Article

Challenges with Harmonic Compensation at a Remote Bus in Offshore Wind Power Plant

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Abstract: The interaction between the grid network and the offshore wind power plant (WPP) network can lead to the amplification of certain harmonics and potentially resonant conditions. Offshore WPP should limit the increment of harmonic voltage distortion at the point of connection to the grid network as well as within their internal network. The harmonic distortion should be limited within the planning level limits using harmonic compensation, which is usually achieved by using static filters. In this paper an active damping compensation strategy with a STATCOM using emulation of resistance at the harmonic frequencies of concern is analysed. Such a compensation is effective for the local bus, though the performance is not guaranteed at the remote bus. This paper investigates the challenges associated with remote harmonic compensation in the offshore WPP, which is connected to the onshore grid through long high-voltage cables and transformers. First, the harmonic distortion and the compensating effects of the filter are theoretically assessed. Afterwards, they are demonstrated using harmonic propagation studies and time domain simulations in PSCAD.

Keywords: harmonic distortion; active power filter; resonance; damping; wind power plants

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1. Introduction

Several large offshore wind power plants (WPP) have been installed in Europe and many more are under different stages of development. These usually comprise of type III or type IV wind turbines (WT) with power electronic converters and are connected to the ac network through High Voltage AC (HVAC) or High Voltage DC (HVDC) transmission systems. HVAC transmission systems are widely used in large scale WPPs closer to the shore, within 50-100 km from the shore [1], due to simple installation and maintenance, higher reliability and less complexity in comparison to HVDC systems. Anholt, Horns Rev and Nysted WPPs in Denmark and Barrow wind farm in United Kingdom are some of the WPPs HVAC connection to the grid [2,3].

HVAC connection of Offshore Wind Power Plants (WPPs) typically comprise of long submarine and underground HVAC cables up to the point of grid connection and step up transformers. Meanwhile, huge number of medium voltage (MV) submarine cables of network collection of wind turbines should not be overlooked. The combination of the transformer inductance and the submarine cable capacitance might produce a resonant circuit, which may cause amplification of harmonics [4]. Harmonic emission level of power electronic based generation sources should meet

30 the requirements mentioned in the relevant standards including recommended (IEEE and IEC) and
31 planning (G5/4-1) limits [5–7].

32   Power electronic converters and non-linear loads produce the major part of grid harmonics. Grid
33 background harmonic at a particular terminal reflects the overall impact of aforementioned harmonic
34 sources at that specific bus, e.g. the Point of Connection (POC). Existence of harmonics in the grid is
35 inevitable even in the absence of WPP. Connection of WPP to the grid, influences the effective grid
36 impedance at POC. Depending on the interaction between the WPP and grid impedances, there may
37 be an amplification or an attenuation of the harmonic voltage distortion. New resonant modes may
38 appear and/or the existing resonant modes may move to undesirable frequencies, thereby amplifying
39 the harmonic distortion leading to poor power quality at the POC exceeding the permissible levels of
40 harmonic distortion. Moreover, the injection of harmonics by built-in power electronic converters of
41 WPPs, may also worsen the situation.

42   Current work addresses magnification of grid background harmonic due to the interaction
43 between the WPP and grid impedances. The main focus is devoted to the grid background harmonics
44 as the main source of harmonics and the share of Wind Turbines (WTs) in current harmonic injection is
45 considered as future works. Later on, active damping of harmonics is performed by the emulation of
46 resistive behaviour by the STATCOM at particular frequencies. The research findings confirm that the
47 harmonic compensation is efficient at the local bus. However, its performance is not guaranteed at the
48 remote buses. Due to practical considerations and current state of the art of STATCOM technology,
49 the STATCOM is not connected to the high voltage buses (POC and PCC) close to the grid. To meet the
50 requirements of grid codes associated with harmonics, the harmonic level should be within the limits
51 specified at the PCC or POC which appear to be the remote bus with respect to the point of connection
52 of the STATCOM. This paper investigates the challenges and difficulties in harmonic mitigation and
53 compliance with the power quality at such remote buses.

54   This paper is organized as follows. The test WPP grid network is presented along with the
55 mathematical analysis of the amplification or attenuation of harmonics and the effect of harmonic
56 compensation in section 2. The effect of harmonic compensation upon the harmonic impedance of
57 WPP network is illustrated in in section 3. The Nyquist criterion is applied to assess the overall
58 stability of the compensation strategy in section 4. The results of the harmonic propagation studies
59 and time domain simulation are presented in section 5. Finally, the paper is concluded in section 6.

60 **2. Test WPP Grid Network**

61 *2.1. Wind power plant model*

62   The Anholt offshore WPP in Denmark with the capacity of 400 MW is chosen as a case study
63 for harmonic study of WPP network as shown in Figure 1 [8]. Three step up transformers (3x140
64 MVA, 225/34 kV) connect the WPP collection network to the submarine cable. The submarine cable
65 size and length are 3*1600 mm^2 and 24.5 km respectively. It is connected to the underground cable
66 (3*2000 mm^2) with the length of 58 km. The generated power is delivered to the onshore grid using
67 two units of 450 MVA, 410/233 kV transformers in parallel. Two switched shunt reactors (120 and
68 240 MVar) are employed to compensate the reactive power of cable capacitance in the submarine and
69 underground cables, respectively. A STATCOM is connected to the 220 KV bus, T_2 for the dynamic
70 reactive power compensation as well as the active damping of resonance and mitigation of harmonic
71 voltage distortion .

72   The medium voltage (MV) cables in the 34-kV collector network of the WPP is collectively
73 represented by 3 sets of 4x11 km cable of 500 mm^2 at 34 kV voltage level. The capacitance of the MV
74 cables is selected such that the overall capacitance of resultant cable network remains unchanged.
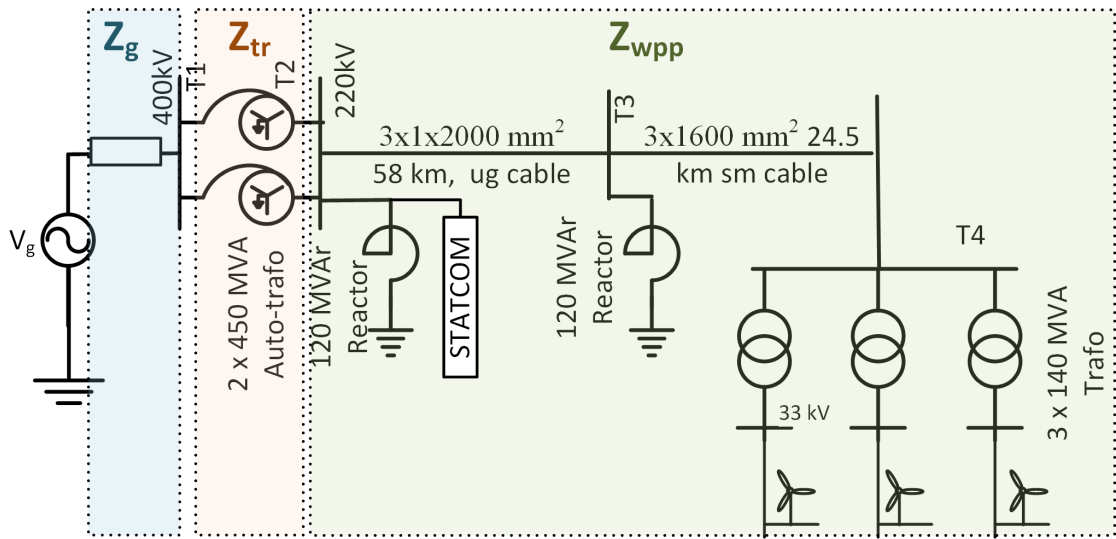
Figure 1. WPP electrical network model.

Table 1. Base Values.

	Unit	Grid and at T_1	At T_2, T_4, and HV Cables
Power	[MW]	400	400
RMS voltage	[kV]	400	220
RMS current	[kA]	577.4	1049.7
Resistance	[Ω]	400	121

2.2. Grid

The main grid is modelled by three phase voltage sources with background voltage harmonics. The grid impedance is considered in series with the voltage source in accordance to the Thévenin equivalent circuit [9]. Figure 2-a represents the magnitude of voltage harmonics at the PCC and other buses (T_1, T_2 and T_4). Figure 2-b indicates the current harmonic injected by the grid into the WPP in different locations. The bar values are shown in pu calculated according to the base values given in Table 1.

The frequency spectrum of grid impedance is available as magnitude and phase in term of frequency. Although, the aforementioned data can be directly utilized for frequency domain analysis, such as the harmonic propagation studies, it cannot be applied to the time domain simulation studies. In this case the data needs to be transformed to a frequency domain transfer function using vector fitting technique [10]. The frequency sweep data of grid impedance (actual grid impedance data) and the resultant Frequency Dependent Network Equivalent (FDNE) transfer function is shown in Figure 3.
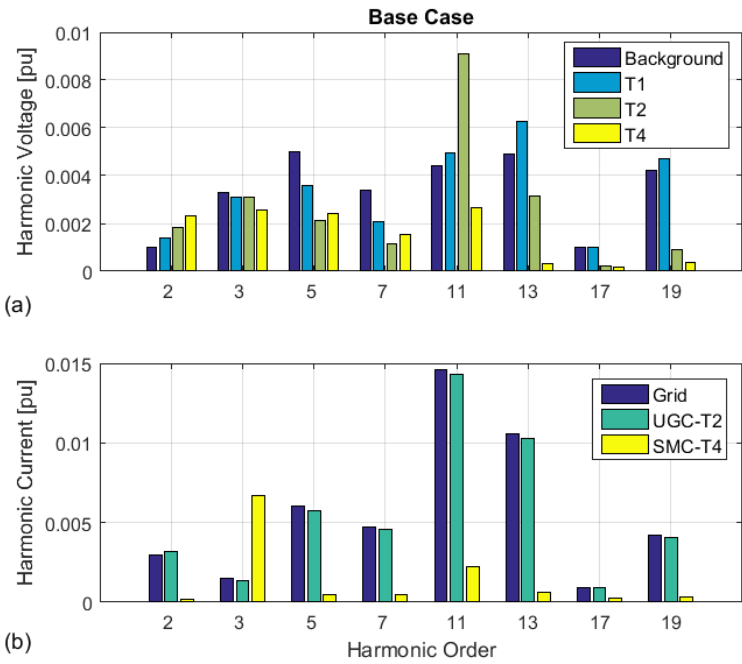
Figure 2. . Base case. (**a**) Background harmonic levels, and the harmonic voltages at T_1, T_2 and T_4, and (**b**) Harmonic current flow in the grid and the HV cables (UGC: underground cables and SMC:submarine cables) at T_1, T_2 and T_4.
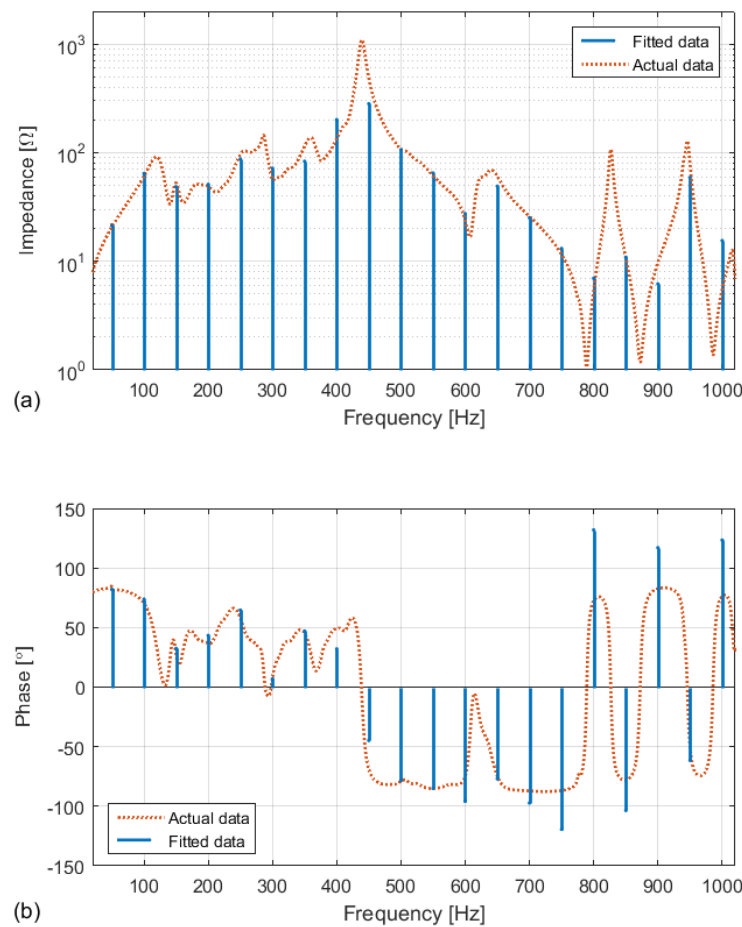
Figure 3. Grid impedance characteristics. (**a**) Magnitude, and (**b**) Phase angle.

2.3. Amplification/Attenuation of harmonic distortion

Magnification or attenuation of harmonics at different buses may happen due to the interaction between the grid impedance in series with the equivalent impedance of the WPP and its submarine, underground cables and collection network. In this study, the 400 kV bus , i.e. T_1 is considered as PCC, and thus the objective is to reduce the harmonic distortion at bus T_1.

By excluding the harmonic emission of WTs and considering the grid as the main source of harmonic distortion, the amplification of harmonic voltage distortion at buses T_1 and T_2 are given by:

$$\left.\begin{array}{l} A_1 = \dfrac{V_{1h}}{V_{gh}} = \dfrac{Z_{tr,h}+Z_{wpp,h}}{Z_{g,h}+Z_{tr,h}+Z_{wpp,h}} \\[2ex] A_2 = \dfrac{V_{2h}}{V_{gh}} = \dfrac{Z_{wpp,h}}{Z_{g,h}+Z_{tr,h}+Z_{wpp,h}} \end{array}\right\}, \tag{1}$$

where, $Z_{tr,h}$, $Z_{wpp,h}$ and $Z_{g,h}$ are the impedance of transformer, WPP and the grid at the hth harmonic order represented in Figure 4. The amplification ratios A_1 and A_2 in (1) versus frequency are plotted in Figure 5. Values greater/smaller than one is interpreted as amplification/attenuation. At bus T_1, the harmonic orders 2nd, 9-15th, 17th and the 19th are amplified. At bus T_2, the 2nd, 11th and the 12th harmonic orders are amplified.
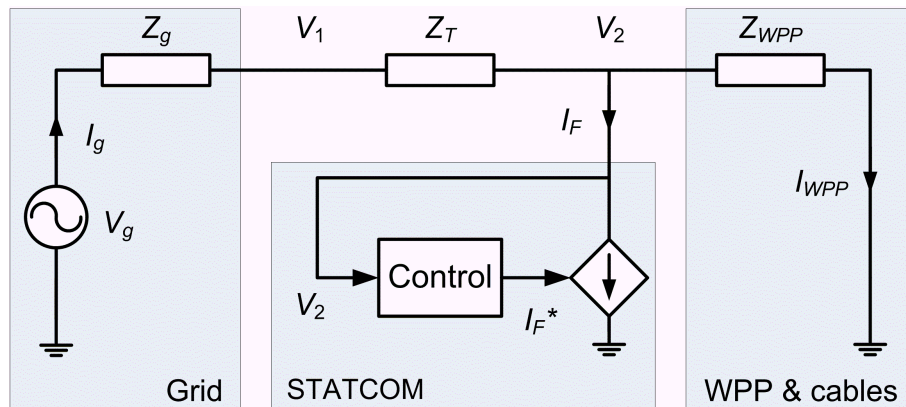
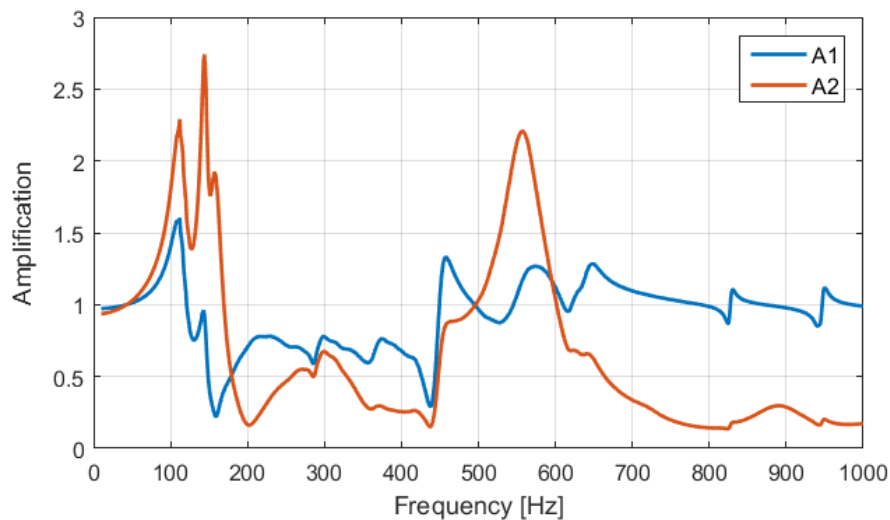**Figure 4.** An equivalent single line drawing of the test system.

Figure 5. Amplification of the background harmonics in the grid.

The amplification of 13th harmonic order at T_1 by 1.27 times makes sense due to the positive sequence impedance values of, $Z_{g,13} = (17 - j59)\,\Omega$ on the grid side and $(Z_{tr,13} + Z_{wpp,13}) = (48 + j233)\,\Omega$ on the WPP side at the bus T_1 when referred to the 400 kV voltage base. Typically, the odd harmonics at the 5th, 7th, 11th, 13th, 17th and 19th have a relatively higher content in the background harmonics in the grid. Hence, the amplification of these harmonics should be checked to the extent feasible.

2.4. STATCOM controller for harmonic compensation

When a resistor is connected in shunt, it reduces the overall impedance and hence the voltage drops. However, it would affect the harmonic as well as the fundamental frequency components. Moreover, it leads to high losses and hence connecting a resistor for harmonic compensation is not feasible. It is therefore emulated by a STATCOM, which provides reactive power compensation at the fundamental frequency and selective harmonic filtering. Figure 6 shows the block diagram of the STATCOM controller for the active power filter (APF) functionality. It will be in addition to the reactive power regulation, which happens at the fundamental frequency. The aspect of reactive power compensation is not described in this paper.
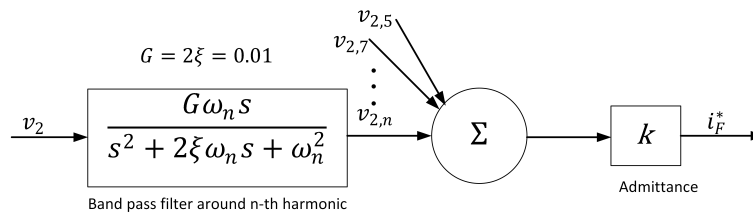
Figure 6. STATCOM controller for harmonic compensation.

The terminal voltage v_2 is measured at T_2 and the harmonic components are extracted using band-pass filters tuned around the desired harmonic frequency orders. Afterwards, the harmonic components are added together and multiplied by a constant admittance, k, to produce the harmonic current reference, i_F^* to provide the harmonic compensation. The individual band pass filter around the harmonic frequency, ω_n, has the transfer function,

$$HF_n(s) = \frac{G \cdot \omega_n \cdot s}{s^2 + 2 \cdot \xi \cdot \omega_n \cdot s + \omega_n^2}. \tag{2}$$

Such a filter is required for each of the individual harmonic orders concerned. Therefore, the resultant filter transfer function is,

$$HF(s) = \sum_n^N \frac{2 \cdot \xi \cdot \omega_n \cdot s}{s^2 + 2 \cdot \xi \cdot \omega_n \cdot s + \omega_n^2} \tag{3}$$

The frequency vs. magnitude and phase characteristic of the multiple harmonic band-pass filters in parallel are shown in Figure 7. Here the individual filter characteristics are shown by the curves for the legends G_n, where the subscript n denotes the corresponding harmonic order. The thick curve for the legend H indicates the overall combination of all six harmonic filters used in this work. Once the harmonic components are extracted, the harmonic current reference is given by (4),
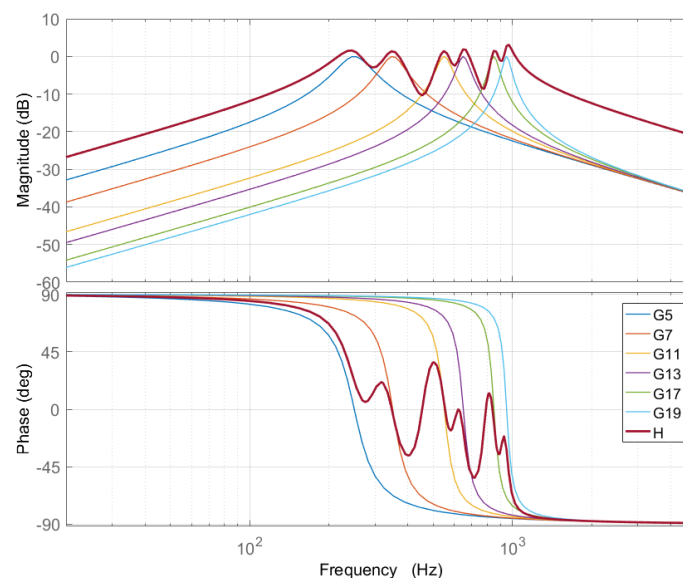
$$I_{f,h}(s) = k \cdot HF(s) \cdot V_{2,h}(s), \tag{4}$$

Figure 7. Bode plot of the individual harmonic filter transfer functions and their parallel combination.

128 where, k has the unit of admittance. It may be the same for all the desired harmonic orders, or different
129 for each of the different harmonic components. Thus, the current references are proportional to the
130 corresponding harmonic voltages. Since k is a real constant number, the emulated impedance is
131 resistive.

132 Applying the superposition theorem, the resultant harmonic voltage at the terminal T_2 due to
133 the background harmonic voltage in the grid, $V_{g,h}(s)$, and the harmonic current, $I_{g,h}(s)$, drawn by the
134 STATCOM as shown in Figure 4, is given by,

$$V_{2,h}(s) = \frac{Z_{wpp,h}(s) \cdot V_{g,h}(s) - Z_{wpp,h}(s) \cdot \left(Z_{g,h} + Z_{tr,h}(s)\right) \cdot I_{f,h}(s)}{Z_{\Sigma}(s)}, \tag{5}$$

135 where, $Z_{\Sigma}(s) = Z_{g,h}(s) + Z_{tr,h}(s) + Z_{wpp,h}(s)$. Substituting the harmonic current reference from (4),

$$V_{2,h}(s) = \frac{Z_{wpp,h}(s) \cdot V_{g,h}(s)}{Z_{\Sigma}(s) \cdot \left(1 + \frac{k \cdot HF(s) \cdot Z_{wpp,h}(s) \cdot \left(Z_{g,h}(s) + Z_{tr,h}(s)\right)}{Z_{\Sigma}(s)}\right)}. \tag{6}$$

136 Thus, in comparison to the base case (i.e. without any compensation) the harmonic voltage is
137 changed by a factor of,

$$F_{2,h}(s) = \left(1 + \frac{k \cdot HF(s) \cdot Z_{wpp,h} \cdot \left(Z_{g,h} + Z_{tr,h}\right)}{Z_{\Sigma}}\right) \tag{7}$$

138 Since, the harmonic voltage at T_1 is given by,

$$V_{1,h}(s) = \frac{Z_{tr,h}(s) \cdot V_{g,h}(s) - Z_{g,h}(s) \cdot V_{2,h}(s)}{Z_{g,h}(s) + Z_{tr,h}(s)} \tag{8}$$

139 Using (6), (7) and (8), we get,

$$V_{1,h}(s) = \left(\frac{Z_{tr,h}(s) - \frac{Z_{g,h}(s) \cdot Z_{wpp,h}(s)}{Z_{\Sigma}(s) \cdot F_{2,h}(s)}}{Z_{g,h}(s) + Z_{tr,h}(s)}\right) \cdot V_{g,h}(s) \tag{9}$$

140 3. Harmonic compensation analysis

141 The WPP network is largely a radial network. When a compensating resistor is connected at a
142 bus, the equivalent impedance of the network, downstream from that bus, decreases. Thus the system
143 impedance characteristic gets changed. Consequently, the harmonic voltages at different buses in the
144 system would change. The resultant amplification ratios for different cases with two different values
145 of the harmonic filtering resistance connected at two different buses are numerically analyzed using
146 (1).

147 *3.1. Active damping using harmonic resistance at bus T_2*

148 When a resistance is connected at T_2, it is in parallel to the WPP impedance. Hence, the effective
149 WPP impedance is lower in magnitude and its phase angle moves closer to $0°$, implying that it is more
150 resistive as shown in Figure 8. The solid arrows indicate the 5th, 11th and the 13th harmonic impedance
151 when there is no compensation. The dotted lines indicate the locus of the tip of the impedance move
152 from the initial uncompensated values towards the origin, as the emulated resistance is decreased
153 from 10 pu to 0.03 pu. The asterisk marks indicate the points for 2, 1.5, 1, 0.5, 0.25 pu resistive
154 compensation.

155 Physically, the resistors in harmonic power filters dissipate energy, and thus provide damping
156 to harmonic amplifications. Likewise, the APF can provide damping to harmonic amplifications by

157 emulating resistive behaviour at the selected harmonic frequencies [11]. This is the case for providing
158 harmonic compensation at the local bus.

159   For the frequency domain analysis, a shunt resistor is connected at bus T_2, in parallel to the WPP
160 impedance, Z_{wpp}. The resultant amplifications at bus T_1 and bus T_2 are shown in Figure 10. These
161 curves show that while the compensation works for the full range of harmonics at bus T_2, it is not
162 effective at the remote bus T_1 as the 6th, 7th, 10th, and 11th harmonic voltages get amplified.

Figure 8. WPP impedance at T_2. (**a**) Impedance values at different harmonic orders. (**b**) 5th, 11th and 13th order Impedance locus as the compensating resistance at T_2 is decreased from 10 *pu* to 0.03 *pu* (1 *pu* = 121 Ω)
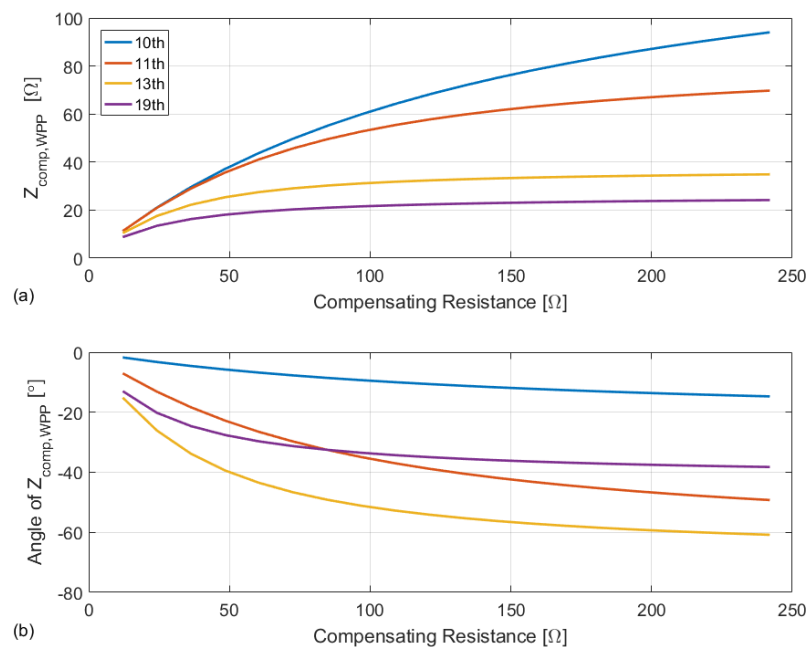

Figure 9. Variation of WPP impedance with resistance connected at T_2. (**a**) Magnitude. (**b**) Phase.

163   As shown in Figure 10, the harmonic compensation, provided by the resistances of sizes 1 pu
164 (121 Ω) and 0.5 pu (62.5 Ω) respectively at bus T_2, reduces the local amplification ratio. However,
165 it is not the same for the remote bus, T_1, which is upstream. An amplification is observed here, in
166 the base case, as the grid impedance is capacitive while the WPP side impedance is inductive largely

167 due to the inductive impedance of the grid transformers. Even though there is an attenuation of the
168 10th harmonic at the local bus T_2, it gets amplified in comparison to the base case at T_1. This can be
169 attributed to the reduced damping due to the reduction of the effective resistance of the WPP from
170 424 Ω to 210 Ω and due to the compensation as shown in Table 2.
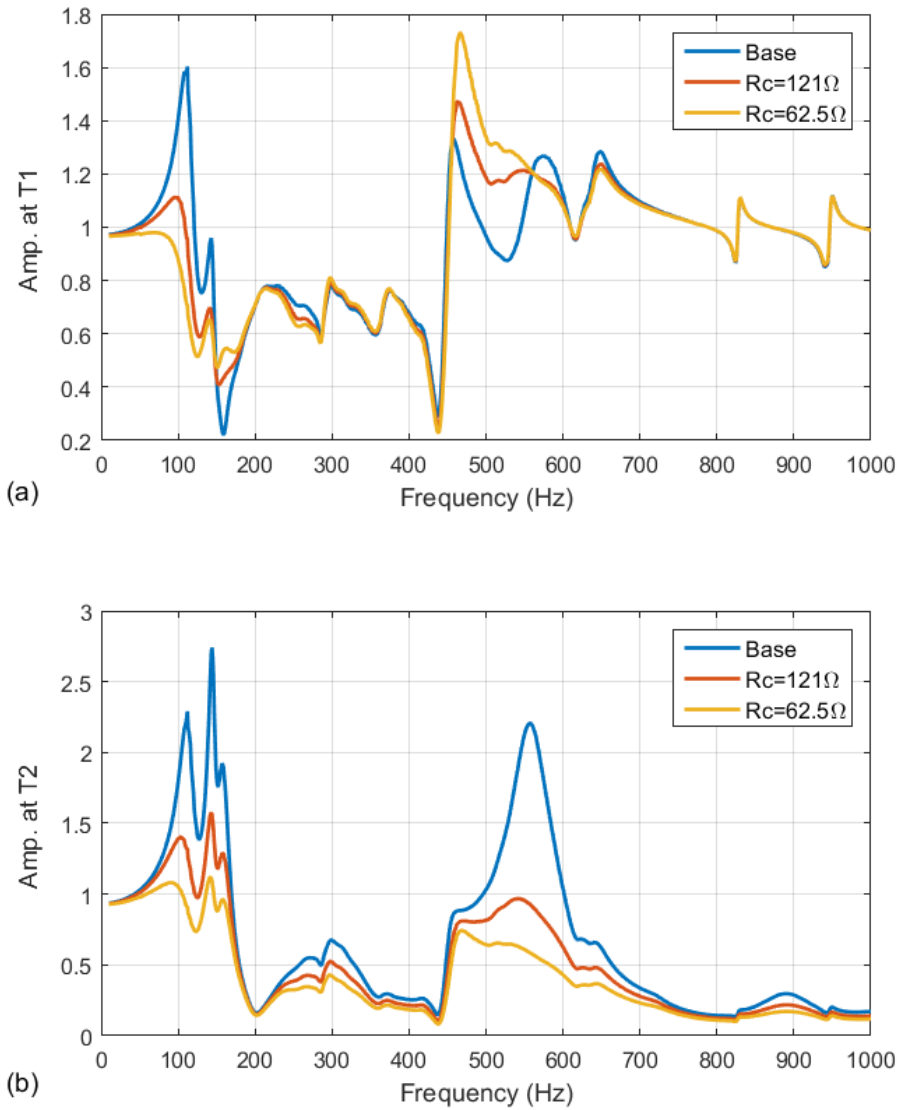

Figure 10. Amplification due to compensation at T_2.

Table 2. 10th harmonic impedance (referred to 400 kV) observed at T_1 with $1pu$ resistive compensation at T_2.

	Unit	Real	Imaginary
Z_g	[Ω]	20	−108
Z_{tr}	[Ω]	3	261
Z_{wpp}	[Ω]	421	-185
$Z_{wpp,comp}$	[Ω]	207	-39
$Z_{wpp} + Z_{tr}$	[Ω]	424	76
$Z_{wpp,comp} + Z_{tr}$	[Ω]	210	222

171   *3.2. Active damping using harmonic resistance at bus T_1*

172   As shown in Figure 11, when the harmonic compensating resistances of sizes 1 pu (i.e. 400 Ω)
173   and 0.5 pu (i.e. 200 Ω) respectively are connected at bus T_1, the harmonic voltage gets reduced for
174   the local bus T_1 as well as bus T_2, which lies downstream. It is expected, as the harmonic voltages are
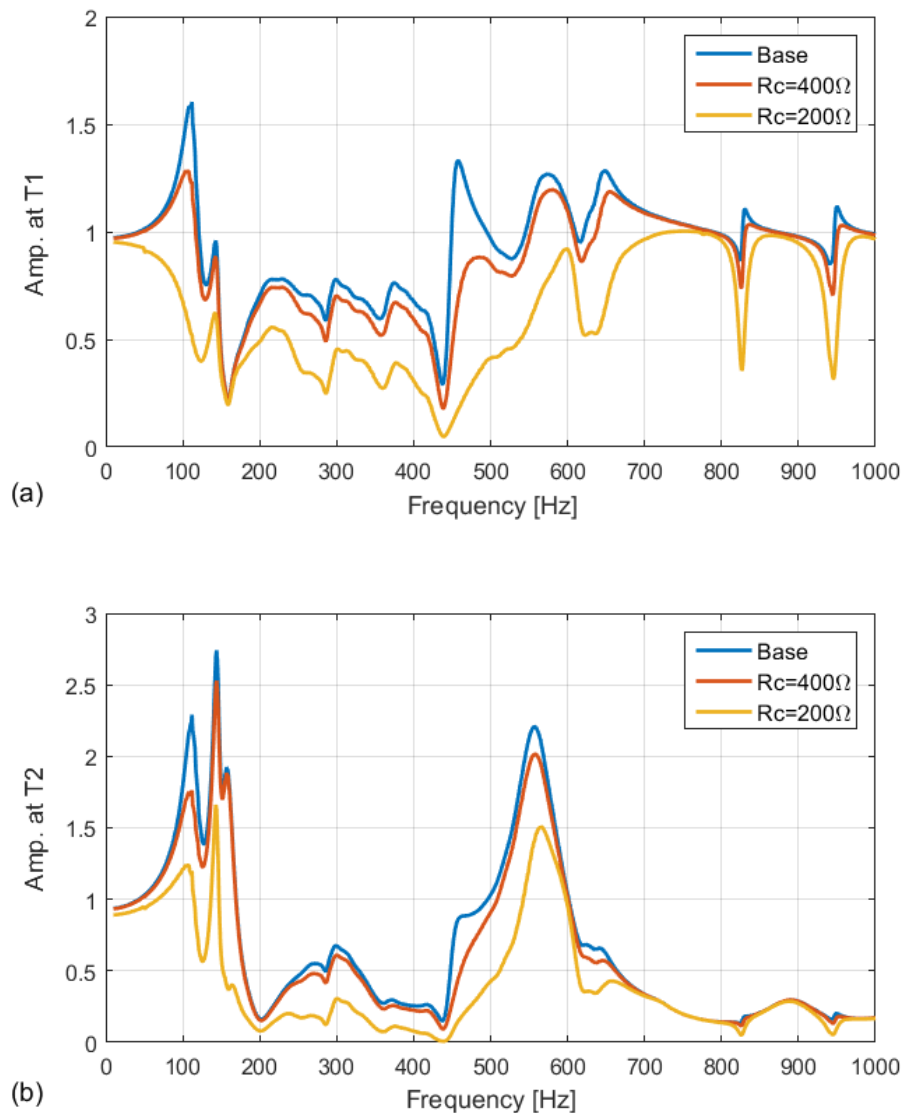**175**   appearing due to background harmonics in the grid.

Figure 11. Amplification due to compensation at T_1.

4. Nyquist Stability Analysis

177   Equation (7) for the harmonic voltage reduction factor is analogous to the characteristic equation
178   of a closed loop transfer function. Therefore, the stability of the proposed control algorithm can be
179   studied using Nyquist stability criterion on the loop gain,

$$F_{ol}(s) = \frac{k \cdot HF(s) \cdot Z_{wpp,h} \cdot \left(Z_{g,h} + Z_{tr,h}\right)}{Z_{\Sigma}}. \tag{10}$$

180   If all the poles of (10) are on the right half plane, it will be stable for all values of the scalar gain
181   constant k. The Nyquist plot of this factor shown in Figure 12. It appears to be stable for all positive

182 values of k as it does not encircle the point $(-1.0, 0)$. The frequency characteristics of the harmonic
183 voltage reduction factor is further elaborated in Figure 13. The phase margin at the gain crossover
184 frequency of 240 rad/sec i.e. 38.2 Hz is 5 deg. This implies that there will be amplification of the
185 frequency components less than 38 Hz. The phase always remains within ± 180 deg.
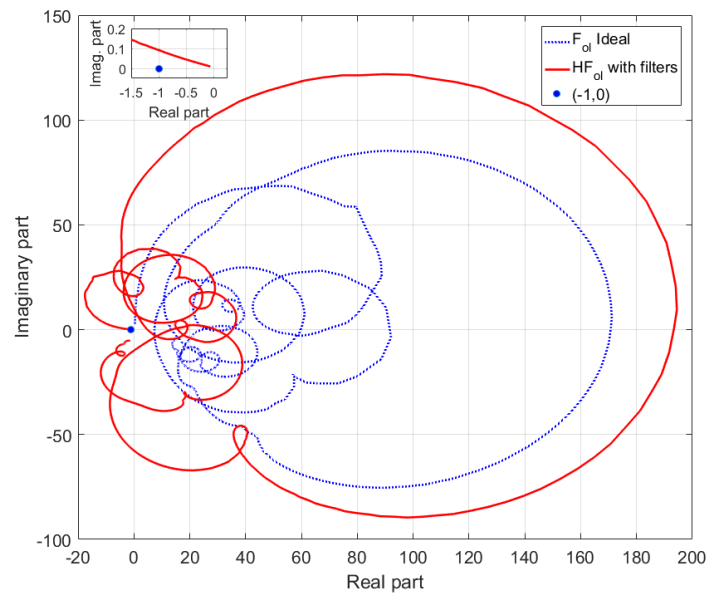

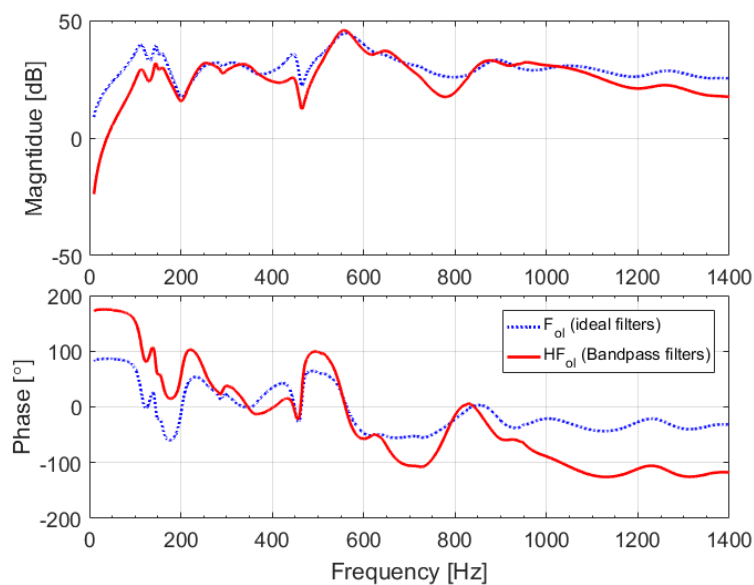**Figure 12.** Nyquist plot of the harmonic resistance emulation.

Figure 13. Bode plot of the of the harmonic voltage reduction factor at T_2.

186 **5. Simulation Results**

187   Harmonic propagation studies [12] is used to compare the harmonic voltage levels at different
188 buses and harmonic currents through different components in the system. Afterwards, the
189 performance of dynamic harmonic compensation is shown using time domain simulation in PSCAD.

5.1. Harmonic propagation studies

In harmonic propagation studies, the network model is created for a specific harmonic frequency and the network equations are solved for that particular frequency. Since the power frequency is not considered and only one frequency is considered at a time, the emulation of resistance at the specific harmonic frequency by the STATCOM is simulated by a connecting a resistance in the network at the concerned bus. In this work, a 1-*pu* resistance is separately connected to bus T_1 and T_2. The resultant harmonic voltages at buses T_1, T_2 and T_4 are observed in the test system. The results are then compared in Figure 14. In line with the amplification ratios described in the previous section, the compensation at bus T_1 leads to a reduction of voltage harmonics at all the aforementioned buses. The compensation at bus T_2 leads to the reduction of harmonics at bus T_2 and T_4, which are downstream, while there is an amplification of the 7th and the 11th harmonic at bus T_1. The results corroborate the prediction made in the previous section as the distortion levels at bus T_2 is decreased for all the harmonic orders, whereas, for bus T_1, it gets decreased only for the 5th and the 13th harmonic orders.
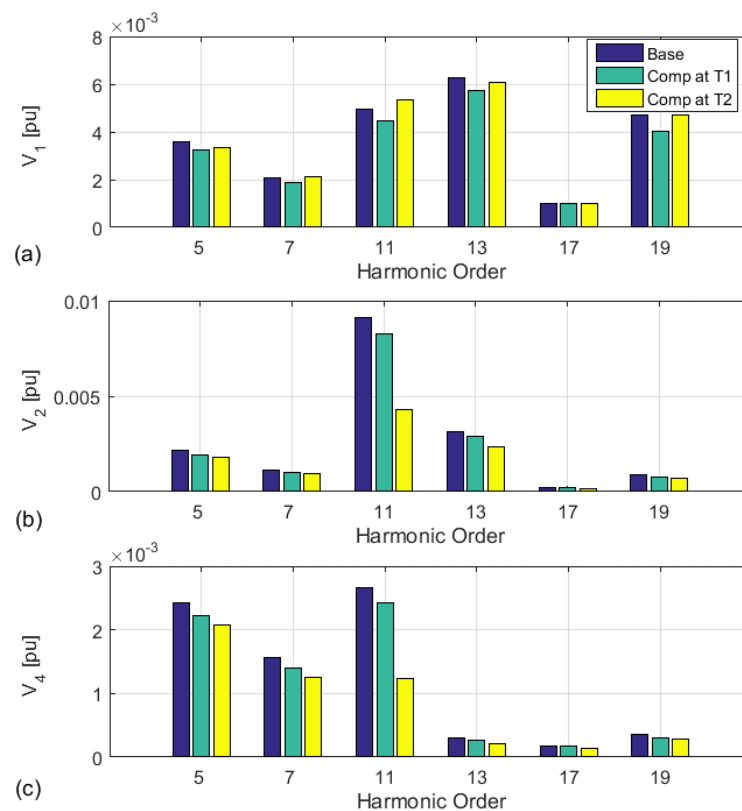

Figure 14. Harmonic voltages in pu at (**a**) T_1, (**b**) T_2, and (**c**) T_4.

The harmonic current flow in the different components as well as in the STATCOM is shown in Figure 15. The harmonic current drawn from the grid is higher than that in the base case, when the compensation is provided at bus T_1. By Kirchhoff's law, it is obvious that the grid has to supply the current drawn by the WPP as well as the compensating resistance. Thus, the resultant harmonic current in the grid will be the phasor sum of the WPP current and the STATCOM current. When the compensation is provided at bus T_2, the grid currents are reduced by over 50% for the 11th harmonic, while there is a smaller reduction for other harmonics, except the 5th harmonic, for which there is an amplification. This amplification is due to the reduction of the total impedance for the 5th harmonic.
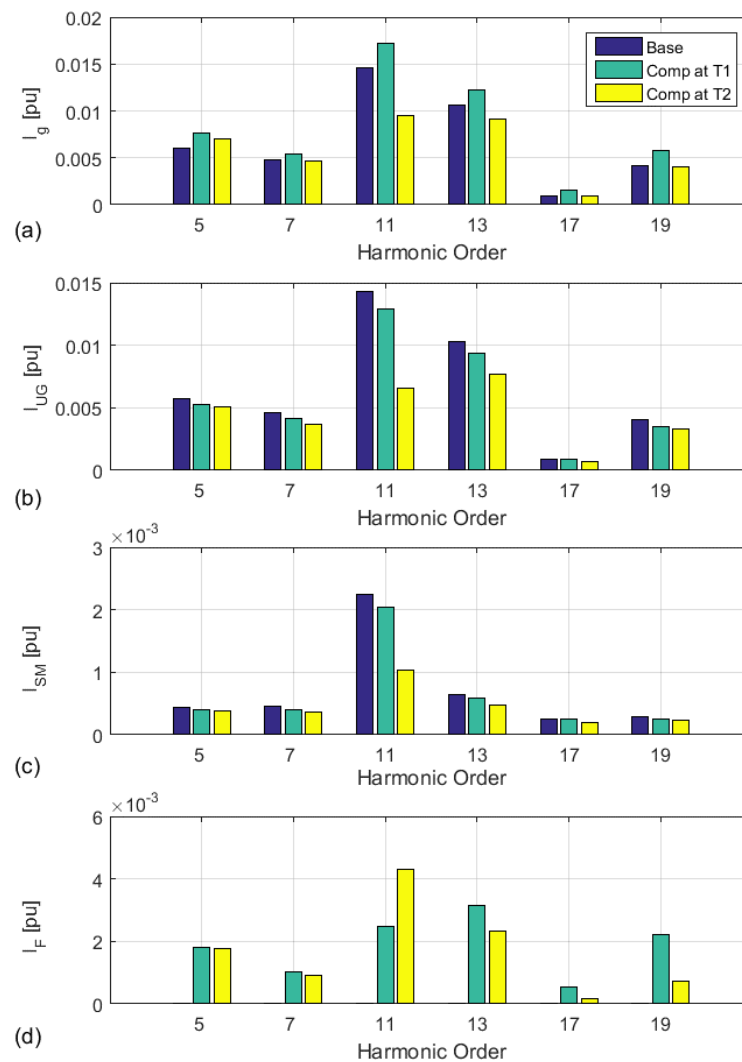
Figure 15. Harmonic currents in pu. (**a**) Grid at T_1, (**b**)Underground (UG) cable at T_2, (**c**) Sub-marine (SM) cable at T_4 and (**d**) STATCOM.

5.2. Time domain simulation

A time domain simulation model has been developed in PSCAD to show the STATCOM controller emulating the resistive behavior. The harmonic current source model of the STATCOM is connected to bus T_2 as shown in Figure 4. Its controller measures the T_2 bus voltage and extracts the 5th, 7th, 11th, 13th, and the 19th harmonic voltages. Then the corresponding harmonic current references are generated. When the voltage and currents are stated in *pu* values, setting the gain $k = 1$ results in the emulation of $1pu$ resistance (i.e. 121 Ω) at the selected harmonics.

The harmonic filtering functionality of the STATCOM is activated at 5s. The dynamics of the 5th and 11th order harmonic voltages and the filter currents at T_1 and T_2 are shown in Figure 16 and Figure 17. The harmonic components of the voltage decrease at the local bus T_2. The 5th harmonic component of the voltage at the local terminal T_2 decrease from 0.34% to 0.29%. Similarly the 11th harmonic component decrease from 1.42% to 0.64%. The 5th and 5th harmonic currents from the STATCOM is 0.22% and 0.44% respectively. Table 3 shows that all the 5 selected harmonic voltage components get attenuated at the local bus T_2 due to the compensating harmonic currents from the STATCOM. The total rms value of the selected harmonic compensating currents is 0.57% of the nominal.

For the remote bus T_1, the 5th and the 13th harmonic orders show attenuation while the 7th and the 11th orders get amplified as shown in Table 3. The attenuation of the 5th harmonic voltage component from 0.43% to 0.40% and the amplification of the 11th harmonic voltage component from 0.47% to 0.51% as a result of the compensation from the STATCOM is shown in Figure 17. Though the numerical values intime domain simulation differ from the numbers obtained in the harmonic propagation studies, they exhibit similar trend.

Table 3. Harmonic voltages in the base case and after compensation (pu values are shown in percentage to reduce the leading zeros).

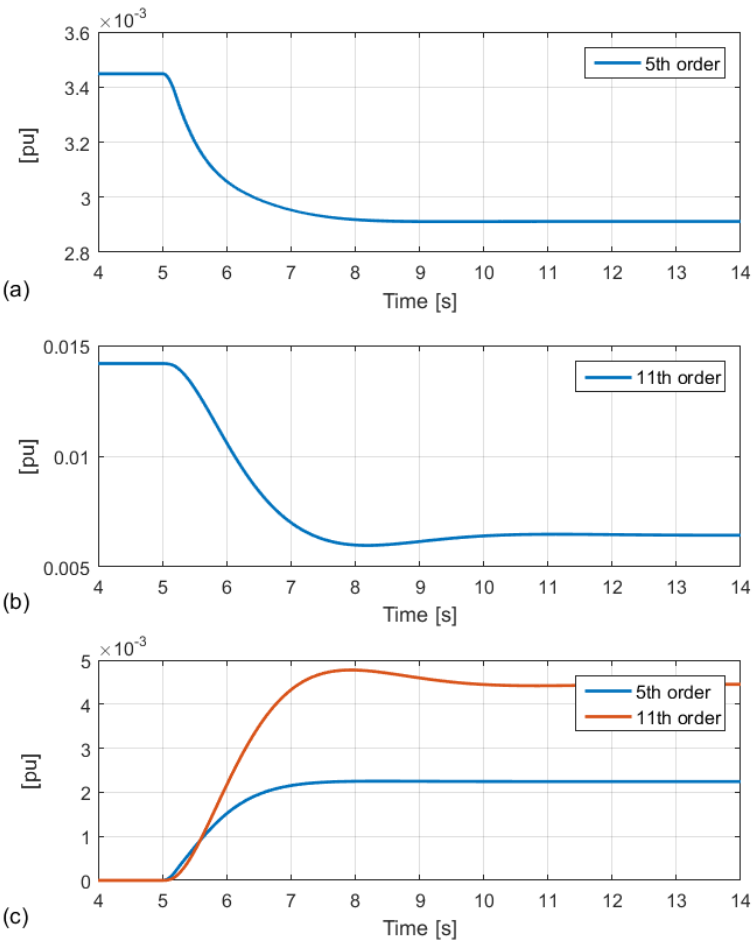| Harmonic order	5th	7th	11th	13th	19th
Bus T_1					
Base (%)	0.43	0.23	0.47	0.60	0.47
Compensated (%)	0.40	0.23	0.52	0.58	0.47
Change (%)	7	-1	-11	2	0
Bus T_2					
Base (%)	0.34	0.12	1.42	0.25	0.06
Compensated (%)	0.29	0.09	0.64	0.21	0.05
Change (%)	16	19	55	18	12
Current (IF in %)	0.22	0.10	0.44	0.24	0.06

Figure 16. (**a**) 5th harmonic voltage at T_2. (**b**) 11th harmonic voltage at T_2. (**c**) 5th and 11th harmonic resistive currents by the STATCOM.

Figure 17. Harmonic voltages at T_1. (**a**) 5th order. (**b**) 11th order.

6. Conclusion

This work investigates the amplification of the harmonic voltage distortion due to the background harmonics in the grid at two different buses in a test WPP model. The effect of ideal resistive compensation is numerically analysed and then corroborated using harmonic propagation studies. Afterwards, a time domain simulation is used to include the validate the performance of this scheme including the bandpass filters for the extraction of harmonic voltage components.

The resistive compensation is realized using a STATCOM, which emulates the resistive behavior for the selected harmonic orders. Since the STATCOM controller determines the harmonic current references, its effective resistance can be adapted dynamically in real time. Harmonic resistive compensation has the following salient features:

- It can attenuate the harmonic voltages at its own bus, that is bus T_2.. Since the WPP has a radial network, the harmonic voltage level gets attenuated downstream from the point of compensation, i.e. at the buses T_3 and T_4.
- The attenuation at remote buses upstream from the point of compensation is not guaranteed. Rather, in some cases, there may be an amplification of harmonic distortion levels. In the test system, the 5th and 13th orders were attenuated while there was an amplification for the 7th and 11th orders at the bus T_1 . Therefore, all different scenarios should be evaluated to ensure that there is no undue amplification at the PCC and other buses upstream.
- This method is found to be stable for all values of the emulated resistance as per the Nyquist stability criterion.

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