Harmonic Analyzing of Wind Farm Based on Harmonic Modeling of Power System Components

Hassan Abniki1, Student member IEEE, Saeed Nateghi2, Reza Ghandehari2, Mohammad Nabavi Razavi1

1ECE School, University of Tehran, Tehran, Iran
2Faculty of Electrical and Computer Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran
hnabniki@ut.ac.ir

Abstract—The aim of this paper is to present a harmonic model of wind farms using DFIG whereas all power system components are modeled in harmonic domain. After analyzing the effects of harmonics in power system, it is tried to model all the power system components such as transmission line, transformer, shunt reactor, load and back to back converter in harmonic domain. When the inverter DC voltage is converted into an AC output, during this transformation from DC to AC, harmonics affect the power quality of the network a lot. The simulation results show that the presented model has enough accuracy to extract the futures of power system harmonics.

Keywords—Power system harmonic, harmonics modeling, wind farm, doubly fed induction generator (DFIG), inverter.

I. INTRODUCTION

With the advent of PWM modulation in switching, harmonic sources increasing extendedly. Modeling strategies for harmonic sources are sometimes insufficient for power system harmonic analysis. Simulation techniques in time and frequency domains and modeling of the wind turbines as harmonic sources should be more accurate rather than what now are available. So, the way to find a very good agreement between theory and experiment is necessary. Power electronic converters in harmonic analysis can be simply represented by a harmonic current source suggested in standards or voltage source taking into consideration the nature of back-to-back as voltage source inverters but unfortunately both cases give inappropriate results. Power quality is very important to commercial and industrial power system designs. In fact, appropriate electrical supply should have perfect sinusoidal waveform without any kind of distortion. So far many researches are studied in the field of harmonic analyzing. Ref [1] develops a framework for analysis of harmonics in a doubly fed induction generator (DFIG) caused by non-sinusoidal conditions in rotor and unbalances in stator. In this paper, a generalized steady-state equivalent circuit for DFIGs is presented. In fact, a systematic method to calculate electromagnetic torque by computing the interactions of harmonic stator and rotor currents, derived from the equivalent circuit is presented, and the development of positive-and negative-sequence equivalent circuits are studied too. Also in [2], a case study is presented for a 10-MW wind farm, intended to be connected to a network with extended high voltage submarine cable lines. In this method at first, the system modeling approach and the harmonic load-flow calculation are described. Then, the harmonic impedance of system is calculated for a variety of configurations and operating conditions. Also, Ref [3] shows the necessity to produce new knowledge of power converters, as a harmonic source and modeling. In the paper, differences between already developed models prepared for harmonic studies are shown. Not so good agreement between simulations and measurements as a premise for future work is shown too. At present, applied methods of full scale converters modeling are insufficient in reference to standards and measurements. Also, both IEEE and IEC standards consider harmonics in a general sense, without regard to characteristic harmonics generated by certain types of equipment or special operation modes. These documents present the need to extend harmonic sources description in standards. Moreover, Ref [4] presents that currents fed into the grid and at the wind turbine transformer have a considerable harmonic content. Accurate estimation of harmonics is crucial to guarantee reliable operation of a power system with wind generation. In this method, fast Hilbert transform is able to estimate harmonics accurately and could be used for analysis of harmonics of DFIG wind turbines. In [5], using Power Factory software (DigSILENT) all power system components modeled in harmonic domain and also harmonic impedance is calculated in harmonic and time models. Also, Ref [6] gives an overview of the frequency spectrum of the stator and rotor currents in a doubly fed induction generator (DFIG) used in wind power applications. The paper also presents a method to eliminate higher harmonics and inter harmonics in the DFIG stator current. The method is implemented on a 40 kW laboratory model connected to the utility grid, where the DFIG is supplied by a back-to-back converter. Moreover in [7], a system harmonic modeling approach and the harmonic load flow calculation are described. 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 calculations are provided to indicate potential voltage distortion problems. Also, a simplified methodology, suggested in relevant IEC publications, is applied to the system and its results are compared to those of
the harmonic load flow. Also in [10], diagnosis and fault detection in wind energy conversion system are analyzed.

This paper explains the effects of harmonics in wind farms and a step to model all power system components in harmonic domain is analyzed. It presents the harmonic modeling of power system components and the related technique to improve harmonic performance of power system. Also, this paper describes different types of harmonic models of converter which are used in the harmonic modeling of power system. During the transformation from DC to AC, harmonics critically affect on the power quality; so harmonic reduction will improve the harmonic performance of system operation.

II. HARMONIC MODELING OF SYSTEM COMPONENTS

Harmonic problems are one of the major concerns in power systems. Harmonics cause distortion in current and voltage waveforms resulting into deterioration of the power system. One of the major parts of harmonics is the harmonic generated by non-linear loads. The results of such analysis are complex.

A) Line and shunt reactor

Normally, overhead lines and cables are modeled using multiple nominal sections, connected in series [2]. According to another reference [7], an error of less than 1.2 % is achieved using three nominal sections for each line segment whose length is equal to the wavelength (1500 km at 50 Hz). Since the analysis extends to the 50th harmonic order, satisfactory results are obtained using one section for every 10 km of a 150 kV overhead line. The line modeling accuracy can be further improved by using the equivalent models [7-8]. Considered shunt elements are basically compensating reactor coils and capacitors, which are modeled as concentrated impedances.

B) System load

In fact, harmonics have non-integer multiples of the fundamental frequency and have periodic waveform. Some critical generated harmonics in a power system are studied in [8] that are generated by different types of loads. The proper selection of the load model is very important for correctly assessing the magnitude of harmonic resonances. However, no generally applicable harmonic model exists and case specific measurements and evaluations are needed for detailed studies. From the variety of harmonic load models proposed in the literature, three alternative representations are shown in Fig. 1, selected for their simplicity [2]. In all cases, R and X are the fundamental frequency resistance and reactance, corresponding to the nominal power of the load. Results from the application of these models are included in later sections.

![Fig. 1. Alternative harmonic models considered for the system load.](image)

The slip at frequency is given by equation (1):

$$s_h = \frac{w_r - w_p}{w_p}$$  \hspace{1cm} (1)

where \(w_p\) is the rotor speed. More accurate results may be obtained using the steady state equivalent for double cage rotor [7]. Also synchronous machines harmonic model are simulated according to Fig. 2(b), where \(R_2\) and \(X_2\) are the negative-sequence resistance and reactance, often approximated using the axis sub transient reactance.

![Fig. 2. (a) Induction and (b) synchronous machine harmonic equivalents.](image)

The simulated transformer parameters shown in equation (3) are summarized in Table 1 [1].

<p>| TABLE 1. VALUES FOR THE TRANSFORMER MODEL |</p>
<table>
<thead>
<tr>
<th>C0</th>
<th>C1</th>
<th>C2</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7-0.8</td>
<td>0.1-0.13</td>
<td>0.1-0.13</td>
<td>0.9-1.4</td>
</tr>
</tbody>
</table>

C) Back to back converter

For simulation purposes, two power converter models have been used. Harmonic current and voltage sources with harmonic levels defined as look-up tables which have been applied during simulation [3]. The current source model has some limitations in the load current which is in reality not independent of the voltage. There is possibility to linearize the voltage dependence around an operational point by representing the load by its Norton equivalent (current source in parallel with source impedance). But the way how to determine the impedance is not straightforward. This matter neglects a lot of dependencies between power converter internal control working in closed loop and the whole system and so this may not give any better results than the pure current source model [2]. The traditional way of representing a nonlinear load in a harmonic penetration study is using harmonic current source. The underlying assumption is that the harmonic current spectrum is not too much affected by the system voltage (or by its fundamental or by its distortion). For
of waveform distortion such as HVDC links, this is a very acceptable model.

The grid side converter with a large capacitor can be recognized as a DC voltage source, seen from the AC side of the converter (or a variable resistance). This model is shown in Fig. 3. There are two switches for each phase. Each switch connects the DC voltage source to the AC network. The resulting current is due to the difference between the voltage of AC side (typically distorted) and the DC voltage. Depending on which of the switches is closed the DC voltage source of the same magnitude but opposite polarity can be recognized. During the conduction period the VSC can be represented as a voltage source. However, this does not yet justify the use of harmonic voltage sources for harmonic penetration studies. A serious argument against it is that the voltage outside the conduction period is not defined by the source. Outside the conduction period the current is zero, so that a current source model would be more appropriate. In the time domain modeling, a voltage source model would be possible, but not in frequency domain studies. As the voltage is not defined during the whole cycle, it is not possible to determine the spectrum of the voltage waveform, and thus it is not possible to determine the harmonic voltage sources needed for the some studies. Also, land and submarine cables commonly have been modeled as long lines with skin effect approximated as a square root function against harmonic order. All of them are simulated based on the implemented models in the simulation software without including any frequency dependent characteristics.

III. SIMULATION RESULTS AND VALIDATION

The harmonic power flow study has been conducted to determine fundamental and harmonic line currents and bus voltages for different scenarios. Odd harmonic distortion is typically dominant in power networks. In fact, a measurement of the supply voltage shows that the amount of even harmonics is indeed very small. Even harmonics may be also generated by transformer energizing what should not be taken into consideration for steady state of DFIGs. Even harmonic distortion of voltage or current is normally rather small as it can be calculated. Even harmonics are generated by some large converters, but modern rules on harmonic distortion state that equipment should not generate any even harmonics. The harmonic changes might be due to unbalances situation in the network during measurement time. During simulations, unbalanced situation has been taken into consideration. The main assumption has been to show obvious differences in results dependent on power electronic devices modeling.

In this paper, three scenarios are simulated as following parts. The first is analyzing the harmonic performance of wind farm while harmonic current injection is used; the second scenario is analyzing the harmonic performance of wind farm while it is disconnected from network. The third scenario is analyzing the harmonic performance of wind farm while wind turbine is connected to network without current harmonic injection. Fig. 4 shows schematic of simulated network in harmonic domain. In this figure, for modeling of converter, especially harmonic current injection is used. In fact, in all scenarios, the different model of harmonic modeling is used in the simulated network. Harmonic source characteristics can be really measured during a harmonics survey in real networks. These typical characteristics are applied at the grid substations. The frequency impedance of system at capacitor bus bar is shown in Fig. 5. The results of all scenarios are shown in later sections.

A) Harmonic analyzing during harmonic current injection

Frequency scans, or “driving point impedance” plots, are frequently used in harmonic analysis to gain physical insight into the response of the network. Figs. 5 and 6 show the results from various cases including a line out of service contingency that results in resonance at the 5th harmonic frequency. Magnitude of the harmonic impedance for different buses can be seen in Figs. 5 and 6.

The current source model for distorting devices can also be used to explain a phenomenon called harmonic resonance. Due to a combination of the source reactance and shunt capacitance at a certain location, the impedance seen by the current source becomes very large. The effect of this matter is a large voltage distortion, even for moderate current distortion. In this section, harmonic analysis in the stator circuits with harmonic current injection is investigated. Commonly PWM technique is used for rotor injection while the ac voltage injected to the rotor usually comes from a dc/ac bridge converter [1]. Also, a six-step switching technique is another possibility to simplify the control circuit and reduce the switching losses. Fig. 5 shows the magnitude of the harmonic impedance at the capacitor bus bar and Fig. 6 shows the magnitude of the harmonic impedance at the MV bus bar. Also Fig. 7 shows D axis current at PCC point of DFIG. The effect of the harmonic model which is used to represent loads is illustrated in these figures. Results show for the MV buses the load modeling is critical for the local bus impedance (three
load models), but not so much for the HV system. Frequency scan results have limitations particularly on transmission systems where harmonic sources may be widely distributed and there are many possible sources of resonance.

A full harmonic solution case is necessary, where the harmonic voltage distortion is evaluated at all network locations. Harmonics is measured where the wind turbine feeds in to the grid. Similarly harmonics are measured at the wind turbine transformer. The result of current and voltage at PCC point can be seen in the mentioned figures. Fig. 7 shows D axis current at PCC point of DFIG. In all simulation conditions of this paper, if the amount of voltage swell is lower than 0.75 pu, then the turbine disconnected from network and if voltage sag is more than 0.3 pu, the capacitor bank will be disconnected. Parallel resonance occurs when the capacitive and inductive reactance cancel each other. The frequency at which this phenomenon occurs is called the parallel resonant frequency. The ideal current source will lead to an infinite harmonic voltage at the connection bus and an infinite harmonic current through the capacitor and the inductor. It is resulted that the harmonic distortion will be limited practically by two effects:

- The resistance presented in the system will determine the impedance at the resonance frequency.
- The current source model is no longer valid for HV distortion.

Fig. 4. Shematic of simulated network in harmonic domain.

Fig. 5. Magnitude of the harmonic impedance at the capacitor bus bar.

Fig. 6. Magnitude of the harmonic impedance at the MV bus bar.
The resonance phenomenon is especially common with MV capacitor banks. Also, long AC cables can lead to a resonance but normally at higher frequencies where the amount of current distortion is less and the amount of damping is higher.

There are certain instances when a shunt capacitor and the inductance of a transformer or long cables may appear as a series LC circuit to a source of harmonic currents. If the resonant frequency corresponds to a characteristic harmonic frequency of the analyzed system, the LC circuit will attract a large portion of the harmonic current that is generated in the wind power plant.

**B) Harmonic analyzing while DFIG disconnected from network without harmonic current injection**

It is determined by the characteristic impedance of the capacitor connected to the DFIG posts that in this condition the bus bars had no resonance. This causes an increase in harmonic and therefore we cannot avoid higher harmonics of the permitted level. Also it is found that the harmonic generated by power factor correction capacitor has very high and installation location has plays important role in power system operation performance, so capacitors and other restrictions placement is one of the critical issues.

**C) Harmonic analyzing while DFIG connected to network without harmonic current injection**

In this section, harmonic analysis in the stator circuits with quasi-sine rotor voltage injection is investigated. The ac voltage injected to the rotor usually comes from a dc/ac bridge converter, while PWM technique is used for rotor injection [1]. Six-step switching introduces $6n \pm 1$ harmonics in the voltages and the resultant output is called a quasi-sine waveform. Unlike PWM, this does not need sine and triangular waves. It is easy to adjust the rotor injection frequency by simply varying a control voltage. The output line voltage of the inverter is a quasi-sine wave with levels 0, V, and −V. If installed in a network of nonlinear loads, harmonic currents in the network are due to series and parallel impedance; voltage distortion created in the bus bars and can affect sensitive loads. In power system harmonic studies, models selected for the characteristic elements of power system harmonic affects on the system under study which are important, so choosing an appropriate model for the system is very important. In addition, a small amount of harmonic currents due to the fifth harmonic voltage cross the transmission network flows. According to the simulation, high impedance at the fifth harmonic of the fifth harmonic current in this network is inevitable. In order to reduce the amount of harmonic in system and improve the harmonic performance of system, we can use active filter. Simulations are done according to the modeling of characteristic harmonic in addition to familiarity with the system, to reduce the high costs prevent harmonic. Harmonic studies are conducted to inspect the impact of non linear devices and to analyze certain harmonic situations.

In fact an impedance scan, also known as a frequency scan, is a plot of the magnitude of driving point impedance at the bus of interests versus harmonic order or frequency and is useful in identifying resonance conditions. A dip occurring in the impedance value implies series resonance. Parallel resonance, on the other hand, is identified a sharp rise in the
impedance value. In the analyzed case study of this paper, the system configuration has been constant but all the components are modeled in harmonic domain. Also power converter as a harmonic source modeling method has been changed to show its influence on the whole system impedance in the PCC point. Different power converter models for harmonic load flow analysis have also shown that different modeling approach has different effects on harmonic impedance in the PCC point. This affects harmonic level changes. It is found that appropriate power converter modeling can play a crucial role in analysis process and power quality assessment. In Figs. 5 to 6 it is shown that there are different values and frequencies of resonance points in the frequency response at the PCC point. This slight difference can have significant influence on harmonic assessment; especially if there will be a harmonic source in the system corresponding resonance points. The most dominant harmonics in the stator current are the 5th, 250Hz as shown in Figs. 8 and 9. Results show the harmonic simulations shows that distortion exceeds standard levels when the harmonic model is analyzed. The total harmonic distortion measured after using harmonic model of inverter and at the wind turbine transformer are 10.3853% and 12.9236% respectively. It has been shown that classical harmonic analysis in frequency domain, which is normally used for assessment of disturbances to the public grid, could be insufficient. Lack of reliable models for power converters in relevant frequency range, manufacturer data normally are provided according to applicable standards, also contributes to obtain insufficient results.

IV. CONCLUSION

Simulations of the time and harmonic-based model of a DFIG wind turbine were presented in this paper. Simulations were carried out using an extended harmonic based model. The proposed model is more accurate rather than the conventional model of DFIG in the field of harmonic domain studies. In this paper, in three steps harmonic analyzing are performed as following: the first one scenario was harmonic analyzing while DFIG connected to network with harmonic current injection, the second scenario was harmonic analyzing of DFIG without harmonic current injection and the third scenario was harmonic analyzing of DFIG while it is disconnected from network. Harmonic analyzing of whole system (harmonic-based model) is performed and accurate model of harmonic analyzing is presented. As a result it is found that exact harmonic estimation and detection depends on harmonic model of all power system components such as DFIG in order to guarantee reliable operation of a power system with wind generation.

REFERENCES