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Evolution of Harmonic Distortion in a Cablified Grid Island after Separation from the Meshed Transmission Grid – A Case Study from Denmark

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Abstract

Green transition in Denmark with more renewable energy production and electrification of consumption, transport, heating, energy conversion and storage accelerates expansion and reconstruction of the transmission grid. When electricity generation and consumption have common connection cables and substations in the transmission grid, such centres are called prosumers. The prosumers do not necessarily increase the net energy exchange with the transmission grid but their short-circuit current contribution may significantly increase due to utilization of inverter-based units. To keep the short-circuit current contribution below the required rating, the meshed 150 kV transmission grid will be separated into islands that are interconnected through the 400 kV meshed transmission system. At the same time, 150 kV overhead lines will be replaced with underground cables as part of the ongoing grid reconstruction in Denmark. This paper presents the simulation results of the 5th harmonic voltage distortion evolution from the present grid stage with the meshed 150 kV transmission grid and, mainly, with overhead lines, through a long-term grid development process with cabling and separation of the meshed grid into 150 kV grid islands. The paper explains foreseen changes of the 5th harmonic voltage distortion within a specific grid island using a measurement-validated simulation model for harmonic assessment and benchmarking the simulation results to the harmonic voltage measurements in the present grid stage. The paper also demonstrates identification and usage of early warnings for not-yet-occurred critical increases of the harmonic voltage distortion and proposal of mitigation solutions.

1 Introduction

In Denmark, large inverter-based generation units, such as wind and solar power plants, and large consumption and energy conversion units, such as data centres and Power-to-Hydrogen facilities, will utilize the same connection cables to existing or new 150 kV, 220 kV or 400 kV substations in the meshed transmission grid. Such electricity production and consumption units that often belong to the same developer and have common transmission lines and substations are called prosumers.

Deploying prosumers will not necessarily increase the net energy exchange with the transmission grid since large part of the energy production, such as a wind power plant, will be used within the consuming units, such as a Power-to-Hydrogen facility. However, the short-circuit current contribution of the inverter-based prosumers in the common coupling substations may significantly increase with a risk of exceeding the short-circuit current rating of the existing equipment. Upgrading the equipment in the existing substations to higher short-circuit current rating can be quite costly, when considering that upgrading shall be done under uninterrupted operation of the grid and, later, more equipment upgrading may again be needed.

For economically efficient utilization of the existing infrastructure, i.e., without upgrading the equipment to higher short-circuit current rating, one of the ideas is to separate the 150 kV meshed grid into the so-called grid islands. The 150 kV grid islands will be interconnected through the 400 kV grid. According to the political agreement in the Danish Parliament from October 2020, the 150 kV overhead lines (OHL) shall be replaced with 150 kV underground cables (UGC) when the 150 kV grid infrastructure is in vicinity of new 400 kV OHL. New 150 kV transmission lines shall be established as UGC.

Thus, reconstruction of the 150 kV transmission grid includes both commissioning of UGC and separation of the meshed grid into islands. Each 150 kV cablified grid island will include both meshed and radial sections. The challenge is that increasing share of the inverter-based units in combination with more UGC and separation into the grid islands may lead to increased background harmonic distortion in some areas of the transmission grid, i.e., within the grid islands.

Prediction of the harmonic distortion and proposal of mitigation solutions in cases with excessive harmonic voltage magnitudes shall be conducted by simulation studies ahead of completion of the grid expansion projects. The studies shall apply measurement-validated, accurate simulation models and specify proper mitigation solutions. On the one hand, establishment of mitigation solutions, such as passive filters,

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is costly, and unnecessary harmonic filters shall be avoided. On the other hand, overlooking extremely high harmonic distortion in a future grid development stage may jeopardize secure operation of the new lines and the grid as such without proper mitigation [1].

First, this paper will present a grid development project with extensive reconstruction of the 150 kV transmission grid with replacement of OHL with UGC and separation of the meshed grid into grid islands.

Second, the paper will introduce the measurement-validated simulation model developed for the assessed grid reconstruction.

Third, the paper will describe evolution of the 5th harmonic voltage magnitude in the 150 kV substations of the new grid island following the stages of the grid reconstruction. The paper will also identify and demonstrate the usage of so-called early warnings. Early warnings shall alert about excessive increases in the harmonic voltage magnitudes to occur in the following grid development stages using predicted-by-simulations specific behaviour of the harmonic voltage in certain substations in an earlier grid development stage. When that earlier grid development stage is taken into operation and the predicted-by-simulations behaviour is confirmed by harmonic voltage measurements, the harmonic voltage distortion will become excessive and need mitigation in the following (not-yet-commissioned) grid development stage.

Fourth, the paper will discuss distorting sources and present a mitigation solution with highlighting most suitable and not suitable substations within the 150 kV island for connection of a harmonic filter.

Finally, the findings of the presented work and conclusion will be given.

2 Securing the 150 kV grid of Western Jutland

The West Coast 400 kV line between Denmark and Germany is on the European Union list of important infrastructure projects contributing to the interconnection of the European electricity markets and networks, the so-called Projects of Common Interest (PCI). The West Coast 400 kV line shall be established by 2025. On the Danish side, the entire connection will be 174 km long and utilize a double-system OHL and 26 km double-system UGC sections per single OHL system [1].

The project "150 kV grid reconstruction of Western Jutland" (WJ150) and the project "Kassø-Lykkegård grid reconstruction" (KL150) are among several projects within the 150 kV meshed transmission grid alongside the West Coast 400 kV line in Western Denmark. Those two projects are illustrated in Fig. 1 and will replace the existing 150 kV OHL with 150 kV UGC in vicinity of the West Coast 400 kV line. The KL150 project shall establish 240 km UGC fully substituting the existing 150 kV OHL by 2023 [2] within the respective area in Fig. 1(c). The WJ150 project shall replace 135 km of the existing 150 kV OHL with 162 km UGC by 2026.

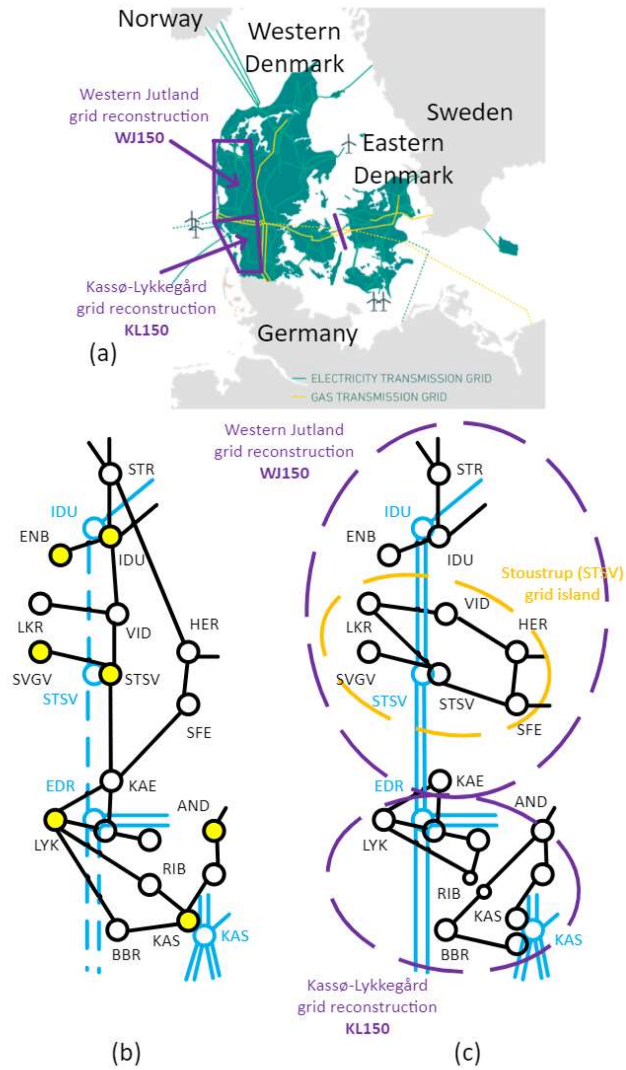

Fig. 1 – 400 kV and 150 kV grid structure during establishment of the West Coast 400 kV line and reconstruction of the 150 kV grid: (a) – Grid map of Denmark with the two 150 kV grid reconstruction projects, (b) – the 2021 grid structure before start of the grid reconstruction, (c) – the final grid structure. Legend: ○ - 400 kV substation, ○ - 150 kV substation, ● - 150 kV substation with harmonic voltage measurement, ▬ - 400 kV line, ▬ - 150 kV line, ⌞⌟ - grid reconstruction, ⌞⌟ - 150 kV grid island.

In the beginning of the presented harmonic assessment, the West Coast 400 kV line is not yet established and shown by dotted blue lines in Fig. 1(b). In the final grid development stage of the harmonic assessment, the line will be fully established and shown by solid blue lines in Fig. 1(c).

At the same time, the 150 kV grid reconstruction shall enable the grid-connection of new renewables and large consumption centres as prosumers, and secure that the short-circuit current contribution in the 150 kV substations do not exceed the short-circuit current rating of the equipment. Ensuring that the short-circuit currents in the grid will not exceed the designed short-circuit current rating of the substation equipment will be achieved by separation of the meshed interconnected 150 kV grid into the so-called grid islands. Thus, the meshed 150 kV grid will be cablified [2] and separated into the 150 kV grid islands and mainly interconnected via the 400 kV grid.

The substation Ribe (RIB) in Fig. 1(b-c) will be in separated operation, and a new substation will be established and separated from Kassø, after completion of the KL150 project. Several 150 kV lines will also be removed separating the 150 kV grid. The grid separation will result in several 150 kV grid islands, which is seen in Fig. 1(c), with weaken or no 150 kV connections to each other. The grid development around the Stoustrup 150 kV grid island, which will be discussed in this paper for evolution of the 5th harmonic voltage distortion, is illustrated in Fig. 1(b-c).

The yellow marking of the 150 kV substations in Figure 1(b) is for the harmonic voltage measurements available at the beginning of the assessment due 2022 and applied for the simulation model preparation and validation.

3 Simulation model

Energinet applies the PowerFactory® simulation software from DIgSILENT for modelling of the transmission grid. The simulation method is the harmonic load flow.

The passive transmission grid model includes electro-geometrical representations and data of the OHL, UGC and submarine cables, electrical data of the power transformers, shunt reactors and harmonic filters in all of Western Denmark. The models of the existing passive components are measurement validated. The models of not yet established lines apply the catalogued vendor-specific data and design practice of Energinet for getting the best possible approach for the passive grid representation for the new grid development stages of the harmonic assessment. Tolerances of the electrical parameters of not-yet-established lines are included as variants of the new grid development stages.

The passive transmission grid corresponds to the harmonic impedance matrix of the simulation model. The (n-1) operation conditions, removal of lines and establishment of new lines including data tolerances as variants represent modifications of the harmonic impedance matrix.

The harmonic sources are the active part of the simulation model. The largest contribution to the 5th harmonic voltage distortion originates from distributed harmonic sources under the 150 kV substations. Energinet does not have readily available data of such numerous distributed harmonic sources. Therefore, Energinet apply the deterministic method described in reference [3], and according to this reference:

- Distributed harmonic sources are identifiable from the measured magnitudes of the harmonic voltages.
- Characteristics of distributed harmonic current sources are numerically tuned to represent the measured magnitudes of the harmonic voltages in the 150 kV substations.
- The numerical tuning is conducted for various (n-1) operation conditions of the passive 150 kV (and 400 kV) transmission grid.
- Considering the model preparation there are two types of (n-1) operation conditions [2]. The first type is when changes of the (n-1) operation conditions are followed by changes of the measured magnitudes of the harmonic voltages. The second type is when the measured magnitudes of the harmonic voltages do not change with changes of the (n-1) operation conditions.
- Application of the periods with both types of the (n-1) operation conditions for the model preparation establishes relationships between modifications of the harmonic impedance matrix and the harmonic voltages [2].
- The numerical tuning results in the sets of magnitudes and phase-angles of the harmonic current sources. When the numerical tuning is completed, the magnitudes and phase-angles of the sources are locked [3].

In the applied deterministic method, the same sets of the numerically tuned magnitudes and phase-angles of the harmonic current sources shall cover all snapshots with (n-L), $L \geq 0$, operation conditions in the present grid stage and are applied for simulation the harmonic voltage magnitudes in future grid development stages with changes of the passive transmission grid.

In the applied method, future grid development stages with the reconstructed passive transmission grid are modifications of the harmonic impedance matrix. With properly tuned harmonic current sources, the method shall accurately simulate the harmonic voltages in the substations of the present grid development stage and predict the harmonic voltages in future grid development stages.

For the assessment of the 5th harmonic voltage distortion within the Stoustrup 150 kV grid island, which includes six 150 kV substations with six 5th harmonic current sources as depicted in Fig. 1(c), the numerical tuning has been conducted for approx. eighty 5th harmonic current sources within, north and east to the area of the WJ150 project, and within the area of the KL150 project. Such extensive numerical tuning of the harmonic current sources is necessary for properly representing the harmonic propagation within the meshed transmission grid as well as cancellation of the harmonic propagation due to separation into the 150 kV grid islands.

3.1 Realistic worst-case magnitudes

The 5th harmonic voltage distortion in the 150 kV transmission grid may have hourly, daily, and seasonal variation, which for the 150 kV substation Stoustrup (STSV) is shown in Fig. 2.

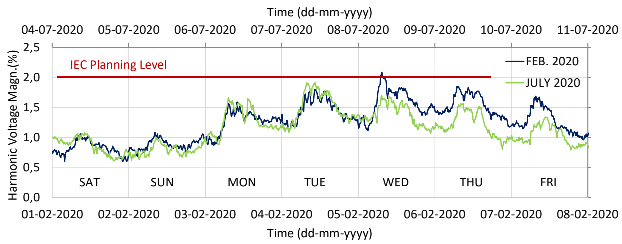

Fig. 2 – Weekly and seasonal variations of the measured 5th harmonic voltage magnitude in the 150 kV substation Stoustrup. The grid is as depicted in Fig. 1(b).

Energinet applies the IEC planning levels [4] in means of the 95th weekly percentiles as a measure of excessive magnitudes of harmonic voltages and necessity of mitigation solutions. Thus, the simulation model shall work with evaluation of the 95th weekly percentiles of the 5th harmonic voltage distortion, while natural variation of the harmonic voltage is excluded from the model preparation.

For the 5th harmonic voltage, the IEC planning level is 2% of the nominal frequency voltage for the transmission grids above 100 kV [4].

When the simulation model shall work with the 95th weekly percentiles, this introduces a realistic worst case of the harmonic voltage distortion. On the one hand, the model will simulate a higher range of the harmonic voltage magnitudes. On the other hand, the model excludes both high and rare magnitudes as well as low magnitudes that are not relevant for making decision on necessity of mitigation solutions.

3.2 Automated numerical tuning

For the harmonic assessment of the 150 kV grid reconstruction of Western Jutland, Energinet developed a script for automated numerical tuning of the harmonic current sources under the 150 kV substations. The script inputs are the combinations of:

- The grid change log since the grid development has continued during the period of the model preparation.
- The (*n-L*), $L \geq 0$, operation regimes.
- The measured 5th harmonic voltage as ten-minute average magnitudes.

The script outputs are:

- The relative magnitudes and phase-angles of the harmonic current sources included in the numerical tuning [3].

The script has conducted simultaneous numerical tuning of approx. eighty harmonic current sources and applied eight periods with up to ten consecutive snapshots pr. period. The consecutive snapshots within the eight periods are for accurate representation of not only magnitudes but also steps (change tendencies) of the 5th harmonic voltage in response to changes through the grid operation regimes.

These eight periods have covered eleven months of historical operation regimes and measurements. Commissioning of new lines or permanent removal of lines, which occurred within these eleven months, have changed the harmonic voltage magnitudes in certain substations and introduced new (*n-L*), $L \geq 0$, operation regimes as well. For example, removal of the KAS-RIB and BBR-LYK 150 kV OHL depicted in Fig. 1(b) and establishment of the BBR-RIB 150 kV UGC in Fig. 1(c) (yet without separation of the RIB substation) have occurred within the measurement periods applied for the model preparation. Therefore, the grid change log was relevant as input to the script.

The script includes several tuning loops with different numbers and locations of the harmonic current sources per loop. Inclusion of the same sources in different loops is allowed as partial overlap between the loops.

Within each loop the algorithm is straightforward:

- Receiving the measured harmonic voltage magnitudes for a given snapshot.
- Normalizing the harmonic voltage magnitudes to a common base.
- Adjusting magnitudes and phase-angles of each harmonic current source one at a time until the discrepancy of the simulated magnitudes to the measured magnitudes is lowest.
- Evaluating the discrepancy simultaneously for all substations with available harmonic measurements.

However, construction and execution order of the loops with the substations (and their harmonic current sources) seems to be grid specific, i.e., it requires knowledge of the grid.

The numerical tuning of the 5th harmonic current sources has required four loops. The progress of the automated numerical tuning is illustrated by the two snapshots in Fig. 3 and Fig. 4.

The index "1" at the substation abbreviations indicates 150 kV. The abbreviations FGV, FOU, FVO, RYT, and TJE are the 150 kV substations being outside of the grid area depicted in Fig. 1(b-c), i.e., outside of the assessment area, but their harmonic voltage measurements and grid areas are also included in the model preparation.

Fig. 3 illustrates a case of easier convergence meaning that good agreement between the model and measurements is reached after the third loop. Fig. 4 illustrates a case of difficult convergence where all four loops are needed for the model to reach good agreement with the measurements.

The term "good agreement" means that:

- The simulated magnitudes are within ±10% of the measured magnitudes when the measured magnitudes are high, i.e., above 50% of the IEC planning level. For the 5th harmonic voltage, 50% of the IEC planning level is 1% of the fundamental-frequency voltage.
- The simulated magnitudes are low when the measured magnitudes are low, i.e., below 50% of the IEC planning level, though a higher relative discrepancy of the simulated magnitude to the measured magnitude can be accepted.

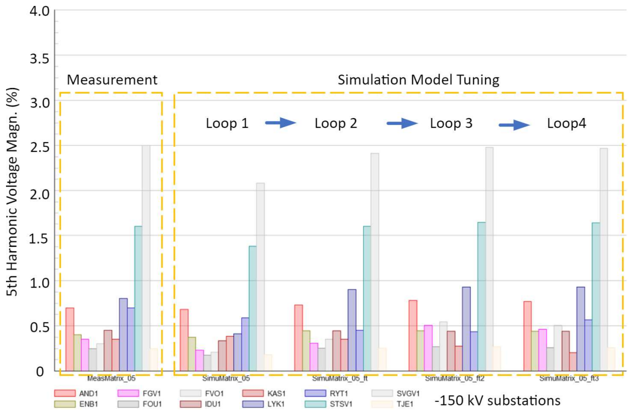

Fig. 3 – Numerical tuning of the model to match the measured 5th harmonic voltage magnitudes in the 150 kV substations in Western Denmark. Easier convergence.

Fig. 4 – Numerical tuning of the model to match the measured 5th harmonic voltage magnitudes in the 150 kV substations in Western Denmark. Difficult convergence.

The (*n-L*), *L*>0, grid operation conditions of the two cases shown in Fig. 3 and Fig. 4, respectively, are different, which explains the difference in the measured 5th harmonic distortion in the 150 kV substations between these two cases.

The model accurately simulates high magnitudes of the 5th harmonic voltages, which is relevant for decision making on necessity and design of mitigation solutions.

The simulation model accurately predicts that the harmonic voltage distortion is with low magnitudes in given substations and grid operation regimes. The accuracy requirement to the simulated magnitudes can be lowered meaning no need of exact match between the simulated magnitudes and low measured magnitudes of the harmonic voltage distortion. Difficulty of perfectly accurate match of low magnitudes in various operation regimes is characteristic for many numerical algorithms, which is also the case for the presented simulation model.

4 Harmonic assessment results

The harmonic assessment has been conducted for the grid expansion stages starting from the grid model 2021 and ending with the grid model 2028 with completed the WJ150 project. The four stages which are relevant for this presentation are listed below:

- Grid 2021 before start of the KL150 project.
- Grid 2022 after commissioning of the first 150 kV UGC, BBR-RIB, and removal of the BBR-LYK and KAS-RIB 150 kV OHL.
- Grid 2023 after completion of the KL150 project with all 150 kV UGC, see Fig. 1(c).
- Grid 2028 after completed the WJ150 project with separation of the cablified meshed grid into the 150 kV grid islands.

The model preparation applied the periods and measurements during the first two above listed stages. The measurements during the third stage are getting available now due to continuing work on the KL150 project, but those measurements were not available at the time of the model preparation in the first half of 2022.

Fig. 5 compares the change tendencies of the 5th harmonic voltage magnitudes due to commissioning of the BBR-RIB 150 kV UGC. The 5th harmonic voltages are shown for the 150 kV substations KAS and AND, which are within the KL150 area, and the substations SVGV and STSV, which are within the Stoustrup grid island (not yet established).

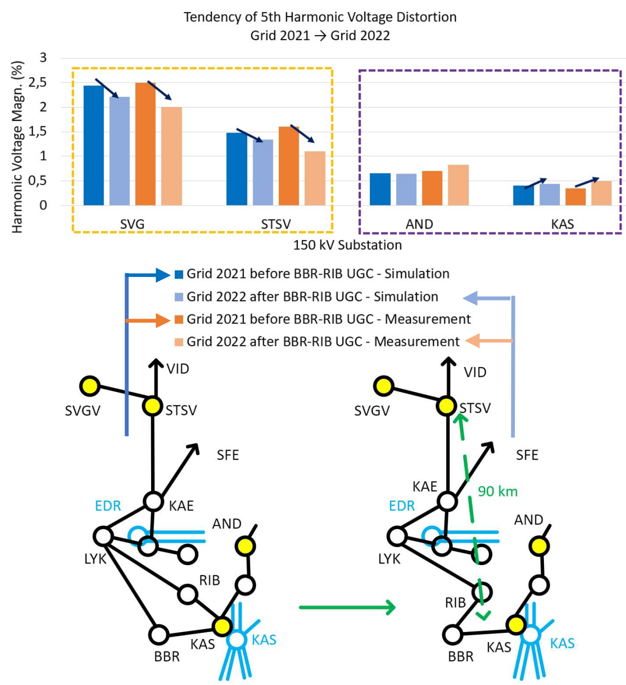

Fig. 5 – Comparison of simulated and measured magnitudes of the 5th harmonic voltages in the 150 kV substations with available harmonic voltage measurements: [purple box] - AND and KAS are within the Kassø-Lykkegård grid reconstruction, [yellow box] - SVGV and STSV are within the Stoustrup grid island (not yet established).

As can be seen, establishment of the 150 kV UGC in Southern part of the 150 kV meshed grid contributes to:

- Reduction of the 5th harmonic voltage in the substations STSV and SVGV, and
- Small increase of the 5th harmonic voltage in the substations KAS and AND.

Establishment of the BBR-RIB 150 kV UGC, which is apparently contributing to this change of the 5th harmonic voltage, is approx. 90 km away from the substations STSV and SVGV.

The simulated tendencies of the 5th harmonic voltages in the substations within the Stoustrup 150 kV grid island and in the substations AND and KAS through the four grid expansion stages are depicted in Fig. 6. The arrows show the change tendencies of the simulated harmonic voltages in the substations up to the completion of the KL150 project and separation of the substations RIB and KAS by 2023.

The simulations predict that:

- The 5th harmonic voltage within the Stoustrup 150 kV grid area gradually decreases while the KL150 project is continuing and reaches the lowest magnitudes when it is completed at by 2023.
- Then, the 5th harmonic voltage shall significantly increase after the Stoustrup 150 kV grid island is cablified and separated from the meshed 150 kV grid of Western Jutland by 2028 as depicted in Fig. 6.

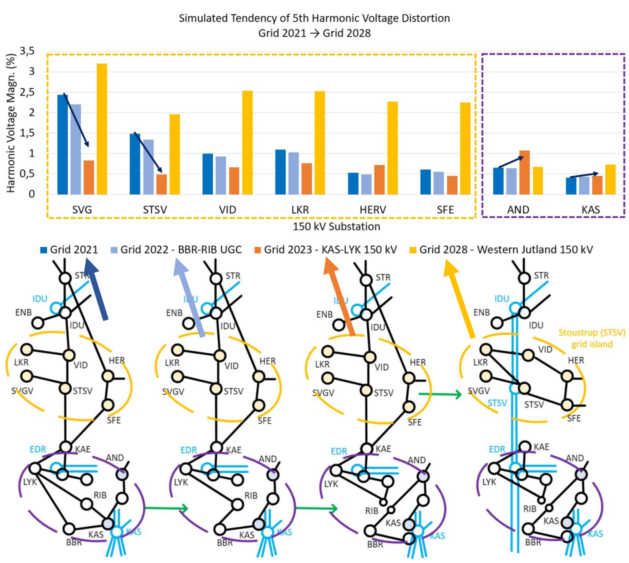

Fig. 6 – Evolution of the simulated magnitudes of the 5th harmonic voltages in the 150 kV substations: - within the Stoustrup 150 kV grid island, - AND and KAS within the Kassø-Lykkegård grid reconstruction. The shown results are for the (*n*-0) operation regimes. The arrows illustrate grid development.

Considering the 5th harmonic voltage within the Stoustrup 150 kV grid island by 2028:

- Increasing tendencies and a risk of the IEC planning level violation may occur through a major part of the 150 kV grid island.
- The simulated magnitudes shall be treated with precaution as preliminary values.

At present, a better accuracy of the simulated magnitudes of the 5th harmonic voltage in the 2028 grid cannot be achieved since several grid expansion and reconstruction projects are conducted simultaneously with the KL150 and WJ150 projects, where some projects can be postponed, and some other projects are accelerated. Uncertainty of the data of not-yet-commissioned lines and not included harmonic emission of not-yet-established active sources may influence the accuracy of the simulated magnitudes as well.

4.1 Early warning of future harmonic amplification

Early warning relates to prediction accuracy of the 5th harmonic voltage tendencies using the simulation model. The simulation model has predicted a decreasing tendency of the 5th harmonic voltage in the substations STSV and SVGV, and a small increasing tendency in the substations AND and KAS, during commissioning of the cablified 150 kV grid of the KL150 project.

These harmonic voltage change tendencies opposing each other in the different parts of the meshed 150 kV grid are the early warning of that after the continued reduction there will come an increase of the 5th harmonic voltage within the Stoustrup 150 kV grid island, in the 2028 grid. The nature of the opposed tendencies may have several explanations, that includes increasing propagation of the 5th harmonic voltage from north to south of the meshed 150 kV grid with establishment of more UGC in the southern part of the grid. This work does not establish all such explanations but just evaluates the model following the measured tendency so far.

Since the first BBR-RIB 150 kV UGC was established in October 2021, the KL150 project has continued through 2022 -2023 with more established UGC and longer measured harmonic voltage series available in the substations SVGV, STSV, KAS and AND. These measurements are now applied for evaluation of the early warning for expected evolution of the 5th harmonic voltage in the future grid following the KL150 project.

The 95th weekly percentiles of the measured 5th harmonic voltage magnitudes in the substations STSV and KAS are plotted in Fig. 7.

The largest seasonal magnitudes occur during the late fall through early spring (over winter) periods which is why those periods are the indicators of long-term evolution of the 5th harmonic voltage distortion. At the time of preparation of this paper, the fall 2023 measurements are not available, which is why the remaining 2023 is not included in the plots.

The lowest 5th harmonic voltages are seen at the so-called Christmas dips, i.e., sudden drop of the 5th harmonic distortion during the Christmas holidays in Denmark, at the end of December. Change tendencies of the Christmas dips serve also as the indicators of evolution of the 5th harmonic voltage distortion over long time.

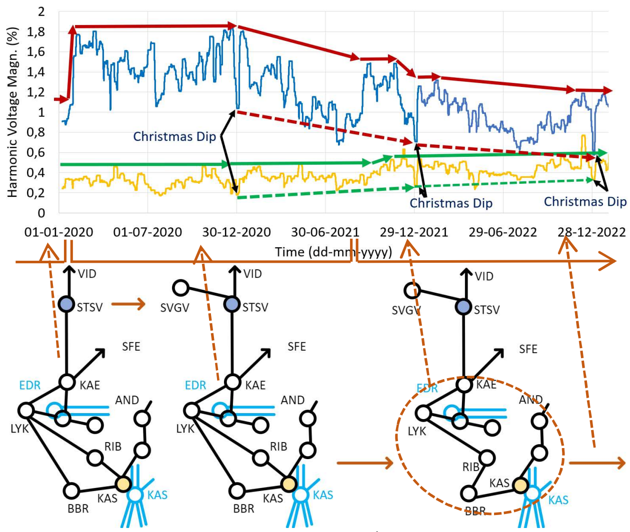

Fig. 7 – Evolution of the measured 95th weekly percentiles of the measured 5th harmonic voltage in the substations: - STSV, - KAS. The tendency lines of the maximum magnitudes in: - STSV, - KAS, and those of the lowest magnitudes during the Christmas dips in: - STSV, - KAS. The arrows illustrate grid development.

As seen in Fig. 7, both maximal magnitudes over the winter periods and the lowest magnitudes during the Christmas dips of the 5th harmonic voltage in the substation STSV have reduced during the last three years, while these magnitudes in the substation KAS have increased during the last three years, starting from October 2021 with commissioning of the first BBR-RIB 150 kV UGC. The reduction over summer 2021 is a seasonal variation and shall be disregarded.

The early warning for evolution of the 5th harmonic voltage in the meshed 150 kV grid seems to be on track, which is why the predicted increase of the 5th harmonic voltage distortion can be expected after completion of the WJ150 project.

The last remark relates to the 5th harmonic voltage step in STSV at the beginning of 2020. At that time, the STSV-SVGV 150 kV UGC was energized and brought in operation. Since that time, the 5th harmonic voltage magnitude remains high though there are no active harmonic sources yet under the 150 kV substation SVGV.

4.2 Identifiability of future harmonic amplification using measurements in the present grid

Since the meshed 150 kV grid will be separated into the grid islands, the tendencies of the 5th harmonic voltage changes in the future grid islands are identifiable from certain (*n*-1) events in the present grid stage.

On April 19th, 2021, the KAE-STSV 150 kV line was out-of-service. This line will be permanently taken out-of-service in the future grid stage with creation of the Stoustrup 150 kV grid island, see Fig. 1(b-c) for details. Therefore, the (*n*-1) event with the KAE-STSV line out-of-service is a good opportunity for evaluation of the simulated tendency of a significant increase of the 5th harmonic voltage magnitudes within the Stoustrup 150 kV grid island in the future grid.

The measured 5th harmonic voltage magnitudes in the substations AND, KAS, STSV and SVGV together with the (*n*-1) regimes of the relevant 150 kV lines are shown in Fig. 8. The measurements show that outage of the KAE-STSV line causes a significant step up of the 5th harmonic voltage magnitudes in the substations STSV and SVGV. The arrows in Fig. 8 denote the steps in outage of the KAE-STSV 150 kV line. At the present grid conditions, the largest step is approx. 0.7% in SVGV and approx. 0.5% in STSV, which is a large change compared to the IEC planning level of 2%.

The presented evaluation has confirmed the simulation results with expected drastic increase of the 5th harmonic voltage magnitudes within the Stoustrup 150 kV grid island that are shown in Fig. 6 (the dark yellow bars).

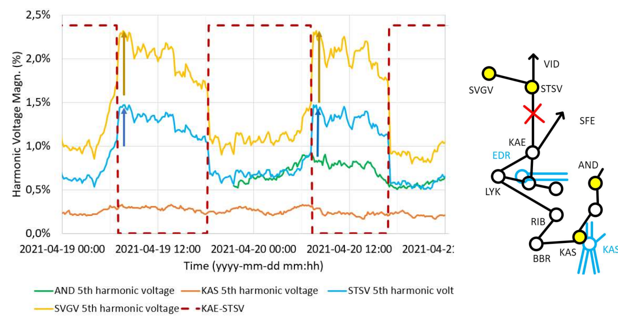

Fig. 8 – Measured 5th harmonic voltage magnitudes in the substations AND, KAS, STSV, and SVGV, and status of the KAE-STSV 150 kV line.

The evaluation also confirms that the 5th harmonic voltage increase is related with cancelled propagation of the 5th harmonic voltage from the 150 kV grid area around Stoustrup down to the southern part of the 150 kV grid. When the KAE-STSV and KAE-SFE lines, compare Fig. 1(b-c) and Fig. 8, will be removed, it reduces the harmonic propagation existing in the present grid stage from north to south and isolates the 5th harmonic sources within the Stoustrup 150 kV grid island. Thus, the 5th harmonic voltage magnitudes will increase within the 150 kV grid islands with almost isolated harmonic sources.

The exact magnitudes of the 5th harmonic voltage magnitudes within the Stoustrup 150 kV grid island will also depend on the UGC characteristics due to changed harmonic impedance, despite the separation of the grid island from the southern part of the 150 kV grid can be the main reason for the predicted increase of the 5th harmonic voltage.

Establishment of more converter-interfaced units, which will contribute to harmonic emission, will also influence the 5th harmonic voltage magnitudes in the 150 kV grid. Evolution of harmonic emission is under attention when the simulation model will be revalidated and reevaluated in the years to come.

5 Distorting sources

In the present grid, the 5th harmonic sources are located under the 150 kV substations, such as in the 60 kV and 10 kV distribution networks, where from the 5th harmonic voltage propagates up to the 150 kV grid via the 150/60 kV transformers. Energinet does not have readily available data of such harmonic sources in the 60 kV and 10 kV networks, and it is extremely difficult to define which sources are the most distorting, i.e., most contributing to the high 5th harmonic voltage in the 150 kV grid.

Presence of the Christmas dips in the measured 5th harmonic voltage, see Fig. 7, indicates that the most distorting sources can be found among large industrial power consumers because their facilities will not operate during the Christmas holidays in Denmark. This deduction is also confirmed by the daily and weekly variation of the 5th harmonic distortion, shown in Fig. 2 and Fig. 9, with the largest magnitudes during working hours of working days and the lowest magnitudes during weekends and nights.

Fig. 10 gives interpretation of the 5th harmonic voltage variation over time referring to Fig. 9.

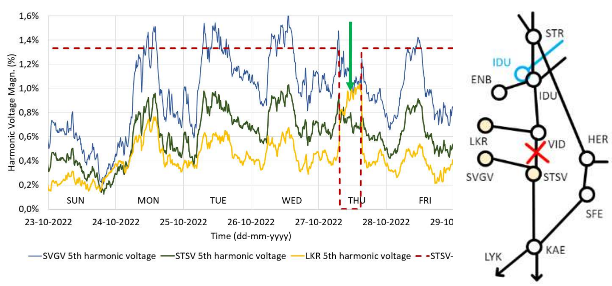

Fig. 9 – Measured 5th harmonic voltage magnitudes in the substations SVGV, STSV, LKR (temporary measurement) and status of the STSV-VID 150 kV line.

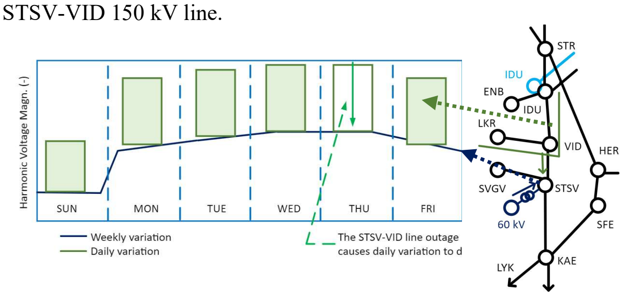

Fig. 10 – Interpretation of the measured 5th harmonic voltage variation in the substations SVGV and STSV including outage of the STSV-VID 150 kV line.

The interpretation shows that the 5th harmonic voltage in SVGV and STSV, those with the largest magnitudes, can be split up into:

- Weekly variations that peak through Wednesdays and Thursdays and reduce through weekends.
- Daily variations that peak during active, working or daylight hours and decay during nights.

It suggests that the distorting sources causing the weekly variation are located around the substation STSV, while the distorting sources causing the daily variation may be located within the grid behind the 150 kV substations VID, IDU, and LKR. When the STSV-VID line is out-of-service, the distorting sources causing the daily variations to be disconnected from STSV, which entails the 5th harmonic voltage in STSV to drop down to the weekly variation level, see THU in Fig. 9 and Fig. 10. The interpretation of the 5th harmonic voltage contributions on the grid map is illustrated in Fig. 10.

Thus, identifying the most distorting sources becomes a challenging task which may include searching through a larger part of the 60 kV and 10 kV networks with connections to the 150/60 kV transformation 60 kV terminals under the substations STSV, VID, IDU and LKR, or by applying exploratory analyses on the historic measurements in order to identify possible trends and correlations [3]. This work shall continue in close cooperation with relevant distribution system operators.

Notice that the peaks of the measured 5th harmonic voltage in LKR in Fig. 9 are in a range of 0.65% and 1%, which fits with the light-blue and orange bars of the simulated 95th percentiles in LKR for 2022 -2023 shown in Fig. 6. The harmonic voltage measurements in LKR were not available at the time of the model preparation. This observation strengthens the statement on accuracy of the simulation model.

6 Mitigation solution

Commissioning of a harmonic filter within the Stoustrup 150 kV grid island can be necessary as a global mitigation solution. Fig. 11 shows the simulation results of evaluation of the 150 kV substations as possible candidates for connection of the 5th order harmonic filter, $h_h = 5$. For comparison between the 150 kV substations, the quality factor, $q_f = 2$, is kept unchanged and only the reactive power rating, Q_R, of the filter is varied.

The success criterion is that the harmonic filter shall reduce the 5th harmonic voltage magnitudes in the 150 kV substations of the Stoustrup grid island below 70% of the IEC planning level, i.e., below 1.4%.

Connection of the harmonic filter in LKR shows almost the same result as for VID, and in SFE as for HER.

The results can be summarized as follows:

- Connection of a harmonic filter to VID or LKR will have the best dampening effect on the 5th harmonic voltage within the Stoustrup 150 kV grid island.
- Connection to STSV, HER or SFE will also be suitable, but the harmonic filter will require a larger reactive power rating than when connected to VID or LKR.
- Connection to SVGV is not recommended.

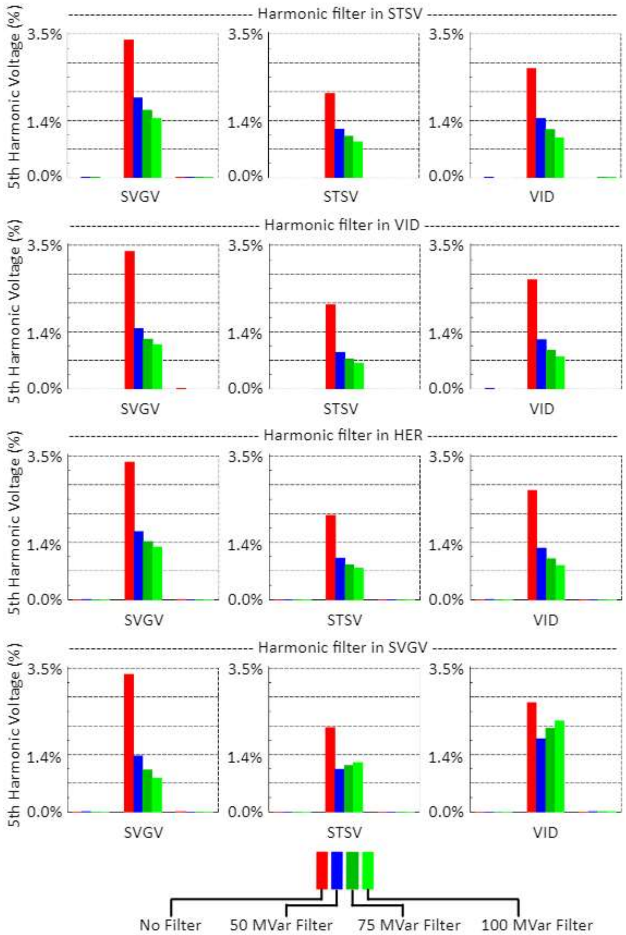

Fig. 11 – Simulated 5th harmonic voltage magnitudes in the 150 kV substations SVGV, STSV and VID as result of a harmonic filter connected to either STSV, VID, HER, or SVGV.

The substation SVGV remains a radial UGC within the Stoustrup 150 kV grid island. When the harmonic filter is connected to SVGV, the 5th harmonic voltage magnitude in SVGV is better dampened when the reactive power rating increases. However, increasing the reactive power rating will have an opposite effect on the 5th harmonic voltages in the other 150 kV substations within the grid island, see Fig. 11. This result needs further analysing, i.e., need of clarification of whether the terminals of radial connections to the grid islands are not suitable for connection of harmonic filters because of increasing the harmonic voltages in the other substations of the grid.

At present, the mitigation solution is not optimized in regards to specifying the tuning order, quality factor or reactive power rating of the harmonic filter. The connection substation for harmonic filter is selected but specification is postponed until after completion of the KL150 project due 2023 and the following separation of the substations RIB and KAS. Here, the assessment results with predicted 5th harmonic voltage magnitudes will be revalidated, the newest available UGC data applied, and if the simulation model is still deemed valid and accurate, the specification of the harmonic filter will be completed.

7 Conclusion

This paper has described the expected evolution of the 5th harmonic voltage distortion following massive replacement of the existing 150 kV OHL with UGC and separation of the meshed 150 kV transmission grid into the grid islands.

The assessment has been conducted by simulations on a measurement-validated model of the 150 kV transmission grid of Western Denmark for a project to be fully implemented by 2028 using harmonic voltage measurements in the present 150 kV grid. The assessment starts from an accurate level of the 5th harmonic voltage in the model of the present grid stage in Western Denmark.

The assessment has demonstrated that the harmonic voltage in the meshed transmission grid can be influenced by the grid expansion (or reconstruction) occurring tens of kilometres away from the assessed project. Therefore, a significantly larger area of the grid has been included in the model preparation and assessment than the project area itself. The reason for that influence is linked to harmonic propagation in the meshed transmission grid.

The assessment has found that separation of the meshed transmission grid into grid islands may significantly increase the harmonic voltage within the islands. The assessment has also identified early warnings, which are predicted-by-simulations specific changes of the harmonic voltage magnitudes in certain areas of the grid during earlier grid stages. In later grid stages, those specific changes will be followed by a significant increase of the harmonic voltage magnitudes within certain area of the reconstructed grid. When those earlier grid stages are completed, the early warnings shall be evaluated by harmonic voltage measurements and if confirmed, then the following grid stages will have a risk of significantly increased harmonic voltage magnitudes. Thus, necessary mitigation solutions can be prepared in advance for the following grid stages.

In the assessed project, the early warning are opposite tendencies of the 5th harmonic voltage magnitudes in the two different grid areas. The early warning has highlighted that in the WJ150 project area, the 5th harmonic voltage would reduce while it slightly increases in the KL150 project area, during the ongoing commissioning of the KL150 project. Then, the assessment has predicted that the reduction will be followed by an increase of the 5th harmonic voltage within the assessed grid island of the WJ150 project. Since newer measurement series become available, the above described opposite tendencies of the 5th harmonic voltages, i.e., the early warning, have been confirmed so far. Therefore, the predicted significant increase of the 5th harmonic voltage within the 150 kV grid island can be expected to occur after completion of the WJ150 project by 2028.

Using the harmonic voltage measurements in the present grid stage, the assessment has linked such predicted increase of the 5th harmonic voltage to the separation, i.e., permanent interruption of connections in the 150 kV grid and splitting up the meshed grid into the grid islands. The cause of the significant harmonic amplification is most likely due to cancellation of the harmonic propagation in the meshed grid. Strong harmonic sources will be locked and increase the harmonic voltage distortion within the grid island. Reduced meshing of the grid may cause local harmonic amplification as in the presented case of the Stoustrup 150 kV grid island in Denmark. Replacement of the existing 150 kV OHL with UGC complicates exact prediction of the harmonic voltage magnitudes to be in the grid island by 2028 due to uncertainty of the data of not yet established UGC lines.

A growing share of converter-interfaced units with active harmonic emission also complicates the long-term harmonic prediction, which is why the results of this work will be revalidated and reevaluated in the coming years up to the project commissioning.

The assessment has looked on most suitable and not suitable connection substations for a harmonic filter within the 150 kV grid island of the assessed project. The substations remaining within the meshed grid of the island are pronounced suitable while the substation on a radial UGC to the island is found to be not suitable for connection of a harmonic filter. When connected to the opposite terminal of the radial 150 kV UGC, the harmonic filter may cause an adverse effect on the 5th harmonic voltages in the other substations within the 150 kV grid island. This outcome needs further investigation and should not be generalised so far.

6 References

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