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POWER QUALITY IMPROVEMENT FOR WIND POWER SYSTEM WITH DFIG USING PREDICTIVE DIRECT POWER CONTROL SCHEME

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ABSTRACT

A new control technique is proposed in this work for efficient operation of DFIG (Doubly Fed Induction Generator) operating in unbalanced condition of grid voltage using Model Predictive Direct Power Control (MPDPC) along with a power compensator. In MPDPC method, a controlled system model predicts the imminent behavior of the system over a long range to regulate the direct reactive and active powers in the stator instantaneously. Also, MPDPC selects the appropriate rotor voltage vector which has least ripples using an optimization cost function. Then, power compensation scheme generates power references to MPDPC without the amputation of negative sequence components of the stator current. The proposed method reduces the distortions in the stator currents and eliminates the electromagnetic torque oscillations. The effectiveness of the proposed control algorithm is realized in Matlab/Simulink and the dynamic response of the controller in improving the power quality is studied.

Keywords: DFIG, power compensator, model predictive direct power control.

1. INTRODUCTION

In recent years, wind turbine with DFIG became more popular because of its variable speed, low cost, fast dynamic and steady state responses and maximum power capture characteristics. Unbalance in voltage exists due to load impedance mismatch, type or values of load added to the grid. In unbalanced grid voltage conditions, wind turbines require special control efforts to avoid oscillations in electromagnetic torque and to eliminate non-sinusoidal stator current exchange with the grid [1] - [3].

Several control strategies for DFIG's in unbalance have been developed. The popular approaches are Vector Control or Field Oriented Control [4]-[7] which has slow transient performance because of complex decoupling and coordinate transformation. The large amount of tuning work required in VC and control complexity can be overcome by Direct Power Control [8] or Direct Torque Control [9], [10]. Under unbalanced voltage conditions, DFIG can be controlled by using the improved Direct Power Control or Direct Torque Control strategies [11] - [13]. Also other improved control strategies like predictive current control [14] and Sliding Mode Control (SMC) [15] has been proposed for obtaining fast dynamic response and to regulate DFIG. However, all these strategies reduce only the electromagnetic torque oscillations while the stator currents are not given much importance in improving power quality.

In this work, Model Predictive Direct Power Control (MPDPC) along with power compensator is proposed which improves the performance of DFIG. This new control algorithm has the enhanced control flexibility deprived of abc-αβ transformation, PWM modulator, PI controllers and switching tables. By this control scheme, excellent dynamic response has been achieved. Also the stator current exchange with the grid becomes more sinusoidal and symmetric without the extraction of negative sequence components. This scheme gives lesser total harmonic distortion (THD) and the power quality is improved significantly in unbalanced grid voltage circumstances.

2. SYSTEM DESCRIPTION

The wind power system with DFIG studied in this proposed work is shown in Figure-1. The gear box which is used to produce more torque when the wind speed is low connects DC motor to DFIG. Then, the stator of DFIG is tied to the utility grid directly, although the rotor has provided with power converter which is of back-to-back connected to the grid through coupling inductor which minimizes the frequency ripples due to switching harmonics.

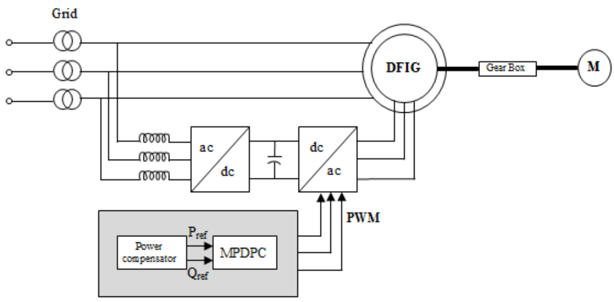

Figure-1. Power system with DFIG based wind turbine.

The DC link capacitor is connected between power converters to balance the power with minimum DC voltage. The first control MPDPC is used to regulate direct reactive and active powers of the stator stationary reference frame instantaneously. The second control is to generate references for reactive and active power to MPDPC for dealing with the problems in unbalance conditions [1].

3. MODELLING OF DFIG

An induction machine with wound rotor in which both stator and rotor are connected to electrical source is referred as DFIG. The variation in shaft speed is achieved by controlling the amount of power transferred to the rotor via bi-directional back-to-back power converter using IGBT which enables high speed switching capability. The different reference frames in which DFIG can be articulated are the synchronous frame, the stator stationary frame and the rotor frame fixed to either flux or voltage of the stator. The DFIG modelling using mathematical expressions for the stator stationary frame can be expressed by voltage, flux and current equations.

$$V_s = R_s I_s + \frac{d\psi_s}{dt} \tag{1}$$

$$V_r = R_r I_r + \frac{d\psi_r}{dt} - j\omega_r \psi_r \tag{2}$$

$$\psi_s = L_s I_s + L_m L_r \tag{3}$$

$$\psi_r = L_m I_s + L_r L_r \tag{4}$$

$$T_e = \frac{3}{2} p \mathrm{Im}\{\psi_s^* I_s\} \tag{5}$$

$$S = P + jQ = \frac{3}{2} I_s^* V_s \tag{6}$$

where
V_s , V_r voltage vectors of stator and rotor;
I_s , I_r current vectors of stator and rotor;
L_s, L_r self-inductances of stator and rotor;
L_{ls}, L_{lr} leakage inductances of stator and rotor;
L_m magnetizing inductance;
ψ_s, ψ_r flux vectors of stator and rotor;
R_s, R_r resistances of stator and rotor;
P, Q stator active and reactive powers;
p number of pole pairs;
T_e electromagnetic torque;
ω_r rotor electrical speed;
* donates the complex conjugate operation;

The system parameters required for this work are shown in Table-1.

Table-1. System parameters.

Rated Power	**20 kW**
Line-to-line voltage (RMS)	415 V
R_s	0.21 Ω
R_r (referred to the stator)	0.22 Ω
L_{ls}	2.43 mH
L_{lr} (referred to the stator)	2.43 mH
L_m	85.00 mH
L_s	87.43 mH
L_r (referred to the stator)	87.43 mH
Number of pole pairs	2
Sampling period	100 µs
DC-link voltage	V

4. MPDPC TECHNIQUE OF DFIG

Predictive control becomes an effective control strategy for high power converters with good dynamic and steady state responses. Different schemes had emerged from predictive control like trajectory, deadbeat, hysteresis and model predictive control (MPC) [16]. Proposed MPDPC is a flexible control technique which has easy insertion of non-linearities and system constraints that improves system performances. In this control, a model system is used to predict the future behavior of the system over a long range of prediction horizon. The cost function optimization is used to assess the effects of all possible voltage vectors in order to select one vector that minimizes the output voltage error. Depending upon the objective, the cost function can be defined. In earlier days, it is difficult to implement MPDPC for power converters because of its large computations to achieve optimization. But nowadays, with the development of high speed, high precision microprocessors we have high speed DSP to sort out this problem. Figure-2 shows the block diagram of MPDPC.

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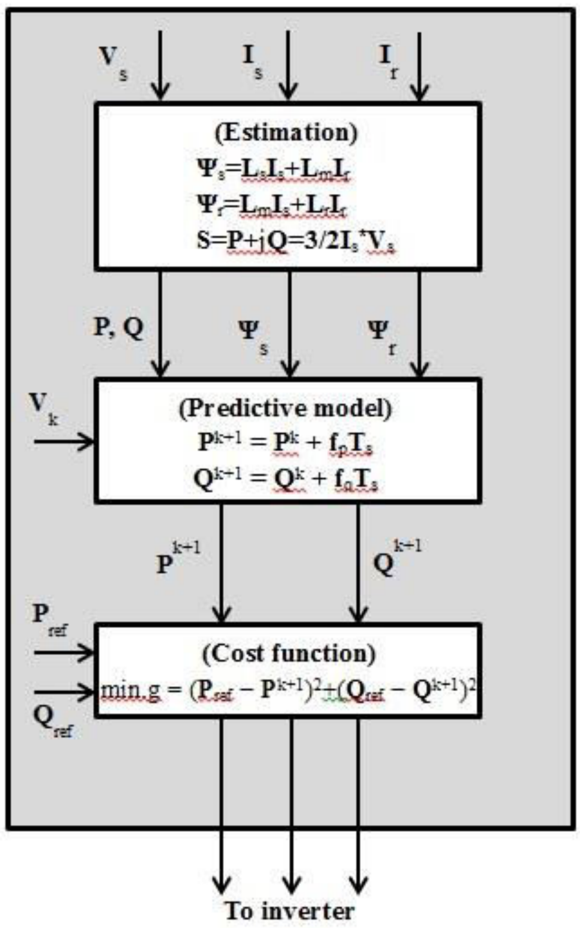

Figure-2. MPDPC block diagram.

In MPDPC, the system parameters such as stator voltage, stator currents and rotor currents are first measured to estimate stator and rotor fluxes and the apparent power. Then they are given to the predictive model system along with conceivable voltage vectors to predict P^{k+1} and Q^{k+1}. Thereafter predicting, P^{k+1} and Q^{k+1} are given to optimized cost function along with reactive and active power references for evaluating the voltage vector. So the vector having least power ripple is then applied to the next sampling period.

The steady state relationship between flux and voltage of stator can be obtained by neglecting the stator resistance from (1) as

$$\mathrm{V_s} = \mathrm{j}\omega_1\psi_\mathrm{s} \tag{7}$$

The stator current can be expressed from (3) and (4) by the stator and rotor flux as

$$\mathrm{I_s} = \lambda(\mathrm{L_r}\psi_\mathrm{s} - \mathrm{L_m}\psi_\mathrm{r}) \tag{8}$$

where $\lambda = 1 - L_m^2/L_sL_r$, leakage factor. The stator apparent power using ψ_s and ψ_r is given as

$$S = j\frac{3}{2}\lambda\omega_1[L_r|\psi_s|^2 - L_m(\psi_r^*\psi_s)] \tag{9}$$

Decomposing real part and imaginary part, the reactive and active powers are expressed as

$$P = \frac{3}{2}\lambda\omega_1 L_m Im\{\psi_r^*\psi_s\} \tag{10}$$

$$Q = \frac{3}{2}\lambda\omega_1[L_r|\psi_s|^2 - L_m Re\{\psi_r^*\psi_s\}] \tag{11}$$

From (10) and (11), it is clearly seen that the output power of stator mainly depends on fluxes of both stator and rotor. Mostly P and Q variations depend on rotor flux ψ_r variations as the rotor voltage V_r controls it is stated in (2) because the amplitude of the stator flux is constant and rotating at constant frequency. From this study, it is found that the need of MPDPC is to assess all possible rotor voltage vectors on output power of stator. The voltage vector will be then applied, which in turn satisfies in minimizing a specified cost function and the derivatives of reactive and active powers with respect to time t can be expressed from (10) and (11) as

$$\frac{\mathrm{dP}}{\mathrm{dt}} = \frac{3}{2}\lambda\omega_1\mathrm{L_m}[\mathrm{Im}\{\mathrm{V_r^*}\psi_\mathrm{s}\} + \omega_\mathrm{s}\mathrm{Re}\{\psi_\mathrm{r}^*\psi_\mathrm{s}\} - \lambda\mathrm{R_r}\mathrm{L_s}\mathrm{Im}\{\psi_\mathrm{r}^*\psi_\mathrm{s}\}] \tag{12}$$

$$\frac{\mathrm{dQ}}{\mathrm{dt}} = -\frac{3}{2}\lambda\omega_1\mathrm{L_m}[\mathrm{Re}\{\mathrm{V_r^*}\psi_\mathrm{s}\} - \omega_\mathrm{s}\,\mathrm{Im}\{\psi_\mathrm{r}^*\psi_\mathrm{s}\}$$

$$-\lambda\mathrm{R_r}\mathrm{L_s}\mathrm{Re}\{\psi_\mathrm{r}^*\psi_\mathrm{s}\}+\lambda\mathrm{R_r}\mathrm{L_m}|\psi_\mathrm{s}|^2] \tag{13}$$

When the rotor resistance is neglected in (12) and (13), the power derivatives are be similar to

$$\frac{dP}{dt} = \frac{3}{2}\lambda\omega_1 L_m[Im\{V_r^*\psi_s\}$$

$$+\omega_s Re\{\psi_r^*\psi_s\}] = f_p \tag{14}$$

$$\frac{dQ}{dt} = \frac{3}{2}\lambda\omega_1 L_m[Re\{V_r^*\psi_s\}$$
$$-\omega_s Im\{\psi_r^*\psi_s\}] = f_q \tag{15}$$

Using the rotor voltage as input and the reactive and active power as state variables, DFIG has been modelled as a discrete - time model. The instant powers for next sampling can be expected as

$$\mathrm{P^{k+1}} = \mathrm{P^k} + \mathrm{f_p}\mathrm{T_s} \tag{16}$$

$$\mathrm{Q^{k+1}} = \mathrm{Q^k} + \mathrm{f_q}\mathrm{T_s} \tag{17}$$

where T_s is the sampling period. After obtaining anticipated power, it is essential to assess the effects of all conceivable rotor voltage vectors and select one vector that minimizes the following cost function

$$\mathrm{min.\,g} = (\mathrm{P_{ref}} - \mathrm{P^{k+1}})^2 \quad + (\mathrm{Q_{ref}} - \mathrm{Q^{k+1}})^2 \tag{18}$$

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Once voltage vector is selected, it is given to PWM generator for generating duty cycles required for the inverter.

5. SIMULINK MODEL OF THE PROPOSED SYSTEM WITH MPDPC IN UNBALANCED GRID VOLTAGE CONDITION

Figure-3 represents the simulink model of the proposed system with MPDPC in unbalanced voltage condition. By using three individual sources, an unbalance in grid voltage is created in phase A by making 25% voltage dip.

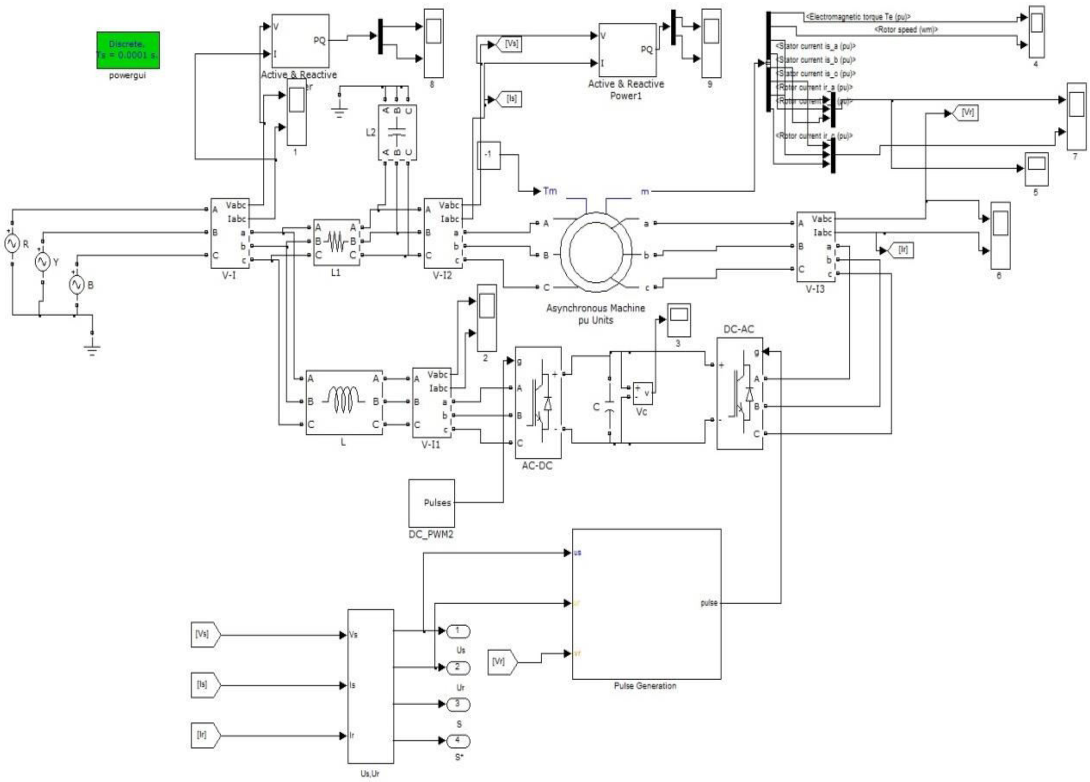

Figure-3. Simulink model with MPDPC in unbalanced condition.

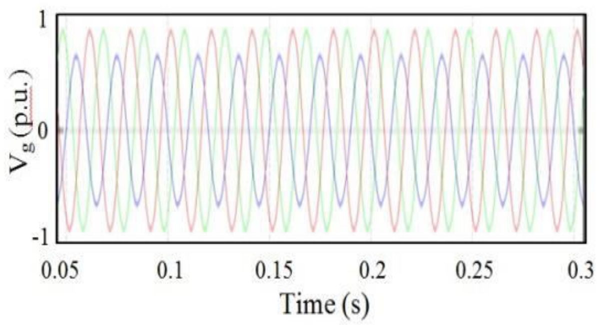

Figure-4. Unbalanced grid voltage.

Figure-4 depicts the waveforms of the unbalanced grid voltage which is utilized in this work. Figure-5 represents the responses of the proposed system without a controller. Figure-6 illustrates the responses of DFIG in unbalanced grid voltage using MPDPC without power compensator scheme. It was observed that without any controller in unbalanced grid voltage condition, active and reactive power has ripples. Also, electromagnetic torque has oscillations. The stator and rotor current distortions are higher in magnitude. After the implementation of MPDPC, it can be seen that the active and reactive power is well controlled. Also stator currents are quite smoothened with low distortions. This distortion is due to the constant power references applied to the MPDPC. Hence, to generate reference powers MPDPC has to be used with power compensator.

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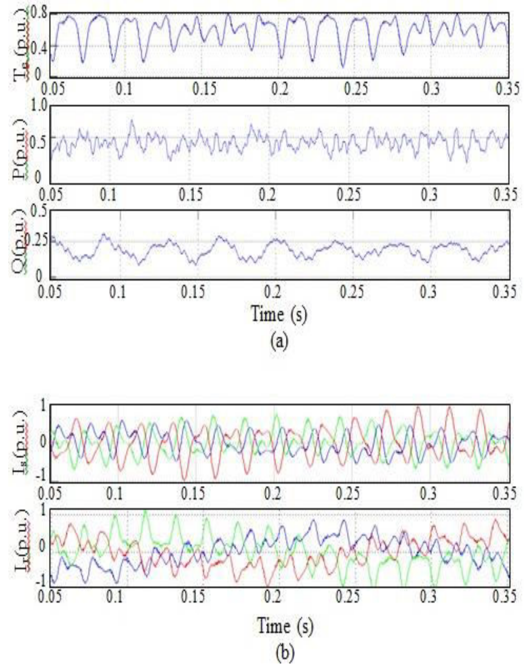

Figure-5. Responses of DFIG in unbalanced grid voltage condition without controller (a) Electromagnetic torque, Active and reactive power (b) Stator and rotor currents.

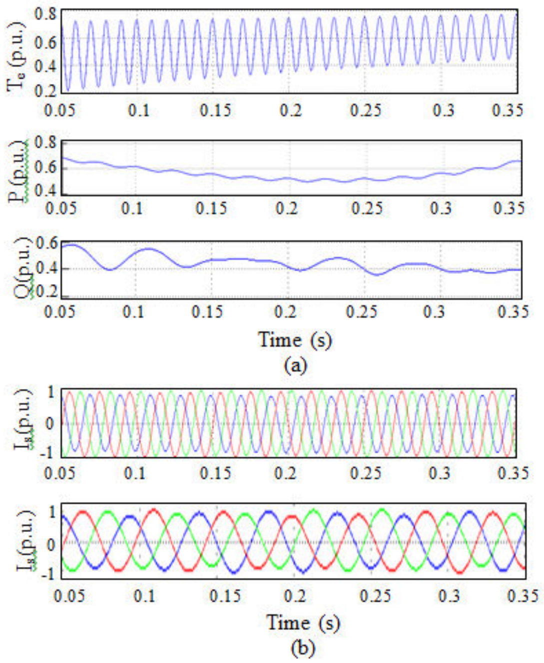

Figure-6. Responses of DFIG in unbalanced grid voltage condition using MPDPC without power compensator (a) Electromagnetic torque, Active and reactive power (b) Stator and rotor currents.

6. POWER COMPENSATOR SCHEME

In unbalanced condition of grid voltage, the stator currents are seriously distorted due to the presence of negative sequence components. So it is necessary to eliminate negative sequence components in order to achieve sinusoidal and symmetric stator currents. Positive components of reactive and active power can be reduced to zero in order to make negative sequence component of stator currents to zero. In MPDPC strategy, reactive and active power references are given as 0.75p.u. and 0.25p.u. respectively. Since constant power references are applied in unbalanced condition, it is evident that electromagnetic torque has oscillations. Also, both the stator and rotor currents have distortions. This is not allowed for grid connected DG systems. Power compensator is used to generate instant power references which is delivered to MPDPC.

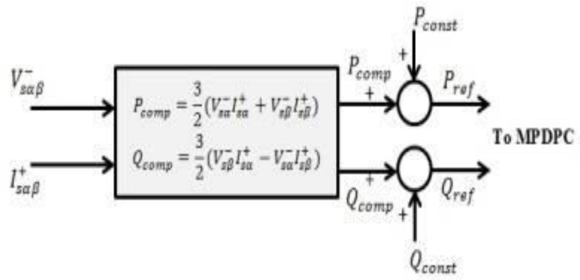

Figure-7. Block diagram of power compensator.

The power compensation scheme for DFIG based wind turbine in unbalanced condition of grid voltage is revealed in Figure-7. The stator voltage negative sequence components and the stator current positive sequence components are given as input to the power compensators for generating compensation terms. The output from power compensator is added with actual constant power references to generate new power references. Then, the new power references will be sent to MPDPC.

7. ANALYSIS OF POWER COMPENSATOR

The zero sequence component, positive sequence component and negative sequence component of an unbalanced three-phase system can be obtained from

$$\begin{pmatrix} x^0 \\ x^+ \\ x^- \end{pmatrix} = \frac{3}{2}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}\begin{pmatrix} x_a \\ x_b \\ x_c \end{pmatrix} \tag{19}$$

where $a = e^{j\left(\frac{2\pi}{3}\right)}$. The three-wire connection system with no neutral is considered in this analysis as three- phase system. Hence, the zero sequence components of current and voltage becomes zero. Using both positive sequence and negative sequence components in unbalanced condition of grid voltage, the stator voltage and current is stated as

$$V_s = V_s^+ + V_s^- = (V_{s\alpha}^+ + V_{s\alpha}^-) + j(V_{s\beta}^+ + V_{s\beta}^-) \tag{20}$$

$$I_s = I_s^+ + I_s^- = (I_{s\alpha}^+ + I_{s\alpha}^-) + j\left(I_{s\beta}^+ + I_{s\beta}^-\right) \tag{21}$$

The expression for actual reactive and active powers can be obtained by substituting (20) and (21) in (6) as

$$P = 1.5 \times (P_0 + P_1 + P_2) \tag{22}$$

$$Q = 1.5 \times (Q_0 + Q_1 + Q_2) \tag{23}$$

where
$P_0 = V_{s\alpha}^+ I_{s\alpha}^+ + V_{s\beta}^+ I_{s\beta}^+ + V_{s\alpha}^- I_{s\alpha}^- + V_{s\beta}^- I_{s\beta}^-$
$P_1 = V_{s\alpha}^+ I_{s\alpha}^- + V_{s\beta}^+ I_{s\beta}^-$
$P_2 = V_{s\alpha}^- I_{s\alpha}^+ + V_{s\beta}^- I_{s\beta}^+$
$Q_0 = V_{s\beta}^+ I_{s\alpha}^+ + V_{s\beta}^- I_{s\alpha}^- - V_{s\alpha}^+ I_{s\beta}^+ - V_{s\alpha}^- I_{s\beta}^-$
$Q_1 = V_{s\beta}^+ I_{s\alpha}^- - V_{s\beta}^+ I_{s\beta}^-$
$Q_2 = V_{s\beta}^- I_{s\alpha}^+ - V_{s\alpha}^- I_{s\beta}^+$

Using the stator voltage from (1), the stator flux can be stated as

$$\psi_s = \frac{j}{\omega_1}(R_s \boldsymbol{I}_s - \boldsymbol{V}_s) \tag{24}$$

The torque is obtained by substituting (24) in (5) as

$$T_e = \frac{3}{2} p Im\left\{\frac{j}{\omega_1}\boldsymbol{V}_s^* \boldsymbol{I}_s - \frac{j}{\omega_1} R_s |\boldsymbol{I}_s|^2\right\} \tag{25}$$

Substituting (20) and (21) in (25), the torque can be expressed as

$$\mathrm{T_e} = \frac{3\mathrm{p}}{2\omega_1}(\mathrm{T_0} + \mathrm{P_1} - \mathrm{P_2}) \tag{26}$$

where
ω_1 is the grid angular frequency and

$$\mathrm{T_0} = \mathrm{V_{s\alpha}^+ I_{s\alpha}^+ - V_{s\alpha}^- I_{s\alpha}^- + V_{s\beta}^+ I_{s\beta}^+ - V_{s\beta}^- I_{s\beta}^- + R_s}(|\mathbf{I_s}^-|^2 - |\mathbf{I_s}^+|^2$$

8. POWER QUALITY IMPROVEMENT USING POWER COMPENSATOR

The new power references which is used to achieve sinusoidal and symmetric stator current can be expressed as

$$\mathrm{P_{ref}} = \mathrm{P_{const}} + \mathrm{P_{comp}} \tag{27}$$

$$\mathrm{Q_{ref}} = \mathrm{Q_{const}} + \mathrm{Q_{comp}} \tag{28}$$

where P_{const} and Q_{const} are the actual power references in balanced condition while P_{comp} and Q_{comp} are the compensation terms which is required for unbalanced condition. The original power references and compensation terms are summed up to generate new reference value by controlling actual powers by MPDPC method.

$$\mathrm{P_{const}} = \frac{3}{2}(\mathrm{P_0} + \mathrm{P_1} + \mathrm{P_2}) - \mathrm{P_{comp}} \tag{29}$$

$$\mathrm{Q_{const}} = \frac{3}{2}(\mathrm{Q_0} + \mathrm{Q_1} + \mathrm{Q_2}) - \mathrm{Q_{comp}} \tag{30}$$

By controlling P_1 *and* Q_1 to zero, the negative sequence component of stator current can be eliminated, while (29) and (30) becomes

$$\mathrm{P_{const}} = \frac{3}{2}(\mathrm{P_0} + \mathrm{P_2}) - \mathrm{P_{comp}} \tag{31}$$

$$\mathrm{Q_{const}} = \frac{3}{2}(\mathrm{Q_0} + \mathrm{Q_2}) - \mathrm{Q_{comp}} \tag{32}$$

For making (31) and (32) as constant, it can be deduced since P_0 *and* Q_0 are constant, P_2 *and* Q_2 are oscillating

$$\mathrm{P_{comp}} = \frac{3}{2}\mathrm{P_2} \tag{33}$$

$$\mathrm{Q_{comp}} = \frac{3}{2}\mathrm{Q_2} \tag{34}$$

When this P_{comp} *and* Q_{comp} are added with actual power references to generate new power references which in turn force P_1 *and* Q_1 to zero in order to eradicate negative sequence component of stator current.

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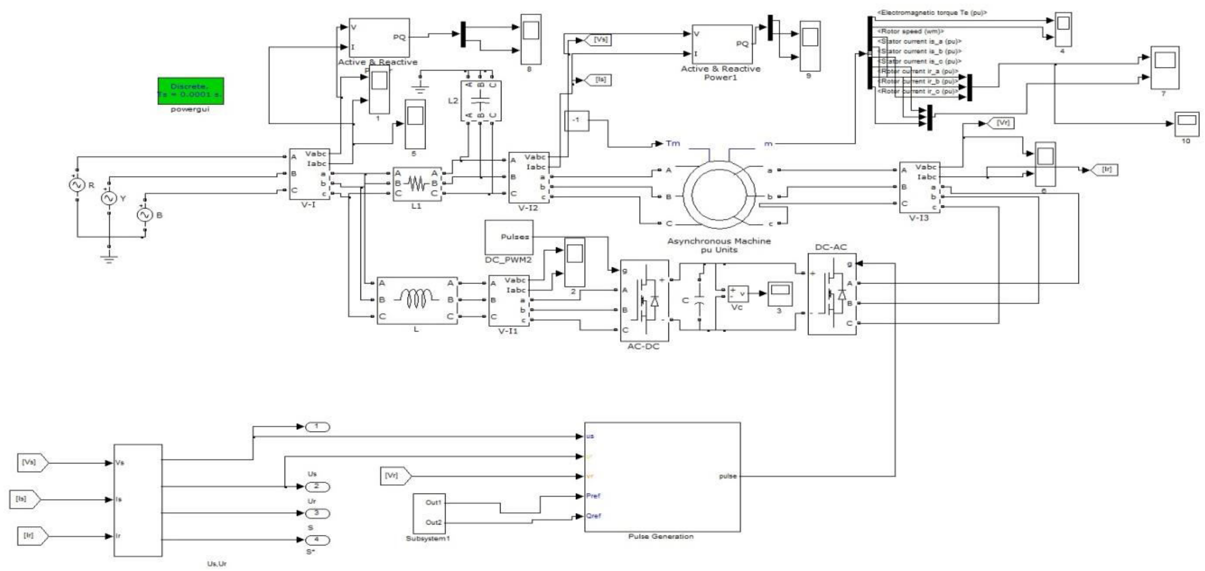

Figure-8. Simulink model of MPDPC with power compensator in unbalanced condition.

The power quality improvement using power compensator is described as

$$P_{ref} = P_{const} + \frac{3}{2}\left(V_{s\alpha}^{-} I_{s\alpha}^{+} + V_{s\beta}^{-} I_{s\beta}^{+}\right) \tag{35}$$

$$Q_{ref} = Q_{const} + \frac{3}{2}\left(V_{s\beta}^{-} I_{s\alpha}^{+} - V_{s\alpha}^{-} I_{s\beta}^{+}\right) \tag{36}$$

Figure-8 shows the simulink model of the proposed system in unbalanced condition of grid voltage using MPDPC along with power compensation scheme. Figure-9 shows the responses of DFIG based wind turbine using MPDPC with power compensator in unbalanced condition of grid voltage. It was observed that there are some oscillations in electromagnetic torque in unbalanced condition due to the presence of oscillating terms as mentioned in (26). In the decomposition of stator current, it can be seen that only positive sequence component is presented relatively requires smaller negative sequence component which leads to less extraction of negative sequence component in unbalanced network.

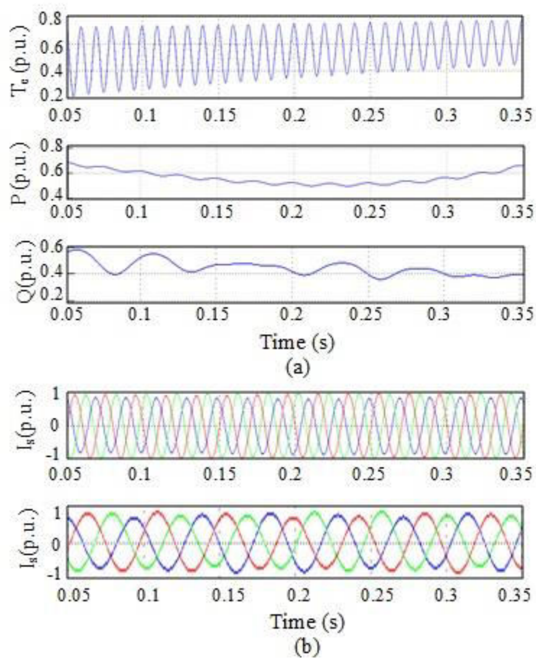

Figure-9. Responses of MPDPC with power compensator in unbalanced condition.

Thus, by generating reference powers using power compensator, the power quality has been improved which is the main objective of this work.

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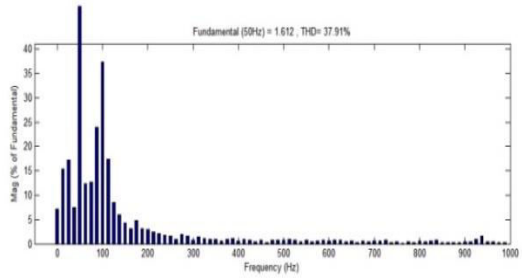
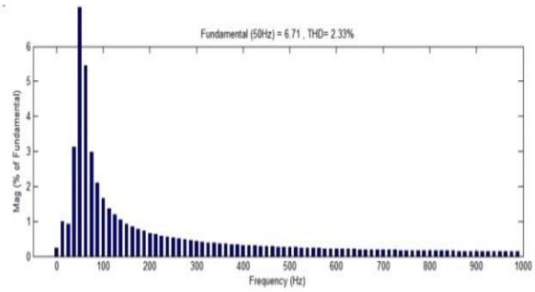
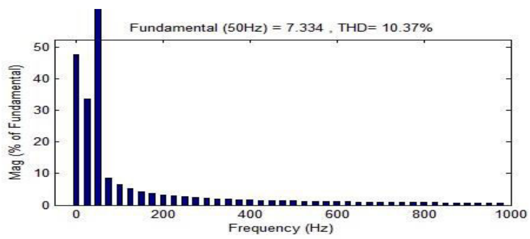
9. QUANTITATIVE COMPARISON



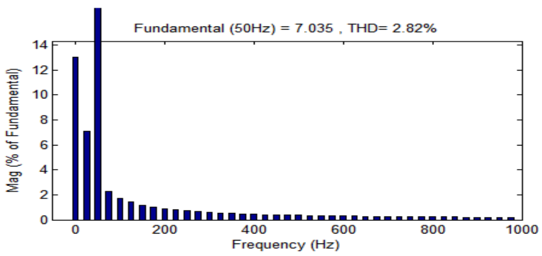
(a)



(b)



(c)



(d)

Figure-10. Total Harmonic Distortion of stator current for different cases. (a) In unbalanced condition of grid voltage without controller (b) In balanced condition of grid voltage using MPDPC without power compensator (c) In unbalanced condition of grid voltage using MPDPC without power compensator (d) In unbalanced condition of grid voltage using MPDPC with power compensator.

The stator current distortions are more when the grid voltage is unbalanced with MPDPC and without power compensator. The measured THD is 10.37%. After implementing MPDPC with power compensator for DFIG in unbalanced condition of grid voltage, the stator current is sinusoidal and symmetric while the THD is considerably reduced to 2.82%. This indicates the effectiveness of the proposed controller in power quality improvement of DFIG based wind turbines in unbalanced condition of grid voltage.

10. CONCLUSIONS

The proposed work has verified the effectiveness of MPDPC along with power compensator for DFIG based wind turbines in unbalanced grid voltage condition. It was seen that without the need of PI regulators, switching tables, co-ordinate transformation, extraction of negative sequence component and PWM modulators excellent steady state and dynamic response was achieved. The first control MPDPC selects the apt voltage vector that reduces the optimized cost function to regulate the direct reactive and active powers respectively. Using MPDPC along with power compensator improves the power quality of stator current exchange with the grid.

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