CONTROL FOR DFIG WITH SERIES GRID SIDE CONVERTER UNDER UNBALANCED GRID VOLTAGE CONDITIONS

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***Abstract*— This paper addresses the main problems related to doubly-fed induction generators (DFIG) connection to grids with unbalanced voltages. Series compensation is used to achieve balanced voltage on the stator of the machine, avoiding torque oscillations and high currents due to the grid voltage unbalance. A DC-link control of the back-to-back converter at the rotor side is proposed, reducing the complexity of the converter if compared to the alternatives considered in the literature. The close to no-load operation of the DFIG is also depicted. Simulation results of a 2MW wind turbine generator are presented to demonstrate the performance of the system with the proposed controller.**

***Keywords*— Unbalanced voltages, DFIG, series compensation.**

I. Introduction

The connection of wind turbines to non-ideal grids has many challenges. The voltage unbalance and disturbances are some of these issues, resulting in torque pulsations that may reduce the lifetime of the wind turbine.

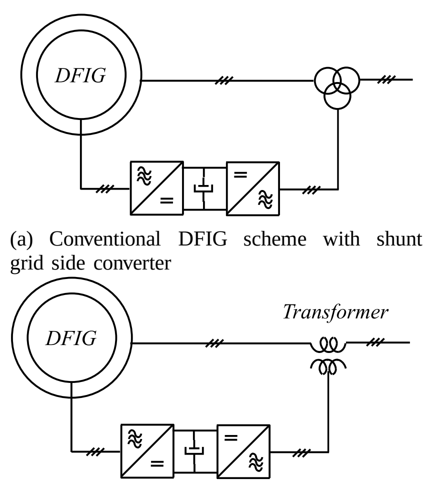
Power system voltage disturbances may be caused by several reasons. In the case of voltage unbalance, a major cause of it is the uneven distribution of single-phase loads, that may continuously change along a three-phase power distribution system. The unbalanced voltages can result in adverse effects on equipment, which is intensified by the fact that a small unbalance in the phase voltages can cause a disproportionately larger unbalance in the phase currents [1].

In addition, under voltage sags, the stator flux of the DFIG oscillates because the dynamic of the DFIG has two poorly damped poles and, as a result, high currents can damage the machine and the rotor side converter, forcing the disconnection of the wind turbine. Several papers are presented in the literature to deal with the DFIG connection under these conditions. Some of them minimize the torque pulsation and high stator and rotor currents using a series compensator [2] [3] [4], while others propose compensators on the rotor side converter of DFIG with shunt grid-side converter [5]. The two main DFIG configurations are presented in Figure 1. Although the configuration with shunt grid-side converter of Figure 1a is more popular, there are some appealing features of the one with series grid-side converter of Figure 1b.

Petersson [2] analyzed the series converter with the focus on handling voltage sags. The control strategies for the series converter and the rotor current were presented. However, to control the DC-link voltage, the conclusion was that it should be used an additional converter in parallel in order to keep the DC-link voltage when the system operates close to no-load. Even for a small parallel converter, this is an additional cost and complexity.

Mohan *et al.* [3] proposed a system where the grid side converter is connected in series through three single-phase transformers, each one fed by one single full-bridge converter. In the sense of semiconductor switches, the configuration is similar to the presented in [2] and does not have advantage in financial terms. The control strategy is based on [6] with an additional series converter used to limit short-circuit currents. Moreover, each converter plays one role. One converter maintains the DC-link voltage, the second compensates the unbalanced voltage and the third limits fault currents, that is, the control strategy is not unified and it is required a large number of semiconductors (12 switches) just to implement the series grid-side converter.

For voltage fluctuations, Barker *et al.* [4] attacked the DFIG fault ride-through capability and assert that there is a large amount of negative sequence components on voltage/current appearing in the stator and rotor windings when an asymmetrical fault occurs. This leads to over-currents and over-speeds under voltage sags.



(a) Conventional DFIG scheme with shunt grid side converter

(b) DFIG with a series grid-side converter

Fig. 1: DFIG configurations

The main contribution of this paper is to present a simple control strategy based on symmetric components for the DFIG with a series grid-side converter, with the focus on the unbalanced grid voltage. A conventional three-phase three-leg converter with single-phase transformers implements the series grid-side converter. This converter performs two functions, that are: (i) injects a voltage in series to balance the stator voltages, minimizing the torque oscillations as well as (ii) regulates the DC-link voltage.

This paper is organized as follows. Section II presents the

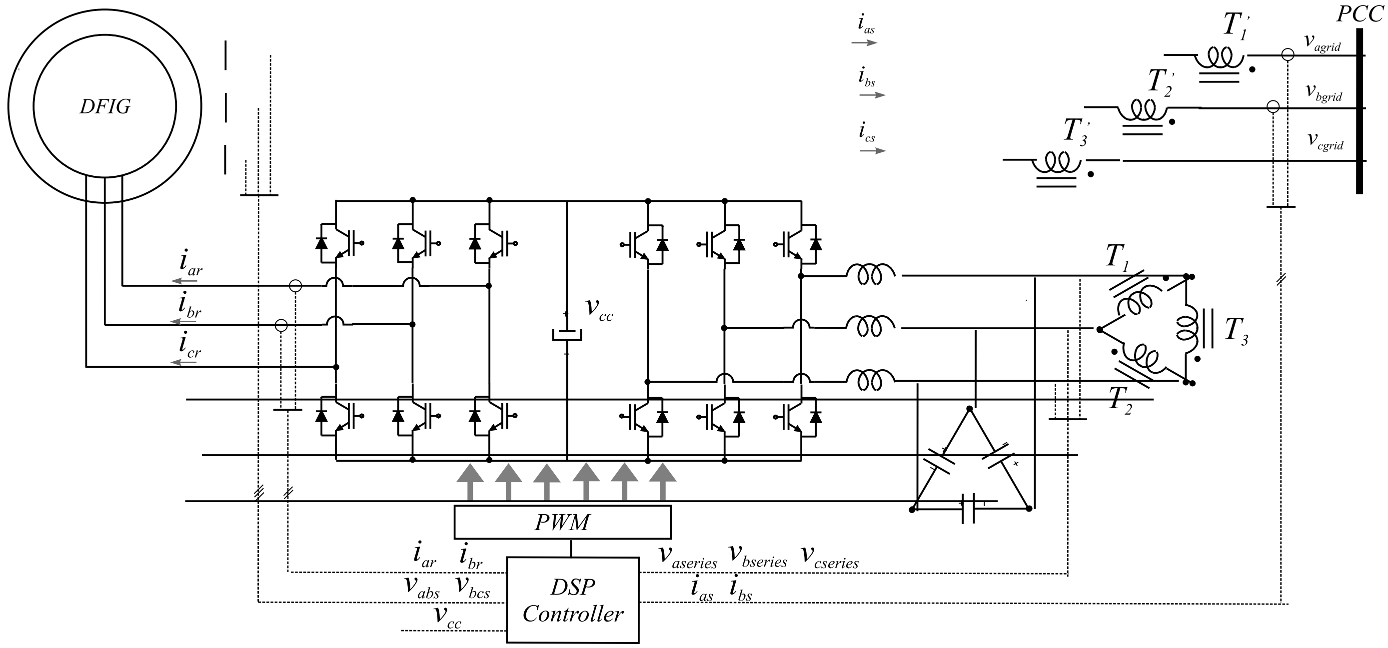


Fig. 2: DFIG with a series converter on the grid side

conventional DFIG configuration, presenting the problems under grid disturbances. Section III shows the proposed methodology, presenting the contributions of this work. Section IV presents some simulations which validate the theoretical background presented in the previous sections.

II. Conventional DFIG System Description

The conventional configuration of the DFIG with a shunt converter at the rotor side is presented in Figure 1a. The shunt grid-side converter regulates the DC-link voltage while the rotor-side converter supplies current for the rotor [7]. The stator is connected directly to the grid. This way, any voltage disturbance affects directly the stator flux. It means that a voltage unbalance leads to torque oscillations when the conventional power regulation is applied. Furthermore, to decouple the active and reactive power, the orientation of the dq rotating frame is on the estimated stator flux.

In this configuration, [5] presents the positive and negative sequence model of the DFIG. However, it is not possible to compensate the torque and active power oscillations at the same time, as well as the algorithm is very complex.

In the next section the description of the proposed configuration and control is presented.

III. Proposed Controller for the Series Grid Side Converter

The following section describes the proposed controller for the series grid-side converter. It is comprised of two main parts: the first one compensates the unbalanced grid voltage and the second one regulates the DC-link voltage.

A. System Description

The proposed system with the series compensator is shown in details in Figure 2. The DFIG rotor side converter is controlled in the same manner proposed in the literature for the conventional configuration with the shunt grid-side converter. As it is possible to see, it is used a three-phase three-leg converter on the series grid side. Three single-phase transformers connected in Δ provides the series voltage between the stator of the machine and the grid.

The saturation of the transformers was addressed in [8] for application on dynamic voltage restorers (DVRs). The use of one three-phase or three single-phase transformers depends on the design of the transformers and its capability to experience high flux linkage without saturation.

The rotor current control is the same used in the conventional connection and it is oriented in the dq stator flux reference frame.

B. Voltage Unbalance Compensation

The grid voltage can be written on the stationary $\alpha\beta$ reference frame as

$$v_{g\alpha\beta} = \begin{bmatrix} v_{g\alpha} \\ v_{g\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

and, neglecting the harmonics, decomposed as sum of a positive and a negative sequence voltages

$$v_{g\alpha\beta} = v_{g\alpha\beta+} + v_{g\alpha\beta-} \tag{2}$$

Some methods to obtain the positive grid voltage symmetrical component were presented in [9] and [10]. For the negative sequence, some changes are necessary.

Concerning the torque oscillations and high currents due to the voltage unbalance, the series compensator must cancel the negative sequence voltage in order to keep the stator voltage balanced and only with positive sequence voltage. So, the series voltage to compensate the unbalanced voltage is

$$v_{series\alpha\beta-} = -v_{g\alpha\beta-} \tag{3}$$

and the resulting stator voltage is

$$v_{s\alpha\beta} = v_{g\alpha\beta+} \tag{4}$$

If the voltage at the stator side is balanced, then the resultant current is also balanced. As the active power involved in the product of a positive sequence current with a negative sequence voltage is zero, then there is no active power involved in the process of compensate the negative sequence voltage. If the above conditions are satisfied, then

$$i_{s\alpha\beta} = i_{\alpha\beta+} \tag{5}$$

and there is only positive sequence voltage in steady state conditions.

In the following section a review of some DC-link control strategies are presented and the proposed strategy is described.

C. DC-link Voltage Control

For the proper operation of the back-to-back converter, the DC-link voltage must be regulated at fixed value greater then the largest peak of the line voltage, allowing it to inject into the rotor or to deliver active power to the grid.

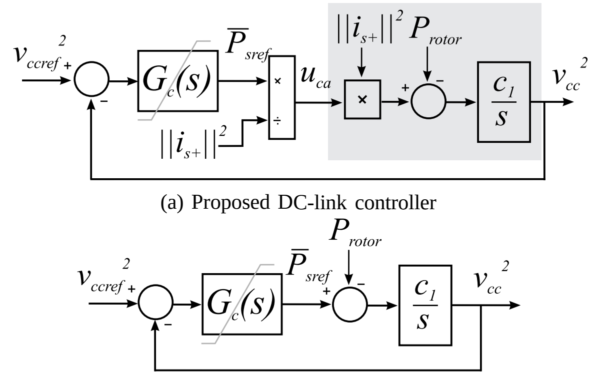
Let us consider that the grid current has only a positive sequence component. In order to absorb from or inject power into the grid, it is necessary to inject a voltage in series which is in phase or in opposition with the series current, that is, a positive sequence voltage. Therefore, the amplitude of the positive sequence stator voltage varies depending on the wind turbine speed. When the wind turbine is operating under the synchronous speed, the rotor side absorbs active power and the stator voltage increases. On the other hand, when the wind turbine operates above the synchronous speed, the stator voltage decreases.

This is a very important aspect and must be carefully analyzed. For the sub-synchronous speed, the power delivered by the stator is higher than the real power delivered to the grid because the series converter absorbs power. Though, for the super-synchronous speed, the power delivered by the stator is smaller than the real power delivered to the grid because the series converter also injects power and the stator voltage decreases, reducing therefore the generator losses.

As the series converter injects positive and negative voltage and the current, if the system is balanced, has only positive sequence, the active power involved in this case has a constant component in addition with a oscillating component on the double of the fundamental frequency.

$$P_{series}(t) = 3I_{+}\left[V_{+} + V_{-}cos(2\omega t)\right] \tag{6}$$

where I_{+}, V_{+} and V_{-} are the rms positive sequence current, the positive and negative sequence voltages, respectively. This oscillating power component appears as an oscillation on the



(a) Proposed DC-link controller

(b) DC-link control loop simplified block diagram

Fig. 3: DC-link voltage controller

DC-link voltage and this component cannot affect the positive sequence reference voltage responsible to keep the DC-link voltage. This way, a PI controller was selected to achieve zero steady-state error and in series with it is associated a controller that rejects this disturbance.

In steady-state condition in the DC-link, the following equality must be satisfied:

$$\bar{P}_{series}(t) = P_{rotor}(t) \tag{7}$$

It means that in steady-state the energy on the capacitor is constant. The capacitor energy is given by

$$E_c(t) = C\frac{v_{cc}(t)^2}{2} \tag{8}$$

Note that, by selecting

$$x_1(t) = v_{cc}^2(t), c_1 = \frac{2}{C} \tag{9}$$

and applying the Laplace transform, it is found the following linear equation

$$x(s) = \frac{c_1}{s}\left[P_{series}(s) - P_{rotor}(s)\right] \tag{10}$$

In order to the series grid-side converter absorb power from or inject power into the grid, its voltage must be proportional to the current. Here, it is proposed that

$$v_{series\alpha\beta+} = u_{ca}i_{\alpha\beta+} \tag{11}$$

From the active power equation of the series converter, one can find that

$$\begin{aligned}\bar{P}_{series\alpha\beta+} &= v_{series\alpha\beta+}i_{\alpha\beta+}\\ &= u_{ca}i_{\alpha\beta+}\cdot i_{\alpha\beta+}\\ &= u_{ca}\left[i_{\alpha+}^2 + i_{\beta+}^2\right]\\ &= u_{ca}\|i_{s+}\|^2\end{aligned} \tag{12}$$

where u_{ca} is the control action of the DC-link loop. It has a resistance characteristic and its signal depends if the series converter is injecting or absorbing power.

The equation (12) is nonlinear. In order to linearize (12), $\bar{P}_{sref}$ is divided by $\|i_{s+}\|^2$ as shown in Figure 3a. As a result, the equivalent block diagram of the DC-link loop becomes as shown in Figure 3a. In addition, to achieve zero steady-state error, a *PI* controller has been selected. To avoid that the DC-link voltage oscillation affects the computation of u_{ca}, the following controller structure is proposed

$$G_c(s) = \left(k_p + \frac{k_i}{s}\right) \cdot \frac{s^2 + \omega_d^2}{s^2 + 2\zeta\omega_d s + \omega_d^2} \tag{13}$$

where $\omega_d = 2\omega = 2(2\pi f)$. This structure makes the controller be causal.

With the computation of u_{ca}, it is possible to obtain the grid-side converter positive sequence voltage given in (11) that must be synthesized. The oscillation on the DC-link voltage can be minimized with higher capacitor and the PWM Space Vector Modulation must be normalized in these conditions.

D. Close to No-Load Operation

One constraint presented in [2] is that the DFIG with the series compensator on the rotor side converter has problems concerning the close to no-load operation. When the stator current is zero, it is not possible to absorb or inject active power to regulate the DC-link voltage and for this reason an extra converter was used to play this role. However, his problem was not attacked in [3] and the problem lays on the start-up, when the system has no current flowing through the stator.

Here it is assumed that at the wind cut-in speed there will be enough power to compensate for the system losses. Furthermore, it is assumed as well that the capacitor voltage is at its nominal value. Under these conditions, the close to no-load operation is no longer a concern.

IV. Simulation Results

In this section, simulation results are presented to validate the theory. They were carried out using the 2MW wind turbine parameters given in [2] and presented in Table I.

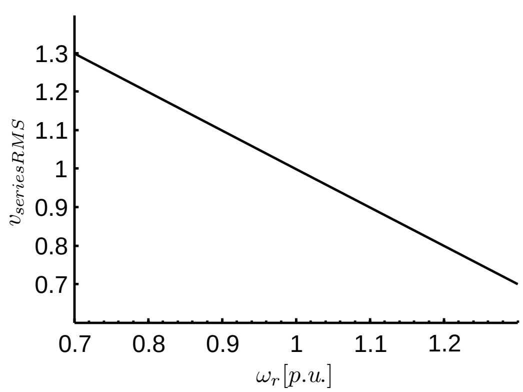


Fig. 4: Steady-state stator voltage (V_{rms}) as a function of rotor speed

Figure 4 shows the steady-state stator voltage as a function of the rotor speed. It is possible to see that the voltage amplitude varies depending on the speed because the stator has to deliver different powers for different speeds. On the other hand, the rotor power varies also, in order to keep the output power equal $1p.u.$ An additional advantage of this system is that it is expected that the generator efficiency will be higher than in conventional *DFIG* with parallel converter since the generator will be at the nominal voltage and flux when the stator is delivering its rated power.

Table I: Parameters of the induction machine

NOMINAL VALUES OF THE DFIG				
Rated power	P_n	$2.27MVA$		
Rated voltage (Y)	$V_{rms,l-l}$	$690V$		
Rated current	I_n	$1900A$		
Rated frequency	f_n	$60Hz$		
Number of pole pairs	n_p	2		
BASE VALUES				
Base voltage (phase-phase)	V_b	$690V$		
Base current	I_b	$1900A$		
Base impedance	Z_b	0.2105Ω		
PARAMETERS OF THE INDUCTION MACHINE				
Stator resistance	R_s	0.0022Ω	$\Leftrightarrow$	$0.01p.u.$
Rotor resistance	R_r	0.0018Ω	$\Leftrightarrow$	$0.009p.u.$
Stator leakage inductance	L_s	$0.12mH$	$\Leftrightarrow$	$0.18p.u.$
Rotor leakage inductance	L_r	$0.05mH$	$\Leftrightarrow$	$0.07p.u.$
Magnetizing inductance	M	$2.9mH$	$\Leftrightarrow$	$4.4p.u.$

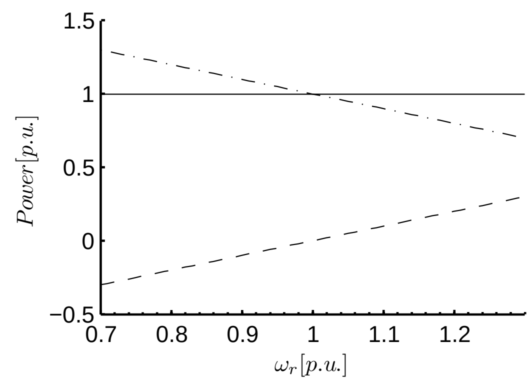


Fig. 5: Steady-state power. Grid power (continuous line), series power (dashed $--$ line) and stator power (dashed $-\cdot$ line),

The steady-state power as a function o rotor speed is shown in Figure 5, similar to the shunt grid-side converter case.

Figure 6 presents the dynamic behavior of the system when the generator is on its synchronous speed ($\omega_r = 1p.u.$). To get this result, it was considered that:

- Until $t = 0.5s$, the machine was not generating active power and let us consider the DC-link with its nominal voltage.
- At $t = 0.5s$, a step on the active power reference for the rotor side converter was given;
- At $t = 0.75s$ a negative sequence voltage was injected on the grid voltage. Only the DC-link controller was working;
- And finally, at $t = 1.0s$ the control action that cancels

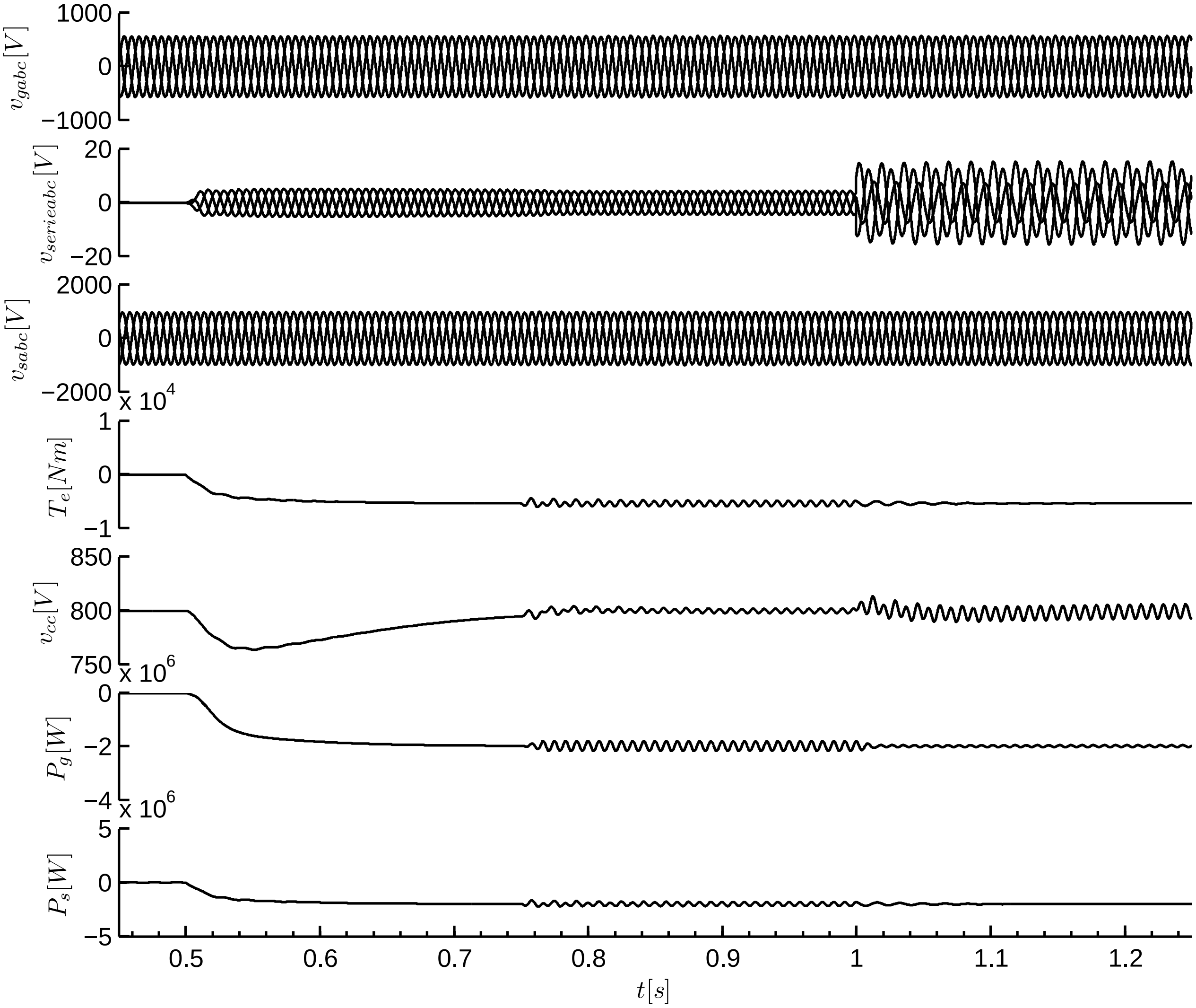


Fig. 6: Simulation results. From top to bottom: Grid voltages (v_{gabc}), series voltages ($v_{serieabc}$), stator voltages (v_{sabc}), electromagnetic torque (T_e), DC-link voltage (v_{cc}), power delivered to the grid (P_g) and machine active stator power (P_s)

the negative sequence was introduced.

The voltages on each part of the system are presented in the three first plots. It is possible to see that the amplitude of the series voltage is small on the condition of this simulation, where the DFIG is on the synchronous speed.

The DC-link voltage dynamic is also presented. Let us consider the DC-link on its nominal voltage and no power delivered to the grid. Under a step of 2MW on the active power reference at $0.5s$, the DC-link voltage drops and the controller acts to regulate it on the reference value (800V).

At $t = 0.75s$ a negative sequence voltage is added to the grid voltage (2%). Between $0.75s$ and $1.0s$, while the voltage unbalance is not corrected, the power delivered to the grid (negative signal) and the power delivered by the machine stator have both a 120Hz component. Furthermore, it is possible to see the undesired torque pulsations at 120Hz. It happens because the series voltage has only a positive sequence component until $1.0s$ required to keep the DC-link voltage at the desired level.

The torque pulsation is eliminated at $t = 1.0s$ when the series converter compensates the negative component of the grid voltage, keeping the stator voltage balanced. Due to the balanced voltages, the stator power was kept constant and even the power delivered to the grid has a significantly reduction of the oscillation, delivering a better power quality to the distribution system.

Summarizing, due to the unbalanced stator currents, the behavior of the torque is oscillatory when the negative voltage grid in not canceled. Under voltage unbalance condition, it is possible to see the moment the control action which cancels the grid negative sequence voltage is applied on the grid-side series converter, minimizing greatly the torque oscillations.

The grid active power pulsation is reduced since the grid currents has only a positive sequence component. Note that the DC-link capacitor voltage oscillation becomes larger. However, this is not a concern since the impact of this ripple on the converter output current (rotor side) and voltage (grid side) can be compensated by the modulation and the controller presented in (13) eliminates its impact on u_{ca} that will define the series compensator reference voltage.

V. Conclusion

This paper presents a configuration for connection of DFIG that reduces the problems of voltage unbalance on the wind turbine lifetime. Torque pulsations due to this unbalance are eliminated with the use of a series converter between the machine stator and the grid. A simple configuration to connect a DFIG with a series grid-side converter is presented. This scheme simplifies the series grid-side converter and its controller is based on the symmetrical components theory. The proposed controller greatly reduces torque oscillations as well as control the DC-link voltage. The number of switches used to implement the back-to-back converter is also reduced comparing to other configurations presented for series compensation. Simulations of a 2MW wind turbine are presented to demonstrate the good performance of the proposed approach.

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