Development of a Harmonic Analysis Model for a Meshed Transmission Grid with Multiple Harmonic Emission Sources

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***Abstract*—The transmission grid of Denmark-West is part of the Continental European synchronous area with HVAC connection to Germany and multiple HVDC interconnectors to Norway, Sweden, Denmark-East (part of the Nordic system not synchronized to the Continental European area), The Netherlands and, in few years, to Great Britain. Denmark-West has become a hub where the meshed HVAC grid includes numerous converter stations of the HVDC connections, large offshore wind and photovoltaic power plants. The converter-interfaced transmission and production are necessary steps in the green transition of the energy system and require expansion of the 400 kV (HVAC) meshed grid to support the transition. With strong public opposition to new overhead lines (OHL), there is high demand for the application of underground cables in the Danish transmission grid. Underground cables give rise to a range of technical challenges, one of which is the amplification of harmonic voltage distortion. This work presents the method and model development of the transmission grid of Denmark-West for the harmonic assessment. The model range is up to the 50th harmonic order. This work demonstrates that both harmonic impedance (passive-part), harmonic emission sources (active-part) and feedback are relevant for accurate and sufficient harmonic assessment of the meshed transmission grid with multiple harmonic emission sources. The method and model are confirmed by the validation cases by the measured harmonic voltage distortion.**

Keywords—harmonic load-flow, harmonic measurements, harmonic voltage distortion, meshed transmission grid, method, model, overhead lines, validation, underground cables

I. Abbreviations

HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
LCC	Line Commutated Converter
OWPP	Offshore Wind Power Plant
PQ	Power Quality
PV	Photovoltaic
VSC	Voltage Source Converter

1) HVAC Subtations

The HVAC substations with the PQ measurements are marked in Fig. 1 illustrating the 400 kV transmission grid of Denmark-West, the development stage 2017-2020.

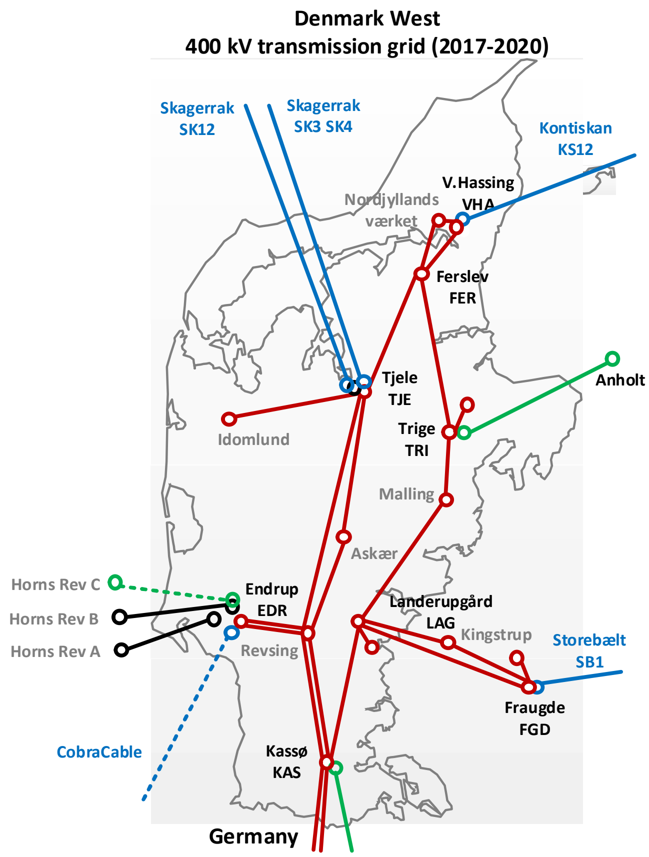

Fig. 1. 400 kV transmission grid of Denmark-West Legend: **red** – 400 kV transmission lines and substations, **blue** – HVDC and converter stations, **green** – 220 kV lines and substations, **black** – 150 kV OWPP grid connection and substations. The highlighted names with the abbreviations show the 400 kVsubstations with the established PQ measurements.

The substations are listed from north to south of the grid:

NVV	Nordjyllandsværket	VHA	V. Hassing
TJE	Tjele	FER	Ferslev
IDU	Idomlund	TRI	Trige
ASR	Askær	MAL	Malling
EDR	Endrup	REV	Revsing
LAG	Landerupgård	KIN	Kingstrup
KAS	Kassø	FGD	Fraugde

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2) HVDC Connections and Converter Stations

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

KS12	Konti-Skan 1, 2 (Denmark-West – Sweden)
SK12	Skagerrak 1, 2 (Denmark-West – Norway)
SK3	Skagerrak 3 (Denmark-West – Norway)
SK4	Skagerrak 4 (Denmark-West – Norway)
SB1	Storebælt (Denmark-West – Denmark-East)
--	CobraCable (Denmark-West – The Netherlands)

II. Introduction

The transmission grid of Denmark integrates a significant amount of the offshore (OWPP) and onshore wind power and photovoltaic (PV) power plants. At present, the wind power alone stays for more than 40% of the annual electric energy consumption, with several wind and photovoltaic projects to be added [1]. During specific days 100% of the consumption is covered by renewable energy sources. Future OWPPs counting 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 among the OWPP to be HVAC connected to the Danish transmission grid by 2026-2028. 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 have been proposed and, if shown economically beneficial, connected to the Danish and foreign transmission grids by the year 2030 [1].

The transmission grid of Denmark is divided between the two large synchronous areas. The transmission grid of Denmark-West includes the peninsula of Jutland and the island of Funen and is part of the Continental European synchronous area. Denmark-East includes the main island of Zealand with the Danish Capital of Copenhagen and the islands of Lolland, Falster and Moen and belongs to the Nordic synchronous area. The largest share of wind power and PV power plants is integrated in Denmark-West. The modern wind turbines and PV modules are converter-interfaced units, which have become the main-stream technology within the electric power supply.

The transmission grid of Denmark-West is a 400 kV and 150 kV meshed system with HVAC connection to Germany and multiple HVDC interconnectors to Norway (Skagerrak, 1700 MW), Sweden (Konti-Skan, 740 MW) and Denmark-East (Storebælt, 600 MW), The Netherlands (CobraCable, 700 MW), and in few years, to Great Britain (Viking Link, 1400 MW). Denmark-West has become a hub where the meshed HVAC transmission grid includes numerous converter stations of the HVDC interconnectors, large wind and PV power plants. Grid integration of more converter-interfaced transmission and production is a necessary step in the green transition of the energy system and requires expansion of the 400 kV (HVAC) meshed grid to support the transition. With strong public opposition to new overhead lines (OHL), there is high demand for the application of underground cables in the Danish transmission grid. Underground cables give rise to a range of technical challenges, one of which is the amplification of the harmonic voltage distortion. The amplification of the harmonic voltage distortion is already known from the 220 kV connections to OWPP [2, 3] and, by more recent experience, in the 400 kV meshed grid of Denmark-West due to extensive application of underground cables [4].

This work presents the method and model development of the transmission grid of Denmark-West for the harmonic assessment by simulations. The model range is up to the 50^{th} harmonic order. This work demonstrates that both harmonic impedance (passive-part), harmonic emission sources (active-part) and feedback are relevant for accurate and sufficient harmonic assessment by simulations of the meshed transmission grid with multiple harmonic emission sources.

The harmonic emission of the HVDC interconnectors in the 400 kV and 150 kV transmission grid are modelled by the vendor-specific, non-linear, harmonic emission magnitudes and, as a novice of the method, by the empirically defined phase angles. The distributed harmonic emission sources under the 150 kV substations are modelled using unified generic-level sources with fixed magnitudes and phase angles to fit the harmonic voltage distortion in the 400 kV system level.

The Danish transmission system operator (TSO) Energinet applies the presented method in replacement of standardised superposition rules which are developed for radial systems and fail working in the meshed grid with multiple harmonic emission sources. The method and model are confirmed by the validation cases by the measured harmonic voltage distortion.

III. Motivation

Fig. 2 illustrates the part of the 400 kV transmission grid of Denmark-West where the first challenging experience with significant amplification of the harmonic voltage distortion has arrived. The amplification of the harmonic voltage distortion has been initiated due to commissioning of the Vejle-Ådal 400 kV underground cable system, which is the two parallel approx. 7 km long cables, in combination with a 40 km OHL between the substations Landerupgård (LAG) and Malling (MAL). The commissioning time is July 6^{th} 2017.

After the commissioning, a significant amplification of the 11^{th} and 13^{th} harmonic voltage distortion has been measured in the two other substations Trige (TRI) and Fraugde (FGD), which are distant to the location of the Vejle-Ådal cable system, see Fig. 2. In the substation TRI, the 11^{th} harmonic voltage has violated the planning level. Energinet applies the IEC planning levels [4].

Fig. 3 shows the measurements of the harmonic voltages in TRI, FGD and V. Hassing (VHA) around the commissioning of the Vejle-Ådal cable system.

In the beginning, the harmonic assessment has mostly been conducted by analysis of the measurements [5] and later by extensive simulations using the harmonic assessment model of Denmark-West. The applied solution includes reprogramming of the RPC controlling the existing filters of the Konti-Skan HVDC interconnector in the substation VHA. The RPC reprogramming shall enforce more extensive utilization of the harmonic filters in VHA. The solution includes also establishment of a reactor as reactive-power compensation of the more extensive usage of the filters with capacitive characteristics.

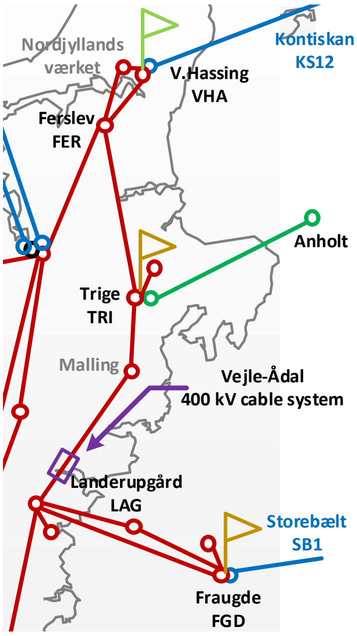


Fig. 2. Part of the 400 kV transmission grid of Denmark-West with notification of the Vejle-Ådal 400 kV underground cable system, the **yellow flags** marking the substations with noticeable harmonic amplification, and the **green flag** marking the substation with existing filters applied for dampening the harmonic voltage distortion caused by the Vejle-Ådal cable system in the yellow flagged substations.

The substation VHA is ever more distant to the location of the Vejle-Ådal cable system. There is no noticeable amplification of the harmonic voltage distortion in V. Hassing due to the Vejle-Ådal cable system though this substation is part of the solution.

In the studies [5], the harmonic amplification in TRI and FGD has been linked to the harmonic emission of the Konti-Skan and Storebælt HVDC converter stations. The strange looking behaviour, with regard to location, harmonic propagation and dampening of the harmonic voltages, has been linked with the factum that Denmark-West is a meshed transmission grid with multiple harmonic emission sources. Depending on the magnitudes and phase angles of the harmonic emission sources, the harmonic voltage distortion can be amplified in some substations and dampened in some other substations of the meshed transmission grid.

The Danish 400 kV transmission grid stays afront of a major expansion and reconstruction to support the green transition and integration of more HVDC interconnectors to foreign grids. In Denmark, the public opinion wishes that the 400 kV grid development shall most possible utilize underground cables and the existing OHL shall most possible be replaced by underground cables.

Development of accurate and validated model of the Danish transmission grid for the harmonic assessment becomes a necessity for the green transition and grid expansion being technically and economically sound and socially accepted.

IV. Model Development

Development of the harmonic assessment model of Denmark-West is conducted in steps:

1. Empirical approach.
2. Lessons learned from the Vejle-Ådal harmonic analysis.
3. Securing accuracy of the passive part (harmonic impedance) of the transmission grid model.
4. Representation of the active part (harmonic emission sources) and feedback of the model.
5. Validation by the measurements.

Each model development step is discussed in detail.

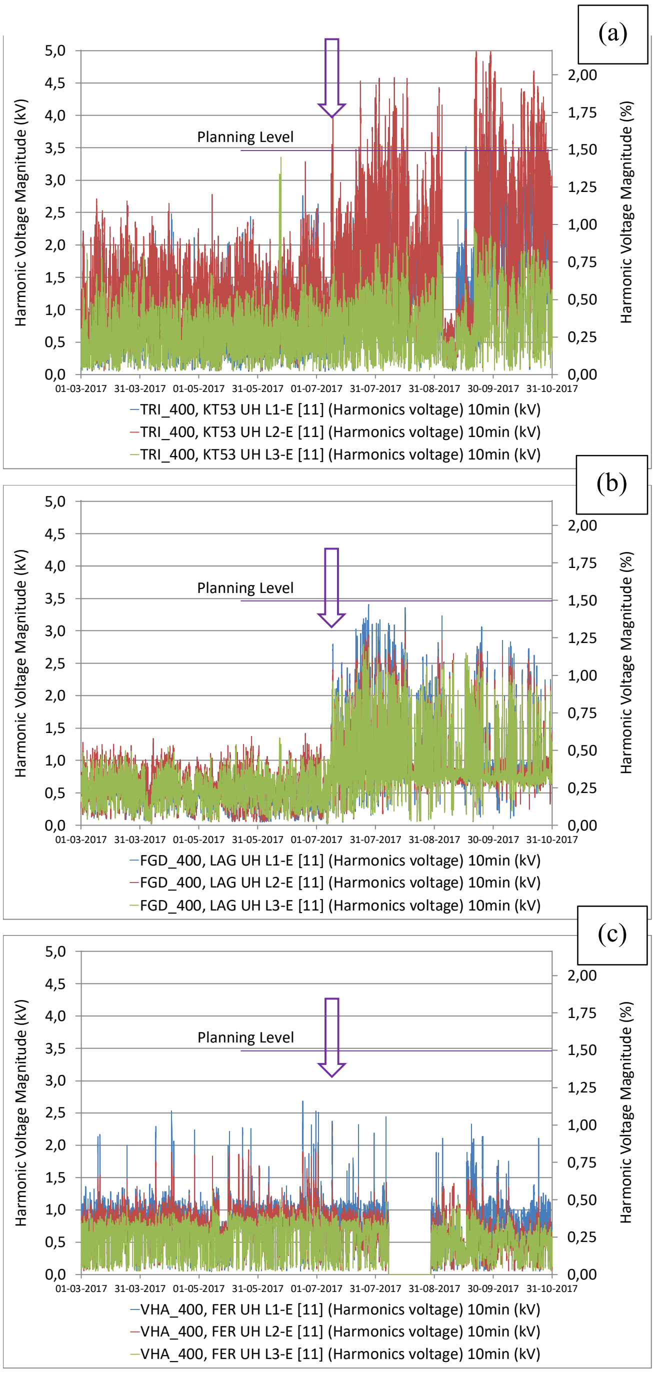


Fig. 3. Amplification of the 11th harmonic voltage distortion in the 400 kV substations around the commissioning of the Vejle-Ådal underground cable system measured in: (a) – Trige, (b) – Fraugde, (c) – V. Hassing. The shown substations are flagged in Fig. 2. The arrows mark the commissioning time.

A. Empirical approach

The empirical approach implies that development and accuracy of the harmonic assessment model rely on the measurements of the harmonic voltage distortion. Energinet has established the power-quality (PQ) measurements of the phase-to-ground harmonic voltage magnitudes in the three phases. The harmonic order of the measurements, which are applied for the model development, is up to the 50th harmonic order and the magnitudes are ten-minute average values. The PQ measurements do not provide phase angle measurements of the harmonic voltage distortion. In the 400 kV grid, the PQ measurements are present in the highlighted substations in Fig. 1 and have been available for the harmonic study of the Vejle-Ådal project [5] and later for development of the harmonic assessment model of Denmark-West. The PQ measurements in the different substations are time-synchronised.

The model shall be validated against the measurements, which means that the model is able of reproducing the measured harmonic voltage distortion in all relevant substations and historical operation conditions in the existing transmission grid. When the model is successfully validated against several varying operation conditions, the model can be applied for the harmonic assessment of the transmission grid expansion, i.e. where neither grid nor measurements yet exist. The model shall again be validated and, if necessary, corrected for reproducing the measured harmonic voltage distortion when the grid has expanded.

The grid operation conditions include:

- Power transport and production of the HVDC converter-interfaced stations because this directly relates to their harmonic emission (active-part).
- Which filters are in-service (harmonic dampening).
- Which transmission lines and components are out-of-service (passive-part, harmonic impedance of the grid).
- Case specific switch- and tap-positions of the switchable and controllable components since influencing the (harmonic) grid impedance.

The above listed operation conditions are acquired from the SCADA, where the time calibration is with slips between the SCADA signals are not time-synchronised with the PQ measurements. By experience of Energinet there are two kind of time slips:

1. Within ten to twenty minutes between the PQ-measurements and the records in the SCADA.
2. Mutually between the records of grid events and changes of the operation conditions throughout the transmission grid in the SCADA.

Such time slips are not relevant for monitoring of the transmission grid operation as such, but significant for linking the harmonic voltage distortion to the recorded grid events and changes of operation conditions. Complete mitigation of such time slips would be beneficial for the model validation, but it would require significant time and effort.

Instead the model development and validation are conducted for (more or less) stationary periods of the grid operation and harmonic voltage distortion.

First, through conducting manual “time-calibration” between such periods of stationary operation conditions of the power transport, filters in-service and 400 kV lines out-of-service, and measurements of the harmonic voltage distortion. Periods with several operation point changes and grid events within short periods are excluded from the model development and validation because of uncertainty of which change or event causing which harmonic voltage response.

Second, through applying longer than the “instant”, ten-minute, averaging periods of the harmonic voltage distortion for smoothing sometimes very fluctuating behaviour of the harmonic voltage distortion. Since the harmonic assessment model shall have a built-in conservative margin, the 95% percentiles of up to two-hour averaging periods are applied (by interpolation). This averaging approach does not evaluate compliance of the harmonic voltage distortion to the IEC planning level by the 95% weekly percentiles [4]. The applied averaging approach just removes some irrelevant fluctuation of the measured harmonic voltage distortion within the stationary operation periods without overseeing changes of the harmonic voltage distortion at relevant changes of the operation conditions in the 400 kV transmission grid between the stationary periods.

Third, the significant harmonic orders are defined for which the maximum harmonic phase voltage magnitudes are greater than 0.1% (of the fundamental phase voltage magnitudes) during the assessment period. This definition complies with measurement inaccuracy [4]. The model development and validation targets primarily the significant harmonic orders.

The applied empirical approach is illustrated in Fig. 4 for the 400 kV substation TRI for the period from Sept. 1st to Sept. 5th, 2017. The “instant” harmonic voltage magnitudes of the significant harmonic orders are compared to the averaged magnitudes, i.e. the 95% percentiles over two-hour period. The “instant” values are shown by the maximum phase voltage magnitudes. For the 400 kV substation TRI, the 3rd, 5th, 7th, 11th and 13th harmonic orders are the significant harmonic orders during the shown period.

The first grid event at Sept. 4th leading to the drop of the 11th and 13th harmonic magnitudes is a planned outage of the KS12 converter station with the filters in V. H. The second grid event at the same date leading to the second drop of the 11th and 13th harmonic voltage magnitudes is a planned outage of the 400 kV line Ferslev-Nordjyllandsværket (FER-NVV).

The 11th and 13th harmonic voltage behaviour before (and after) these two drops is caused by varying power transport and filter utilization of the LCC HVDC converter stations and, for the lower harmonic orders, by the harmonic emission and absorption under the 150 kV substations and, to less extend, by the LCC HVDC converter stations. The information about the operation of the LCC HVDC converter stations, their harmonic filters and outage of the FER-NVV transmission line is acquired from the SCADA and “time-calibrated” to the harmonic voltage measurements in Fig. 4.

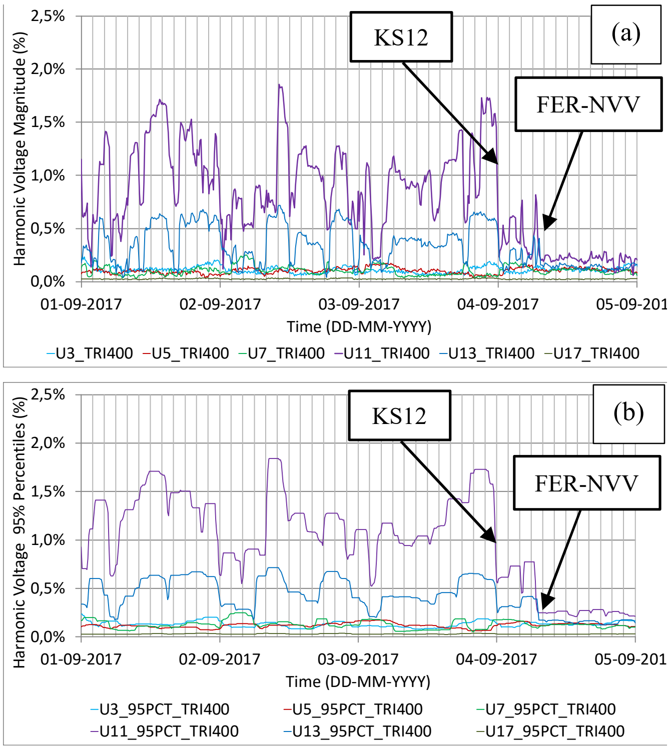


Fig. 4. Comparison of (a) – the "instant" maximum phase voltage magnitudes to (b) – averaged 95% percentiles over two-hour period values of the significant harmonic orders, the 400 kV substation TRI. Marks are KS12 – planned outage of KS12 converter station and filters, FER-NVV – planned outage of the 400 kV line FER-NVV. The ploted signals are: UN_TRI400 – the Nth harmonic order maximum phase voltage magnitudes and UN_95PCT_TRI400 – the Nth harmonic order averaged maximum magnitudes.

As seen, the 95% percentiles over two-hour period capture very well the harmonic picks but overestimate the harmonic dips of the instant magnitudes. The last observation confirms that the usage of the 95% percentiles over two-hour period as reference of the empirical model will lead to that the model gets a built-in conservative margin overestimating the harmonic voltage distortion which is much lower than the planning level.

Decisions for mitigation of excessive harmonic voltage distortion shall not be influenced by such foreseen discrepancy for low harmonic voltage magnitudes rising from the harmonic assessment by the model.

B. Lessons learned

The LCC HVDC converter stations are located in the substations FGD (Storebælt 1, SB1), VHA (Konti-Skan 12, KS12) and Tjele (TJE, Skagerrak 3, SK3) and shown in Fig. 1. The harmonic study of the Vejle-Ådal project by analysis of the measurements [5] and later using the model has linked the noticeable amplification of the 11th and 13th harmonic voltage distortion in the substations TRI and FGD to the SB1 and KS12 converter stations.

The study has also shown that the KS12 filters located in VHA can efficiently dampen the 11th and 13th harmonic voltage distortion in TRI. The SB1 filters dampen the 11th and 13th harmonic voltage distortion in FGD.

The SK3 converter station (or its filters) does not contribute to amplification (or dampening) of the 11th and 13th harmonic voltage distortion in TRI and FGD. The 11th and 13th harmonic voltage distortion in the other 400 kV substations remains almost unchanged after commissioning of the Vejle-Ådal 400 kV cable system. The harmonic emission of the VSC HVDC converter stations of Skagerrak 4 in TJE and Cobra Cable in Endrup (EDR), shown in Fig. 1, do not contribute to such orders of the harmonic voltage distortion.

Commissioning of the Vejle-Ådal 400 kV cable system has changed the harmonic impedance of the 400 kV transmission grid. Normally, assessment of the gain factors is used for calculating and foreseeing harmonic amplification between the two substations due to changed harmonic impedance considering unchanged harmonic emission. The assessment is widely applied for radial systems [4].

Assessment of the gain factors has been used for analysing the measured harmonic amplification occurred in the 400 kV transmission grid of Denmark-West due to the Vejle-Ådal 400 kV underground cable system. The measured 11th and 13th harmonic voltage magnitudes have been applied for assessment of the gain factors between the emitting (FGD, VHA and TJE) and receiving (TRI, EDR) substations. The harmonic emission from the German transmission grid is via the border substation Kassø (KAS).

Fig. 5 illustrates the principle of the gain factor assessment using the emitting and receiving substations.

First, the assessment of the gain factors cannot explain such significant harmonic amplification in the substation FGD, which is shown in Fig. 3. No new harmonic emission sources have been established in vicinity of the substation FGD when the harmonic amplification has occurred.

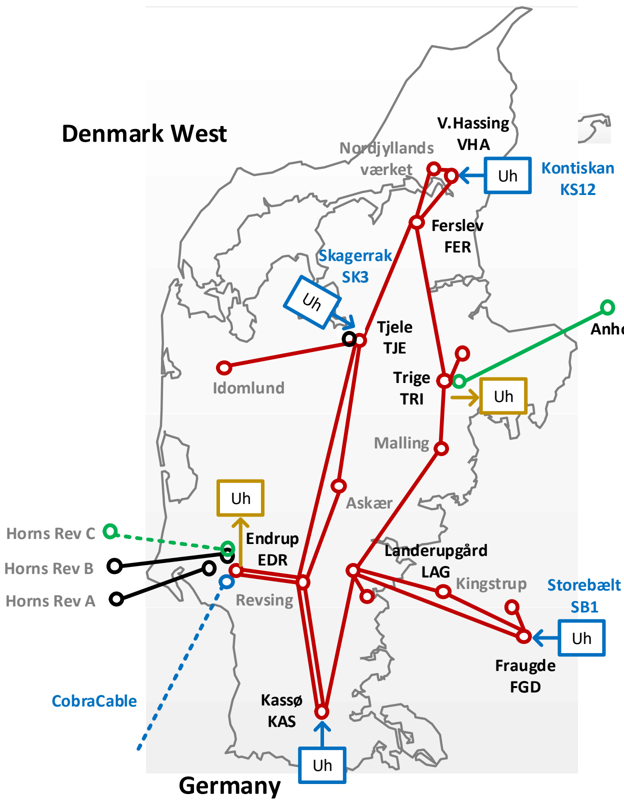


Fig. 5. Principle of assessing the gain factors in the receiving substations [Uh] with refernce to the emitting substations [Uh].

Second, the assessment shows increase of the gain factor $k_{TRI/TJE} = \left|\frac{u_{TRI}}{u_{TJE}}\right|$ due to commissioning of the Vejle-Ådal 400 kV underground cable anticipating the 11th harmonic voltage amplification between the substations TRI and TJE. The analysis of the measurements [5] has shown that the harmonic emission or filters of the SK3 converter station located in TJE does not influence the 11th harmonic voltage in TRI. The anticipated amplification does not exist.

Third, the assessment shows reduction of the gain factor $k_{EDR/FGD} = \left|\frac{u_{EDR}}{u_{FGD}}\right|$ anticipating the 11th harmonic voltage dampening between the substations EDR and FGD due to commissioning of the Vejle-Ådal underground cable. The measurements show that the 11th harmonic voltage distortion in EDR is unchanged, so that the 11th harmonic dampening in EDR does not exist.

The analysis of the measurements [5] shows that the 11th harmonic voltage in the receiving substation EDR depends from the emitting substation TJE (SK3) and the harmonic emission from the German grid via the border substation Kassø (KAS). In the receiving substation TRI, the 11th harmonic voltage depends from the emitting substations VHA (KS12) and FGD (SB1).

Therefore, the assessment is modified so that the gain factors of the receiving substations, EDR and TRI, include only the relevant emitting substations: $k_{EDR/(TJE||KAS)} = \frac{|u_{EDR}|}{½\cdot(|u_{TJE}|+|u_{KAS}|)}$ and $k_{TRI/(VHA||FGD)} = \frac{|u_{TRI}|}{½\cdot(|u_{VHA}|+|u_{FGD}|)}$.

The modified assessment shows that the gain factors in EDR and TRI remain almost unchanged before and after commissioning of the Vejle-Ådal. This result anticipates no harmonic amplification in TRI due to the harmonic impedance change unless the harmonic emission in VHA (KS12) and FGD (SB1) has altered causing the measured harmonic amplification.

The outcome of this section leads to the three principal findings:

1. The 11th (and 13th) harmonic voltage amplification occurred in the 400 kV transmission grid of Denmark-West cannot only be explained in the terms of the harmonic impedance change. The harmonic emission sources and their location in the meshed transmission grid of Denmark-West influence the harmonic amplification in FGD (SB1) and TRI due to commissioning of the Vejle-Ådal 400 kV underground cable system.
2. The standardised method [5] working well for radial systems is not applicable for the meshed transmission grids with multiple emission sources. The harmonic assessment model of Denmark-West shall represent both passive-part (the transmission grid itself) and active-part (the harmonic emission sources) in such a way reflecting the measured relationships between the harmonic emission sources and the other substations of the existing transmission grid. The relationships are the feedback of the passive-part to the active-part.
3. At present stage, the measurements of the harmonic voltage distortion and consecutive benchmarking of the model against the measurements after the transmission grid expansion are necessary for the model development and adaption for assessment of the next grid expansion stage.

C. Passive part – Harmonic impedance of the grid

The passive-part is the harmonic impedance of the transmission grid model. The OHL and underground cables are modelled using the asset-specific geometrical (electrical) models with distributed parameters. Securing the accuracy and completeness of the passive-part is prerequisite of the model development before addressing the active-part and feedback with the harmonic emission sources.

For evaluation of accuracy and completeness of the harmonic impedance of the transmission grid model, the harmonic response of the model has been made invariant from the active-part and feedback of the harmonic emission sources and the harmonic filters.

The 400 kV substations with available measurements of the harmonic voltage distortion have been divided into the emitting and receiving substations. The emitting substations are with the LCC HVDC converter stations and harmonic filters: VHA (KS12), TJE (SK3) and FGD (SB1). The receiving substations are Ferslev (FER), EDR, Landerupgård (LAG), TRI and KAS. The harmonic current emission source of the Anholt OWPP conducts the harmonic emission of the full wind power production and will be explained in the next subsection D. Fig. 6 presents the applied setup with the emitting and receiving substations.

The border substation KAS performs also as a slack terminal representing the short-circuit contribution of the German 400 kV transmission grid and allowing the fundamental-frequency load flow solution of the Danish grid.

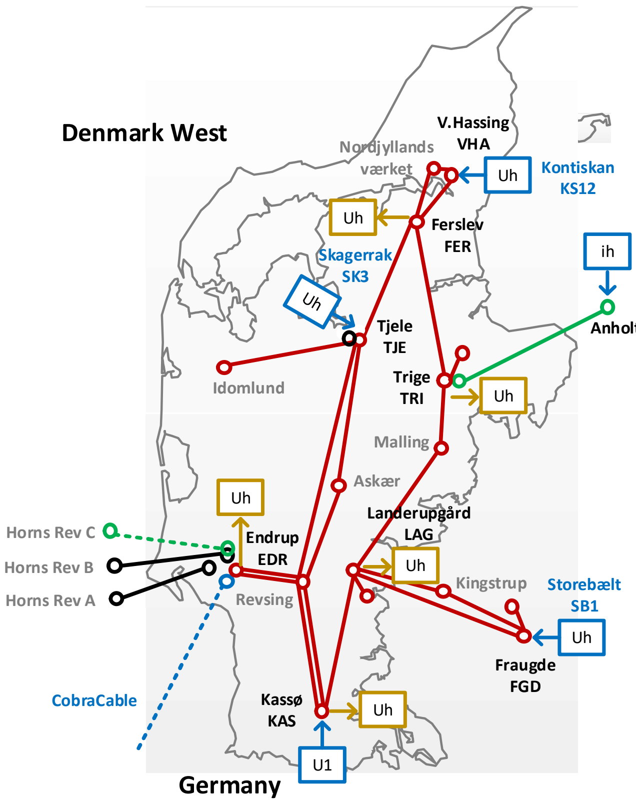


Fig. 6. Validation of the harmonic impedance of the transmission grid using the harmonic voltage distortion in the receiving substations → Uh with refence to the emitting substations ← Uh and ← ih.

The fundamental-frequency load flow is necessary for the simulation program DigSilent PowerFactory® conducting the harmonic load flow.

The measured magnitudes of the harmonic voltage distortion of the emitting substations VHA, TJE and FGD are applied as fixed inputs of the transmission grid model. In practice, the Thevenin harmonic voltage sources using the measured magnitudes and zero impedances are established in these three emitting substations. In the model, the harmonic voltage distortion is made invariant from the operation points of the converter stations and the contributions of the harmonic filters in the same substations are bypassed since the simulated harmonic voltages remain unchanged and equal to the measured magnitudes.

The simulated harmonic voltage distortion in the receiving substations is compared to the measured magnitudes of the harmonic voltage distortion. The simulation method is the harmonic load flow of the simulation program DigSilent PowerFactory®.

The idea behind the harmonic impedance evaluation is that the harmonic impedance of the meshed transmission grid is accurately represented in the model when the simulated and harmonic voltage magnitudes in all the receiving substations match the measured harmonic voltage magnitudes.

The assessment has been conducted for the 50% percentiles and the 95% percentiles of the harmonic voltage distortion in the emitting substations. The expectation is that the model reaches also to the 50% percentiles and 95% percentiles of the measured harmonic voltage magnitudes in the receiving substations. This expectation is from analysis of the harmonic measurements by the gain factors and relationships of the harmonic amplification between certain emitting and receiving substations described in the previous subsection B.

The Thevenin harmonic voltage sources require both magnitudes and phase angles of each included harmonic order. Adjustment of the phase angles of the Thevenin sources is part of the method. Adjustment of the phase angles shall result in that the simulated harmonic voltage distortion matches the measured harmonic voltage magnitudes for all significant harmonic orders, i.e. greater than 0.1%. It is important to emphasise that once adjusted the phase angles are locked (so not adjusted any longer) for all other simulated cases.

Adjustment of the phase angles starts with the Thevenin sources in VHA (KS12) and FGD (SB1). The adjustment step is 15°. The phase angle of the Thevenin source in VHA is kept 0°, and the phase angle of the Thevenin source in FGD is stepped by 15° starting from 0° to 345° (= –15°). This adjustment shall result in a closest possible match between the simulated and measured harmonic voltage magnitudes in the substations TRI and LAG.

The adjustment continues with including the third Thevenin source in TJE (SK3). The number of possible combinations increases drastically when the third source is part of the adjustment. Table I presents the final adjustment round of the phase angles of the three Thevenin sources with the labelled combinations – the phase angle sets.

The final adjustment shall result in the best possible match between the simulated and measured harmonic voltage magnitudes in all the receiving substations. Therefore, the phase angle sets resulting from the adjustment of the two Thevenin sources is only a starting point of and, if necessary, can be changed during the final adjustment round with the three Thevenin sources.

The result is that the phase angle sets no. 9 through no. 10 of Table I, which represent the phase angles VHA: 0°, FGD: 135…150°, and TJE: -150…-135°, give the best possible match of the simulated harmonic voltage distortions in all the substations. Fig. 7 presents graphically the phase angles of these three emitting substations (relatively to the substation VHA keeping 0°).

TABLE I. COMBINATIONS (ANGLE SETS) OF PHASE ANGLES OF THEVENIN HARMONIC VOLTAGE SOUCES DURING FINAL ADJUSTMENT.

Angle Set	Phase Angle (deg.)		
	VHA (KS12)	FGD (SB1)	TJE (SK3)
0	0	0	0
1	0	15	-15
2	0	30	-30
3	0	45	-45
4	0	60	-60
5	0	75	-75
6	0	90	-90
7	0	105	-105
8	0	120	-120
9	0	135	-135
10	0	150	-150
11	0	165	-165
12	0	180	180
13	0	-165	165
14	0	-150	150
15	0	-135	135
16	0	-120	120
17	0	-105	105
18	0	-90	90
19	0	-75	75
20	0	-60	60
21	0	-45	45
22	0	-30	30
23	0	-15	15

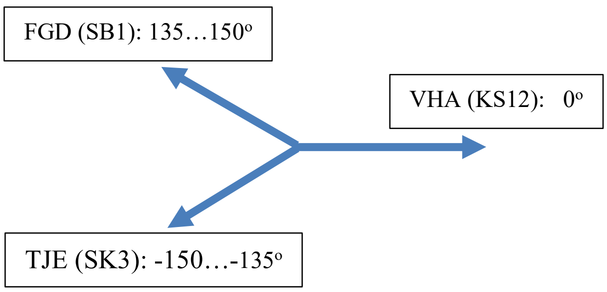


Fig. 7. Illustration of the phase angle displacement of the Thevenin harmonic voltage sources of the emitting substations VHA, FGD and TJE for assessment and evaluation of the passive-part of the model.

This result is verified in Table II, Table III, and Table IV, for the three substations EDR, TRI and KAS for the 95% percentiles of the harmonic voltage magnitudes. The results are presented for the 3rd, 5th, 7th, 11th and 13th harmonic orders among the significant harmonic orders.

As seen from the comparison presented in Table II, Table III and Table IV, the simulated harmonic voltage distortion is in good agreement with the measured harmonic magnitudes for all shown significant harmonic orders.

The three Thevenin harmonic voltage sources in VHA, TJE and FGD use symmetrical harmonic phase voltages as the inputs. The measurements have confirmed that the harmonic phase voltages are (almost) symmetrical in these three substations, see Fig. 3 for VHA and FGD. The simulated harmonic phase voltages in the shown receiving substations are also symmetrical except of the 3rd and 11th harmonic voltages in the substation TRI. Especially the simulated 11th harmonic voltage in TRI is with a strong asymmetry of the phase voltages becoming noticeable due to the excessive magnitude.

TABLE II. MEASURED AND SIMULATED HARMONIC VOLTAGE DISTORTION IN % IN THE 400 KV SUBSTATION ENDRUP (EDR). THE SIMULATION IS USING FINAL ADJUSTMENT OF THE PHASE ANGLE SETS.

Harmonic Order	3	5	7	11	13
Measured	0.14%	0.14%	0.38%	0.75%	0.42%
Simulated	0.14..0.16%	0.06..0.12%	0.35..0.38%	0.61..0.89%	0.45..0.46%
Evaluation	Good	Good	Good	Good	Good

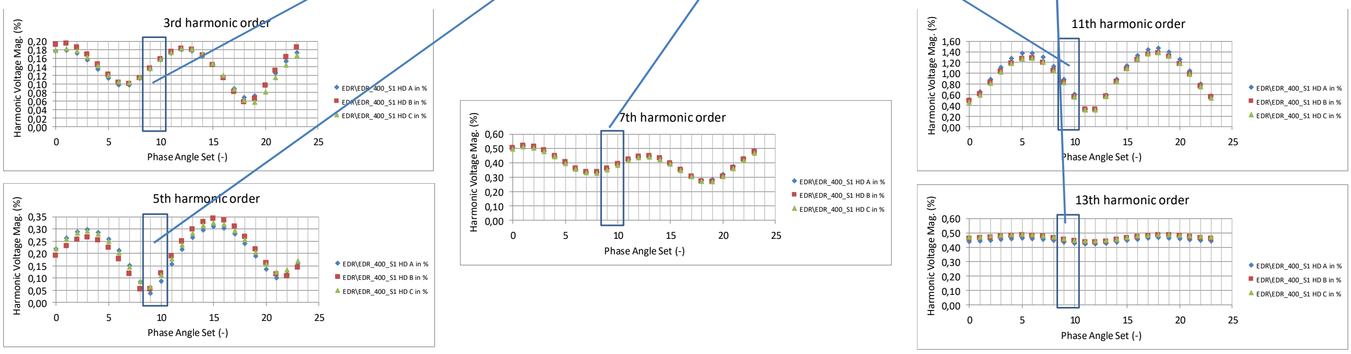


TABLE III. MEASURED AND SIMULATED HARMONIC VOLTAGE DISTORTION IN % IN THE 400 KV SUBSTATION TRIGE (TRI). THE SIMULATION IS USING FINAL ADJUSTMENT OF THE PHASE ANGLE SETS.

Harmonic Order	3	5	7	11	13
Measured	0.15%	0.13%	0.19%	1.47%	0.67%
Simulated	0.09..0.13%	0.15..0.16%	0.23..0.26%	1.42%	0.38%
Evaluation	Good	Good	Good	Good	Needs Improvement

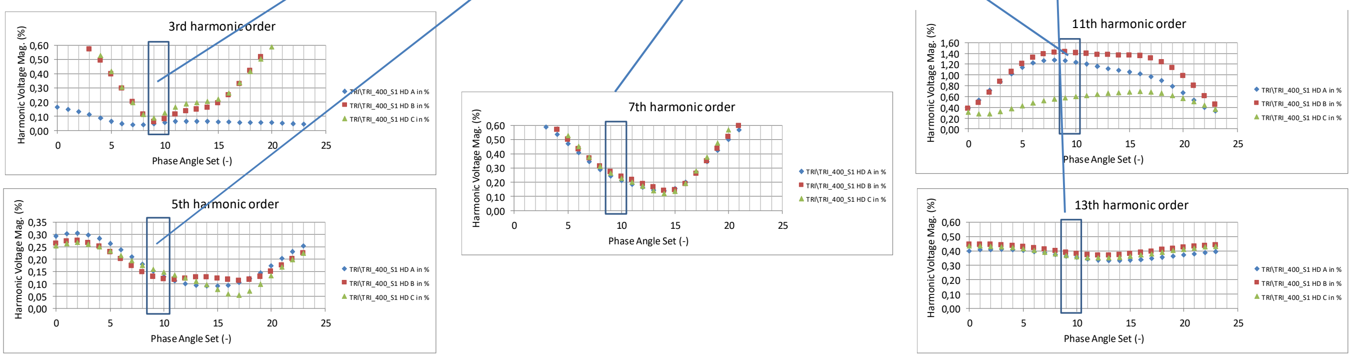
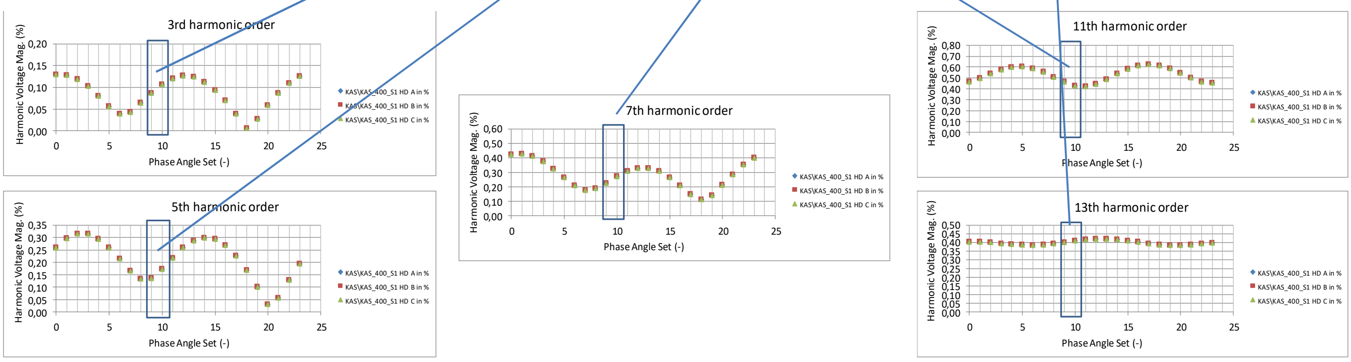


TABLE IV. MEASURED AND SIMULATED HARMONIC VOLTAGE DISTORTION IN % IN THE 400 KV SUBSTATION KASSØ (KAS). THE SIMULATION IS USING FINAL ADJUSTMENT OF THE PHASE ANGLE SETS.

Harmonic Order	3	5	7	11	13
Measured	0.10%	0.13%	0.32%	0.46%	0.43%
Simulated	0.09..0.11%	0.14..0.17%	0.23..0.27%	0.43..0.46%	0.40..0.42%
Evaluation	Good	Good	Neutral	Good	Good



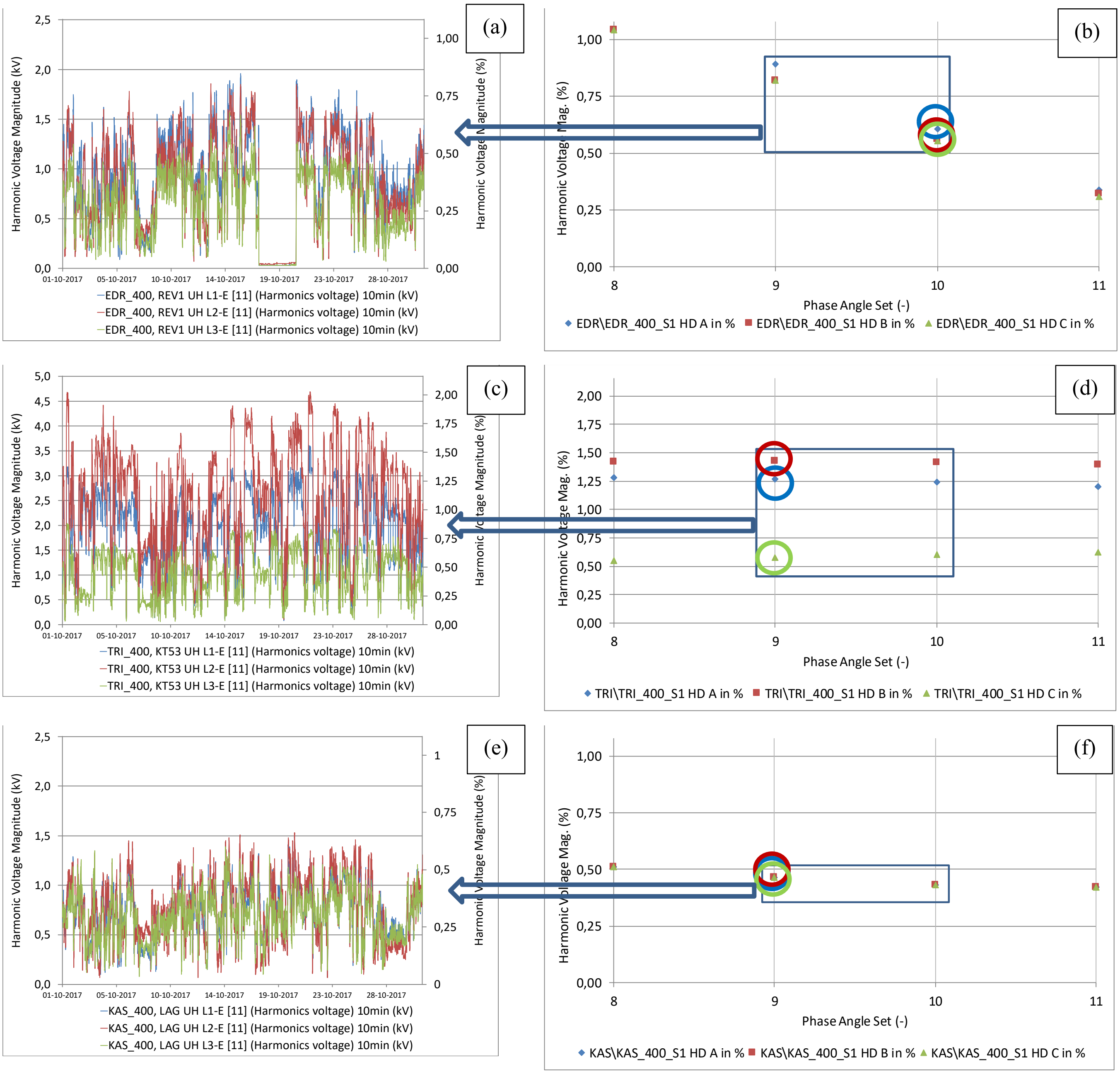


Fig. 8. The 11th harmonic phase voltage magnitudes: (a) - measured ten-minute-resolution and (b) – simulated for the best match phase-angle sets in the substation EDR, (c) - measured ten-minute-resolution and (d) – simulated for the best match phase-angle sets in the substation TRI, (e) - measured ten-minute-resolution and (f) – simulated for the best match phase-angle sets in the substation KAS. Both measured and simulated phase voltages are symmetrical in EDR and KAS, and strongly asymmetrical in TRI. Good agreement between measurements and simulations.

Fig. 8 compares the measured and simulated 11th harmonic phase voltages in the substations EDR, TRI and KAS. Both measured and simulated 11th harmonic phase voltages in EDR and KAS are symmetrical. Both measured and simulated 11th harmonic phase voltages in TRI are strongly asymmetrical. In fact, this comparison has not only confirmed sufficient accuracy of the model, but also accuracy of the measurements in TRI, which previously has been considered as the measurement needing improvement.

There are two principal partial conclusions of this presentation:

1. The passive-part of the transmission grid model is accurate and adequate for the harmonic assessment of Denmark-West.
2. The phase angle of the harmonic emission sources is essential for accuracy of the simulation results and, therefore, must be included in the model.

Once adjusted into a right position, the phase angles of the harmonic emission sources shall be kept locked. The slack terminal shall absorb the cumulative deviations of the phase angles of each harmonic order.

D. Active part and feedback – Harmonic emission sources

The harmonic emission of the HVDC converter stations is represented with the vendor-specific characteristics.

The vendor-specific characteristics of the LCC HVDC converter stations in Denmark-West include the maximum harmonic current magnitudes of the 2nd through the 50th harmonic orders. The harmonic current magnitudes are nonlinear dependencies of the power transport through the converter stations, which represent the harmonic emission sources of the harmonic assessment model of Denmark-West.

There is no information on mutual phase angle displacements between the HVDC converter stations or between the distributed harmonic sources across the transmission grid. Therefore, the phase angles of the harmonic emission sources of the LCC HVDC converter stations shall be adjusted in a similar manner as in the previous subsection C for the Thevenin harmonic voltage sources.

The harmonic emission of the OWPP, such as Anholt in the 220 kV system level, is also included with harmonic magnitudes which are dependent of the power production.

The distributed harmonic emission sources (and absorption) under the 150 kV substations account for the industrial loads, converter-interfaced power generation, and converter-interfaced and conventional consumption. The distributed harmonic sources have the 2nd, 3rd, 5th, and 7th harmonic orders as the most significant contributions in Denmark-West in the range up to the 50th harmonic order. The distribution harmonic sources are represented with generic-level models. Each harmonic order ranges few types of the generic-level representations which distinguish by the magnitudes and phase angles of the harmonic current emission. The different magnitudes account for the different intensity of the harmonic emission sources. The necessity of the phase angles is due to the following explanation:

- When the two harmonic sources with the same magnitudes are in the same substation and in-phase with each other, the sum harmonic contribution is amplified.
- When the sources are in the same substation and in-opposite-phase with each other, the sum harmonic contribution is reduced or cancelled.
- When the harmonic sources are in two different substations, the outcome such as either amplification or reduction becomes also dependent of the harmonic impedance between the harmonic source substations and the point-of-evaluation substations. In the meshed transmission grid, the outcome can be amplification in the one point-of-evaluation and reduction in the other point-of-evaluation.

Therefore, the sum harmonic contributions of the 2nd, 3rd, 5th and 7th orders in the different 400 kV substations become dependent from the magnitudes and phase-angles of the distributed harmonic emission sources under the 150 kV substations.

The harmonic emission of the LCC HVDC converter substations and that of the OWPP, which are grid-connected through the long 220 kV cables (and further to the 400 kV grid), dominate the 11th and higher harmonic voltage distortion in the 400 kV grid of Denmark-West.

Both LCC HVDC and distributed harmonic emission sources under the 150 kV substations define the 7th and lower harmonic voltage distortion in the 400 kV grid of Denmark-West.

Complete data of the above-mentioned emission sources, which are needed for the harmonic assessment, are not available. Therefore, incompleteness of the available data is filled up using series of adjustments followed up by validation against the measured harmonic voltage distortion in the 400 kV substations. Since incomplete data are of different character, refer to the different harmonic orders and by the different emission sources, the adjustment series are conducted separately:

- First, the LCC HVDC converter stations and OWPP are adjusted to comply with the measured 11th and higher harmonic voltage distortion in the 400 kV grid.
- Next, the distributed harmonic sources are adjusted to match the measured 7th and lower harmonic voltage distortion in the 400 kV transmission grid.
- The simulation results of each adjustment series are validated from the measured harmonic voltage distortion in the 400 kV substations. This implies that the validation cases are already prepared the measurements are acquired according to the description of subsection A.

Fig. 9 presents the model setup for the harmonic assessment of the 400 kV transmission grid of Denmark-West. In this model, the harmonic emission sources are the harmonic current sources. The points-of-evaluation are all the 400 kV substations, including the substations with the harmonic current sources.

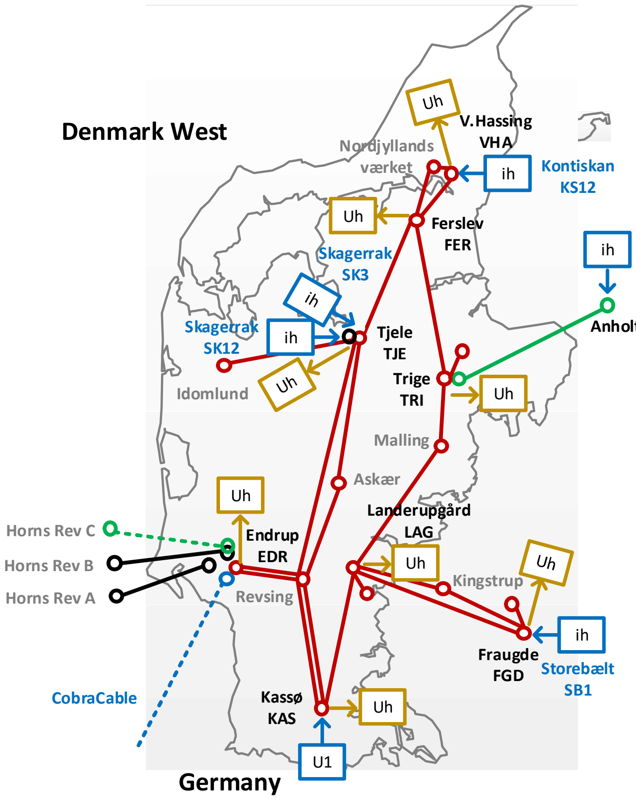


Fig. 9. Model of the 400 kV meshed transmission grid of Denmark-West with multiple harmonic emission sources. All substations are the points of evaluation → Uh with the harmonic voltage distortion superimposed from the harmonic emission sources ← ih . The harmonic voltage distortion in each substation is induced by its own harmonic emission sources as well as by the harmonic emission sources of the other substations.

The harmonic voltage distortion in each 400 kV substation becomes superposition of the harmonic emission sources originated from its own and the other substations of the transmission grid. In this model setup, the harmonic voltage distortion is influenced by the harmonic filters. This model setup is applied for the adjustment of the harmonic emission sources and validation against the measured harmonic voltage distortion.

1) HVDC Converter Stations and OWPP

First, the harmonic current sources of the LCC HVDC converter stations shall include the phase angles. The phase angles are applied as relative angles between the harmonic current and harmonic voltage vectors of each harmonic order, i.e. up to the 50^{th} harmonic order. The phase angle displacements between the harmonic voltages which are found for the Thevenin harmonic voltage sources in subsection C during the passive-part assessment, are applied as the initial values of the adjustment process. The final result is KS12: 0°, SB1: -15°, SK3: -165°, and in the 150 kV level, SK12: -150°, giving the best match between the simulated and measured harmonic voltage distortion in all the 400 kV substations (with available PQ-measurements).

Fig. 10 illustrates the final result of the phase angles applied in the harmonic current sources of the LCC HVDC converter stations.

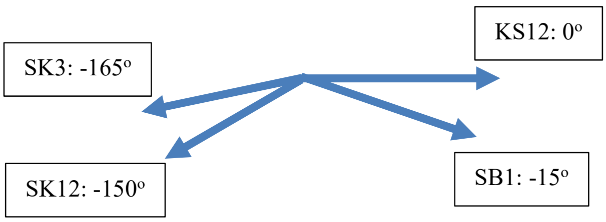


Fig. 10. Illustration of the harmonic current phase angles relative to the harmonic voltage phase angles of the harmonic current sources of the LCC HVDC converter stations KS12 (VHA), SB1 (FGD), SK3 and SK12 (TJE) for assessment and validation of the active-part and feedback of the model.

The harmonic current source representing the Anholt OWPP has been adjusted at this model development stage and reapplied in the passive-part model evaluation, the previous subsection C. This approach is for reducing the adjustment complexity of the phase angles of the Thevenin harmonic voltage sources, so that inclusion of one more Thevenin source in the adjustment loop has been avoided.

2) Distributed Harmonic Emission Sources

Next, the distributed harmonic emission sources are to be adjusted for both magnitudes and phase angles. Since each generic-level representation of the distributed sources is typified by sets of specific magnitudes and phase angles of each harmonic order, the “adjustment” is conducted by applying those generic-level representations under the 150 kV substations. The “adjustment” continues until the harmonic model response matches with the measured harmonic voltage distortion.

The measurements show that the 7^{th} and lower harmonic voltage distortion in the different 150 kV substations vary daily (consumption and PV power generation profiles vary over a day), weekly (cycles of industrial loads) and seasonal (more consumption and less PV generation in cold, cloudy months and opposite in warm, sunny months). The target has been to match the 95% percentiles of the 7^{th} and lower harmonic voltage distortion and not daily, weekly or seasonal variations of these harmonic orders under each 150 kV substation. Therefore, the resulting adjustment of the distributed harmonic sources shall end up with a realistic conservative approach for the 7^{th} and lower harmonic voltage distortion in the 400 kV substations. Some discrepancy between the measured and simulated results, which do not affect investment decisions in e.g. harmonic filters, will be expected and accepted in the simulation results.

The adjustment has resulted in inclusion of, in round figures, 400 harmonic emission source models under the 150 kV substations.

3) Model Adjustment

Once adjusted, the models of the harmonic emission sources of all components are locked. Changes in the model data are no longer permitted, unless necessary due to a significant change in the transmission grid, such as the transmission grid expansion followed by change of the harmonic emission of the existing sources or establishment of more harmonic emission sources.

4) Harmonic Phase Voltage Symmetrization

The symmetrization procedure becomes useful to conduct for the operation scenarios where violation of the planning level relates to strong asymmetrical simulated behaviour of the harmonic phase voltages.

The harmonic current emission sources of the LCC HVDC converter stations are represented by the vendor-specific maximum harmonic current magnitudes, i.e. a single current magnitude for each phase for each harmonic order. The harmonic current sources of the distributed harmonic emission sources are also given by a single current magnitude for each phase for each harmonic order. This representation is applied because there is no provided data on asymmetry of the harmonic emission sources. Such asymmetry will also be dependent from the operation conditions of both harmonic emission sources and transmission grid. The applied representation of the harmonic emission sources results in the harmonic emitted currents are symmetrical for each harmonic order.

The harmonic impedance is phase asymmetrical which is obvious from the flat layout topologies of the underground cables [2] and asymmetry of the conductor topologies of several OHL and indicated by the results of Fig. 8.

Application of the symmetrical harmonic phase currents as the emitting sources of the model leads to comparison of the asymmetrical harmonic phase voltages (reached in the simulations) with the measurements showing symmetrical harmonic phase voltages. Due to excessive complexity of the presented model and uncertainty of the data related to the harmonic emission sources, it is practically unfeasible to resolve the above described issue of how to align on symmetry versus asymmetry of the harmonic phase voltages in the simulations for each substation and for each simulated scenario.

However, the principal question is whether the expected discrepancy due to (a)symmetry of the simulated harmonic phase voltages introduces significant differences between the measured and simulated maximum harmonic phase voltage magnitudes around the planning levels. For answering this question, a simulation procedure of harmonic phase voltage symmetrization has been added to the representation of the harmonic current sources.

This procedure is demonstrated for the 11th, 13th, 23rd and 25th harmonic orders of the three LCC HVDC converter stations in Denmark-West. The operation scenario is presented in Table V and corresponds to a specific day of 2019. The power transport is in % of the power capacities listed in Section III. The 400 kV transmission grid is in (n-0) operation conditions.

TABLE V. OPERATION CONDITIONS OF HVDC CONVERTER STATIONS IN DENMARK-WEST.

HVDC / OWPP	SB1	KS12	SK3	SK12	Anholt
Power (%)	10%	75%	75%	100%	100%
Filters in-service	1	3	4	2	NA
Filters in total	4	6	4	3	NA

The procedure starts with conducting an initial harmonic load-flow using the vendor-specific, symmetrical, harmonic current emission into the grid model. When the initial harmonic load-flow results in asymmetrical harmonic phase voltages in the LCC HVDC substations, the procedure assigns additional harmonic current contributions to the harmonic current sources of the LCC HVDC converter station models. The additional contributions are calculated for all the harmonic source models of the LCC HVDC converter stations, and not only for the converter station located in the substation with significant phase voltage asymmetry, because the harmonic voltages in the grid are influenced by all the harmonic emission sources – feedback of the model.

The demonstration example is chosen with the two LCC HVDC converter stations with high power transports and the one station with low power transport. The example shows that the converter station with lower power transport is most affect by additional asymmetrical current contributions of the two other converter stations with high power transports and less so by additional asymmetrical current contributions of its own converter station.

Thus, all the emitting converter stations participate in the harmonic phase voltage symmetrization of the given substation. The additional harmonic current contributions are assigned for relevant harmonic orders and in a way that the additional contributions do not change the sum of the phase currents of those harmonic orders with reference to the vendor-specific data. The target is that only the harmonic phase voltage symmetrization is conducted without affecting the harmonic voltage distortion in the LCC HVDC substation as such.

Fig. 11, Fig. 12 and Fig. 13 present the results of the harmonic phase voltage symmetrization procedure for the substations FGD, VHA, and TRI, respectively.

The additional harmonic current contributions in % are given in Table VI. As seen, the minor contributions producing asymmetry of harmonic currents are in position to symmetrize and bring the simulated harmonic voltage distortion of the LCC HVDC substations inline with the harmonic measurements.

The results of the symmetrization procedure of the simulated harmonic voltage phase are:

1. The simulated 11th and 13th harmonic phase voltages of the LCC HVDC substations are more symmetrical, which is inline with the harmonic measurements.
2. The simulated 7th and lower harmonic order voltages are not affected and remain asymmetrical, because not included in the conducted symmetrization.
3. The asymmetry of the simulated harmonic phase current is smaller than 5% of the rated current. This magnitude range is confirmed by the largest magnitude of the fundamental current which is within 5% and the largest contributions are seen in Northern Jutland (the substations VHA, NVV and FER in Fig. 1).
4. The largest additional phase current asymmetry is in the north of the transmission grid. The symmetrization procedure assigns the KS12 harmonic current source the largest asymmetrical contributions, according to Table VI.

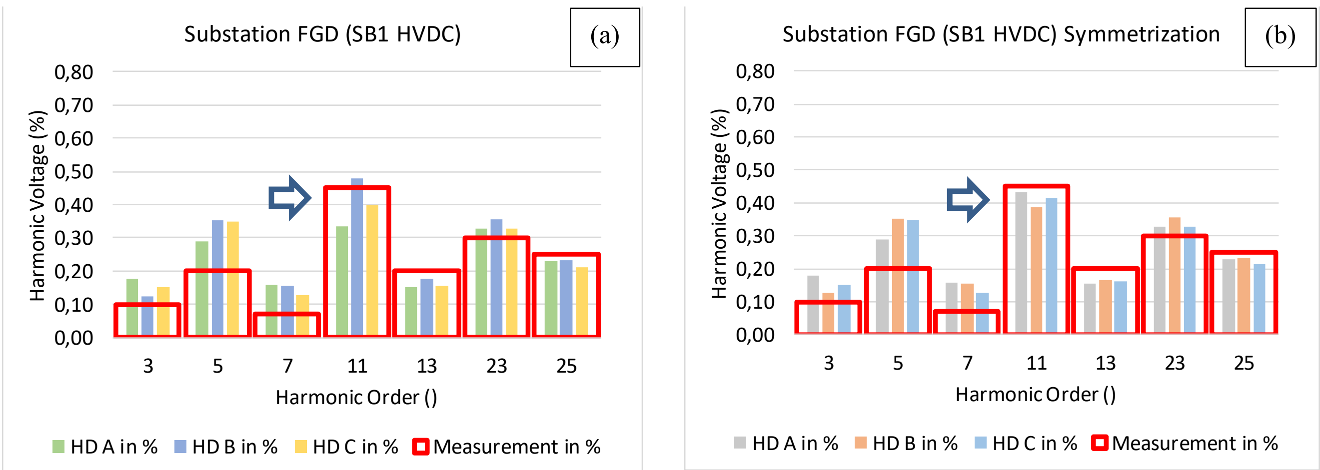


Fig. 11. Comparison of the measured and simulated harmonic voltage distortion of the 400 kV substation FGD (SB1 LCC HVDC converter station) with: (a) – an initial harmonic load-flow with noticeable asymmetry of the 11th harmonic phase voltages, (b) – harmonic load-flow after the phase voltage symmetrization with increased symmetry. Compare to Fig. 3 for the measured symmetrical behaviour of the 11th harmonic phase voltages in FGD. The 13th harmonic phase voltage symmetry is also improved after the symmetrization procedure.

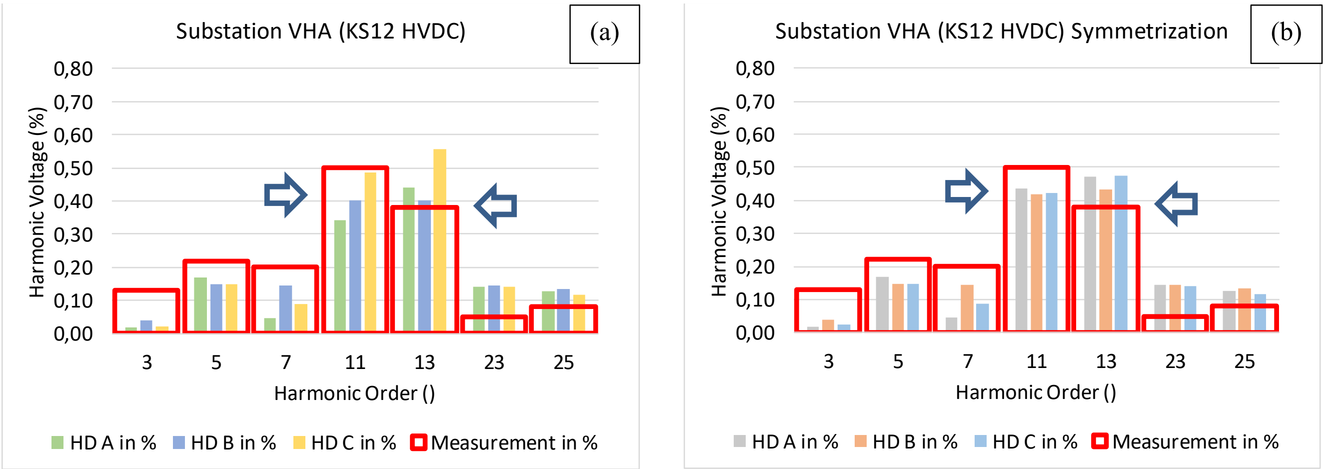


Fig. 12. Comparison of the measured and simulated harmonic voltage distortion of the 400 kV substation VHA (KS12 LCC HVDC converter station) with: (a) – an initial harmonic load-flow with noticeable asymmetry of the 11th and 13th harmonic phase voltages, (b) – harmonic load-flow after the phase voltage symmetrization with increased symmetry. Compare to Fig. 3 for the measured symmetrical behaviour of the 11th harmonic phase voltages in VHA.

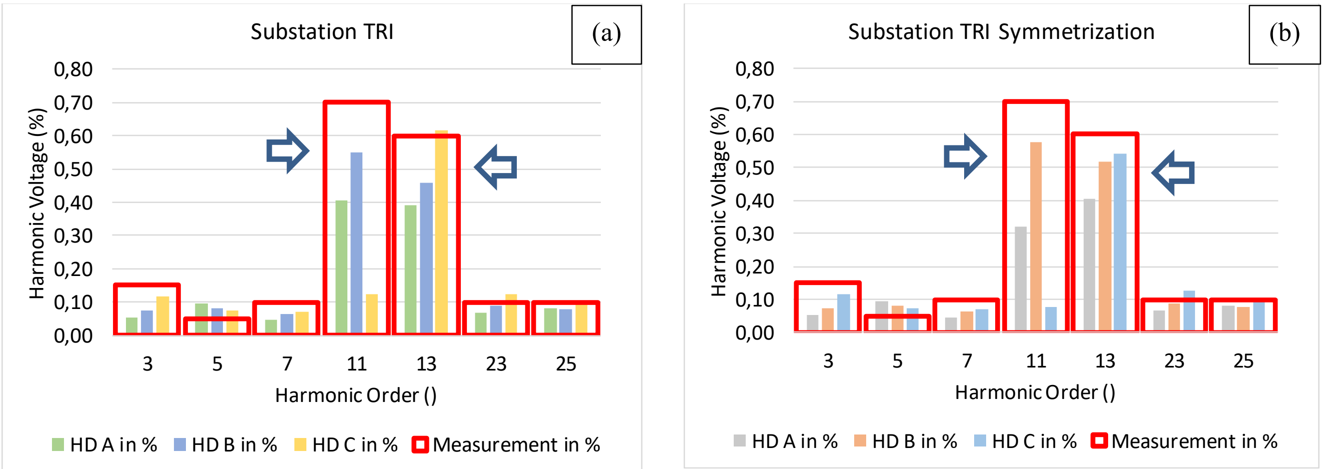


Fig. 13. Comparison of the measured and simulated harmonic voltage distortion of the 400 kV substation TRI with: (a) – an initial harmonic load-flow, (b) – harmonic load-flow after the phase voltage symmetrization in the LCC HVDC substations. Compare to Fig. 3 for the measured strongly asymmetrical behaviour of the 11th harmonic phase voltages in this substation.

TABLE VI. ADDITIONAL HARMONIC CURRENT CONTRIBUTIONS IN % TO VENDOR-SPECIFIC (SYMMETRICAL) PHASE CURRENT MAGNITUDES RESULTING FROM SYMMETRIZATION PROCEDURE.

HVDC Station	Harmonic Order	Added Contribution in Phase (%)			Sum
		A	B	C	
KS12	11	2	-3	1	0
KS12	13	-2	-1	3	0
SK3	11	1	1	-2	0
SB1	11	-1	2	-1	0

This presentation shows that symmetrization of the simulated harmonic phase voltages does not result in significant change of the simulated harmonic voltage distortion in the 400 kV substations in comparison to the measurements.

E. Validation and Harmonic Margins

The model validation is conducted using consecutive measured sequences with changed operation conditions of the LCC HVDC converter stations and the 400 kV transmission lines brought in- and out-of-service.

1) Harmonic Margins

The target of the model validation is not only confirming good alignment between the measured and simulated harmonic voltage distortion across the 400 kV transmission grid, but also alignment with the harmonic margins. The harmonic margins show how much "headroom" there is between the present harmonic distortion and the planning level in the given substation for each harmonic order.

Energinet needs to know the harmonic margins, as these are integral in setting the harmonic emission limits for grid connected plants [6]. Among the reasons there is also timely and accurate specification of mitigation solutions, i.e. design and location in the grid of the harmonic filters, when the simulations foresee that the harmonic margins will be exhausted or violated due to planned grid expansion.

Table VII presents the gradation of the harmonic margins which is applied in this presentation. Energinet follows the harmonic voltage distortion planning level of the IEC standard [4]. The harmonic margins are defined according to the planning level of [4] for each harmonic order.

The harmonic margins have become a commodity due to both rapidly increasing penetration of the converter-interfaced transmission, production and consumption units, and transmission grid expansion with more extensive usage of underground cables. Conducted together, this grid development accelerates the harmonic amplification, which is why the transmission grid model for the harmonic assessment shall be accurate in calculations of both harmonic distortion and harmonic margins of the present grid and for the grid planning under uncertainty of where in the grid and which next units will be connected.

2) Validation Cases

The presented validation cases originate from a consecutive operation scenario, which is measured in the transmission grid on Sept. 3rd through Sept. 4th 2017.

The presented validation cases are from a different period comparing to the period where the measurements have been applied for the final numerical tuning of the simulation model. Successful validation shall strength validity and confidence of the simulation model and the applied method.

Table VIII presents the operation conditions of the grid in the four presented validation cases. Fig. 14, Fig. 15, Fig. 16, and Fig. 17, show the measured 95% percentiles (over two-hour averaging periods) harmonic voltage magnitudes of the significant harmonic orders in the LCC HVDC substations VHA (KS12) and FGD (SB1) and in the substations TRI and EDR. The instances of the four validation cases are marked in the measured harmonic voltage plots by the case letters A through D.

The measured operation conditions of the HVDC converter stations and the transmission grid (with the 400 kV components either in- or out-of- service) are entered in the model of Denmark-West. The harmonic load-flow is the method of the assessment.

The measured and simulated harmonic voltage distortions are compared and presented in Fig. 14, Fig. 15, Fig. 16, and Fig. 17, together with the consecutive plots of the measured harmonic voltages. The simulated harmonic voltages are shown by the maximum phase voltage magnitudes. These maximums are also applied for definition of the simulated harmonic margins of each significant harmonic order.

The measurements and simulations are in good agreement for both direct comparison between the harmonic voltage magnitudes and for the harmonic margins.

The validation shows that the simulations and measurements are in good agreement for all significant harmonic orders, i.e. the harmonic voltage distortion is greater than the 0.1% threshold [4].

This successful outcome is for the 400 kV substations with the different locations in Denmark-West and for the operation conditions with a 400 kV line brought out-of-service, and a significant HVDC converter station is taken out of the "model equation" – the cases with KS12 out-of-service.

The discrepancies are mostly present for the harmonic voltage magnitudes much below the planning level and with sufficient harmonic margins. This outcome is expected due to the conservative adjustment approach of the model and uncertainty of the data.

TABLE VII. GRADATION OF HARMONIC MARGINS IN %. 100% DENOTES THE PLANNING LEVEL OF THE GIVEN HARMONIC ORDER.

Gradation in % of the planning level		Interpretation
	Below 70%	Sufficient harmonic margin. No mitigation action needed. Discrepancy between the simulations and measurement has inferior character, when both simulated and measured harmonic distortion remains below this margin.
	Above 70% and below 90%	Harmonic margin filling up. Attention needed. Minimum harmonic limits may be applied to future grid connected plants Only minor discrepancy between the simulations and measurements is permitted. Alignment of both simulated and measured harmonic distortion being within these margin limits, with minor discrepancy only.
	Above 90% and below 100%	Exhausted harmonic margin. Immediate attention needed. Action with mitigation measures can be needed. Alignment of both simulated and measured harmonic distortion being within these margin limits, with minor discrepancy only.
	Above 100% and below 150%	Exceeded harmonic margin. Action needed. Mitigation measures needed before grid-connection of the next customer permitted. Alignment of both simulated and measured harmonic distortion being within these margin limits, with minor discrepancy only.
	Above 150%	Severely exceeded harmonic margin. Immediate action with mitigation measures required. Alignment of both simulated and measured harmonic distortion being within these margin limits, with minor discrepancy only.

TABLE VIII. OPERATION CONDITIONS OF HVDC CONVERTER STATIONS IN DENMARK-WEST FOR PRESENTED VALIDATION CASES.

Validation Case:	**A (n-0)**				
HVDC / OWPP	SB1	KS12	SK3	SK12	Anholt
Power (%)	100%	100%	100%	100%	25%
Filters in-service	3	4	3	2	NA
Filters in total	4	6	4	3	NA

Validation Case:	**B (n-0)**				
HVDC / OWPP	SB1	KS12	SK3	SK12	Anholt
Power (%)	50%	100%	100%	100%	25%
Filters in-service	1	4	3	2	NA
Filters in total	4	6	4	3	NA

Validation Case:	**C (n-1): KS12 HVDC converter station out-of-service**				
HVDC / OWPP	SB1	KS12	SK3	SK12	Anholt
Power (%)	75%	0%	25%	100%	25%
Filters in-service	2	0	1	2	NA
Filters in total	4	6	4	3	NA

Validation Case:	**D (n-2): KS12 HVDC converter station and FER-NVV 400 kV line out-of-service**				
HVDC / OWPP	SB1	KS12	SK3	SK12	Anholt
Power (%)	100%	0%	100%	100%	25%
Filters in-service	3	1	3	2	NA
Filters in total	4	6	4	3	NA

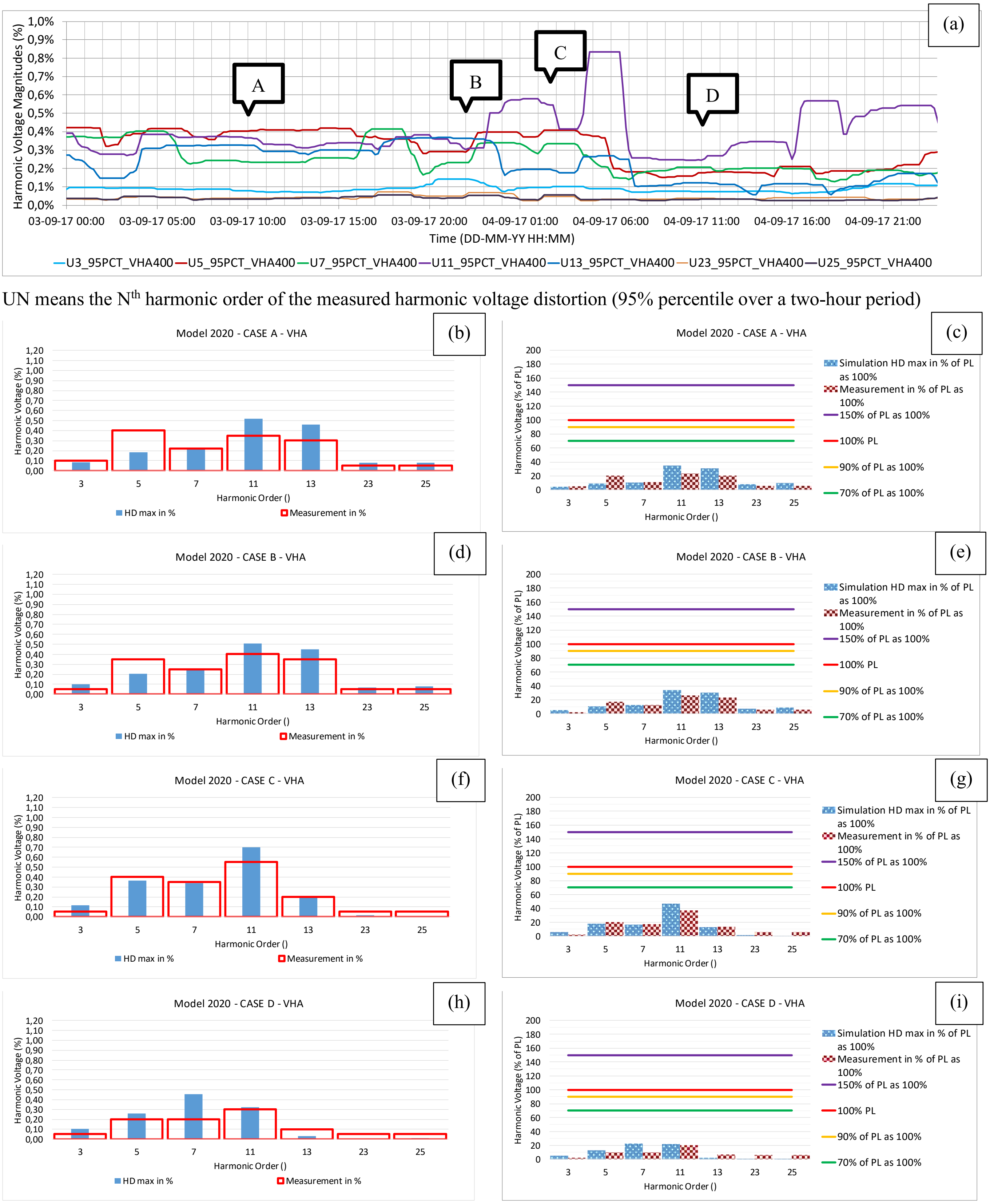


Fig. 14. Hamonic voltage distortion in the 400 kV substation VHA (KS12): (a) – measured and presented as 95% percentiles over two-hour window with marking of the validation cases from A to D, (b) – comparison of the measured and simulated harmonic voltages and (c) – of the measured and simulated harmonic margins of the validation case A, (d) – comparison of the measured and simulated harmonic voltages and (e) – of the measured and simulated harmonic margins of the validation case B, (f) – comparison of the measured and simulated harmonic voltages and (g) – of the measured and simulated harmonic margins of the validation case C, (h) – comparison of the measured and simulated harmonic voltages and (i) – of the measured and simulated harmonic margins of the validation case D. The model is in good agreement with the harmonic measurements.

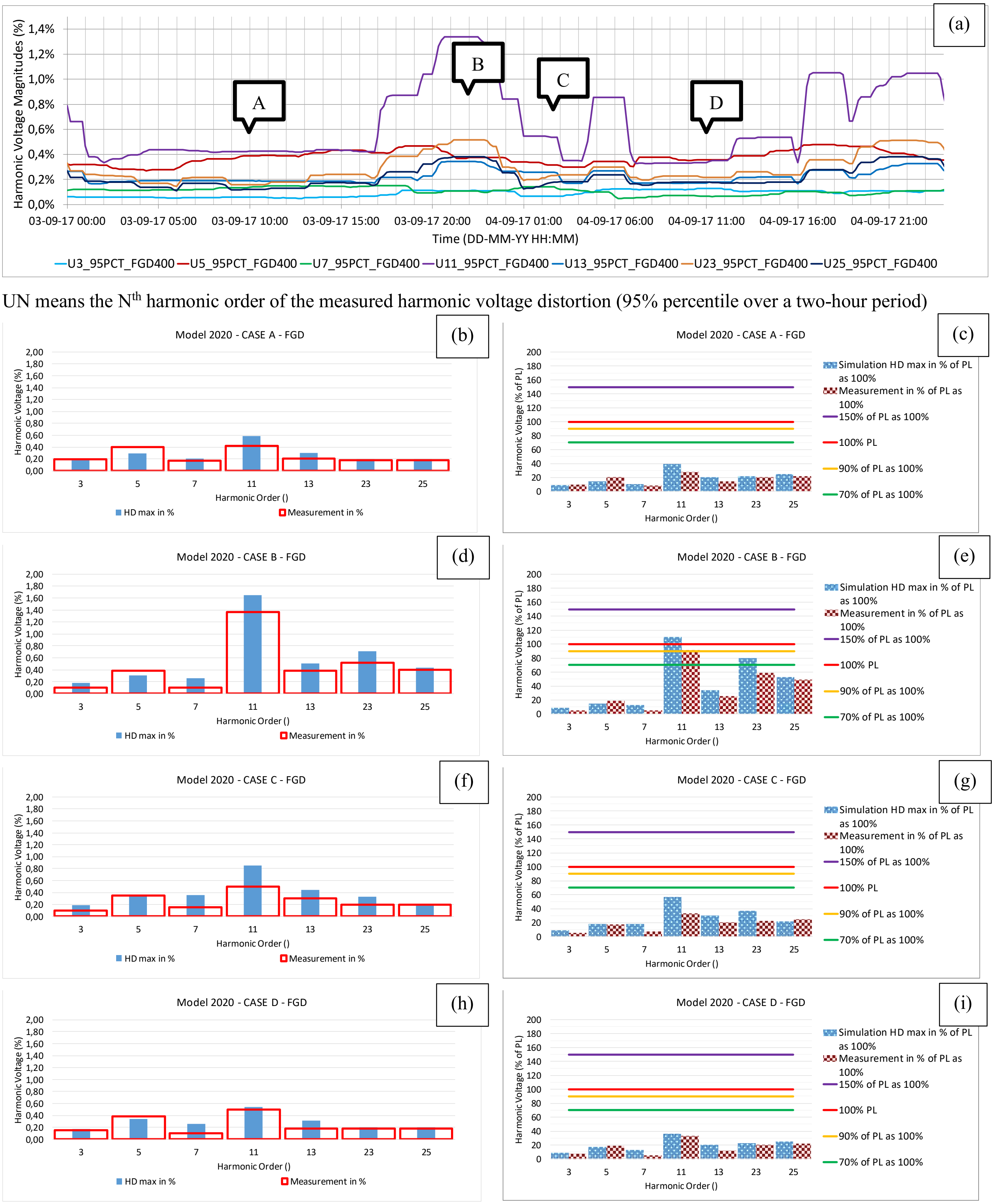
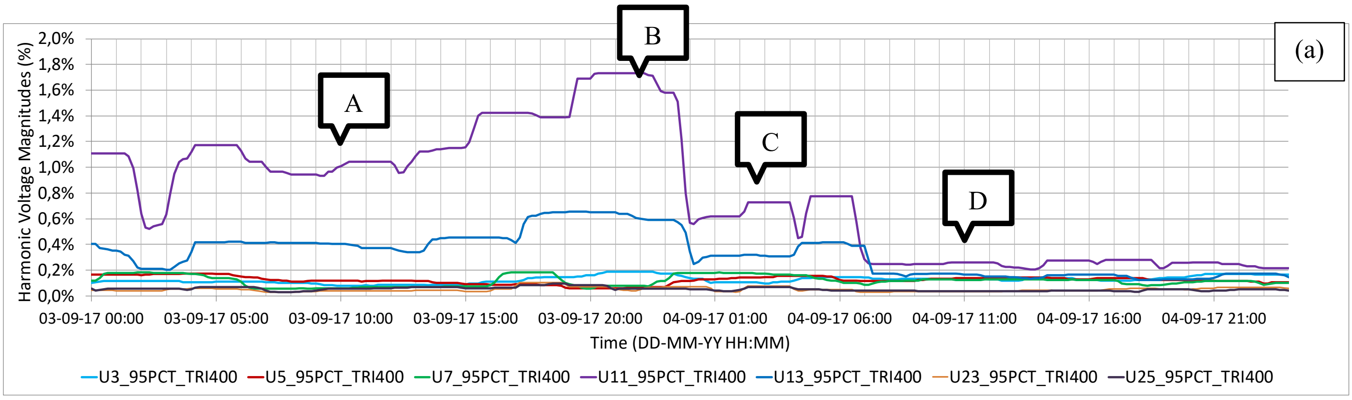


Fig. 15. Hamonic voltage distortion in the 400 kV substation FGD (SB1): (a) – measured and presented as 95% percentiles over two-hour window with marking of the validation cases from A to D, (b) – comparison of the measured and simulated harmonic voltages and (c) – of the measured and simulated harmonic margins of the validation case A, (d) – comparison of the measured and simulated harmonic voltages and (e) – of the measured and simulated harmonic margins of the validation case B, (f) – comparison of the measured and simulated harmonic voltages and (g) – of the measured and simulated harmonic margins of the validation case C, (h) – comparison of the measured and simulated harmonic voltages and (i) – of the measured and simulated harmonic margins of the validation case D. The model is in good agreement with the harmonic measurements except of the model overestimates the 11th and 23rd harmonic orders in stressed conditions of the cases B and the 11th harmonic order in the case C.



UN means the N^th^ harmonic order of the measured harmonic voltage distortion (95% percentile over a two-hour period)

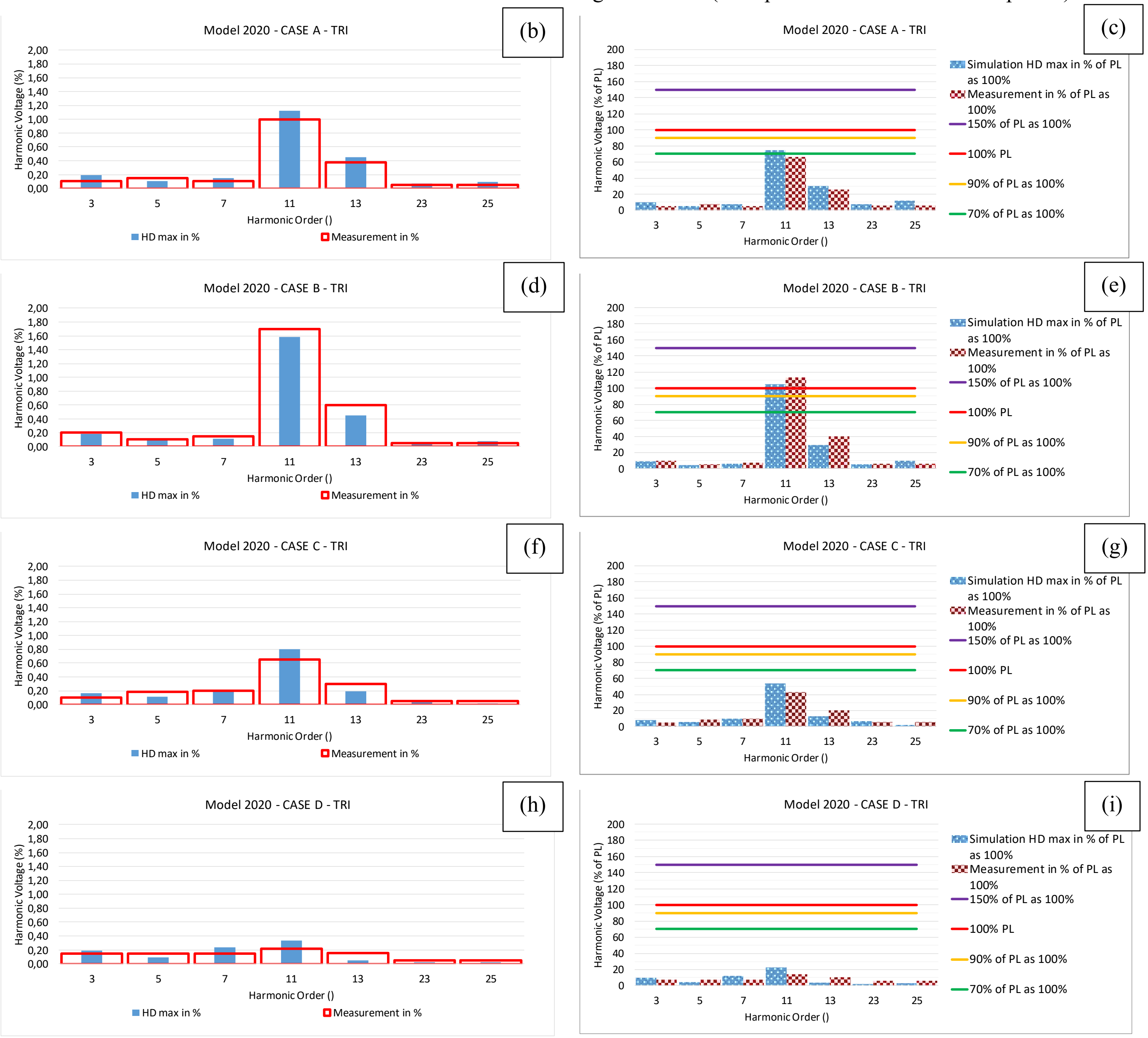


Fig. 16. Hamonic voltage distortion in the 400 kV substation TRI: (a) – measured and presented as 95% percentiles over two-hour window with marking of the validation cases from A to D, (b) – comparison of the measured and simulated harmonic voltages and (c) – of the measured and simulated harmonic margins of the validation case A, (d) – comparison of the measured and simulated harmonic voltages and (e) – of the measured and simulated harmonic margins of the validation case B, (f) – comparison of the measured and simulated harmonic voltages and (g) – of the measured and simulated harmonic margins of the validation case C, (h) – comparison of the measured and simulated harmonic voltages and (i) – of the measured and simulated harmonic margins of the validation case D. The model is in good agreement with the harmonic measurements. Especially accuracy of the stressed cases A and B is significant for right decisions on the mitigation measures.

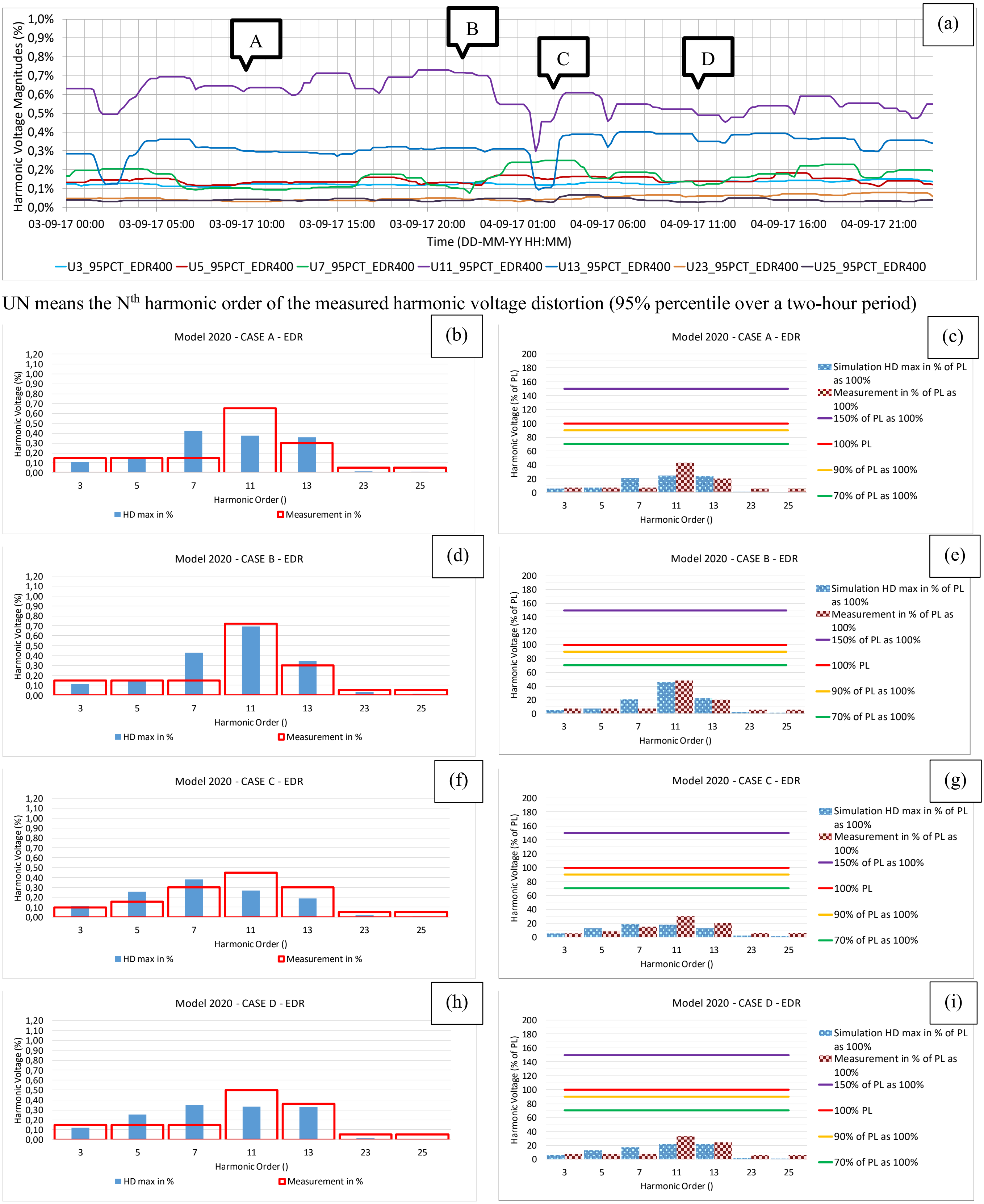


Fig. 17. Hamonic voltage distortion in the 400 kV substation EDR: (a) – measured and presented as 95% percentiles over two-hour window with marking of the validation cases from A to D, (b) – comparison of the measured and simulated harmonic voltages and (c) – of the measured and simulated harmonic margins of the validation case A, (d) – comparison of the measured and simulated harmonic voltages and (e) – of the measured and simulated harmonic margins of the validation case B, (f) – comparison of the measured and simulated harmonic voltages and (g) – of the measured and simulated harmonic margins of the validation case C, (h) – comparison of the measured and simulated harmonic voltages and (i) – of the measured and simulated harmonic margins of the validation case D. The model is in good agreement with the harmonic measurements. Accuracy is relevant for right decisions in regard to the planned grid expansion in the West-coast of Jutland.

In total, the model has been validated against approx. fifty cases of several consecutive operation scenarios. The success rate of the model is above 80% implying that the model is very accurate in calculation of the harmonic distortion and the harmonic margin in more than 80% of the conducted cases and shows some inaccuracy in remaining less than 20% of the cases. Inaccuracy is usually due to overestimation of the harmonic voltage distortion by the model in difficult operation scenarios, such as with 400 kV lines out-of-service.

In practice, such inaccuracy can be reduced by conducting a larger number of similar operation cases and excluding few cases not-complying with the common behaviour of the modelled transmission grid from the decision making and mitigation proposals.

V. Conclusion

The green transition of the Danish energy sectors with tremendous integration of renewable energy sources and HVDC interconnectors to the foreign systems requires expansion of the 400 kV (HVAC) meshed grid to support the transition. A strong public opposition to the new overhead transmission lines increases the demand for utilization of more HVAC underground cables in the Danish transmission grid. Utilization of the 400 kV underground cables is exposed to several technical challenges with increasing harmonic distortion amplification among the challenges. A case with significant amplification of the harmonic voltage distortion after commissioning of a 7 km long 400 kV underground cable in summer 2017 has already been seen in Denmark-West. There are more 400 kV grid expansion projects with the HVAC connectors combining OHL and underground cables in Denmark. Therefore, there has been a demand for a practical method and simulation model of the Danish transmission grid for the harmonic assessment.

This paper has presented a method and a simulation model developed and now applied by Energinet for the harmonic assessment of the 400 kV meshed transmission grid of Denmark-West with multiple harmonic emission sources distributed through the grid. The presented method and model have replaced the standardised methods which are suitable for radial networks but fail working in the meshed grid with multiple harmonic emission sources.

The empirical method implies that the simulation model is developed and validated using the measurements of the harmonic voltage distortion in the 400 kV grid. The model is developed in steps starting from the analysis of the measured harmonic distortion in different operation scenarios of the grid, preparing and confirming the passive-part of the simulation model – the harmonic impedance of the meshed transmission grid itself, inclusion and adjustment of the active-part and feedback – the representations of the harmonic emission sources of different types. The types of the harmonic emission sources include the LCC HVDC converter stations in both 400 kV and 150 kV grids, OWPP and distributed harmonic sources under the 150 kV substations.

The range of the simulation model is up to the 50^{th} harmonic order.

The simulation model is successfully validated from the measured harmonic voltage distortion. In many operation scenarios, the model accurately represents the harmonic voltage distortion and harmonic margin in the 400 kV substations for all harmonic orders. When discrepancy is observed, this is mostly due to overestimation of some harmonic orders in the simulation model in comparison to the harmonic measurements. Overestimation can be because the model is developed by a realistic conservative approach.

The success rate of the model validation is above 80% meaning good agreement with the measured harmonic voltage distortion and harmonic margins. In studies, accuracy can be improved by conducting a larger number of the scenarios and excluding such few cases not-complying with the common behaviour of the modelled transmission grid from the conclusion and proposals.

VI. Acknowledgement

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Further Reading

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