Methods and Results of Harmonic Simulation Assessment of a Reconstructed Meshed Transmission Grid with Distributed Harmonic Emission Sources

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Abstract—**In Denmark, the green transition follows up with integration of more underground cables (UGC) in the HVAC meshed transmission grid. This paper shares the experience of Energinet, Transmission System Operator of Denmark, and describes the applied simulation methods for the harmonic assessment of the meshed transmission grids using the Kassø-Lykkegård 150 kV transmission grid reconstruction project in Western Denmark as a case study. The Kassø-Lykkegård grid reconstruction project shall be completed by 2023 and establish 240 km 150 kV UGC fully replacing the overhead lines (OHL) of the meshed grid area. The harmonic assessment and applied methods shall result in robust conclusion on the harmonic amplification and specific recommendation for the mitigation solution. At the same time, the applied methods shall cope with modelling uncertainty due to data uncertainty of not yet commissioned components, data tolerances of the existing components and not explicitly defined data of the distributed harmonic emission sources. The harmonic assessment has concluded noticeable harmonic amplification within the reconstructed 150 kV UGC grid and proposed a passive harmonic filter as the mitigation solution. The mitigation solution defines both layout and substation for commissioning of the harmonic filter in the not yet established meshed transmission grid.**

Keywords—harmonic assessment, harmonic amplification, meshed transmission grid, method, power quality measurements, underground cables, simulation, validation

I. Abbreviations

DKE	Eastern Denmark (Transmission Grid)
DKW	Western Denmark (Transmission Grid)
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
LCC	Line Commutated Converter
OHL	Overhead Line
OWPP	Offshore Wind Power Plant
PQ	Power Quality
PV	Photovoltaic
VSC	Voltage Source Converter
UGC	Underground Cable

1) HVAC Subtations

The 400 kV substations with relevance for the presented harmonic assessment.

FGD	Fraugde (Storebælt LCC)
KAS	Kassø

The 150 kV substations with relevance for the presented harmonic assessment. The substation Almindegård is yet to be established by 2023.

ALD	Almindegård	KAS	Kassø
AND	Andst	LAG	Landerupgård
BBR	Bredebro	LYK	Lykkegård
BDR	Bramdrup	MAG	Magstrup
EDR	Endrup	RIB	Ribe
HOD	Holsted	STSV	Stovstrup
KAE	Karlsgårde		

2) HVDC Connections and Converter Stations

The HVDC converter stations are according to Fig. 1 of the 400 kV transmission grid in Western Denmark.

KS12	Konti-Skan 1, 2 (DKW – Sweden, LCC)
SK12	Skagerrak 1, 2 (DKW – Norway, LCC)
SK3	Skagerrak 3 (DKW – Norway, LCC)
SK4	Skagerrak 4 (DKW – Norway, VSC)
SB	Storebælt (DKE – DKW, LCC)
CO1	Cobra Cable (DKW – The Netherlands, VSC)
--	Viking Link (DKW – Great Britain, VSC)

II. Introduction

Fig. 1 illustrates the energy transmission grid of Denmark. The Danish electricity transmission grid is divided between the two large synchronous areas. The peninsula of Jutland and the island of Funen defines the DKW transmission grid being part of the Continental European

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synchronous area. The main island of Zealand with the Danish Capital of Copenhagen and the islands of Lolland, Falster and Moen forms the DKE transmission grid belonging to the Nordic synchronous area.

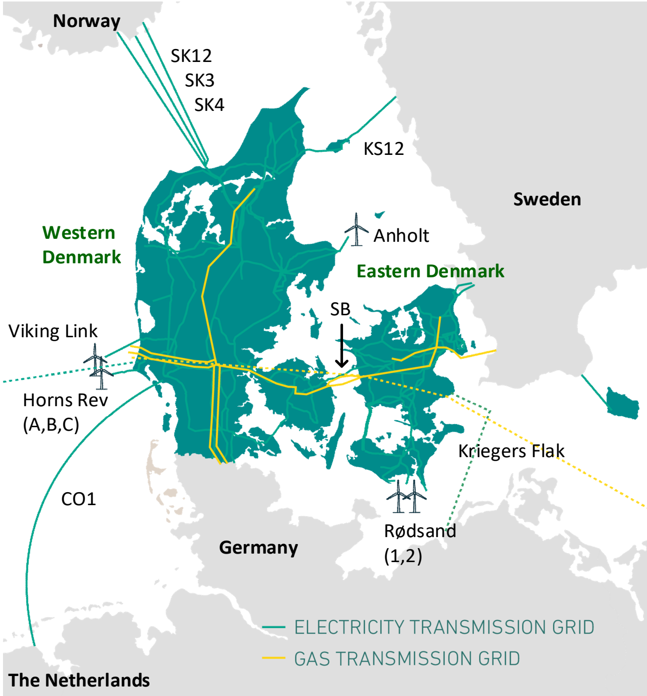

Fig. 1. Denmark within the European energy transmission grids.

The electricity transmission grid of Denmark includes the 400 kV, 150 kV (DKW), 132 kV (DKE) meshed systems with HVAC connections between DKW and Germany, and DKE and Sweden, as well as 220 kV export cables of large OWPPs.

The Danish transmission grid includes multiple LCC HVDC interconnectors to Norway (SK12 and SK3, 1000 MW), Sweden (KS12, 740 MW) and between the two Danish asynchronous systems (SB, 600 MW). In DKW, the VSC HVDC interconnectors to Norway (SK4, 700 MW) and the Netherlands (CobraCable, 700 MW) are commissioned in 2014 and 2019, respectively.

In 2024, the VSC HVDC interconnector to the Great Britain (Viking Link, 1400 MW) and the 400 kV connection to Germany on the West Coast of DKW shall be completed.

The modern wind turbines and PV modules are converter-interfaced units and have become the main-stream technology within the electric energy supply in Denmark. At present, the wind power and PV cover more than 50% of the annual electric energy consumption of the country. There are already days with the renewable power supply exceeding electric power consumption. The share of power-electronics within the consumption is getting significant as well.

Future OWPPs including Thor with the planned production capacity between 0.8 and 1 GW in the North Sea and Hesselø with the planned production capacity of 1 GW in Kattegat are to be connected to the Danish transmission grid by 2026-2028. Using the Kriegers Flak Combined Grid Solution, which is successfully completed due 2020 and combines offshore wind power in the Baltic Sea and an offshore interconnector between Eastern Denmark and Germany, as inspiration, the Energy Islands with (initial) wind power capacities of 2 GW in the Baltic Sea (the Danish island of Bornholm) and 3 GW in the North Sea are now in a conceptual survey.

The Danish transmission system has become a hub where the meshed HVAC transmission system includes numerous converter stations of the HVDC interconnectors, large wind and PV power plants. Integration of more renewables and stronger interconnection with foreign transmission grids require expansion of the domestic transmission system as well. The political agreement from October 2020 has defined principles for developing the electricity infrastructure in Denmark:

- New 400 kV transmission lines must be established as UGC to the extent that is technically feasible. Beyond what is technically feasible to establish with UGC, OHL must be used for 400 kV lines.
- Existing 132-150 kV OHL are replaced with UGC as the need for extensive reinvestment of the lines arises. Furthermore, existing 132-150 kV OHL are replaced with UGC if the lines are in the vicinity of new 400 kV OHL.
- New 132-150 kV transmission lines are established as UGC.

The share of UGC in the Danish transmission grid is going to increase together with the share of power-electronics converters is rapidly increasing. The first incidents of significant, systemwide, harmonic amplification caused by the harmonic interaction between the converter stations and following integration of the 400 kV and 220 kV UGC in DKW have already been reported [1], [2]. These incidents have provided valuable first-hand experience and highlighted the complexity of the harmonic amplification and propagation mechanisms in the meshed transmission grid with numerous harmonic emission sources [3], [4].

The significance of harmonic assessment and ability to predict and mitigate systemwide harmonic amplification by proper measures before the new transmission lines are energized and taken in operation are among the preconditions for successful green transition in Denmark. The PQ monitoring in the present transmission grid using the measurements and harmonic assessment by simulations on the projects yet to be commissioned are becoming part of the daily grid operation and grid planning of Energinet. The target is development, validation and application of the methods for the harmonic assessment by simulations with the following goals:

- Credible simulation methods identifying harmonic distortion in the meshed transmission grid with the new lines. The precondition is that the electro-geometrical data of the lines to be commissioned, the new grid topology and operation regimes are available from the project design phase.
- Identification and handling of modelling uncertainty and assigning proper numerical margins of the simulated harmonic distortion and mitigation needs.
- Proposal of mitigation solutions such as harmonic filters. For passive harmonic filters, the mitigation solution shall result in specification of the layout including the power rating, tuning frequency and quality factor, tolerances, grid-connection substation,

as well as the harmonic distortion spectra ready for handing over to the vendors for design and cost of the harmonic filter.

Energinet is at the beginning of the journey with development and application of such harmonic assessment methods [4]. Referring to the present development stage of the Danish transmission grid, the practical experience has been significant, systemwide, harmonic amplification can be seen in the 400 kV grid (and 220 kV export cables of OWPP) but not yet within the 150 kV grids [1-3]. In the years to come, such experience may change due to increasing UGC integration in the 150 kV grids. Increasing amount of the UGC increases the capacitance, *C*, and reduces the resonance frequency, *f*, of the grid, according to the equation $f = 1/(2\cdot\pi\cdot(L\cdot C)^{1/2})$, with *L* being inductance. Therefore, Energinet has initiated the work on numerical methods for the harmonic assessment of the 150 kV meshed grids with numerous distributed harmonic sources.

This paper presents the methods developed and applied by Energinet and shares the experience of the harmonic assessment conducted for the 150 kV meshed transmission grid area in Southwestern Jutland (in the DKW transmission system) where the existing OHLs are to be decommissioned and replaced with 150 kV 240 km UGCs. The paper discusses uncertainty arising from the model itself, gives interpretation of the simulation results for harmonic mitigation, and proposes further steps for application of the presented methods.

III. Kassø-Lykkegård Grid Reconstruction

The Kassø-Lykkegård grid reconstruction deals with replacement of the existing 150 kV OHL with 150 kV UGC in Southwestern Jutland and is illustrated in Fig. 2. The length of the new 150 kV UGC is approx. 240 km. The commissioning shall be completed by 2023.

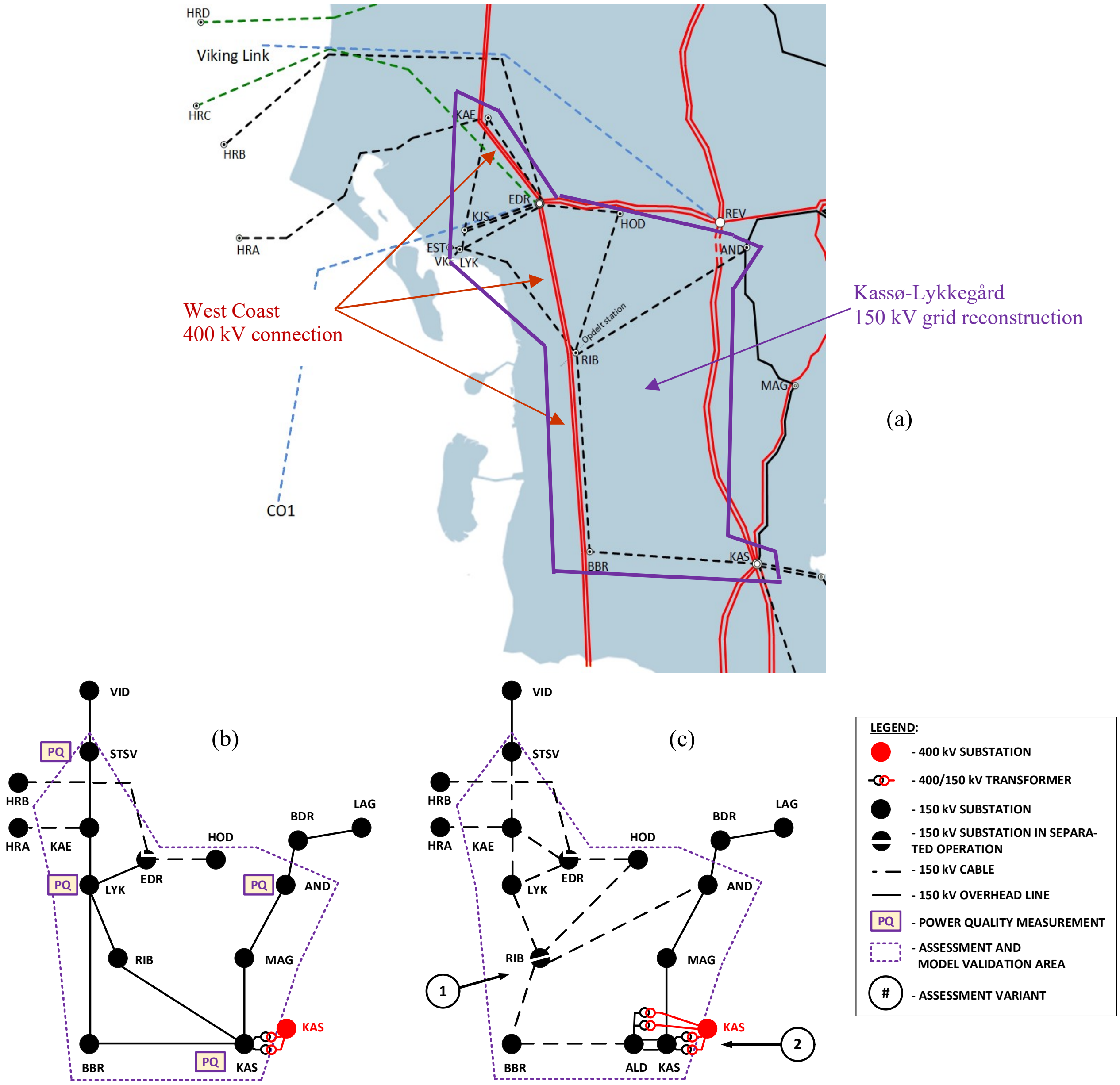

Fig. 2. The Kassø-Lykkegård grid reconstruction area in the transmission system of Western Denmark: (a) – reconstructed grid of Southwestern Jutland with solid magenta line marking the project area, (b) – the 2020/2021 grid development stage and (c) – the 2023 grid development stage after completed grid reconstruction with the UGC. The stipled magenta line marks the harmonic assessment area. PQ marks the 150 kV substations with the PQ measurements available at the time of the assessment.

At the time of the harmonic assessment in the 2020/2021, the 150 kV cable vendor has already been selected, the guaranteed cable data are received, and the reactive-power compensation solution is developed. However, there can be uncertainty of the reconstructed grid data because the impedances of the 150 kV UGC connections are not verified from the measurements (the grid is not yet commissioned).

At the same time, the new 150 kV substation ALD shall be established in vicinity of the existing 400 kV and 150 kV substations KAS. Normal operation implies that the 150 kV substation ALD is connected to the 400 kV substation KAS via the new 400/150 kV transformers. Alternatively, the connection from ALD to the 400 kV grid can be maintained using the short 150 kV UGC to the 150 kV substation KAS and via the existing 400/150 kV transformers to the 400 kV substation KAS.

The West Coast 400 kV connection between DKW and Germany including both OHL and UGC sections will be commissioned during 2023-2024. Reinforcement of the 400 kV transmission grid nearby the Kassø-Lykkegård grid reconstruction area, stronger coupling to the 400 kV system at the substation KAS, commissioning of the Viking Link VSC HVDC with connection in the 400 kV substation Revsing, as well as continuing integration of the converter-interfaced renewables, are among the factors increasing the short-circuit capacity within the 150 kV grid of Southwestern Jutland. As countermeasure, the reconstructed 150 kV substation RIB can be operated with separated sections during periods with excessive short-circuit capacity in this 150 kV grid area.

Therefore, the reconstructed grid topology includes the two major variants: (1) – the substation RIB with either separated or coupled sections, (2) – connectivity of the substation ALD to the 400 kV substation KAS. Both variants are included in the harmonic assessment.

The transmission system model of Western Denmark has also included the West Coast 400 kV connection for securing the long-term robustness of the harmonic assessment and the proposed mitigation solution for the Kassø-Lykkegård grid reconstruction.

IV. Applied Method of Harmonic Assessment

The simulations are harmonic load-flow applying the meshed transmission system model of Western Denmark. The simulation model represents the 400 kV and 150 kV transmission grids with harmonic source models of the LCC HVDC converter stations, OWPP and distributed harmonic emission sources under the 150 kV substations. For the 2020 grid development stage, the model section simulating the harmonic voltage distortion in the 400 kV meshed transmission grid has been validated using the PQ measurements [4].

The model sections representing the 150 kV meshed transmission grids shall have an accurate passive-part such as the electro-geometrical models of the OHL and UGC and electrical models of the 400/220 kV and 400/150 kV transformers. The distributed harmonic emission sources under the 150 kV substations are not explicitly described. Initially, these distributed sources apply generic-level models for simulating an accurate harmonic voltage distortion in the 400 kV substations [4]. Regarding the Kassø-Lykkegård 150 kV grid area, the models of the distributed harmonic emission sources shall be adjusted specifically for representing the harmonic distortion in the assessed 150 kV grid area.

The target of the model preparation is possibility of projecting of the harmonic voltage distortion in a future grid development stage using the present 2020/2021 grid as reference. With the reference grid denoted (n-0), the future grid of the harmonic assessment is either (n-P_1+P_2) meaning substitution of P_1 OHL with P_2 UGC or (n+P_3) meaning addition of new P_3 connections as OHL or UGC.

A. Model Development Principles

The basic model equation is:

$$\begin{bmatrix} U_{S1} \\ U_{S2} \\ \vdots \\ U_{SK} \end{bmatrix} = \begin{bmatrix} Z_{S1} & Z_{S1S2} & \cdots & Z_{S1SK} \\ Z_{S1S2} & Z_{S2} & \cdots & Z_{S2SK} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{S1SK} & Z_{S2SK} & \cdots & Z_{SK} \end{bmatrix} \cdot \begin{bmatrix} I_{S1} \\ I_{S2} \\ \vdots \\ I_{SK} \end{bmatrix}$$

where U_{Si} are the harmonic voltage vectors in the substation Si, I_{Si} are the harmonic current vectors injected in the substation Si, Z_{Si} are the diagonal elements of the harmonic impedance matrix referring to the substation Si, Z_{SiSj} are the nondiagonal elements of the harmonic impedance matrix, i.e. between the substations Si and Sj. The indexes i and j are in the range from 1 to K with K being the number of substations. The model equations as above are written for each harmonic order.

In the basic model equation, the harmonic current vectors represent the harmonic emission sources and the harmonic voltage vectors are the harmonic voltage distortion to be found from the simulations.

The harmonic voltage vectors, the harmonic current vectors and the elements of the harmonic impedance matrix are defined by their magnitudes and phase angles. The basic matrix equation can be split up into $2\cdot K$ algebraic equations. Assuming that the harmonic voltage magnitudes are in the present 2020/2021 grid stage known from the PQ measurements (as ten-minute values) and that the harmonic impedance matrix is defined for all diagonal and nondiagonal elements from the passive-part of the transmission grid model, the basic equations will have the harmonic voltage phase angles and the harmonic current vectors (both magnitudes and phase angles) as unknown variables. In this assumption, the number of unknown variables is greater than the number of algebraic equations. Further, the PQ measurements providing the harmonic voltage magnitudes in the present 2020/2021 grid stage are not necessarily available in all substations of the assessed grid area reducing the number of known variables in the algebraic equations.

Obviously, the basic model equation cannot be solved analytically. However, the harmonic current vectors can be found from the numerical adjustment. The adjustment shall result in that the simulations match the measured harmonic voltage magnitudes for different operation conditions such as (n-0) and (n-1). The model preparation process is illustrated in Fig. 3.

Inclusion of the different operation conditions enables the different harmonic impedance matrices, [Z_{SiSj}], representing the specific (n-0) and (n-1) conditions of the grid, which for the given harmonic current vector [I_{Sj}] shall reproduce the measured harmonic voltage vectors [U_{Si}]:

$$
\begin{aligned}
[U_{Si}]_{(\text{n-0})} &= [Z_{SiSj}]_{(\text{n-0})} &\cdot[I_{Sj}],\\
[U_{Si}]_{(\text{n-1}),1} &= [Z_{SiSj}]_{(\text{n-1}),1} &\cdot[I_{Sj}],\\
[U_{Si}]_{(\text{n-1}),2} &= [Z_{SiSj}]_{(\text{n-1}),2} &\cdot[I_{Sj}],\\
&\vdots\\
[U_{Si}]_{(\text{n-1}),\text{M}} &= [Z_{SiSj}]_{(\text{n-1}),\text{M}} &\cdot[I_{Sj}],
\end{aligned}
$$

with the index M being the number of the different (n-1) operation conditions of the assessed grid area. The harmonic current vectors are relative to the fundamental current vectors. The adjustment procedure serves the three purposes:

- Increase the number of equations for reducing the outcome space of possible numerical solutions of the harmonic current vectors.
- Define the relative harmonic current vectors, $[I_{Sj}]$, which are independent from and giving best-possible match of the measured harmonic voltage distortion for the different operation conditions of the passive-part, $[Z_{SiSj}]$.
- Increase probability of that the numerical solution of the relative harmonic current vectors, $[I_{Sj}]$, is robust to changes within the harmonic impedance matrix, because inclusion of the different (n-1) operation conditions corresponds to changes of the passive-part of the grid model.

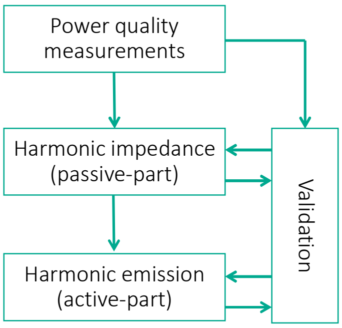

Fig. 3. Model preparation process for harmonic assessment.

After the numerical solutions of the relative harmonic current vectors are defined for the (n-0) and (n-1) operation conditions of the grid, the magnitudes and phase angles of the relative harmonic current vectors are locked. The harmonic assessment of the reconstructed grid may continue with the changed passive-part, such as representing new lines or UGC of the meshed grid, such as (n-0) → (n-1+1) or (n-0) → (n+1), and locked harmonic emission sources.

Attention is brought to that the method of the model preparation does not restrict to (n-1) operation conditions. The (n-L) operation conditions of the grid with L>1 may apply as well when such conditions are relevant and beneficial for better accuracy of the prepared simulation model.

B. *Power Quality Measurements*

The PQ measurements have been conducted during the three months of summer 2020. This period is chosen because the PQ measurements in a foreign system have also been available and time-synchronized with the measurements in the Danish substations. Availability of such foreign data has been useful for evaluation of the cross-border harmonic flow in the 2020/2021 grid model, especially because the Kassø-Lykkegård 150 kV grid area is bordering to the foreign transmission grid via the 400/150 kV substation KAS.

In this period, the PQ measurements have been available in the four 150 kV substations of the Danish transmission grid, which are denoted in Fig. 2(b) and located within or in vicinity of the Kassø-Lykkegård grid area: KAS, AND, LYK, and STSV.

C. *Passive Grid Model*

For the model preparation and numerical adjustment of the harmonic current vectors, the transmission grid model of the 2020/2021 grid development stage is applied. The Kassø-Lykkegård 150 kV grid area is illustrated in Fig. 2(b). The OHL and UGC are represented with the electro-geometrical data. The nominal-frequency impedances of the existing transmission lines are validated by measurements, which is a common procedure of Energinet.

For the harmonic assessment of the Kassø-Lykkegård 150 kV reconstructed grid, the OHL models are replaced with the UGC models using the guaranteed electro-geometrical data of the vendor and the connection lengths and reactive-power compensation of the 150 kV UGC grid available from the project design phase.

The topology of the reconstructed grid with possible grid operation variants is depicted in Fig. 2(c). By inspection of Fig. 2, the Kassø-Lykkegård grid reconstruction will not only result in replacement of the OHL with the UGC but also in changed connection routes between the 150 kV substations. Within the assessment area, the seven existing OHL connections shall be substituted with the nine new UGC connections, implying (n-0) → (n-7+9).

In terms of the basic model equation, the Kassø-Lykkegård grid reconstruction corresponds to a significant change of the harmonic impedance matrix, $[Z_{SiSj}]$. Therefore, definition and projection of the harmonic emission sources and interpretation of the harmonic assessment results shall be conducted with extra care.

D. *Operation Conditions*

The operation conditions of the 150 kV grid, such (n-0) and (n-1), have been available from the SCADA. During the period of the PQ measurements, the four 150 kV transmission lines have been out-of-service, one at a time. These four lines are depicted in Fig. 4.

The time instances of the line switching events, such as (n-0) → (n-1) and (n-1) → (n-0), have been synchronized with the time of the PQ measurements. The time synchronisation is extremely important for the model preparation because it shows which harmonic order, in which substation, and how much, reacts on which specific events in the meshed transmission grid.

E. *Numerical Tuning of Harmonic Emission Sources*

The measured 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonic voltage distortion has been with the magnitudes above the signal/noise threshold of 0.1% of the nominal-frequency voltage magnitude [5]. Therefore, the harmonic current vectors are primarily adjusted to match the PQ measurements of these four harmonic orders.

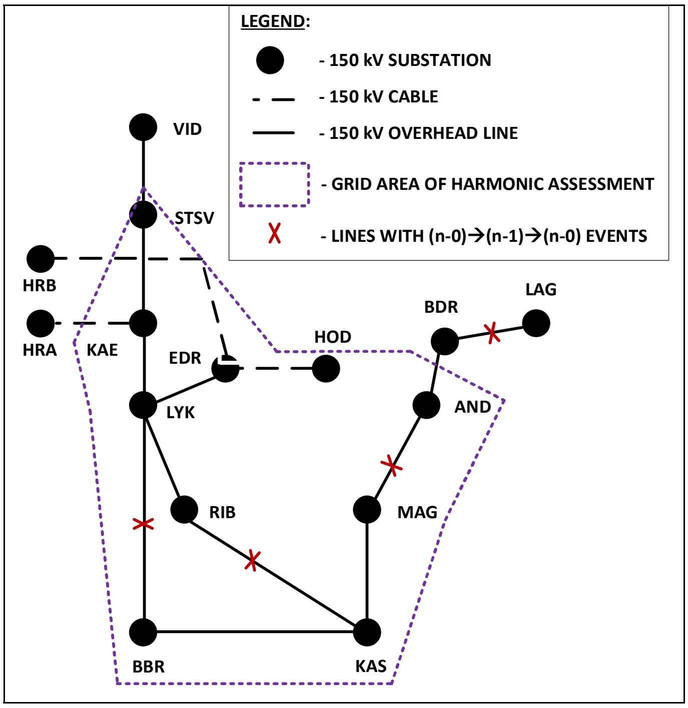

Fig. 4. Operation conditions with (n-1) events in the 150 kV grid, the 2020/2021 grid development stage. The events are registered one at a time.

The model is empirically developed based upon numerical tuning of the harmonic emission sources to fit in with the measured harmonic voltage distortion [4].

The numerical tuning has dealt with the two different phenomena of the measured harmonic voltage distortion:

- Levelling of the simulated harmonic voltage magnitudes within natural variation of the measured harmonic distortion over time.
- Step responses to the line switching events.

1) Natural variation over time: The measured harmonic voltage magnitudes are subject to daily and weekly variations. The natural variations over time relate to dynamic behaviour of the harmonic emission sources and dampening, such as varying PV and wind power generation and consumption. For the presented harmonic assessment, such natural variations are not initiated by the (n-0) → (n-1) or (n-1) → (n-0) line switching events within the Kassø-Lykkegård 150 kV grid area.

The harmonic load-flow is a static method and uses stationary representations of the harmonic emission sources. Thus, the dynamic variations over time are not explicitly included in the simulation model.

Instead, the variations are represented by stationary means using the 5th and 95th weekly percentiles of the measured harmonic voltage magnitudes as the low and high ranges of the harmonic distortion. The ranges are defined for each of the four above-listed harmonic orders for each substation. Application of the 5th and 95th weekly percentiles shall exclude the extremely low and extremely high rarely occurring distortion. The simulation model includes the two parameter sets of the harmonic current sources:

- Normal case.
- Simultaneous worst case.

In the normal case, the simulated harmonic voltage magnitudes shall be within the range from the 5th to 95th weekly percentiles of the measured harmonic distortion. Though the line switching events do not contribute to natural variation, such events may cause steps of the measured harmonic voltage distortion and be implicitly included in the 95th weekly percentiles of the harmonic distortion. Fig. 5 compares the simulated harmonic voltage magnitudes of the normal case to the maximum of the (measured) 95th weekly percentiles over the period of the PQ measurements. The measured 95th weekly percentiles are shown by red shaded background plots.

Because the harmonic assessment shall result in clarification and, if deemed needed, proposal of a mitigation solution, the simulated harmonic voltage magnitudes of the normal case are wished to be closer to the 95th weekly percentiles than to the 5th weekly percentiles of the measured harmonic voltage distortion. This wished condition is, however, difficult to fulfil in the normal case because the maximum harmonic voltage magnitudes do not necessarily occur simultaneously in all four 150 kV substations.

In the simultaneous worst case, the simulated harmonic voltage magnitudes of all four harmonic orders in all substations with the available PQ measurements shall reach the 95th weekly percentiles at the same time.

Fig. 6 compares the simulated harmonic voltage magnitudes of the simultaneous worst case to the maximum of the (measured) 95th weekly percentiles over the period of the PQ measurements. For the normal-case representation of the harmonic emission sources, the comparison shows a good agreement of the simulated 5th and 7th harmonic voltages to the measured 95th weekly percentiles. For the simultaneous worst-case modelling, the comparison shows a good agreement of the simulated 5th, 7th, 11th and 13th harmonic voltages to the measured 95th weekly percentiles. The concluded good agreement to the measurements in the present 2020/2021 grid is a proper start for projection of the harmonic emission sources for the harmonic assessment of the grid reconstruction project by 2023.

The analysis of the PQ measurements has shown that the maximum magnitudes of the measured 11th and 13th harmonic voltage distortion can be present simultaneously in the four 150 kV substations. However, the maximum magnitudes of the 5th and 7th harmonic voltage distortion are only rarely seen in all four substations at the same time. The observations on simultaneity of the measured harmonic orders through the 150 kV substations suggest that the normal case is representative for evaluation of the 5th and 7th harmonic orders, while the simultaneous worst case is for the 11th and 13th harmonic orders, in the assessed 150 kV grid area. The other contributions in the range from the 2nd to the 50th harmonic orders are also represented in the model using the harmonic current sources with small magnitudes and 0 deg. phase angles relatively to the nominal-frequency current angles.

2) Step responses: The measured harmonic voltage magnitudes may have a step due to an (n-0) → (n-1) or (n-1) → (n-0) line switching event in the meshed transmission grid. The measured harmonic voltages may remain stationary magnitudes during the step, which is why such step responses to the line switching events shall be part of the model preparation.

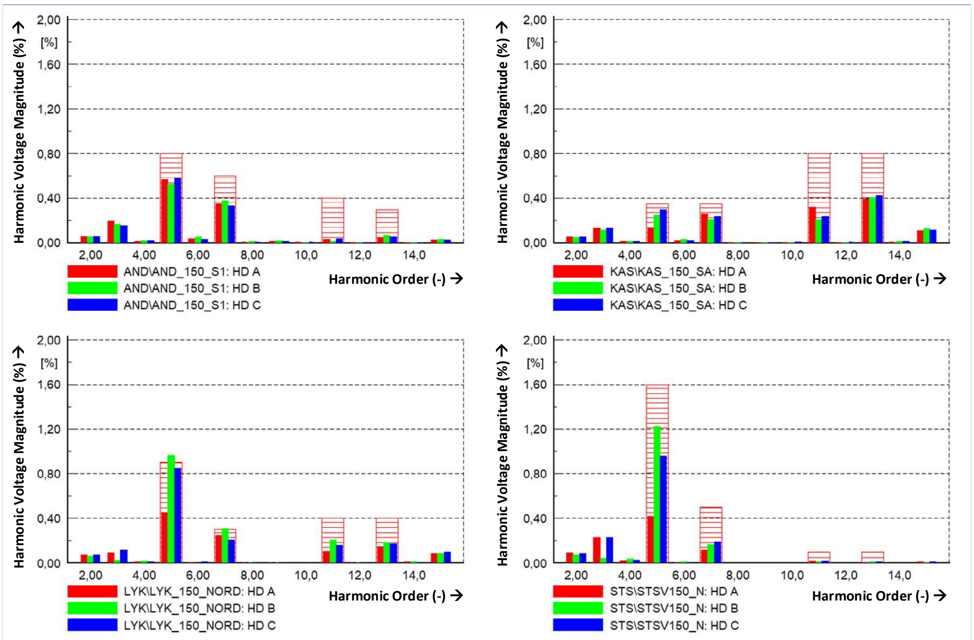

Fig. 5. Normal case. Comparison of the simulated harmonic voltage magnitudes to the maximum (measured) 95^{th} weekly percentiles in the four 150 kV substations with available PQ measurements: AND, KAS, LYK, and STSV. depicts the 95^{th} weekly percentiles. The simulation is for (n-0) grid.

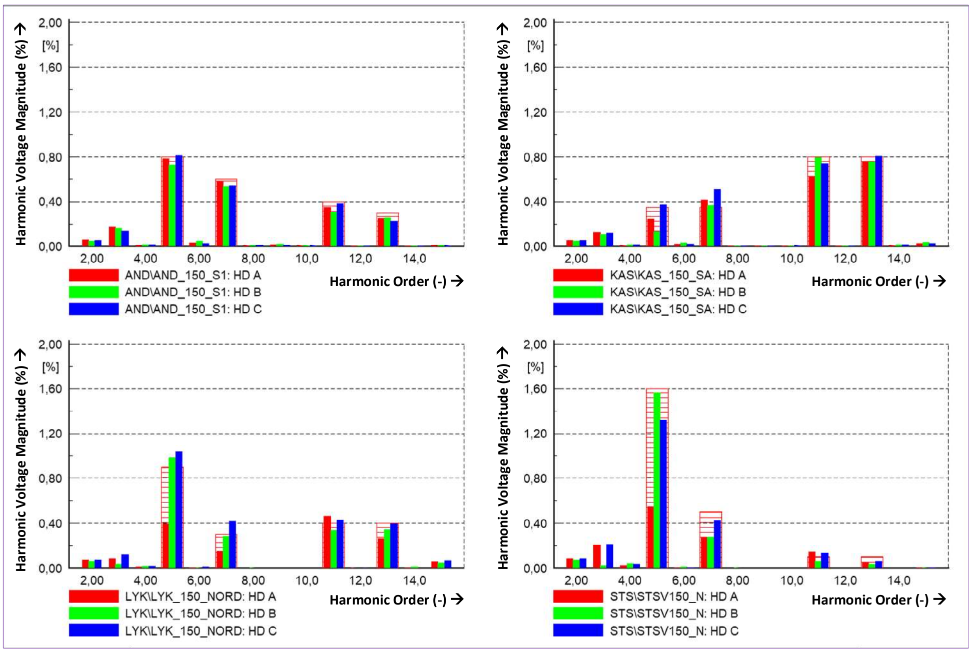

Fig. 6. Simultaneous worst case. Comparison of the simulated harmonic voltage magnitudes to the maximum (measured) 95^{th} weekly percentiles in the four 150 kV substations with available PQ measurements: AND, KAS, LYK, and STSV. depicts the 95^{th} weekly percentiles. The simulation is for (n-0) grid.

Attention shall be paid to that some, and not all, harmonic orders in some, and not all, substations will have such steps of the measured harmonic voltage magnitudes to a specific line switching event, while the remaining harmonic orders are unaffected by the switching event. This behaviour is important for positioning of the harmonic current vectors under the 150 kV substations respectively to each other and so for numerical adjustment of the harmonic emission sources in the simulation model.

In this presentation, the steps of the harmonic voltage distortion are shown for the substations AND and KAS as response to the AND-MAG line switching events, see the locations of the substations and the switched line in Fig. 4.

Fig. 7(a-d) and Fig. 8(a-d) show the measured harmonic voltages in the substations AND and KAS, respectively, as response to the AND-MAG line switching events.

In the substation AND, the measured 5^{th} harmonic voltage is increased by 50% to 80%, and the 7^{th} harmonic voltage is increased by 10% to 20%, when the AND-MAG line is disconnected, in comparison to the harmonic voltage magnitudes in the grid with the (re-)connected line. The measured 11^{th} and 13^{th} harmonic voltages in AND, and the measured harmonic voltages in KAS, do not change as response to the AND-MAG line switching events.

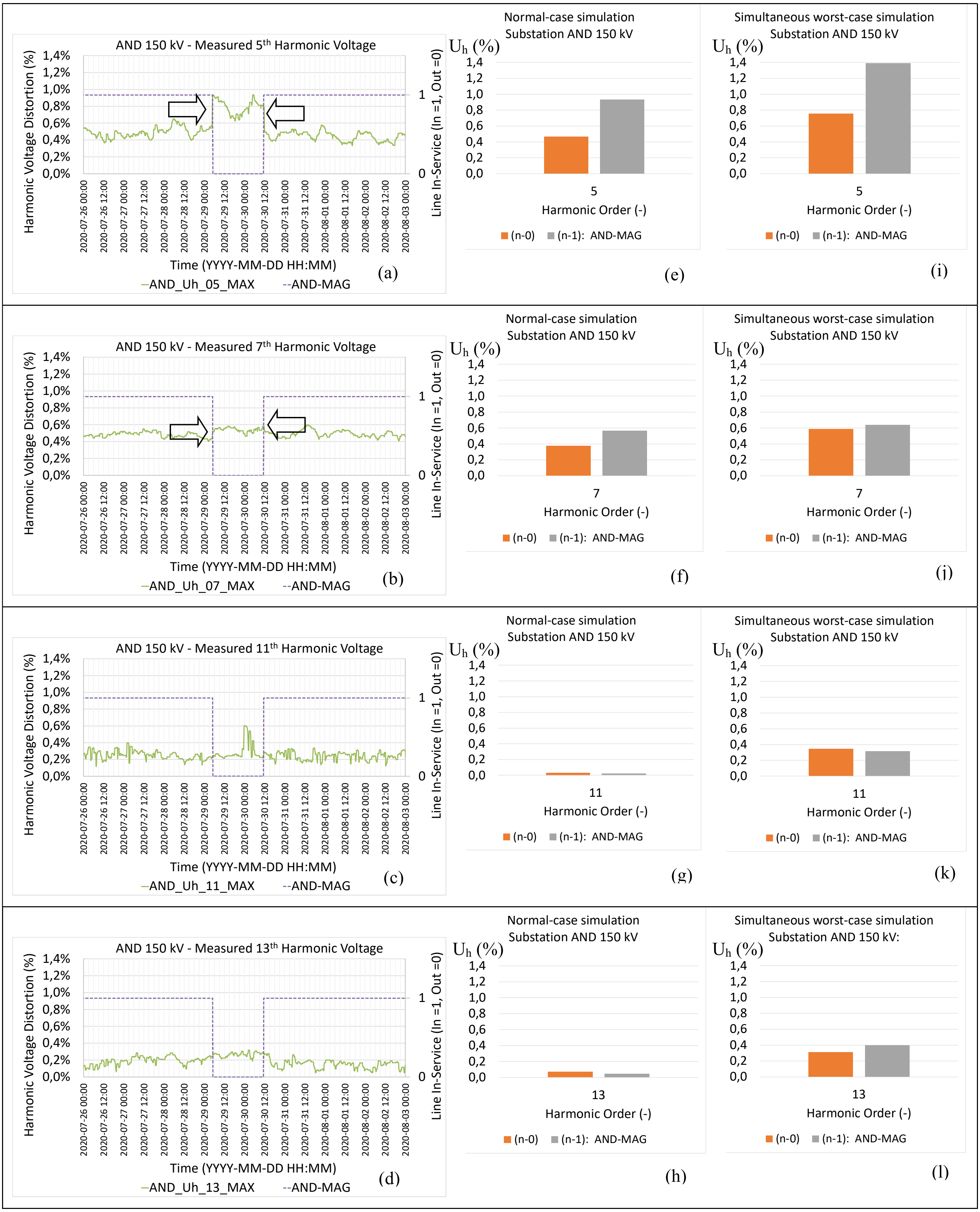

Fig. 7. Harmonic voltage distortion in the substation AND as response to the AND-MAG line switching event: (a), (b), (c), (d) – measured, (e), (f), (g), (h) – simulated normal case, and (i), (j), (k), (l) – simulated simultaneous worst case. The measurements and simulations are shown as the maximum magnitudes of the three phases of the harmonic voltage. The arrows mark steps of the harmonic voltage magnitudes.

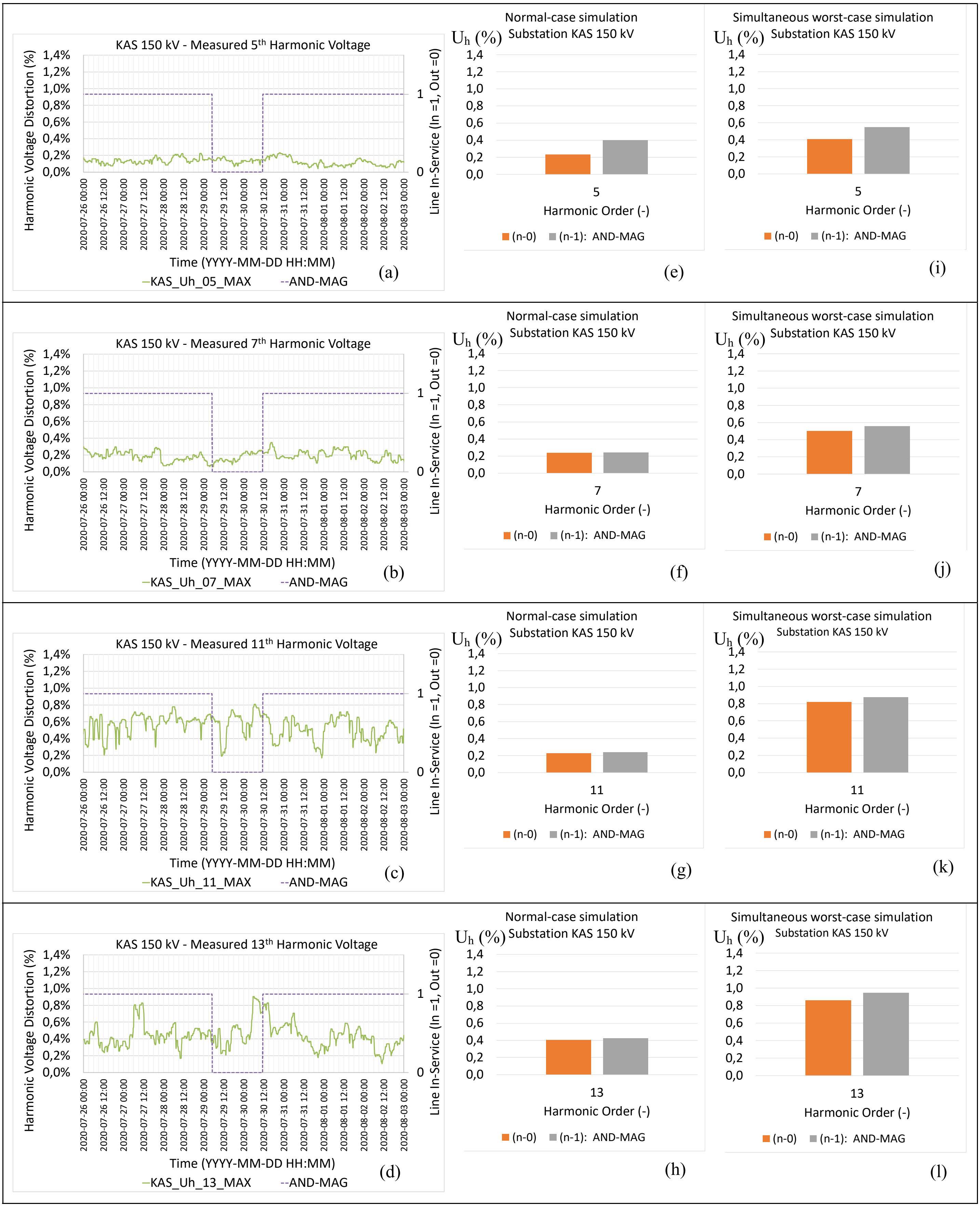

Fig. 8. Harmonic voltage distortion in the substation KAS as response to the AND-MAG line switching event: (a), (b), (c), (d) – measured, (e), (f), (g), (h) – simulated normal case, and (i), (j), (k), (l) – simulated simultaneous worst case. The measurements and simulations are shown as the maximum magnitudes of the three phases of the harmonic voltage. The arrows mark steps of the harmonic voltage magnitudes.

Now, the step responses of the measured and simulated harmonic voltages are compared to each other.

Fig. 7(e-h) and Fig. 7(i-l) show the simulated magnitudes of the 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonic voltages in AND for the (n-0) and (n-1) grid operation with the AND-MAG line out-of-service, for the normal-case and the simultaneous worst-case modelling, respectively.

Fig. 8(e-h) and Fig. 8(i-l) show the simulated magnitudes of the same harmonic order voltages in KAS for the (n-0) and (n-1) with the AND-MAG line out-of-service, for the normal-case and the simultaneous worst-case modelling, respectively.

For the substation AND, the simulated 5^{th} harmonic voltage magnitude increases with up to 95% and the simulated 7^{th} harmonic voltage magnitude with up to 30% for the (n-1) operation condition in comparison to the (n-0) condition. The simulation predicts accurate tendency but may overestimate the magnitude of the step response of these two harmonic orders to the shown line switching event.

The simulated 5^{th} harmonic voltage in KAS shows also an up to 30% increase comparing to no such step in the measured response. However, the absolute magnitude of the 5^{th} harmonic voltage in KAS is small for both (n-0) and (n-1), meaning comparison of two small numbers. If the assessment of the reconstructed grid does not show significant increase of the 5^{th} harmonic voltage in KAS, such discrepancy between the two small numbers in the reference model can be accepted.

The simulated 7^{th} harmonic voltage in KAS, and the simulated 11^{th} and 13^{th} harmonic voltages both in KAS and AND show small changes for the assessed line switching event. Such minor discrepancy of the model can be acceptable for the purpose of the assessment and pronounced in agreement with the measurements.

The line switching events represent changes of the harmonic impedance of the meshed transmission grid. The analysis of the step responses of the harmonic voltage distortion to the line switching events show that the simulation model and the harmonic emission sources are suitable for the harmonic assessment with changes of the harmonic impedance of the grid.

F. *Methods for determining future harmonic distortion*

The harmonic assessment of the Kassø-Lykkegård 150 kV grid reconstruction begins with the simulation model preparation which is sufficient and accurate of matching the measured harmonic voltage distortion in the present 2020/2021 grid. As the harmonic assessment shall result in recommendation on whether, which type and in which substation a mitigation solution can be needed, the projection of the 95^{th} weekly percentiles of the harmonic voltage distortion from the present 2020/2021 grid to the reconstructed future grid is essential.

In the present stage grid, the normal case simulations may underestimate the harmonic voltage distortion in comparison to the (measured) maximum values of the 95^{th} weekly percentiles. The differences between the measured 95^{th} weekly percentiles, a, and the simulated harmonic voltage magnitudes, b_{NC}, are the modelling margins, $(a-b_{NC})$.

The modelling margins, $(a-b_{NC})$, are defined separately for each harmonic order and each substation. For the substations with the available PQ measurements, the modelling margins are directly defined from comparison to the measurements. For the substations without the PQ measurements, the modelling margins are defined by linear interpolation of the margins of the neighbouring substations with such measurements. For example, the modelling margins of the substation BBR are defined by linear interpolation of the margins of KAS and LYK. Similar interpolation applies for the “measured” distortion for the substations without such measurements.

In the present stage grid, the simulated harmonic voltage magnitudes of the simultaneous worst case, b_{WC}, are matching the (measured) maximum values of the 95^{th} weekly percentiles, a. The modelling margins are zeros, $(a-b_{WC}) = 0$.

Utilizing both PQ measurements and harmonic load-flow simulations for the present and the reconstructed grids, this harmonic assessment has proposed and applied the three methods of determining the harmonic voltage distortion in the reconstructed (future) grid. The three methods are graphically illustrated in Fig. 9.

The first two methods work with the normal-case of the harmonic emission sources:

- The first method is arithmetical summation of the modelling margins, $(a-b_{NC})$, and the simulated distortion in the reconstructed grid, c_{NC}, giving the harmonic distortion in the reconstructed grid: $d_1 = c_{NC} + (a-b_{NC})$.
- The second method applies multiplication factors using the present grid as reference of the reconstructed grid. The harmonic distortion in the reconstructed grid is: $d_2 = (c_{NC}/b_{NC}) \cdot a$, with the gain-factor, (c_{NC}/b_{NC}).

These two methods shall result in conservative but realistic values of the simulated harmonic voltage distortion in the reconstructed grid.

The third method utilizes the simultaneous worst case of the harmonic emission sources:

- The third method is direct simulation and shall produce highest values of the simulated harmonic voltage distortion. The harmonic distortion in the reconstructed grid, d_3, is $d_3 = c_{WC}$, with c_{WC} being the simulated harmonic distortion of the the simultaneous worst case:

When both normal-case and worst-case methods show excessive harmonic distortion in the simulations, there is a risk of such in the physical reconstructed grid.

Simultaneous application of the three methods shall reduce uncertainty of the modelling and minimize a risk of miscalculation, when the 150 kV grid is reconstructed.

G. *Understanding Risks from Simulation Model*

The risks arising from the simulation model relate to:

- Passive-part such as the harmonic impedance of not yet established components as well as data tolerances of the existing components.

- Active-part such as empirically developed models of the harmonic emission sources.
- Method and evaluation of the results.

For the passive-part, the harmonic assessment is conducted for the grid development stage which is not yet established and applying the new connection data which are yet to be validated by the measurements. Though the applied electro-geometrical data are guaranteed by the vendor and the connection length and location in the grid are acquired from the project design phase, there is still uncertainty of such data.

The uncertainty will exist until the connection is commissioned and the impedance is validated from the measurements. For the grid reconstruction, this uncertainty can be higher than for a single new connection because the grid reconstruction includes several new connections replacing a large part of the meshed transmission grid.

The risk can be reduced by benchmarking the data of the new connections to the measurement-validated data of the already existing similar connections in other parts of the grid.

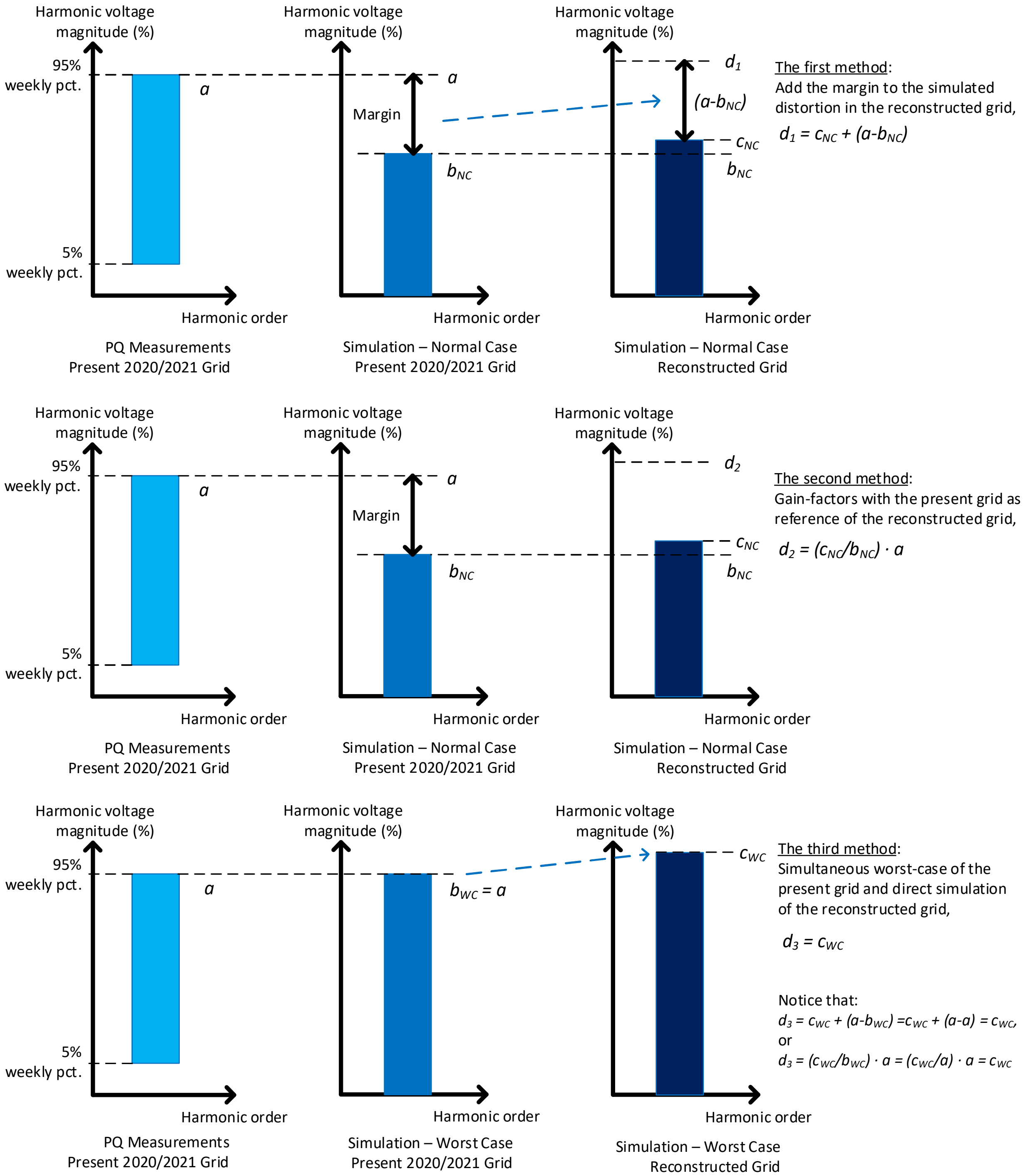

Fig. 9. Illustrations of the three methods for determining the simulated harmonic voltage distortion in the reconstructed grid: (a) – the first arithmetical method, (b) – the second gain-factor method, (c) – the third direct method.

The harmonic emission sources are the active-part and tuned until best-possible match of the available PQ measurements in the present grid. Often the distributed harmonic emission sources are not explicitly defined as ready for inclusion in the simulation model. Therefore, both magnitudes and phase angles of the harmonic emission sources are numerically adjusted. The numerical adjustment of the sources is simultaneously conducted in several substations. The PQ measurements are not available in all substations of the assessed grid area, which further emphasizes the the numerical tuning challenge. Discrepancy within numerical tuning of the harmonic emission sources may introduce the largest risk of the simulation model.

The risk is reduced, but not fully mitigated, by adjustment of the harmonic emission source models to match as many operation conditions as possible in the present grid. The different (n-L), $L \geq 0$, conditions correspond to the different harmonic impedance matrices of the assessed grid area, [Z_{SiSj}]. By matching the measured harmonic voltage magnitudes in as many (n-L) operation conditions as possible, the robustness and reliability of the numerical models of the harmonic emission sources to changes of the passive-part, [Z_{SiSj}], will improve.

The risk can also arise from the methods applied for postprocessing and evaluation of the simulation results. For example, the second method, using the gain-factors c_{NC}/b_{NC}, will fail if directly applied for small magnitudes of b_{NC}. The method will fail because division by a small number may produce unrealistic outcome.

The risk of the result misinterpretation can be reduced by assigning $c_{NC}/b_{NC} = 1$ when b_{NC} is small. In this assessment, the gain-factors are assigned $c_{NC}/b_{NC} = 1$ with $b_{NC} < 0.2\%$. The range of $b_{NC} > 0.2\%$ is at least twice above the signal/noise threshold suggested in [5] and shall be sufficient for evaluation of the gain-factors as c_{NC}/b_{NC} though small b_{NC} values.

At present, all three methods are applied for evaluation of the simulation results of the reconstructed grid as well as the evaluation includes the measurements in the present grid stage and modelling margins besides performing the simulations. The model development procedure and the evaluation methods are newly developed in-house and will be evaluated at the first given opportunity, which arises after completion of the Kassø-Lykkegård 150 kV grid reconstruction due 2023.

V. Results of Harmonic Load-Flow Assessment

The harmonic assessment uses the simulation model of Western Denmark, which includes the 400 kV and 150 kV meshed transmission grids. The Kassø-Lykkegård 150 kV grid reconstruction and the West Coast 400 kV connection are included in the simulation model.

Thus, the assessed grid development stage is 2023/2024 and the reference grid is 2020/2021.

Fig. 10 shows the harmonic voltage magnitudes in the 150 kV substations KAS, AND, and LYK, evaluated for several operation conditions included in the harmonic assessment. Each operation condition is shown by the three sub-columns accordingly to the three evaluation methods of Section IV-F.

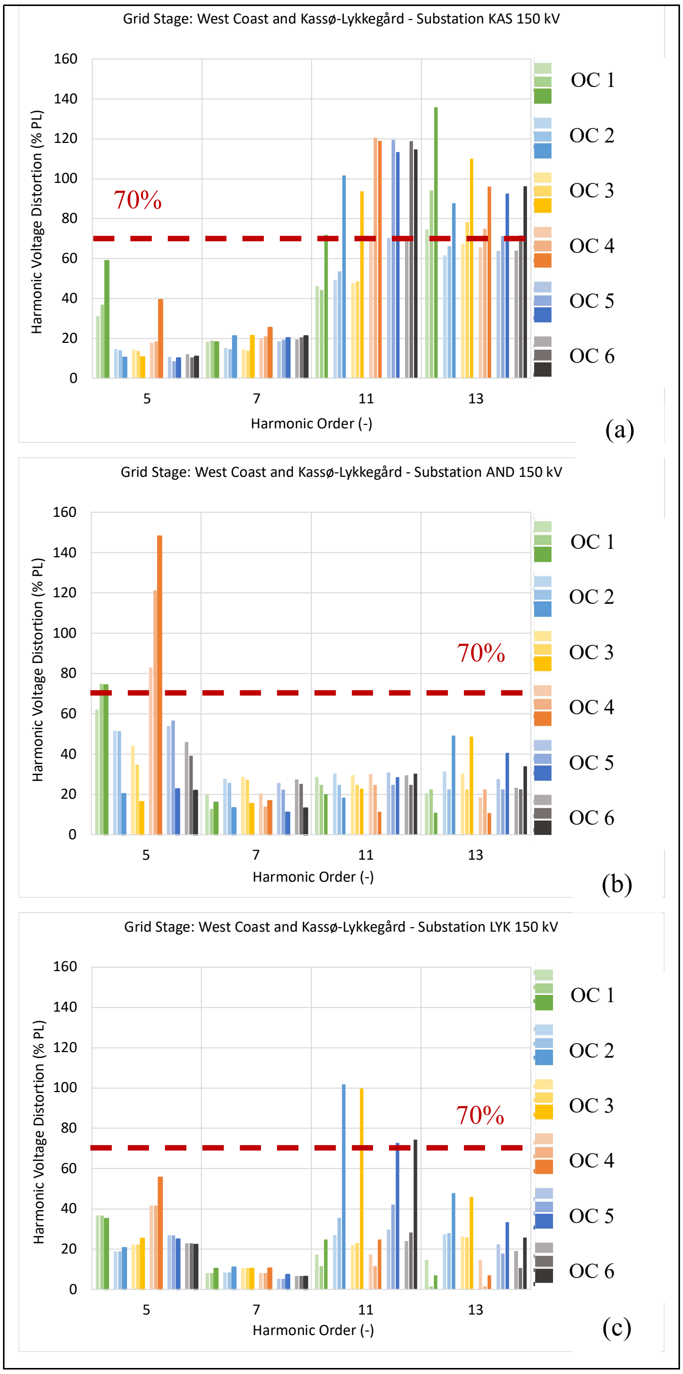

Fig. 10. Harmonic voltage magnitudes in the substations (a) – KAS, (b) – AND, and (c) – LYK, of the 150 kV reconstructed grid. Depicted operation conditions:

OC 1 - ALD connected to 150 kV substation KAS via 150 kV UGC, RIB with separated substation sections;

OC 2 - ALD connected to 150 kV substation KAS via 150 kV UGC, RIB with coupled substation sections;

OC 3 - ALD connected to 150 kV substation KAS via 150 kV UGC, RIB with coupled substation sections, and 400/150 kV transformer in EDR disconnected;

OC 4 - ALD connected to 400 kV substation KAS via 400/150 kV transformers, RIB with separated substation sections;

OC 5 - ALD connected to 400 kV substation KAS via 400/150 kV transformers, RIB with coupled substation sections;

OC 6 - ALD connected to 400 kV substation KAS via 400/150 kV transformers, RIB with coupled substation sections, and 400/150 kV transformer in EDR disconnected.

Energinet applies the IEC planning levels of the harmonic voltage distortion [5]. The plotted magnitudes are in % of the IEC planning levels, with 100% being the IEC planning levels. Recognizing the uncertainty arising from the simulation model, the 70% threshold of the IEC planning levels is the value which crossing shall define excessive harmonic voltage distortion in the 150 kV reconstructed grid. Furthermore, noticeable increase of the simulated harmonic voltage magnitudes in the reconstructed grid in comparison to the reference, such as with the ratios above 2, is also used as an indication of possible harmonic amplification, though remaining under 70% of the IEC planning levels.

An overview of the harmonic voltage distortion on the stylistic map of the Kassø-Lykkegård 150 kV grid area is shown in Fig. 11.

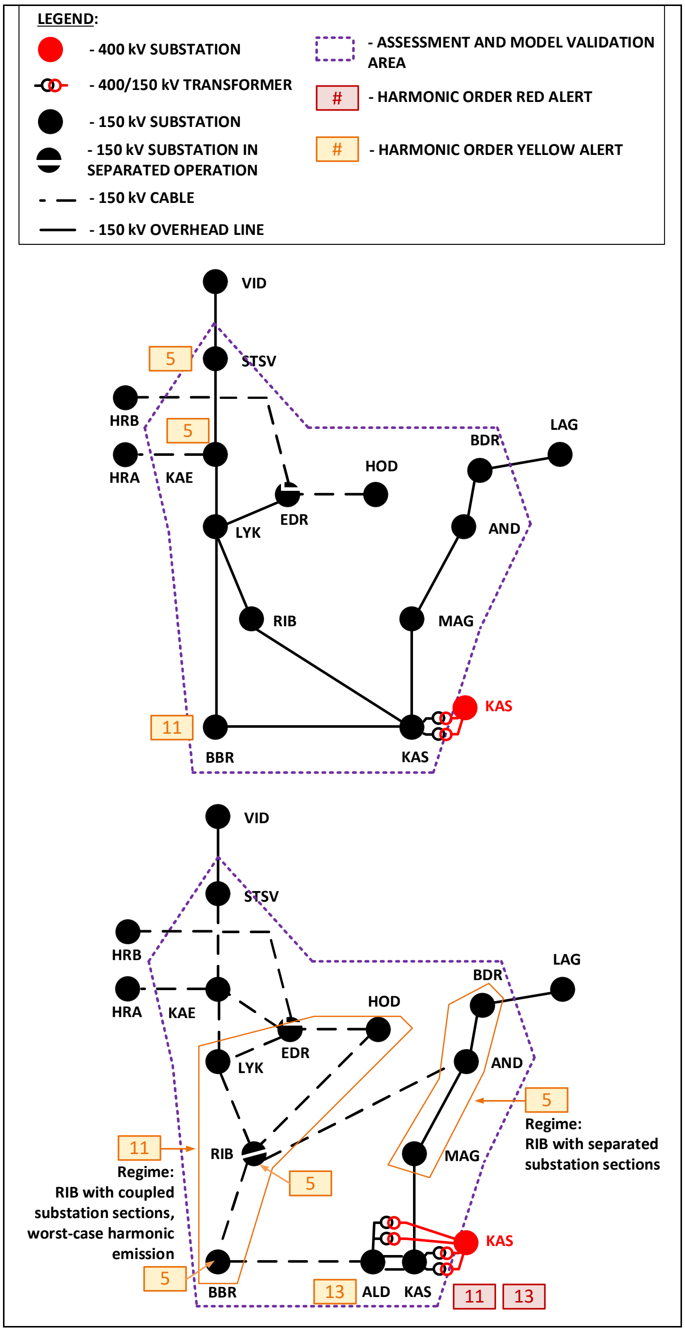

Fig. 11. Harmonic voltage distortion in the Kassø-Lykkegård 150 kV grid area with indication of yellow and red alerts: (a) – present 2020/2021 grid and (b) – reconstructed grid.

The results of the evaluated harmonic voltage distortion are presented accordingly:

No alert: When all three evaluation methods in all operation conditions show that the harmonic voltage distortion remains below 70% of the IEC planning level, there is no risk of excessive harmonic voltage distortion in the reconstructed grid.

Yellow alert: When only a single method or a single operation condition results in the harmonic voltage distortion above 70% of the IEC planning level, there is a risk of periods with excessive harmonic voltage distortion. Needs of mitigation will depend on how often such operation conditions can be present in the grid by experience from the present grid or planning of the operation regimes and how large section of the reconstructed grid is affected.

Red alert: When all three methods and in most operation conditions show that the harmonic voltage distortion above 70% of the IEC planning level, there is clear indication of excessive harmonic voltage distortion. An adequate mitigation solution shall be proposed and evaluated by simulations.

Referring to Fig. 10, the 150 kV substation KAS is clearly red alerted for the 11th and 13th harmonic voltage distortion. When compared to the present 2020/2021 grid, with the measured 95th weekly percentiles shown in Fig. 5 and Fig. 6, the 11th and 13th harmonic voltages in KAS will be amplified due to the 150 kV grid reconstruction substituting the OHL with the UGC. The 150 kV substations AND and LYK are both yellow alert for the 5th harmonic voltage and for the 11th harmonic voltage, respectively.

Fig. 11 shows that in the present 2020/2021 grid stage there are already substations with high harmonic voltage distortion which can be classified as yellow alert:

- The 5th harmonic voltage in STSV (measured) and KAE (interpolated from neighbouring measurements) approaching the planning levels and
- The 11th harmonic voltage in BBR (interpolated from neighbouring measurements).

In the reconstructed grid, the harmonic distortion will amplify showing the pattern as in Fig. 11:

- The 11th and 13th harmonic voltages in KAS become red alert and the 13th harmonic voltage in ALD is yellow alert.
- The 5th harmonic voltage in AND, BDR, MAG and RIB is yellow alert for the separated operation of the reconstructed substation RIB.
- The 11th harmonic voltage in BBR, EDR, HOD, LYK and RIB for the coupled operation of the substation RIB.

The 11th and 13th harmonic voltage distortion in KAS may violate the applied 70% threshold of the IEC planning levels in the most operation conditions of the reconstructed grid. Therefore, the mitigation for the substation KAS shall be proposed.

Considering further grid development, two more approved projects to be commissioned by 2024 are included in the harmonic assessment as grid variants:

- Grid connection of Thor OWPP to the 400 kV substation Idomlund using 220 kV cables and 400/220 kV transformers.
- Årslev Engsø connection, which is a 5 km 400 kV UGC replacing a section of the OHL in proximity of the 400 kV substation Trige.

These two projects have not changed the outcome of the harmonic assessment for the Kassø-Lykkegård 150 kV grid reconstruction and are not elaborated in this presentation.

VI. MITIGATION

The harmonic assessment has resulted in proposing a new passive harmonic filter to be established in the 150 kV substation KAS. The main target of the harmonic filter is dampening of the 11^{th} and 13^{th} harmonic voltage distortion within the Kassø-Lykkegård grid area without introducing adverse effects on the other harmonic orders.

Other substations within the Kassø-Lykkegård grid area have also been assessed for establishment of the harmonic filter, but the efficiency of the harmonic distortion mitigation is found poorer than in KAS.

A. Applied Method

The applied method is the harmonic load-flow using the simulation model of Western Denmark including the 400 kV and 150 kV meshed transmission grid. Representations of the West Coast 400 kV connection and the Kassø-Lykkegård 150 kV reconstructed grid are included in the model.

B. Filter Design Study

The three filter types are evaluated:

- The high-pass 2^{nd} order filter,
- The C-type filter,
- The double-tuned filter.

Fig. 12 shows the single-line diagrams of the evaluated harmonic filter types.

The design study shall identify the type and parameters of the harmonic filter for best-possible dampening of the 11^{th} and 13^{th} harmonic voltage distortion at the lowest possible energy losses and capital expenditure. This target can be reached with either one of the damped filter types: high-pass 2^{nd} order filter or C-type filter.

The double-tuned filter is included for possibility of dampening the 11^{th} and 13^{th} harmonic voltages as well as the 5^{th} harmonic voltage in the operation conditions of the substation RIB with separated substation sections.

Since the design study is conducted for the meshed transmission grid, the simulated harmonic voltage distortion in several substations of this meshed grid is monitored. The design process is illustrated in Fig. 13.

The process starts from an initial design, which for the damped harmonic filter types implies the 12^{th} harmonic order and the quality factor of 2. For the double-tuned filter type, the 5^{th} and 12^{th} harmonic orders and the same quality factor are used as an initial design.

The harmonic order multiplied by the nominal frequency of 50 Hz (in Europe) gives the tuning frequency of the harmonic filter.

During the tuning process, both harmonic order and quality factor are adjusted within the simulation loops of the harmonic load-flows. The harmonic load-flows simulate the harmonic voltage distortion in the meshed transmission grid.

When the adjustments of the harmonic order and quality factor do not further reduce the harmonic voltage distortion, the rating of the harmonic filter is stepped up and the adjustment process is continued.

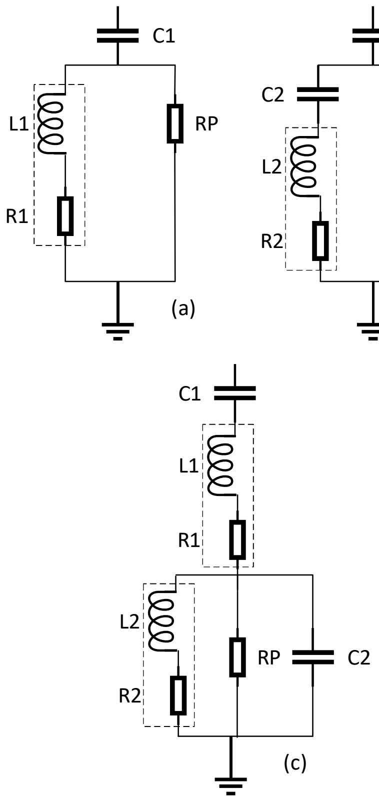

Fig. 12. Harmonic filter types: (a) – high-pass 2^{nd} order filter (b) – C-type filter, and (c) – double-tuned filter.

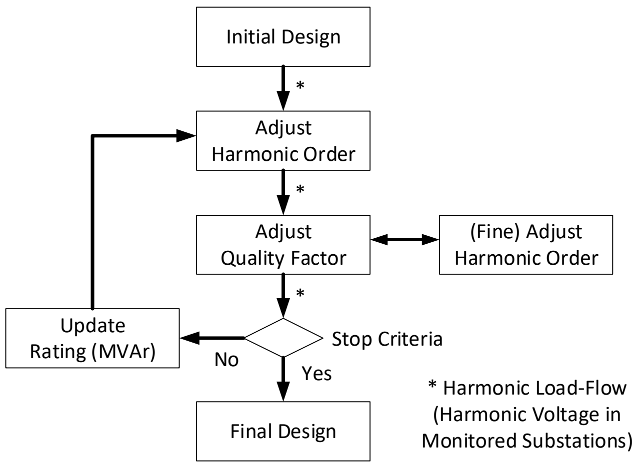

Fig. 13. Process of the harmonic filter design for the meshed transmission grid.

The tuning process continues until the stop criteria are fulfilled. Ideally, the tuning process shall stop when the harmonic voltage distortion across the entire assessed grid area becomes well dampened. Such ideal outcome is difficult to achieve in the meshed grid because the passive harmonic filter itself may change the harmonic impedance of the grid and displace the harmonic resonances through several substations.

In this design study, the tuning process of the damped filter types has stopped for the 50 MVAr rating with the tuned harmonic order of 10.8 and the quality factor of 4.1, due to the following reasons:

- The 11th and 13th harmonic voltages in KAS are suppressed well below the threshold value of 70% of the IEC planning levels.
- The 13th harmonic voltage in ALD and the 5th harmonic voltages in AND, MAG and KAS started to increase.
- Decaying improvement of the 11th and 13th harmonic voltages in KAS at continuing adjustment loops.

The tuning process of the double-tuned filter has stopped as the quality factor was becoming too large at stagnating dampening the 5th harmonic voltages in the substations AND and MAG. At the same time, the 5th harmonic voltage in KAS was slowly increasing. The tuning process has reached to the design with the harmonic orders of 5.4 and 11.5, and the quality factor of 17.5.

Fig. 14 presents the harmonic impedance sweeps of the three assessed filter types.

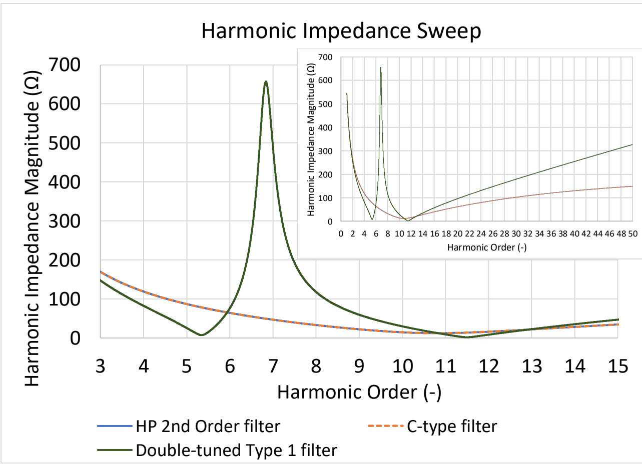

Fig. 14. Harmonic impedance sweeps of the three assessed filter types.

The harmonic impedance sweeps of the two damped filter types are almost identical. These two filter types will be almost equally efficient for dampening of the 11th and 13th harmonic voltage distortion in the 150 kV grid.

The double-tuned filter has a resonance close to the 7th harmonic order. The harmonic assessment has not shown excessive magnitudes of the 7th harmonic voltage distortion in the 150 kV grid. The reason is that there are yet no such background distortion to be amplified in the present grid and the models of the harmonic emission sources are derived from the PQ measurements in the present grid. However, this filter design would introduce a potential amplification risk of the 7th harmonic voltage distortion when such background distortion becomes present in a future grid stage. Considering this potential risk, the double-tuned filter type is excluded from future consideration.

Considering the capitalized energy losses, the difference between the high-pass 2nd order filter and the C-type filter is small in comparison to the total capital expenditure. Since the capitalized energy losses are not among the factors of which filter type to choose and since the high-pass 2nd order filter uses one less capacitor than the C-type filter, the high-pass 2nd order filter type is proposed for commissioning.

C. *Performance and Detuning Studies*

The performance and detuning studies are combined into the same study because the filter design shall remain robust and efficient at detuning due to specified component tolerances. Besides the robustness check, the combined performance and detuning study shall produce the harmonic distortion spectra at the filter terminals in the grid-connection substation. This harmonic distortion spectra will be needed for definition of the filter component ratings and the sound power requirements which shall be handed over to the vendor. Therefore, the combined performance and detuning study is conducted as the harmonic load-flow.

Publicly available component tolerances, which includes both manufacturing and operational tolerances, can be found in [6]. Specifically, tolerances to temperature variations are among the operational tolerances of the capacitors to be determined and included in the detuning assessment. Both publicly available data, which are recommended for the filter design assessment [6], and the component tolerances acquired from previous projects are applied for the combined performance and detuning study.

Fig. 15 illustrates the results of the combined performance and detuning study using the stylistic map of the Kassø-Lykkegård 150 kV reconstructed grid.

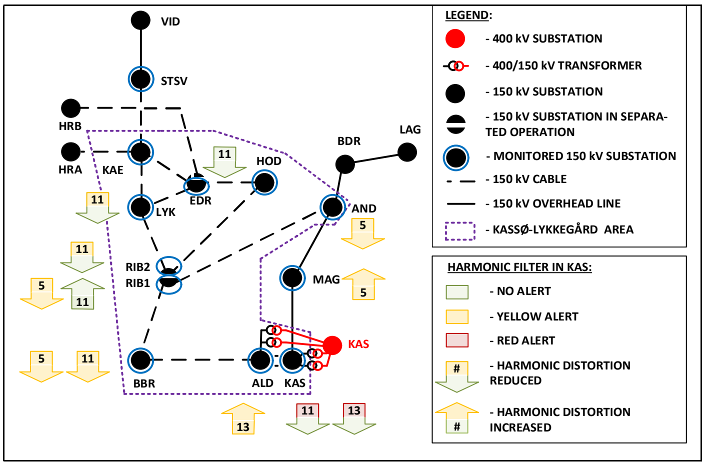

Fig. 15. Results of the combined performance and detuning study of the high-pass 2nd order filter in the 150 kV substation KAS.

As can be seen, the proposed filter design has a positive effect on the 11th and 13th harmonic voltages in KAS and on the 11th harmonic voltages across the 150 kV grid area. However, the filter has an adverse effect on the 13th harmonic voltage in ALD, presumably due to the connection via the 400/150 kV transformers between ALD and KAS. As expected, the filter is not suitable for efficient dampening of the 5th harmonic voltage distortion as such and shows an adverse effect in MAG.

Though the 5th harmonic voltage distortion is depicted as yellow alert in many substations and may exceed 70% of the IEC planning level, such violations are the results of the rarely occurring simultaneous worst case in specific operation conditions of the reconstructed grid. Such specific operation conditions refer to RIB operated with separated substation sections, which can be present while after the Kassø-Lykkegård 150 kV grid reconstruction is completed.

There will be enough time to revalidate the simulation model and outcomes of this harmonic assessment by the PQ measurements before utilization of such operation conditions take place and may introduce the excessive 5th harmonic voltage. Possibility of one more harmonic filter, such as for the 5th harmonic order, has been discussed and decided to keep on hold.

D. *Component Rating and Sound Power Requirements*

The harmonic load-flow of the performance and detuning study has produced the simulated harmonic voltage spectrum in the 150 kV substation KAS in the reconstructed grid. Together with the PQ measurements in the present 2020/2021 grid, this simulated spectrum has been applied for preparing the harmonic voltage spectra for determination of the component ratings and the sound power requirements of the harmonic filter. These harmonic voltage spectra are handed over to the harmonic filter vendor.

VII. Analysis of Harmonic Resonances

In addition to the harmonic load-flow, the frequency sweep method, which identifies the harmonic impedance resonances, is applied for interpretation and completeness check of the results of the harmonic assessment.

A. *Present Grid Stage*

Fig. 16 shows the frequency sweeps of the harmonic impedance magnitudes in the substations KAS and AND for the present 2020/2021 grid. The frequency sweeps are for the (n-0) and the (n-1) with the AND-MAG line out-of-service.

For the substation KAS, the frequency sweeps are almost identical for (n-0) and this specific (n-1) operation condition. The simulated frequency sweeps for KAS are in-line with the measured harmonic voltage magnitudes in Fig. 8 showing no (noticeable) steps due to the AND-MAG line switching events.

For the substation AND, the frequency sweeps show an approx. 50% increase of the harmonic impedance magnitude for the 5th harmonic order when the AND-MAG line is out-of-service. This result is in-line with the measured harmonic voltage magnitudes in Fig. 7(a-d).

The frequency sweeps show a harmonic resonance (with a significant, approx. 200%, increase) appearing in AND at the 7th harmonic order when the AND-MAG line is out-of-service. The measured 7th harmonic voltage distortion in AND, plotted in Fig. 7(b), does not have such significant step. This is not a discrepancy between the simulations and measurements, but this result is rather because there is no coherent vectorial harmonic emission behind AND to amplify the 7th harmonic order resonance.

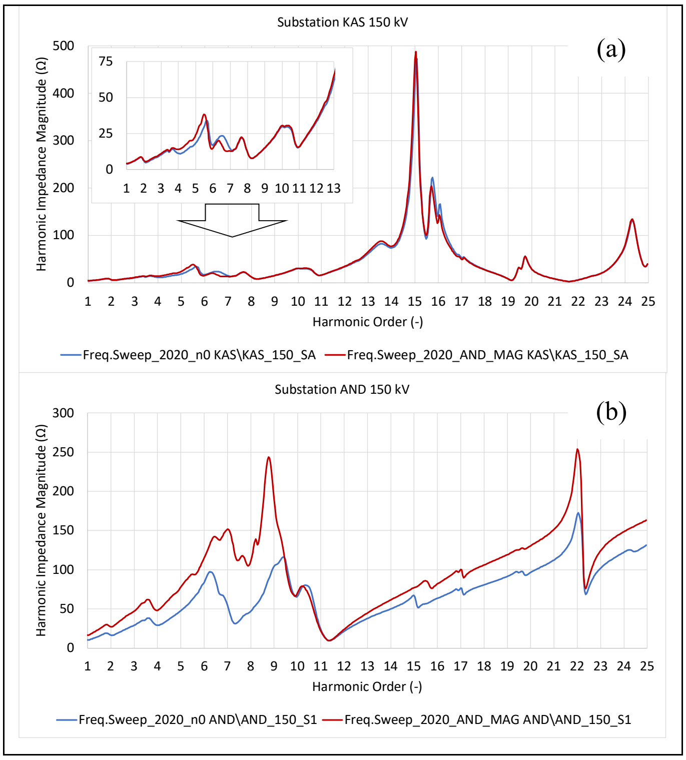

Fig. 16. Harmonic impedance magnitude for the present 2020/2021 grid in the substations: (a) – KAS, (b) - AND. Blue curves – (n-0) and red curves – (n-1) for the AND-MAG 150 kV line out-of-service.

This result emphasizes why both harmonic load-flow method, requiring modelling and validation by the PQ measurements of the harmonic emission sources, and frequency sweep method are complementary to each other for the harmonic assessment.

B. *Reconstructed Grid*

Fig. 17 presents changes of the frequency sweeps of the harmonic impedance magnitudes in the substations KAS and AND from the present grid to the reconstructed grid of the 2023/2024 development stage. The frequency sweeps are for both operation regimes of RIB in the reconstructed grid.

If the assessment has alone relied on the frequency sweep method, the 11th harmonic voltage amplification in KAS would probably have been overseen because there is no such resonance in the harmonic impedance characteristic, neither before nor after the grid reconstruction.

The 5th harmonic resonance in AND for RIB with separated substation sections would be captured. Needs of a new 5th harmonic order filter for dampening this resonance would be highlighted for the grid development stage when this operation regime in RIB becomes relevant.

Further, the 13th harmonic resonance in AND would get attention. Needs of a new 13th harmonic order filter would also be analyzed. Here it is important to emphasize that neither the PQ measurements in the present grid nor the harmonic load-flow have shown excessive 13th harmonic voltage distortion in AND. This outcome is not a discrepancy caused by the frequency sweep method, but this outcome is because there is no coherent vectorial harmonic emission behind AND to amplify the 13th harmonic order resonance.

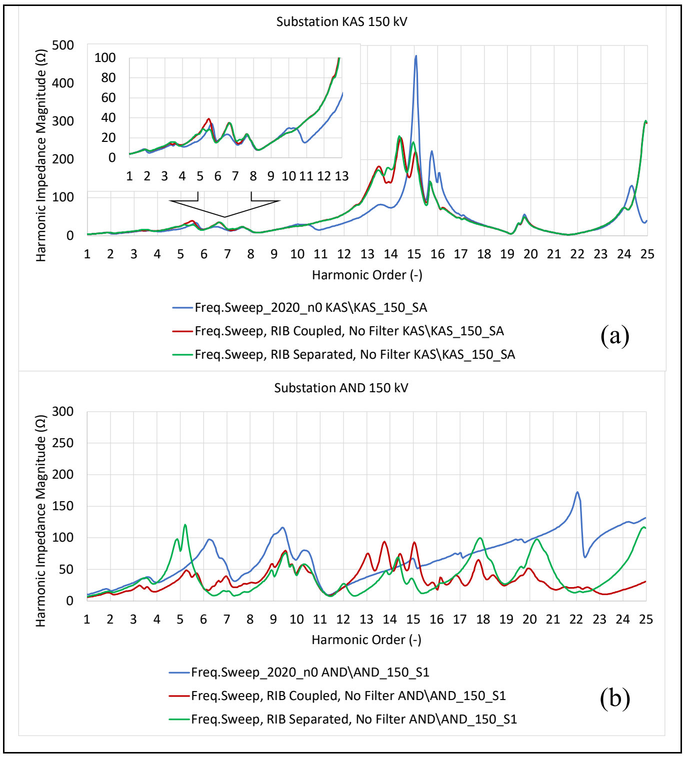

Fig. 17. Harmonic impedance magnitude in the substations: (a) – KAS, (b) - AND. Blue curves – the present 2020/2021 grid, red curves and green curves – the reconstructed grid with coupled and separated operation of RIB, respectively.

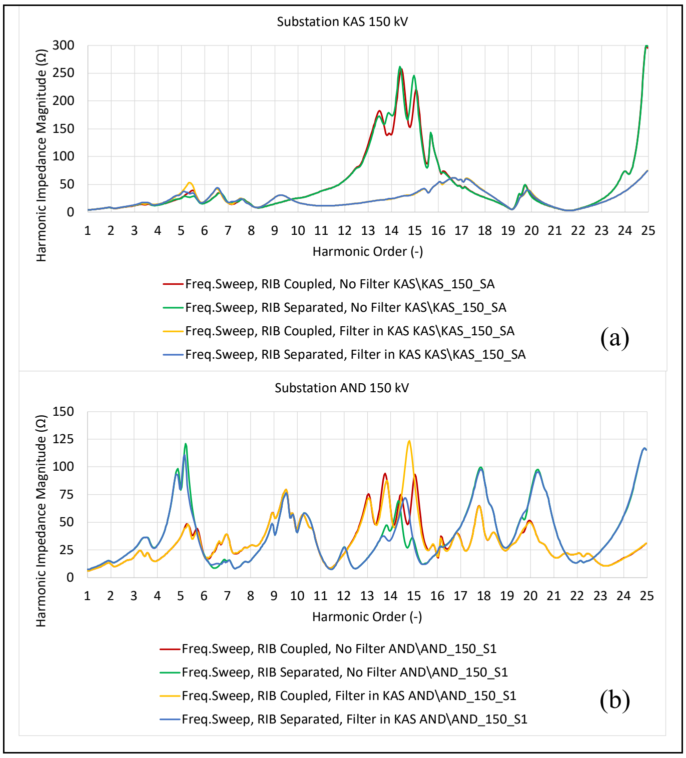

Fig. 18. Harmonic impedance magnitude for the reconstructed grid in the substations: (a) – KAS, (b) - AND. Red curves and green curves – no harmonic filter and with coupled and separated operation of RIB, respectively. Yellow curves and blue curves – harmonic filter in KAS and with coupled and separated operation of RIB, respectively,

C. Harmonic Filter in Reconstructed Grid

Fig. 18 presents changes of the frequency sweeps of the harmonic impedance magnitudes in the substations KAS and AND in the reconstructed grid imposed by the new harmonic filter in KAS. The frequency sweeps are for both operation regimes of RIB in the reconstructed grid.

The frequency sweeps show that the harmonic filter will have the greatest positive effect on dampening of the 11th and 13th harmonic distortion in KAS. The harmonic filter shall also dampen the 25th harmonic order resonance in KAS.

The frequency sweeps show no noticeable effect of the harmonic filter in KAS on the harmonic impedance characteristics in AND when considering the 7th, 11th and 13th harmonic orders. Exception is a small reduction of the harmonic impedance magnitude at the 5th harmonic order, which is in-line with the results of the harmonic load-flow in Section VI.

Attention is paid to that the frequency sweep method is subject to uncertainty of the data and electro-geometrical models of not yet commissioned components. Accuracy of the method relies on the data accuracy and tolerances of the passive-part components in the transmission grid.

This underlines the necessity of the data revalidation at the first given opportunity which will be after commissioning of the Kassø-Lykkegård 150 kV reconstructed grid due 2023.

VIII. CONCLUSION

Integration of renewable energy sources follows up with commissioning of more UGC in the HVAC meshed transmission grid. In Denmark, the political decision is that the new 400 kV connections shall be established as UGC to the extent that is technically feasible while the new 150 kV and 132 kV lines shall always be established as UGC. The 150 kV and 132 kV OHL in the vicinity of new 400 kV OHL shall be replaced with UGC. The practical experience so far has been that significant harmonic amplification has been reported in the 400 kV and 220 kV systems. However, the harmonic amplification in the years to come may also start occurring in the 150 kV and 132 kV meshed grids as the UGC share is increasing. Development and application of the simulation methods for prediction and mitigation of possible systemwide harmonic amplification in the 150 kV (and 132 kV) meshed transmission grids with the lines been planned but not yet commissioned are among preconditions for successful green transition and grid expansion with UGC.

The methods of harmonic assessment for the meshed transmission grid shall be credible and reliable tools for decision making on investments and secure operation in the years to come. The methods shall both quantify the harmonic voltage distortion and propose (cost effective) mitigation solutions, which is why both frequency sweeps and harmonic load-flow shall be conducted using the simulation model of the meshed transmission grid with not yet established transmission lines.

For conducting the harmonic load-flow, the methods utilize the present grid stage as reference and define empirically developed models of the harmonic emission sources as the harmonic current vectors. The harmonic current vectors are relative to the fundamental current vectors and determined using several operation conditions of the assessed transmission grid. Such operation conditions include (n-0) and various (n-1) and apply for both confirming robustness of the empirically derived numerical models of the harmonic current vectors to changes of the harmonic grid impedance and reduction of the outcome space of possible numerical solutions.

The harmonic emission sources in such 150 kV and 132 kV meshed transmission grids are mostly of distributed character either originating from the MV grids or directly connected to the 150 kV and 132 kV substations as larger units. The harmonic propagation from the 400 kV grid is also among the harmonic sources in the 150 kV substations with 400/150 kV transformation.

The harmonic emission sources are numerically tuned to match the PQ measurements in the present transmission grid. The tuning level shall reproduce both normal-case and simultaneous worst-case in means of the numerical tuning and postprocessing of the simulation results targeting the 95th weekly percentiles of the measured harmonic voltage distortion of the present grid stage.

The methods treat the grid expansion as the harmonic grid impedance changing from (n-0) to either (n-K+L) for replacement of K OHL with L UGC connections or (n+M) for establishment of M new lines. The methods simulate the harmonic voltage distortion in the new grid development stage with locked models of the harmonic emission sources. The goal is projection of the 95th weekly percentiles of the harmonic voltage distortion in the present grid towards the new grid development stage. The projection shall not only identify risks of possible harmonic amplification, but also suggests the level of the harmonic voltage distortion in the new transmission grid and, when deemed necessary, propose the mitigation solution as ready for an investment decision and specification for handing over to the vendors.

The frequency sweeps identify resonances in the harmonic grid impedance and complement the results of the harmonic load-flow with simulated harmonic voltage distortion and mitigation in the new grid development stages.

The presented methods are illustrated using the Kassø-Lykkegård 150 kV grid reconstruction project in Western Denmark as a case study. In this project, the existing 150 kV OHL will be replaced with 150 kV UGC with the total length of 240 km forming the new meshed transmission grid by 2023. The harmonic assessment has concluded a systemwide harmonic amplification in the reconstructed grid and proposed a passive harmonic filter with specified layout parameters and grid-connection substation.

The simulation model is subject to uncertainty of the data of not yet established lines, tolerances of the existing components as well as data uncertainty, numerical tuning and determining of the harmonic emission sources. Such uncertainties are addressed and, to the best-possible extent, reduced in this work. The model and proposed methods will be evaluated and revalidated by the PQ measurements at the first given opportunity, which arises after completion of the Kassø-Lykkegård 150 kV grid reconstruction by 2023.

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IX. FURTHER READING

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