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A Critical Review of Contemporary Issues Related to DFIG

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Abstract

The DFIG is a type of induction machine which has been serving extensively in the WEC system. Many researchers have worked on the DFIG and its integration to the grid system, proposed control schemes and designs for the DFIG. However, there have not been a comprehensive critical review on the contemporary issues related to the DFIG. This paper presents a critical review of the contemporary issues related to DFIG. The research findings of this paper are the issues related to the DFIG ranging from the unbalanced voltage dip which results to an induction of very large torque pulsations and DC ripples in the rotor circuit; the preferences and relativities on which control strategy is best for the DFIG considering the FOC and the DTC control schemes, and down to the LVRT issues. The contemporary issues relating to the DFIG operation and their effects on the DFIG operation are also discussed.

Keywords: Doubly-fed Induction Generator, Wind Energy Conversion System, Synchronous speed

1.0 INTRODUCTION

Wind generated power is argued to be the most reliable and sustainable renewable power owing to its obvious advantages like low capital cost, low pollution rate, variable speed operation etc [1]. The successful generation of electric power from the wind power conversion technology was pioneered in the early 1970s [2]. Some of the European countries adopted this technology at the time which accounted for nearly one-quarter of the entire power generated [3]. The early designs of wind energy generation were operated strictly on fixed wind turbine systems. Those old wind turbine systems were mostly synchronous generators which operated strictly at synchronous parameters. A more recent approach or design now focuses on the different types of induction generators (IG). Although the simple induction generators were preferred to synchronous generators, however, they still had some drawbacks such as reactive power utilization and unregulated voltage profile during variable rotor speed [4].

The solutions to those setbacks associated with simple induction generators were seen in electronic power converters [5]. Unlike other conventional power systems, the wind power system faces the challenge of irregular wind characteristics such as the random wind speed which can be extremely variable and turbulent [6]. This prompted the establishment of standard grid codes for the integration of the wind farm into the grid system, these grid codes are commonly authorized by grid operators and are mainly for large-scale wind farms connected to transmission networks. The basic requirements common to various countries for wind power integration into the grid includes; frequency regulation ability, reactive power support and fault ride-through [7].

Most recently, in an attempt to explore green energy, power engineers have developed and simulated various wind conversion systems employing the DFIG, In their study, Amevi and Essel [8] presented a DFIG model, where the rotor speed was efficiently stabilized with a negligible variation relative to the wind speed with a pitch angle using a PID controller, in a related study, Aman et.al [9] presented the modeling, rapid control prototyping, and hardware-in-the-loop testing for real-time simulation and control of a grid-connected doubly fed induction generator (DFIG) in a laboratory-size wind turbine emulator for wind energy conversion systems, and this time the effectiveness of the control strategy employed was validated using Opal-RT real-time simulator (OP5600), which effectively and simultaneously controlled the DC-link voltage, active and reactive power of the machine. Due to the enhancement in the wind energy conversion systems using the DFIG, many researchers have delved into investigating so many applications and developed lots of the DFIG designs, and various issues relating to the

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DFIG operation has been observed and investigated. Hence, this paper presents a critical review of the contemporary issues related to the operation of DFIG. This study, therefore deals with some of the contemporary issues related to the DFIG. It highlights the different areas that many researchers have contributed in the operation of DFIG and reviews some of the contemporary issues associated with the DFIG. There are many issues relating to the operation of DFIG, however, the major issues are centered on; Unbalanced grid voltage issues, Control strategies of the DFIG, and the Low Voltage Ride-through of the DFIG.

2.0 SYNOPSIS OF DOUBLY-FED INDUCTION GENERATOR (DFIG)

A typical grid connected DFIG is shown in fig.1. the stator of the DFIG is connected through a transformer to the grid, while the rotor of the DFIG is connected to the grid via slip rings and mostly back-to-back connected power electronic converters. The DFIG can successfully operate on variable speed and frequency operation while controlling the active and reactive power generation of the system. It is a very good alternative to synchronous generator since it can operate like a synchronous generator at sub-synchronous and super-synchronous speed. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed while minimizing the mechanical stress on the turbine during the gusts of wind. The power electronic converters of the DFIG can be tuned to regulate the absorption and generation of real and reactive power to and fro the grid, thus eliminating the need for installing capacitor banks [10].

The overall control scheme of the DFIG is divided into two subsystems namely the electrical and mechanical control systems. These controls have distinct job descriptions but their main aim is to control the power injected into the grid [11].While the active power control is done by the rotor side converter (RSC), the reactive power control is done by both the RSC and the grid side converter. The mechanical component of the DFIG system plays the role of ensuring optimal mechanical power extraction from the turbines with reduced mechanical losses using the pitch adjustment technique.

The electrical component of the DFIG system ensures the voltage and current limits of both the grid and the machine are not exceeded and that the DC-link voltage and RSC terminal voltage are within range. It also goes further to ensure the standard grid codes as regards power quality and fault ride-through of the DFIG is met.

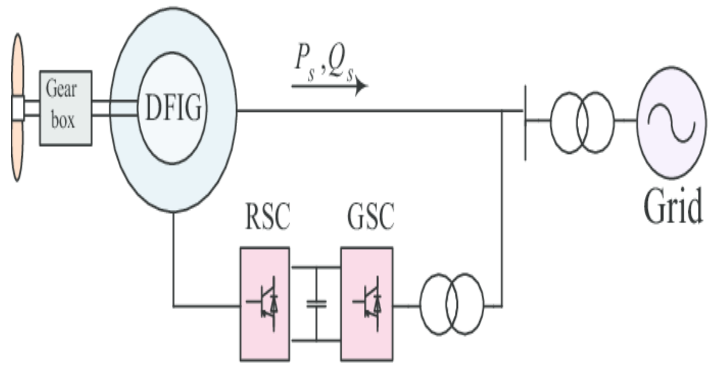

Figure 1: Grid connected DFIG [12].

The positive (dq)+ and negative (dq)- synchronous rotating reference frames are the most popular expressions conventionally used to model the DFIG based on the fifth-order two-axis representation, and the model of DFIG is commonly known as the "Park model" [13]. Fig.2. depicts the equivalent circuit model of the DFIG, where RSC and GSC is the rotor side converter and grid side converter respectively, Pm, Ps and Pr are the mechanical power, stator and rotor power respectively.

where V_{ds}, V_{qs}, V_{dr}, V_{qr} are the direct and quadrature components of the stator and rotor voltages respectively; R_s, R_r are the stator and rotor resistance of the DFIG;
I_{ds}, I_{qs}, I_{dr}, I_{qr} are the direct and quadrature components of the stator and rotor currents respectively, Ψ_{ds}, Ψ_{qs}, Ψ_{dr}, Ψ_{qr} are the direct and quadrature components of the stator and rotor flux respectively, ω_s, ω_r are the synchronous and rotor speed of the DFIG respectively.
L_s, L_m, L_r are the stator inductance, magnetizing inductance and rotor inductance respectively.

3.0 UNBALANCED GRID VOLTAGE ISSUES

Unbalanced grid voltage occurs due to unsymmetrical faults, which induce unbalanced voltage and current values into the grid.

This phenomenon has been given little or no attention by researchers, while the symmetrical fault analysis has been investigated by many researchers. In reality, however, unsymmetrical faults happens much more frequently than symmetrical fault [14]. This can occur in a weak power grid and during normal operation as identified in [15-17]. Under this unbalanced voltage state, the DFIG produces an electric torque which has very large pulsations at twice the grid frequency, which can cause wear and tear of the gearbox, acoustic noise at low levels, and at high levels can damage the rotor shaft, gearbox and induce large voltage ripple in the dc link of the back-to-back voltage source converter that can damage the dc capacitance [14, 17].Recently, interest has been developed towards controlling the effect of the unbalanced grid voltage on the DFIG, literature [17] presented the "grid flux oriented" control scheme which was aimed at enhancing the standard speed and reactive power control with controllers that can compensate the issues related to unbalanced voltage grid by eliminating the large torque and reactive power pulsations. However, the control scheme did not consider the grid side converter in his analysis, which leaves the DC link unprotected during unbalanced grid voltage conditions. On the control system of DFIG under unbalanced grid voltage, [17, 19] presented a feedforward loop on the classical-field oriented current (FOC) controller to reduce the resulting torque ripple, which [14] agreed was simple and robust.

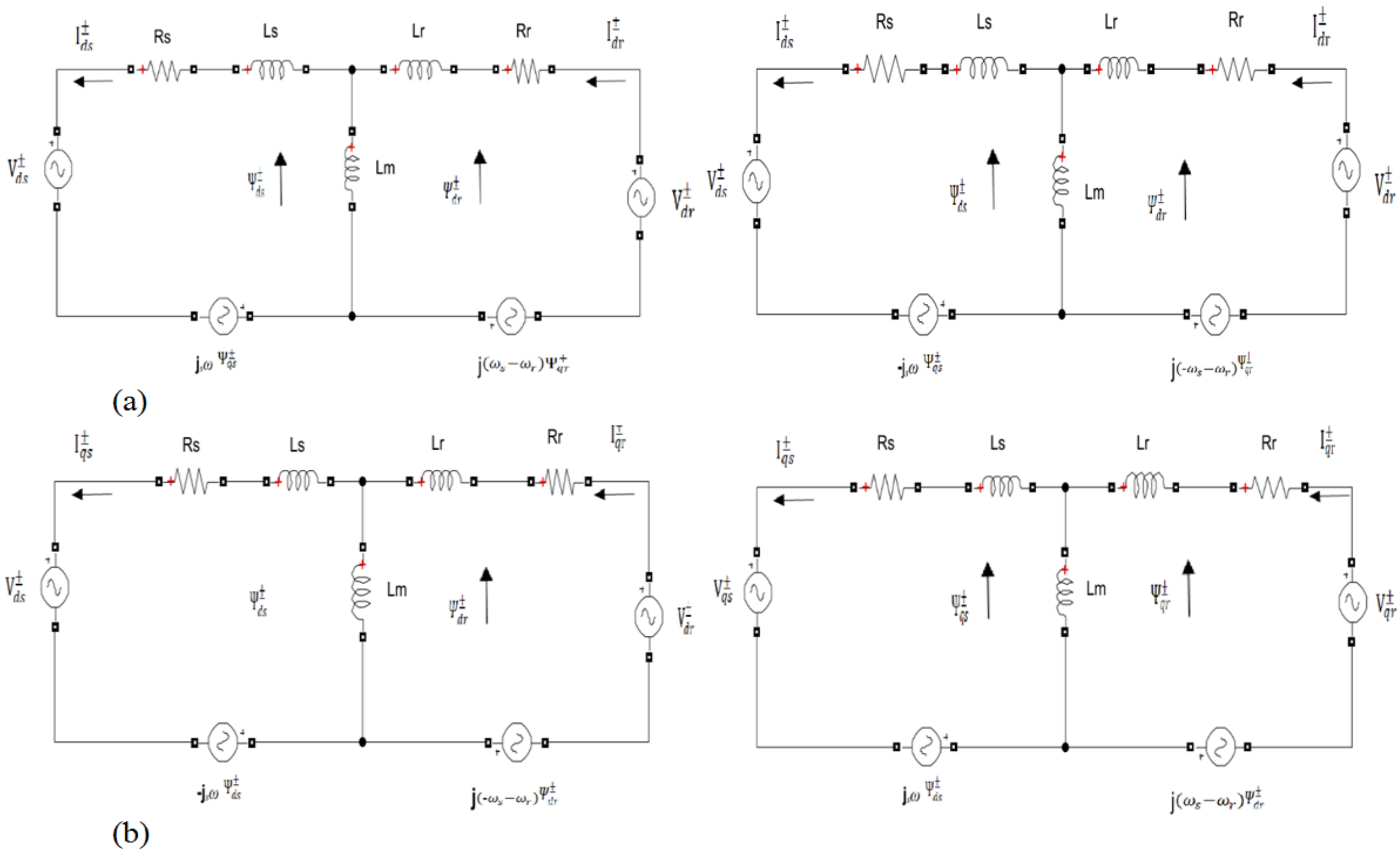

Figure 2: Equivalent circuit model of the doubly-fed induction generator (DFIG). (a) Equivalent circuit model of the DFIG in the positive dq reference frame rotating at the synchronous speed ω_1; and (b) equivalent circuit model of the DFIG in the negative dq reference frame rotating at the synchronous speed ω_2.

However, its ability was dependent on the filter. Literatures [20-25] worked on the detailed definition of the instantaneous active and reactive power that can be used to model and operate the grid connected VSC under unbalanced grid voltage conditions. In a related work, [18] proposed a STATCOM controlled grid VSC which supplies reactive power to make up for the unbalanced grid voltage. Its performance depended on the current ratings of grid VSC and impedance between the fault location and the generator terminal. A dual-sequence field-oriented controller (FOC) was proposed in [14], the rotor VSC was controlled to limit the torque pulsation, and the grid VSC was controlled to limit the dc voltage ripple. The results of the proposed control scheme effectively reduced the torque pulsations and dc ripples. To solve this problem, however, the scheme was limited to dedicated grid systems, when in reality, the doubly-fed induction wind generator is mostly found in rural areas where the grid system is very weak.

4.0 CONTROL ISSUES OF DFIG

Since the development of the DFIG for wind power conversion and integration into the grid, a number of control strategies of the DFIG has been developed and implemented by researchers, ranging from the common vector control schemes of DFIG to the Direct torque control of the DFIG and some other control configurations springing out.

4.1 *Vector Control Approach*

This is the most common control strategy of the DFIG. It basically involves transforming the 3-phase variable of the synchronous axes (a,b,c) into the d-q reference frame. A lot of work has been done extensively with the vector control strategy [14, 17, 26, 27]. The Vector or Field oriented control (FOC) is seen as the standard technique for the control of induction machines in general [18, 28].

4.1.1 Dual Sequences—Positive and Negative Sequences Field-Oriented Current Controller

Assuming the DFIG itself is symmetric, the voltage equations of positive and negative *dq* sequences in generator convention are listed as in equation (1).

$$\begin{bmatrix} v_{ds}^{\pm} \\ v_{qs}^{\pm} \\ v_{dr}^{\pm} \\ v_{qr}^{\pm} \end{bmatrix} = \begin{bmatrix} -R_s i_{ds}^{\pm} & -(\pm\omega_s \Psi_{qs}^{\pm}) & -\dfrac{d\Psi_{ds}^{\pm}}{dt} \\ -R_s i_{qs}^{\pm} & +(\pm\omega_s \Psi_{ds}^{\pm}) & +\dfrac{d\Psi_{qs}^{\pm}}{dt} \\ -R_r i_{ds}^{\pm} & -(\pm\omega_s - \omega_r)\Psi_{qr}^{\pm} & +\dfrac{d\Psi_{dr}^{\pm}}{dt} \\ -R_s i_{ds}^{\pm} & -(\pm\omega_s - \omega_r)\Psi_{dr}^{\pm} & +\dfrac{d\Psi_{qr}^{\pm}}{dt} \end{bmatrix} \quad (1)$$

In (1), ω_s is the stator electrical angular velocity, and ω_r is the rotational speed of rotor times the number of pole pairs $\omega_m \cdot P$.

The positive and negative sequences are completely decoupled as shown in (1), thus the DFIG can be controlled in positive and negative *dq* sequences independently [14]. The controller of rotor VSC is designed from (1), which uses rotor voltages to control stator currents, and uses stator currents to control active and reactive power as shown in Fig.3.

In rotor VSC controller, the cross-coupling terms between *d* and *q* are $(\pm\omega_s - \omega_r)\Psi_{qr}^{\pm}$ and $(\pm\omega_s - \omega_r)\Psi_{dr}^{\pm}$. They are different in positive and negative sequences. In order to completely decouple *d*- and *q*-axes, these cross-coupling terms are feedforwarded and added with the outputs of PI controllers. A unique FOC for the DFIG, called stator-FOC was presented in [29-31] that had the system model represented in the synchronously rotating *dq* reference frame. This algorithm allows a decoupled control of the dual sequence (positive and negative sequence of P and Q) by regulating the *dq* components of the rotor currents that are injected to the DFIG [32], [33], and [34]. The FOC current control algorithm allows a decoupled control of the dual sequence (positive and negative sequence of P and Q) by regulating the *dq* components of the rotor currents that are injected to the DFIG [35]. In this control strategy, the rotor side acts as a current controlled converter whose variables are referred to a rotating reference frame that is oriented alongside the stator magnetic flux vector position as shown in fig.4. Literatures [29, 36] gave a detailed description of the FOC for DFIG.

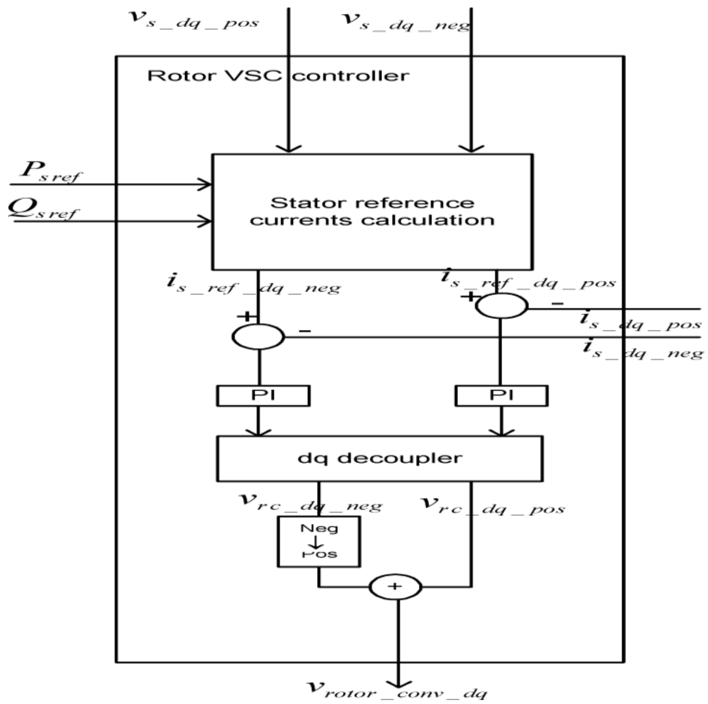

Figure 3: Dual sequence current controller of rotor VSC [12]

Recently, the sensor-less FOC or Direct Torque Control has been argued to be a better alternative to FOC especially when the DFIG is operating at a super-synchronous mode [39] and also the sensor-less nature of the DTC simplifies the model and makes it easier.

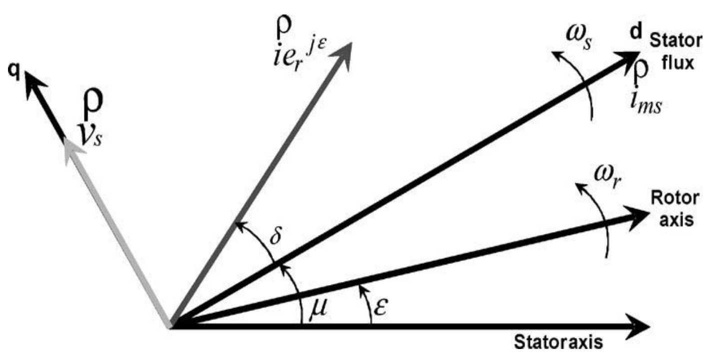

Figure 4: Vectorial diagram in the dq reference frame, considering a field-oriented control scheme [32].

4.2 *Direct Torque Control (DTC) Scheme*

The Direct torque control, also known as the sensor-less vector control was introduced in the late 90's [38, 39]. While the FOC is based on stator current control in the field rotating reference frame using PWM inverter control, the DTC is based on stator flux control in the stator fixed reference frame using direct control with the inverter switching [40]. A lot of comparative works have been carried out on the use of either FOC or DTC for the control of DFIG [37, 41, 42]. Unlike the FOC, the DTC does not require any current regulator, coordinate transformation and PWM signal generator, it is also very simple and controls the torque of the machine in both steady-state and transient state [41]. However, it becomes difficult to control torque of the at sub-synchronous speeds, and has setbacks of high current and torque ripples as well. Therefore, some researchers, [41], picks the FOC over the DTC, while many others [37, 42] prefers the DTC as regards to its simplicity and good torque control.

4.3 Low Voltage Ride-through Issues

In electrical power engineering, fault Ride Through (FRT), sometimes referred to Under-Voltage Ride Through (UVRT) or Low-voltage Ride Through (LVRT) is the capability of electric generators to stay connected in short periods of lower electric network voltage (voltage dip). It is needed at distribution level to prevent a short-circuit at High voltage or Extra High voltage from causing a wide-spread loss of generation. A voltage dip or voltage sag is a term referred to when there is a short reduction in rms voltage which can be caused by a short-circuit, overload or starting of electric motors.

The LVRT capability of DFIG under symmetrical voltage dip has been studied and investigated by many researchers [43-45], but DFIG characteristics during unsymmetrical voltage sag has been seldom looked into by the likes of [14], who argued that unsymmetrical faults occur more frequently than the symmetrical fault. The most obvious challenge during a symmetrical fault condition has been observed to be the stator transient overcurrent which a relatively effective solution has been proposed in [43-45] mainly consisting of the crowbar circuit. The most obvious issues faced during unsymmetrical voltage dip in DFIG is the large electric pulsation and voltage ripple in the dc-link of the back-to-back VSC that may decrease the lifetime of the dc capacitance. Literatures [19] and [35],wrote on the control system of a DFIG during unbalanced grid voltage situation where a feed-forward loop on classical field-oriented current (FOC) controller to limit torque ripple was used, which according to [14], is simple and robust. Literature[14] gave a theoretical analysis of DFIG under unsymmetrical fault, and presented two methods to limit both torque pulsation and dc voltage ripple using the delay cancellation method which [14], picked over the low pass filter method, the focus was on how to improve the performance of DFIG itself under unsymmetrical voltage integrated with a strong power grid, but the analysis on how to use DFIG to improve grid performance when it is connected with a weak power grid such as to limit the grid voltage unbalance is missing.

4.4 *FOC Control with Rotor-connected Low-Pass* Filter: Proposed solution to large torque pulsations of a DFIG during an unsymmetrical voltage dip

This FOC control performs an accurate separation of positive and negative sequences of the DFIG variables. It is based on the fact that the negative sequence component would appear as a second-order harmonic in the synchronous rotating frame i.e., positive *dq*, and the positive sequence component would appear as a second order harmonic in the negative synchronous rotating frame i.e., negative *dq*. The low-pass filter will be used to bypass the dc values and suppress the high-frequency oscillations. The schematic description of this method is shown in fig.5.

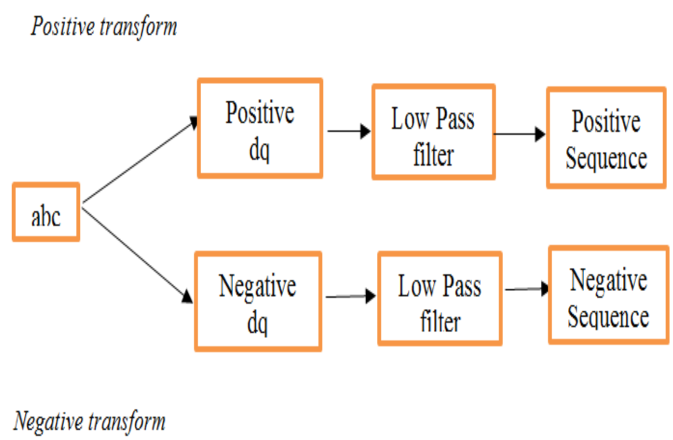

Fig. 5: Separation of positive and negative sequences by low-pass filter

The main interest of the work is to curtail the large torque pulsations on the rotor circuit caused by unsymmetrical voltage dip. To that effect, the low pass filter will be integrated on the rotor circuit which would filter out the large torque pulsations. To validate the efficiency of the low pass filter with respects to solving the identified problem, a 10kW DFIG model would be simulated on MATLAB/Simulink software package, an unsymmetrical fault will be initiated on the system, and hence, the response to normal operation of the DFIG, the response of the system during unsymmetrical voltage dip with and without the low pass filter will be simulated and the results will further be analyzed.

5.0 CONCLUSION

In this paper the major contemporary issues related to the DFIG are reviewed. The contributions many researchers have made in the successful operation and integration of the DFIG-wind turbine system into the grid are also highlighted and reviewed. There are so many contributions from researchers on how to solve the issues relating to the DFIG. some of these issues have not been arrested effectively and still gives room for more research work to be done especially on the area of the fault ride-through of the DFIG during an unsymmetrical fault situation. A field-oriented control scheme with rotor connected low pass filter is proposed as a means of reducing the large torque pulsations experienced by a grid-connected DFIG during unsymmetrical voltage dip, However, this is still currently under study.

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