A Novel Method to Reduce Power Oscillations of DFIG in Unbalance Grid Voltage Conditions

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Abstract— **Double-Feed Induction Generators (DFIG) are one of the most commonly used generators in wind power plants. Therefore, studying this type of generators in different grid conditions such as unbalanced grid voltage is of great importance. In this paper, DFIGs, in synchronous reference frame, and back-to-back convertors are reviewed and modeled. The advantage of this model, compared to previous ones, is that it can be used in unbalanced grid voltage conditions. Hence, different parts of generator in synchronous positive reference frame are studied and governing equations in such conditions are analyzed. Stator output power, rotor side convertors (RSC), grid side convertors (GSC) and electromagnetic torque, mentioned in the model, are analyzed, as well. The model is also applied in balanced conditions. Therefore, the model proposed in this paper is perfect for analyzing wind turbine-based power plants with DFIGs. The accuracy of suggested function was confirmed through simulation.**

Keywords—unbalanced grid voltage, double fed induction generator, oscillations, modeling.

1. Introduction

In recent years, DFIG-based 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 convertors (see Fig.1). Accordingly, power losses and final price of convertors are reduced significantly, compared to generators with convertor 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]. 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 [3]. While, according to the above criteria, around 2% voltage unbalancing in grid is permissible and grid systems are supposed to have a reasonable function in such conditions [4-6]. To relieve the mentioned destructive effects mentioned above, an appropriate model is required to analyze DFIGs as well as their convertors in unbalanced voltage conditions of grid. Many studies focused on voltage unbalancing and function of control systems based on different DFIG models in such conditions [7-8]. Decomposing positive and negative sequences of rotor current components as well as current control loop of negative sequence and studying rotor side converter (RSC) model, [9-10] focused on reduced torque oscillation in such conditions. In [11-12], resonance controllers in grid side converter (GSC) and their model were applied to control positive and negative sequences of current, without decomposing it into positive and negative components that reduced computations. In [13-14], slip mode control strategy in direct power control (DPC) method, without decomposing it into positive and negative components, as well as zero-order DFIG model were applied. In [15-18], a dynamic review of GSC was carried out to eliminate oscillating stator output power.

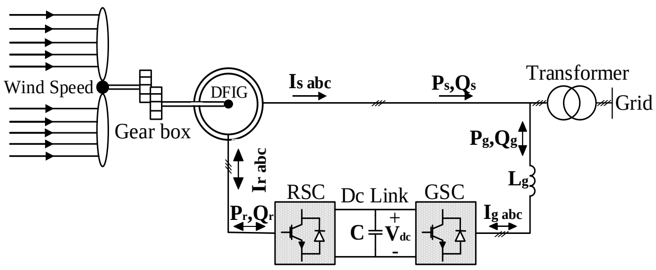

Fig. 1. *DFIG with back-to-back convertors*

In all references, various control strategies have been investigated, mainly on RSC, and effective control has been made to eliminate or reduce the oscillations of the power from GSC to grid. In this article, a method is proposed to improve DFIG control and back to back convertors during unbalanced grid voltage which functions based on DPC method. Positive sequence decomposition, DFIG model and back to back convertors in synchronous reference frame were used in the proposed method and each GSC and RSC was controlled in such a way that they eliminated or minimized system oscillations. To this end, several different control strategies, such as sinusoidal or balanced stator current, stabilization of active and reactive powers from stator, and elimination of electromagnetic torque oscillations, have been investigated. It should be noted that the distinction between the proposed method and previous methods is the changes in control structure and use of DC link oscillations to eliminate oscillations of output power of GSC. In each of the control strategies, DC link oscillations decreased, compared with common methods, as a result of which, active power oscillations declined and output reactive power of GSC was eliminated completely.

2. 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:

$$\begin{bmatrix} P_s^* \\ Q_s^* \end{bmatrix} = \begin{bmatrix} P_{s\_required} \\ Q_{s\_required} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} P_g^* \\ Q_g^* \end{bmatrix} = \begin{bmatrix} P_{g\_required} \\ Q_{g\_required} \end{bmatrix} \tag{2}$$

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. 3.

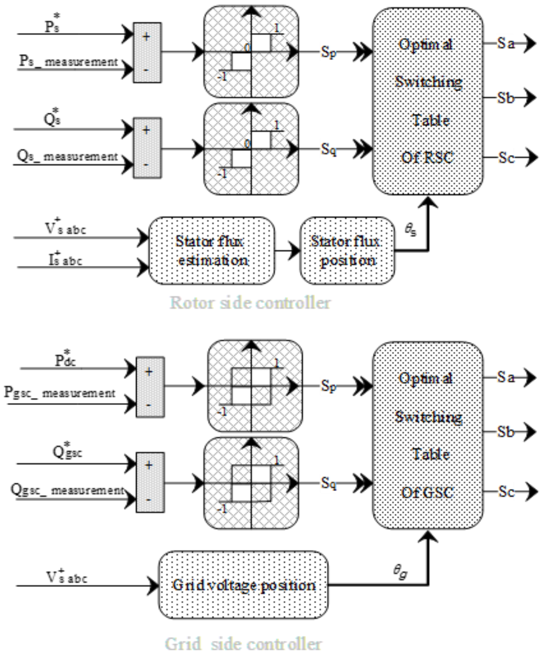

***Fig. 2.** DPC strategy for GSC and RSC*

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.

3. 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. Accordingly, calculating positive and negative sequences to find oscillation components serves enough. If **f** is the function (**f** can be voltage, current, flux or any desired quantity), then in double-phase $\beta\alpha$ we'll have:

$$f_{\alpha\beta}(t) = f_{\alpha\beta+}(t) + f_{\alpha\beta-}(t) = |f_{\alpha\beta+}(t)|e^{j(\omega_s+\phi_+)} + |f_{\alpha\beta-}(t)|e^{-j(\omega_s+\phi_-)} \tag{3}$$

Where + and – are positive and negative sequences, ω_s is the speed of synchronous reference frame and ϕ is initial phase. Fig. 3 displays 2-phase frame $\beta\alpha$ in dq^+ و dq^- frames.

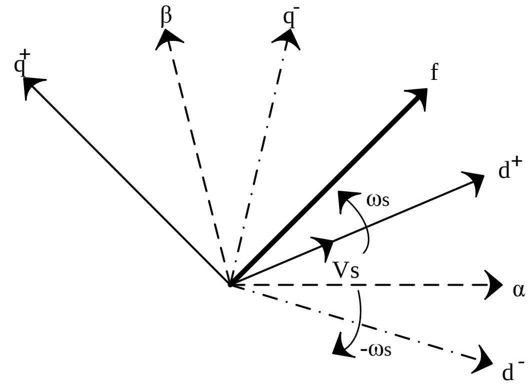

***Fig. 3.** Sample vector in positive and negative frames*

According to Fig. 3, following equations are obtained:

$$f_{dq}^+ = f_{dq}^- e^{-j2\omega_s t} \tag{4}$$

$$f_{dq}^- = f_{dq}^+ e^{j2\omega_s t} \tag{5}$$

According to (4) and (5) and Fig. 3, following equation is obtained:

$$f_{dq}^+ = f_{dq+}^+ + f_{dq-}^+ = f_{dq+}^+ + f_{dq-}^- e^{-j2\omega_s t} \tag{6}$$

As is seen, the oscillation term is in negative frame and negative sequence and its oscillation frequency is twice as much as the synchronous frequency. Therefore, expounding (6), we'll have:

$$\begin{bmatrix} f_d^+ \\ f_q^+ \end{bmatrix} = \begin{bmatrix} f_{d+}^+ \\ f_{q+}^+ \end{bmatrix} + \begin{bmatrix} f_{d\sim}^+ \\ f_{q\sim}^+ \end{bmatrix} \tag{7}$$

where

$$\begin{bmatrix} f_{d\sim}^+ \\ f_{q\sim}^+ \end{bmatrix} = \begin{bmatrix} f_{d-}^- & f_{q-}^- \\ f_{q-}^- & -f_{d-}^- \end{bmatrix} \begin{bmatrix} cos2\omega_s t \\ sin2\omega_s t \end{bmatrix} \tag{8}$$

Also, to calculate power in 2-phase environment, we'll have:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \frac{3}{2} \begin{bmatrix} V_d^+ & V_q^+ \\ V_q^+ & -V_d^+ \end{bmatrix} \begin{bmatrix} I_d^+ \\ I_q^+ \end{bmatrix} \tag{9}$$

Now, according to (7) and (8) and calculated power from (9), we'll have:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_{d+}^+ + V_{d\sim}^+ & V_{q+}^+ + V_{q\sim}^+ \\ V_{q+}^+ + V_{q\sim}^+ & -V_{d+}^+ - V_{d\sim}^+ \end{bmatrix} \begin{bmatrix} I_{d+}^+ + I_{d\sim}^+ \\ I_{q+}^+ + I_{q\sim}^+ \end{bmatrix} \tag{10}$$

To simplify (10), it is proved that:

$$V_{d\sim}^+ I_{d\sim}^+ + V_{q\sim}^+ I_{q\sim}^+ = \left(V_{d-}^- cos2\omega_s t + V_{q-}^- sin2\omega_s t\right)\left(I_{d-}^- cos2\omega_s t + I_{q-}^- sin2\omega_s t\right) + \left(V_{q-}^- cos2\omega_s t - V_{d-}^- sin2\omega_s t\right)\left(I_{q-}^- cos2\omega_s t - I_{d-}^- sin2\omega_s t\right) = V_{d-}^- I_{d-}^- cos^2 2\omega_s t + V_{d-}^- I_{q-}^- cos2\omega_s t + sin2\omega_s t - V_{q-}^- I_{d-}^- cos2\omega_s t\, sin2\omega_s t + V_{q-}^- I_{q-}^- sin^2 2\omega_s t + V_{q-}^- I_{q-}^- cos^2 2\omega_s t + V_{q-}^- I_{d-}^- cos2\omega_s t\, sin2\omega_s t - V_{d-}^- I_{q-}^- cos2\omega_s t\, sin2\omega_s t + V_{d-}^- I_{d-}^- sin^2 2\omega_s t = V_{d-}^- I_{d-}^- + V_{q-}^- I_{q-}^- \tag{11}$$

As a similar proof:

$$V_{q\sim}^+ I_{d\sim}^+ - V_{d\sim}^+ I_{q\sim}^+ = V_{q-}^- I_{d-}^- - V_{d-}^- I_{q-}^- \tag{12}$$

Therefore, equations for active and reactive powers are obtained as follows:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} P_{DC} \\ Q_{DC} \end{bmatrix} + \begin{bmatrix} P_{1\sim} + P_{2\sim} \\ Q_{1\sim} + Q_{2\sim} \end{bmatrix} \tag{13}$$

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. (13) is explained as:

$$P_{DC} = \frac{3}{2}\left(V_{d+}^{+} I_{d+}^{+} + V_{q+}^{+} I_{q+}^{+} + V_{d-}^{-} I_{d-}^{-} + V_{q-}^{-} I_{q-}^{-}\right)$$

$$P_{1\sim} = \frac{3}{2}\begin{bmatrix} V_{d\sim}^{+} & V_{q\sim}^{+} \end{bmatrix} \begin{bmatrix} I_{d+}^{+} \\ I_{q+}^{+} \end{bmatrix} \tag{14}$$

$$P_{2\sim} = \frac{3}{2}\begin{bmatrix} V_{d+}^{+} & V_{q+}^{+} \end{bmatrix} \begin{bmatrix} I_{d\sim}^{+} \\ I_{q\sim}^{+} \end{bmatrix}$$

$$Q_{DC} = \frac{3}{2}\left(V_{q+}^{+} I_{d+}^{+} - V_{d+}^{+} I_{q+}^{+} + V_{q-}^{-} I_{d-}^{-} + V_{d-}^{-} I_{q-}^{-}\right)$$

$$Q_{1\sim} = \frac{3}{2}\begin{bmatrix} V_{q\sim}^{+} & V_{d\sim}^{+} \end{bmatrix} \begin{bmatrix} I_{d+}^{+} \\ I_{q+}^{+} \end{bmatrix} \tag{15}$$

$$Q_{2\sim} = \frac{3}{2}\begin{bmatrix} V_{q+}^{+} & V_{d+}^{+} \end{bmatrix} \begin{bmatrix} I_{d\sim}^{+} \\ I_{q\sim}^{+} \end{bmatrix}$$

where, in (14) and (15), 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.

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 double-feed induction machine (DFIM) and then for GSCs and RSCs.

4.1 *Modeling DFIM in unbalanced grid voltage conditions*

Fig. 4 displays DFIM's model in synchronous reference frame [19] according to which, basic equations in positive frame can be written as follows:

$$V_s^{+} = R_s I_s^{+} + \frac{d\Psi_s}{dt} + j\omega_s \Psi_s^{+} \tag{16}$$

$$V_r^{+} = R_r I_r^{+} + \frac{d\Psi_r}{dt} + j(\omega_s - \omega_r)\Psi_s^{+} \tag{17}$$

$$\begin{bmatrix} \Psi_s^{+} \\ \Psi_r^{+} \end{bmatrix} = \begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix} \begin{bmatrix} I_s^{+} \\ I_r^{+} \end{bmatrix} \tag{18}$$

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 (13), are included in machine equations, as follows:

$$\begin{bmatrix} P_s \\ Q_s \end{bmatrix} = \begin{bmatrix} P_{s\,DC} \\ Q_{sDC} \end{bmatrix} + \begin{bmatrix} P_{s1\sim} + P_{s2\sim} \\ Q_{s1\sim} + Q_{s2\sim} \end{bmatrix} \tag{19}$$

Where in (19), 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.

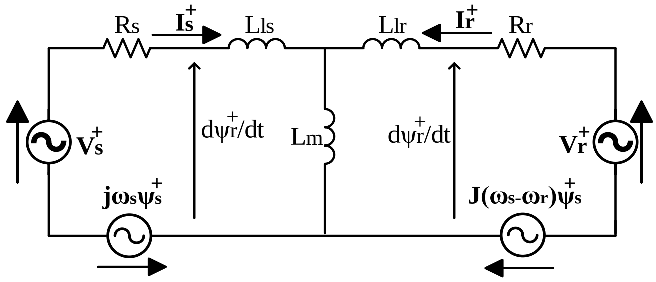

Fig. 4. *Equivalent circuit of DFIG in synchronous reference frame*

Additionally, electromagnetic torque in synchronous reference positive frame [20] is:

$$T_{em} = \frac{3}{2}P\left(\Psi_{sd}^{+} I_{sq}^{+} - \Psi_{sq}^{+} I_{sd}^{+}\right) \tag{20}$$

Given the unbalanced grid voltage, positive and negative sequence range is proved to be constant [21], therefore we'll have:

$$\frac{d}{dt}\Psi_{sdq+}^{+} = \frac{d}{dt}\Psi_{sdq-}^{+} = 0 \tag{21}$$

Ignoring stator resistance and simplifying (16), following equation is obtained:

$$V_{sdq}^{+} = V_{sdq+}^{+} + V_{sdq\sim}^{+} = j\omega_s \Psi_{sdq}^{+} + \frac{d\Psi_{sdq}^{+}}{dt} = j\omega_s\left(\Psi_{sdq+}^{+} + \Psi_{sdq-}^{-} e^{-j2\omega_s t}\right) + \frac{d}{dt}\left(\Psi_{sdq+}^{+} + \Psi_{sdq-}^{-} e^{-j2\omega_s t}\right) = j\omega_s\left(\Psi_{sdq+}^{+} - \Psi_{sdq-}^{+}\right) \tag{22}$$

Following is expounded (22):

$$\Psi_{sd+}^{+} = \frac{1}{\omega_s} V_{sq+}^{+} \quad , \; \Psi_{sd\sim}^{+} = -\frac{1}{\omega_s} V_{sq\sim}^{+}$$

$$\Psi_{sq+}^{+} = -\frac{1}{\omega_s} V_{sd+}^{+} \, , \; \Psi_{sq\sim}^{+} = \frac{1}{\omega_s} V_{sd\sim}^{+} \tag{23}$$

Accordingly, electromagnetic torque in such conditions, based on (2٠) and (2٣) is as follows:

$$T_{em} = \frac{P}{\omega_s}\left(P_{TDC} - P_{s1\sim} + P_{s2\sim}\right) = \frac{P_e}{\omega_s} \tag{24}$$

Where P_{TDC} is:

$$P_{TDC} = \frac{3}{2}\left(V_{sq+}^{+} I_{sq+}^{+} + V_{sd+}^{+} I_{sd+}^{+} - V_{sd-}^{-} I_{sd-}^{-} - V_{sd-}^{-} I_{sd-}^{-}\right) \tag{25}$$

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 convertors. Hence, it is very important to determine constant and oscillating components of back to back convertors in order to meet control strategies.

Equations for stator power are similar for convertors, as is displayed in Fig. 5:

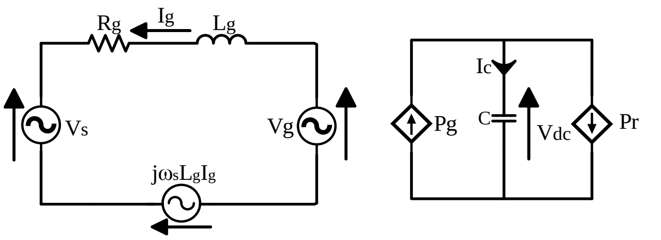

Fig. 5. *Equivalent circuit for convertors to analyse power*

$$P_g = P_{gDC} + P_{g1\sim} + P_{g2\sim} + P_{gDC} + P_{g\sim} \tag{26}$$

According to power direction in (19) and (24) and Fig. 1, rotor power can be calculated through following equation:

$$P_r = P_e - P_s = \left((1-S)P_{TDC} - P_{SDC}\right) - (2-S)P_{s1\sim} - SP_{s2} = P_{rDC}P_{r\sim} \quad (27)$$

To calculate GSC output power, regarding Fig. 5. Following equation is obtained:

$$C\frac{dV_{dc}}{dt}.V_{dc} = P_{DC} = P_g - P_r = \left(P_{gDC} - P_{rDC}\right) + \left(P_{g\sim} + P_{r\sim}\right) \quad (28)$$

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 (8). 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:

$$P_{c\sim}^{+}(t) = V_{c\sim}^{+}(t).I_{c\sim}^{+}(t) = V_c^{+}\cos(2\omega_s t).I_c^{+}\cos\left(2\omega_s t - \frac{\pi}{2}\right) = \frac{V_c^{+}I_c^{+}}{2}\sin(2\omega_s t) \quad (29)$$

$$Q_{c\sim} = -\frac{V_{c\sim}^{+}I_{c\sim}^{+}}{2} \quad (30)$$

5. Control strategies in unbalanced grid voltage condition

5.1 Eliminated or reduced oscillations of GSC and DC link powers

In the proposed method, two solutions are developed to reduce oscillations of DC link and GSC active power and eliminate oscillations GSC reactive power in all control strategies. First, from oscillation component of DC link obtained from (29) and (30), oscillation components of DC link power are calculated and added to DC link power estimated by PI controller. Then, from oscillation components of GSC output voltage and current, oscillation components of powers are calculated and added to control system input as part of the reference power.

$$\begin{bmatrix} P_{gsc}^{*} \\ Q_{gsc}^{*} \end{bmatrix} = \begin{bmatrix} P_{Dc} \\ Q_{GSC\_required} \end{bmatrix} + \begin{bmatrix} P_{c\sim}^{+} \\ Q_{c\sim}^{+} \end{bmatrix} + \begin{bmatrix} P_{gsc\sim}^{+} \\ Q_{gsc\sim}^{+} \end{bmatrix} \quad (31)$$

It should be noted that P_{Dc} is determined according to reference value of DC link voltage by PI controller. Oscillation power values are applied only to GSC controller and other control objectives are achieved by RSC control system. The method proposed here does not change with different goals and can be implemented in all control strategies. The method stated in [2] is used for deformed current from grid convertor in unbalanced condition, and, to calculate DC link oscillations power, the technique displayed in block diagram of Fig. 6 is appropriate. Fig. 7 shows a commonly used method in scientific papers to meet control strategies for torque stabilization, current balancing and reduction or elimination of output power of stator.

5.2 Elimination of active and reactive powers of stator

In (13), $P_{s1\sim}$ 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:

$$\begin{bmatrix} P_s^{*} \\ Q_s^{*} \end{bmatrix} = \begin{bmatrix} P_{s\_required} \\ Q_{s\_required} \end{bmatrix} = \begin{bmatrix} P_{sDC} \\ Q_{sDC} \end{bmatrix} \quad (32)$$

$$\begin{bmatrix} P_{1s\sim} \\ Q_{1s\sim} \end{bmatrix} + \begin{bmatrix} P_{2s\sim} \\ Q_{2s\sim} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (33)$$

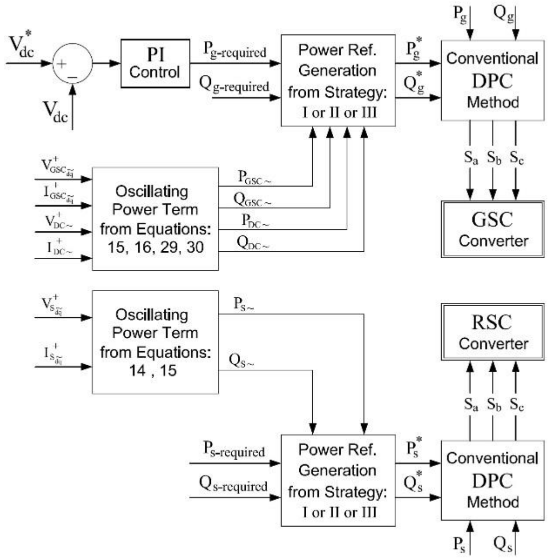

Fig 6: Block diagram of proposed method

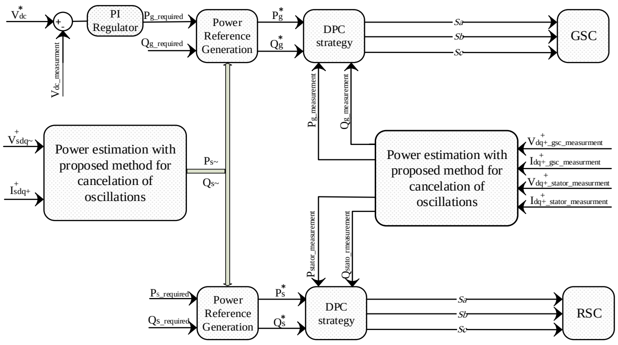

Fig. 7. *Block diagram in common methods*

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 (16), (17) and (27) as well as the relations mentioned above, electromagnetic torque is described using following equation:

$$T_{em} = \frac{p}{\omega_s}(P_{TDC} - 2P_{s1\sim}) = \frac{p}{\omega_s}(P_{TDC} + 2P_{s2\sim}) \quad (34)$$

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 (16) and (17), $P_{1s\sim}$ 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:

$$\begin{bmatrix} P_s^{*} \\ Q_s^{*} \end{bmatrix} = \begin{bmatrix} P_{s\_required} \\ Q_{s\_required} \end{bmatrix} + \begin{bmatrix} P_{s1\sim} \\ Q_{s1\sim} \end{bmatrix} \quad (35)$$

It should be noted that, according to (16), (17) and (34), 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:

$$T_{em} = \frac{p}{\omega_s}(P_{TDC} - P_{s1\sim}) \quad (36)$$

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 (27), following is the only way to stabilize electromagnetic torque:

$$P_{1s\sim} = P_{2s\sim} \quad (37)$$

Which is obtained as follows, regarding stator power:

$$P_s^* = P_{s\_required} + 2P_{1s\sim} \quad (38)$$

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 megawatts 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 direct power control based on optimal switching table in unbalanced voltage conditions with various control strategies such as 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=0.7-0.8. Reduced DC link oscillations and active power of GSC and eliminated reactive power oscillations of GSC in all control strategies were achieved within t=0.5-0.8, by GSC controller.

As is seen in Fig. 8, 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. 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.

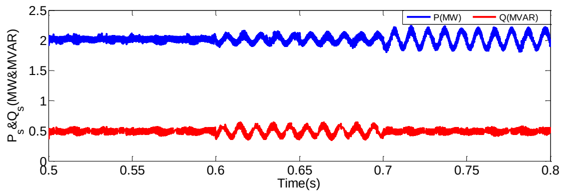

Fig. 8. *Output active and reactive powers of stator in various control strategies*

As is seen in Fig. 9, the three- phase rotor currents had positive and negative oscillation components of $(60 - 50 =)10$Hz and $(60 + 50 =)$ 110Hz, respectively. 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.

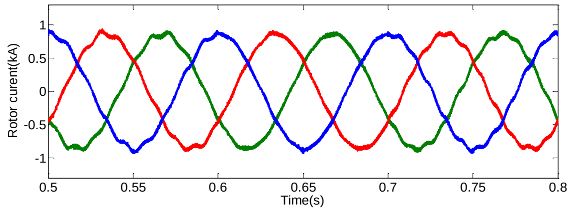

Fig. 9. *Rotor current in various control strategies*

According to Fig. 10, 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. 11) declined from 4.01%, before control strategies (Fig. 12), to 1.15%, with the proposed method.

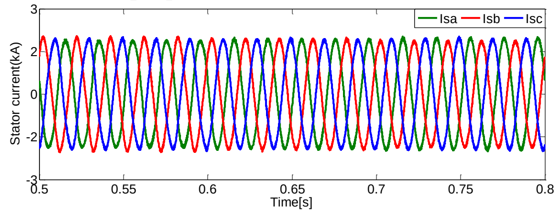

Fig. 10. *Stator current in various control strategies*

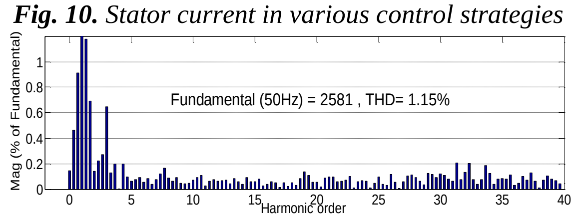

Fig. 11. *Harmonic pollution of stator current during balanced stator current*

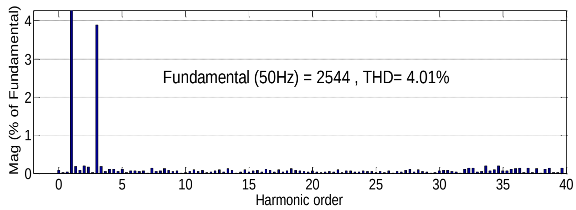

Fig. 12. *Harmonic pollution of stator current before balanced stator current*

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. 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. 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. 13).

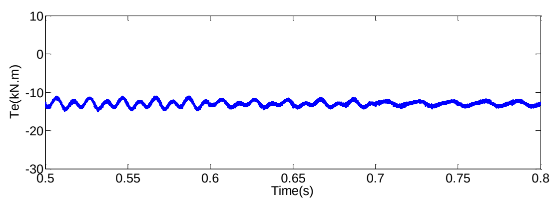

Fig. 13. *Electromagnetic torque in various control strategies*

When applying various control strategies, as is shown in Figures. (14) and (15), powers from GSC oscillate, according to common control methods in unbalanced grid voltage conditions.

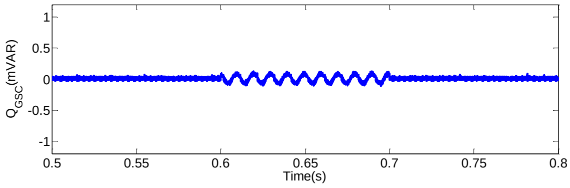

Fig. 14. Reactive power of GSC before the proposed method

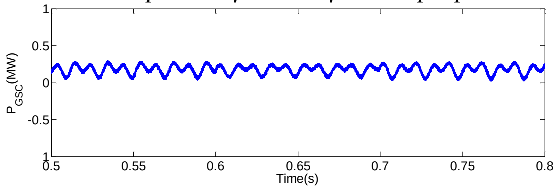

Fig. 15. Active power of GSC in various control strategies before the proposed method

As is seen, once oscillating term is added to active and reactive powers reference in GSC at t=0.5-0.8, based on the proposed method, according to Figures. (16) and, active power oscillations decrease considerably and reactive power oscillations are eliminated.

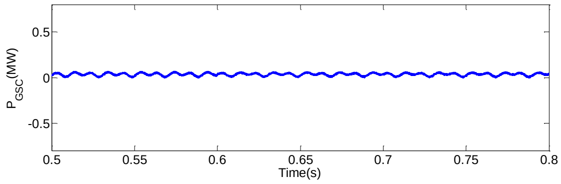

Fig. 16. Active power of GSC in various control strategies after the proposed method

As a result, as shown and proved without the relation, DC link voltage oscillations decreased to a very little extent and oscillation frequencies are twice as much as grid frequencies (Fig. 17).

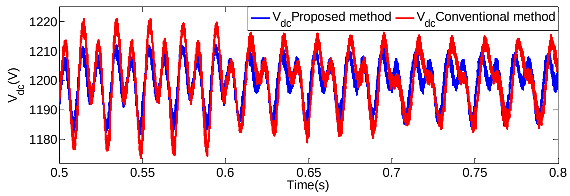

Fig. 17. DC link voltage in various control strategies before and after the proposed method

Figure. 18 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.

7. Conclusion

In this paper, the function of DFIG in unbalanced grid voltage conditions was analyzed and oscillation components of each part of generator and convertor were identified. In this regard, a solution was proposed to eliminate oscillations of different parts of DFIG, called Control Strategies. In the proposed method, GSC was used in all control strategies to reduce DC link voltage oscillations as well as active power and eliminate the oscillations of output reactive power of GSC.

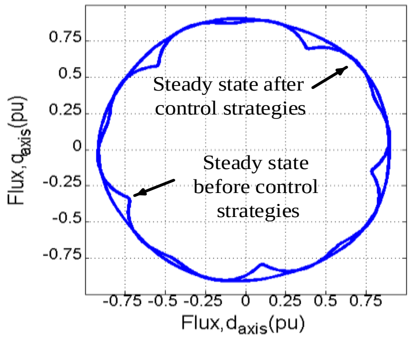

Fig. 18. Stator flux in dq axes in various control strategies

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

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, convertors and DC link increased considerably as a result of reduced oscillations of connected parts.

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