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Harmonic Resonance Study for Wind Power Plant

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Abstract. Harmonic resonance is one of an important aspect being considered in a large network such as a wind power plant (WPP). This paper analyses several factors that affect resonance characteristic in a WPP and possible mitigation measures. The first part of the paper provides an analysis of resonances in WPP. Two methods of identifying resonances are performed which are a common impedance scan method and a harmonic resonance modal method for different operating conditions. Several factors that affect resonances including the usage of passive filters as harmonic mitigation in the network are analyzed. A case study of a 400 MW offshore wind power plant is analyzed for the harmonic resonance including with the integration of a passive filter.

Key words

Harmonic Resonance, Harmonic impedance scan, Harmonic Modal Analysis, Harmonic Filters, Wind Power Plant.

1. Introduction

Harmonic is one of the main concerns as the number of the grid connected wind power plants (WPP) had increased significantly and might cause harmful effect on the network [1]. Integration of many power electronics equipment such as converter, contributes to emission of harmonics. Since WPP comprises of a great number of both inductive sources and capacitive elements coming from large capacities of wind turbines, transmission lines such as long underground cables, reactive power compensation equipment and other passive elements in the network, the need of resonance analysis is essential [2]. These impedances may resonate near a harmonic frequency, that is produced i.e by a voltage source converter. This resonance can exacerbate the harmonic voltage or current [3]. Basically, a resonance will cause the amplification of voltage distortion due to parallel resonance or result in high harmonic current due to series resonance at the resonance frequency. Previous works in [4-7] addresses on the resonance analysis in WPP in various approaches and evaluates several factors concerning resonance.

In this paper, the resonance analyses are performed to study the impact of several conditions in WPP mainly using the impedance scan in PSCAD and also harmonic modal resonance analysis (HRMA) including the effect of cables, the number of wind turbines in operation and the other passive elements in the circuit.

2. Harmonic Resonance in a WPP

Since resonance is characterized by the inductive and the capacitive elements in the network, change in system impedance leads to the alteration of the resonant point. It is helpful to identify the usual cause of resonances. A network of a WPP is usually modelled into an aggregated model to simplify the analysis with valid assumptions and standard model of each equipment or part of the network. All parallel. Wind Turbine (WT) generators are modelled as one WT which are connected to the medium voltage collector through a transformers. The transformers are connected to the grid through the transmission lines with three winding transformers. WPP network can be modelled as in Fig. 1.

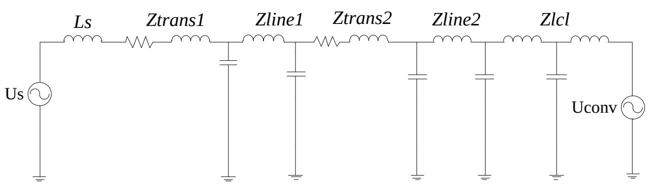

Fig. 1. Equivalent circuit of the WPP model

A. Series and Parallel resonance

Parallel resonance occurs when the reactance of inductive elements that is in parallel with the reactance of capacitive elements cancel each other out. The parallel resonant frequency is calculated as follows:

$$f_p = \frac{1}{2\pi}\sqrt{\frac{1}{L_{eq}C}} \quad (1)$$

At this frequency, the apparent impedance seen from the harmonic current source becomes high [3]. Harmonic voltage experienced at the bus is amplified due to the high impedance. Series resonance occurs when low impedance is seen at resonant frequency, which causes high current and high voltage distortion even at a location with no or little harmonic emission [3]. The series combination of the transformer inductance and capacitor bank is very small and only limited by its resistance. Hence, the harmonic current will flow freely in this circuit. The amplification of the harmonic current will occur and may cause an overheating of equipment.

B. Factors Affecting Resonance in a WPP

Underground and Submarine Cables

In a WPP, long underground or submarine cables are usually used as transmission lines. Long cables introduces a problem of parallel resonance due to the interaction of shunt capacitance of the cables with the rest of the network. As the length increases, the shunt capacitance is increases and the point of the natural resonance frequency moves to a lower value [4]. Since harmonic characteristic emitted by a voltage source converter are usually low order harmonics, a possibility to experience a resonance phenomenon is relatively high. A cable is considered long if it exceed 250 km (for 60 Hz). It is sufficient to model a submarine cable with the length less than 100 km as a simple nominal-pi equivalent circuit as shown in Fig.2.

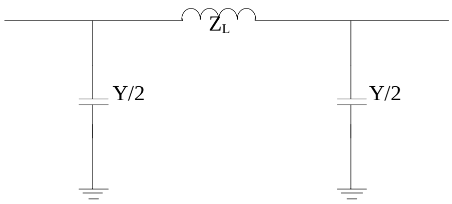

Fig. 2: Basic nominal 'pi' model

Number of Wind Turbine in Operation

Different configuration or operating condition in a large WPP will impose different impedance in the system, where impedance of the system changes with the number of turbines in operation. In a large WPP, not all WTs are in operation at one time. WTs might not be in operation due to malfunction or the lack of of wind. When the number of WTs in service decreases, the impedance of the system increases rapidly. The changing impedance causes the point of a resonant peak to change accordingly, which is an interesting topic for harmonic resonance analysis.

Grid-side Output Filter

In a large WPP with several MW wind turbines, power electronic multilevel converter are widely used for wind energy conversion system. Three-level diode-clamped converters (NPC) are among commonly applied technology. These converters have lower total harmonic distortion (THD) but their harmonic content is still significant. Hence, an output filter (on the grid side) with topologies of LC or LCL filter is usually installed to compensate harmonic at the Point of Common Coupling (PCC). Fig. 3 shows the LCL filter topologies with one type of passive damping. LCL filter is usually preferred as it provides better decoupling between filter and grid impedances and lower current stress across the grid conductor. The design of the LCL filter is to follow has certain requirements; it has to reduce ripple current to 10% and the shunt capacitance has to be 5% of the base capacitance of the network. The resonant frequency of the filter is calculated as:

$$f_{lcl} = \frac{1}{2\pi}\sqrt{\frac{(L_{conv}+L_{grid})}{L_{conv}\cdot L_{grid}\cdot C_f)}} \tag{2}$$

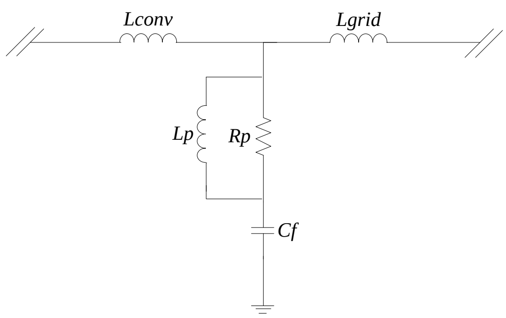

Fig. 3. The topology of LCL filter

This LCL filter, despite its capability in attenuating the harmonics emitted by the converters, interacts with the rest of the WPP network on the grid side. Since WPP networks are heavily composed of inductive-capacitive elements, the resonance characteristics influenced by an output filter is an important subject to study.

The usage of reactive power compensation equipment and power factor correction devices may also alter the impedance of the system. Equipments, such as STATCOM, capacitor bank or Static VAR Compensator (SVC) introduce shunt capacitance in the WPP network and they can resonate with WPP system which is mainly inductive.

C. Resonance identification methods

Impedance Scan

This is the most prevalent method for resonance identification as reported in [7-8] and known as frequency scan. It is a direct manipulation of the nodal analysis, where the nodal admittance matrix is evaluated at every specific frequency for every harmonic current.

$$[V_h] = [Y_h]^{-1} \cdot [I_h] \qquad for \qquad h \neq 1 \tag{3}$$

The nodal harmonic impedance is obtained from the inverse of the nodal admittance matrix. The diagonal elements of this matrix corresponding to the harmonic self-impedance of respective buses and non-diagonal elements are transfer impedances, related to the effect on the voltage of bus *i* when the harmonic current is injected at bus *j*. The impedance scan plot reveals the peaks that indicate the parallel resonance at a certain bus and the valley shows the series resonant. Formation of the admittance matrix is depends on the impedances in the network, hence it is important to accurately determine and represent each element of the network.

Harmonic Modal Resonance Analysis

The harmonic resonance mode analysis (HRMA) is proposed in [9] and further elaborated in [10]. The harmonic resonance occurs when the nodal voltages are very high, which is associated with the admittance matrix approaching singularity. This singularity of *Y* is due to the very small value of eigenvalue which approaches zero. Through eigenvalue decomposition, further analysis on the resonance point and the sensitivity can be performed, which can reveal the 'true' resonance point and the potential point of the most influenced bus in the network. The eigenvalue decomposition of *Y* is given by:

$$[Y]=[L_{EV}]\cdot[\lambda]\cdot[T_{EV}] \qquad (4)$$

Where $[L_{ev}]$ and $[T_{ev}]$ is the left and right eigenvector respectively and $[\lambda]$ is the diagonal eigenvalue admittance matrix. The modal impedances, Z_M is obtained by the inverse of $[\lambda]$, such as:

$$[V]=[L_{EV}]\cdot[\lambda]^{-1}\cdot[T_{EV}]\cdot[I] \qquad (5)$$

Where $[L_{EV}]=[T_{EV}]^{-1}$. The highest Z_M is the point of smallest λ and referred to as the critical mode. The frequency corresponding to this point is resonance frequency. The plot of Z_M as a function of frequency can reveal the modal impedance plot and the critical mode, the point of the resonance.

3. Simulation Results and Discussion

In order to analyze the effects of factors that contribute to resonance in WPP, simulation of an offshore WPP model was carried out. The impedance scan method is performed using PSCAD and the result is plotted using Excel. The HRMA method is performed using MATLAB and is aimed at showing the extent of the result produced resembles the one obtained by the impedance scan.

A. Configuration of The Studied WPP model

The analysis was performed on a 400 MW WPP model as described in [10]. It is based on an offshore WPP in [12]. Fig. 4 shows the aggregated-impedance equivalent model of the 400 MW WPP. All the component parameters are modeled as impedance equivalent at 150 kV-level. The turbines of the wind power plant are modeled as four aggregated turbines (10 turbines each), where each one of them represent the power of 100 MW and every one of them is situated at the end of one branch. Each wind turbine is connected to an output LCL filter and the step-up transformer. Then, an 8 km long collector 33 kV cables connected each of WT section to the 58 km transmission cables through three winding transformers. It is connected to the VSC-HVDC connection through a phase-reactor and a tuned filter. The wind turbines are modeled as ideal harmonic current sources when conducting the harmonic analysis in the case of implementing passive filters.

The transformers have YNdd-configuration that eliminates the zero sequence harmonics. All the cables are modeled as nominal π-models. The transformers are modeled as inductances. The zigzag transformers are excluded in the model.

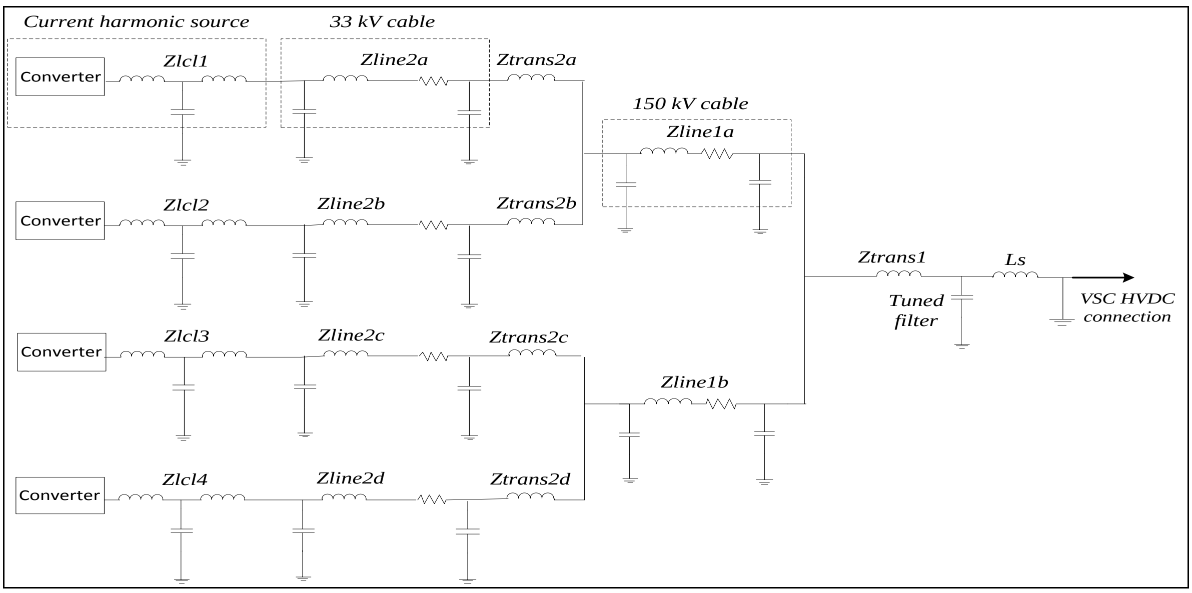

Fig. 4. Aggregated-impedance equivalent model of 400 MW WPP

B. Resonance Analysis

Base case - Cable of 8 km

The impedance scan of WPP model is obtained using the impedance solution in PSCAD for bus 1 to bus 7. Impedance scan using HRMA method is performed using MATLAB for the same case. Through impedance solution, the resonance peak is displayed for each of the buses at its resonance frequency. In HRMA method, the resonance peak is indicated as the critical mode, the point where modal impedance becomes very high.

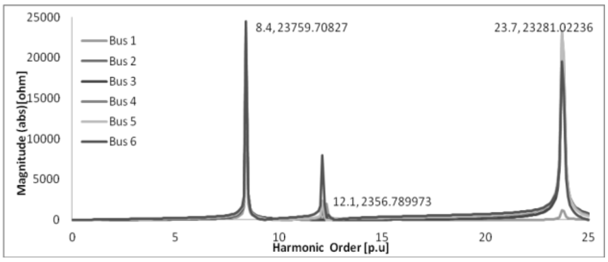

Fig. 5. The impedance scan of WPP model for the base case

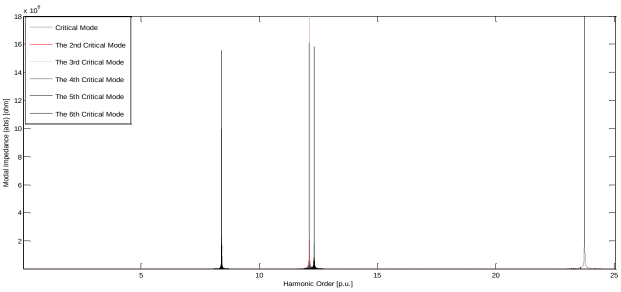

Fig. 6. The modal impedance of critical mode by HRMA

Fig. 5 and Fig. 6 show the result for the base case of the impedance scan and the HRMA method, respectively. Both of the methods show the same resonance frequency experience by the WPP, which are 8th, 12th and 23rd harmonic. In the HRMA method, each of modal impedance can be further characterized by its participation factor which indicates how much involved each of the buses is for respective critical modal impedance.

Impact of the length of collector cable

The length of the collector cable is varied at 8 km, 16 km and 32 km, respectively. In order to see the effect clearly, only impedance scan at one bus is shown. Fig. 7 shows the result performed at Bus 5 which displays the effect of varying the length of the 33kV collector cable. In this network, collector cable mainly influenced the 23rd harmonic.

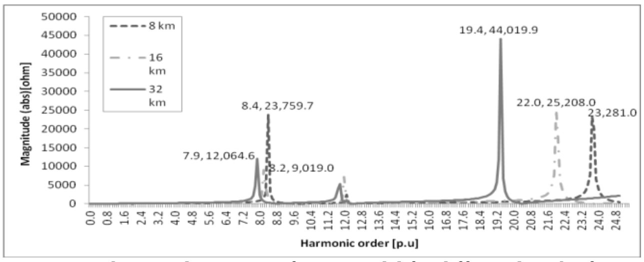

Fig. 7. The impedance scan of WPP model for different length of collector cable

As the length of the collector cable increased, the total internal capacitance has also increased. The resonance frequency is shifted towards lower values. At the 23rd harmonic, the magnitude has also increased with the increased length, which might be due to the lower resistance value respective to system impedance.

Impact of different number of WT in operation

The analysis is performed for four cases where there are ten WTs, nine WTs, eight WTs and seven WTs in operation on each of the branch. In the result obtained, there are two interesting point that can be observed. First, it is observed that configuration of WTs are heavily affecting the 12th harmonic component even though the peak magnitude is relatively small compared with the other. It is also affecting the other resonant peak at the 8th and 23rd, but at a smaller factor. This can be said that it is due to the distance of the WT itself to the 'point' that caused resonant peak at the harmonic component. As the distance of the intended source (in this case WT) to the said 'point' increased, the effect of it on the harmonic component was lower.

Secondly, the overall impact of the numbers of WT on the impedance characteristic is that as the number of WT is increased, the impedance are decreased, and the natural resonance frequency is shifted to a lower value as shown in Fig. 8.

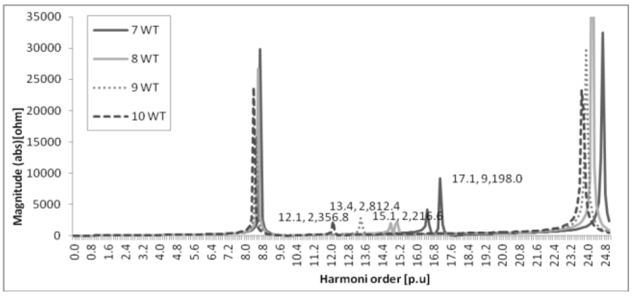

Fig. 8. The impedance scan of WPP model for different number of WTs in operation

Effect of output filter (LCL filter)

An output-LCL filter is a preferred solution besides an LC filter in providing a better harmonic attenuation caused by a grid-connected converter. It also has an advantage of making the filter size smaller than the other topologies. However, this grid-side filter can also be a source of harmonic resonance when interacting with the rest of the system. Hence, an extreme analysis is performed to see the impact of the presence of an output filter, namely LCL filter. The two cases, with and without the LCL filter for each branch is carried out.

Fig. 8 and 9 shows the two case where the LCL filter is present and not present, respectively. Results are obtained for Bus 1 to Bus 5.

Fig. 8. The impedance scan of WPP model for base case without LCL filter

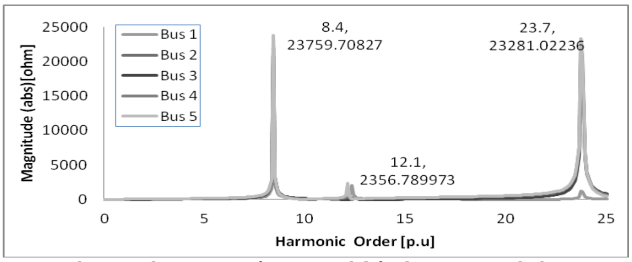

Fig. 9. The impedance scan of WPP model for base case with the present of LCL filter

In this case, the LCL filter case is designed to have the resonance frequency of 600 Hz (or the 12th harmonic). It attenuates effectively the resonance peak at the 23rd harmonic, but also creates another small resonance peak at the 12th harmonic. The peak at the 23rd and 8th harmonic are slightly shifted as a result of the interaction but it still remain since these two are due to the transmission line and collector cable.

Passive Filter Installed

A passive filter is designed to compensate the 8th and 23rd harmonic. Two shunt second-order passive filters of type A and 1 of type B are placed in the grid. The filters have an inductance and resistances in parallel that are in series with a capacitor and filter values are given in Table 1.

The type A filter is placed at Bus 1 to damp the 8th harmonic resonance. The filters of type B are placed at Buses 3 and 8 to damp the 23rd harmonic resonance. The harmonic currents are injected at the end of the branch using the harmonic current source in accordance to German Electricity Association (VDEW) standards. The measured harmonic currents with respect to the injected harmonics current are shown in Fig. 10.

TABLE I. VALUES OF THE COMPONENTS OF THE PASSIVE FILTERS

Filter Type	Bus	Resistance (R)	Inductance (L)	Capacitance (C)
Type A	1	210.96 Ω	83.90 mH	1.89 µF
Type B	3, 8	134.30 Ω	18.60 mH	1.03 µF

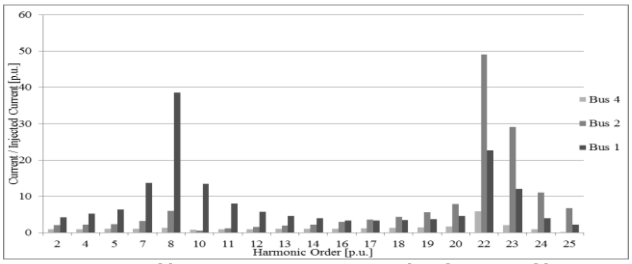

Fig. 10. Measured harmonic currents compared to the injected harmonic currents.

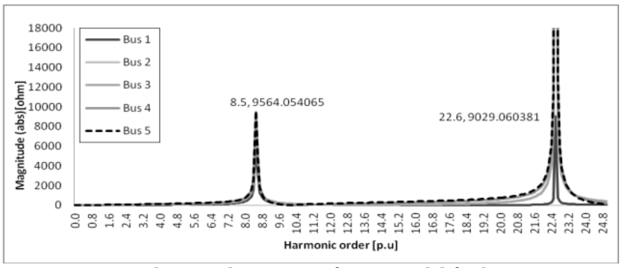

Fig. 11. The impedance scan of WPP model for base case

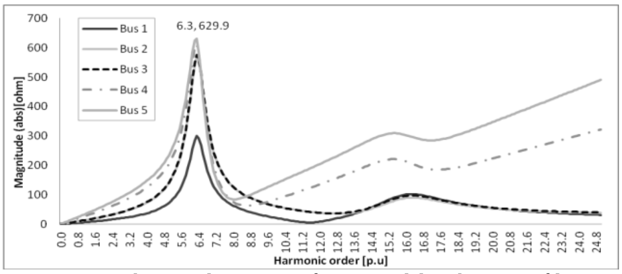

Fig. 12. The impedance scan of WPP model with passive filter

Fig. 11 and 12 are the impedance scans of WPP before and after the passive filters are included, respectively. The passive filter is damping the resonance at the designated frequency but it also introduces another peak due to its interaction with the system impedance. It will not cause any effect since there is no harmonic emission at the particular peak, but may result in harmful effect if the resonance peak and the harmonics coincide due to the changes of system impedance.

4. Conclusion

This paper had presented an analysis of harmonic resonance in a WPP by using the common method of the impedance scan and the harmonic modal analysis method. Several factors that influence the resonance characteristic in WPP are analyzed. It is found that the impact of the collector cables can be very pronounced. For the different numbers of WTs in operation, it is observed that it also contributes in shifting the natural frequency. Depending on the number of WT that is out of services, the effect can be disastrous. Hence, it can be concluded that resonance analysis in WPP is very important.

Acknowledgement

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