Harmonic Mitigation Schemes for Wind Power Plants by Embedding Control in Wind Turbines

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Abstract—Harmonic pollution may damage the electric devices in wind power plants (WPPs), and propagate to the external grid. This paper proposes a harmonic mitigation scheme by embedding harmonic control functions in wind turbines (WTs) to manage the harmonics in WPPs. It can improve the power quality at the remote Point of Common Coupling (PCC), regulated by grid codes. The proposed scheme detects the harmonics at WT buses and PCC based on instantaneous measurements, and calculates the required compensation currents. Both the general compensation scheme for reducing total harmonic distortion at the local WT buses and the specific compensation scheme for reducing the selected-order harmonics at the remote PCC are combined in the proposed harmonic mitigation scheme. Besides, a phase correction algorithm using the frequency-dependent model is proposed to compensate the phase differences between local WT buses and remote PCC. A model of offshore WPP using manufacture’s field-measurement data is implemented in DigiSILENT/PowerFactory to validate the effectiveness of the proposed harmonic mitigation scheme.

Keywords—Harmonic mitigation, phase-shift, power quality, total harmonic distortion (THD), wind power plant.

I. INTRODUCTION

During recent years, the penetration level of wind power has been drastically increased worldwide. For example, wind power capacity increased by circa 11.3GW in 2018: 8.6GW onshore and 2.65GW offshore wind generation [1]. In Denmark, the penetration level of wind power is planned to reach 85% by 2035 [2]. The necessity of mitigating harmonic pollution in wind power plants (WPPs) becomes more urgent, since the power quality of bulk power systems could be severely affected by the harmonics from WPPs [3]-[5]. Meanwhile, due to large numbers of power-electronic devices, the harmonics originated from wind turbines (WTs) can be amplified by the resonance effects of cables and control systems [6]. The excessive harmonics may result in shortened lifespans or even damages of electric devices and may deteriorate the power quality of public consumers. For instance, Energinet—the Danish Transmission System Operator (TSO) received complaints from consumers on an island due to harmonics, where the power is mainly supplied by a large offshore WPP [6]. Accordingly, grid codes have been formulated by international standard organizations and TSOs to ensure a satisfactory power quality in different voltage levels, e.g., the IEC standard 61000-3-6 [7], the IEEE standard 519 [8], and the technical regulation 3.2.5 from Energinet [9].

The harmonics in WPPs are mainly originated from the power-electronic converters of WTs, which could be further amplified by resonances in the network [10]. Moreover, the interactions between harmonics and network parameters may intensify the harmonic issues or even lead to harmonic instabilities [11]. In order to confine harmonics within the standards, passive or active AC filters are usually installed in the WPPs, but with additional cost and space [12], [13]. Besides, hybrid filters combining both active and passive filters [14]-[17], or active dampers for virtual resistances are also invented [18]-[21]. For instance, Ref. [22] focuses on the control strategy optimization and the site selection of shunt active filters, and Ref. [23] integrates both series and shunt active filters, named unified power quality conditioners, to reach high-efficiency performance for harmonic reduction.

Recently, embedded control-based active filters are implemented by just upgrading the control system of existing grid-side converters (GSCs) of WTs [24]. They aroused the interest of research and development, because of their low cost, wide bandwidth and high flexibility. Ref. [25] integrates the functions of active filter into the GSCs of DFIGs to provide needed harmonic compensation, however, without considering the phase-shift between WT buses and Point of Common Coupling (PCC). Ref. [26] simplifies the effect of embedded harmonic control as a transfer function. Then, parameters are tuned according to the Extra Element Theorem, which explores harmonic amplifications based on the law of low entropy.

This paper proposes a harmonic mitigation scheme to manage the harmonics in an offshore WPP. The general compensation scheme is designed and embedded in the WTs to reduce the total harmonic distortion (THD). Meanwhile, unlike the traditional active filters only for the connected buses, a specific compensation scheme is developed to deal with the selected-order harmonics at the remote PCC. The main contributions are as follows:

1) The control system of proposed harmonic mitigation scheme is devised and effectively integrated into the existing control of WTs. Both local WT buses and the remote PCC are selected as the targets for overall harmonic mitigation.

2) The phase-shift correction between the remote measurement point and the local compensation point is proposed in the specific compensation scheme according to the established frequency-dependent model.

3) The general compensation scheme for the THD and the specific compensation scheme for the selected-order harmonics are adaptively integrated into the proposed control system for higher flexibility.

The rest of this paper is organized as follows: Section II introduces the configuration of an offshore WPP and the
design principles of the proposed harmonic mitigation scheme. The concrete structure of the proposed embedded control system is presented in Section III. Case studies are conducted in Section IV to test the performance of the proposed harmonic mitigation scheme. Finally, conclusions are drawn in Section V.

II. THE PROPOSED HARMONIC MITIGATION SCHEME IN AN OFFSHORE WPP

A. The Configuration of an Offshore WPP

Fig. 1 illustrates an offshore WPP consisting of 10 PMSG-based WT systems connected with MV network via 0.69/20 kV step-up transformers. The total power capacity of WPP is 25MW, which is connected to the external transmission grid through 50km 220kV sea cables. The harmonics generated from power-electronic converters of WT systems may be amplified by the impedance along sea cables [10]. In order to effectively improve the power quality in the offshore WPP with low cost, a harmonic mitigation scheme is embedded into the existing control system of WT systems, denoted by the purple dashed box in Fig. 1. All PMSG-based WT systems (Type-IV) are equipped with full-rated back-to-back converters.

The WPP system is modelled under the following criteria. The environmental influence on network parameters, e.g. temperatures and pressure, is neglected. The switching loss in power-electronic converters is neglected and the average-value model is used for the GSCs. The external transmission grid is modelled by a Thevenin equivalent circuit with passive impedance at fundamental frequency, and Norton equivalent circuits with field-measurement data are used to model the harmonic sources of each WT.

B. The Design Principles of the Proposed Harmonic Mitigation Scheme

Essentially, frequency-domain methods and time-domain methods are the two mainstreams of harmonic detection methods. Frequency-domain methods using the Fast Fourier Transform (FFT), enable an efficient estimation of the magnitude, angle and frequency of harmonic signals for a time window. While, time-domain methods are based on the instantaneous measurements, which are transformed and processed in the rotational d-q coordinate [27]. According to the field-measurements of a commissioned WPP, harmonics in WT systems are in fast variation especially for high-order harmonics, so time-domain methods usually have better performance in transient conditions [28]. Besides, time-domain methods can separate the sequence components and calculate the required compensation currents according to the instantaneous measurements. Therefore, the proposed harmonic mitigation scheme adopts time-domain methods.

Fig. 2 shows the principle of the proposed scheme:

i) Both the local general compensation scheme for the THD and the remote specific compensation scheme for the selected-order harmonics at PCC are proposed and combined in the embedded control system.

ii) The parameters for the remote specific compensation scheme are adaptive according to actual harmonic conditions.

iii) Not only the local WT buses but also the remote PCC are the targets for harmonic mitigation. Due to the time delay between the PCC and WT, it is inaccurate to directly sample and transmit the instantaneous harmonic signals at remote PCC and feedback as the input of embedded control system. Hence, phase-shift correction is proposed for the remote specific compensation scheme to enable the local feedback and eliminate the harmonic phase-shift.

III. THE EMBEDDED CONTROL SYSTEM OF THE PROPOSED HARMONIC MITIGATION SCHEME

The control diagram of proposed harmonic mitigation scheme is shown in Fig. 3, which is mainly composed of following modules: input signal processor, phase-locked loop (PLL), local general compensation scheme, remote specific compensation scheme, phase-shift correction and carrier signal output.

Firstly, the α-β and d-q transformations are applied on the instantaneous measurement signals to decompose the harmonics of different orders based on the phase signals supplied by PLL. Then, a high-pass filter (HPF) is employed to filter out all harmonics (i.e. h≥2) for the local general compensation scheme. In contrast, for the remote specific compensation scheme, a low-pass filter (LPF) is applied on the current signals in the d-q coordinates for the hth-order harmonics. To eliminate the harmonic phase difference between local WT buses and remote PCC, phase-shift correction is employed in the specific compensation scheme. Following sub-sections introduce the embedded control system in detail.

Fig. 1. Single-line diagram of a 0.69kV 25 MW offshore WPP comprised of 2.5 MW Type-IV (n=10) WTs with an 220kV external grid.
1) Transformation of Harmonic Coordinates

The $\alpha$-$\beta$ and $d$-$q$ transformations are applied to convert the 3-phase measurement currents (i.e. $i_{a,b,c}$ from WT buses and $i_{ar,br,cr}$ from PCC) into the instantaneous active currents (i.e. $i_{d,dm,dn}$) and instantaneous reactive currents (i.e. $i_{q,qm,qn}$). Meanwhile, measurement voltages (i.e. $u_{a,b,c}$ from WT buses and $u_{ar,br,cr}$ from PCC) are necessary for PLL to generate reference signals to synchronize the $d$-$q$ transformations (i.e. $\theta_1$ for $d_1$-$q_1$ transformation in general compensation scheme and $\theta_{m,n}$ for $d_{m,n}$-$q_{m,n}$ transformations in specific compensation scheme). After the above transformations of harmonic coordinates, different orders of harmonics are decomposed. For the general compensation scheme, all harmonics ($h\geq2$) correspond to AC components in $d_1$-$q_1$ coordinate frame. For the specific compensation scheme, the $h$th-order harmonics correspond to DC components in the $d_h$-$q_h$ coordinate frame.

Then AC and DC components can be extracted by HPF and LPF, respectively. Consequently, different orders of harmonics can be separated by setting corresponding values of $h$. Finally, the needed compensation currents are calculated by $d_h$-$q_h$ inverse and $\alpha$-$\beta$ inverse transformations, and added to the carrier signal, as expressed in (1).

$$\begin{align*}
\{i_{ac,bc,cc}\} &= \{i_{o0}\} - \{i_{a1} + i_{b1} + i_{c1} + \cdots\} \\
i_{ac} &= -\frac{1}{2} \times \left[ i_{ao} - (i_{a1} + i_{b1} + i_{c1} + \cdots) \right] \\
i_{bc} &= -\frac{\sqrt{3}}{2} \times \left[ i_{bo} - (i_{a1} + i_{b1} + i_{c1} + \cdots) \right] \\
i_{cc} &= -\frac{1}{2} \times \left[ i_{co} - (i_{a1} + i_{b1} + i_{c1} + \cdots) \right]
\end{align*}$$

(1)

where $i_{ac,bc,cc}$ are the needed compensation currents, $i_{o0}$ are the current carrier signals, $i_{a1}$-$i_{bo}$ are the general compensation currents for all order harmonics, and $i_{a1}$-$i_{bo}$ are the specific compensation currents for the selected-order (e.g. $m^{th}$, $n^{th}$) harmonics, respectively.

2) High-Pass Filter and Low-Pass Filter

For the general compensation scheme, the HPF filters out fundamental components and retains all harmonics ($h\geq2$) in $d_1$-$q_1$ coordinate frame. For the specific compensation scheme, the LPF extracts DC components in $d_h$-$q_h$ coordinate frame, i.e. the $h$th-order harmonics in $a$-$b$-$c$ coordinate frame, which is finally fed back to the carrier signals after the phase-shift correction introduced later, together with the harmonics...
extracted by the HPF. First-order HPF and LPF are adopted in this paper for computational efficiency and their transfer functions are given in Appendix A. Nevertheless, higher order filters can also be employed depending on the actual harmonic conditions.

3) Phase-Shift Correction for the Remote Specific Compensation Scheme

For eliminating the phase-shift of compensation currents between local WT buses and remote PCC bus, sea cables and transformers in Fig. 1 are modelled by equivalent PI model and harmonic impedance model respectively, with frequency dependent parameters. The component parameters are listed in the Appendix B.

Fig. 4(a) shows an equivalent PI model of a sea cable. The distributed parameters of the cable for different harmonics are calculated by (2) and (3).

\[
Z = Z_l \frac{\sinh(\sqrt{Y_l}Z_l t)}{\sqrt{Y_l}Z_l t} \tag{2}
\]

\[
Y = Y_l \frac{\tanh(\sqrt{Y_l}Z_l t / 2)}{\sqrt{Y_l}Z_l t / 2} \tag{3}
\]

where \(Z_l\) is the series impedance for per unit length, and \(Y_l\) is the shunt admittance for per unit length. Here \(Z_l\) and \(Y_l\) are both frequency dependent, which takes the proximity effect and the skin effect into account.

The harmonic impedance model of a transformer is shown in Fig. 4(b). The reactance \(X_t\) is related to the leakage reactance at fundamental frequency and calculated by (4).

\[
X_t(h) = 2\pi f h L_o \tag{4}
\]

where \(L_o\) is the leakage inductance, \(h\) is the harmonic order, and \(f\) is 50Hz.

The parallel resistance \(R_o\) and series resistance \(R_s\) are independent of frequencies and estimated by (5) and (6).

\[
R_s = \frac{X_t}{\tan \lambda}, \quad R_o = 10X_t \tan \lambda \tag{5}
\]

\[
\tan \lambda = e^{0.693 + 0.796 \ln S_e - 0.042(\ln S_e)^2} \tag{6}
\]

where \(S_e\) is the nominal power of the transformer, and the expression for \(\tan \lambda\) is an empirical relation [29]. Then, the frequency-dependent equivalent circuit of the offshore WPP in Fig. 1 is modelled in Fig. 5. The external grid is modelled by a Thevenin equivalent circuit at the fundamental frequency.

For a general power network with \(p\) nodes, the nodal analysis conforms to (7).

\[
[I(h)]_{p \times 1} = [Y(h)]_{p \times p} [V(h)]_{p \times 1} \tag{7}
\]

\[
[V(h)]_{p \times 1} = [Z(h)]_{p \times p} [Y(h)]_{p \times 1} \tag{8}
\]

\[
[Z(h)]_{5 \times 5} = [Y(h)]_{5 \times 5}^{-1} \tag{9}
\]

Consequently, the phase-shift for \(h\)-th-order harmonics is provided by (10) and the compensation currents considering phase-shift correction is given by (11).

\[
\Delta \theta_h = Z_{l,5}(h) \tag{10}
\]

\[
i_{h,5}^- = i_{h,5}^- \cdot e^{i\Delta \theta_h} \tag{11}
\]

where \(Z_{l,5}(h)\) is taken from \([Z(h)]_{5 \times 5}\), \(\Delta \theta_h\) represents the angle that the local LV WT bus leads the remote PCC for \(h\)-th-order harmonics, \(i_{h,5}^-\) and \(i_{h,5}^+\) correspond to the input and output currents of phase-shift correction module in Fig. 3.

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Fig. 5. The equivalent circuit of the offshore WPP in Fig. 1.
IV. CASE STUDY

The performance of the proposed harmonic mitigation scheme is validated by the implementation on an offshore WPP using DIgSILENT/PowerFactory [30]. The single-line diagram of the tested offshore WPP is shown in Fig. 1. Both the local bus, i.e. LV WT, and the remote bus, i.e. PCC, are the targets for harmonic mitigation. A laptop computer with Intel(R) Core(TM) i5-8265U CPU @ 1.60-1.80GHz with 8.00GB RAM is used for the case study. The original data of harmonic emissions applied in the cases are provided in the Appendix C, which are set based on the field measurements of a commissioned offshore WPP.

Only integer harmonics between the 2\textsuperscript{nd} and 13\textsuperscript{th} are considered, i.e. $h = 2-13$, and the symmetrical parameters are considered for Case A ~ Case D, i.e. the $(3k-1)$\textsuperscript{th}-order corresponds to the negative-sequence and the $(3k+1)$\textsuperscript{th}-order corresponds to the positive-sequence, where $k = 1, 2, \ldots, n$. Zero-sequence harmonics are not considered since the transformers in the tested offshore WPP are Y-\Delta types, i.e. 3\textsuperscript{rd}, 6\textsuperscript{th}, 9\textsuperscript{th}, 12\textsuperscript{th}-order harmonics are neglected. The maximums of field measurements on each order are considered as the harmonic injection values in order to validate the effectiveness on a worst harmonic condition.

Fig. 6. The relationship between the five cases.

Five cases are tested to validate the effectiveness of the proposed harmonic mitigation scheme, illustrated in Fig. 6:

i) Case A: the basic case without the proposed mitigation scheme.

ii) Case B: the case only with local general compensation scheme.

iii) Case C: the case only with remote specific compensation scheme considering phase-shift correction.

iv) Case D: the complete harmonic mitigation scheme consisting of both general and specific compensation.

v) Case E: Case D with Additive White Gaussian Noise (AWGN).

A. Case A: The Basic Case without Mitigation Scheme

The THD of target bus is calculated by (12) to quantify the performance of the proposed scheme, i.e. LV WT and PCC.

\[
THD = \sqrt{\frac{2}{V_1^2} + V_{2}^2 + V_{4}^2 + \cdots + V_{h}^2} \]  

(12)

where $V_h$ is the voltage magnitude of $h$\textsuperscript{th}-order harmonic component, and $V_1$ is the voltage magnitude of fundamental component.

Fig. 7 shows the harmonic voltage magnitudes of target buses for Case A, where the harmonic values of all orders are listed concretely in TABLE II. It can be noticed that the 5\textsuperscript{th}, 7\textsuperscript{th}, 11\textsuperscript{th}, and 13\textsuperscript{th}-order harmonics are the primary harmonics in both local LV WT and remote PCC, accounting for 82.48% of harmonics in LV WT and 74.78% at PCC, respectively. More specifically, the 5\textsuperscript{th} and 7\textsuperscript{th}-order harmonics account more than the 11\textsuperscript{th} and 13\textsuperscript{th}-order harmonics at PCC. These low frequency harmonics are harmful to the system, especially when they are in resonance with the grid impedance. The parameters of remote specific compensation scheme in the embedded control system are chosen according to 5\textsuperscript{th} and 7\textsuperscript{th}-order harmonics in the following cases to achieve the better power quality, i.e. $m=5$ and $n=7$ in Fig. 3 and Eq. (1).

B. Case B: Only Local General Compensation Scheme

Fig. 8. Harmonic voltage magnitudes in LV WT and PCC with only the general compensation scheme (Case B).

Case B only tests the local general compensation scheme. As shown in Fig. 8, the 5\textsuperscript{th}, 7\textsuperscript{th}, 11\textsuperscript{th} and 13\textsuperscript{th}-order harmonics are still the dominating components at the target buses, but obviously reduced compared with Fig. 7 of Case A. The voltage THDs of Case B are reduced by 31.25% in LV
WT and 23.00% at PCC, respectively, showing the effectiveness of the general harmonic mitigation scheme.

C. Case C: Only Remote Specific Compensation Scheme Considering Phase-Shift Correction

The harmonic phase-shift and impedance between LV WT and PCC is calculated by Eq. (9)-(10) and shown in Fig. 9. The phase-shift correction in specific compensation scheme for the 5th- and 7th-order harmonics is achieved by eliminating the corresponding phase-shift, i.e. 56.133° for 5th-order and 50.386° for 7th-order. Then, the voltage magnitudes of 5th- and 7th-order harmonics at PCC are measured without and with phase-shift correction, the results are shown in Fig. 10 and the values are recorded in TABLE I.

| Busbar | Case C - Without Phase-Shift Correction | Case C - With Phase-Shift Correction |
|--------|----------------------------------------|-------------------------------------|
|        | 5th[10e-3 p.u.] | 7th[10e-3 p.u.] | 5th[10e-3 p.u.] | 7th[10e-3 p.u.] |
| PCC    | 1.395         | 0.577         | 0.990         | 0.416         |

It can be noticed that the phase-shift correction improves the performance of the specific compensation scheme. After the implementation of phase-shift correction, the harmonic voltages at PCC are reduced by 29.03% for the 5th-order and 27.90% for the 7th-order, respectively. It indicates that the phase-shift correction in the specific compensation scheme is efficient for the mitigation of the selected-order harmonics.

D. Case D: Complete Harmonic Mitigation Scheme

The proposed complete compensation scheme is validated in this case. The effectiveness of harmonic mitigation in Case A, B, and D is compared in Fig. 11 (i.e. LV WT) and Fig. 12

| Busbar | Order | Case A [10e-3 p.u.] | Case B [10e-3 p.u.] | Case D [10e-3 p.u.] |
|--------|-------|---------------------|---------------------|---------------------|
| LV WT  | 2     | 0.073              | 0.040              | 0.039               |
|        | 4     | 0.383              | 0.237              | 0.240               |
|        | 5     | 1.053              | 0.740              | 0.643               |
|        | 7     | 2.603              | 1.607              | 1.230               |
|        | 8     | 0.360              | 0.233              | 0.243               |
|        | 10    | 0.693              | 0.477              | 0.470               |
|        | 11    | 1.220              | 0.777              | 0.780               |
|        | 13    | 2.227              | 1.750              | 1.732               |
| PCC    | 2–13  | 3.885              | 2.671              | 2.424               |
|        | 2     | 0.163              | 0.103              | 0.100               |
|        | 4     | 0.208              | 0.109              | 0.110               |
|        | 5     | 1.633              | 1.500              | 0.852               |
|        | 7     | 1.066              | 0.670              | 0.308               |
|        | 8     | 0.623              | 0.512              | 0.510               |
|        | 10    | 0.727              | 0.680              | 0.679               |
|        | 11    | 1.029              | 0.655              | 0.650               |
|        | 13    | 1.078              | 0.520              | 0.519               |
| THD    | 2–13  | 2.643              | 2.035              | 1.502               |

The proposed complete compensation scheme is validated in this case. The effectiveness of harmonic mitigation in Case A, B, and D is compared in Fig. 11 (i.e. LV WT) and Fig. 12.
(i.e. PCC), and TABLE II lists all the values of harmonic voltages. Compared with Case A, the voltage THDs in target buses are significantly reduced with the reduction rates of 37.61% in LV WT and 43.17% at PCC, respectively. The harmonic mitigation effect of Case D is more obvious than that of Case B. The 5th- and 7th-order harmonics in Case D are decreased, compared with Case B, by 13.11% and 23.46% in LV WT, 43.20% and 54.03% at PCC, while other harmonics are almost the same. The voltage THD of Case D, compared with Case B, is reduced by 9.25% in LV WT and 53.30% at PCC, and is much lower than the IEEE Standard 519-2014 (i.e. Appendix D).

In summary, the complete compensation scheme enhances the performance for harmonic mitigation for both remote and local buses by effectively combining the general compensation scheme and the specific compensation scheme.

E. Case E: Robustness of the Proposed Harmonic Mitigation Scheme

In this case, the AGWN are added on the frequencies and angles of the 3-phase harmonic source. The parameters of AGWN are given in Appendix E. The 3-phase voltages of PCC, without and with the proposed harmonic mitigation scheme, are shown in Fig. 13 and Fig. 14. TABLE III quantifies the harmonic voltages of all orders at PCC by FFT. Compared Fig. 14 with Fig. 13, it is obvious that the voltages become closer to sinusoidal curves after the implementation of the proposed harmonic mitigation scheme. As shown in TABLE III, all order harmonics are significantly reduced with the harmonic mitigation scheme, and the reduction rates of voltage THDs are 71.43% in A-phase, 54.81% in B-phase, and 53.57% in C-phase. In summary, the proposed harmonic mitigation scheme is satisfactory with robustness under harmonic noises.

V. CONCLUSION

This paper proposes a comprehensive harmonic mitigation scheme by embedding the designed control system in the existing control of WTs for improving the power quality in both local and remote buses. All targeted harmonics in LV WT and PCC are effectively suppressed by the combination of the local general compensation scheme and the remote specific compensation scheme. Additionally, phase-shift correction algorithm based on frequency-dependent model is proposed to effectively decrease the error caused by the harmonic phase-shift between the remote measurement point and the local compensation point. Furthermore, the proposed scheme has been validated for robustness, which decreases the voltage THDs under AWGN.

APPENDIX

A. Transfer Functions of HPF and LPF

The transfer function of first-order HPF is designed in (AI).

$$G_H(s) = G_{OH} \frac{s}{s + \omega_{cH}} \quad \text{(AI)}$$

where $G_{OH} = 1$ represents the gain, and $\omega_{cH} = 125 \text{ rad/s}$ is the cut-off angular frequency.

The transfer function of first-order LPF is shown in (AII).

$$G_L(s) = \frac{G_{OL}}{s + \omega_{cL}} \quad \text{(AII)}$$

where $G_{OL} = 1$ represents the gain, and $\omega_{cL} = 125 \text{ rad/s}$ is the cut-off angular frequency.

B. Parameters of the Offshore WPP Components

TABLE AI

| Component       | Parameter      | Value       |
|-----------------|----------------|-------------|
| WT              | Nominal apparent power | 25 MVA      |
|                 | Power factor    | 0.9         |
| Trf. 0.69/20 kV | Voltage ratio   | 0.69/20 kV  |
|                 | Rated power     | 2.8 MVA     |
| Trf. 20/220 kV  | Voltage ratio   | 20/220 kV   |
|                 | Rated power     | 100 MVA     |
| Cable           | Length of line  | 3 km        |
|                 | Rated current   | 0.32 kA     |
|                 | Pos. seq. impedance | 0.73 Ohm 30,1 deg |
C. Field-Measurement Data

| Frequency [Hz] | Max [%] | Min [%] | St. dev. [%] |
|---------------|---------|---------|-------------|
| 100           | 0.41    | 0.35    | 0.045752651 |
| 150           | 0.86    | 0.66    | 0.018735390 |
| 200           | 0.45    | 0.32    | 0.008896392 |
| 250           | 2.10    | 1.40    | 0.011384334 |
| 300           | 1.50    | 0.90    | 0.006277405 |
| 350           | 2.00    | 1.37    | 0.004979179 |
| 400           | 0.45    | 0.30    | 0.008228340 |
| 450           | 0.80    | 0.66    | 0.009900897 |
| 500           | 0.41    | 0.28    | 0.014882430 |
| 550           | 1.00    | 0.62    | 0.008121717 |
| 600           | 0.82    | 0.51    | 0.006257875 |
| 650           | 1.20    | 0.70    | 0.019674703 |

*Max – Maximum; Min – Minimum; St. dev. – Standard deviation.

D. IEEE Standard 519-2014 [8]

| Bus Voltage V | Individual Harmonic (%) | THD (%) |
|---------------|--------------------------|---------|
| V ≤ 1.0 kV    | 5.0                      | 8.0     |
| 1 kV < V ≤ 69 kV | 3.0              | 5.0 |
| 69 kV < V ≤ 161 kV | 1.5              | 2.5     |
| 161 kV < V     | 1.0                      | 1.5     |

*THD – Total harmonic distortion.

E. Parameters of Additive White Gaussian Noise (AWGN)

Phase-A: 2000 Hz 0.010 W Gaussian;  
Phase-B: 1500 Hz 0.005 W Gaussian;  
Phase-C: 2500 Hz 0.015 W Gaussian.

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