Optimized DFIG electrical design under voltage sags

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Abstract—**This paper addresses the dual problem (electrical-mechanical) of DFIG-based wind turbines under voltage sags and proposes an optimized solution that, starting from a design aimed to mitigate the mechanical loads in the structural components of the wind turbine, provides the electrical capability to meet the most demanding grid codes.**

Keywords—wind energy, variable speed drive, voltage sag compensators, vector control, passive component.

I. INTRODUCTION

Although doubly fed induction generator (DFIG) based wind turbines (WT) with partial rated power converter have been predominant in the first decade of the 2000s, in the second decade the WT manufacturers have increasingly shifted towards permanent magnet synchronous generator with full rated power converter (PMSG-FC) and the tendency is not expected to stop in the short-term future. The main reason explaining this decision is the sensitivity of the DFIG to grid faults, since its stator terminal is directly connected to the grid. The electrical problem has been extendedly studied in literature. When a grid fault occurs, a transient magnetic flux -often so called "natural flux" - appears in order to assure the continuity of the machine's flux, which cannot change instantaneously as the stator's voltage does [1]. Additionally, in asymmetrical faults, part of the stator's flux -so called "negative-sequence component"- rotates in opposite direction in comparison with the stator flux's direction in normal operation. The larger relative motion between the rotor's windings of the DFIG and the natural and negative-sequence components compared to the positive-sequence of the stator magnetic flux (the only component present in normal conditions) induces larger electromotive force (EMF) in the rotor circuit. As a result, overcurrent in the rotor-side converter (RSC) as well as overvoltage in the DC-bus appear, which might lead to the loss of low voltage ride through (LVRT) capability required by the utility grid operators and exceed the safety limits of the electrical components. For this electrical issue affecting to DFIG-base WT, several methods have been proposed: including control and hardware solutions [2]. However, none of these authors have analyzed the mechanical problem involved in LVRT events, thus, the existing electrical solutions have not been designed considering the influence they could have on the stresses suffered by the structural components. Causebrook *et al.* published in 2007 the contribution that is closest related to the approach of this paper [3]. However, it was based on a fixed-speed WT with induction generator and did not verify with simulation tools the impact of voltage sags in the mechanical structure of a WT. On the other hand, few articles ([4], [5]) can be found in the literature that analyze the foregoing mechanical issue, but they have not proposed any solution to mitigate these loads nor addressed the electrical problem explained above.

This paper makes a novel approach to the real challenge DFIG-based WT manufacturers face by analyzing the impact of the generator's electrical behavior under LVRT on the main mechanical components of the WT including the low-speed shaft, blades and tower. The starting point is understanding what is necessary to mitigate the mechanical loads. Then, the most convenient electrical solution that meets these requirements and further enhance the LVRT capability will be obtained. Therefore, an optimized design of the DFIG is proposed. Its electrical and mechanical response under grid faults will be simulated and compared to the conventional DFIG.

II. MECHANICAL PROBLEM

When a grid fault occurs, the voltage in the point of common connection (PCC) with the utility grid is reduced and the capacity of the WT to deliver electrical power to the grid does so. Every imbalance between the mechanical power coming into the generator from the high-speed rotating shaft and the electrical power going out from the generator to the grid, results in a generator speed's trip. Thus, under a voltage sag, the reduction of the output's electrical power accelerates the generator, which could reach dangerous speeds if fasts actions are not adopted. Precisely in order to avoid it, the pitch control reacts in a fraction of second to reduce the power captured from the wind and reset again the power balance. The weight of a 5 MW WT blade stands at around 20 tons [6]; hence, it is apprehensible that the sharp turn of such heavy structures induces large mechanical loads that are transferred along the different components comprising the structural chain of the turbine. Moreover, the sudden reduction of the braking electrical torque with the appearance of the voltage sag and the following change in the mechanical torque originated by the pitch control action, lead to a strong transient in the speed of the generator which also affects the rest of components in the powertrain, blades (since drag and lift forces are subject to the rotor speed) and, ultimately, the whole structural components.

Therefore, it is clear the mechanical interest of maintaining the generator speed constant under a voltage sag. As explained, the generator speed rise and following transient is originally due to the reduction of the output electrical power. Then, in order to avoid it, it is necessary to find an alternative way for the electrical power that cannot be delivered to the

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grid. There are two alternatives: store this energy with an energy storage system (ESS) or dissipate it by means of resistors. This paper is focused in the resistors alternative, but the ESS is another encouraging line.

All in all, the addition of braking resistors is a promising electrical solution to mitigate the large mechanical loads WT suffer under LVRT events. The reasoning performed also evidence that only active methods based in improvements on the control are insufficient by themselves and do not address the whole problem that grid faults represent, specially, to DFIG-based WT. Thus, hardware solutions are necessary, and resistors are the most convenient components to meet this need. From now on, an electrical design will be performed in order to find the optimal features of the solution, with the ultimate goal of providing LVRT capability and operation under safe electrical limits to the DFIG.

III. ELECTRICAL SOLUTION DESIGN

The connection of dynamic braking resistors (DBR) to improve the performance of DFIGs under LVRT is not a novel idea. Nevertheless, the reasoning from a mechanical point of view standing behind and the purpose of maintaining the electromagnetic torque as a method to mitigate the mechanical effects is certainly a novelty. Within the category of solutions based in dynamic breaking resistors, a wide variety coexists: protection schemes based in resistors connected in series with rotor's windings ([8], [9], [10]) as well as with stator's windings ([11], [12]) have already been proposed. These approaches are designed to minimize the severity of the electrical transient induced in the machine and power converters either by resetting the voltage in the terminals of the stator or limiting the current flowing through the machine´s circuit or by a combination of both of them.

For the purpose of this paper, however, it is also necessary to dissipate the power from the blades, hence, providing the rated braking torque. Some possibilities have been considered:

- Connecting a resistor in the DC-link. A simple solution that, however, implies oversizing the back-to-back converter of the DFIG so it can handle the rated power as well.
- Connecting resistors in series with the rotor windings. It would avoid the need of a full rated converter and can dissipate the power to give the rated torque. However, since the stator's voltage of the DFIG remains low during the grid fault, it is straightforward to determine that the spinning frequency of the machine's flux will be below the rated value -typically 50 or 60 Hz- and, as a result, the frequency of the electric variables in the stator will not be at grid frequency. This can be tolerable if the generator is off-grid (in case, for example, of an emergency stop), but it is not a solution when the generator is required to remain connected to the grid (as is mandatory in recent grid codes). In fact, most of the solutions proposed so far, based in control solutions or hardware solutions connected to the rotor circuit, have not taken into account the importance of maintaining the braking electromagnetic torque under the conditions and regulation subject to LVRT.
- Connecting resistors in series to the stator (Fig. 1). It allows to dissipate the rated power and providing rated torque as well as to boost the voltage in the stator's terminals to pre-fault levels, thus, assuring that the machine's flux not only reaches its rated value but also turns at rated frequency.

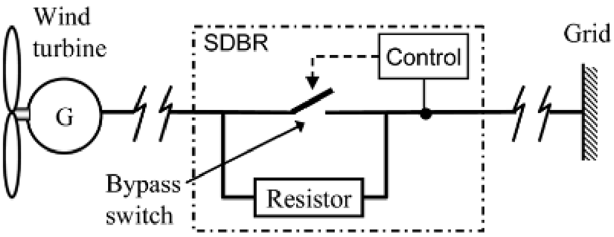

Fig. 1. DBR schematic arrangement [3]

Furthermore, the connection of DBR in series with the stator windings offers additional benefits regarding the reduction of initial electrical transient:

- The augmented value of the stator's resistance accelerates the damping of the natural flux. As it can be depicted from (1), during a three-phase fault the machine´s flux is composed, on one hand, by the flux that the remaining voltage in the grid generates and, on the other hand, by the natural flux. The amplitude of the latter one decays exponentially from its initial value to zero with the time constant of the stator. The initial value takes the difference between the previous voltage ($\widehat{V}_{pre}$) and the voltage during the fault ($\widehat{V}_{fault}$) seen by the stator, in other words, the depth of the dip.

$$\vec{\psi}_s^s=\frac{\widehat{V}_{fault}}{j\omega_s}+\vec{\psi}_{n0}\cdot e^{-t/\tau_s} \qquad (1)$$

where

$$\begin{cases} \tau_s=\frac{R_s+R_{DBR}}{L_s} \\ \vec{\psi}_{n0}=\frac{d\cdot\widehat{V}_{pre}}{j\omega_s} \\ d=\text{depth of the dip} \end{cases}$$

- For a given over-voltage in the circuit, the DBR limits the over currents in the circuit as it is by nature an impedance to the flow of electrons.
- DBR can be connected independently in asymmetric faults so that the negative-sequence component of the stator's voltage, which strongly affects the control of the machine, is minimized.

In normal operation, the DBR will be bypassed by three switches with bidirectional current conduction capability. In order to cut off the high currents of the stator, the most suitable solutions are thyristors or a contactor. Contactors are presented as the simplest solution. Their major drawback: significantly slower compared to any semiconductor, with operating times in the range between 10 and 100 ms. However, they have clear advantages as well:

- Reduced number of components and great robustness.
- Their power losses are negligible compared to semiconductor-based solutions.
- More cost-effective. In fact, most of the volume and cost of a contactor is brought by the arch extinction

mechanism. But, since the DBR provides a way for the current when the switch opens the circuit, there is no breaking capacity required for a contactor in this application, in other words, it can be simpler and cheaper.

For these reasons, contactors are found the most convenient and practical option for this application. The rest of the analysis of this paper will consider them as switching devices for the operation of the DBR.

Regarding resistors, it is essential to select a suitable single value for the resistors that allow the machine to maintain the torque under different power operating points, rotor speed and depth of voltage dips. In this way, current and voltage limitations of the machine as well as reactive current requirements (according to the depth of the positive-sequence component of the grid voltage) must be considered when the DBR is connected under a voltage dip. For that purpose, an optimization program has been created in *Matlab* to obtain the value of the resistors and the active output current needed to maintain the pre-fault torque operating inside the boundaries mentioned. The value obtained for the DBR that best meets all the criteria is 70% of nominal impedance. As it is summarized in Fig.2, the active output current, sum of the stator and GSC current, is the degree of freedom that the RSC control will count on to maintain the torque. The active current is obtained by means of (2).

$$P_{out} = (i_d^2 + i_q^2) \cdot R + i_q \cdot V_{grid} \tag{2}$$

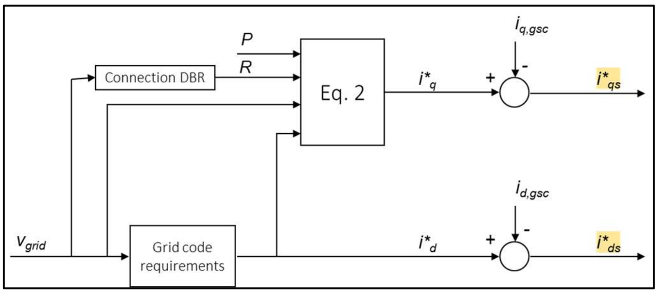

Fig. 2. Scheme of RSC vector control under a voltage dip

Besides, it should be noticed that the connection of the DBR makes a difference in the dynamic equations of the machine. These are normally derived under the assumption that the resistance of the stator windings is negligible compared to the grid voltage. Then, the machine's flux vector is aligned with the d-axis while the grid voltage vector does so with the q-axis. However, when the DBR is connected an additional resistance is connected which voltage drop cannot be neglected (in fact a voltage drop is what we are looking for).

The voltage equations, considering DBR, are expressed in (3) and (4).

$$V_{sd} = 0 = -\omega_s \cdot \psi_{sq} + R_{DBR} \cdot i_{sd} \tag{3}$$

$$V_{sq} = V_{grid} = \omega_s \cdot \psi_{sd} + R_{DBR} \cdot i_{sq} \tag{4}$$

The flux is not aligned with the d-axis anymore as defined in (5) and (6).

$$\psi_{sd} = \frac{V_{grid} - R_{DBR} \cdot i_{sq}}{\omega_s} = L_s \cdot i_{sd} + L_m \cdot i_{rd} \tag{5}$$

$$\psi_{sq} = \frac{0 + R_{DBR} \cdot i_{sd}}{\omega_s} = L_s \cdot i_{sq} + L_m \cdot i_{rq} \tag{6}$$

Ultimately, the new values of the machine's fluxes are used in the RSC control to relate the rotor currents to the stator currents, as shown in (7) and (8).

$$i_{rd} = -\frac{L_s}{L_m} \cdot i_{sd} + \frac{V_{grid} - R_{DBR} \cdot i_{sq}}{\omega_s \cdot L_m} \tag{7}$$

$$i_{rq} = -\frac{L_s}{L_m} \cdot i_{sq} + \frac{R_{DBR} \cdot i_{sd}}{\omega_s \cdot L_m} \tag{8}$$

IV. ELECTRICAL SIMULATIONS

The electrical performance of the optimized DFIG is validated using an electrical model in *Simscape* which includes the electrical parameters of the Repower 5M and connects the machine to a 33 kV grid via a 5.5 kVA transformer. The short circuit ratio of the point of connection to the grid is 20. The DBR is composed by three resistors of 0.07 Ω (one in each phase).

Regarding the electrical performance, two aspects are fundamental to meet the grid operator requirements. Firstly, when the grid fault occurs, a reactive current must be injected proportional to the voltage change in the positive-sequence system. In this way, Germany is one of the most demanding countries and sets this proportion at any value between 2 and 6 times the voltage drop [13]. The second aspect comes once the fault has been cleared: the active power must be recovered in less than 1 second. Both requirements should be met at any given operating point, regardless the output power, slip of the machine and type of fault. From all the simulations performed, two of the most representative are shown in Fig.3 and Fig.4.

In Fig.3, the optimized DFIG is operating at rated power with the DBR bypassed by the contactors. At t = 0.3 s, a 90% depth three-phase dip occurs, and the appearance of the natural flux leads ultimately to a peak (and following transient) in the generator torque. However, 15 ms after the fault, the contactors open and the current start flowing through the DBR. The vector control of the machine forces the machine to deliver a reactive current with rated value that dissipated power in the DBR and helps to maintain the generator torque. At t = 0.8 s, the grid voltage is reset again to normal value. From the point of view of the machine, this is seen as another disturbance, thus generating another transient in the torque of the machine. When the control notices the grid voltage level is back, it stops injecting reactive current and closes the contactors to bypass the DBR again. Finally, avoiding the use of the blades to maintain the torque during the fault allows the active power to recover in less than 100 ms once the fault is cleared.

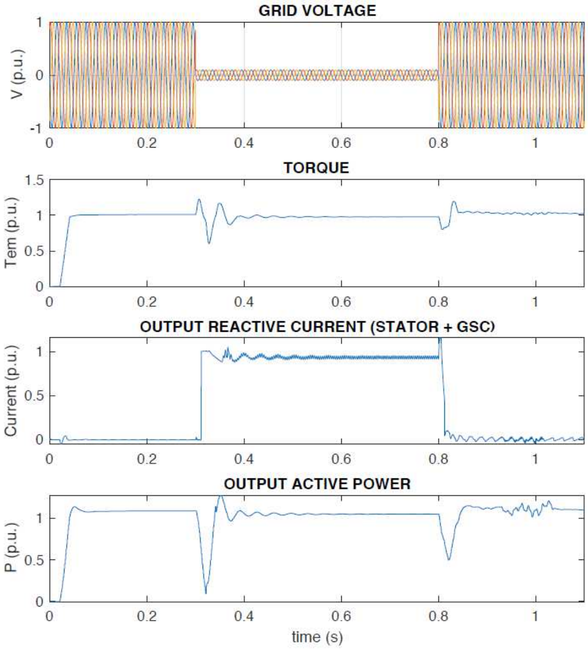

Fig. 3. Electrical results for a 5MW DFIG based WT under 500 ms 90% depth 3-phase voltage sag

In Fig.4, the response of the optimized DFIG at rated power under a single-phase fault is presented. At t = 0.3, the voltage of one of the phases drops dramatically to 10% of its rated value. This type of fault not only generates a natural flux but also a negative-sequence component that produces a stronger transient than symmetrical faults. On the other hand, the positive-sequence voltage drops one third of the change in the faulty phase. In other words, a 90% single-phase dip means a 30% positive-sequence voltage reduction. In this way, the vector control forces the machine to deliver reactive current at 60% of rated output current and manages the remaining current capacity available to keep the output power constant. In this case, the control detects the fault and only opens contactor of the faulty phase, thus connecting one resistor. Again, after the fault, at t = 0.8, the active power recovery is achieved in less than 100 ms.

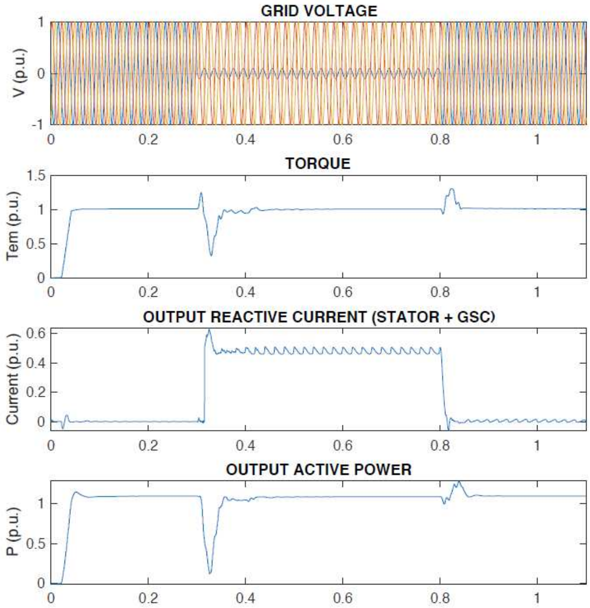

Fig. 4. Electrical results for a 5MW DFIG-based WT under 500 ms 90% depth single-phase voltage sag

V. MECHANICAL SIMULATIONS

In order to compare the mechanical performance between the optimized DFIG with contactors and the normal DFIG, simulations have been performed using *FAST* v8 as it is a recognized and well-known model for WT control design. Developed by NREL, *FAST* provides a 5 MW baseline WT model which is mainly based on the design information of the Repower 5M. *FAST* includes an interface which links to *Simulink*, where DFIG's dynamics and vector control, according to the changes discussed, are implemented parallelly. Baseline torque and pitch controllers, also provided by NREL, are used. In this way, the impact of the electrical behavior of the DFIG on the mechanical loads calculated by *FAST* can be assessed.

In Fig. 5, the mechanical loads in the baseline and optimized DFIG are compared under a 90% depth three-phase dip lasting 500 ms.

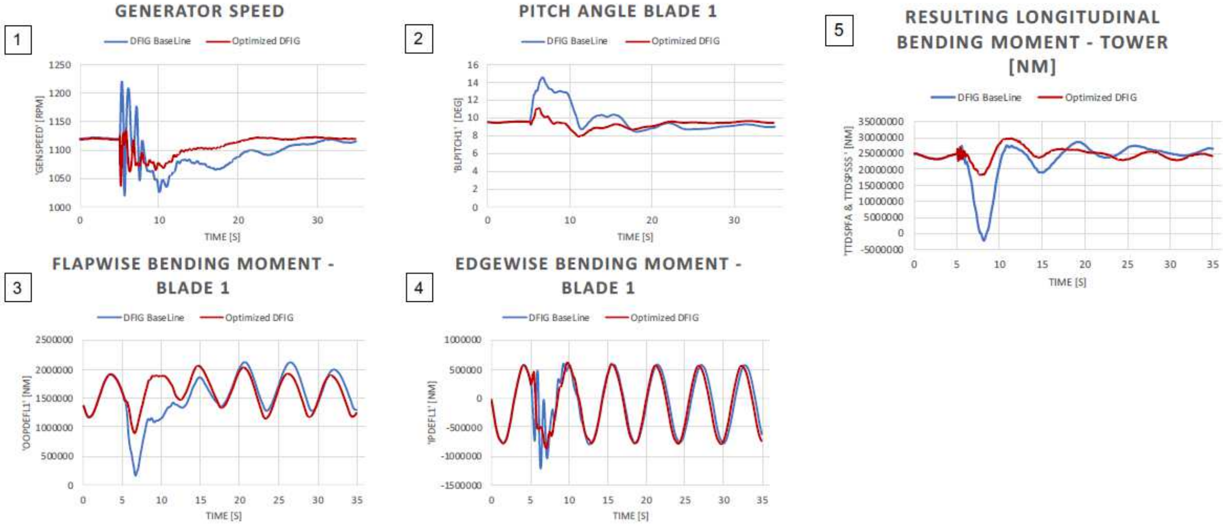

Fig. 5. Mechanical results for a 5MW DFIG-based WT under 500 ms 90% depth 3-phase voltage sag

In this simulation, the initial states are set so the WT is operating at steady state conditions, this is 14 m/s horizontal wind, generator rotating at 1119 rpm and rated output power (5MW). At t = 5s, the fault takes place and produces a strong disturbance in the generator speed as it creates a power imbalance between the input and output of the generator. In the conventional DFIG, the only way to reduce this power imbalance is reducing the power captured from the wind by increasing very fast the pitch angle of the blades. As a result, severe mechanical moments are suffered not only by the blades but also by the rest of mechanical components, including the tower. Moreover, although the fault is cleared after 500 milliseconds, the steady state is not achieved again until 30 seconds later. On the other hand, the optimized DFIG connects the DBR a few tens of milliseconds after the fault and avoids the blades to further increase their pitch angle. The fact of resetting the power imbalance with the DBR brings a substantial reduction of the mechanical loads, both peak values and transient time, compared to the conventional DFIG.

Since grid faults are events considered for the mechanical sizing of a WT, from the point of view of a manufacturer, the reduction brought by the optimized DFIG could be translated into a lighter and more cost-effective mechanical design for the same electrical features of the machine or, on the other hand, a stiffer and more reliable WT for the same mechanical design and cost of its components. Either way, it is an attractive solution.

VI. CONCLUSION

Grid faults not only threaten the capability of DFIG-based to meet these grid codes but also lead to oversize of the structural components so they can handle the large mechanical forces induced during these events, thus, increasing the price of the WT. This work proposes a DBR as the best solution to address both problems. Firstly, it has been showed through simulation how dissipating power in the DBR during the fault prevents the blades to sharply increase their pitch angle and leads to a substantial reduction in the magnitude of the bending moments suffered by the WT. On the other hand, from an electrical point of view, it has been analyzed the influence of the DBR connection in the conventional vector control of the DFIG, which is usually developed under the assumption of a negligible stator resistance. Finally, the LVRT capability of the optimized DFIG has been proved by showing reactive current injection and short active power recovery time under different type of faults. The results are promising and provides an attractive solution to solve the problems of conventional DFIG-based WT.

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