A Wavelet Based Technique for DFIG Harmonic Reduction in Frequency Domain Based Model of Power System Using Active Filter

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Abstract This paper presents a technique to reduce the harmonics in wind turbines by using active filter. In this paper, using a frequency based model of power system and using an active filter, the power system harmonics are decreased and consequently power quality of electrical network will be improved. In fact the technique is a combination of wavelet analysis and active filter in a frequency domain based model of the power network. The results show the powerfulness of the presented method for improving the power quality indexes of the electrical network. Vast simulations are performed by PSCAD/EMTDC software and the results are satisfactory in all scenarios.

Keywords Shunt Active Filter, Wavelet Transform, DFIG, Wind Turbine, Harmonic

1. Introduction

The main goal of power system is generation of electrical energy. Also, power quality is a very important feature in electrical systems. In this regard Ref[1] presents performances of passive and active filters to reduce harmonics in electrical systems. The results of the paper show that the active filter can simultaneously attenuate various frequencies. Also, Ref[2] presents a controller for activating filter modules using a special 3-level PWM switching strategy that results in a 50% reduction in overall switching losses compared with the 2-level one. Moreover, Ref[3] studies a combined series systems with passive and active filters. In[4], a new developed control algorithm is presented in order to reduce the harmonic voltage distortion using Neural Network theory. In this regard feedback filter improves the steady-state performance of the harmonic mitigation and the feed forward filter improves the dynamic response. In[6], the proposed active compensation technique is based on a series active filter. In[5], a method is presented that brings simultaneously characteristive advantages of both active filters. Ref[7] describes the control operation of two active power filters. The filters are coupled in a combined topology in which one filter is connected in a feedback loop and the other is in a feed forward loop for harmonic compensator based technique. Also, Ref[8] describes a single phase PWM current source inverter connected in the

DC link of a current source drive that may be used to filter out AC side current inter harmonic components. In[9], the harmonic components in the current from the VSC has larger peak than expected for the fundamental component. Therefore, active filter action is investigated to eliminate these harmonic components in the current from the VSC.

During the transformation from DC to AC, harmonics affect the power quality a lot; so using wavelet as a detection criterion, and using a shunt active filter, harmonic performance of wind farms will be improved in this paper.

2. Harmonic Reduction Technique

A) Active filter

Where reactive power requirement is low, active harmonic filters are used for low voltages. In this way, the output load with the voltage waveform is obtained by boosting the voltage throughout each half cycle by the filter. After that, the voltage tends to rectifiers in the power supply to gain current. Depending on the used active harmonic filter, the output distortion will be reduced. So, the produced current is monitored by the harmonic filter and generates a waveform which coincides with the exact shape of the nonlinear portion of the load current.

B) Passive filter

Passive harmonic filters are used for different voltage levels. In this regard, harmonics are reduced by using series or parallel resonant filters. In this method, a filter connected in parallel with the load and in series with inductance and
capacitance is a current acceptor. In fact, a current acceptor is a parallel filter with the load and is in series with the inductance and capacitance. This filter provides maximum attenuation. The filter passes as much current as the harmonic voltage near the filter resonant point. So, the passive filters eliminate the harmonics. If the individual load requirement is more than that of the input load, the harmonic current should be eliminated. For example, a capacitor in series with an inductance is a passive filter. The reduced harmonic frequency must be equal to the resonant frequency of the circuit. The impedance of the network and the low impedance of the filter eliminate the harmonic current.

Sinusoidal Pulse Width Modulation (PWM) is a bit different compared to the Sinusoidal Pulse Width Modulation (SPWM). Figs. 1 and 2 show three phase active filters for shunt and series configuration respectively. Normally, more than 3 filters are connected in a system to reduce the harmonics. In case of sinusoidal pulse width modulation, all the pulses are modulated individually. Each and every pulse is compared to a reference sinusoidal pulse, and then they are modulated accordingly to produce a waveform, which is equal to the reference sinusoidal waveform. Thus, sinusoidal pulse width modulation modulates the pulse width sinusoidal.

Figure 1. Three phase active filter in series configuration
3. Simulation Details

A) Line and shunt reactor harmonic models

According to [10], 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 (wavelength km at 2.5 kHz), satisfactory results are obtained using one section for every 10 km of a 150 kV overhead line. The line modelling accuracy can be improved using the equivalent model which is presented in [10-11]. Shunt elements are considered basically compensating reactor and capacitors, and modelled as concentrated impedances.

B) Harmonic model for system load

The proper selection of load model is very important for harmonic studies. 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 which are in [10], those selected for their simplicity are shown in Fig. 3. In this figure, $R_1$ and $X_1$ are the fundamental frequency resistance and reactance, corresponding to the nominal power of the load. The results of using these models are included in next sections.

C) Electric machine and transformer harmonic models

Asynchronous machines are simulated using their simplified equivalent circuit, referred to the harmonic frequency shown in Fig. 4(a). $R_B$ and $X_B$ are the resistance and reactance, as determined from the blocked-rotor test. The slip at frequency is given by equation (3).

\[ S_H = \frac{\pm hw_1 - w_r}{\pm hw_1} \]  

where ‘$w_r$’ is the rotor speed, also the of sign ‘$hw_1$’ 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[10]. More different and detailed models are also available, which are suited for the analysis of specific motors previously. The simulated synchronous machines is shown in Fig. 4(b), where $R_2$ and $X_2$ are the negative sequence resistance and reactance, often approximated using the axis sub transient reactance as equation (4).

\[ X_2 = \frac{(X_q - X_d)}{2} \]  

For the zero sequence, the neutral grounding impedance of a Y-connected stator winding is taken into account. In the positive and negative sequences of transformer, the resistances are modelled by their series harmonic impedance, as equation (5).

\[ R_{k,H} = R_k \left( c_0 + c_1 H^b + c_2 H^2 \right) \]  

\[ R_k = \sqrt{R_2} \left[ \alpha \sqrt{\beta + \frac{(1 - \alpha) \sqrt{\beta - 1}}{\beta}} \right] \]  

\[ X_k = \sqrt{X_2} \]  

Table 1. Values for transformer modeling

<table>
<thead>
<tr>
<th>$c_0 + c_1 + c_2$</th>
<th>$c_0$</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7-0.8</td>
<td>0.14-0.13</td>
<td>0.14-0.13</td>
<td>0.9-1.4</td>
<td></td>
</tr>
</tbody>
</table>

D) Back to back harmonic model of converter

For simulation purposes, two power converter models can be used. Harmonic current and voltage sources with harmonic levels defined as look-up tables have been applied during analysis process[13]. The current source model has its limitations whereas the load current 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 neglects a lot of dependencies between power converter internal control working in closed loop and the whole system. The traditional way of representing a nonlinear load in a harmonic study is harmonic current source model. The 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 the traditional sources of waveform distortion such as HVDC links, this is a very acceptable model. It is supposed that the basic model of the grid converter as a part of back-to-back converter. The grid-side converter with a large capacitor can be recognized as a DC voltage source, seen from the AC side of the converter. This model is shown in Fig. 5. 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 and the DC voltage. Depending on which of the switches is closed, the two DC voltage sources with the same magnitude but opposite polarity can be recognized.

During the conduction period, 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 the voltage outside the conduction period which is not defined by the source. Outside the conduction period the current is zero, so that a current source model (with zero current) would be more adequate. In the time domain, modelling 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 penetration studies.

4. Methodology

Nowadays, wavelet has many applications in power systems. Brahma in[20] introduces wavelet transform for reliably and quickly detection of faults during a power swings. In the paper, a logic block based on the wavelet transform has been developed. Valsan and Swarup in[19] present a novel wavelet transform based directional technique for bus bar protection. Also Hong and Chen in[18] study a new method to locate the positions of the switching capacitors using discrete wavelet transform. Tarasuik in [17] analyzes the detection and evaluation of different kinds of waveform distortions such as harmonics, inter harmonics and transients. Another expert system developed by Reaz [21] combined with discrete wavelet transform and fuzzy logic to have better power quality disturbance classification accuracy which uses a different type of randomly optimized neural network. Moreover, the need to analyse power quality signals to extract their distinctive features made by Gargoom in[22] to use Hilbert and Clarke transforms for the classification of power quality signals. Also Elkalashy in[23] uses DWTs to detect high impedance faults due to leaning trees. Wireless sensors have been considered for processing the DWTs. Mishra in[24] presented S transform based probabilistic Neural Network classifier for the recognition of power quality disturbances. Also Ref[25] claims that wavelet Daubechies at level of d4 to d8 presents the amount of harmonic; and Ref[26] shows that the level d8 of wavelet Daubechies exactly presents the amount of harmonics in a signal. So in this paper, the average value of Daubechies wavelet d8 and d4 is selected as harmonic detection technique as a threshold value. The result of this criterion (the value of |d4+d8|/2 for the signal using wavelet) is presented in Fig. 6. Another criterion for harmonic detection in this paper is the energy of wavelet coefficients. By introducing a threshold, so we can detect the whole harmonics of a signal. In Fig. 7(a), a signal can be seen and also its wavelet coefficients are shown in Fig. 7(b). As shown in this figure, wavelet coefficients of d4 and d8 are used in order to detect harmonics of that signal. So two following criterion are used as harmonic detectors in this paper:

1. Average value of wavelet coefficient d8 and d4
2. The slop at wavelet coefficient signal energy

In the Fig. 6, the scale and levels of wavelet and the preset criterion (|d4+d8|/2) can be seen. In Fig. 7(a) the original signal is shown, and in Fig. 7 (b) the energy of wavelet coefficient frequency spectrum is shown.
Figure 7.  (a) Sample signal, (b) Energy of wavelet coefficients of the signal among frequency spectrum
According to Fig. 7(b), the slope at wavelet coefficient energy curve can be an appropriate criterion in order to detect harmonics of a signal. In fact in these levels, the energy of wavelet that changes to ohmic loss are shown. Fig. 8 shows the energy of wavelet coefficients of the voltage signal. It is shown in Fig. 8, by setting an appropriate threshold, harmonics of a signal can be detected. After harmonic detection of the signal, the shunt active filter will be connected in parallel form in order to reduce the harmonics of the signals. It is found that similar to Figs. 6 and 7 by introducing a threshold, we can detect the harmonics of a signal. Also, Fig. 9 shows current harmonic components of \( d \) axis before using the active filter. This figure is related to the voltage at PCC point. For the conditions where both voltage and current are leading to a deterioration in power system, more complex filters are used which are made up of combination of active and passive filters. Such filters are called Hybrid Filters[9]. Fig. 10 shows current harmonic components after using active filter. It is obvious that using active filters, the amount of harmonics critically decrease, so the results show the correctness of the proposed technique. Form the results it is obviously resulted that the amounts of harmonics decrease. It is shown that by reducing the voltage distortion due to the 3rd, 5th, and 7th harmonics, the harmonics of signal reduces, so the THD criterion significantly decreases. Non linear devices such as power electronics converters can inject harmonics alternating currents in the electrical power system. To maintain the quality limits proposed by standards to protect the sensitive loads, it is necessary to include some form of filtering device to the power system. Harmonics also increase overall reactive power demanded by equivalent load. Filters have been devised to achieve an optimal control strategy for harmonic alleviation problems. In this paper, using an active filter, the amounts of harmonics of power converter are decreased and the power quality was examined based on a harmonic based model of the power system. One of the disadvantages of active filters rather than the passive filter is that active filters cost more than the passive filters. Active filters cannot be used for small loads in a power system.

![Figure 8. Energy of wavelet coefficients for voltage signal](image)

![Figure 9. Voltage harmonics at PCC point without active filter](image)
5. Conclusions

A method which is a combination of wavelet and active filter is presented in this paper to reduce the harmonics of DFIGs and to improve the power quality of the electrical networks. After presenting a harmonic based model of power components such as wind turbines, transmission line, transformer and converters, the paper introduces a criterion to detect and decrease the harmonics of the network. So, using the presented technique, the harmonic performance of wind farms is improved. The simulation results show the power of the introduced method. Some further practical incentives using active filters in the presence of DFIGs can be the future works.

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