A STUDY CASE ON HARMONIC DISTORTION CREATED BY WIND TURBINES

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SUMMARY

The grid-side converters of variable speed wind turbines inject harmonic currents in the network, which may potentially create voltage distortion problems. In this paper, a case study is presented for a wind farm, intended to be connected to a network with extended HV subsea cable lines. First, the system modelling approach is presented and the harmonic load flow calculation is outlined. Then, the harmonic impedance of the system is calculated for a variety of configurations and operating conditions, and its main characteristics are discussed. Harmonic load flow results are then provided, to indicate potential voltage distortion problems.

1. INTRODUCTION

Although variable speed wind turbines (WTs) are grid-friendly machines in most power quality respects, harmonics generated by the grid-side power converters may be of concern in networks with possible harmonic resonance conditions. Such a case is presented in this paper, dealing with a 20x500 kV wind farm, intended to be connected to the Medium Voltage (MV) network of the Greek island of Kefalonia, situated in the Ionian Sea, in western Greece. The islands Kefalonia, Lefkas and Zakynthos are connected to the mainland 150 kV grid by successive overhead and submarine line sections of significant length, as shown in Fig. 3 (Section 3). Due to the large capacitance of the submarine cables, which might give rise to resonances, an investigation was deemed necessary to rule out possible harmonic distortion problems.

In Section 2 of the paper, the modelling methodology is briefly outlined. The studied system is presented in Section 3, where results are provided from the harmonic simulation. First, the harmonic impedance of the system is calculated at selected buses, its characteristics are discussed and its sensitivity with respect to various parameters is investigated. Then, harmonic load flow results are given, to indicate potential voltage distortion issues.

2. MODELLING OF THE SYSTEM

2.1 Fundamental principles

The modelling approach presented in this paper permits the basic representation of the system harmonic impedance variation at all buses and the execution of harmonic load flow calculations, to determine the resulting voltage distortion for a given harmonic excitation. The modelling approach adopted is based on IEC 61000-3-6 [1], CIGRE Guides [2-4] and IEEE Task Force recommendations [5], as well as on other relevant literature (e.g [6]) and attempts to maintain a balance between the required modelling complexity, on one hand, and the ease of implementation and scarcity of reliable data for actual systems, on the other hand. Fundamental assumptions and considerations are the following:

- Harmonic sources are the power electronics converters at the output of the WTs, modelled as current injections of given amplitudes per frequency. This is a justified assumption for current controlled converters with PWM hysteresis controllers, as in the present case.
- A direct harmonic solution ([6]) is obtained, that is the coupling between harmonics of different order is ignored.
- In the general case, the network is modelled by its 3-phase equivalent, transformed in the symmetrical component domain. This is required, to properly represent the propagation of zero sequence harmonics, as well as to cater for asymmetries of the harmonic sources.

The overall harmonic model has been implemented in the software package WindNet, developed for the analysis of the impact from the connection of WTs to the grid, [7].

2.2 Harmonic load flow

The harmonic load flow at frequency \( f_h = h f_1 \) (where \( h \) is not necessarily an integer) is based on the solution of the set of linear equations:

\[
[I_h] = [Y_h] [V_h]
\]  

where \([I_h] \) is the vector of the harmonic current injections of each busbar, \([V_h] \) is the vector of the resulting voltage harmonics, \([Y_h] \) is the network admittance matrix at \( f_h = h f_1 \)

Formulation of the admittance matrix of the network is a standard power system analysis practice, using the characteristic equations of all network elements (lines, transformers, rotating machines etc.), discussed in the following sections. In this case, the sequence equivalents of the network are employed (positive, negative and zero sequence), as mentioned in Section 2.2.1. Eq. (1) can be solved independently for each one of the three sequences, or simultaneously, as a set of 3Nx3N equations, where \( N \) is number of system buses. In the latter case, each element of vectors \([I_h] \) and \([V_h] \) is a 3x1 sub-vector, comprising the three sequence components of the harmonic current or voltage of a specific bus. Similarly, each element of matrix \([Y_h] \) is a 3x3 sub-matrix, the non-diagonal elements of which are zero for symmetrical network elements.

The network harmonic impedance matrix, \([Z_h] \), is the inverse of the admittance matrix, \([Y_h] \). Its diagonal elements are the
harmonic impedances of the respective system buses. Hence, a “frequency scan”, to reveal possible harmonic resonance conditions at specific buses, is simply performed by calculating \([Z_h]\) for varying frequencies \(f_h = hf_s\).

2.3 Harmonic sources

Representing harmonic sources as current injections, a 3-phase source would be completely described by the magnitude and angle of each phase current per harmonic frequency. Data available in practice, however, usually comprise only a current magnitude per frequency (as in the power quality certificates per IEC 61400-21 [8]). Based on such data, the modeling should properly represent superposition (summation) effects of harmonics from different sources, as well as harmonic current asymmetries, inherent in hysteretic PWM controllers.

For the summation of harmonic sources connected to the same bus, the 2nd summation law of [1] is adopted:

\[
I_k = a \sum_{h} I_{h,k}^a
\]

(2)

where \(I_{h,k}\) is the \(h^{th}\) order contribution from source \(k\). The summation exponent is \(a=1.0\) for \(h<5\), \(a=1.4\) for \(5 \leq h \leq 10\) and \(a=2.0\) for \(h>10\), reflecting the fact that the phase angles tend to become uncorrelated random variables, as the harmonic frequency increases. For harmonic sources connected to neighbouring buses, the phase angles of each source may be considered to be random variables with increasing variance, as the harmonic order \(h\) increases, to create the summation effect of eq. (2).

With respect to the current symmetry, it may be assumed that all three phases have the same current magnitude, but the phase angles can be properly randomized for higher order harmonics, to create current asymmetries. Attention should be paid to exclude zero sequence components from the harmonic currents, when the source connection does not permit them.

2.4 System load

The system load may be simulated using any of the three models shown in Fig.1 ([2-5]). In all cases \(R_1\), \(X_1\) are the fundamental frequency resistance and reactance. Proper selection of the load model is very important for correctly assessing the magnitude of possible resonances. However, no generally applicable harmonic model exists and case-specific measurements and evaluations are needed for detailed studies.

2.5 Electric machines and transformers

Asynchronous machines are simulated using their simplified equivalent circuit, referred to harmonic frequency \(f_h = hf_s\), shown in Fig.2(a). \(R_g\) and \(X_g\) are the blocked-rotor test resistance and reactance. Factor \(a = R_1/R_0\), where \(R_1\) is the resistance of the stator (typical value \(a=0.45\)). The slip at frequency \(f_h = hf_s\) is given by

\[
s_k = \frac{\pm h\omega_r - \omega_s}{\pm h\omega_r}
\]

(3)

where \(\omega_r\) is the rotor speed and the + or – sign depends on the sequence (positive or negative) of the considered harmonics. More accurate results may be obtained using the steady-state equivalent for double-cage rotor.

\[
R_s \left[ \sqrt{h} R_1 + jh X_2 \right]
\]

Figure 2. (a) Induction and (b) synchronous machine harmonic equivalents.

Synchronous machines are simulated as shown in Fig. 2(b), where \(R_2\) and \(X_2\) are the negative sequence resistance and reactance, often approximated using the \(d\) and \(q\) axis subtransient reactances, as \(X_2 = (X_{2q'} + X_{2q})/2\). For the zero sequence, the neutral grounding impedance of the stator is taken into account.

In the positive and negative sequence, transformers are modelled by their series short-circuit harmonic impedance \(Z_{k,h} = R_{k,h} + jh X_{k,h}\), where:

\[
R_{k,h} = R_{dc} (c_0 + c_1 h^b + c_2 h^c)
\]

(4)

\(R_k\) and \(X_k\) are the fundamental frequency short-circuit resistance and reactance. Values for the parameters of eq. (4) are given in [4]. In the zero-sequence, the transformer equivalent circuit takes into account the connection of the windings and the neutral grounding impedance. The phase shift angle associated with the transformer vector group is also taken into account.

2.6 Transmission lines and shunt elements

Overhead lines and cables are modelled using multiple \(\pi\)-equivalent sections, connected in series. For the analysis extending to the 50th harmonic order, satisfactory results are obtained using one \(\pi\)-section every 10 km of 150 kV overhead lines or 1.5 km of 150 kV submarine cable line. The application of more sophisticated line models has not been favoured because it is contradicted by the lack of data for the rest of the system.

Shunt elements considered are basically compensating reactor coils and capacitors, which are modelled as concentrated impedances.
3. APPLICATION RESULTS

3.1 The study case system

In Fig. 3 the one line diagram of the system under study is shown. The mainland grid is represented by its Thevenin equivalent circuit at Kastraki. Reactors are connected to the island substations, to compensate the high capacitance of the oil-insulated submarine cables. The 20x500 kW wind farm is intended to be connected to the Argostoli 15 kV busbars, via a dedicated double circuit, overhead line.

The MV network of the Argostoli substation comprises several hundred km of overhead 15 kV lines, as well as a 6.5 km long submarine cable line. The overall shunt capacitance of this network affects the first order harmonic resonance at the Point of Common Coupling (PCC) of the wind farm. It has been roughly evaluated at 400 kVAR and it is assumed associated with the first order resonance of the total shunt capacitance with the upstream system series inductance. At approximately 100 Hz (also discernible in Fig. 5), which is calculated for minimum and maximum load conditions, at the MV busbars of Argostoli substation, as well as at the 150 kV side of the substation. The results are shown in Fig. 5. It is observed that at light load conditions the impedance magnitude increases by a factor of 2.0, since lightly loaded systems are known to exhibit more pronounced resonance peaks. The harmonic impedance at the 150 kV side is very little affected by variations of the load. It is noted that the compensating coils are connected only at minimum load conditions. It can be shown, however, that they do not have a significant impact on the harmonic impedance in the frequency range of interest.

The harmonic impedance at a specific bus will depend on the load level and harmonic representation. To illustrate the effect of the load, the harmonic impedance of the system is calculated for minimum and maximum load conditions, at the Point of Common Coupling (PCC) of the wind farm, i.e. at the 15 kV busbars of Argostoli substation, as well as at the 150 kV side of the substation. The results are shown in Fig. 5. It is observed that at light load conditions the impedance magnitude increases by a factor of 2.0, since lightly loaded systems are known to exhibit more pronounced resonance peaks. The harmonic impedance at the 150 kV side is very little affected by variations of the load. It is noted that the compensating coils are connected only at minimum load conditions. It can be shown, however, that they do not have a significant impact on the harmonic impedance in the frequency range of interest.

Observation of Fig. 5 reveals the fundamental harmonic characteristics of the studied system, which remain the same, regardless of the load level. At the MV busbars, the variation of the harmonic impedance is dominated by the first parallel resonance of the aggregate busbar capacitance ($Q_c=400$ kVAR) with the upstream system inductive impedance (short circuit capacity $S_i=145$ MVA). Up to this frequency, between 1.0-1.5 kHz, the system is basically inductive, becoming capacitive thereafter. At the HV side, the diagram exhibits several resonance peaks, associated with the multiple cable/line sections. These are not affected by variations of the load, with the exception of the lowest frequency peak at approximately 100 Hz (also discernible in Fig. 5), which is associated with the first order resonance of the total shunt capacitance with the upstream system series inductance. At higher frequencies the system impedance is inductive, up to 2.0-2.5 kHz.

3.2 Harmonic impedance characteristics

The voltage harmonic distortion, $U_h$, created by the injection of harmonic current $I_h$ at a certain node of a system is simply given by:

$$U_h = Z_h \cdot I_h \quad (5)$$

where $Z_h$ is the harmonic impedance of the upstream system, as viewed from the terminals of the specific node. Given the harmonic current injection, application of eq. (5) to find $U_h$ becomes then an issue of evaluating $Z_h$.

The harmonic impedance at a specific bus will depend on the load level and harmonic representation. To illustrate the effect of the load, the harmonic impedance of the system is calculated for minimum and maximum load conditions, at the Point of Common Coupling (PCC) of the wind farm, i.e. at the 15 kV busbars of Argostoli substation, as well as at the 150 kV side of the substation. The results are shown in Fig. 5. It is observed that at light load conditions the impedance magnitude increases by a factor of 2.0, since lightly loaded systems are known to exhibit more pronounced resonance peaks. The harmonic impedance at the 150 kV side is very little affected by variations of the load. It is noted that the compensating coils are connected only at minimum load conditions. It can be shown, however, that they do not have a significant impact on the harmonic impedance in the frequency range of interest.

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The diagrams in Fig. 5 present the positive/negative harmonic impedance. The zero sequence impedance is not shown, as no zero sequence harmonic excitation exists, due to the D-connected MV windings of the WT transformers.

An issue equally important to the load level is the harmonic model used to represent loads. In Fig. 6 the results obtained for the MV bus at Argostoli are shown, using the three different models of Fig. 1. It is noted that the load modelling is critical for the local MV bus impedance, but not so much for the HV system. Model C expectably yields too optimistic results at high frequencies. This is actually an empirical model, based on measurements on a specific MV network, and it is suitable for low order harmonics. Concerning Models A and B, the latter tends to underestimate the damping effect of the load due to the series RL connection. Model A is considered to be more appropriate here, its shunt inductance corresponding to the aggregate load of small induction motors within each MV network, which do not provide essential damping at high frequencies. Hence, Model A is used for the results presented in this paper.

Since the current spectrum of the considered harmonic sources is concentrated around the 25th order (Fig. 4), variations of the PCC harmonic impedance in the frequency range 1-1.5 kHz are most critical. The resonance frequency in this range varies inversely with the aggregate capacitance $Q_c$ connected to the MV busbars, as shown in Fig. 7. $Q_c$ represents the total shunt capacitance of the whole MV network and therefore its exact value is unknown. The adopted value $Q_c=400$ kVAr, besides being a reasonable estimation, based on available network data, represents also a worst-case scenario, producing a resonance within the high distortion area of the harmonic excitation spectrum in Fig. 4.

### 3.3 Harmonic load flow results

After presenting the characteristics of the system harmonic impedance, results are now presented from the harmonic load flow. Inputs are the harmonic injections of the wind turbines, whose magnitude per harmonic order is given in Fig. 4. These currents are reported to have been measured at the MV output of the Dyn WT transformer. Therefore, they cannot include any zero sequence components (not even the triplen ones), a situation possible with hysteresis PWM current controllers.

The calculated voltage THD coefficients for the 12 buses of the system (Fig. 3) are shown in Fig. 8, for minimum and maximum load conditions. Expectedly, the harmonic distortion of the voltage is high near the wind farm (local MV network - buses 7 and 12) and it increases at minimum load. Nevertheless, the calculated THD values are too small to be of any concern.
The situation, however, is not equally good when the individual voltage harmonics are examined and compared to limit values. This is shown in Fig. 9 for the MV and HV buses at Argostoli (minimum load). A relatively high voltage distortion appears at the MV busbars between 1.0-1.5 kHz, associated with the coincidence of the resonant impedance peak (Fig. 5) with the harmonic excitation spectrum (Fig. 4). At the HV side, the voltage distortion is very reduced.

The compatibility limit and indicative planning levels of IEC 61000-3-6 are also marked on the diagrams, for comparison purposes. If these planning levels were used by the utility as permissible distortion values for the specific wind farm, violations would occur for even and triplen harmonics between 1.0 and 1.5 kHz. The situation would be have been aggravated if the utility applied a limit allocation procedure ([1,9]), in which case an individual user of the network is allocated a part of the total available voltage distortion limit.

Reduction of the calculated voltage harmonics is obtained if the shunt capacitance of the internal MV cable network of the wind farm is considered, in which case the planning limit violations are much reduced. Further reduction of the voltage distortion, even below the set limit, could be easily achieved if an increased capacitance (in fact a high-pass filter) were considered either at the Argostoli MV busbars, or at the wind farm connection point.

At this point, the limitations of the modelling approach should be pointed out, with respect to the load representation, as well as the crude modelling of the whole MV network, which has been reduced to an aggregate capacitance, connected to the busbars. A detailed and reliable evaluation of the harmonic distortion would require a more detailed representation of the MV network of the substation (rather than the HV system) and its load. On the other hand, in real world situations it is difficult to imagine that a modelling and analysis, even of the detail and sophistication presented in this paper, would be undertaken by the average utility for a single 10 MW wind farm. For this reason, even more simplified analysis methods are applied in practice, which provide fast and safe (albeit, too conservative in many cases) estimations (e.g. [9]).

4. CONCLUSIONS

In this paper a harmonic penetration study is presented, for a wind farm consisting of variable speed turbines, scheduled to be connected to a network with extended submarine cable sections. After presenting the system modelling approach, frequency scan and harmonic load flow results are given. The current harmonics of the wind turbine output converters fall near a parallel resonance of the system, resulting in a marginally acceptable situation regarding the voltage harmonic distortion.

5. REFERENCES