be neglected without a noticeable impact in the results. Given the difficulties in estimating some key parameters for the calculation of the zero-sequence impedance during the planning stage, this reduces the uncertainty in the harmonic studies.
- The maximum harmonic voltage and/or current might be not at the substations, but along a line. A simple screening method to estimate the location of this maximum was provided.
- Harmonic voltages propagate easily from the higher voltage levels to the lower voltage levels than the opposite. This happens because seen from a higher-voltage level, the impedance of a lower-voltage level multiplies by a conversion factor, with the opposite happening when seeing the impedance from a lower-voltage level. As a result, grid upgrading in the lower voltage levels has a smaller impact on the existing harmonic distortion at the higher voltage levels. This does not mean that harmonics injected in the downstream network can be neglected, just that harmonic propagation is easier from upstream to downstream.
- The best location to install a mitigation solution might not be at the harmonic source. It might be more efficient to remove or damp the resonance condition causing the harmonic issues. Homotopy method can be used for a fast ranking of the optimal locations for installing passive filters for multiple planning and operating scenarios.

VII. References

[1] CIGRE/CIRED JWG C4.24, "Power Quality and EMC Issues with Future Electricity Networks", CIGRE TB 719, 2018

[2] CIGRE JWG C4/B4.38, "Network modelling for Harmonic studies", TB 766, CIGRE; 2019

[3] Y. Fillion, S. Deschanvres, "Background harmonic amplifications within offshore wind farm connection projects", International Conference on Power System Transients, 2015

[4] K. Velitsikakis, C. S. Engelbretcht, K. Jansen, B. van Hulst, "Challenges and Mitigations for the Energization of Large Offshore Grids in the Netherlands", International Conference on Power System Transients, 2019

[5] J. B. Kwon, C. S. Hansen, C. F. Flytkjær, "System-wide amplification of background harmonics due to the integration of high voltage power cables", CIGRE Session 48, 2020

[6] N. Cunniffe, M. val Escudero, A. Mansoldo, E. Fagan, M. Norton, C. Ellis, "Investigating the Methodology and Implications of Implementing Long HVAC Cables in the Ireland and Northern Ireland Power System", CIGRE Session 46, 2016

[7] Energinet, "Technical issues related to new transmission lines in Denmark – West Coast Line from German border to Endrup and Endrup-Idomlund", Energinet, 2018

[8] Chris Hansen, Kristian Lund, "Harmonic Modelling & Analysis of a Cable Based Transmission System", Master Thesis, 2016

[9] Eli Maria Stenseth, Jakob Poulsen, "Harmonic Amplification and Mitigation in a Modern Meshed Transmission System", Master Thesis, 2019

[10] Kaleb Christensen, Mads Jensen, Mathilde Sørensen, "Harmonic Distortion at 400 kV due to Undergrounding of the 132/150 kV Grid", Master Thesis, 2020

[11] Morten Vadstrup, Troels Jakobsen, "Filter Position Optimisation in transmission System using Homotopy Analysis Method", Master Thesis, 2019

[12] C. F. Jensen, L. H. Kocewiak, Z. Emin "Amplification of Harmonic Background Distortion in Wind Power Plants with Long High Voltage Connections", CIGRE Session, 2016

[13] C. F. Jensen, "Harmonic Background Amplification in Long Asymmetrical High Voltage Cable Systems", International Conference on Power System Transients, 2017

[14] CIGRE WG C4.502, "Power System Technical Performance Issues Related to the Application of Long HVAC Cables", CIGRE TB 556, 2013

[15] E. W. Dubois, J. F. Fairman, D. E. Martin, J. B. Ward, C. M. Murphy, "Extra-long-distance transmission", IEEE Trans. Power Apparatus Syst., Vol. 81, No. 2, 1962

[16] F. Hubert, M. R. Gent, "Half-wavelength power transmission lines", IEEE Trans. Power Apparatus Syst., Vol. 84, No. 10, 1965

[17] R. J. Densley, "An Investigation into the Growth of Electrical Tress in XLPE Cable Insulation", IEEE Trans. Electr. Insul, Vol. 14, 1979

[18] G. Chen, C. H. Tham, "Electrical Treeing Characteristics in XLPE Power Cable Insulation in Frequency Range between 20 and 500 Hz", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 16, No. 1, 2019

[19] Jos Arrillaga, Neville R. Watson, "Power System Harmonics", John Wiley & Sons, Second Edition, 2003

[20] IEEE Std 519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems", IEEE, 1993

[21] Oscar Lennerhag, "A Power System Model for Resonance Studies", Luleå University of Technology, 2019

[22] Shijun Liao, "Beyond Perturbation: Introduction to the Homotopy Analysis Method", Chapman and Hall/CRC, 2003