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Abstract—**Under unbalanced grid voltage conditions, the doubly fed induction generator (DFIG) stator voltage, in addition to positive sequence component has negative sequence component. The negative sequence component causes oscillations in the output power, electromagnetic torque and DC link voltage at twice the supply frequency. This paper presents a modified configuration of DFIG with series grid-side converter (SGSC) and its control system, which is suitable not only for unbalanced grid voltage conditions, but also for small voltage sags. The proposed configuration improves all the DFIG signals under unbalanced grid voltage and small voltage sag conditions without needing additional DC link capacitor or energy storage unlike other methods. The control system includes negative and positive sequence controllers which make the stator voltage balanced and keep it constant at the nominal value. Matlab/Simulink is used for simulation of a 1.5-MW DFIG and the results demonstrate the good efficiency of the proposed scheme.**

Keywords—doubly fed induction generator (DFIG);unbalanced voltage; voltage sag; series grid-side converter (SGSC)

I. INTRODUCTION

In recent years, the use of renewables such as wind, solar and water for the electrical energy generation has been increased significantly due to their advantages such as their low emissions and availability. One of the most important renewable energy sources is wind.

Thanks to its variable speed operation capability and independent yet cost-effective active and reactive power control, doubly fed induction generator (DFIG) has the largest share in the global wind turbine market [1]. Since the DFIG's stator is directly connected to the grid, the DFIG system is sensitive to grid disturbances such as voltage sag and voltage unbalance.

Under grid voltage unbalance conditions, the stator and rotor voltages and currents, in addition to positive sequence components, have negative sequence components. The presence of these negative sequence components and their interaction with the positive sequence components create oscillations in the output power, electromagnetic torque and DC link voltage at twice the supply frequency. These result in acoustic noise, mechanical stress, and gear box and shaft wearing and reduce the lifetime of the DC link capacitor.

To reduce these oscillations under unbalanced grid voltage conditions, various control methods are presented. These methods are divided into two general categories: vector control and direct torque/power control. In [2], a control strategy based on dual controller and power theory is presented to reduce oscillations in the electromagnetic torque and DC link voltage. In the proposed strategy, the rotor-side converter (RSC) is controlled to reduce the oscillation of electromagnetic torque, while the grid-side converter (GSC) is controlled to reduce DC link voltage oscillation. In [3], a control method is used to reduce both power and torque oscillations, in which GSC reduces power oscillation and RSC reduces torque oscillation. In [4], a new direct torque control method is proposed, in which the angle and magnitude of the rotor voltage are regulated to achieve independent control of electromagnetic torque and reactive power, respectively. Under unbalanced grid voltage conditions, the torque angle is controlled to reduce the oscillation of torque. For this purpose, a proportional-integral and resonant (PI+R) controller is used. A strategy for generation of the active and reactive power references for the RSC and the GSC can be added to the conventional direct power control method to reduce the electromagnetic torque oscillation and make the stator current sinusoidal [5].

Abovementioned control methods improve only one or two signals of the DFIG. For example, a method can reduce electromagnetic torque oscillation while DC link voltage oscillation does not change or even increases. The reason is that the main origin of oscillations is stator voltage unbalance and these methods do not compensate it and only reduce oscillations of one or two signals of the DFIG. Also, most of these control methods are suitable only for voltage unbalances and are not efficient for voltage sags.

DFIG with series grid-side converter (SGSC) is another solution. In [6] and [7], a DFIG with SGSC is presented. The presented method is based on the stator flux control and has a good voltage sag ride-through capability. In [8], DFIG system with a SGSC and without parallel grid-side converter (PGSC) is suggested, which has a good voltage sag ride-through capability, but shows deficiency in power processing. In [9], a Dynamic voltage restorer (DVR) has been added to the DFIG system. It requires additional DC link capacitor or energy storage which increases cost. Also this method is able to compensate only short term voltage sags and is not efficient for long term voltage sags.

Considering the shortcoming of the previous methods, in this paper, a modified configuration of DFIG with SGSC and its control system is presented. The modified configuration of DFIG can balance the stator voltage without needing additional DC link capacitor or energy storage and consequently it improves all of the DFIG signals. The modified configuration can compensates not only small voltage unbalances, but also severe voltage unbalances and small voltage sags (less than 30%). In the proposed scheme, during voltage sag or voltage unbalance, the stator voltage is controlled and compensated instead of the stator flux. The control system includes negative and positive sequence controllers. The negative sequence controller eliminates the negative sequence component of the stator voltage and the positive sequence controller keeps the positive sequence component constant at the nominal value of the stator voltage. This makes the DFIG bus voltage, i.e. the DFIG stator voltage, balanced and equal to the nominal value of the stator voltage. Therefore, oscillations in the output power, electromagnetic torque and DC link voltage can be reduced and consequently the operation of DFIG is considerably improved. It should be noted that by compensating DFIG stator voltage unbalance, all DFIG signals are improved. Also, the loads connected to the DFIG bus will have balanced nominal voltage. Simulation results for a 1.5-MW DFIG show efficiency and good performance of the proposed scheme.

II. DFIG Model under Unbalanced Grid Voltage Conditions

An unbalanced three-phase sinusoidal system can be analyzed by symmetrical components theory. According to this theory, an unbalanced three-phase sinusoidal system is decomposed to the positive, negative and zero sequence components. Since the neutral point of DFIG system is not grounded, there is no path for zero sequence components and they can be eliminated from the analysis.

DFIG system model under unbalanced grid voltage conditions has already been studied in detail [10]–[12]. DFIG system configuration and its equivalent circuit in the synchronous reference frame are shown In Fig. 1 and Fig. 2, respectively.

Taking into account the positive and negative sequence components of the voltage and current, under unbalanced conditions, electromagnetic torque, active and reactive powers

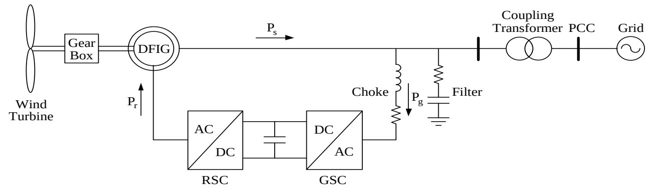


Figure 1. DFIG system configuration.

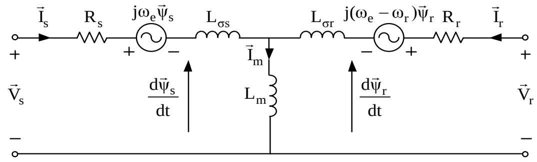


Figure 2. Equivalent circuit of DFIG in the synchronous reference frame.

of the stator, rotor and grid-side converter and DC link voltage can be expressed as follows [10]–[12]:

$$T_e = T_{e\_av} + T_{e\_\sin 2}\sin(2\omega_e t) + T_{e\_\cos 2}\cos(2\omega_e t) \quad (1)$$

$$P_s = P_{s\_av} + P_{s\_\sin 2}\sin(2\omega_e t) + P_{s\_\cos 2}\cos(2\omega_e t) \quad (2)$$

$$Q_s = Q_{s\_av} + Q_{s\_\sin 2}\sin(2\omega_e t) + Q_{s\_\cos 2}\cos(2\omega_e t) \quad (3)$$

$$P_r = P_{r\_av} + P_{r\_\sin 2}\sin(2\omega_e t) + P_{r\_\cos 2}\cos(2\omega_e t) \quad (4)$$

$$P_g = P_{g\_av} + P_{g\_\sin 2}\sin(2\omega_e t) + P_{g\_\cos 2}\cos(2\omega_e t) \quad (5)$$

$$Q_g = Q_{g\_av} + Q_{g\_\sin 2}\sin(2\omega_e t) + Q_{g\_\cos 2}\cos(2\omega_e t) \quad (6)$$

$$V_{dc} = V_{dc\_av} + V_{dc\_\sin 2}\sin(2\omega_e t) + V_{dc\_\cos 2}\cos(2\omega_e t), \quad (7)$$

Where, constant and oscillating terms are defined as follows:

$$\begin{bmatrix} T_{e\_av} \\ T_{e\_\sin 2} \\ T_{e\_\cos 2} \end{bmatrix} = \frac{-3pL_m}{2\omega_e L_s} \begin{bmatrix} -V_{ds}^p & -V_{qs}^p & V_{ds}^n & V_{qs}^n \\ V_{qs}^n & -V_{ds}^n & V_{qs}^p & -V_{ds}^p \\ V_{ds}^n & V_{qs}^n & -V_{ds}^p & -V_{qs}^p \end{bmatrix} \begin{bmatrix} I_{dr}^p \\ I_{qr}^p \\ I_{dr}^n \\ I_{qr}^n \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} P_{s\_av} \\ Q_{s\_av} \\ P_{s\_\sin 2} \\ P_{s\_\cos 2} \\ Q_{s\_\sin 2} \\ Q_{s\_\cos 2} \end{bmatrix} = \frac{-3}{2\omega_e L_s} \begin{bmatrix} 0 \\ (V_s^p)^2 - (V_s^n)^2 \\ 2V_{ds}^p V_{ds}^n \\ -2V_{ds}^p V_{qs}^n \\ 0 \\ 0 \end{bmatrix} + \frac{3L_m}{2L_s} \begin{bmatrix} V_{ds}^p & V_{qs}^p & V_{ds}^n & V_{qs}^n \\ V_{qs}^p & -V_{ds}^p & V_{qs}^n & -V_{ds}^n \\ V_{qs}^n & -V_{ds}^n & -V_{qs}^p & V_{ds}^p \\ V_{ds}^n & V_{qs}^n & V_{ds}^p & V_{qs}^p \\ -V_{ds}^n & -V_{qs}^n & V_{ds}^p & V_{qs}^p \\ V_{qs}^n & -V_{ds}^n & V_{qs}^p & -V_{ds}^p \end{bmatrix} \begin{bmatrix} I_{dr}^p \\ I_{qr}^p \\ I_{dr}^n \\ I_{qr}^n \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} P_{r\_av} \\ P_{r\_\sin 2} \\ P_{r\_\cos 2} \end{bmatrix} = \frac{-3}{2} \cdot \begin{bmatrix} sV_{ds}^{p} & sV_{qs}^{p} & (2-s)V_{ds}^{n} & (2-s)V_{qs}^{n} \\ (2-s)V_{qs}^{n} & -(2-s)V_{ds}^{n} & -sV_{qs}^{p} & sV_{ds}^{p} \\ (2-s)V_{ds}^{n} & (2-s)V_{qs}^{n} & sV_{ds}^{p} & sV_{qs}^{p} \end{bmatrix} \begin{bmatrix} I_{ds}^{p} \\ I_{qs}^{p} \\ I_{ds}^{n} \\ I_{qs}^{n} \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} P_{g\_av} \\ Q_{g\_av} \\ P_{g\_\sin 2} \\ P_{g\_\cos 2} \\ Q_{g\_\sin 2} \\ Q_{g\_\cos 2} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} V_{ds}^{p} & V_{qs}^{p} & V_{ds}^{n} & V_{qs}^{n} \\ V_{qs}^{p} & -V_{ds}^{p} & V_{qs}^{n} & -V_{ds}^{n} \\ V_{qs}^{n} & -V_{ds}^{n} & -V_{qs}^{p} & V_{ds}^{p} \\ V_{ds}^{n} & V_{qs}^{n} & V_{ds}^{p} & V_{qs}^{p} \\ -V_{ds}^{n} & -V_{qs}^{n} & V_{ds}^{p} & V_{qs}^{p} \\ V_{qs}^{n} & -V_{ds}^{n} & V_{qs}^{p} & -V_{ds}^{p} \end{bmatrix} \begin{bmatrix} I_{dg}^{p} \\ I_{qg}^{p} \\ I_{dg}^{n} \\ I_{qg}^{n} \end{bmatrix} \quad (11)$$

$$V_{dc\_\sin 2} = \frac{1}{2\omega_e C V_{dc\_av}} (P_{g\_\cos 2} - P_{r\_\cos 2}) \quad (12)$$

$$V_{dc\_\cos 2} = \frac{1}{2\omega_e C V_{dc\_av}} (P_{g\_\sin 2} - P_{r\_\sin 2}), \quad (13)$$

Where p and n superscripts denote the positive and negative sequence quantities, respectively. s is the rotor slip and is defined as follow:

$$s = \frac{\omega_r - \omega_e}{\omega_e} \quad (14)$$

Equations (1) to (13) show that unbalanced conditions result in oscillations in electromagnetic torque, power and DC link voltage at twice the supply frequency.

III. DFIG Configuration with SGSC

DFIG Configuration with SGSC is shown in Fig. 3. A three-phase voltage source converter is connected between DFIG bus and grid bus through a series injection transformer. SGSC uses DC link capacitor of DFIG system as energy storage, and there is no need for additional capacitor or energy storage. This is the one of advantages of this configuration. In normal voltage conditions, SGSC injects no voltage vector, but under abnormal voltage conditions injects a voltage vector between DFIG bus and grid bus in series. DFIG bus voltage vector can be expressed as follow:

$$\vec{V}_{DFIG} = \vec{V}_{inj} + \vec{V}_{grid}, \quad (15)$$

Where $\vec{V}_{\mathrm{DFIG}}$, $\vec{V}_{\mathrm{inj}}$ and $\vec{V}_{\mathrm{grid}}$ are DFIG bus voltage vector, injected voltage vector by SGSC and grid bus voltage vector, respectively. The injected voltage vector by SGSC should be such that three-phase DFIG bus voltage, i.e. the three-phase stator voltage, is balanced under unbalanced grid voltage conditions, and the magnitude of the stator voltage becomes equal to the nominal value of the stator voltage.

IV. SGSC Control Strategy

SGSC injects a voltage vector between DFIG bus and grid bus in series. Summation of injected voltage vector and grid bus voltage vector leads to DFIG bus voltage vector. The injected voltage vector by SGSC should be such that three-phase DFIG bus voltage, i.e. the three-phase stator voltage, is balanced under unbalanced grid voltage conditions, and magnitude of the stator voltage matches its nominal value.

Elimination of the negative sequence component makes the stator voltage balanced, but if the unbalanced voltage condition is severe, the magnitude of the positive sequence component decreases. Therefore the magnitude of the positive sequence component should be increased to the nominal value of the stator voltage. SGSC control block diagram is shown in Fig. 4. There are two controllers:

- Negative sequence controller.
- Positive sequence controller.

Negative sequence controller eliminates the negative sequence component of the stator voltage. Therefore the reference values of this controller are as follows:

$$V_{d-DFIG}^{n^*} = 0 \quad (16)$$

$$V_{q-DFIG}^{n^*} = 0 \quad (17)$$

Positive sequence controller keeps the positive sequence component of the stator voltage equal to its nominal value. Therefore the reference values of this controller are as follows:

$$V_{d-DFIG}^{p^*} = V_{s\_nom} \quad (18)$$

$$V_{q-DFIG}^{p^*} = 0 \quad (19)$$

The positive sequence controller causes the SGSC to have a good compensation not only under unbalanced voltage, but also in small balanced voltage sag (about 20%) and restores the voltage very well.

To extract positive sequence component of the stator voltage, three-phase stator voltage is transferred to positive synchronous reference frame using (20). Positive and negative sequence components of the stator voltage in positive synchronous reference frame are a DC component and an oscillating component at twice the supply frequency, respectively. So using a notch filter tuned at twice the supply frequency, the positive sequence component of the stator voltage is obtained in positive synchronous reference frame. Equation (21) can be used to transform the positive sequence component of dq voltages to abc three-phase voltage form.

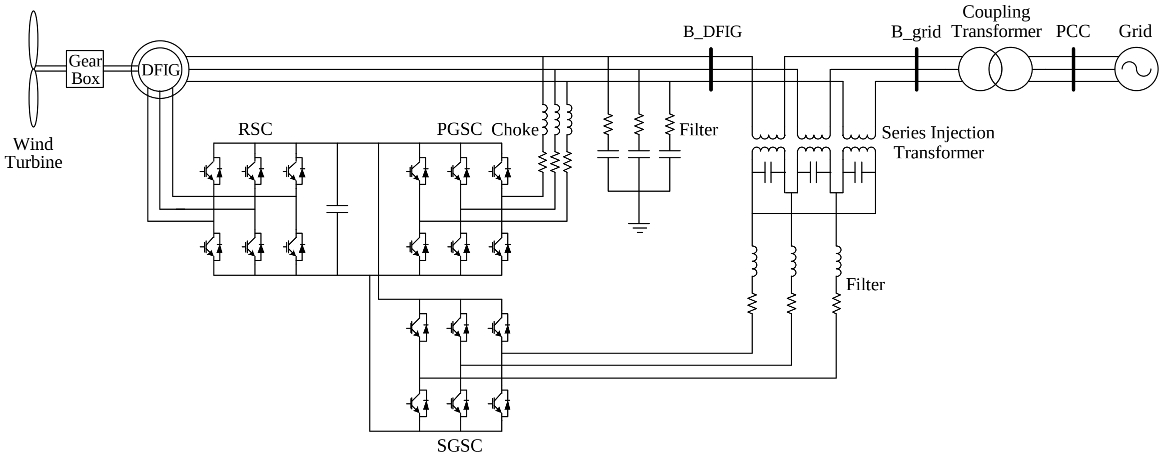


Figure 3. DFIG Configuration with SGSC.

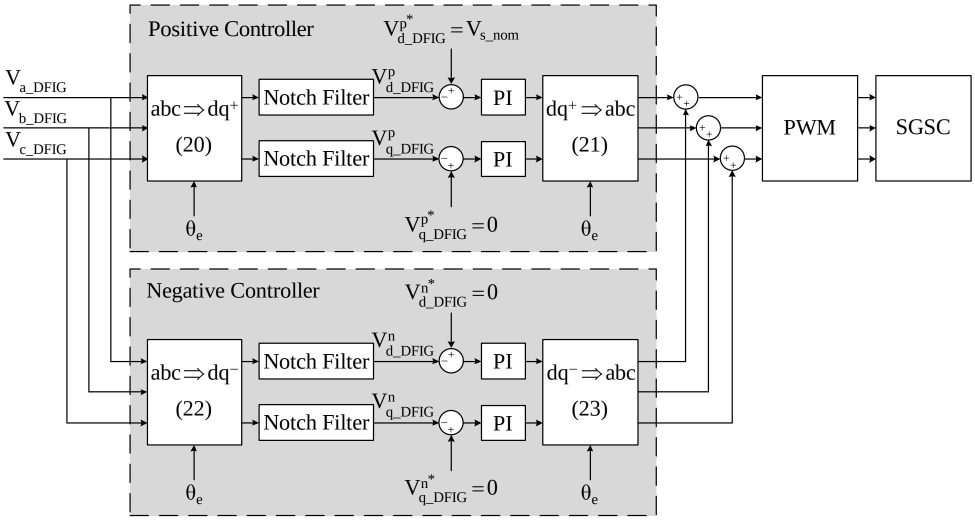


Figure 4. SGSC control block diagram.

$$\begin{bmatrix} V_d^p \\ V_q^p \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta_e) & \cos(\theta_e + \frac{2\pi}{3}) & \cos(\theta_e - \frac{2\pi}{3}) \\ \sin(\theta_e) & \sin(\theta_e + \frac{2\pi}{3}) & \sin(\theta_e - \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (20)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos(\theta_e) & \sin(\theta_e) \\ \cos(\theta_e + \frac{2\pi}{3}) & \sin(\theta_e + \frac{2\pi}{3}) \\ \cos(\theta_e - \frac{2\pi}{3}) & \sin(\theta_e - \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_d^p \\ V_q^p \end{bmatrix} \quad (21)$$

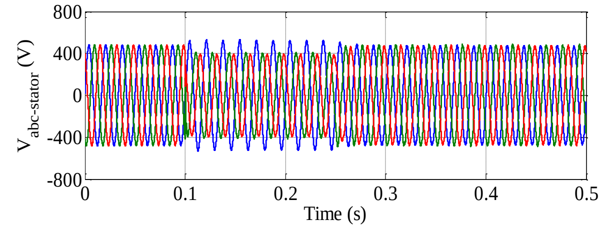
The same discussion is true for the negative sequence component of the stator voltage. However, this time the negative synchronous reference frame must be used. For this purpose, following equations apply:

$$\begin{bmatrix} V_d^n \\ V_q^n \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(-\theta_e) & \cos(-\theta_e + \frac{2\pi}{3}) & \cos(-\theta_e - \frac{2\pi}{3}) \\ \sin(-\theta_e) & \sin(-\theta_e + \frac{2\pi}{3}) & \sin(-\theta_e - \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (22)$$

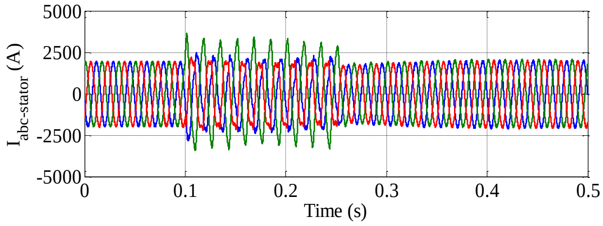
$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos(-\theta_e) & \sin(-\theta_e) \\ \cos(-\theta_e + \frac{2\pi}{3}) & \sin(-\theta_e + \frac{2\pi}{3}) \\ \cos(-\theta_e - \frac{2\pi}{3}) & \sin(-\theta_e - \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} V_d^n \\ V_q^n \end{bmatrix} \quad (23)$$

V. SIMULATION RESULTS

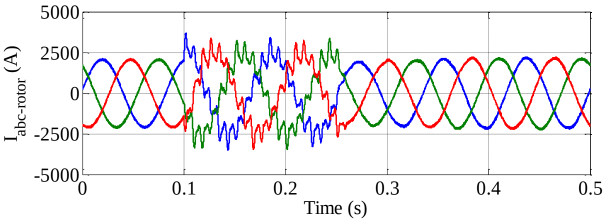
Performance of the proposed DFIG system with SGSC has been evaluated in Matlab/Simulink environment. A 1.5-MW DFIG was simulated and its parameters are shown in table I.



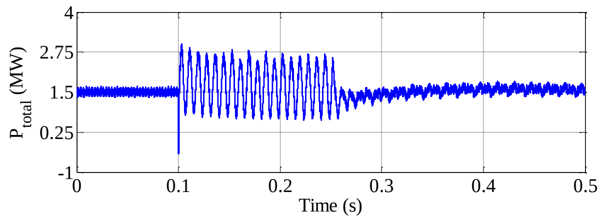
(a) Stator voltage.



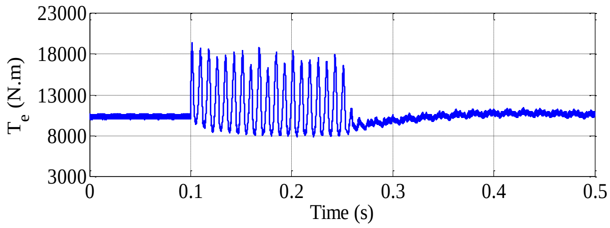
(b) Stator current.



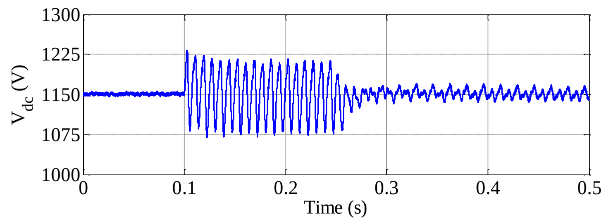
(c) Rotor current.



(d) Output power.

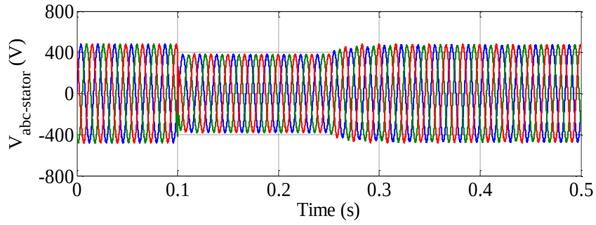


(e) Electromagnetic torque.

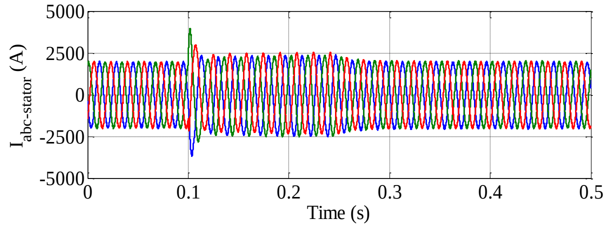


(f) DC link voltage.

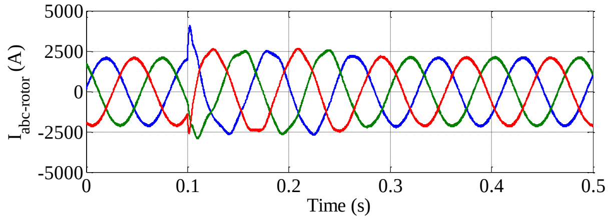
Figure 5. Simulation results for 20% voltage unbalance applied at t=0.1s. t=0–0.1s: balanced nominal voltage, t=0.1–0.25s: 20% voltage unbalance without SGSC compensation, t=0.25–0.5s: 20% voltage unbalance with SGSC compensation.



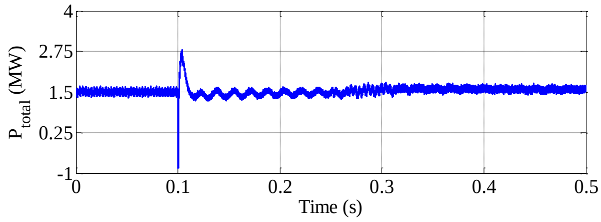
(a) Stator voltage.



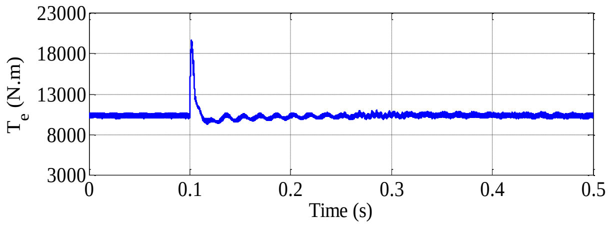
(b) Stator current.



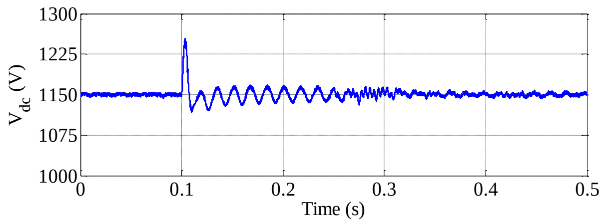
(c) Rotor current.



(d) Output power.



(e) Electromagnetic torque.



(f) DC link voltage.

Figure 6. Simulation results for 20% balanced voltage sag applied at t=0.1s. t=0–0.1s: balanced nominal voltage, t=0.1–0.25s: 20% balanced voltage sag without SGSC compensation, t=0.25–0.5s: 20% balanced voltage sag with SGSC compensation.

Operation of DFIG under both severe voltage unbalance and small balanced voltage sag conditions are investigated. In both cases, the rotor speed is 1.2pu. In Fig. 5, at t=0–0.1s, the stator voltage is balanced and equal to the nominal value. At t=0.1s a severe voltage unbalance (20%) is applied to DFIG bus. To illustrate the effects of the voltage unbalance on the DFIG signals, SGSC does not compensate till t=0.25s. According to the Fig. 5, the applied voltage unbalance at t=0.1s makes the stator and rotor currents unbalance and distortion and consequently, leads to oscillations in the output power, electromagnetic torque and DC link voltage. At t=0.25s, SGSC starts to compensate the DFIG bus voltage. This makes the stator and rotor currents balanced and decrease the distortions. Elimination of stator voltage and stator and rotor currents unbalances decreases the mentioned oscillations. In Fig. 6, at t=0–0.1s, the stator voltage is balanced and equal to the nominal value. At t=0.1s a small balanced voltage sag (20%) is applied to DFIG bus. SGSC does not compensate till t=0.25s. According to the Fig. 6, the applied balanced voltage sag at t=0.1s causes the stator and rotor currents to increase and thus warms up the stator and rotor windings gradually and shortens the lifespan. Moreover, some oscillations are created in output power, electromagnetic torque and DC link voltage. At t=0.25s, SGSC starts to compensate the DFIG bus voltage and increases it to the nominal value. This leads the stator and rotor currents to reach their nominal values. Also the mentioned oscillations are decreased. Abovementioned statements indicate the efficiency of SGSC under unbalanced voltage and small balanced voltage sag conditions.

VI. CONCLUSION

In this paper a modified DFIG Configuration with SGSC and its control system were presented which is suitable not only for unbalanced grid voltage conditions, but also for small voltage sags and has a good performance under both cases. Unlike the other conventional methods, the modified configuration of DFIG can balance the voltage stator and is kept constant at the nominal value without needing additional DC link capacitor or energy storage. Therefore, the modified configuration of DFIG improves all the DFIG signals such as the output power, electromagnetic torque and DC link voltage. The results of computer simulation confirm successful operation of the proposed scheme.

Other benefits of the proposed configuration of DFIG and its control scheme are:

- The control system is simple and fast.
- Needs no PLL and no estimation of amplitude and phase of grid voltage.

TABLE I. PARAMETERS OF THE SIMULATED DFIG

Parameter	Symbol	Value
Rated power	P_n	1.5 MW
Rated stator voltage	V_n	575 V
Rated frequency	f_n	60 Hz
Stator resistance	R_s	0.00706 pu
Rotor resistance	R_r	0.005 pu
Stator leakage inductance	$L_{\sigma s}$	0.171 pu
Rotor leakage inductance	$L_{\sigma r}$	0.156 pu
Mutual inductance	L_m	2.9 pu
Number of pole pairs	p	3
Lumped inertia constant	H	5.005 s
DC link voltage	V_{dc}	1150 V
DC link capacitor	C_{dc}	10 mF

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