The DFIG WT Performance under Grid Voltage Distortion with Proportional Integral and Multi Resonant Current Controller

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Abstract— Doubly fed induction generators (DFIG’s) became the predominant generator installed for wind generation applications today. Sources pertaining to the operation and control of DFIG’s subsequently became apparent, particularly in weak areas of the grid network. One of the problems that emerged was the quality of the voltage in the network at the point of common coupling (PCC) with the DFIG. This investigation study were undertaken for a 2MW DFIG connected to the grid have a background voltage distortion of 5th, 7th, 11th and 13th order harmonics. This paper proposes a control schemes to alleviate the problem caused by the voltage distortion in the grid, which is introduce the stator current harmonics in the DFIG wind turbine, the control techniques to improve the performance of DFIG during voltage distortion in the grid including measures to controlling the grid side converter and the rotor side converter in a DFIG. The proposed current controller is developed based on proportional integral and multi resonant (PI+MR) controller to suppress the stator current, a six and twelve order resonant controller. As a result, the THD for the stator current are minimized from 5.63% using proportional (P), 4.22% using Proportional Integral (PI) and 1.95% using Proportional Integral and Derivative (PID) to 0.37% using (PI+MR) for full load. Finally the behavior of DFIG’s to the effect of distortion grid voltage under the effect of wind speed, voltage and frequency variation is further investigated and the results validated by MATLAB simulation.

Keywords- DFIG; PI+MR; PID; harmonics; voltage distortion.

ABRIVATION:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi_{dq} )</td>
<td>Stator and rotor flux along direct and quadrature axis</td>
</tr>
<tr>
<td>( \omega_{ch} )</td>
<td>Cut off frequency for different harmonic orders</td>
</tr>
<tr>
<td>( \omega_s, \omega_p, \omega_L )</td>
<td>Synchronous, rotor and rotating angular speed.</td>
</tr>
<tr>
<td>( \omega_{ch} )</td>
<td>Synchronous angular speed for different harmonic order</td>
</tr>
<tr>
<td>( A, J, P, S )</td>
<td>Area, Moment of inertia, Number of pole and Slip</td>
</tr>
<tr>
<td>( i_{dq}, i_{rdq} )</td>
<td>Two phases Stator and rotor current</td>
</tr>
<tr>
<td>( L_s, L_r )</td>
<td>Stator and rotor leakage inductance</td>
</tr>
<tr>
<td>( L_m, P_m )</td>
<td>Mutual inductance and Mechanical power</td>
</tr>
<tr>
<td>( L_s, L_r )</td>
<td>Stator and rotor self inductance</td>
</tr>
<tr>
<td>( P_c, Q_c )</td>
<td>Active and reactive power for grid side converter</td>
</tr>
<tr>
<td>( P_r, Q_r, P_e, Q_e )</td>
<td>Rotor and Stator active and reactive power</td>
</tr>
<tr>
<td>( R_s, R_r )</td>
<td>Stator and rotor resistance</td>
</tr>
<tr>
<td>( T_e, T_L, t_d )</td>
<td>Electromagnetic Torque, Load torque and time delay</td>
</tr>
<tr>
<td>( \nu_1, \nu_2 )</td>
<td>Wind speed change from value to another value</td>
</tr>
<tr>
<td>( V_{sdq}, V_{rdq} )</td>
<td>Two phases Stator and rotor voltage</td>
</tr>
<tr>
<td>( V_{wind}, B_r, \nu )</td>
<td>Wind speed, Pitch angle and Tip speed ratio</td>
</tr>
</tbody>
</table>

LIINTRODUCTION

Today, the world is going the way of green energy, its energy consumption, and use of wind energy for electricity generation purposes is becoming an increasing attractive energy source partly due to the increase in energy demand worldwide and environmental concerns. The wind energy has appeared as the fastest spreading source of renewable energy and will continue to grow in the near future. It is also the most mature and cost-effective renewable energy technology available today [1]. Generator is one of the most important components of wind energy system. Most of the wind turbines are equipped with induction generators; they are simple, rugged in construction, offer impressive and required minimum maintenance and care [2].

The most common type of wind turbine generator is the DFIG. The DFIG configuration consists of the grid and the rotor windings connected to a voltage – source back-to-back power converter which transfer fraction of extracted power to the grid [3]. The DFIG can operate at a wider range of speed depending on the wind speed or other specific operation requirements, thus it allows a better capture of wind energy [4]. Various methods have been proposed to control the DFIG under grid voltage distortion have been widely investigated in the literatures. In 2006 [5], to compensate the multiple harmonics of DFIG wind turbine the PI and resonant controllers were used. In 2009 [6], to regulate the negative sequence and positive sequence without decomposition of sequential components for DFIG under unbalance network also the PI+R rotor current controller was used.

In 2011 [7], they developed a harmonic elimination method based on the PI+R rotor current controller implementation in the fundamental frame at PCC for a stand-alone DFIG with non linear load. In 2012 [8], have presented the enhanced control strategies for DFIG wind power generation under the distorted network. The
proportion integration and resonant current controller was used with software PLL when the grid voltage is distorted. In 2014 [9], during voltage distortions for DFIG and to eliminate both negative 5th and positive 7th order current harmonics a PI+R current regulator technique was used.

In this paper, we develop an effective control strategy using PI+MR regulators for a DFIG wind turbine system for grid voltage distortion at PCC, to suppress harmonics in rotor side converter to eliminate four harmonic components; negative sequence fifth and eleventh and positive sequence seventh and thirteenth harmonics in stator current in order to meet the requirements without tripping even under distorted grid. The two resonant controllers with resonant frequency of 6th and 12th multiples of synchronous frequency and proportional integral controller can applied to remove the four selected harmonic components. The proposed control scheme is implemented solely with respect to the RSC of the DFIG, to demonstrate the feasibility of the controller in DFIG system, a further investigation on the control performance and stability of control scheme with respect to frequency, voltage and wind speed variation. The robustness and effectiveness of proposed current controller is verified by simulations verification.

I. THE DYNAMIC MODEL OF DFIG

The DFIG is, an induction generator where both stator and rotor terminals are available for power flow. The only electrical machine that is able to operate with rated torque to twice synchronous speed for a given frequency of excitation is the wound rotor doubly fed electrical machine. When the DFIG works, the slip power can flow in both directions, from the rotor to the supply or from the supply to the rotor and hence the speed of the machine can be controlled from either rotor or stator side converter in both sub and super synchronous speed ranges as shown in Figure (1).

```
\[
V_{sdq} = R_s i_{sdq} + \frac{d}{dt} \varphi_{sdq} + j\omega_s \varphi_{sdq}
\]
\[
V_{rdq} = R_r i_{rdq} + \frac{d}{dt} \varphi_{rdq} + j\omega_s \varphi_{rdq}
\]
\[
\varphi_{sdq} = L_s i_{sdq} + L_m i_{rdq}
\]
\[
\varphi_{rdq} = L_m i_{sdq} + L_r i_{rdq}
\]
where:
\[
L_s = L_{Ls} + L_m \quad \text{and} \quad L_r = L_{Lr} + L_m
\]

According to Equation (1), (3) and (4) the stator currents, the rotor flux and the stator flux can be determined as:
\[
i_{sdq} = \frac{1}{L_s} \varphi_{sdq} - \frac{L_m}{L_s} i_{rdq}
\]
\[
\varphi_{rdq} = \frac{L_m}{L_r} \varphi_{sdq} + \delta i_{rdq}
\]
\[
\varphi_{sdq} = \frac{1}{b+j\omega_s} V_{sdq} - \frac{R_s}{b+j\omega_s} i_{sdq}
\]

where \(b\) is the differential operator. Neglecting the stator resistance the Equation (7) can be written:
\[
\varphi_{sdq} \approx \frac{1}{b+j\omega_s} V_{sdq}
\]

From Equation (2) and (6) the rotor voltage can be written as:
\[
V_{rdq} = (R_r + \delta L_r \left(\frac{d}{dt} + j\omega_s\right)) i_{rdq} + \frac{L_m}{L_s} \left(\frac{d}{dt} + j\omega_s\right) \varphi_{sdq}
\]

where: \(\delta = 1 - \frac{L_{Lr}}{L_{Ls}}\)

The electromagnetic torque and the active/reactive power at the stator windings can be calculated as follows:
\[
T_e = \frac{3}{2} \frac{L_m}{L_s} \left(\varphi_{sdq} \varphi_{sq} - \varphi_{sd} \varphi_{sq}\right)
\]
\[
P_s = V_{sd} i_{sd} + V_{sq} i_{sq}
\]
\[
Q_s = V_{sd} i_{sq} - V_{sq} i_{sd}
\]
\[
T_e = \left(\varphi_{sq} - \varphi_{sd}\right) B_{ew} + T_L
\]

Neglecting the high order harmonics in rotor voltage and the relation with stator voltage can be written as:
\[
V_{sdq} = V_{sdq}^{(1)} + V_{sdq}^{(5)} e^{-j6\omega_s t} + V_{sdq}^{(7)} e^{j6\omega_s t} +
V_{sdq}^{(11)} e^{-j12\omega_s t} + V_{sdq}^{(13)} e^{j12\omega_s t}
\]
\[
V_{rdq} = V_{rdq}^{(1)} \approx \frac{L_m}{L_s} \text{ SY} V_{sdq}^{(1)}
\]

The rotor resistance is small to affect the (5th, 7th, 11th and 13th) order current harmonics by substituting Equation (14) and (15) into Equation (5), (8) and (9), the rotor and stator current in synchronous reference frame can be written as:
\[
i_{rdq} = i_{rdq}^{(1)} + i_{rdq}^{(5)} e^{-j6\omega_s t} + i_{rdq}^{(7)} e^{j6\omega_s t} +
i_{rdq}^{(11)} e^{-j12\omega_s t} + i_{rdq}^{(13)} e^{j12\omega_s t}
\]
\[
i_{rdq} = i_{rdq}^{(1)} + \frac{L_m}{L_s} \left(\varphi_{sdq}^{(5)} + \frac{V_{sdq}^{(11)}}{\varphi_{sdq}^{(15)}} e^{-j12\omega_s t} - \frac{V_{sdq}^{(13)}}{\varphi_{sdq}^{(15)}} e^{j12\omega_s t}\right)
\]

Figure (1): The schematic diagram of a grid-connected DFIG wind turbine system.

The control system for a DFIG under grid voltage distortion is based on rotating two axes reference frames (d-q). For modeling of DFIG in synchronous rotating frame we need to represent the two phase stator (d-q') and rotor (d'-q') circuit variable in a synchronous rotating frame (d-q).
\[ i_{sdq} = \frac{i_{sdq}}{3} + i_{rdq} e^{-j60\omega_1 t} + i_{sdq} e^{j60\omega_1 t} + i_{sdq} e^{-j120\omega_2 t} + i_{sdq} e^{j120\omega_2 t} \]

\[ i_{sdq} = \frac{i_{sdq}}{3} e^{-j120\omega_2 t} + i_{sdq} e^{-j120\omega_2 t} \]

\[ V_{rdq} = \frac{V_{rdq}}{f(5\dot{\omega}_n)\delta L} e^{-j60\omega_1 t} - \frac{V_{rdq}}{f(7\dot{\omega}_n)\delta L} e^{j60\omega_1 t} + \]

\[ \frac{V_{rdq}}{f(13\dot{\omega}_n)\delta L} e^{-j120\omega_2 t} - \frac{V_{rdq}}{f(13\dot{\omega}_n)\delta L} e^{j120\omega_2 t} \] (17)

It is clear from the Equation (16) and (17), which contains two terms, the first one is the fundamental component and the second one is the rotor and stator current harmonics respectively, that is introduced by the grid voltage harmonics and is restrained by the stator transient inductance \( \delta L_x \) [11], because the \( \delta L_x \) is often very small, it is difficult to eliminate the current harmonics in DFIG under distorted voltage, especially for the negative sequence (5th and 11th) and positive sequence (7th and 13th) order harmonics by the induction generator impedance. Therefore the required THD of the stator current can be hardly satisfied without controller circuits. According to equation (15), the AC voltage of rotor side cannot be appropriate pure sinusoidal shape when the grid has harmonic background distortion. The current controller must be designed to reject the grid voltage harmonic to increase the quality of grid.

A. The proposed PI+MR Current Controller Schemer in RSC

During the grid voltage distortion the resonant controllers are used, which are an alternative control structure by achieving high bandwidth at certain frequency and eliminating current harmonic in three phase power converter system during voltage distortion. The open loop transfer function of the proposed resonant current controller is expressed below for both ideal and non-ideal case respectively:

\[ G_R(s) = \frac{k_{ref} s}{s^2 + (\omega_0 s)^2} + \frac{k_{ref} s}{s^2 + (\omega_1 s)^2} \] (18)

To reduce the sensitivity toward possible grid frequency variation, a component with cutoff frequency \( \omega_c \) can be introduced that uses the frequency information provided by PLL [10].

\[ G_R(s) = \frac{k_{ref} s}{s^2 + 2\omega_c s + (\omega_c s)^2} + \frac{k_{ref} s}{s^2 + 2\omega_1 s + (\omega_1 s)^2} \] (19)

Figure (2) illustrates the control scheme of the PI+MR rotor current controller with Resonant tuned at 60\( \omega_0 \) and 120\( \omega_0 \), as seen that the PI and harmonic resonant parts work in depend from each other, making it convenient to deal with any order harmonic control.

Figure (2): The closed loop (PI+MR) rotor current controller implemented in RSC.

Figure (3) shows the proposed overall control scheme for DFIG.

It can be seen from Figure (3) that the reference rotor voltage can be determined as:

\[ V_{rdq} = V_{rdq}^p - V_{rdq}^r + V_{rdq}^c \] (20)

The reference rotor voltage consists of the fundamental component \( V_{rdq}^p \) of rotor current loop, the harmonic component introduced by resonant controller of the stator current loop, \( V_{rdq}^h \) and the decoupling voltage components \( V_{rdq}^c \) which are added to rotor voltage reference.

\[ V_{rdq}^c = \delta L_r i_{rdq} \] (21)

B. DESIGN AND CHOOSING CURRENT CONTROLLER GAINS

In order to determine the PI+MR controller effectively guaranties zero- steady- state error, an analytical regulating its frequency response in a closed-loop system performed as shown in Figure (2) The s-domain open loop transfer function of a PI+MR current controller in continuous time domain is defined as:

\[ G_P(s) + G_R(s)G_3(s) = \frac{k_p + \frac{k_h}{s}}{s^2 + 2\omega_0 s + \omega_0^2} + \frac{k_h}{s^2 + 2\omega_0 s + \omega_0^2} \] (22)

\[ (G_P(s) + G_R(s))G_3(s) = \frac{k_p + \frac{k_h}{s}}{s^2 + 2\omega_0 s + \omega_0^2} + \frac{k_h}{s^2 + 2\omega_0 s + \omega_0^2} \] (23)

In practical situation, the time delay caused by PWM transport always exists. Then the open loop transfer function of the control system with time delay is expressed below:
\[
\left( G_p(s) + G_R(s) \right) G_3(s) e^{-\tau_d} = \left( k_p s^2 + \left( k_p \omega_{ch} + k_i \right) s + \left( k_p \omega_{ch} + k_i \right) s + k_i \omega_{ch} \right) e^{-\tau_d}
\]

where the \( \tau_d \) is the time delay equal to the sample time [9]. For the purpose of the harmonic compensation in the stator current, the PI+MR are used. For higher order controller, the design can be quit heavy especially for higher order than three, they are almost impossible. The current controller design for determining the controller gain based on superposition and Naslin polynomial technique [12], the parameters of the controller gain are given in Table (1).

Table (1): The theoretical value for the current controller

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>( K_p )</th>
<th>( K_i )</th>
<th>( K_r6 )</th>
<th>( K_r12 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superposition method</td>
<td>957.8</td>
<td>49.4*10^4</td>
<td>8.48*10^4</td>
<td>28.22*10^4</td>
</tr>
</tbody>
</table>

The time delay has an effect on the PM system due to the sample-hold function of PWM, and the time delay 6e-\( \mu \)sec is used because of sample rate of 16.67 KHz. If the time delay is considered, the bode diagram of open-loop transfer function using PI+MR regulator with and without time delay for both 6\( \omega \) and 12\( \omega \), is shown in Figure (4). The results are explained in Table (2) for both the cases with and without time delay.

![Bode Diagram](image)

Figure (4): The bode diagram of open-loop transfer function for different frequency using PI+MR regulator for both cases with and without time delay.

Table (2): The variation of \( K_{rh} \) with time delay with respect of the peak gain and PM when the time delay taken into consideration

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>( K_{rh} )</th>
<th>( \text{Peak gain (dB)} )</th>
<th>( \text{PM (degree)} )</th>
<th>( \text{Peak gain (dB)} )</th>
<th>( \text{PM (degree)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega_{ch} = 5 \text{ rad/sec} )</td>
<td>( \omega_{ch} = 6 \text{ rad/sec} )</td>
<td>56</td>
<td>716</td>
<td>116</td>
<td>107</td>
</tr>
</tbody>
</table>

C. SIMULATION AND RESULTS

In order to verify the performance and effectiveness of the proposed control method, the simulation is carried out with a DFIG under grid voltage distortions at PCC. The simulations are performed using Matlab software 2013. The DFIG parameters are given in Appendix (A). The controller gains are given in Table (1). The DC-link voltage is set to 1200V, a switching frequency of 16.67 KHz and 6 KHz for RSC and GSC respectively, at a sampling period of 5\( \mu \)s. The grid volt is set to have a background distortion of 5\%, 4\%, 3\% and 2.5\% for 5\( \text{th} \), 7\( \text{th} \), 11\( \text{th} \) and 13\( \text{th} \) order harmonics respectively in all simulations. In this section the performance of the system are simulated for full load on the DFIG also the effect of varying the supply voltage, frequency of the supply and the wind speed is taken in to account.

C.1 THE STATOR OUTPUT CURRENT SET AT 100% OF FULL LOAD

The output stator current is set to 1p.u. Also there is a comparison between the (P, PI and PID) methods and multi resonant proposed method. The total harmonic distortion using MATLAB/Simulink THD calculation methods are given in Table (3).

Table (3): The THD comparison between different methods (P, PI and PID) with PI+MR for 1p.u

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>PI</th>
<th>PID</th>
<th>PI+MR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator output current (p.u)</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Rotor output current (p.u)</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>

C.2 SYSTEM PERFORMED UNDER VARIABLE WIND SPEED

A wind speed variation has been developed to support studies of the dynamic interaction with the grid. The power flow performance of DFIG wind turbine can be used to study the behavior of control system for variable wind speed, to verify the model under steady state and different operating wind conditions. If the wind speed suddenly changes from \( v_1 \) to \( v_2 \), then the angular speed of the wind turbine and consequently that of the wind generator should change. However, the wind turbine cannot respond quickly to these step changes of wind speed due to high inertia.
associated, then the turbine, generator and gearbox, start to increase smoothly from initial to final value of wind generator angular speed corresponding to the wind speeds $v_1$ and $v_2$. Also the mechanical output power of the wind turbine is varied with the wind speed as in Equation (27).

$$P_m = 0.5 \ C_p(\alpha, \beta_r) \ V_{\text{wind}}^3$$  \hspace{1cm} (27)

In this section we explain one case during the simulations with proposed multi resonant controllers, when the wind speed is varied from cut-in speed to cut-out speed. Figure (5) shows the simulation results of DFIG for wind speed increased from cut-in speed to cut-out speed.

![Simulation Results of DFIG for Wind Speed Variation](image)

Figure (5): The simulation results of DFIG for: (a) Wind speed (m/sec). (b) Three phase stator current (p.u). (c) Three phase rotor current (p.u). (d) Electromagnetic torque (p.u). (e) Power (MW), and (f) DC voltage (V).

According to the Figure (5), it is shown that during the wind speed variation, the stator and rotor output current remains as a sinusoidal, also power remains constant during the speed variation, this result shows that the proposed control scheme is totally robust to the wind speed variation.

### C.3 THE GRID CODE ISSUES

The electrical behavior of the network in terms of grid code issues, which is referring to the frequency and voltage limits, active and reactive power generation, etc, the frequency and voltage variation, due to the dynamic nature is continuously changed. Where the supply voltage reduced and increased by %10, the simulation results are shown in Figure (6) and Figure (7) respectively.

![Simulation Results for DFIG during Voltage Variation](image)

Figure (6): The simulation result for DFIG during the voltage decreased by %10 for a: (a) The three phase stator current (p.u). (b) The three phase rotor current (p.u). (c) The output voltage command of resonant controller in (p.u).

![Simulation Results for DFIG during Voltage Variation](image)

Figure (7): The simulation result for DFIG during the voltage increased by %10 for a: (a) The three phase stator current (p.u). (b) The three phase rotor current (p.u). (c) The output voltage command of resonant controller in (p.u).

To validate the availability of the proposed design technique of PI+MR on the grid frequency variation, from the Figure (8) and (9) shows the frequency of the supply is variation by ±2% for 0.4 sec from the rated value.

![Simulation Results for Dynamic Performance](image)

Figure (8): The simulation results of dynamic performance of the proposed control method with frequency variation are 51Hz in distorted grid voltage.
Figure (9): The simulation results of dynamic performance of the proposed control method with frequency variation is 49Hz in distorted grid voltage

Figure (8) and (9) show the results of stator, rotor current and output voltage command for 51 Hz and 49 Hz respectively. The period under frequency changing was 0.4 sec and the stator current remains as sinusoidal waveform; therefore, the proposed control method is totally robust under frequency and voltage variation.

D. CONCLUSION

Due to the background distortion in the grid voltage at the PCC, the PI multi resonant controller techniques are used for harmonic reductions in the stator currents. The value of the regulator gains, have an effect on the control system, depending on PM and bandwidth, which depends on the cutoff frequency. For robust and good implementation the dynamic performance of the system, must be synchronous with best value of $\omega_{cr}$.

Also the effect of the time delay which is caused by PWM functions, it has an effect of designing the parameters of the controller especially have an effect on the PM, which is effect on the system stability it is determined by inversing the switching frequency for the RSC. A high value of gains of the resonant controller caused to minimize the steady state error.

The P, PI and PID control methods compared to the proposed control method, it can be noted, that the PI+MR control method is more robust and have a large effect to reduce the harmonic components in the stator current than other conventional control methods.

With the wind speed variation from cut-in region to cut-out region and vice versa, the output power of the system during the wind speed remain constant with the proposed control method. The proposed PI+MR controller is investigated under frequency variation for 0.4 sec by ±2% the system is remained stable and robust. Also the system with PI+MR is robust when the supply voltage are reduced and increased by 10%.

APPENDIX (A)

Table (4): The DFIG parameters.

<table>
<thead>
<tr>
<th>Rated power</th>
<th>2 MW</th>
<th>$L_{ds}$</th>
<th>0.1386 p.u</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated stator voltage (v.r.m.s)</td>
<td>690 V</td>
<td>$L_{ds}$ (referred to the stator)</td>
<td>0.1493 p.u</td>
</tr>
<tr>
<td>$R_s$</td>
<td>0.0048 p.u</td>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>$R_f$ (referred to the stator)</td>
<td>0.00549 p.u</td>
<td>Number of poles</td>
<td>4</td>
</tr>
<tr>
<td>$L_m$</td>
<td>3.9527 p.u</td>
<td>Stator/rotor turns ratio</td>
<td>0.45</td>
</tr>
</tbody>
</table>

REFERENCES: