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Amplification of Harmonic Background Distortion in Wind Power Plants with Long High Voltage Connections

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SUMMARY

Assessment of harmonic disturbance in offshore wind power plants (WPPs) is becoming an increasingly important task as the WPPs are increasing in size. It has been customary in the past to base all compliance and design studies on positive sequence simulation models. However, the use of long high voltage (HV) cable connection systems gives rise to the need for more sophisticated modelling. It is justified that in case of unsymmetrical cable systems, such as flat formation single phase HV cable systems a decoupled sequence model can lead to underestimation of the harmonic distortion in the system.

The electrical connection to the 400 MW Anholt offshore WPP is used as a study case example. Synchronized harmonic voltage measurements were taken at the Point of Common Coupling (PCC) for Anholt (400 kV) and at the Point of Connection (PoC) (33 kV). Based on the measurements, corresponding per phase harmonic voltage gains are determined. Furthermore, the harmonic voltage sequence components are determined at the PCC of Anholt. It is shown that at and near resonances the harmonics do not follow their natural sequence order, but the voltages contain some portion of all three components (i.e. positive, negative and zero sequence components).

KEYWORDS

Cable crossbonding, Cable modelling, Electromagnetic compatibility, Harmonics, Harmonic amplification, Harmonic propagation, Inter-Sequence coupling, Phase domain,

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1 INTRODUCTION

An AC cable system comprising of submarine and land cable sections is the most common way of integrating a large offshore WPP to the onshore transmission network. The length of the combined cable system can, in some cases, be very long – in Denmark for instance the longest WPP cable connection is 84 km. Furthermore, the array cable system interconnecting the individual wind turbines (WTs) to a collection point can be over 100 km long making the total length of the cable system close to 200 km. The total length of HV cables for future offshore projects is expected to be even longer, perhaps beyond 150 km. Experience shows that operation of such a long cable system can have a significant impact on power quality in terms of harmonic background amplification due to resonances caused by the offshore WPP electrical infrastructure as well as the onshore and offshore transmission system. During low power production or in some cases under normal production, the background harmonic distortion in the onshore grid can potentially be amplified towards the offshore WPP leading to potential design or compliance issues both at the PoC and internally in the park array cable system. Such harmonics amplification at different locations within the WPP and transmission system electrical infrastructure can possibly bring concerns in relation to estimated harmonic voltage distortion levels or limits specified in grid codes.

The importance of the phenomenon is gaining momentum due to the growing number of large-scale WPP connection into the transmission grid. In Denmark, the HV export system is owned and operated by the transmission system operator (TSO) and therefore harmonic compliance is evaluated and specified at the PoC designated as on the secondary side of the park transformers at the offshore platform. Hence it is the responsibility of Energinet.dk as the Danish TSO to ensure power quality at the PoC is compliant before the connection of the WPP. However, due to the combined length of the array cables and other passive components within the WPP electrical infrastructure, amplification can increase due to the shift in resonance conditions or introduction of new resonances when the WPP is switched in. Therefore it is equally important for both the TSO and the WPP developer to understand and limit the cause of the background harmonic voltage amplification due to resonances within the electrical infrastructure. Due to the availability and access to measurements data, Anholt WPP was utilised to illustrate possible difficulties that may be encountered and hence should be taken into account during harmonic assessments where the grid connection system is unsymmetrical (i.e. with unbalanced impedance) in nature and wherefore simplified positive sequence analysis may be inadequate.

2 SYSTEM DESCRIPTION

The electrical infrastructure of the Anholt WPP is shown in Figure 1.

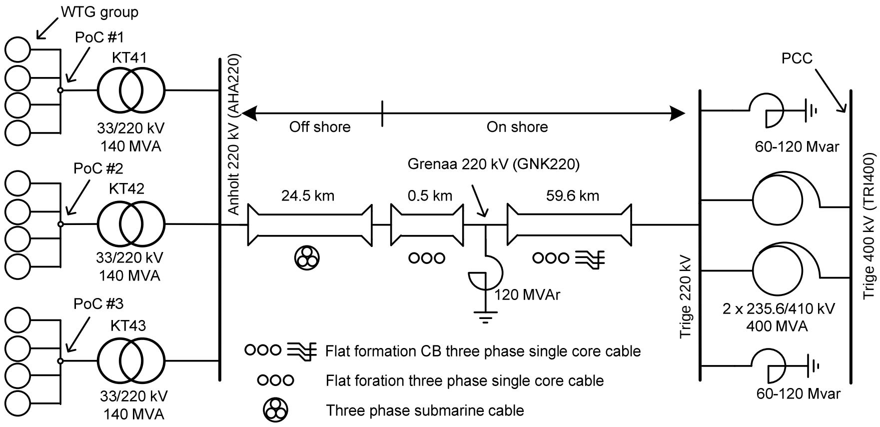

Figure 1 The electrical connection of the 400 MW Anholt WPP to the Danish transmission system.

The export system consists of two 400 MVA transformers and three 220 kV cable parts; a 59.6 km cross-bonded land cable laid in flat formation, a 0.5 km beach cable and a 24.5 km three-core submarine cable. A reactor station (GNK220) is placed at the transition point between the land and beach cable. The offshore platform includes three 140 MVA, 220/33 kV transformers. In the medium voltage (MV) array cable system, 150 mm^2, 240 mm^2 and 500mm^2 copper cables are used to connect the wind turbines (WTs) to the offshore substation. The layout of the array cable system is non-uniform leading to differences in the total length of the MV cables connected to each PoC as presented in Figure 1 [1].

The 33 kV array cable system has a combined length of 152 km and the details are presented in Table I.

Table I Anholt array grid details.

Connected to	WTs	Arrays	Array cable length [km]	Capacitance of array grid [μF]
PoC#1	37	4	50	14
PoC#2	37	4	48	13
PoC#3	37	4	54	15

Because the array cable system at each PoC is different in length and structure, the effect of harmonic amplification can also be different at the three PoCs and hence they must be evaluated individually.

2.1 POWER QUALITY MEASURING AND ANALYSIS SYSTEM

Power quality measurements are recorded at Trige 400 kV substation which is the PCC of the Anholt WPP.

Traditional HV and extra high voltage (EHV) instrument transformers are not capable of correctly representing all harmonic frequencies in their secondary circuits due to the internal resonance in the measuring systems; this is certainly the case for capacitive voltage transformers and for the electromagnetic wound voltage transformers beyond a certain frequency [2]. Because of this, correct evaluation of the harmonic content of HV and EHV signals can be problematic. Hence, in recent years specially designed transducers have been developed which can be incorporated into traditional capacitive voltage transformers providing a bandwidth of the measuring unit well beyond the 50th harmonic [3]. The wound voltage transformer (VT) at the PoC can reflect the harmonic content in the high voltage signal up until some cut-off frequency. This frequency is typically around 800-1000 Hz (around about 20th harmonic order) at 33 kV. In this study only measured harmonics until the 13th order are discussed; hence the 33 kV VTs can be used directly. Time domain voltages are recorded at the PCC and PoC at a sampling frequency of 20 kHz. The harmonic phase-to-ground voltage magnitudes and their phase angles are determined using the Discrete Fourier Transform (DFT) at each location.

3 TRANSMISSION LEVEL HARMONIC VOLTAGE BACKGROUND DISTORTION

For transmission level simulation studies and system design purposes, it is a common approach to assume that either all harmonic voltages are purely positive sequence or that all non-triplen harmonics are positive sequence and triplen harmonics are zero-sequence. However, field measurements indicate that especially on and near cable systems in unsymmetrical formations (as in case with the flat formation single core HV cables used for the land cable part of the grid connection system for Anholt WPP), the harmonic voltages can be v unbalanced. An unbalanced harmonic order will contain a portion of all tree sequence components rendering the former assumption invalid.

A typical Danish transmission level harmonic spectrum from the 2nd to the 20th harmonic taken at Trige 400 kV is shown in Figure 2. The signals used for the analysis are measured using the specially developed high bandwidth high voltage sensors described in Section 2.1

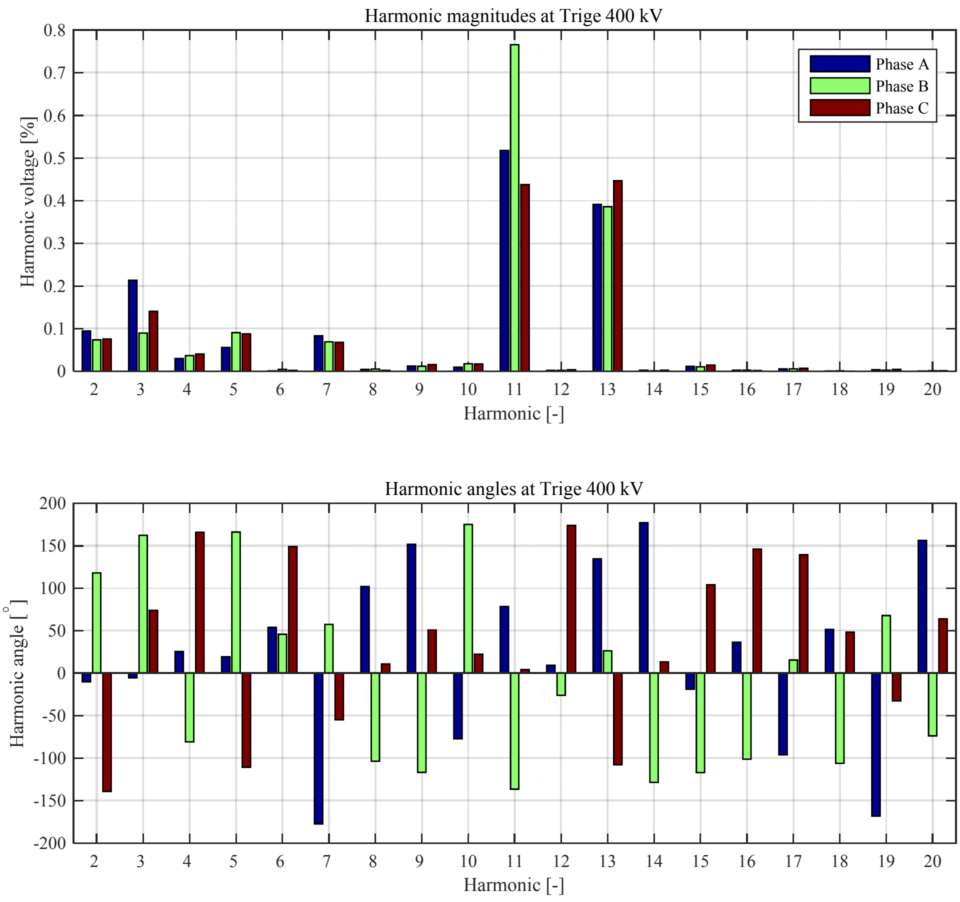

Figure 2 Harmonic magnitudes and phase angles obtained at Trige 400 kV.

Figure 2 shows strong unbalanced behaviour for some of the harmonics and more balanced behaviour at others. For instance, the magnitude of the 11th order harmonic voltage on phase B is almost twice as large as the magnitude of phase C. Also, the 3rd order harmonic, often assumed to be a pure zero-sequence harmonic, shows strong unbalanced behaviour indicating a diverse content of the three sequences.

With both the harmonic magnitudes and phase angles correctly determined for each phase, the sequence components of the harmonic voltages can be determined using Fortescue transform. This is done for the harmonic voltages shown in Figure 2 and the results are presented in Figure 3.

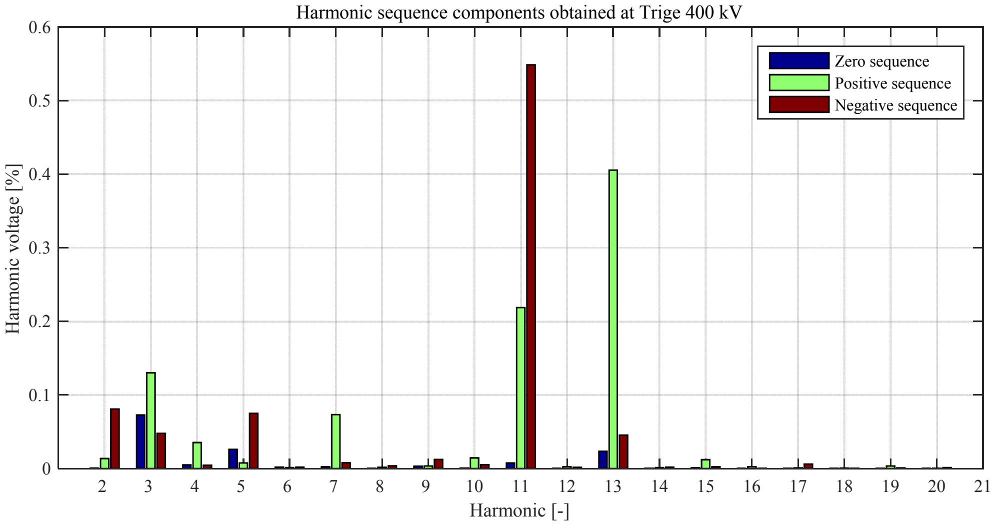

Figure 3 Harmonic voltages in sequence component form at Trige 400 kV.

The sequence decomposition of the harmonics shows that there is a tendency that most of the harmonics follow their natural sequences under the balanced system assumption. For instance the 2nd order harmonic is predominantly a negative sequence harmonic, the 4th is predominantly a positive sequence harmonic, the 5th is predominantly a negative sequence harmonic and so on. However, the 11th order harmonic, that is expected to be negative sequence, contains a non-negligible positive sequence component. The 3rd order harmonic contains all three sequence components with a slightly higher content of positive sequence. Hence, it is safe to conclude that the assumption that individual harmonic orders contain only one unique sequence component will lead to an underestimation of the highest phase-to-ground harmonic voltage which can be an issue for planning and design purposes. The reason for the unbalanced behaviour at some harmonic orders is analysed in Section 4.

4 PHASE DOMAIN HARMONIC MODELLING

Harmonic propagation studies are most often conducted before system components are selected because changes to the system are either not an option or very expensive after the installation process begins. Hence, the designer relies on trustworthy simulation results for design- and compliance studies. Such harmonic design studies are often carried out in the decoupled sequence domain where positive sequence and sometimes zero-sequence data is used to build a simplified harmonic model of the system under study. Such modelling approach can be inaccurate on a system with a significant amount of cables laid in flat formation due to the inherent unbalance introduced naturally as indicated by the measurements in Section 3. Furthermore the detailed phase-domain modelling requires appropriate representation of harmonic sources (e.g. harmonic background distortion measured at Trige 400kV) including information about phase amplitudes and angles.

A phase-domain model is necessary to predict the correct behaviour of the harmonic voltages in an unbalanced system like the Anholt WPP. The land cable part of the electrical connection is comprised of three single-core cables cross-bonded and laid in flat formation. Such a flat formation cable system introduces strong asymmetry at several harmonic frequencies. Even at power frequency the impedance of the middle laid phase can be 12-15% lower than the two outer phases [4]. Near resonance, the phase impedance of one cable core conductor can be significantly lower or higher than the two others, causing unsymmetrical harmonic currents to flow in the system even under balanced harmonic injection. As a consequence of the unbalanced series-impedance matrix of the flat formation cable, pure positive sequence injection can, besides energizing the positive sequence system, also energize the negative sequence system and the zero sequence system to some degree, with unsymmetrical phase voltages as a consequence.

A full detail frequency dependent phase-domain model of the Anholt grid-connection cable system and array cable system is constructed in DIgSILENT Power Factory. All cables are modelled based on a geometrical description and all cross-bondings are manually implemented. The frequency dependence of the transformers and reactors is included using appropriate multiplication factors [5]. The WTs are modelled using a Thévenin equivalent including turbine transformers and WT internal filters.

To illustrate the importance of phase domain modelling, an ideal positive sequence harmonic voltage is applied behind the system impedance at Trige 400 kV at each integer frequency from the 2nd to the 20th harmonic and the three phase-to-ground voltages and the positive, negative and zero-sequence voltages at the 220 kV offshore substation are calculated as shown in Figure 4.

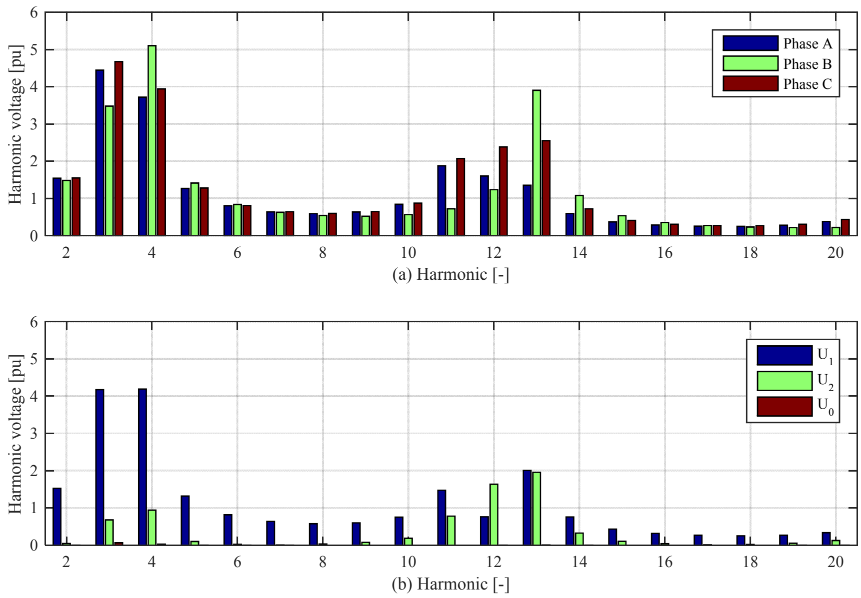

Figure 4 (a) Phase A, B, C and (b) positive, negative and zero-sequence harmonic voltage at the 220 kV offshore substation for an applied positive sequence harmonic voltage at Trige 400 kV

The resulting phase impedance as seen from Trige 400 kV ($Z_p(h)=U_p(h)/I_p(h)$) where p is equal to A, B or C) is presented in Figure 5.

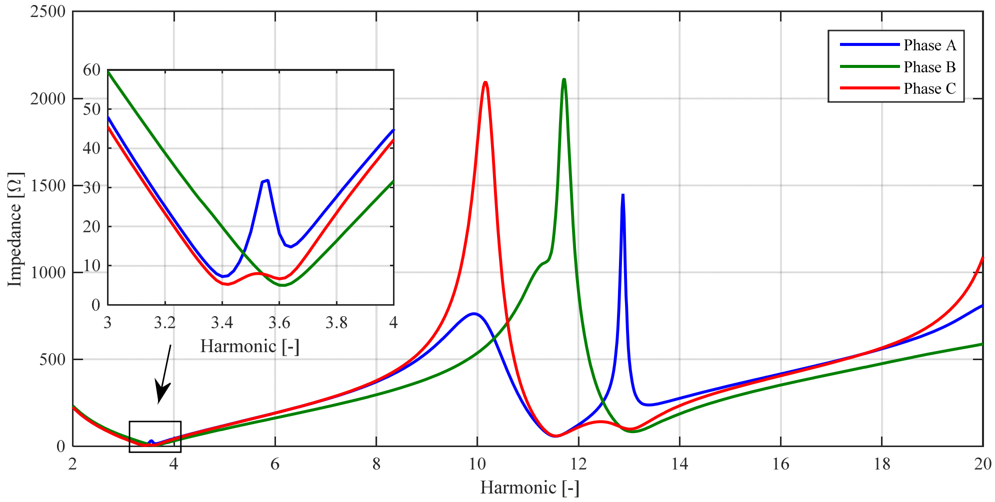

Figure 5 Phase A, B and C impedances seen from Trige 400

By comparing Figure 4 and Figure 5, it can be clearly seen that the application of positive sequence voltage only predicts well the harmonic phase-to-ground voltage at frequencies far from resonance. This is at conditions where the phase impedances of the three phases are balanced as seen from the location of harmonic injection. At resonance and near resonance (i.e. harmonic range from the 3th to 4th and between the 9th and 14th in Figure 5), the three phase impedances differ and hence inter-sequence coupling will occur. Notice for instance the negative sequence voltage at the 12th harmonic in Figure 4 is larger than the positive sequence voltage – this is under positive sequence injection only into the system as explained. Notice also that at the 13th harmonic, the phase B voltage is more than double in magnitude compared to the magnitude of phase A voltage. In sequence domain this manifests itself as a much lower (almost half) positive sequence voltage implying that assessment based on positive sequence will lead to underestimation of the harmonic voltage. In a decoupled sequence networks based model this phenomena would be missed altogether. Therefore, using only the positive sequence component for compliance analyses at planning/design stage can be problematic in unbalanced systems.

5 PHASE DOMAIN HARMONIC VOLTAGE GAIN

During harmonic compliance studies it is common practice to calculate harmonic voltage gains to establish effect from one node to another. In the decoupled sequence domain, the positive sequence harmonic voltage gain from Bus X to Bus Y at the h^{th} harmonic can be determined as:

$$G_1(h)=\frac{U_{1Y}(h)}{U_{1X}(h)} \quad (1)$$

where $U_{1X}(h)$ and $U_{1Y}(h)$ are the positive sequence harmonic voltage at the h^{th} harmonic at Bus X and Y respectively. The negative and zero sequence harmonic voltage gains are defined in the same manner but not often used in practical studies.

The harmonic voltage gains of the three sequence components are well defined due to the definitions governing the decoupled sequence domain. There is a linear relationship between the sequence components of the voltage at the two busses; increasing the harmonic distortion at Bus A by some factor will lead to an increase at Bus B by the same factor in a one-source system. This is one of the main benefits of the decoupled sequence domain when it comes to harmonic propagation studies. The same cannot be said in the phase domain. The per phase harmonic voltage gain would naturally be defined as:

$$G_p(h) = \frac{U_{pY}(h)}{U_{pX}(h)} \tag{2}$$

where $U_{pX}(h)$ and $U_{pY}(h)$ are the harmonic voltage of phase p (A, B, or C) at the h^{th} harmonic at Bus X and Y.

Many TSOs use a decoupled sequence model for harmonic studies. However, harmonic emission limits are issued and measured in relation to the highest phase-to-ground value. Because mutual coupling between the three phases differs in an unsymmetrical conductor configuration (such as that introduced by a cable system laid in flat formation), the decoupled sequence assumption is violated. In the decoupled sequence domain, the three sequences are independent of each other. However, the harmonic phase voltage gain depends on the unique flows in the other system conductors. This makes the calculation of the phase harmonic voltage gain complicated in an unbalanced system.

To illustrate the error introduced by using per default the decoupled sequence domain and hence positive sequence gains, the harmonic phase and positive sequence voltage gains from Trige 400 kV to the reactor station GNK220 and the gains from the reactor station to the off-shore platform are determined (see Figure 1 for system diagram and bus references). The results are shown in Figure 6.

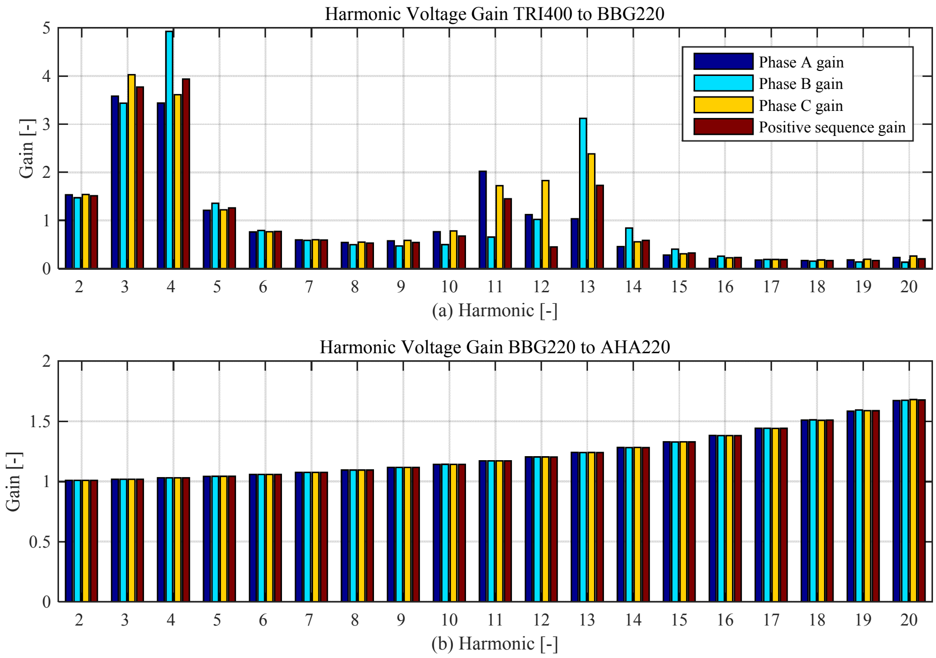

Figure 6 Harmonic voltage gains from (a) TRI400 to GNK220 and (b) GNK 220 to AHA220.

Figure 6(a) shows that the per phase and the positive sequence harmonic voltage gains from TRI400 to GNK 220 (asymmetrical flat cable formation) differ in magnitude. This is more pronounced at and near resonance frequencies.

The displayed phase and positive sequence gains in Figure 6(b) confirm that on symmetrical conductor configurations (such as the submarine cable laid for the Anholt WPP), the positive sequence gain can be used without loss of information. Notice the small deviations for instance at the 19th and 20th harmonic in Figure 6(b). The deviations are caused by the 0.5 km flat formation beach cable used between the reactor station and the beach cable/submarine cable joint.

To emphasise the point at an individual harmonic level, the 13th order harmonic voltage phase gains from Trige 400 kV to Anholt 33 kV are calculated based on measurements over two days. The 13th order harmonic voltage as function of time (10 min avg. values per IEC 61000-4-30) are shown in Figure 7(a) and the resulting harmonic voltage gains calculated using Eq. 2 in Figure 7(b).

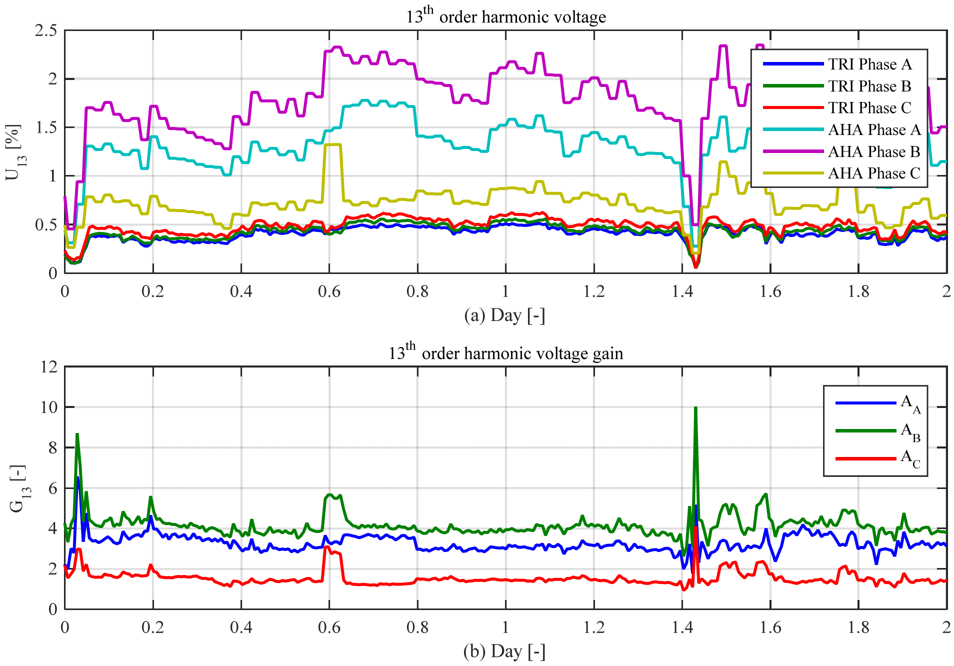

Figure 7 (a) Trige 400 kV and Anholt 33 kV harmonic 13th order voltages and (b) corresponding harmonic voltage gains.

Figure 7(b) shows that the measured 13th order harmonic voltage gains differ by a more than a factor of 2 between the three phases. Unfortunately, due to the inherit limitation of the MV IVTs, the phase voltage angles cannot be determined at Anholt 33 kV and hence the positive sequence gain cannot be calculated and compared to the phase gains. However, with the displayed differences between the lowest and highest phase gains, the positive sequence gain will not correctly represent all three phases as discussed in the previous section.

The positive sequence harmonic voltage gain in the decoupled sequence domain is per definition not dependent on the negative or zero-sequence component and vice versa. However, the harmonic voltage phase gain can be strongly dependent on which sequence components are energized if the system is unbalanced. This is illustrated in Figure 8 where two cable systems are energized by a 1 pu balanced harmonic voltage at all harmonics from the 2nd to the 20th. Gradually, a harmonic phase voltage unbalance is introduced by increasing the negative sequence content of the voltage from 0 pu to 1 pu while the harmonic positive sequence voltage component is kept constant. One cable system is laid in touching trefoil formation (symmetrical) and the other in a flat formation (unsymmetrical). The harmonic voltage gain from Trige 400 kV to Anholt 33 kV for phase A is then plotted for both cases.

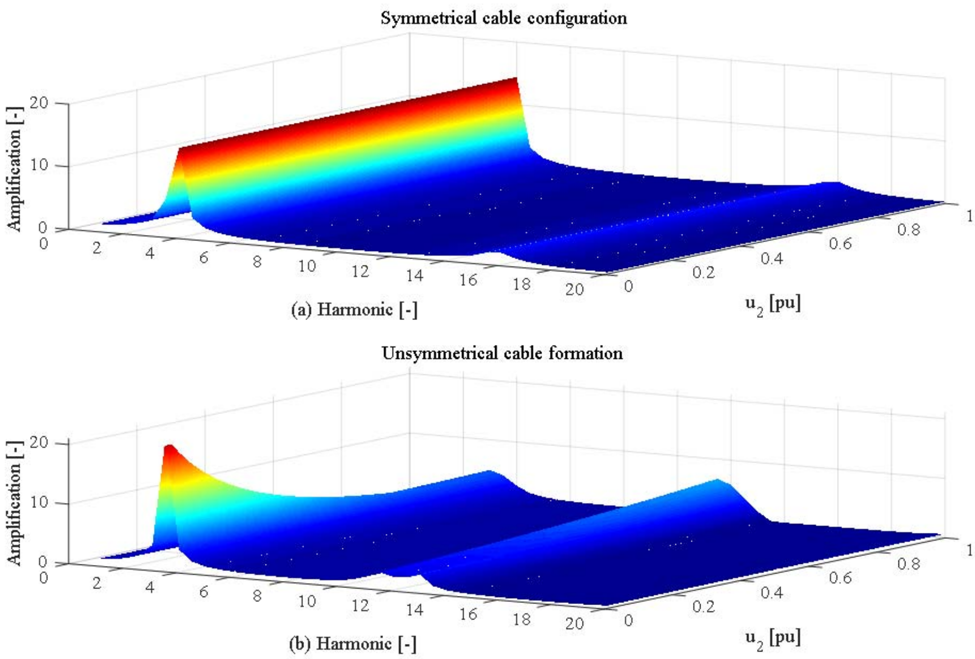

Figure 8 Phase A harmonic voltage gains from Trige 400 kV to Anholt 33 kV on a (a) cable system in touching trefoil (symmetrical), and (b) a cable system in flat formation (unsymmetrical) as the negative sequence voltage is varied from 0 pu to 1 pu.

Inter-sequence coupling is absent on the cable system in touching trefoil system as the harmonic phase impedance matrix is balanced (in contrast to flat-formation system) and as a result, the harmonic sequence impedance matrix is dominated by the diagonal elements (off-diagonal elements are close to zero). Therefore, the per phase harmonic voltage gain is not dependent on the magnitude of negative sequence harmonic voltage applied. For the unsymmetrical cable system, the per phase harmonic voltage gain is strongly dependent on the magnitude of the negative sequence voltage applied (or present) at and near resonance due to inter-sequence coupling as seen in Figure 8(b). Additionally, there will be dependence on the angle of the sequence components, complicating the issue further, but this is not covered here.

Phase-domain modelling becomes increasingly relevant as more and more cables are installed at transmission level and the degree of (harmonic) unbalance thereby increases. The MV array cables and most often the HV submarine cables are symmetrical due to construction characteristics and hence the phenomenon of inter-sequence coupling is less important. However, even with a relative short land cable section laid in an unsymmetrical formation in the system, inter-sequence coupling should not be ignored.

6 CONCLUSIONS

The paper discussed the modelling approach for harmonic propagation and assessment studies on systems consisting of long EHV cable systems. The 400 MW Anholt offshore WPP is used as a case study example.

Decomposition of high accuracy measurements taken at the PCC of Anholt WPP into sequence components shows that individual harmonic orders in general follow their natural sequences (that is negative for the 2nd, zero for the 3rd, positive for the 4th and so on). However, this is not the case at and close to resonances as each individual harmonic will contain some portion of the two other sequence components. This is expected to be the case in almost all systems due to the inherent unbalanced nature of the power networks. However, the situation may be exacerbated in certain situations and especially when there is a high degree of natural unbalance introduced around the assessment location. The analysis has shown that when modelling highly unsymmetrical cable systems as is the case with EHV and HV cable systems laid in flat formation, determination of voltage gains to a remote node or amplification of background distortion at the local node can vary depending on the complexity of modelling assumed.

The concept of per phase harmonic voltage gain is introduced and synchronized measurements at the PCC and PoC of Anholt WPP are used to determine the per phase harmonic voltage gain for the 13^{th} order harmonic. The sequence harmonic voltages are compared to the phase-to-ground harmonic voltages. It is shown that the highest harmonic phase-to-ground voltage can be significantly higher than the positive sequence voltage, and hence underestimation of the harmonic content can occur when considering only decoupled sequence modelling. Although not the case in the utilised case study, the shortcomings of using an oversimplified assumption (use of models where inter-sequence coupling is ignored) can be two fold; likely distortion may be underestimated and hence may bring uncertainties in the design with possible non-compliance issues at a stage where the cost may be severe to the WPP developer or TSO.

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