A New DPC-based Control Algorithm for Improving the Power Quality of DFIG in Unbalance Grid Voltage Conditions

Ali Mirzakhani*, Reza Ghandehari*‡, S.Alireza Davari*

* Electrical Engineering, Shahid Rajaee Teacher Training University, Lavizan, Tehran, Iran

(Mirzakhani.ali@sru.ac.ir, r_ghandehari@sru.ac.ir, davari@sru.edu)

‡ Reza Ghandehari; Ali Mirzakhani, Lavizan, Tehran, Iran, Tel: +98 912 489 8756, Fax: +98 212 297 0006, r_ghandehari@sru.ac.ir

Received: 12.10.2018 Accepted:17.11.2018

Abstract- Conventional direct power control methods in unbalanced grid voltage conditions have undesirable effects on the performance and power quality of wind power plants based on DFIG. In this paper, a control algorithm based on direct power control for DFIG in unbalanced grid voltage conditions is presented with the aim of reducing the output power oscillations and current THD of back-to-back converters. For this purpose, the oscillatory component of DC link power in unbalanced condition at the grid voltage is identified from its fixed value and is added as a compensator to the reference value of input power of the hysteresis controller as part of the grid side converter controller. In addition to reducing the power oscillations of grid side convertor and its current THD, the proposed method decreases the current THD from DFIG and does not impose any additional oscillation in different parts of DFIG. The proposed control algorithm is simply implemented on conventional direct power control methods in unbalanced grid voltage conditions to improve its performance. Also, the results show that, using the proposed method, in addition to controlling the output power of DFIG and back-to-back converter, the output power oscillations and current THD of back-to-back converters are reduced simultaneously, and the output current become more sinusoidal.

Keywords Doubly fed induction generator, unbalance grid voltage, direct power control, active and reactive power oscillations, power quality.

Nomenclature

V_s, V_r	Stator, rotor voltage vectors	P_{s_m}, Q_{s_m}	Three-phase instantaneous active and reactive powers which exist on stator
I_s, I_r	Stator, rotor current vectors	s	Slip
P_g, Q_g	Grid active and reactive power		**superscripts**
P_r, P_e	Rotor and electromagnetic active power	+, -	Positive, negative reference frame
L_s, L_r	Stator, rotor self-inductance	*	Reference value for controller or mixed conjugate
L_m	Mutual inductance		**subscripts**
T_{em}	Electromagnetic torque	+, -	Positive, negative sequence component
R_s, R_r	Stator, rotor resistance	*d, q*	Synchronous d, q axis
ω_s, ω_r	Synchronous, rotor angular frequency	~	Oscillating term of variable
P_{s_r}, Q_{s_r}	Stator active and reactive power which operator want	*DC*	Constant term of power
P_{g_r}, Q_{g_r}	GSC active and reactive power which operator want	*abc*	abc reference frame
P_{gsc_m}, Q_{gsc}	Three-phase instantaneous active and reactive powers which exist on GSC		

1. Introduction

In recent years, doubly-fed induction generator (DFIG) wind power plants have been increasingly used. This type of generators can transmit about 30% of their nominal power from rotor to grid through connected back-to-back converters (see Fig.1). Accordingly, power losses and final price of converters are reduced significantly, compared to generators with converter in their stator circuit. Many wind turbines are installed in remote areas where there are multiple sources of voltage unbalancing; including heavy non-symmetric loads (single- phase loads), non-symmetric impedances of transmission lines and voltage dips.

If little voltage oscillations resulted from mentioned factors in a grid with DFIGs are not avoided, serious consequences may follow in electrical and mechanical parts of wind power plants, such as severe oscillation in active and reactive powers, torque oscillation in generator's shaft, high current in rotor, increased DC link voltage, harmonic stator current and turbine speed up [1]. These consequences can also affect generator's operation and result in increased temperature of windings, increased losses and considerable life loss of expensive power plant equipment [2-4].

Therefore, connection of this type of wind power plants with DFIG to grid, with no proper control, to eliminate destructive effects of unbalanced voltage, can result in their disconnection from the grid under such conditions [5]. While, according to the above criteria, around 2% voltage unbalancing in grid is permissible and grid systems are supposed to have a reasonable performance in such conditions [6].

To relieve the mentioned destructive effects mentioned above, an appropriate model is required to analyze DFIGs as well as their converters in unbalanced voltage conditions of grid [7-9]. Many studies focused on voltage unbalancing and performance of control systems based on different DFIG models in such conditions [10, 11].

In [12, 13], analyzing the components of positive and negative sequences of rotor current as well as negative sequence current control loop, various goals are pursued in unbalancing conditions based on vector control method, including the reduction of oscillations in torque and stator output power. One of the disadvantages of vector control method is the high sensitivity of control system to system parameters as well as the regulation of coefficients of its PI controllers [14, 15]. On the other hand, compared to vector control method, direct power control (DPC) for controlling back-to-back convertors in DFIGs has advantages that lead to more use of this method [16]. The advantages include rapid dynamic response, resistance to generator parameters and its system and their changes over time, and simple implementation [17, 18].

Several studies were conducted on improvement of DPC in unbalanced voltage conditions, including [19], in which, by decomposing positive and negative sequence components, the reduction of electromagnetic torque oscillations and the sinusoid stator current in DPC were considered separately. In [20], decomposing the positive and negative sequence components, Zandzadeh and Vahedi sought reduced oscillations of electromagnetic torque and stator output power. In [21], combining vector control and DPC, goals similar to previous references were achieved. In [22], the advantages of DPC and vector control were used simultaneously, but only DFIG outputs improved under different control strategies, and the performance of back-to-back convertors did not change.

In [23], resonance controller was used at main frequency and twice the grid frequency in control loop of DPC. For example, in [23], use of a current control loop based on PI controller, and resonance controller in rotor side converter controller is proposed. The experimental results of this study show the optimal performance of DFIG in unbalanced conditions at grid voltage. In this method, reference values of negative sequence current from components decomposition should be calculated continuously.

Reference [24] provides a PI controller based on current control loop with a single-side resonance controller for solving the problem of [23]. In the proposed method of this reference, power and torque are proposed as reference values for the resonance controller, which eliminates current balance strategy and improves the stator Current THD. Refrence [25] used the generalized theory of DPC, in which, in order to apply estimated reactive power to rotor side converter, a method was considered to reduce stator current oscillations for estimation of available reactive power of the system. By applying the method proposed by this reference, some oscillations are imposed on DFIG's reactive power, but there is no need to decompose positive and negative sequence components.

In [26, 27], slip mode control strategy in DPC, without decomposing it into positive and negative components, as well as zero-order DFIG model were applied. In this method, which is based on DPC, high current THD from back-to-back converters, as well as the distinction of each of control objectives, are clearly seen.

In [28-31], a dynamic review of grid side converter (GSC) was carried out to eliminate oscillating stator output power. In these references, modeling DFIG and back-to-back converters in synchronous reference frame, with negative sequence current injected through the controller of rotor-side convertor (RSC), the stator output power improved, but the oscillations of torque and back-to-back convertors did not changed.

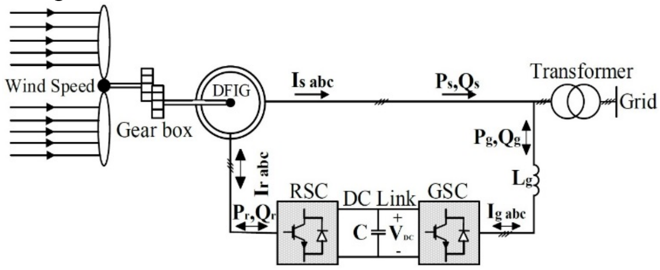

Fig. 1. DFIG with back-to-back converters

In all the references, the proposed control methods in unbalanced grid voltage were only able to improve power outputs and current from stator and electromagnetic torque as different control strategies. But when meeting any of the control objectives mentioned above, the power and current from back-to-back converters are in an unpleasant state including high output current THD and high power oscillation, and in each of these strategies, the oscillation level also varies.

In this paper, a method is presented for reducing the current THD from back-to-back converters, and the output power oscillation. The proposed method can be implemented on all control strategies. The proposed method contains less power oscillation and lower THD in the output current of back-to-back converters in all control strategies. The proposed method meets the above mentioned objectives as it does not impose new oscillations to converters or other parts of the system. Therefore, the proposed method is compared with the previous methods at unbalanced grid voltage, which confirms the effectiveness and efficiency of the proposed method.

In the proposed method, to obtain lower current THD and to reduce output power oscillation of back-to-back converters, the oscillations occurred in DC link voltage at unbalanced grid voltage for calculating the oscillation power in this part and compensating it through the controller of GSC is used. It is worth noting that the proposed method well responses in all control strategies with no additional oscillations imposed on the system.

2. Identifying and Calculating Power in Unbalanced Grid Voltage Conditions

In unbalanced grid voltage conditions, three-phase system is decomposed into three symmetric positive, negative and zero components. Given that machine terminals usually have a Y/Δ connection with no ground transformer, zero component can be ignored. In order to calculate the constant and oscillating power in the two-phase environment according to [2] and [10]:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} P_{DC} \\ Q_{DC} \end{bmatrix} + \begin{bmatrix} P_{1\sim} + P_{2\sim} \\ Q_{1\sim} + Q_{2\sim} \end{bmatrix} \tag{1}$$

Where Q_{DC} and P_{DC} are constant terms of active and reactive powers, $P_{1\sim}$ and $P_{2\sim}$ are oscillating components of active power in unbalanced grid voltage conditions and $Q_{2\sim}$ and $Q_{1\sim}$ are oscillated components of reactive power in such conditions. Equation (1) is explained as:

$$\begin{cases} P_{DC} = \frac{3}{2}\left(V_{d+}^{+}I_{d+}^{+} + V_{q+}^{+}I_{q+}^{+} + V_{d-}^{-}I_{d-}^{-} + V_{q-}^{-}I_{q-}^{-}\right) \\ P_{1\sim} = \frac{3}{2}\begin{bmatrix} V_{d\sim}^{+} & V_{q\sim}^{+} \end{bmatrix} \begin{bmatrix} I_{d+}^{+} \\ I_{q+}^{+} \end{bmatrix} \\ P_{2\sim} = \frac{3}{2}\begin{bmatrix} V_{d+}^{+} & V_{q+}^{+} \end{bmatrix} \begin{bmatrix} I_{d\sim}^{+} \\ I_{q\sim}^{+} \end{bmatrix} \end{cases} \tag{2}$$

$$\begin{cases} Q_{DC} = \frac{3}{2}\left(V_{q+}^{+}I_{d+}^{+} - V_{d+}^{+}I_{q+}^{+} + V_{q-}^{-}I_{d-}^{-} + V_{d-}^{-}I_{q-}^{-}\right) \\ Q_{1\sim} = \frac{3}{2}\begin{bmatrix} V_{q\sim}^{+} & V_{d\sim}^{+} \end{bmatrix} \begin{bmatrix} I_{d+}^{+} \\ I_{q+}^{+} \end{bmatrix} \\ Q_{2\sim} = \frac{3}{2}\begin{bmatrix} V_{q+}^{+} & V_{d+}^{+} \end{bmatrix} \begin{bmatrix} I_{d\sim}^{+} \\ I_{q\sim}^{+} \end{bmatrix} \end{cases} \tag{3}$$

where, in (2) and (3), V_{dq+}^{+} ،I_{dq+}^{+} ،I_{dq-}^{-} ،V_{dq-}^{-} are constant values and $I_{dq\sim}^{+}$ ،$V_{dq\sim}^{+}$ are oscillating values which oscillate in voltage unbalancing conditions with frequency of $2\omega_s$. The above equations display a power model in non-symmetric grid voltage conditions and this unbalancing results in oscillation components with twice as much as the synchronous frequency in active, reactive and current in grid.

3. DPC Method in Balanced Condition

In the proposed method, DPC method is divided into two parts. In the first part, power reference values are produced to meet each control strategy, displayed in Fig. 1. Following relations are observed in balanced condition:

$$\begin{bmatrix} P_s^* \\ Q_s^* \end{bmatrix} = \begin{bmatrix} P_{s\_r} \\ Q_{s\_r} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} P_g^* \\ Q_g^* \end{bmatrix} = \begin{bmatrix} P_{g\_r} \\ Q_{g\_r} \end{bmatrix} \tag{5}$$

where P_s^* and Q_s^* are stator power references as RSC references and P_g^* and Q_g^* are rotor power references as GSC references. The second part is the most commonly used technique for direct control of active and reactive powers of stator, displayed in Fig. 2.

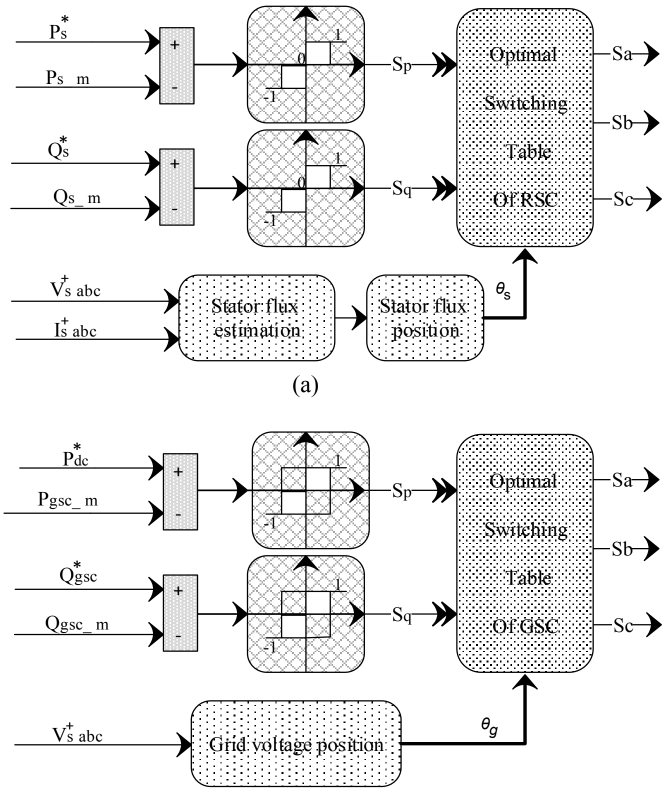

Fig. 2. DPC strategy for: (a) RSC, (b) GSC

The active and reactive powers of stator are first determined by wind and then according to demand. Two hysteresis controllers are responsible for specifying Sp and Sq. Regarding Sp and Sq values and the position of stator flux, using optimal switching table, appropriate voltage vector for rotor circuit is selected. Similarly, the same process is used to determine optimal voltage vector of GSC, with the difference that reference power is determined by DC link voltage.

4. Modeling and Studying DFIG's Behavior in Unbalanced Grid Voltage Conditions

To model and study DFIG's behavior in unbalanced grid voltage conditions, equations and models are investigated first for doubly fed induction machine (DFIM) and then for GSCs and RSCs.

4.1. Modeling DFIM in Unbalanced Grid Voltage Conditions

Figure (3) displays DFIM's model in synchronous reference frame [32] according to which, basic equations in positive frame can be written as follows [2]:

$$V_s^+ = R_s I_s^+ + \frac{d\Psi_s}{dt} + j\omega_s \Psi_s^+ \quad (6)$$

$$V_r^+ = R_r I_r^+ + \frac{d\Psi_r}{dt} + j(\omega_s - \omega_r)\Psi_s^+ \quad (7)$$

$$\begin{bmatrix} \Psi_s^+ \\ \Psi_r^+ \end{bmatrix} = \begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix} \begin{bmatrix} I_s^+ \\ I_r^+ \end{bmatrix} \quad (8)$$

With unbalanced grid voltage and following unbalanced stator voltage (according to Fig. 1, DFIG's stator is connected directly to grid), oscillation components in power equations, mentioned in (1), are included in machine equations, as follows:

$$\begin{bmatrix} P_s \\ Q_s \end{bmatrix} = \begin{bmatrix} P_{s\,DC} \\ Q_{sDC} \end{bmatrix} + \begin{bmatrix} P_{s1\sim} + P_{s2\sim} \\ Q_{s1\sim} + Q_{s2\sim} \end{bmatrix} \quad (9)$$

Where P_s and Q_s, respectively, are active and reactive powers from stator, each of which contains a constant and oscillating terms in unbalanced grid voltage condition.

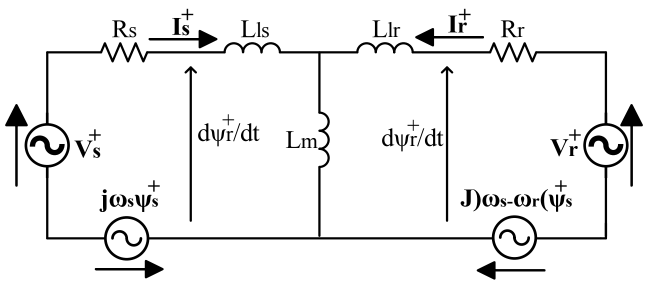

Fig. 3. Equivalent circuit of DFIG in synchronous reference frame

Given the unbalanced grid voltage, positive and negative sequence range is proved to be constant [33], therefore according to [2, 5- 6] electromagnetic torque is:

$$T_{em} = \frac{P}{\omega_s}(P_{TDC} - P_{s1\sim} + P_{s2\sim}) = \frac{P_e}{\omega_s} \quad (10)$$

Therefore, in unbalanced grid voltage condition, the electromagnetic torque will also contain constant and oscillating terms.

4.2. Investigating GSC and RSC Model and Behaviour

Due to the fact that RSC controls rotor circuit and therefore stator output of DFIG, GSC is also responsible for stabilizing DC link voltage and output power from converters. Hence, it is very important to determine constant and oscillating components of back to back converters in order to meet control strategies. Equations for stator power are similar for converters, as is displayed in Fig. 4:

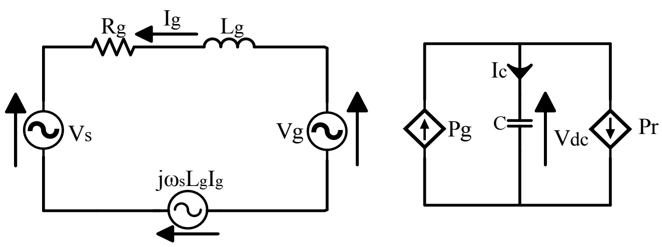

Fig. 4. Equivalent circuit for converters to analyze power

$$P_g = P_{gDC} + P_{g1\sim} + P_{g2\sim} + P_{gDC} + P_{g\sim} \quad (11)$$

According to power direction (11) and Fig. 1, rotor power can be calculated through following equation:

$$P_r = P_e - P_s = \left((1-s)P_{TDC} - P_{SDC}\right) - (2-s)P_{s1\sim} - sP_{s2} = P_{rDC} + P_{r\sim} \qquad (12)$$

To calculate GSC output power, regarding Fig. 4. Following equation is obtained:

$$C\frac{dV_{dc}}{dt}.V_{dc} = P_{DC} = P_g - P_r = \left(P_{gDC} - P_{rDC}\right) + \left(P_{g\sim} + P_{r\sim}\right) \qquad (13)$$

Therefore, in unbalanced grid voltage condition, DC link oscillations are proportional to $P_{r\sim}$ ‘ $P_{g\sim}$, each of which will be twice as much as the frequency of grid, according to (1),(2) and (3). So, in such condition, DC link contains an offset value equal to reference value of GSC voltage in DPC method and an oscillating value with a frequency twice as much as grid frequency. Therefore, following oscillation powers are presented for the oscillating term of capacitor in DC link:

$$P_{c\sim}^{+}(t) = V_{c\sim}^{+}(t).I_{c\sim}^{+}(t) = V_c^{+}\cos(2\omega_s t).I_c^{+}\cos\left(2\omega_s t - \frac{\pi}{2}\right) = \frac{V_c^{+}I_c^{+}}{2}\sin(2\omega_s t)$$
(14)

$$Q_{c\sim} = -\frac{V_{c\sim}^{+}I_{c\sim}^{+}}{2} \qquad (15)$$

5. Control Strategies in Unbalanced Grid Voltage Condition

The main objective of this section is to design different control strategies to eliminate the oscillations of different parts of DFIG and back-to-back converters, as well as to improve the output power of wind power plants through the proposed method and to select correct power reference values at the input of grid side and rotor side controllers.

5.1. Proposed Method to Reducing the Output Power Oscillations

According to (11), (13), (14) and (15) in grid voltage unbalancing with oscillated DC link power, the output power of GSC is oscillated and its current also has many harmonics that can change the sinusoid current, with each of the oscillations listed, changing corresponding to each control strategy (mentioned in this section).

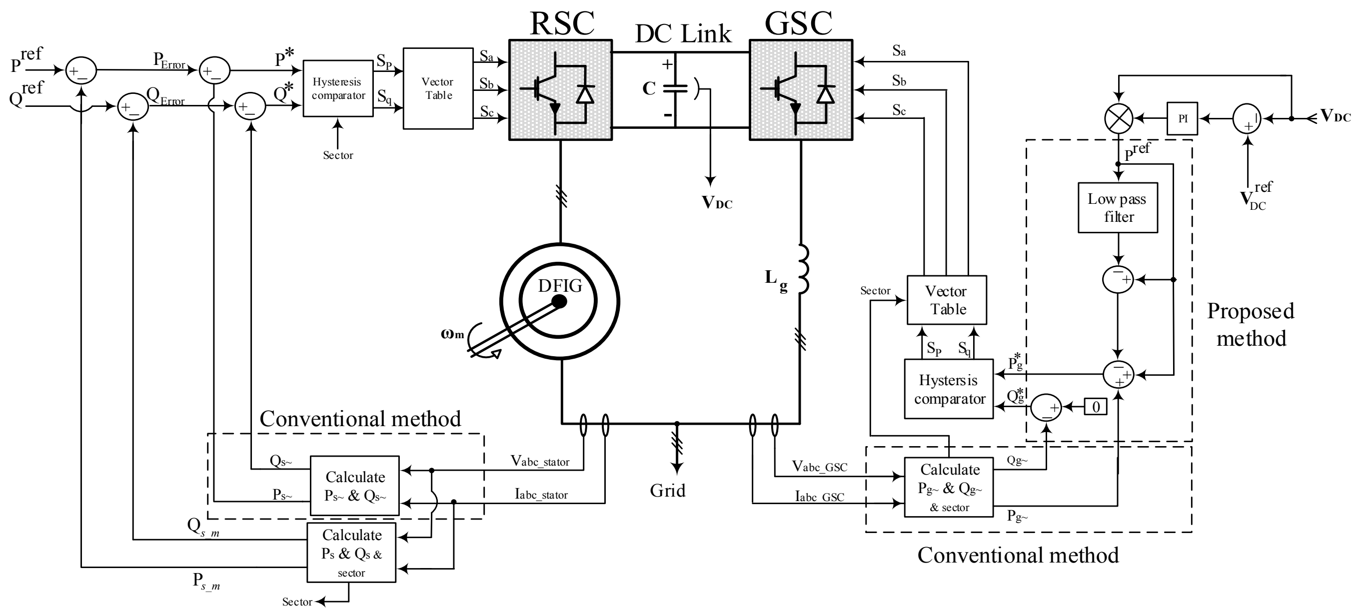

Fig. 5. Scheme diagram of proposed method

In order to improve the performance of GSC in grid voltage unbalancing, in conventional methods in [2, 5], DC link power oscillation components are calculated using DC link oscillation components obtained from (13) and (14), and are calculated as equation (15) of the oscillation components of DC link power and added to the reference value of power in DC link controller. To calculate the oscillating power of DC link, the technique displayed in block diagram of Fig. 5 is used. Also Fig. 6 show conventional DPC method in unbalance grid voltage.

$$\begin{bmatrix} P_{gsc}^{*} \\ Q_{gsc}^{*} \end{bmatrix} = \begin{bmatrix} P_{Dc} \\ Q_{GSC\_r} \end{bmatrix} + \begin{bmatrix} P_{c\sim}^{+} \\ Q_{c\sim}^{+} \end{bmatrix} + \begin{bmatrix} P_{gsc\sim}^{+} \\ Q_{gsc\sim}^{+} \end{bmatrix}$$
(16)

In order to mitigate the GSC voltage output power oscillation and reduce resulted current THD, oscillatory power compensator is used which is displayed in the block diagram of Fig. 5 The proposed method for removing power oscillations and reducing current THD of GSC does not require the use of oscillatory components decomposition and, using a low-pass filter, set on $2\omega_s$, directly calculates DC link oscillatory power and compensates for the DC power through input reference.

Figure 5 reports on the method for calculating the DC link oscillator power and its compensator. The proposed method does not undergo any change when meeting other control goals and it is very effective in reducing the THD of output current of GSC and its power oscillations. The proposed method was implemented in all of the control strategies mentioned in this section on GSC controller and its results were compared with conventional method in [2].

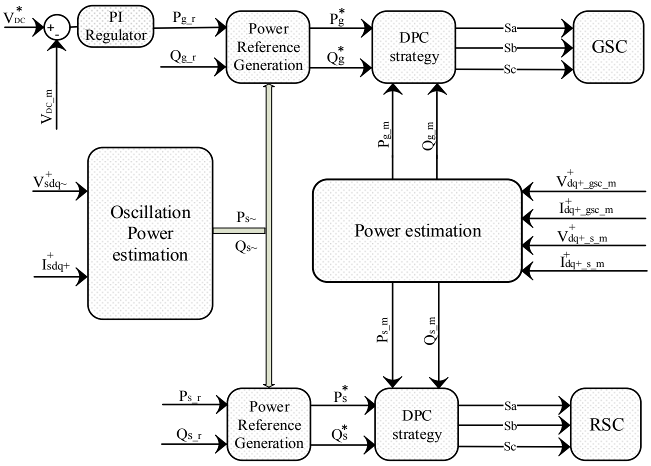

Fig. 6. DPC method in [2] on unbalance grid voltage block diagram

5.2. Elimination of Active and Reactive Powers of Stator

In (9), $P_{s1\sim}$ and $P_{s2\sim}$ should be removed to eliminate the oscillations of active power and $Q_{s1\sim}$ and $Q_{s2\sim}$ should be limited to eliminate the oscillations of reactive power. Changing power references, the strategy is implemented as followed:

$$\begin{bmatrix} P_s^* \\ Q_s^* \end{bmatrix} = \begin{bmatrix} P_{s\_r} \\ Q_{s\_r} \end{bmatrix} = \begin{bmatrix} P_{sDC} \\ Q_{sDC} \end{bmatrix}$$
(17)

$$\begin{bmatrix} P_{1s\sim} \\ Q_{1s\sim} \end{bmatrix} + \begin{bmatrix} P_{2s\sim} \\ Q_{2s\sim} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$
(18)

It should be noted that, due to dependency on both positive and negative sequence of stator current, there is no possibility for $P_{1s\sim}$ and $P_{2s\sim}$ as well as $Q_{1s\sim}$and $Q_{2s\sim}$ to be simultaneously zero. According to (17), (18) and (10) as well as the relations mentioned above, electromagnetic torque is described using following equation:

$$T_{em} = \frac{p}{\omega_s}(P_{TDC} - 2P_{s1\sim}) = \frac{p}{\omega_s}(P_{TDC} + 2P_{s2\sim})$$
(19)

Accordingly, the electromagnetic torque is oscillated twice as much as synchronous frequency to stabilize the output power of stator.

5.3. Balanced Stator Current

For a balanced stator current, negative sequence component should be eliminated from stator current. Therefore, as negative sequence components in form of *dq* positive reference, $I_{sd\sim}^{+}$ and $I_{sq\sim}^{+}$ should be zero. Accordingly, based on (9), $P_{1s\sim}$ and $Q_{1s\sim}$ are the only oscillation terms for active and reactive output powers of stator. Therefore, for a balanced stator current, power references are defined as follows:

$$\begin{bmatrix} P_s^* \\ Q_s^* \end{bmatrix} = \begin{bmatrix} P_{s\_r} \\ Q_{s\_r} \end{bmatrix} + \begin{bmatrix} P_{s1\sim} \\ Q_{s1\sim} \end{bmatrix}$$
(20)

It should be noted that, according to (9) and (10), constant terms for active and reactive powers of stator form with positive sequence of current as well as the stator voltage with no negative sequence. In such case, while $P_{s2\sim}$ is zero, the electromagnetic torque oscillates and following equation is obtained:

$$T_{em} = \frac{p}{\omega_s}(P_{TDC} - P_{s1\sim})$$
(21)

5.4. The strategy to eliminate electromagnetic torque oscillation

As was mentioned earlier, $P_{1s\sim}$ and $P_{2s\sim}$ are never simultaneously zero, therefore, according to (10), following is the only way to stabilize electromagnetic torque:

$$P_{1s\sim} = P_{2s\sim}$$
(22)

Which is obtained as follows, regarding stator power:

$$P_s^* = P_{s\_required} + 2P_{1s\sim}$$
(23)

Therefore, in such conditions, the electromagnetic torque remains constant but stator power including oscillation $2P_{1s\sim}$ and stator current will be non-sinusoidal.

6. Simulation Results

The control method proposed here was investigated in MATLAB simulation environment. The nominal power of DFIG is 2 MW and its various parameters are reported in table.1 hysteresis controller with a bandwidth of 4% nominal power was used in the stabilizations conducted in RSC and GSC. The applied method was the DPC based on optimal switching table in unbalanced voltage conditions with various control strategies such as eliminating the output power oscillations resulted from the GSC and reducing the current THD from it, elimination of electromagnetic torque oscillations, elimination of oscillations in output powers of stator, stator current balancing and elimination of oscillations in output and input power of GSC.

In this simulation, the rotor speed was considered 1.2 per unit. The first strategy was to have constant active and reactive powers of stator and minimize its torque oscillations at t=0.5-0.6s. The second strategy was to balance stator and rotor current and reduce its THD so that sinusoidal current was obtained. The objective was achieved within t=0.6-0.7s. The third strategy was to limit electromagnetic torque, achieved within t=0.7-0.8s. Reduced DC link oscillations and active power of GSC and eliminated reactive power oscillations of GSC in all control strategies were achieved within t=0.5-0.8s, by GSC controller.

Figure 7 shows the power from GSC in all control purposes by applying the proposed method. As is clear, the amplitude of power oscillations in all strategies is significantly lower than usual, and the overall amplitude of the oscillations is proportional to $2\omega_s$. According to Fig. 7, the range of power oscillations in the proposed method is constant for all control strategies, that is about 100 kW, but in conventional methods [2, 14, 16], it is about 300 kW. In different control strategies, the range of oscillations changed.

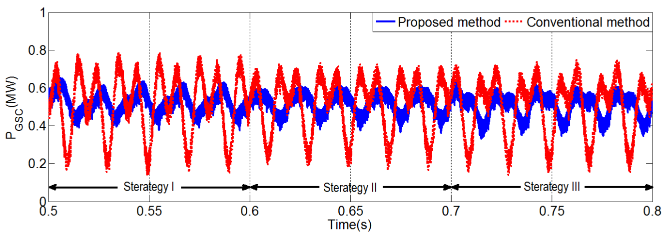

Fig. 7. Active power of the GSC with the proposed and conventional method in all control strategies

Also, with fixed wind speed of 1.2 pu, the power received from grid side converter is about 30% of nominal power of the stator, which should be about 600 kW, given the 2 MW nominal power of the studied generator. As shown in Fig. 7, the DC of the power received from GSC is about 600 kW. With regard to selected zero reference value for reactive power in the controller of grid-side convertor, the DC of received reactive power is fixed to zero without any osillations, according to Fig.8.

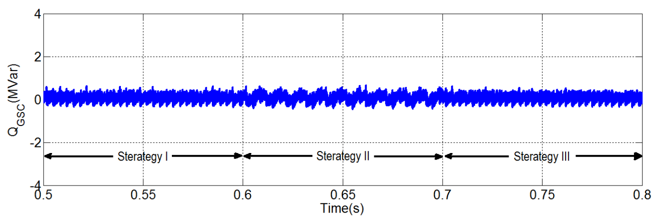

Fig. 8. Shows the reactive power generated by GSC.

The proposed method did not impose any additional oscillations on the converter in any of the control strategies compared with methods in [2, 14, 16]. Figures (9) and (10) represent the current of GSC. As shown in Fig. 9, at unbalanced voltage, in all control strategies, the current is no longer sinusoidal and this results in a high harmonic contamination.

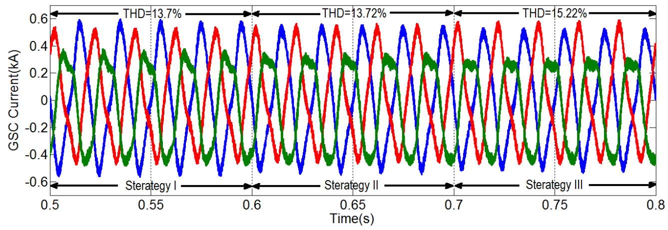

Fig.9. GSC current before proposed method in all control strategies

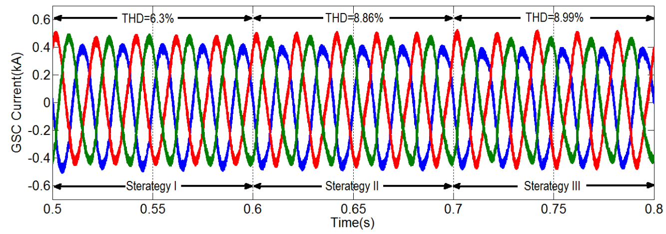

Fig. 10. GSC current after proposed method in all control strategies

Therefore, due to constant unbalanced level in grid voltage, the power oscillations observed in Fig. 7, influence the current, remove its sinusoidal form and place a wide range of harmonics. Figure (10) illustrates the sinusoidal current and a dramatic reduction of harmonic contamination in all control strategies in the proposed method.The sinusoidal current in Fig. 10 shows the effective and successful deletion of oscillatory components of negative sequence in the proposed method. As the quality of the output current of GSC in the proposed method improves, the total amount of current injected to the grid (total current of stator and back-to-back converters,Fig. 1) has less THD, which is shown in Figures 11 and 12.

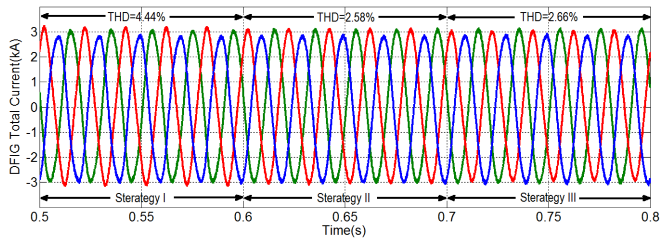

Fig. 11. DFIG and back to back converter total current before proposed method in all control strategy

Due to the reduction of current THD of GSC in the proposed method, in all control strategies, the total current injected into the grid by DFIG and back-to-back converters has a lower THD. It is worth noting, however, that total current THD from GSC and DFIG in different control strategies varies greatly depending on the stator current.

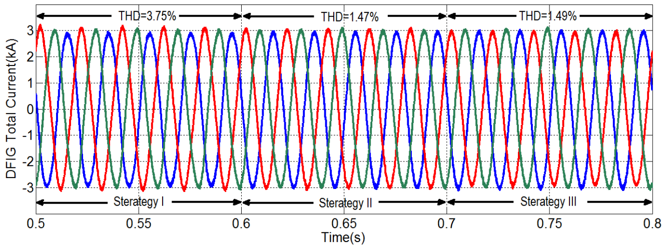

Fig. 12. DFIG and back to back converter total current after proposed method in all control strategy

Considering the fact that the injected current of stator is greater than the total back-to-back converters, the effect size of total output current THD will definitely depend on the state of control strategies. For example, in the second strategy, where the goal is to reduce the THD from the stator and to sinusoidize it, the total current generated by DFIG and back-to-back convertors is very close to sinusoid form and its THD drops sharply.

Figure (13) show the harmonic range of GSC current before and after the proposed method. As is seen, with the proposed method, third harmonic of the current in all control strategies reduced considerably, which resulted in reduced and sinusoid current THD from 14.21% to 8.26%.

The reduction of harmonic currents, especially the third harmonic, is the result of limiting the power oscillations with the frequency of $2\omega_s$ in GSC in the proposed method (see Fig. 5), through which the input negative sequence currents are limited as much as possible.

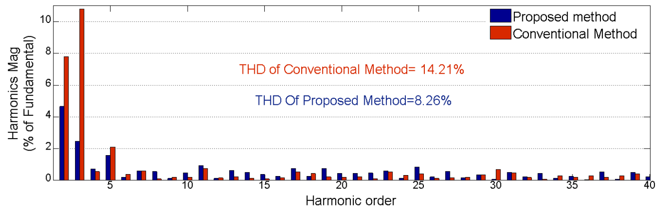

Fig. 13. GSC current harmonic spectrum before\after proposed method in all control strategy

Reduction of GSC current harmonics in all control strategies, as well as the stator current balance strategies, reduces the current THD from DFIG and back-to-back converters (the current from wind power plant, Fig. 14). Figure 14 show the harmonic range of total current from DFIG and back-to-back convertors in the second strategy, i.e. stator current balance. When the stator current is balanced, adding the oscillatory components P_{s1} and Q_{s1}, the active and reactive power from stator are oscillated, but the oscillations of stator current and, consequently, the THD resulted from it, drop from 4.07% to 2.08%, following the limited input negative sequences of stator current.

As is seen in Fig. 15, when the controller is set on the first strategy, active and reactive powers had no oscillations. However, the electromagnetic torque oscillated at 100Hz and the stator current was non-sinusoidal.

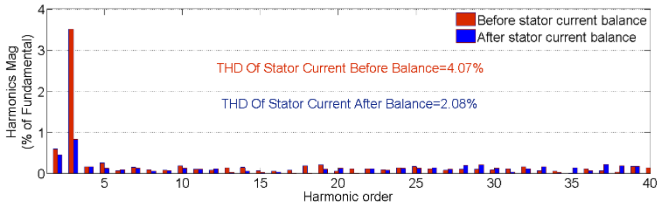

Fig. 14. Total current harmonic spectrum from DFIG and back-to-back converters before\after stator balanced current

It is worth noting that in the conventional DPC method, based on switching table, reference power of stator was constant and the generator produced constant power. Therefore, DFIG behavior with typical DPC would be similar. The currents induced into rotor by positive and negative sequence flux had slip frequencies of $f_s - f_r$ and$f_s + f_r$, respectively. f_s and f_r are synchronous and rotor frequencies, respectively. As is seen in Fig. 16, the three-phase rotor currents had positive and negative oscillation components of $(60 - 50{=})10$Hz and $(60 + 50{=})$ 110Hz, respectively.

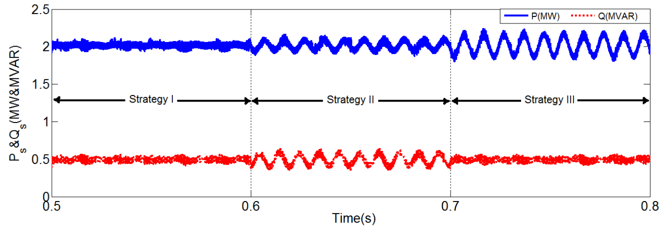

Fig. 15. Output active and reactive powers of stator in various control strategies

When the controller is set on the second strategy, active and reactive powers will oscillate in order to add $P_{s1\sim}$ and $Q_{s1\sim}$ to the reference value. However, the stator current is balanced and harmonic pollution of rotor current is minimized. According to Fig. 17, applying the second strategy to balanced stator current within 0.6 to 0.7 seconds, the stator current was sinusoidal and as a result, THD current (Fig. 18) declined from 4.27%, before control strategies (Fig. 18), to 1.97%, with the proposed method. Neglecting magnetization current, it can be said that $N_s I_s = N_r I_r$ where N_s and N_r are the number of stator and rotor winding.

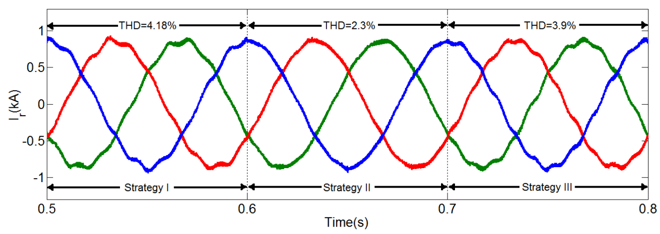

Fig. 16. Rotor current in various control strategies

Therefore, rotor current is proportional to stator current. So, it is concluded that, limiting negative sequence component of stator current, negative sequence current of rotor (higher harmonic order) is eliminated and the wave form is milder.

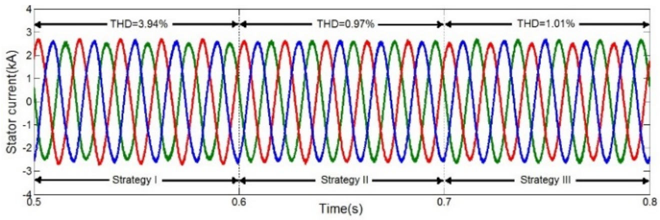

Fig. 17. Stator current in various control strategies

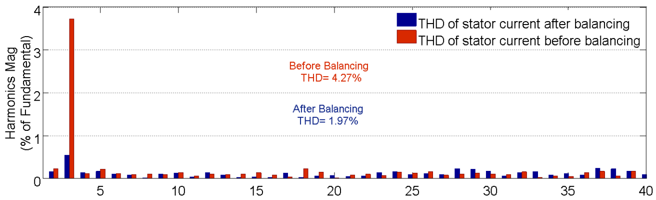

Fig.18. Stator current harmonic spectrum after\before balancing

Table 1. Generator parameters used in simulation

DFIG parameters	Rated power	2MW
	Stator voltage	690V
	Stator/rotor turn ratio	0.3
	R_s	0.0108pu
	R_r	0.0121pu
	L_m	3.362pu
	L_{ls}	0.102pu
	L_{lr}	0.11pu
	H	0.5s
	Pole pair. No	2
AC/DC/AC parameters	DC link voltage	1200V
	DC link capacitor	16mF
	GSC inductance	0.4mH

In such conditions, the electromagnetic torque oscillations decrease but not eliminated. At t= 0.7, the controller is set on the third goal and the electromagnetic torque is stabilized soon, however; 100Hz oscillation frequency is added to active and reactive powers with $2P_{s1\sim}$ added to the reference power values (Fig. 19).

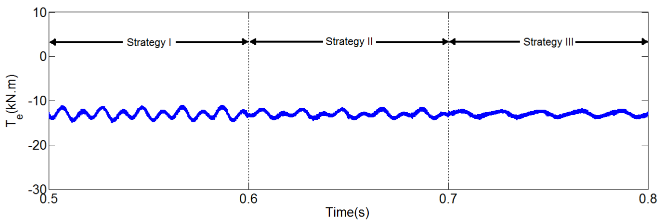

Fig. 19. Electromagnetic torque in various control strategies

Figures 20 and 21 show the stator flux before and after all control strategies are applied to GSC and RSC where, as is shown, deviation from flux references (1 per unit) decreased considerably after control strategies were applied.

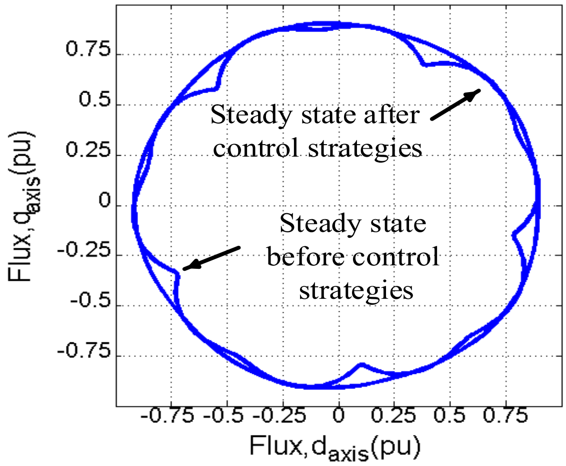

Fig. 20. Stator flux in dq axes in various control strategies

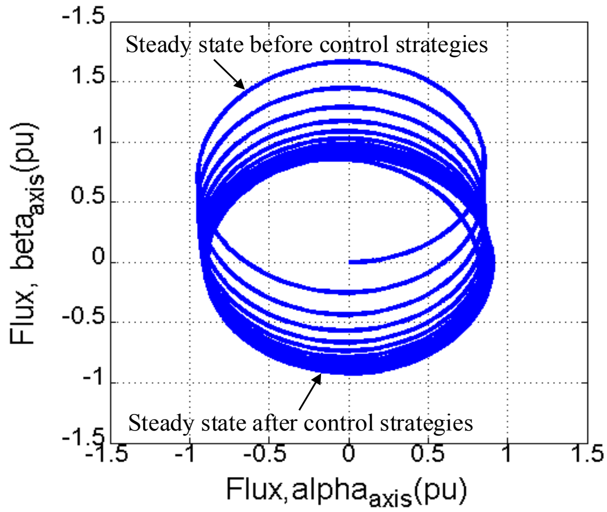

Fig. 21. Stator flux in desired perpendicular axes in various control strategies

Regarding Figures 20 and 21, in constant conditions, if there is no effective control on DFIG controllers, with gradual increase in the flux from voltage and frequency, the oscillations will be instable twice the grid frequency of DFIG, causing the shutdown of generator. Applying the proposed method, the steady-state stabilization of DFIG and back-to-back converters results in the stabilization of the ratio of voltage to frequency (proportional to the flux ratio in electric machines), which indicates the stable performance of machine in unbalanced conditions at grid voltage.

7. Conclusion

In this paper, a method was proposed for improving the performance of DFIG based on DPC method. In the proposed method, the DC link oscillator power in GSC controller was first estimated using the technique presented and then added to the reference power in the GSC controller as a compensator. The proposed method had a satisfactory performance in the remaining control strategies and its performance was analyzed with conventional methods in unbalanced grid voltage. The results show that the proposed method in all control strategies is able to reduce the output power oscillation of GSC and also reduce the current THD. The proposed method does not require the decomposition of the components. Also, eliminating the output power oscillation and improving the current THD in GSC, our proposed method does not impose any additional oscillations on other parts of the system. RSC was also used to eliminate the oscillations of electromagnetic torque as well as output powers of stator and balance stator current in unbalanced grid voltage conditions. The improved method enables the control system to operate in various parts of the system in unbalanced conditions and allows simultaneous elimination or reduction of oscillations in different parts of DFIG by controlling GSC or RSC, as a result of which, the functionality of DFIG in unbalanced grid voltage conditions increases considerably. According to the proposed method, with reduced torque oscillations and harmonic pollutions of stator current, the quality of output power of wind power plants with DFIG as well as lifetime of equipment of power plants, converters and DC link increased considerably as a result of reduced oscillations of connected parts.

References

[1] Z.S. Zhang, Y.Z. Sun, J. Lin, G. J. Li, "Coordinated frequency regulation by doubly fed induction generator-based wind power plants", IET Renew. Power Generation, Vol. 6, No. 1, pp. 38–47, 2012.

[2] M.J. Zandzadeh, A. Vahedi, "Modelling and improvement of direct power control of DFIG under unbalance grid voltage condition", international journal of electrical power and energy systems, Vol. 59, pp. 58-68, Jan 2014.

[3] H. Tiegna, Y.Amara, G.Barakat, B. Dakyo, "Overview of high power wind turbine generators", Renewable Energy Research and Applications (ICRERA), 2012 International Conference, pp. 1-6, Nov 2012.

[4] S. Cunningham, A. Nasiri, "Control and implementation of back to back grid converters utilizing IEEE 519", Renewable Energy Research and Applications (ICRERA), 2017 International Conference, Nov 2017.

[5] A. Petersson , "Analysis, Modelling and Control of Doubly-Fed Induction Generators for Wind Turbines", PhD thesis, Division of Electric Power Engineering ,Department of Energy and Environment Chalmers university of technology, G¨oteborg, Sweden 2005.

[6] G. Michalke, "Variable Speed Wind Turbines, Modelling, Control, and Impact on Power Systems", PhD thesis, Department of Renewable Energies at Darmstadt Technical University (Germany), 2008.

[7] S. Choudhury, "Performance Analysis of Doubly-fed Induction Generator in Wind Energy Conversion System", A Thesis of Master of Technology in Electrical Engineering (Power Control & Drives), June National institute of technology Rourkela, 2011.

[8] A.D. Hansen, L.H. Hasen, "Market Penetration of Wind turbine concepts over the years,‖ European Wind Energy, EWEA, vol. 10, pp. 81-97, 2007.

[9] S. Ozdemir, U. Selamogullari, O. Elma, "Analyzing the effect of inverter efficiency improvement in wind turbine systems", Renewable Energy Research and Applications (ICRERA), 2014 International Conference, pp. 572-575, Oct 2014.

[10] M. Tazil, V. Kumar, R.C. Bansal, S. Kong, Z.Y. Dong, W. Freitas, H.D. Mathur, "Three-phase doubly fed induction generators: an overview", IET Electric Power, Vol. 4, no. 2, pp. 75–89, 2010.

[11] Y. Komatsu and T. Kawabata, "A control method of active power filter where system voltage contains negative-phase-sequence component or zero-phase-sequence component" in Proc. International Power Electronics and Drive Systems Conf, pp. 583–586, 1995.

[12] J. Hu, Y. He, L. Xu, W.Williams, "Improved control of DFIG systems during network unbalance using PI-R current regulators", IEEE Transactions on Industrial Electronics, Vol.56, No. 2, pp. 439-451, Feb 2009.

[13] J. Hu, H. Xu, Y. He, "Coordinated control of DFIG's RSC and GSC under generalized unbalance and distorted grid voltage conditions", IEEE Transactions on Industrial Electronics, Vol. 60, Issue. 7, pp. 2808-2819, July 2013.

[14] O. B. k. Hasnaou, M. Allagui, J. Belhad, "PMSG Gear-Less Wind Turbine Equipped with an Active and Reactive Power supervisory", International Journal of Renewable Energy Research, Vol. 4, No.2, 2014.

[15] M. Quraan, Q. Farhat, M. Bornat, ""A new control scheme of back-to-back converter for wind energy technology", Renewable Energy Research and Applications (ICRERA), 2017 IEEE 6th International Conference, pp. 354-358, Nov 2017.

[16] E. Shehata, "Direct power control of wind-turbine-driven DFIG during transient grid voltage unbalance", Journal of Wind Energy, Vol. 17, Issue. 7, pp. 1077-1091, July 2014.

[17] M.N. Amrani, A. Dib, "Predictive Direct Power Control of a Grid Connected Three-Phase Voltage Source Inverter for Photovoltaic Systems", International Journal of Renewable Energy Research, Vol. 6, No.1, 2016.

[18] L. Quéval, H. Ohsaki, "Back-to-back converter design and control for synchronous generator-based wind turbines", Renewable Energy Research and Applications (ICRERA), 2012 International Conference, pp. 1-6, Nov 2012.

[19] H. Nian, Y. Song, "Direct power control of doubly fed induction generator under distorted grid voltage", IEEE Transactions on Power Electronics, Vol. 29, Issue. 2, pp. 894-905, Feb 2014.

[20] P.R. Martinez-Rodriguez, G. Escobar, A.A. Valdez-Fernandez, M. Hernandez-Gomez, J.M Sosa, " Direct power control of a three-phase rectifier based on positive sequence detection", IEEE Transactions on Industrial Electronics, Vol. 61, Issue. 8, pp. 4084-4092, August 2014.

[21] J. Mohammadi, S. Vaez-Zadeh, S. Afsharnia, E. Daryabeigi, "A combined vector and direct power control for DFIG-based wind turbines", IEEE Transaction on Sustainable Energy, Vol. 5,Issue. 3, pp. 767-775, July 2014.

[22] X.Wang, D.Sun, Z.Zhu, "Resonant-Based Backstepping Direct Power Control Strategy for DFIG under both Balanced and Unbalanced Grid Conditions", IEEE Transactions on Industry Applications, Vol. 53, Issue. 5, pp. 4821-4830, Step 2017.

[23] Y. Wang, Q.Wu, W.Gong, M.P.S. Gryning, "H_∞ Robust Current Control for DFIG-Based Wind Turbine Subject to Grid Voltage Distortions", IEEE Sustainable Energy, Vol. 8, Issue. 2, pp. 816-825, April 2017.

[24] D. Sun, X. Wang, "Sliding-mode DPC using SOGI for DFIG under unbalanced grid condition", Electronics Letters, Vol. 53, Issue. 10, pp. 674-676, April 2017.

[25] Y. Zhang, C. Qu, "Table-based direct power control for three-phase AC/DC converters under unbalanced grid voltages", IEEE Transactions on Power Electronics, Vol. 30, Issue. 12, pp. 7090-7099, Dec 2015.

[26] C. Liu, F. Blaabjerg, W. Chen, "Stator Current Harmonic Control with Resonant Controller for Doubly Fed Induction Generator", IEEE transactions on power electronics, vol. 27, no. 7, pp. 3207-3220 , July 2011.

[27] J. Lopez, E. Gubia, P. Sanchis, X. Roboam, and L. Marroyo, "Wind turbines based on doubly fed induction generator under asymmetrical voltage dips", IEEE Trans. Energy Convers, vol. 23, no. 1, pp. 321–330, Mar 2008.

[28] M. Kiani and W.-J. Lee, "Effects of voltage unbalance and system harmonics on the performance of doubly fed induction wind generators", IEEE Trans. Ind. Appl., vol. 46, no. 2, pp. 562–568, Mar/Apr 2010.

[29] L. Fan, S. Yuvarajan, and R. Kavasseri, "Harmonics analysis of a DFIG for a wind energy conversion system", IEEE Trans. Energy Convers, vol.25, no. 1, pp. 181–190, Mar 2010.

[30] J. Hu, H. Nian, H. Xu, and Y. He, "Dynamic modelling and improved control of DFIG under distorted grid voltage conditions", IEEE Trans. Energy Convers, vol. 26, no. 1, pp. 163–175, Mar 2011.

[31] M. Liserre, R. Teodorescu, and F. Blaabjerg, "Multiple harmonics control for three-phase grid converter systems with the use of PI-RES current controller in a rotating frame", IEEE Trans. Power Electron., vol. 21, no. 3, pp. 836–841, May 2006.

[32] E. Okedu, M. Muyeen, "Wind Farms Fault Ride Through Using DFIG With New Protection Scheme Kenneth", IEEE transactions on sustainable energy, vol. 3, no. 2, pp. 242 -254 April 2012.

[33] Y. Suh, T. A. Lipo, "Modelling and analysis of instantaneous active and reactive powers for pwm ac/dc converter under generalized unbalanced network", IEEE Trans. Power Del., vol. 21, no. 3, pp. 1530– 1540, 2006.