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A Control Strategy for DFIM to Minimize DC Bus Voltage Fluctuations and Torque Oscillations

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Abstract

The Direct Power Contro; has many advantages like it avoids the usage of integration of PWM voltages which leads to stable operation even at zero rotor frequency, it is position sensor less and hence will not depend on machine parameters like stator or rotor resistance. In case of network unbalance, if the system is operated with constant active and reactive powers, it leads to oscillations in the electromagnetic torque and currents exchange with the grid will become non- sinusoidal, which is not good for the system as it increases the mechanical stress. In this paper, both the rotor connected converter and grid connected converter are fed with DPC strategy along with that a Torque Oscillations Cancellation scheme is applied to RSC and Proportional Integral control based power references generation strategy without calculating the sequence components and with elimination of DC bus voltage oscillations is applied to stator-side converter in order to achieve non-oscillating torque accompanied by quality improved current exchange with the grid. The simulation results of Doubly Fed Induction Generator with and without fault clearly shows that the performance of the proposed scheme is validated.

Keywords: *doubly fed induction generator, direct power control, rotor connected converter, grid connected converter, torque oscillations cancellation*

1. Introduction

In the recent past and also presently the wind energy generation has developed rapidly both in terms of onshore and offshore wind farms. In variable speed wind energy conversion systems, the Doubly Fed Induction Generator (DFIG) is considered to be common solution [1]. The commonly used control technique for these variable speed wind turbines is the Field Oriented Control (FOC) technique [2] but has drawbacks like nature of linearity and lack of robustness when it is subjected to variations in operational conditions.

The nonlinear control techniques like Direct Torque Control (DTC) or Direct Power Control (DPC) [3-5] have gained importance in the recent past. These techniques are used because of the nature of nonlinearity of the inverter with finite possible states and due to the linear time-varying nature of the DFIG model. The basic principle of these techniques is to control instantaneously the torque or active power and the magnitude of flux or reactive power in one sample time by selecting voltage space vector and an average control signal. In DPC technique, the Rotor Side Converter (RSC) instantaneous switching states are determined based on the active and reactive power measurements made in the stator circuit, which is quite different from the DTC technique i.e., the measurements are taken at one terminal of the DFIG and the switching states are carried at another terminal. There is no necessity of PWM voltages integration in DPC strategy unlike DTC strategy, which leads to stable operation even when rotor frequency is set to zero. The DPC strategy is independent of stator or rotor resistance as it is inherently a position sensor less method.

As the DFIG is directly connected to grid, therefore it is more succumbed to faults which generally cause non-sinusoidal output currents, electromagnetic torque (T_{em}) or power oscillations which leads to more mechanical stress in the wind turbine and ripples in the DC-link voltage, unequal heating and power loss. Various methods were proposed to focus on the solution to control DFIG when there is a network unbalance. In [6], a modified Direct Torque Control technique is applied to rotor side frequency converter and the transient behavior of

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DFIG is described with and without crowbar protection for a sudden voltage dip. DFIM is studied with control of RSC under abnormal condition [7], in which control of active and reactive power can be independently achieved with results showing that speed, torque and power factor can be matched with the reference signals by regulating individually but the inverter has to be disconnected during the fault to avoid high oscillations in stator and rotor currents. In [8], the variations in active and reactive power abd DC bus voltage is addressed and both the GSC and RSC are dynamically controlled by active and reactive power of DFIG. The objective of maintaining DC link voltage at constant level is achieved in [9] for variable speed performance but it is not dealt with the unbalanced voltage case. The DC bus voltage and electromagnetic torque oscillations due to fault in [10] is not addressed properly. A Stator Voltage Oriented Direct Power Control (SVODPC) scheme and a new crowbar control technique was proposed in [11], capable of suppressing the oscillations in currents and T_{em} caused due to fault state along with recovering the grid voltage by injecting the reactive power and limit the peak values of rotor currents by new crowbar protection technique. Mathematical analysis of the stator and rotor fault currents is deduced for the DFIG during a grid fault in presence of crowbar resistors which influence the electrical behavior. The fault currents and Tem are analyzed for different values of crowbar resistances for different DFIG parameter sets [12]. In [13], a novel crowbar protection technique along with a DPC scheme is proposed for DFIG. During grid fault, a voltage dip is caused due to which large transient currents are induced in rotor windings, which has to be avoided otherwise it will damage the RSC. DPC strategy applied to RSC suppresses the fault currents transient oscillations and also Tem oscillations. In [14], a DTC technique along with a reference rotor flux amplitude generation strategy is applied to RSC of DFIM under voltage dip. With the implementation of the scheme, controlled torque and considerable reduction of stator and rotor over currents is achieved but the scheme does not avoid the crowbar protection completely, it is avoided during the low depth voltage dips. The DTC technique is applied to the RSC to control the torque oscillations but the DC bus oscillations and consideration of unbalanced load condition was unaddressed. A new DTC scheme for a DFIG under unbalanced grid voltage condition is proposed in [15]. Independent control of electromagnetic torque and reactive power is achieved by controlling the torque angle (δ) and rotor voltage magnitude because of that the reduction in pulsations of Tem is achievable. In this proposed method, Proportional-Integral and Resonant (PI+R) controller is used to achieve the reduction of pulsations in Tem. A proper value of crowbar resistance is chosen, which is connected to RSC, in order to limit the rotor current which generally increases almost 8 times its nominal rated value and even fluctuations in DC-link voltage are limited by which DFIG performance is improved [16]. A real time adjustable resistance crowbar structure is described in [17], for DFIG variable speed operation system and the performance of the system is analyzed for a grid fault. During the fault the grid voltage is assisted by providing reactive power by supply-side converter and also by machine side converter and the scheme described is used to control rotor currents and DC-link voltage values within the limits.

The various strategies mentioned above are used to minimize the effects of stator and rotor over currents, fluctuations in DC-link voltage, oscillations in Tem, control of active and reactive power on the power converters employed for control of DFIM when there is network unbalance in the DFIG system but in most of the cases crowbar protection is employed and non-sinusoidal currents are exchanged with the grid which is not good for a wind turbine. In [18], the solution for the problem discussed above is explained with the active (P) and reactive (Q) power references generation for the rotor connected converter and for the grid connected converter, the power references are calculated by means of stator voltage and grid current sequence components in order to eliminate the torque oscillations and achieve sinusoidal currents, which are exchange with the grid. In this paper, a new DPC strategy is proposed for both the rotor connected converter and grid connected converter along with the Torque Oscillations Cancellation (TOC) strategy without any sequence calculations for RSC and a new Proportional Integral (PI) control based power references generation strategy along with elimination of DC bus voltage oscillations is employed for Grid Side Converter (GSC) without calculating the stator voltage and grid current sequence components, which is actually taken into consideration in [18]. The performance of the proposed scheme is verified by simulation results for the conditions of with and without grid fault and the results clearly shows that the behavior of the Doubly Fed Induction Generator (DFIG) is improved with elimination of oscillations in T_{em} and achieving exchange of sinusoidal currents with the grid.

2. Proposed System

As shown in Figure 1, the proposed scheme is analyzed by the condition of three phase fault, which is applied near the grid. During the fault there is sudden dip in stator voltage due to which over currents will be produced in stator and rotor currents and the currents become non-sinusoidal and also this condition will lead to oscillations in the T_{em}. If no special control efforts are used these conditions will prevail in DFIG system when operating with constant P and Q reference generations [18]. For both the rotor connected converter and grid connected converter the DPC technique is employed as shown in Figure 1. The stator active power new reference (P_{s_ref}) generation value and the reference value of stator active power ($P_{s\_required}$) are compared and likewise the stator reactive power new reference (Q_{s_ref}) generation value and the reference reactive power of stator ($Q_{s\_required}$) are compared for the generation of pulses for RSC. This DPC technique applied for RSC is used to deal with the problems associated with the grid voltage unbalance. Similarly, the grid side active and reactive power values are compared for the generation of pulses for GSC. This DPC technique applied for grid side converter is used for controlling the active and reactive powers directly. The specifications of the DFIG used are shown the Table 1.

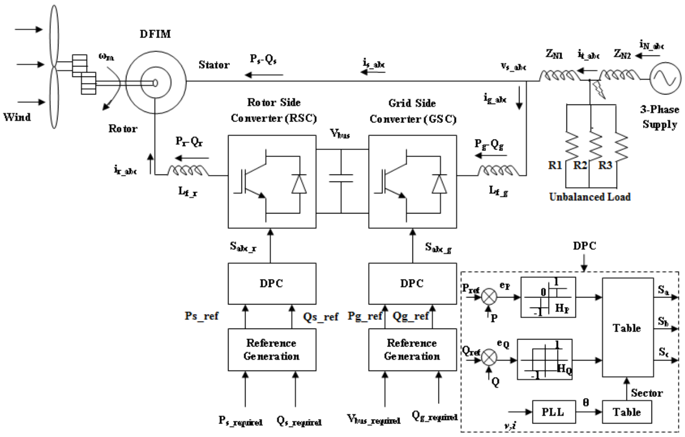


Figure 1. Proposed scheme

Table 1. Ratings of DFIG

Rated Power (P)	2.6MW
RMS Voltage (V_{rms})	690V
Frequency (f)	50Hz
Pairs of Poles (p)	2
Stator Resistance (R_s)	0.0108pu
Rotor Resistance ($R_{r'}$)	0.0121pu
Stator Leakage Inductance (L_{ls})	0.102pu
Rotor Leakage Inductance ($L_{lr'}$)	0.1pu
Magnetizing Inductance (L_m)	3.362pu
Inertia Constant (H)	0.5s
Friction Coefficient (F)	0.05479pu

The stator and rotor voltage and flux equations of DFIG based on the stator reference frame are given below:

$$\bar{v}_s = R_s\bar{i}_s + \frac{d\bar{\psi}_s}{dt} \tag{1}$$

$$\bar{v}_r = R_r\bar{i}_r + \frac{d\bar{\psi}_r}{dt} - j\omega_m\bar{\psi}_r \tag{2}$$

$$\bar{\Psi}_s = L_s\bar{i}_s + L_h\bar{i}_r \tag{3}$$

$$\bar{\Psi}_r = L_r\bar{i}_r + L_h\bar{i}_s \tag{4}$$

The electromagnetic torque of DFIG is given by:

$$T_{em} = \frac{3}{2}p\,\mathrm{Im}\{\bar{\Psi}_s^{*}.\bar{i}_s\} = \frac{3}{2}p\left(\psi_{s\alpha}i_{s\beta} - \psi_{s\beta}i_{s\alpha}\right) = \frac{3}{2}p\frac{L_m}{\sigma L_s L_r}\mathrm{Im}\{\bar{\Psi}_r^{*}.\bar{\Psi}_s\} \tag{5}$$

The instantaneous apparent power representation under unbalanced operating conditions is given by:

$$\vec{S}(t) = P(t) + jQ(t) = \frac{3}{2}\{\bar{v}.\bar{i}^{*}\} \tag{6}$$

From the expression the active and reactive powers can be written as:

$$P(t) = \frac{3}{2}\mathrm{Re}\{\bar{v}.\bar{i}^{*}\} = \frac{3}{2}\left(v_\alpha i_\alpha + v_\beta i_\beta\right) \tag{7}$$

$$Q(t) = \frac{3}{2}\mathrm{Im}\{\bar{v}.\bar{i}^{*}\} = \frac{3}{2}\left(v_\beta i_\alpha - v_\alpha i_\beta\right) \tag{8}$$

The (7) and (8) are used to calculate the estimated values of active and reactive powers of the DFIG.

3. Control Strategy for Rotor Connected Converter

3.1. Stator Active Power Reference Generation

In this section, the Torque Oscillations Cancellation (TOC) scheme without the necessity of sequence calculations method is presented. This strategy is very simple in implementation and makes it possible to avoid T_{em} oscillations caused by grid fault.

Considering the general unbalance case, the stator and rotor flux space vector can be represented mathematically as [18]:

$$\bar{\Psi}_s = \psi_{\alpha s} + j\psi_{\beta s} = \hat{\Psi}_{\alpha s}\cos(\omega t + \delta) + j\hat{\Psi}_{\beta s}\sin(\omega t + \delta) \tag{9}$$

Similarly,

$$\bar{\Psi}_r = \psi_{\alpha r} + j\psi_{\beta r} = \hat{\Psi}_{\alpha r}\cos(\omega t) + j\hat{\Psi}_{\beta r}\sin(\omega t) \tag{10}$$

Substituting the above expressions in the expression of the torque (5), we obtain:

$$T_{em} = \frac{3}{4}p\frac{L_m}{\sigma L_s L_r}\left[\left(\hat{\Psi}_{\beta s}\hat{\Psi}_{\alpha r} + \hat{\Psi}_{\alpha s}\hat{\Psi}_{\beta r}\right)\sin\delta + \left(\hat{\Psi}_{\beta s}\hat{\Psi}_{\alpha r} - \hat{\Psi}_{\alpha s}\hat{\Psi}_{\beta r}\right)\sin(2\omega t + \delta)\right] \tag{11}$$

That can represented as:

$$T_{em} = K^{'}(\text{Constant Term} + \text{Oscillating Term with two times of frequency}) \tag{12}$$

Where $K^{'} = \frac{3}{4}p\frac{L_m}{\sigma L_s L_r}$

The above expression clearly shows that, during the unbalanced situation, the torque has one constant term and other an oscillating term, that is, the overall behavior is oscillating in nature. For normal operation of DFIM, the oscillating component of the torque should be zero that means it has to be compensated or cancelled by any means. This can be obtained with the following condition.

$$\hat{\Psi}_{\beta s}\hat{\Psi}_{\alpha r} - \hat{\Psi}_{\alpha s}\hat{\Psi}_{\beta r} = 0 \tag{13}$$

Which implies,

$$\hat{\psi}_{\beta s}\hat{\psi}_{\alpha r} = \hat{\psi}_{\alpha s}\hat{\psi}_{\beta r} \tag{14}$$

From that, we can write:

$$\frac{\hat{\psi}_{\alpha r}}{\hat{\psi}_{\beta r}} = \frac{\hat{\psi}_{\alpha s}}{\hat{\psi}_{\beta s}} \tag{15}$$

That is ratio of rotor and stator flux amplitudes to be maintained constant to make the torque constant with sinusoidal currents exchange with the grid. And this can be achieved by either direct or indirect way of rotor flux reference generation. Generation of rotor flux reference is explained as follows:

Similar to (5) and (11), the mechanical power and the stator active power can be represented respectively as:

$$P_{mech} = \frac{3}{2}\omega_m \frac{L_m}{\sigma L_s L_r} \mathrm{Im}\{\bar{\psi}_r^{*}.\bar{\psi}_s\}$$
$$\left[P_{mech} \cong \frac{\omega_m}{p} T_{em}\right] \tag{16}$$

$$P_{mech} = \frac{3}{4}\omega_m \frac{L_m}{\sigma L_s L_r}\left[\left(\hat{\psi}_{\beta s}\hat{\psi}_{\alpha r} + \hat{\psi}_{\alpha s}\hat{\psi}_{\beta r}\right)\sin\delta + \left(\hat{\psi}_{\beta s}\hat{\psi}_{\alpha r} - \hat{\psi}_{\alpha s}\hat{\psi}_{\beta r}\right)\sin(2\omega t + \delta)\right] \tag{17}$$

$$P_s = \frac{3}{2}\omega_s \frac{L_m}{\sigma L_s L_r} \mathrm{Im}\{\bar{\psi}_r^{*}.\bar{\psi}_s\} \tag{18}$$
$$\left[\text{Since } P_s \cong \frac{\omega_s}{p} T_{em}\right]$$

$$P_s = \frac{3}{4}\omega_s \frac{L_m}{\sigma L_s L_r}\left[\left(\hat{\psi}_{\beta s}\hat{\psi}_{\alpha r} + \hat{\psi}_{\alpha s}\hat{\psi}_{\beta r}\right)\sin\delta + \left(\hat{\psi}_{\beta s}\hat{\psi}_{\alpha r} - \hat{\psi}_{\alpha s}\hat{\psi}_{\beta r}\right)\sin(2\omega t + \delta)\right] \tag{19}$$

The above expressions (17) and (19) can be written as:

$$P_{mech} = K''\omega_m(\text{Constant Term} + \text{Oscillating Term with two times of frequency}) \tag{20}$$

Where $K'' = \frac{3}{4}\frac{L_m}{\sigma L_s L_r}$.

$$P_s = K'''\omega_s(\text{Constant Term} + \text{Oscillating Term with two times of frequency})$$
(21)

Where $K''' = \frac{3}{4}\frac{L_m}{\sigma L_s L_r}$.

From the equations (20) and (21), it can be clearly seen that, during unbalance situation, the mechanical power and stator active power are also oscillating, similar to the torque.

The simple control strategy applied to obtain constant torque with sinusoidal grid currents, without sequence calculations is subtracting the oscillating component obtained from torque (T_{em}, from the above expression (11)) from the estimated stator active power (P_s, we can notice in the above expression (21), i.e., oscillating term) and then adding it to the reference value ($P_{s\_required}$) to obtain the new reference value (P_{s_ref}).

As shown in Figure 2, the P_{s_ref} is generated by adding the $P_{s\_required}$ to the difference of oscillating term obtained from the electromagnetic torque and the estimated stator power. It is also described by the equation:

$$P_{s\_ref} = P_{s\_required} + \left(P_s - \frac{\omega_s}{p}T_{em}\right) \tag{22}$$

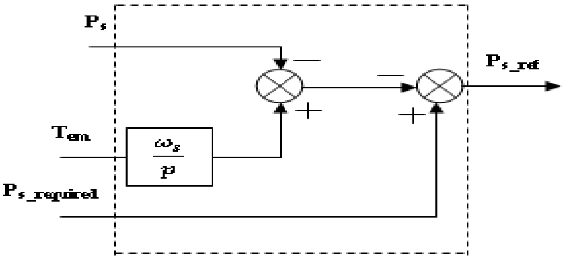


Figure 2. RSC active power reference generation

This new reference value obtained will be oscillating in nature, which indirectly creates the oscillatory rotor flux space vector amplitude that closely follows the oscillatory stator flux. Thus maintaining the torque, i.e., (5) constant, at any instant and even obtaining exchange of sinusoidal currents with the grid, that means, the oscillating term will be become zero, making the torque to be constant.

The advantage of this improved method is that there is no requirement of calculating the sequence components in order to avoid the T_{em} oscillations. Different methods to avoid the power and torque oscillations are presented in [18] including the Torque Oscillations Cancellation Without Sequence Calculation (TOC-WSC), which is the best strategy compared to the other strategies. The complex calculations required for estimating the sequence components is avoided by employing this strategy.

In this paper, the average wind speed is assumed as $12ms^{-1}$, at this average speed of the wind, the DFIG is assumed to be running at 1100rev/min. At this value of the wind speed the reference value of stator active and reactive power is taken as 0.17pu and 0.34pu respectively and reference grid-side reactive power is taken as -0.34pu. When the wind speed changes, the DFIG rotor speed also changes that means active and reactive powers will also change. The required pulses are generated and fed to the RSC and GSC from the three level active hysteresis comparators and two level reactive hysteresis comparators respectively as shown in Figure 1.

4. Control Strategy for Grid Connected Converter

4.1. Grid Connected Converter Analysis

As shown in Figure 1, the grid-side active and reactive power errors are fed to the DPC strategy in order to achieve the objective of the GSC, which is generally used to control the active (P_g) and reactive (Q_g) powers, which are exchanged through the grid connected converter to the grid and also to control the DC bus voltage (V_{bus}) oscillations. And not only that the GSC has to even address the unbalance caused in voltage due to the grid fault and but also the oscillations caused in the rotor active power supplied by the machine side converter to the DC voltage bus. Due to the grid fault as mentioned there will be unbalance in stator voltages, which produces active power oscillations in the DC bus. These DC-link voltage oscillations which are at two times the frequency of the grid are caused because of the oscillations produced in the currents flowing through the DC-link in between the GSC and RSC, which are actually produced because of the oscillations in active and reactive powers at both ac sides of the converter.

4.2. PI based Power References Generation Method

The grid-side active (P_{g_ref}) and reactive power (Q_{g_ref}) new reference values are obtained as shown in Figure 3. The grid-side active power compensating component (D_{g_P}) is obtained from the PI controller, which is fed by the difference of magnitude of reference and estimated three-phase stator voltage. D_{g_P} is added to the reference grid-side active power ($P_{g\_required}$) to get the new reference component, P_{g_ref}. $P_{g_required}$is obtained from DC bus voltage PI regulator, which is fed by the difference of the reference and estimated DC-link voltage.

Likewise, the grid-side reactive power compensating component (D_{g_Q}) is obtained from the PI controller, which is fed by the stationary two-axis reference frame α-component of current, Δi_α (not shown in Figure 3), obtained by applying Clarke's transformation to the difference of $i^*_{g\_abc}$ and i_{g_abc}. D_{g_Q} is added to the reference grid-side reactive power ($Q_{g\_required}$) to obtain the new reference Q_{g_ref} value. The gains of the PI controllers are obtained by using the auto-tunable PI controllers in MATLAB/Simulink, which is made possible by obtaining transfer function from the input and output data set. The data set for auto-tunable DC bus voltage PI controller is obtained by input (error value of DC link voltage) and output (reference grid-side active power).

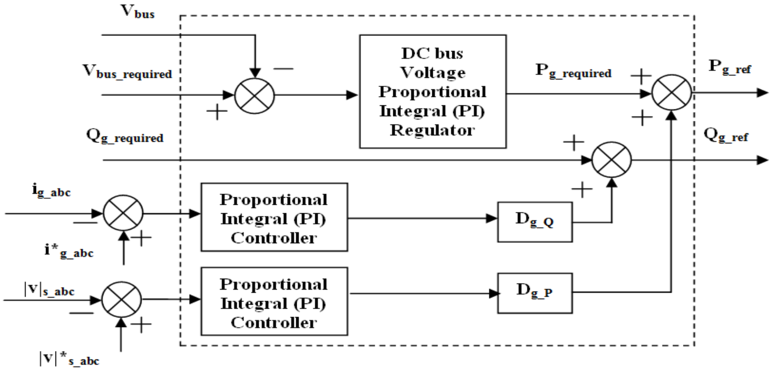


Figure 3. GSC active and reactive power reference generation

The compensating components D_{g_P} and D_{g_Q} are added to the $P_{g\_required}$ and $Q_{g\_required}$, so that the estimated values of grid-side active and reactive powers, P_g and Q_g are within the range of the new reference values, $P_{g_ref}$and Q_{g_ref}, and there are no additional oscillations in the P_g and Q_g; thus, inferring that the oscillating active and reactive powers exchanged through the rotor will address the unbalance voltage operating conditions and also exchange sinusoidal currents with the grid. These will propagate through the rotor as a function of slip speed i.e., indirectly depends on the mechanical speed of the DFIG.

$$\text{slip} = \frac{\omega_s - \omega_m}{\omega_s} \tag{23}$$

The expressions of D_{g_P} and D_{g_Q} from the Figure 3 can be written as,

$$\Delta v_s = |v|^*_{s\_abc} - |v|_{s\_abc} \tag{24}$$

$$D_{g\_P} = K_p \Delta v_s + K_i \int \Delta v_s \, dt \tag{25}$$

Likewise,

$$\Delta i_g = i^*_{g\_abc} - i_{g\_abc} \tag{26}$$

From the Clarke's Transformation,

$$\Delta i_\alpha = -\frac{1}{\sqrt{3}} \Delta i_{gb} - \frac{1}{\sqrt{3}} \Delta i_{gc} \tag{27}$$

$$\Delta i_\beta = \frac{2}{3} \Delta i_{ga} - \frac{1}{3} \Delta i_{gb} - \frac{1}{3} \Delta i_{gc} = \Delta i_{ga} \tag{28}$$

$$D_{g\_Q} = K_p \Delta i_\alpha + K_i \int \Delta i_\alpha \, dt \tag{29}$$

That is,

$$D_{g\_Q} = K_p\left(-\frac{1}{\sqrt{3}}\Delta i_{gb} - \frac{1}{\sqrt{3}}\Delta i_{gc}\right) + K_i \int \left(-\frac{1}{\sqrt{3}}\Delta i_{gb} - \frac{1}{\sqrt{3}}\Delta i_{gc}\right) dt \tag{30}$$

As mentioned the proposed GSC active and reactive power reference generation strategy is shown in Figure 3. The values of P_{g_ref} and Q_{g_ref} from the Figure 3 can be obtained as:

$$P_{g\_ref} = P_{g\_required} + D_{g\_P} \tag{31}$$

$$Q_{g\_ref} = Q_{g\_required} + D_{g\_Q} \tag{32}$$

During unbalance, there is requirement of increase in voltage at both the ac sides of the converters, because of this the DC bus voltage increases. As the active and reactive powers exchanged on both sides of the converters are oscillatory; hence, the DC bus voltage is also oscillatory because the amplitude of the oscillations of DC bus voltage depends on the active and reactive powers exchanged. In particularly the oscillations in DC bus voltage are due to oscillations in active power of the rotor. This can be shown mathematically as follows:

As we know that,

$$P_r \cong T_{em}\frac{\omega_r}{p} \tag{33}$$

where, $\omega_r = \omega_s - \omega_m$

Substituting the expression of the Torque (11), we get:

$$P_r = \frac{3}{4}\omega_r\frac{L_m}{\sigma L_s L_r}\left[\left(\hat{\Psi}_{\beta s}\hat{\Psi}_{\alpha r} + \hat{\Psi}_{\alpha s}\hat{\Psi}_{\beta r}\right)\sin\delta + \left(\hat{\Psi}_{\beta s}\hat{\Psi}_{\alpha r} - \hat{\Psi}_{\alpha s}\hat{\Psi}_{\beta r}\right)\sin(2\omega t + \delta)\right] \tag{34}$$

And also,

$$\langle P_g\rangle = \langle P_r\rangle + P_{converter} \tag{35}$$

That is, mean value of the grid-side active power is equal to the sum of mean value of the exchanged rotor active power and converters active power losses.

From the expressions (34) and (35), it clearly shows that during unbalance, the grid-side active power is also oscillating in nature.

As shown in Figure 3, the DC bus voltage PI regulator must be tuned for smooth dynamics (as the difference between the reference DC bus voltage and the unbalance affected DC bus voltage may produce additional oscillations), so that, it produces only the mean value of the grid-side active power as given by (35), that means, producing mean value of the rotor active power. Further, indicating that there are no additional oscillations in both the grid-side active power and rotor active power, which signifies that there is reduction in the oscillations of DC bus voltage. If the mean value is not generated, then the new reference value of grid-side active power produce oscillations which causes additional oscillations in the estimated grid-side active power and thus, in the rotor active power.

Another approach is to increase the DC bus voltage value, as its amplitude depends on the active and reactive powers exchanged on both sides of the converter. During unbalance, there is requirement of increase in voltage at both ac sides of converters, due to induced voltage oscillations. This fact increases the necessary DC bus voltage [18]. That means, if value of DC bus voltage is increased beforehand, as said above, then there is no requirement of much increase in voltage at both ac sides of converters. From this it can be deduced that the amplitude of the oscillations of active and reactive powers exchanged on both sides of the converter are reduced. Hence, the amplitude of the DC bus voltage oscillations is reduced. But still taking the necessary actions as described above, the DC bus voltage is not constant; there is slight variation, which is shown in results.

The unbalance voltage due to the unbalanced condition will produce unbalance grid voltage which is unfortunately almost equivalent to the unbalance created in the stator currents, which is clearly indicated in the results and discussion section. The proposed control strategy contributes to the elimination of mechanical torque oscillations as T_{em} oscillations are eliminated by which it is possible to avoid the necessity to disconnect the wind turbine from the grid supply whenever there is any unbalance in the system. The proposed method makes the unbalance voltage produced in the system to be less severe without completely avoiding the cause.

5. Results and Discussion

5.1. Simulation Results of Proposed Strategy

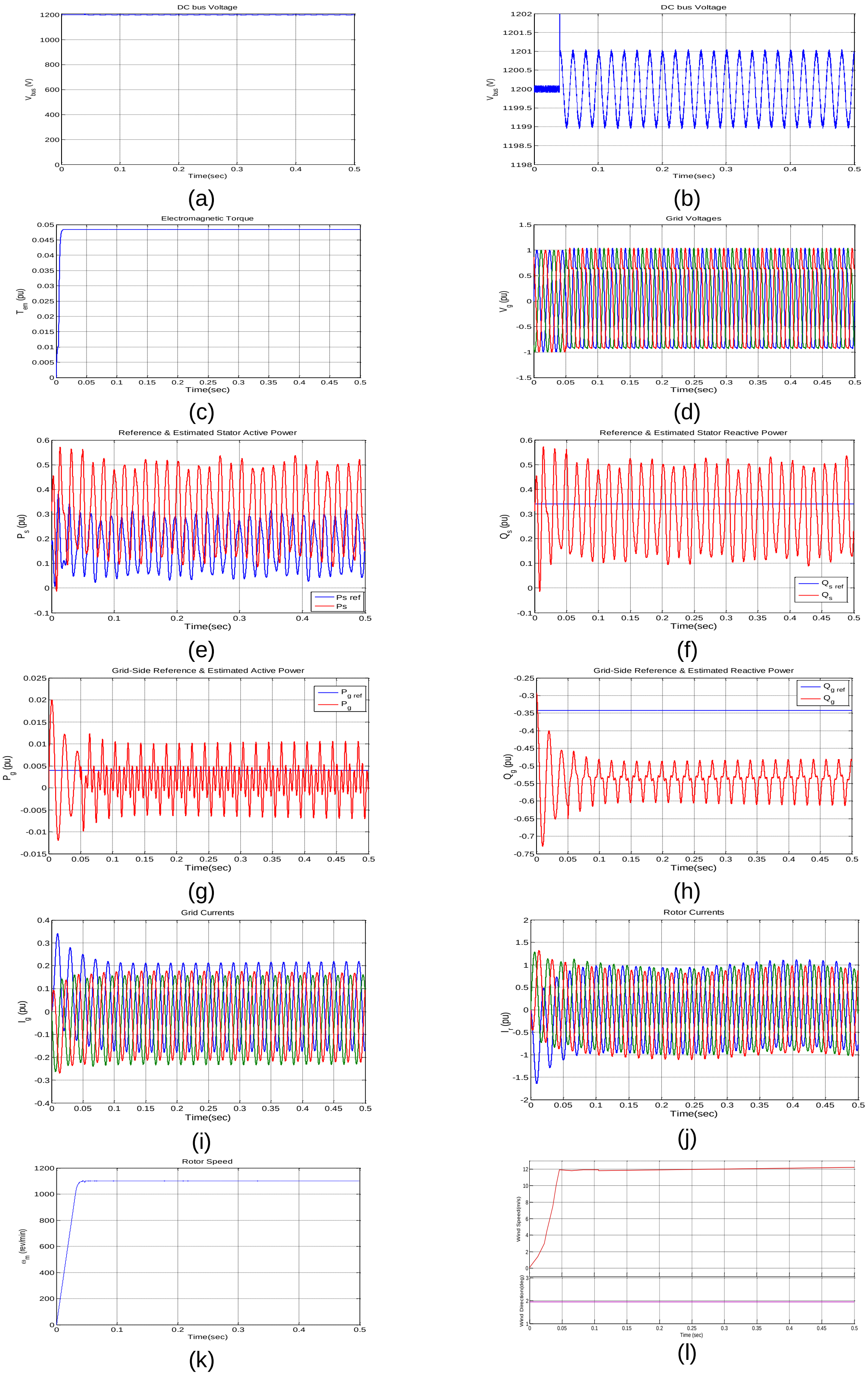
The performance of the proposed system is verified for the steady state operating condition along with grid voltage unbalance, which refers to operation of DFIG with $P_{s\_required}$ and $Q_{s\_required}$ values set to 0.17p.u. and 0.34p.u. respectively, as mentioned and $P_{g\_required}$ is as shown in Figure 3, while the $Q_{g\_required}$ value is set to -0.34p.u. at constant speed of 1100rev/min. The magnitudes of the RSC and GSC with cancellation of oscillations produced in electromagnetic scheme and grid-side power references generation are shown in Figure 4. The control strategy of TOC and the PI based P_{g_ref} and Q_{g_ref} generations are shown in Figure 2 and 3 respectively and these control strategies were discussed in previous section. The power tracking behavior of stator-side active and reactive powers for cancellation of oscillations in T_{em} and also the P_g and Q_g for cancellation of oscillations produces in DC-link voltage are shown in Figure 4(e)-(h) respectively.

A small unbalance can create large torque and active power oscillations. In this paper, 2.2% of line voltage unbalance factor (ratio of maximum stator voltage deviation from the average line voltage of stator to the average line voltage of stator) is taken into consideration as most of the wind farms are located remotely and therefore most of the times the wind farms are succumbed to the unbalance voltage conditions. Therefore, there is large deviation in stator and grid side active and reactive power estimated values with respect to reference values as shown in Figure 4(e), (f), (g), (h).

DC bus voltage waveform in the case of 1198-1202rpm is shown in Figure 4(b). Figure 4(a)-(c) clearly shows the outcomes of the proposed control strategy as it indicates that there is reduction in oscillations in the DC-link voltage and no oscillations are present in T_{em} respectively.

The unbalance load causes non-sinusoidal currents, which are actually reactive currents drawn from grid, these currents cause distortions in the grid voltage, which can be observed from the Fig. 4(d), the unbalanced load is applied at 0.05s.

Figure 4(i) and (j) shows the grid and rotor currents respectively, which are exchanged with the grid and rotor of the DFIG. Eventually, the unbalance caused in the system makes the grid and rotor currents to be unbalanced still they are sinusoidal in nature. Hence, clearly it can be said that sinusoidal currents are exchanged through the grid. The response of the rotor speed is shown in Figure 4(k) and the wind input taken for this simulation is shown in Figure 4(l). In the simulation results, the nonlinearities and losses of the DFIG are not considered.



(a) (b)

(c) (d)

(e) (f)

(g) (h)

(i) (j)

(k) (l)

Figure 4. Simulation results of steady state operation of the proposed system: (a) V_{DC}, (b) exploded view of V_{DC} (c) T_{em}, (d) grid voltage, (e) P_{s_ref} and estimated stator active power, (f) Q_{s_ref} and estimated stator reactive power, (g) P_{g_ref} and estimated grid-side active power, (h) Q_{g_ref} and estimated grid-side reactive power, (i) stator currents, (j) rotor currents, (k) rotor speed, and (l) wind speed

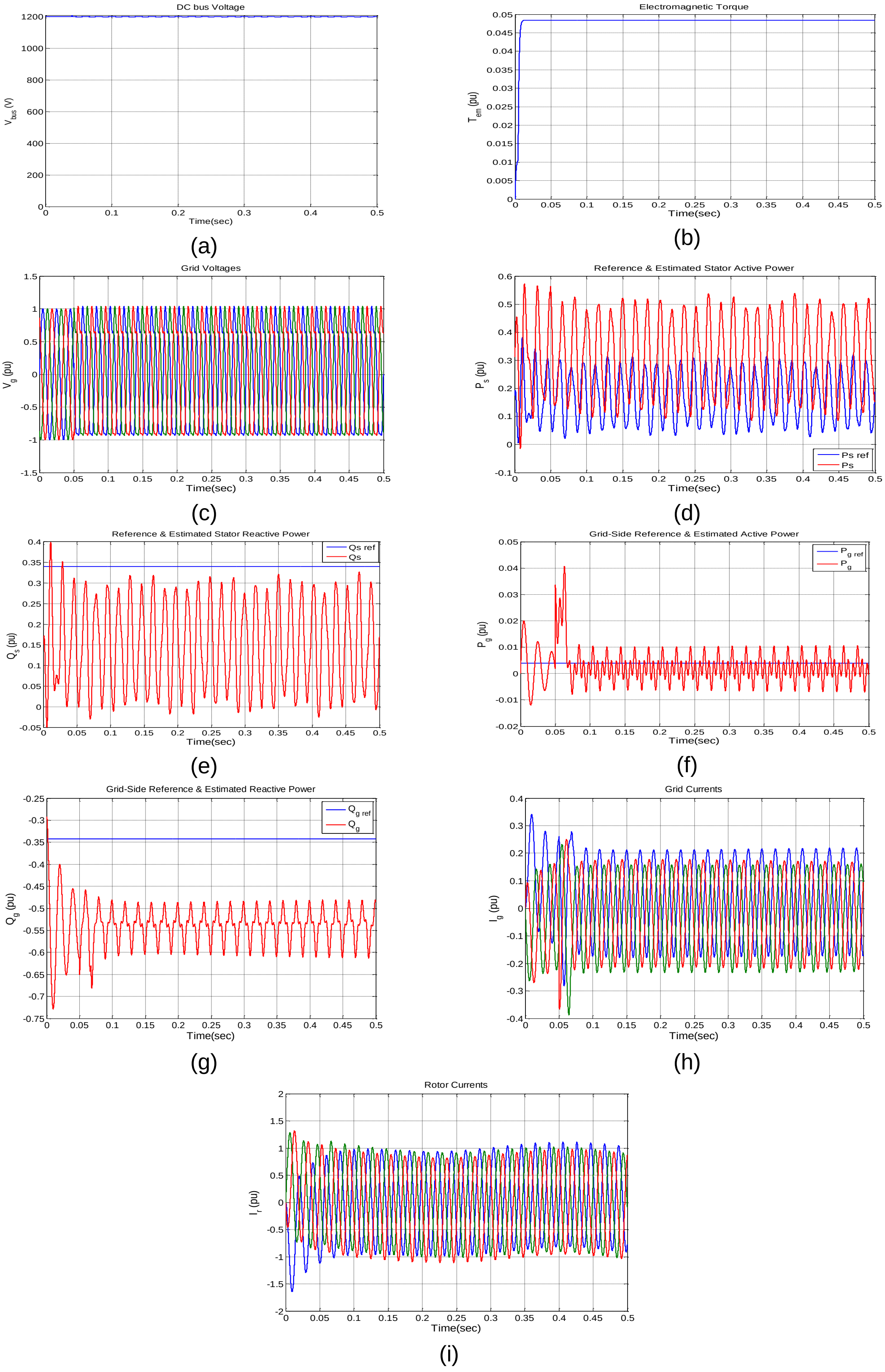


Figure 5. Simulation results of the proposed system with grid fault condition: (a) V_{DC}, (b) T_{em}, (c) grid voltage, (d) P_{s_ref} and estimated stator active power, (e) Q_{s_ref} and estimated stator reactive power, (f) P_{g_ref} and estimated grid-side active power, (g) Q_{g_ref} and estimated grid-side reactive power, (h) stator currents, and (i) rotor currents

In the next context, the performance of the system is analyzed for a three-phase grid fault with all the other parameters considered to be same as previous case. The results shown in Figure 5(a) and (b) describe the outputs of DC-link voltage and the Tem respectively, which are similar to the previous case. Figure 5(c) shows the output of the grid voltage, which clearly shows the deterioration and the unbalance nature of the grid voltage in particularly when the unbalance is created at 0.05s. The results clearly show that the oscillations are completely avoided with the help of the proposed control strategy. The stator and grid-side active and reactive power references and estimated values are shown in Figure 5(d) to (g). From the results, it is clearly indicated that the active and reactive powers of both stator and grid-side are deteriorated at the time of grid fault operation, which is applied for the duration of 0.006s i.e., from 0.05s to 0.056s. Because of this unbalance condition, the estimated values will not completely deviate, will be within the limits as shown in Figure 5(d) to (g) and still it will follow the reference values as close as possible once the unbalance condition is removed. The unbalance in the grid voltage will be reflected onto the stator and rotor currents and this can be seen clearly in Figure 5(h) and (i). The results of stator and rotor currents are little more unbalance in nature compared to the previous case and still the currents are sinusoidal. Hence the behavior of the DFIG is improved even during the grid fault operating condition with the help of the proposed system.

6. Conclusion

In this paper, addressing the problem of DFIG based wind turbines in case of network unbalance due to grid fault has been addressed. Under fault operating condition by implementing the DPC scheme to both rotor connected converter and grid connected converter with Torque Oscillations Cancellation strategy applied to RSC and PI control based generation of power references strategy along with elimination of DC bus voltage oscillations without voltage and current sequence component calculation applied to GSC, it has been shown that the electromagnetic torque oscillations are eliminated which leads to reduction in mechanical stresses and achieving sinusoidal current exchange with the grid hence achieving stable operation of the DFIG.

From the power and torque estimation calculation an oscillating stator active reference is generated by which it is possible to achieve the non-oscillating torque and ensure exchange of sinusoidal currents with grid, thus avoiding completely the sequence components calculation. The simulation results demonstrates that the difficulties of DFIG operation at the time of grid unbalance which can be easily avoided by implementation of proposed new DPC strategy for both rotor connected converter and grid connected converter.

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