WIND ENERGY CONVERSION SYSTEM BASED ON DFIG WITH THREE-PHASE SERIES GRID SIDE CONVERTER AND SINGLE DC-LINK

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Abstract – In this paper, a wind energy conversion system based on doubly-fed induction generator with an additional series grid side converter without transformer is proposed. Stator voltages may be compensated by series grid side converter under distorted and unbalanced grid voltage sags, thus avoiding over-current in the rotor, over-voltage in the dc-link, double-frequency oscillations in the electromagnetic torque, and rotor over-speed. Moreover, the control strategy of the proposed system allows reactive power to be injected during voltage sags. Simulation and experimental results are presented to evaluate the proposed system.

Keywords – Wind Energy Conversion System, DFIG, grid voltage disturbances, Additional Series Converter, transformerless.

NOMENCLATURE

DFIG Doubly-fed induction generator.
DSOGI Dual second order generalized integrator.
DSP Digital signal processor.
DV R Dynamic voltage restorer.
GSC Grid side converter.
LVRT Low voltage ride-through.
PI Proportional integral controller.
PLL Phase-locked loop.
PMSG Permanent magnet synchronous generator.
rms Root mean square.
RSC Rotor side converter.
SGSC Series grid side converter.
VOC Voltage-oriented control.
WECS Wind energy conversion systems.
Lp Inductor of the GSC filter.
rp Resistance of the inductor Lp.
lp Inductance of the inductor Lp.
εg Grid voltage.
v p Grid side converter’s voltage.
v Series grid side converter’s voltage.
i s Stator current.
r Rotor current.
λ s Stator flux.
λ Rotor flux.
r s Stator resistance.
r Rotor resistance.
l Stator inductance.
l Rotor inductance.
lm Mutual inductance.
c e Electromagnetic torque.
c m Mechanical torque.
J Moment of inertia.
F Coefficient of friction.
P Number of pole pairs.
P g Grid active power.
Q g Grid reactive power.
P s Stator active power.
Q s Stator reactive power.

I. INTRODUCTION

Wind energy is one of the most promising among many types of renewable energy sources, with increasing participation in the global electric matrix [1]–[3]. Most WECS are variable speed systems that use two main types of generators [4]–[6]: PMSG and DFIG. Among variable speed wind energy conversion systems, DFIG is the most widely used generator [6], [7] due to, in addition to other characteristics, advantages such as: controllable power factor, improvement of the system efficiency, durability, reduced mechanical stress, lower cost, reduced power converter rating (typically 30% of the generator rating), variable speed control, and four-quadrant active and reactive power control [5], [8]–[11].

However, since the stator windings of the DFIG are directly connected to the grid, these wind energy conversion systems based on DFIG are especially susceptible to grid voltage disturbances. In past years, disconnection of wind energy conversion systems was a possible solution to protect the wind system [12]–[14], however, with increasing wind power’s participation in the power grid, most grid codes require that wind energy conversion systems must remain connected when a grid fault occurs [7], [11], [15]–[19]. According to these grid codes, the wind energy conversion systems must be able to withstand voltage sags, i.e., the system must have LVRT
capability, and must act with reactive power compensation in order to collaborate in the grid voltage recovery [7],[11],[15]–[26]. In addition, some grid codes require that wind energy conversion systems remain connected even in the event of 2% steady-state and 4% short term voltage imbalances [12],[27].

In Brazil, the grid connection code requires that wind farm remains connected according to the LVRT capability curve presented in Fig. 1 [25]. According to the LVRT capability curve, the wind energy conversion systems must be able to withstand voltage sags between 10% and 15% for 5 seconds. Furthermore, from Fig. 1, the system must withstand during 0.5 milliseconds for a voltage sag of 80%. This grid connection code also requires the WECS to supply reactive currents to the grid proportional to the voltage sag.

![Fig. 1. Brazilian low voltage ride-through capability curve [25].](image)

To keep the generator connected to the grid under non-ideal conditions, it is necessary to mitigate the negative effects on the generation system under such conditions [28]. Several solutions have been proposed to reduce the impacts on the generator, such as introducing a crowbar in the rotor circuit of DFIG [26],[29],[30]; DVR [31]; modified control strategies [19],[32]–[34]; or additional converters at grid side [11],[13],[15]–[18],[35].

Solutions like the crowbar in the rotor circuit, DVR, and temporary stator disconnection do not have a good performance during a deep unbalanced voltage sag and they can cause large transient spikes in the generator currents and torque [17],[20]. Furthermore, DVR system requires protection circuits with by-pass switches to prevent overload in the converters. Such DVR system features make this solution unattractive economically [13].

Despite obtaining satisfactory responses to generalized voltage sags, the use of modified control strategies results in a compromised solution between the reduction of double-frequency oscillations in electromagnetic torque and the obtaining balanced stator and rotor currents [13],[15],[17],[20],[35]. Generally, control strategies choose to suppress the electromagnetic torque oscillations in detriment of balanced stator currents [35]. Thus, the unequal heating of stator windings caused by this imbalance in the stator currents will degrade the insulation of the stator coils and reduce their life span [32]–[34],[36]–[38].

Replacing the conventional parallel connection of the grid side converter by a series connection through series injection transformers configures as another solution to keep the WECS connected to the power grid during symmetrical or asymmetrical faults. This solution was investigated in [22],[39]–[42].

In [40]–[42], the series converter composed of three single-phase converters presented in [39] and [22] is replaced by a conventional three-phase converter, thus allowing the use of a simpler and unified control strategy. Despite the grid voltage imbalances compensation, the control strategy presented in [40] does not limit the fault currents and does not completely eliminate the oscillations in the active and reactive stator powers and in the electromagnetic torque. In [41] is proposed a control method that reduces the grid voltage unbalance and the oscillations of the electromagnetic torque by injecting negative sequence components of the stator voltage and rotor current, respectively. Although it achieves the proposed objectives, the method presented in this paper may not protect the electrical components of the DFIG by injecting unbalanced currents into the stator and rotor windings.

The control strategies presented in [22],[39]–[41] do not act on voltage sag compensation, not using the total capacity of the series converter. Differently, the control strategy employed in [42] acts on the grid voltage sag compensation during grid faults. However, despite obtaining stator voltage compensation, the overall system dynamics is worse than the conventional system dynamics.

With an additional series converter at grid side, known as SGSC, it is possible compensate grid voltage disturbances (such as distortions and voltage imbalances), thus compensating the stator voltage, reducing double-frequency oscillations in the electromagnetic torque, active and reactive power and obtaining compensated and sinusoidal stator currents simultaneously. This would further improve the LVRT capability of wind energy conversion systems based on DFIG. Furthermore, as demonstrated in [13],[35], the power flowing through the series grid side converter is proportional to the voltage sag, i.e., the series grid side converter rating needed to cope with a 10% voltage sag is approximately 10% of DFIG-based system rating and the total power losses of the series grid side converter (including series injection transformer losses) is around 2% of DFIG-based system rating. However, this scenario only occurs if the generator power is maintained at the pre-fault value. Some connection codes, such as the Brazilian one, do not require for severe faults of 80-90% proficiency that the active power be maintained at the pre-fault value. With this, the converter will handle a portion of the power even for severe sags.

There are mainly two ways to connect the additional series converter, one through series injection transformers [Figs. 2(a) and 2(b)] and another using the open-end winding of the DFIG [Fig. 2(c)]. In [13],[17],[35] are presented systems in which the additional series converter is connected between the GSC connection point and the DFIG stator terminals [Fig. 2(a)], while in [11],[16],[18] the additional series converter is connected before the grid side converter connection point. Presented results and performance of these topologies are similar despite the differences between the connection types.
In [15], Flannery and Venkataramanan also present topologies in which the additional series converter is connected in the DFIG stator open-end windings, as shown in Fig. 2(c).

![Diagram](image)

Fig. 2. Connection types for additional series grid side converter. (a) Connection between the grid side converter connection point and stator terminals. (b) Connection before the grid side converter connection point. (c) Connection with stator open-end windings.

In [18] is proposed a DFIG integration scheme with an additional series converter at the stator DFIG terminals acting as a DVR to improve the LVRT capability. According to [18], the use of series converter could result in additional benefits, such as active series filtering, reactive power compensation, and electronic isolation. With compensation control proposed in [18], over-current and over-voltage in the rotor windings and electronic isolation are presented and analyzed. The work also presents more complete experimental results for a grid voltage sag, demonstrating the compensation capacity of the proposed system and validating the controls employed in all three converters. In addition, the control strategy proposed for SGSC in this work is able to deal with voltage imbalances and harmonic distortions simultaneously, unlike the controls proposed in [46] and [47]. The present work also brings a detailed controller design to obtain the parameters of the controllers employed in the system.

In this paper, a wind energy conversion system based on DFIG with series grid side converter is proposed, i.e., a standard two-level voltage source inverter, fed Open-End Winding DFIG with single dc-link voltage and without a transformer, as shown in Fig. 3. The proposed system without series injection transformers has less complexity, lower cost, and reduced losses compared to the conventional system with additional series converter [45]. Moreover, the proposed system also compensates the voltages in the stator terminals of DFIG even during distorted and unbalanced grid voltage conditions, thus improving the LVRT. In addition to the series grid side converter, the proposed system is composed of a grid side converter, which ensures a regulated dc-link voltage and maintains a high grid power factor (through the grid current control), and a rotor side converter, which regulates the stator active and reactive power through a voltage-oriented control.

Compared to the conventional system, the proposed system does not require the use of any transformer (series injection transformer or a parallel transformer for connecting the GSC) and reduces the circulation current without using bulky components, resulting in a system with lower cost and weight and with high LVRT capacity.

The proposed system in this work was previously analyzed in [46] for a static voltage sag condition and in [47] for series active filter applications. In [46] and [47], the experimental results were obtained without DFIG and only validated the GSC and SGSC controls. In this work, simulation results for a dynamic voltage sag condition (i.e., with inception and clearance of the voltage sag) with harmonic distortions and imbalances are presented and analyzed. The work also presents more complete experimental results for a grid voltage sag, demonstrating the compensation capacity of the proposed system and validating the controls employed in all three converters. In addition, the control strategy proposed for SGSC in this work is able to deal with voltage imbalances and harmonic distortions simultaneously, unlike the controls proposed in [46] and [47]. The present work also brings a detailed controller design to obtain the parameters of the controllers employed in the system.

![Diagram](image)

Fig. 3. Proposed DFIG system with additional series grid side converter without transformers.

Since the series grid side converter is connected directly
to the terminals of DFIG without any transformer [unlike Fig. 2(c)], there will be a circulating current between the grid side converter and series grid side converter that must be suppressed by the control system (Fig. 3).

To reduce the circulating current without adding bulky components (as common-mode inductors to increase the zero sequence impedance [48], [49]), circulating current control strategies are presented as a simple and effective solution. Differently of previous works, which need a transformer for grid connection and do not discuss the circulating current issue, in this paper a control to reduce the circulating current is proposed and analyzed.

The control strategy of the proposed system ensures i) stator active and reactive power control, ii) compensated and sinusoidal voltages in the stator of DFIG during distorted grid voltage sag conditions, and iii) null circulating current between GSC and SGSC.

This work is organized as follows: in Section II the system models are described, while the control strategies are presented and analyzed in Section III. Simulation and experimental results are presented in Section IV and Section V, respectively, to validate the proposed system.

II. SYSTEM MODELS

A. SGSC and GSC Models

From the proposed system presented in Fig. 3, it is possible to obtain the series grid side converter and grid side converter models as follows [47],[50]:

\[
\begin{align*}
\varepsilon_{sk} &= v_{sk} + v_{tk} \\
\varepsilon_{pk} &= r_p l_p + l_p \frac{dv_{pk}}{dt} + v_{pk} \\
i_{sk} &= I_{sk} + i_{pk} \\
v_{o0} &= \left[\frac{1}{6} \sum_{k=1}^{3} (v_{k0} + v_{pk0})\right] \\
v_{ik} &= v_{ik0} - v_{o0} \\
v_{pk} &= v_{pk0} - v_{o0},
\end{align*}
\]

in which \( k = 1,2,3 \); \( r_p \) and \( l_p \) are the resistance and the inductance of the inductor \( L_p \), respectively; \( \varepsilon_{pk} \) are the grid voltages; \( v_{sk} \) are the DFIG stator voltages; \( v_{ik} \) are the voltages provided by the series converter; \( v_{pk} \) are the voltages provided by the grid side converter; \( v_{pk0} \) are the pole voltages of the grid side converter; \( v_{k0} \) are the pole voltages of the series converter; \( v_{o0} \) is the voltage between of central point of the grid (‘g’) and the central point of dc-link (‘0’); \( i_{sk} \) are the grid currents; \( i_{pk} \) are the DFIG stator currents and \( i_{pk} \) are the parallel currents through GSC.

In this configuration there is a circulating loop between SGSC and GSC, in which the following equations are derived [46],[47]:

\[
v_{ik} - v_{pk} = 0,
\]
in which

\[
\begin{align*}
v_{sk} &= v_{sk0} + v_{tk0} \\
v_{pk} &= v_{pk0} + r_p l_p + l_p \frac{dv_{pk}}{dt}.
\end{align*}
\]

From (7) to (9) it is possible to define the voltage \( v_o \) as follows:

\[
v_o = \sum_{k=1}^{3} v_{pk0} - \sum_{k=1}^{3} v_{k0}.
\]

The circulating current of the SGSC \( (i_{so}) \) and of the GSC \( (i_{po}) \) are defined by (Fig. 3):

\[
i_{so} = \sum_{k=1}^{3} i_{sk} \text{ and } i_{po} = \sum_{k=1}^{3} i_{pk}.
\]

Therefore, the circulating current between the converters can be written as a function of a single circulating current, i.e.:

\[
i_o = i_{so} = -i_{po}.
\]

Replacing (11) and (12) in (10), and taking into account that the stator voltages are balanced (i.e., \( \sum_{k=1}^{3} v_{k0} = 0 \)), the voltage \( v_o \) can be rewritten as a function of the circulating current:

\[
v_o = r_p i_o + l_p \frac{di_o}{dt}.
\]

B. DFIG Model

The vector model in the synchronous stator voltage frame (superscript ‘s’) of DFIG is [51],[52]:

\[
\begin{align*}
\varepsilon^s_s &= r_s i^s_s + d \lambda^m_s + j \omega_l \lambda^e_s \\
\varepsilon^e_s &= r_e i^e_s + d \lambda^e_s + j (\omega_s - \omega_l) \lambda^r_s \\
\lambda^m_s &= l_m i^m_s + l_r i^r_s \\
\lambda^e_s &= l_e i^e_s + l_r i^r_s \\
c_e &= P_m \sum (\lambda^r_s)^2 \\
P(c_e - c_m) &= \frac{J d\omega_s}{dt} + F \omega_s,
\end{align*}
\]

where \( \lambda^m_s = \frac{1}{\sqrt{2}} (x^m_s + j x^m_q) \) is the generic vector of the stator variables, i.e., voltage \( (\varepsilon^s_s) \), flux \( (\lambda^m_s) \), and current \( (i^m_s) \); \( \lambda^e_s = \frac{1}{\sqrt{2}} (x^e_s + j x^e_q) \) is the generic vector of the rotor variables, i.e., voltage \( (\varepsilon^e_s) \), flux \( (\lambda^e_s) \), and current \( (i^e_s) \); \( r_s \) and \( r_r \) are the stator and rotor resistances, respectively; \( l_m \) and \( l_r \) are the stator and rotor inductances, respectively; \( l_m \) is the mutual inductance between the windings of the stator and rotor; \( \omega_s \) is the frequency of the stator voltage; \( \omega_l \) is the electric rotor speed; \( c_e \) is the electromagnetic torque; \( c_m \) is the mechanical torque; \( J \) is the moment of inertia; \( F \) is the coefficient of friction; \( P \) is the number of pole pairs of the machine; \( \Im(z) \) is the imaginary part of \( z \); and the superscript ‘*’ represents the conjugate complex of the term.
III. CONTROL STRATEGIES

Fig. 4 shows the control diagram used in the proposed system. The control system consists of two control loops, one for GSC and SGSC and another for RSC. The grid side converter control has the function of controlling the dc-link voltage and the grid reactive power; while the series grid side converter control ensures compensated and sinusoidal stator voltage even during distorted voltage sag events. Furthermore, both GSC and SGSC control system have the function to keep null circulating current. Meanwhile, the rotor side converter control acts in controlling the rotor speed and regulates the stator active and reactive powers. The control loops will be detailed in the following sections.

A. Control of GSC

According to [53], the voltage over the dc link can be expressed as a function of the capacitors’ power. Also considering that the power of the grid is proportional to the power of the DFIG and the converters, the voltage of the dc link will be:

$$\frac{dv_c^2}{dt} = -\frac{2P_g}{C},$$

in which $v_c$ stands for the dc-link voltage, $P_g$ is grid active power, and $C$ is the dc-link capacitance.

Expressing the grid active power in the synchronous reference frame, in which $e_{ph}^e = 0$ and $e_{eq}^e = e_g$, the dc-link voltage can be rewritten as a function of the $q$-axis grid current, i.e.:

$$\frac{dv_c^2}{dt} = -\frac{2(e_g e_{eq})}{C},$$

while the grid reactive power ($Q_g$) is a proportional to the $q$-axis grid current:

$$Q_g = e_g e_{eq}.$$

The control loop of SGSC and GSC is presented in

Fig. 4. Schematic of control for SGSC, GSC, and RSC.

B. Control of SGSC

The stator voltages ($v_{s1}$ and $v_{s2}$) are also controlled by resonant controllers ($PR_{rs}$ block) and the output signals are added to the harmonic reference components ($e_{ph1}$ and $e_{ph2}$), resulting in the reference voltages ($v_{r1}$ and $v_{r2}$) that regulates the series converter to reduce and compensate imbalances and harmonic distortion at the DFIG stator terminals.

The harmonic reference components are extracted by subtracting the grid voltages ($e_{g1}$ and $e_{g2}$) by their respective fundamental voltages ($e_{gf1}$ and $e_{gf2}$). The fundamental components of the grid voltage are extracted by the DSOGI block (as shown in Fig. 4). Once this block is able to extract the positive sequence components, it is also able to filter the fundamental components of the grid voltage.

The reference stator voltages ($v_{s1}$ and $v_{s2}$) are obtained by the $Gvs$ block. The $Gvs$ block represents the product between the reference amplitude of the stator voltage ($V_s^*$ set as the rated of the stator voltage) and sinusoidal signals, whose phases are the estimated phases from grid voltages (i.e., $\theta_{g1}$ and $\theta_{g2}$). In other words, the stator voltage and the grid voltage
are synchronized. In this way, the series converter ensures balanced and sinusoidal voltages at the terminals of DFIG and eliminates critical problems that affect the DFIG during grid voltage disturbances.

C. Control of Circulating Current

The last control task is based on a resonant controller (PR\textsubscript{io} block), which regulates the circulating current \(i_0\) to zero, providing the reference circulating voltage \(v_0^*\). Therefore, the reference voltages \(v_{11}^*, v_{12}^*, v_{1p}^*, v_{1g}^*\), and \(v_0^*\) are used to define the switch states of SGSC and GSC.

D. Control of RSC

As mentioned before, traditional vector control can be employed at the rotor side converter. Thus, in the rotor side converter control loop a VOC is employed, which performs stator active and reactive powers control [51], [52]. From the DFIG vector model in the synchronous stator voltage frame, in which \(v_{sd} = 0\) and \(v_{sq} = v_x\), and neglecting resistive losses in the stator windings, the active and reactive powers (\(P_s\) and \(Q_s\), respectively) can be written as a function of the rotor currents, such that:

\[
P_s = -\frac{l_m}{l_s} v_r f_q q\]

\[
Q_s = \frac{l_m}{l_s} v_r \left( \frac{v_s}{l_m} \omega_s - i_{rd} \right).\]  

The reactive power can be controlled by \(i_{rd}\) regardless of \(i_{dq}\), thus featuring a fully decoupled control of stator active and reactive powers.

Then, making \(Q^*_s = 0\) to ensure a high power factor, the \(d\)-axis rotor reference current \(i_{rd}^*\) is determined by the output of a PI controller (PI\textsubscript{io} block) with reactive power error as the input signal (see Fig. 4). On the other hand, the \(q\)-axis rotor reference current \(i_{dq}^*\) is obtained from another PI controller (PI\textsubscript{ps} block) that regulates stator active power. Also, reactive power can be injected into the power grid during voltage sags using the rotor side converter or grid side converter, thus acting in the power grid recovery.

The \(dq\)-axes rotor currents provide the reference rotor voltages \(v_{sd}^*\) and \(v_{sq}^*\). Then, the reference voltages \(v_{11}^*, v_{12}^*, v_{13}^*, v_{1p}^*, v_{1g}^*\), and \(v_0^*\) are used to define the switch states of the rotor side converter, as shown in Fig. 4.

E. Controller Design

The design of the controllers is performed using the gains tuning techniques presented in [53]. In this section, the design of the circulating current loop controller (PR\textsubscript{io}) will be presented, while the gains of the other controllers can be similarly tuned.

From (13) it is possible to write the circulating current plant on terms of the Laplace operator \(s\):

\[
\frac{I_o(s)}{V_o(s)} = \frac{1}{s^2 + \omega^2}. \tag{25}\]

The block diagram of the circulating current control loop is shown in Fig. 5, in which the resonant controller is approximated by a PI controller for purposes of calculating the proportional and integral gains, since the gains of a resonant controller can be adjusted similarly to a PI controller [56].

\[
E \xrightarrow{PR_{io}} V_o \xrightarrow{G_i(s)} V' \xrightarrow{1/([p^2 + s^2])} L \]

Fig. 5. Block diagram of the control loop of \(i_o\).

In Fig. 5, \(K_{pio}\) and \(K_{lio}\) are the proportional and integral gains, respectively. Thus using the pole-zero cancellation, i.e., \(K_{pio} = \frac{\omega}{\omega_p}\), the transfer function of open-loop is:

\[
G_{io}(s) = \frac{K_{pio}}{l_p s} \left( s + \frac{K_{lio}}{K_{pio}} \right) = \frac{K_{pio}}{l_p s}. \tag{26}\]

From (26), the transfer function of closed-loop is:

\[
C_{io}(s) = \frac{1}{\tau_{io} s + 1}, \tag{27}\]

where \(\tau_{io} = \frac{l_p}{K_{pio}}\) is the time constant of the transfer function of the closed-loop system. The value of \(\tau_{io}\) is a design parameter that must be chosen according to the desired response speed for the closed-loop system [53]. Observe that:

\[
K_{pio} = \frac{l_p}{\tau_{io}} \tag{28}\]

\[
K_{lio} = \frac{\omega_p}{\tau_{io}}. \tag{29}\]

To calculate the control gains, the speed response was \(\tau_{io} = 0.8\) ms.

IV. PWM Strategies

In this section, the PWM strategies of the GSC and SGSC are presented. The PWM strategy of the RSC is presented in [46], [47].

The reference pole voltages are determined by [47]:

\[
v_{11}^* = v_{11}^* + v_x^* \tag{30}\]

\[
v_{12}^* = v_{12}^* + v_x^* \tag{31}\]

\[
v_{13}^* = v_{13}^* + \frac{v_y^*}{2} + v_x^* \tag{32}\]

\[
v_{p1}^* = v_{p1}^* + v_x^* \tag{33}\]

\[
v_{p2}^* = v_{p2}^* + v_x^* \tag{34}\]

\[
v_{p3}^* = v_{p3}^* + \frac{v_y^*}{2} + v_x^*. \tag{35}\]

The auxiliary voltage can be chosen arbitrarily since the maximum and minimum values of the pole voltages are respected. Thus:

\[
v_{x_{\text{max}}}^* = \frac{v_e^*}{2} - V_{x_{\text{max}}} \tag{36}\]

\[
v_{x_{\text{min}}}^* = -\frac{v_e^*}{2} - V_{x_{\text{min}}} \tag{37}\]

where \(V_{x_{\text{max}}} = \max\{v_{11}^*, v_{12}^*, v_{13}^* - v_y^*/2, v_{p1}^*, v_{p2}^*, v_{p3}^* + v_y^*/2\}\) and \(V_{x_{\text{min}}} = \min\{v_{11}^*, v_{12}^*, v_{13}^* - v_y^*/2, v_{p1}^*, v_{p2}^*, v_{p3}^* + v_y^*/2\}\).
During the sag event, the grid voltage also contains harmonic components with amplitude approximately 9%. Then, the auxiliary voltage $v_x$ can be written by a factor $\mu_x$ with $0 \leq \mu_x \leq 1$, thus:

$$v_x = \mu_x v_{x\text{max}} + (1 - \mu_x) v_{x\text{min}}.$$  \hspace{1cm} (38)

The switch states are defined by comparing the pole voltages with a high frequency triangular carrier PWM.

V. SIMULATION RESULTS

Two sets of simulation results are obtained. One set for an unbalanced voltage sag (Figs. 6 to 8) and another for a three-phase voltage sag of 80% (Figs. 9 to 11). In both sets a fundamental grid voltage of 220 V rms (phase voltage), a 650 V dc-link voltage, a dc-link capacitance of 100 µF, a stator active power of $-1.5$ kW, a rotor speed of 365 rad/s, and an electromagnetic torque of $-2.7$ Nm were considered. The parameters of the DFIG utilized in the computational simulation are shown in Table I. Discrete controllers with a sampling frequency of 10 kHz were used in the computational simulation and the values of the controllers gains are presented in Table II.

A. Unbalanced Voltage Sag

For the results with unbalanced voltage sag, a D-Type voltage sag [57] with a characteristic voltage of 80% of the rated voltage is applied at $t = 0.1$ s and cleared after 0.5 s. During the sag event, the grid voltage also contains 5th and 7th harmonic components with amplitude approximately 9.65% and 3.20% of the fundamental amplitude, respectively.

| Specification of the DFIG parameters. | Parameters | Values |
|--------------------------------------|------------|--------|
| Rated power                          | 2 kW       | 14.9 mH |
| Stator phase voltage                 | 220 V      | 1.4 mH |
| Stator resistance                    | 5.0 Ω      | 2      |
| Rotor resistance                     | 3.99 Ω     | 0.003 kg.m² |
| Stator inductance                    | 14.9 mH    | 1      |
| Stator/rotor turns ratio             | 1          |        |

| Specification of the controllers gains. | Controller | Proportional Gain ($K_p$) | Integral Gain ($K_i$) |
|----------------------------------------|------------|---------------------------|
| $P_{ds}$                               | 5          | 10                        |
| $P_{qg}$                               | 5 × 10⁴    | 0.3                       |
| $PR_{ds}$                              | 60         | 4 × 10⁴                    |
| $PR_{qg}$                              | 0.01       | 200                       |
| $PR_{d}$                               | 10         | 625                       |
| $P_{dl}$                               | 1.4 × 10⁴  | 0.61                      |
| $P_{ql}$                               | 1.4 × 10⁴  | 0.61                      |
| $P_{lu}$                               | 642.82     | 6.52 × 10⁴                |

In Figs. 6 to 8 are shown simulation results for an unbalanced voltage sag. Dynamic responses and a detail of the grid voltage sag inception are presented in Fig. 6. The grid voltages are shown in Fig. 6(a), while the stator voltages are presented in Fig. 6(b). Notice that the series converter ensures sinusoidal and balanced stator voltages despite the unbalance and distortion of the grid voltage. The series voltage of the SGSC rises at the inception of the voltage sag to compensate the grid imbalances and distortions [Fig. 6(c)]. The stator voltages is compensated with a reasonable dynamic response at the inception and at the clearance of the voltage sag. Moreover, it is possible to note that the 5th and 7th harmonic components of the grid voltages are compensated at stator voltages. Thus, the SGSC control ensures sinusoidal and balanced voltages at the DFIG stator terminals.

In Figs. 7(a) is possible to note that the grid currents are sinusoidal and balanced before the entry of the voltage sag. However, with the sag at $t = 0.1$ s, the grid currents become unbalanced and distorted. The control carried out by the GSC does not provide for the compensation of these disturbances in the grid currents, such as reduction of harmonic content and negative sequence components. Although the disturbances remain present in the grid currents, the GSC maintains the amplitude of the currents under control and guarantees the stability of the system. The stator currents, on the other hand, are sinusoidal and balanced, as shown in Fig 7(b), since the series converter maintains balanced and sinusoidal voltages at stator terminals. The $dq$-axes rotor currents in the synchronous reference frame are presented in Fig. 7(c) (top). It can be noted that the RSC control loop regulates the rotor currents to their respective reference value even during the voltage sag.

In Fig. 7(c) (bottom) is presented the result of the circulating current $i_{ds}$. Notice that the control assures a circulating current approximately null and without oscillations. Choosing $\mu_x = 0.5$ the task of controlling the circulating current is divided symmetrically between the GSC and the SGSC, similarly to the methodology used for dual inverters in [49], [58], [59], in which the task of reducing the circulating current is carried out by the two inverters. In fact, when $\mu_x = 0.0$ or $\mu_x = 1.0$, not only oscillations in the circulating current appear as the control and general stability of the system are impaired, since the circulating voltage is not more symmetrically compensated by the converters (GSC and SGSC). Therefore, in addition to the circulating current control loop is necessary to adjust $\mu_x = 0.5$ to maintain the system stability and ensure null circulating current.

Fig. 8(a) shows the dc-link voltage is regulated by its reference voltage of 650 V. At the inception of voltage sag, the dc-link voltage rises to approximately 652V. On the other hand, at the clearance of voltage sag, the dc-link voltage drops to approximately 648 V. Thus, the control system regulates the dc-link voltage to the reference value during the grid voltage sag and the dc-link voltage does not exceed the limits 2% of reference value neither at the inception nor at the clearance of voltage sag. It is worth mentioning here that the dc-link inertia constant is approximately 29 ms, a typical value for WECS [60] and approximately 6% of the grid fault duration. However, double-frequency oscillations appears in the dc-link voltage during the grid sag due the voltage imbalances. Even though, these oscillations represents less than 1% of dc-link voltage and they do not impair the system stability and performance.

Fig. 8(b) shows the result for active and reactive powers with transient oscillations. The stator active power is set to the reference value of $-1.5$ kW even during voltage sag event. During the grid voltage sag, the system supplies 120 var of...
reactive power to the grid, according to the Brazilian grid connection code that requires injection of reactive currents into the grid when a voltage sag occurs [25]. Both the stator and grid reactive powers \( (Q_s \text{ and } Q_g) \) are adjusted to this reference value during the fault [Figs. 8(b) and 8(c)]. When the sag is cleared and the grid voltages are restored, the stator and grid reactive powers are set back to null values, resuming operation with a high power factor both in DFIG and in the grid. Both active and reactive powers do not present double-frequency oscillations even with the presence of the grid voltage imbalances. SGSC compensates for these disturbances and thus prevents these oscillations from occurring in the active and reactive powers of the stator. However, the same is not true for the grid reactive power, which presents double-frequency oscillations during the grid voltage sag, since the control employed at the GSC does not provide for the compensation of these disturbances.

B. Three-Phase Voltage Sag

Simulation results for a three-phase voltage sag are presented in Figs. 9 to 11. For these results, a three-phase voltage sag of 80% of the rated voltage is applied at \( t = 0.1 \text{ s} \) and cleared after 0.5 s, in accordance to the requirements presented in Fig. 1. As for unbalanced conditions, the series converter ensures sinusoidal and compensated stator voltages despite the grid voltage sag [Fig. 9(b)]. The stator voltages is compensated with a reasonable dynamic response at the inception and at the clearance of the voltage sag. Also, the voltage of the SGSC rises to compensate the grid voltage sag, as shown in Fig. 9(c).

Fig. 10(a) shows that the grid currents rises up to nearly 12 A at the moment of the sag inception. However, the control system bring the grid currents back to the pre-fault value in 0.15 s, restoring the stability of the system. The stator currents are sinusoidal and do not present any value rise at the inception of voltage sag, since the series converters guarantees a smooth maintenance of the pre-fault conditions at the stator terminals [Fig 10(b)]. The \( dq \)-axes rotor currents
in the synchronous reference frame are presented in Fig. 10(c) (top). Also for this three-phase voltage sag, the RSC control loop regulates the rotor currents to their respective reference value. As for unbalanced condition, the circulating current $i_o$ is approximately null and without oscillations [Fig. 10(c) (bottom)].

Fig. 11(a) shows that the dc-link voltage is regulated by its reference voltage of 650 V even for a three-phase voltage sag. At the inception and clearance of voltage sag, the dc-link voltage rises to approximately 660 V. As for unbalanced grid voltages, the control system regulates the dc-link voltage to the reference value during the grid voltage sag and the dc-link voltage does not exceed the limits 2% of reference value, even with a inertia constant of 29 ms.

According to the Brazilian grid connection code, during the grid voltage sag of 80%, the system must supplies a 1 p.u. reactive current to the grid [25]. Thus, to meet the requirements of the grid code, both the stator and grid reactive powers ($Q_s$ and $Q_g$) are adjusted to supplies 300 var during the grid voltage sag [Figs. 11(b) and 11(c)]. To prevent high currents in the converters, the stator active power is reduced to zero, since the grid code does not require active power injection during these level of voltage sag [Figs. 11(b)]. When the sag is cleared and the grid voltages are restored, the stator and grid reactive powers are set back to null values and the stator active power returns to $-1.5$ kW, resuming the pre-fault operation.

Simulation results show the proposed system achieves the control objectives, ensuring a regulated dc-link voltage and sinusoidal and balanced voltages at the DFIG stator terminals, while the rotor side converter control ensures regulated stator active and reactive powers during a voltage sag event. Moreover, the proposed system also guarantees null circulating current between GSC and SGSC.

VI. EXPERIMENTAL RESULTS

The proposed topology has been tested in the laboratory to validate the performance of the series grid side converter compensation, the DFIG control through the rotor side converter, and the GSC dc-link voltage regulation. A three-phase autotransformer with voltage regulation is connected between the grid and the proposed topology. A dc machine was employed in the experiment as a primary machine to provide mechanical power to the DFIG (Fig. 12). The switching frequency of the converters (GSC, RSC and SGSC) and the sampling frequency used in the experiment were 10 kHz.

As shown in Fig. 12, the experimental set-up is based on four sets of SEMIKRON manufacturer (based on IGBT SKM50GB123D switches), and a DSP TMS320F28335 with a microcomputer equipped with appropriate plug-in boards and sensors. The results were obtained using an Agilent oscilloscope model DSO 7034A 350 MHz.

A capacitor bank as dc-link with 2200 µF and the GSC was connected to the grid through an inductive filter with 7 mH. The parameters of the DFIG utilized in the experiment are presented in Table I.
Fig. 10. Simulation results: (a) Grid currents in the stationary reference frame ($i_{gd}$ and $i_{gq}$). (b) Stator currents in the stationary reference frame ($i_{sd}$ and $i_{sq}$). (c) Top: $dq$-axis rotor currents in synchronous reference frame ($i_{erd}$ and $i_{erq}$); bottom: circulating current ($i_o$).

Fig. 11. Simulation results: (a) DC-link voltage ($v_c$). (b) Stator active and reactive powers ($P_s$ and $Q_s$). (c) Grid reactive power ($Q_g$).

Steady-state operation mode has been considered in the experimental tests. Experimental results are obtained for a three-phase grid voltage sag of 50%, with a dc-link voltage of 325 V, grid voltage (with sag) equal to 55 V rms (phase voltage), and reference stator voltage equal to 110 V rms (phase voltage). Decoupled stator active and reactive power controls were employed in the rotor side converter in order to validate the DFIG control capability. The rotor angle $\theta_r$ was obtained by an encoder coupled to the DFIG rotor shaft.

Figs. 13 to 15 present the experimental results. In Fig. 13(a), experimental results for grid and stator voltages are presented. The series grid side converter adjusts the stator voltages ($v_{s1}$ and $v_{s2}$) back to the rating value of 110 V despite the grid voltage sag ($e_{g1}$ and $e_{g2}$). The experimental results for stator voltages and currents are presented in Fig. 13(b). The results show compensated and sinusoidal stator voltages with high power factor, since null reactive power is generated.

In Fig. 14(a), experimental result for dc-link voltage is presented. It can be observed that the grid side converter control ensures a dc-link voltage ($v_c$) approximately 325 V. The result for circulating current ($i_o$) is presented in Fig. 14(b). It is noted that the GSC and SGSC control loops ensure approximately null circulating current even with grid voltage sag.

The experimental results presented in Fig. 15 were obtained from the voltage and current sensor measuring by the DSP digital vectors. The results of the $dq$-axes rotor currents in the synchronous reference frame are presented in Fig. 15(a). It is possible to notice that the rotor currents are regulated. Experimental results for DFIG stator active and reactive powers and their respective reference (i.e., 0 var for stator reactive power and $-300$ W for stator active power) are shown in Figs. 15(b) and 15(c), respectively. It can be noticed that the rotor side converter ensures stator active power approximately equal to $-300$ W and stator reactive power approximately null.
VII. CONCLUSIONS

In this paper, a wind energy conversion system based on DFIG with additional series grid side converter connected without transformer was proposed and analyzed. The control of the proposed system is able to maintain balanced and sinusoidal voltages at DFIG stator terminals, thus eliminating the problems related to unbalanced grid voltages, such as over-current in the rotor, over-voltage in the dc-link, double-frequency oscillations in electromagnetic torque and stator power, and rotor over-speed. Moreover, the control strategy of the proposed system keeps null circulating current between the grid side converter and the series converter, avoiding the need for bulky components. During unbalanced grid voltage sags, the grid currents become unbalanced and distorted as well. However, future works could explore more robust control for GSC in order to compensate these disturbances in the grid currents. The proposed system with additional series grid side converter is a solution to improve the low voltage ride-through capability of wind energy conversion system based on DFIG so that meets with grid code requirements.

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Fig. 15. Experimental results: (a) dq-axes rotor currents in the synchronous reference frame ($i_{dq}^*$ and $i_{dq}$). (b) Stator active power ($P_s$). (c) Stator reactive power ($Q_s$).

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