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Detailed Investigation and Performance Improvement of the Dynamic Behaviour of Grid-Connected DFIG-Based Wind Turbines with Fuzzy based LVRT Controller

Bukke Sanjeev Naik[1], P Amrutha[2]

[1]*M.Tech, Sri Krishna Devaraya University, Anantapur, Ananthapuramu dist, AP*
[2]*Asst.Prof, Sri Krishna Devaraya University, Anantapur, Ananthapuramu dist, AP*

Abstract: *This paper presents a comprehensive study of the fuzzy based LVRT of grid-connected DFIG-based wind turbines. It provides a detailed investigation of the transient characteristics and the dynamic behaviour of DFIGs during symmetrical and asymmetrical grid voltage sags. A detailed theoretical study supported by computer simulations is provided. This paper also provides a new rotor-side control scheme for DFIG-based wind turbines to enhance its LVRT capability during severe grid voltage sags. The proposed control strategy focuses on mitigating the rotor-side voltage and current shock during abnormal grid conditions, without any additional cost or reliability issues. As a result, the DFIG performance is improved and utility company standards are fulfilled. Computer simulations are used to verify the expanded ride-through capability of the novel strategy and its effective performance compared to the conventional control schemes.*

Keywords: *Low voltage ride through (LVRT), Fuzzy based LVRT (FLVRT), Conventional Control Schemes (CCS).*

I.INTRODUCTION

In recent years, there has been a huge increase in global demand for energy as a result of not only industrial development, but also population growth. Consequently, the rise in consumption of traditional fossil fuels has led to many serious problems such as energy shortages, pollution, global warming, the shortfall of traditional fossil energy sources, and energy insecurity. These factors are driving the development of renewable energy technologies, which are considered an essential part of a well-balanced energy portfolio [1]-[4]. Wind power is thought to be the most promising near-term alternative energy. As renewable energy sources grow in popularity, wind power is currently one of the fastest growing renewable sources of electrical energy [3], [4].

More than 54 GW of wind power was installed in 2016, and it is expected to be higher in 2017 [1], [2]. With the increased presence of wind energy in the power system over the last decade, a serious concern about its influence on the dynamic behaviour of the electric power network has arisen [4]-[6]. Therefore, it becomes essential that grid-connected wind turbines behave similarly to conventional power plants and support the power network during normal and abnormal grid conditions. This has required many countries to develop specific grid codes for operation and grid integration of wind turbines. Among these grid codes, two main issues are of special concern for engineers in the area of power and energy: a) active and reactive power control in normal conditions, and b) Low-Voltage Ride-Through (LVRT) capability during grid faults, or more succinctly, Fault Ride-Through (FRT) capability [4], [6].

In addition to the progress made in the creation of adequate grid codes for the proper utilization of wind energy, a significant improvement has been achieved in the design and implementation of robust energy conversion systems that efficiently transform wind energy. The Doubly-Fed Induction Generator (DFIG)-based wind turbine has become one of the most favourable choices in wind power generation. This is due to the prominent advantages that it has compared to the other energy conversion systems that are currently available in the market. However, the dynamic response of the DFIG to grid voltage transients is the most serious problem [7]-[9].

DFIG-based wind turbines are sensitive to voltage sags during grid faults. This is due to the partial-scale back-back power converters that connect the rotor of the generator to the power grid. Faults in the power system, even far away from the location of the turbine, can cause an abrupt drop of the grid voltage which leads to an over-voltage in the DC bus and an over-current in the rotor circuit of the generator [10]-[13]. Without any protection scheme, this can lead to power converter damage. Moreover, it may also increase the speed of the turbine above the rated limits if not properly designed, which will threaten the safe operation of the turbine [10]-[16]. Therefore, the LVRT ability of DFIG-based wind turbines during grid faults are intensively investigated in order to provide proper solutions that can protect the turbine during abnormal conditions on the grid.

The objective of this work is to provide a comprehensive and simplified study of the dynamic behavior of grid connected DFIG-based wind turbines under LVRT conditions using fuzzy logic controller. Detailed analysis of the fuzzy logic based LVRT of DFIGs, including the voltage sag profile, transient characteristics and the behaviour of the DFIG at the moments of voltage sag, as well as the subsequent voltage recovery, is investigated. A simplified dynamic model of the DFIG is used to investigate the performance of the wind energy generation system under the influence of symmetrical and asymmetrical grid faults. This work also provides a detailed description of the most cited and commonly used LVRT solutions by improving the Rotor-Side Converter (RSC) control strategies (active methods). It describes the basic

operation principle, advantages and disadvantages of each proposed solution. In the end, a new rotor-side control scheme for DFIG-based wind turbines is developed to enhance its LVRT capability during severe grid voltage sags.
The proposed control strategy focuses on mitigating the rotor-side voltage and current shock during abnormal grid conditions, without any additional cost or reliability issues. As a result, the DFIG performance is improved and the utility company standards are fulfilled. Computer simulations are used to verify the expanded ride through capability of the novel strategy and its effective performance compared to the conventional control schemes.

II. DFIG BASED WIND POWER GENERATION SYSTEM

2.1 *DFIG BASED WIND POWER GENERATION*

At present, commercial wind turbines mix and match a variety of innovative concepts with proven technologies for both generators and power electronics. Different wind turbine configurations can be obtained by combining an induction or synchronous generator with fully or partially rated power converters [10], [17], [18]. The state-of-the-art variable speed wind turbine generators are categorized by two major types: Permanent Magnet Synchronous Generators (PMSGs)-based wind turbines with fully rated power converters and DFIG based wind turbines with partially rated power converters, as shown in Fig. 1 and Fig. 2, respectively. The DFIG is a perfect solution for systems with limited variable-speed range, e.g. ±30% of the synchronous speed.
The reason is that the power electronic converter has to handle a fraction (20–30%) of the total generated power compared to The back-to-back power converter in the DFIG system consists of two converters, i.e., a Rotor-Side Converter (RSC) and a Grid-Side Converter (GSC), which are connected back to-back by a dc-link. Between the two converters, a dc-link capacitor is placed as energy storage in order to limit voltage variations (or ripple) in the dc-link voltage. With the RSC, it is possible to control the torque, the speed of DFIG as well as the active and reactive powers at the stator terminals. The main objective for the GSC is to keep the dc-link voltage constant. It can also be used to control the reactive power flowing from or to the power grid [8], [17]-[21].
DC-link over-voltages may arise as a result of wind turbine response to unbalanced grid faults or load shedding situations [10], [12]-[14]. In this case, the direction of the power flow is reversed and the current flows to the dc-link. Therefore, the DC-link voltage must be limited to its rated value. This can be achieved by using a DC-side crowbar circuit that consists of a chopper and a resistor connected across the DC–link of the converters, as shown in Fig. 2. This configuration can limit the DC bus voltage from exceeding the safe operating range by short-circuiting the dc-link through the chopper resistors.

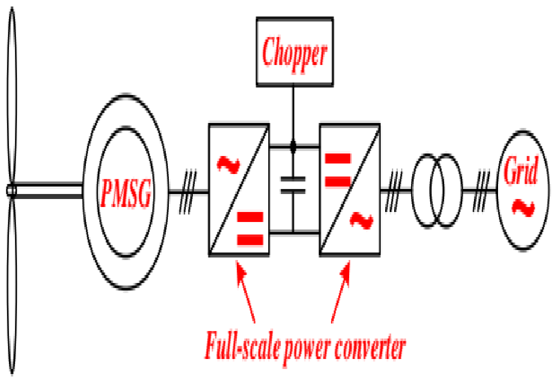

Fig.1. Wind turbine configuration of the PMSG-based wind turbine with fully rated back-back converters.

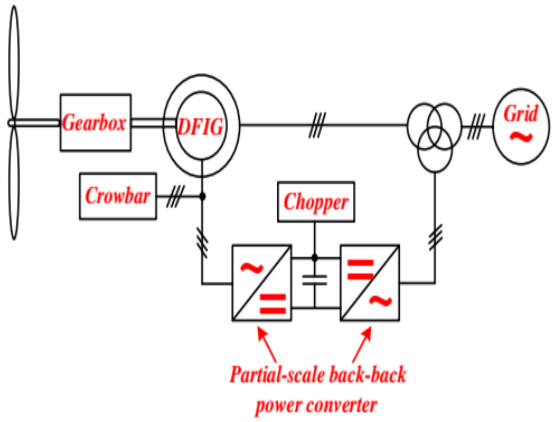

Fig.2. Wind turbine configuration of the DFIG-based wind turbine with partially rated back-back power converters and a gearbox.

2.2 *DYNAMIC MODELING OF DFIG*

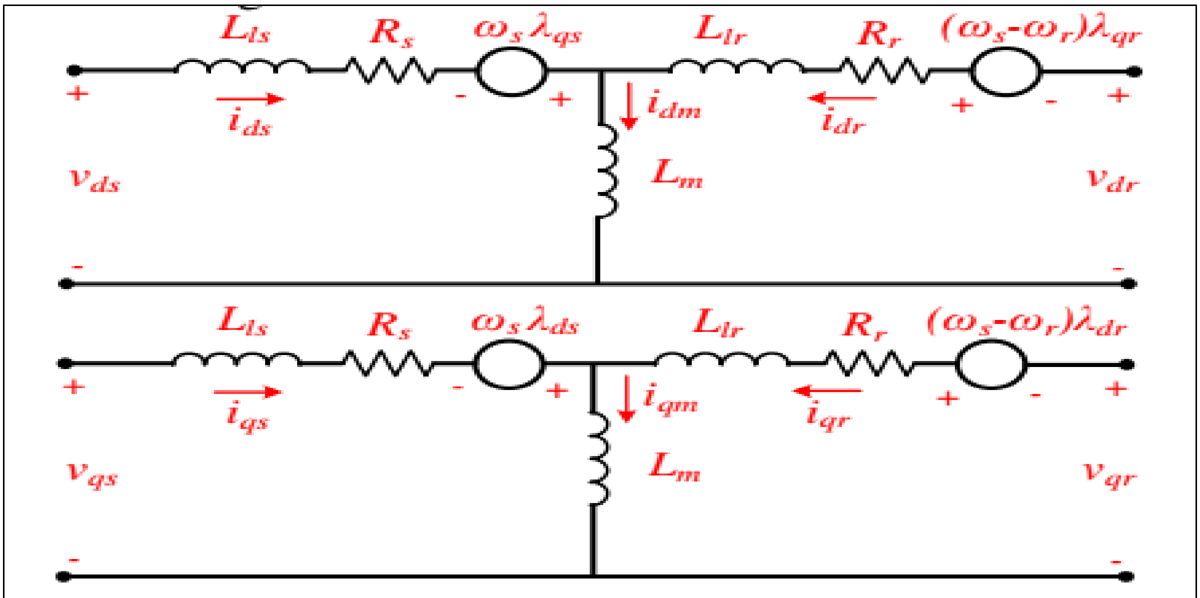

Fig. 3. Equivalent circuit of the DFIG in the *dq*-synchronous reference frame

The operating principle of the variable speed DFIG can be conveniently analysed by the classical rotating field theory with the well-known Park and Clarke transformations [21], [22]. Since the DFIG can be regarded as a traditional induction generator with non-zero rotor voltage, its dynamic equivalent circuit in the dq-synchronous reference frame can be modelled as shown in Fig. 3. The full-order dynamic model of DFIG in the synchronous rotating reference frame can be described as given [21]-[23]:

$$\begin{cases} v_{ds} = r_s i_{ds} + \dfrac{d\lambda_{ds}}{dt} - \omega_s \lambda_{qs} \\ v_{qs} = r_s i_{qs} + \dfrac{d\lambda_{qs}}{dt} + \omega_s \lambda_{ds} \\ v_{dr} = r_r i_{dr} + \dfrac{d\lambda_{dr}}{dt} - (\omega_s - \omega_r)\lambda_{qs} \\ v_{qr} = r_r i_{qr} + \dfrac{d\lambda_{qr}}{dt} - (\omega_s - \omega_r)\lambda_{dr} \\ \lambda_{ds} = L_s i_{ds} + L_m i_{dr} \\ \lambda_{qs} = L_s i_{qs} + L_m i_{qr} \\ \lambda_{dr} = L_r i_{dr} + L_m i_{ds} \\ \lambda_{qr} = L_r i_{qr} + L_m i_{qs} \\ L_s = L_{ls} + L_m \\ L_r = L_{lr} + L_m \end{cases} \tag{1}$$

where the subscripts "s" and "r" represent the stator and rotor sides, r_s and r_r are resistances of the stator and rotor windings, L_m is the magnetizing inductance, L_{ls} and L_{lr} are the stator and rotor leakage inductances, λ_s and λ_r are the stator and rotor magnetic flux linkages, v_s and is are the stator voltage and current, v_r and i_r are the rotor voltage and current, ωs is the electrical angular velocity of the synchronous reference frame, and ω_r is the electrical angular velocity of the rotor. It is shown in [23] that several simplifications can be made to the system given in (1) since the DFIG-based wind turbine is considered to be part of an electrical system that includes other components such as the power converters and electrical networks. The objective of the following analysis is to find a direct relationship between the stator and rotor voltages, currents and flux linkages. It will be assumed that the RSC acts as a current source where the objective of the DFIG is to supply a certain power to the grid by controlling the injected rotor currents. First, the stator flux-oriented synchronous reference frame, where the q-axis is aligned to the positive-sequence stator flux, is applied to the DFIG full-order model given in (1). Neglecting the stator resistance, the rotor voltage equations can be expressed as [24]:

$$v_{dr} = \left(r_r + \sigma L_r \frac{d}{dt}\right) i_{dr} - (\omega_s - \omega_r)\sigma L_r i_{qr} + \frac{L_m}{L_s}(v_{ds}) \tag{2}$$

$$v_{qr} = (\omega_s - \omega_r)\sigma L_r i_{dr} + \left(r_r + \sigma L_r \frac{d}{dt}\right) i_{qr} + \frac{L_m}{L_s}(v_{qs} - \omega_r \lambda_{ds}) \tag{3}$$

Where $\sigma = 1 - \frac{L_m^2}{L_s L_r}$, the previous equations can also be written in a matrix format as:

$$\begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} r_r + \sigma L_r \frac{d}{dt} & -(\omega_s - \omega_r)\sigma L_r \\ (\omega_s - \omega_r)\sigma L_r & \left(r_r + \sigma L_r \frac{d}{dt}\right) \end{bmatrix} \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} + \frac{L_m}{L_s} \begin{bmatrix} v_{ds} \\ v_{qs} - \omega_r \lambda_{ds} \end{bmatrix} \tag{4}$$

Equation (4) holds for both steady-state and dynamic conditions. It provides a direct relationship between the instantaneous values of the stator and rotor dq-voltages to the dq rotor currents. The stator flux is normally estimated by integrating the stator voltage. During steady-state conditions, with neglecting r_r and L_r and approximating $\frac{L_m}{L_s} \approx 1$, the RSC AC-side output voltage is approximately sV_s (referred to the rotor side), where s is the slip and, V_s is the magnitude of the steady-state stator voltage. Since the slip of the DFIG is normally limited between −0.3 and 0.3, then according to equation (4), the RSC needs to be able to output at least 30% of the stator voltage and thereby provide a minimum of 30% of the generator ratings. A specified safety margin is normally required. If a sudden voltage sag happens at the stator terminals, the necessary rotor terminal voltage could be directly determined from (4) such that the rotor current will not be affected and remains unchanged. However, since the RSC rating is limited and cannot generate the necessary rotor voltage, a large transient in the rotor current will appear during grid voltage sags. Considering that the DFIG fifth-order model, given by (1), is linear, and applying the Laplace transform, the dq-stator currents in the synchronous reference frame can be expressed as [23]-[25]:

$$\lambda_{ds} = \frac{s + {}^{1}/_{\tau_s}}{s^2 + 2\frac{1}{\tau_s}s + \omega_s^2} v_{ds} - \frac{L_m/\tau_s(s + {}^{1}/_{\tau_s})}{s^2 + 2\frac{1}{\tau_s}s + \omega_s^2} i_{dr} \tag{7}$$

$$\lambda_{qs} = \frac{-\omega_s}{s^2 + 2\frac{1}{\tau_s}s + \omega_s^2} v_{ds} - \frac{L_m/\tau_s(s + {}^{1}/_{\tau_s})}{s^2 + 2\frac{1}{\tau_s}s + \omega_s^2} i_{qr} \tag{8}$$

Equations (7) and (8) show that stator flux linkage depends on stator voltage and rotor current, explaining the behaviour of the DFIG during grid faults. If a voltage sag happens at the stator terminals and rotor current is kept constant, the stator flux starts to oscillate with the stator frequency (ω_s) and the oscillation damping depends on the stator time constant (τ_s). During asymmetrical faults, a negative sequence will appear and also force oscillations but with a frequency equal to (2ω_s) [23], [26], [27].

III . FUZZY LOGIC BASED LVRT CONTROLLER (PROPOSED METHOD)

This paper proposes fuzzy based LVRT controller for Rotor side converter of DFIG to enhance the LVRT capability of DFIG. Proposed method block diagram representation is shown in fig.4 and fig.5 shows fuzzy based LVRT block diagram respectively.

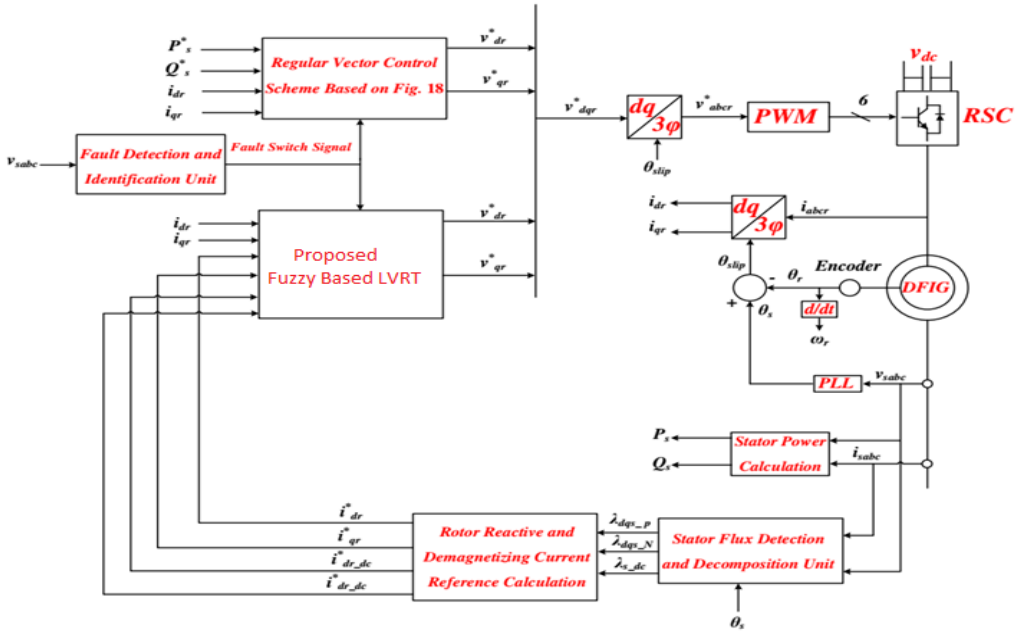

Fig.4. Proposed Control scheme block diagram representation.

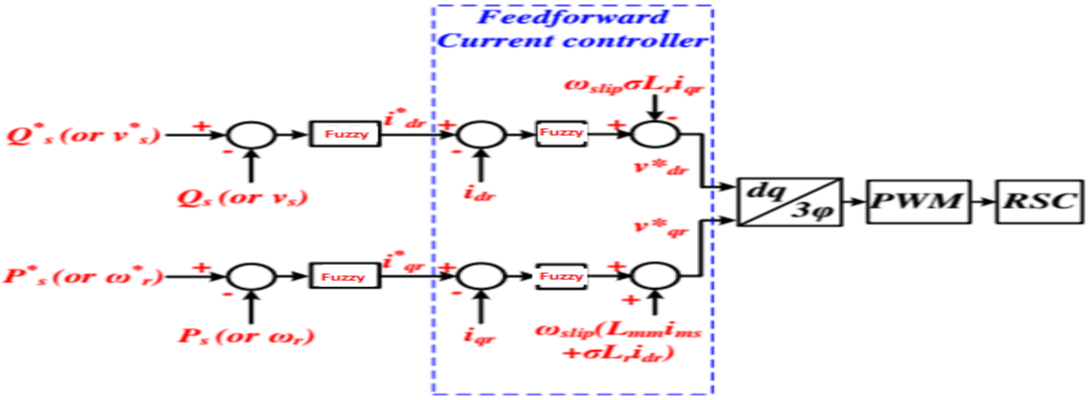

Fig.5. Fuzzy based LVRT block diagram representation (Proposed method).

In this scheme errors are taken as real and reactive powers and are applied to fuzzy logic controller, the outputs of fuzzy logic controller's d-axis reference current and q-axis reference currents. These reference currents are compared with actual currents and these errors are given to another set of fuzzy controllers, these controllers generates outputs, based on these outputs PWM and RSC are working.

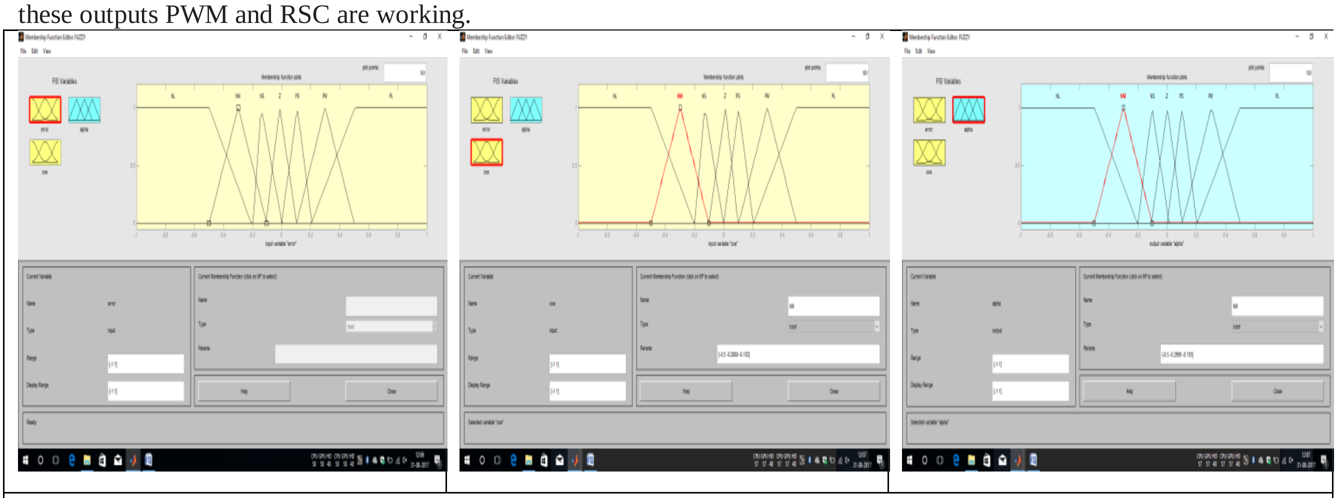

Fig. 6 Fuzzy logic based LVRT controller input and output membership functions

IV . TEST SYSTEM & RESULTS

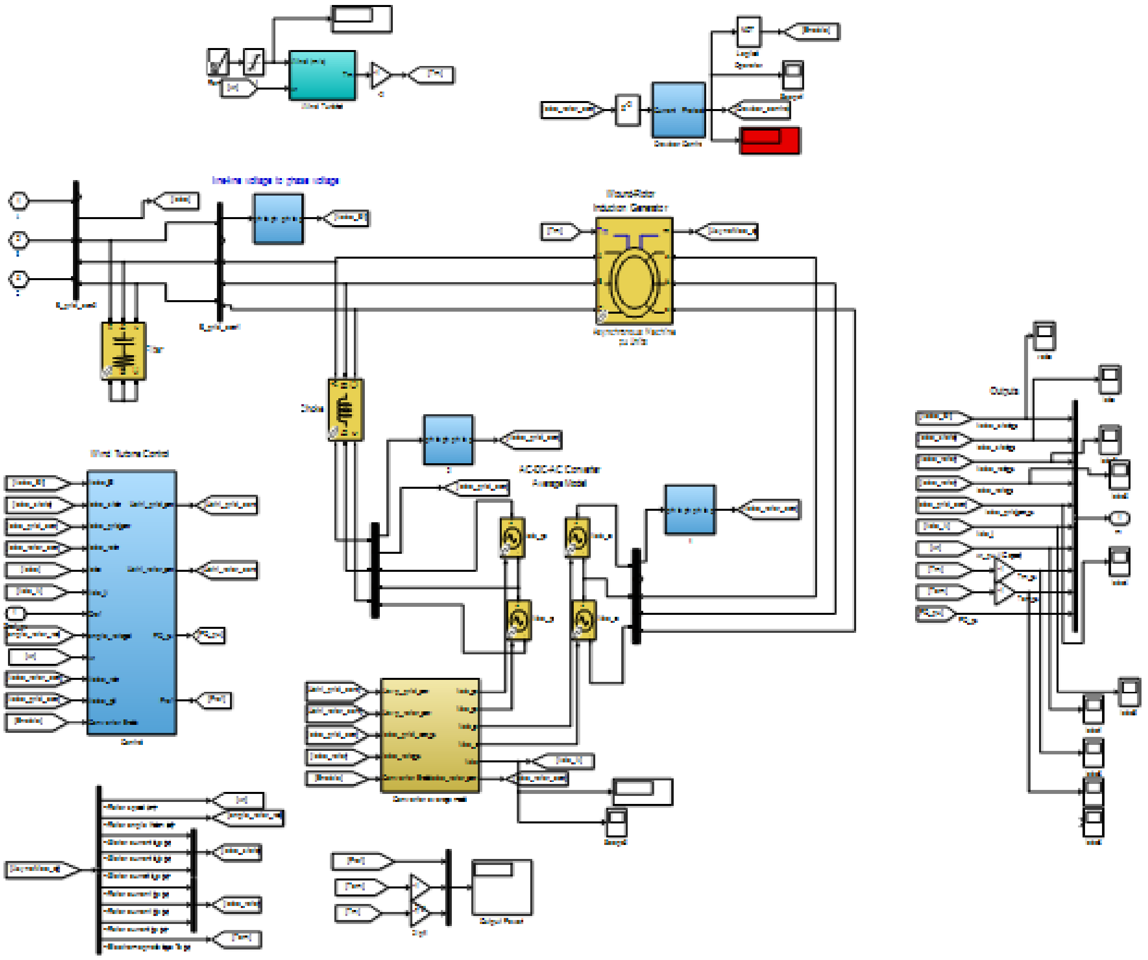

Fig.7. Simulation diagram of DFIG Test system.

MATLAB/Simulink-based simulations have been carried out to verify the proposed low voltage ride through control strategy. The specifications and relevant parameters of the DFIG system are listed in Table.1. Two cases were simulated and the results were compared to each other to verify the effectiveness of the proposed algorithm. For all cases, a grid fault occurs at 7.9 sec and the grid side voltage drops to 30% of the normal operating condition. At 8.21 sec, the grid fault is removed and the system recovery begins.

Case 1: Unlimited DC bus voltage is assumed and the rotor current is controlled tightly to track the command using the conventional vector control scheme.

Case 2: The rated DC bus voltage is assumed and the proposed transient current control is applied.

Table.1 The parameters of the DFIG used in this work

Symbol	Parameter	Value
P_{nom}	Nominal power	1.5 MW
V_{nom}	Nominal line-line voltage (RMS)	690 V
F_{nom}	Nominal grid frequency	50 Hz
R_s	Stator resistance	2.139 mΩ
L_s	Stator inductance	4.05 mH
R_r	Rotor resistance	2.139 mΩ
L_r	Rotor inductance	4.09 mH
L_m	Mutual inductance	4.00 mH
N_{sr}	Stator to rotor turns ratio	0.369
P	Number of pole pairs	2
τ_s	Stator time constant	1.89 s

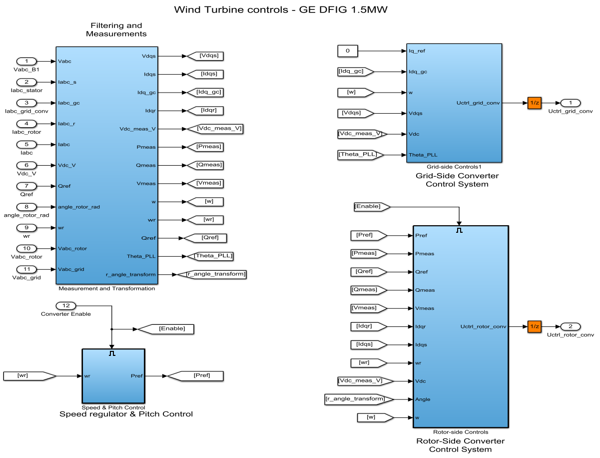

Fig.8. Simulation diagram internal blocks of DFIG Test system.

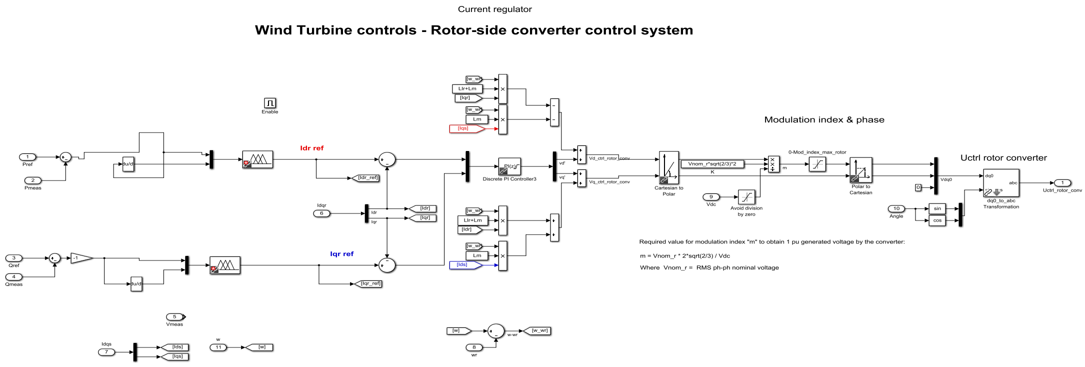

Fig.9. Simulation diagram of proposed method.

Fig.7, 8 & 9 shows the Simulation diagrams of Test system with proposed and conventional controllers.

Since unlimited DC bus voltage is assumed, the results in Case 1 are satisfactory in rotor side current, as shown in Fig.10. However, the rotor voltage is excessively high during the grid voltage sag and recovery, and exceeds the RSC output voltage limit. Fig.11 shows the simulation results of the three phase rotor voltage and current when the LVRT RSC control scheme is applied. Fig.12 shows the simulation results of the three phase rotor voltage and current when the Fuzzy based LVRT RSC control scheme is applied. The results clearly show that both the RSC voltage and rotor current are controlled satisfactorily within the achievable range and low voltage ride through is fulfilled.

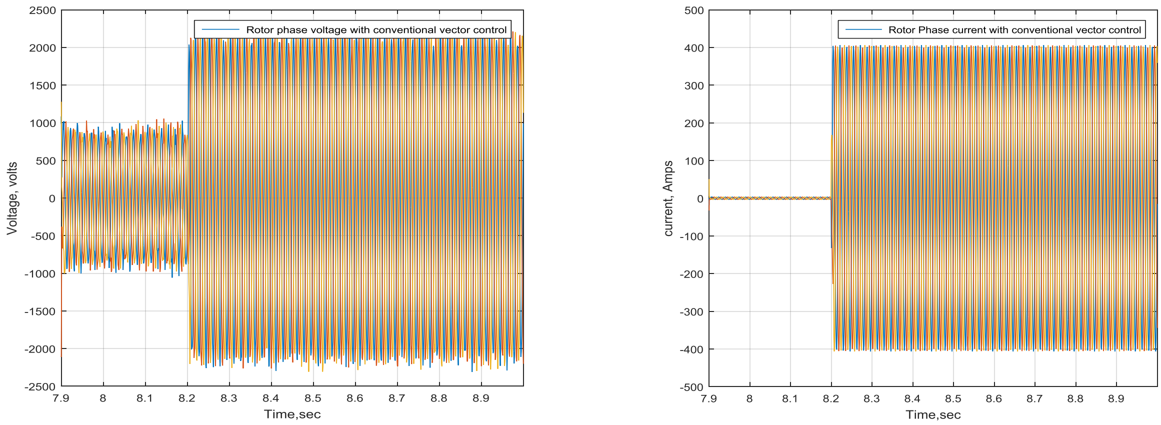

Fig.10 Transient behaviour of the three-phase rotor voltage and current of a three-phase grid voltage dip when the rotor current is controlled tightly to follow the command and unlimited DC bus is assumed (with conventional control method).

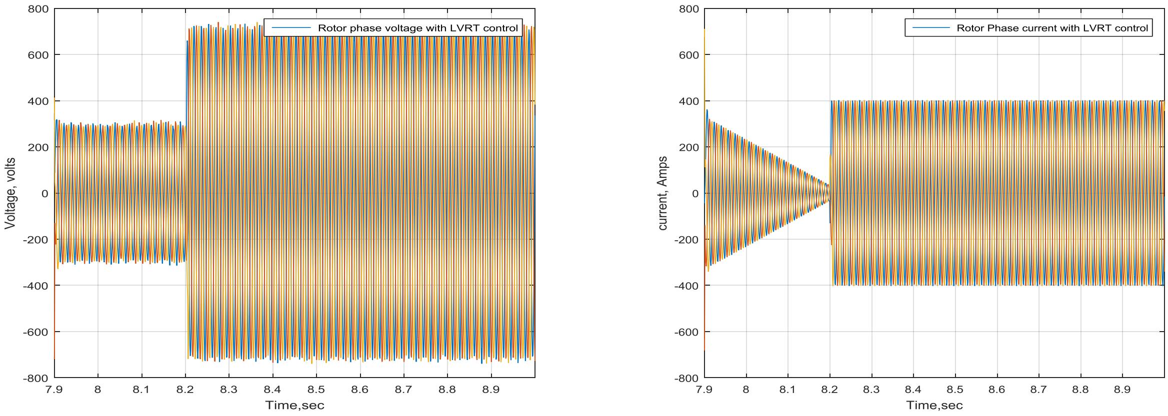

Fig.11 Transient behaviour of the three-phase rotor voltage during a three-phase grid voltage dip using the LVRT control method.

The proposed and conventional control strategies are also compared in terms of DC bus voltage and stator voltages. Fig.13 show those waveforms with a conventional control strategy and Fig.14 shows the wave forms of LVRT control strategy. Fig.15 shows the wave forms with proposed Fuzzy control based LVRT method. From the results it is clear that the proposed method is effectively working compared with LVRT and conventional method.

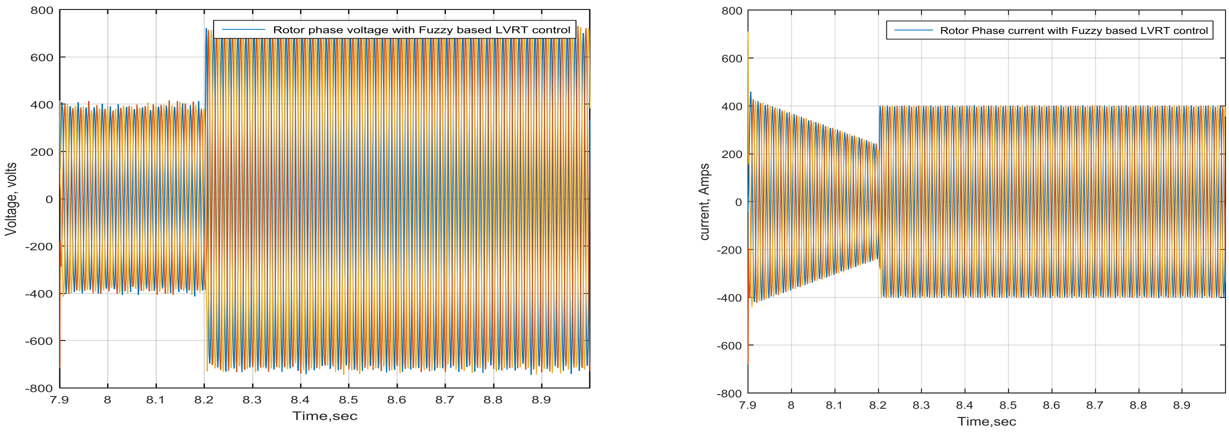

Fig. 12 Transient behavior of the three-phase rotor voltage & current during a three-phase grid voltage dip using the Fuzzy based LVRT control method.

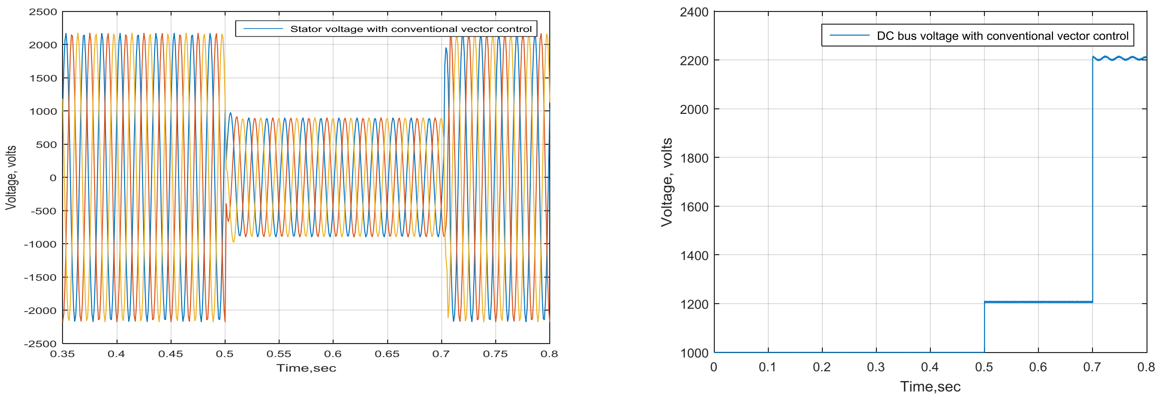

Fig.13 DFIG stator voltage and DC bus voltage during fault with the conventional vector control strategy

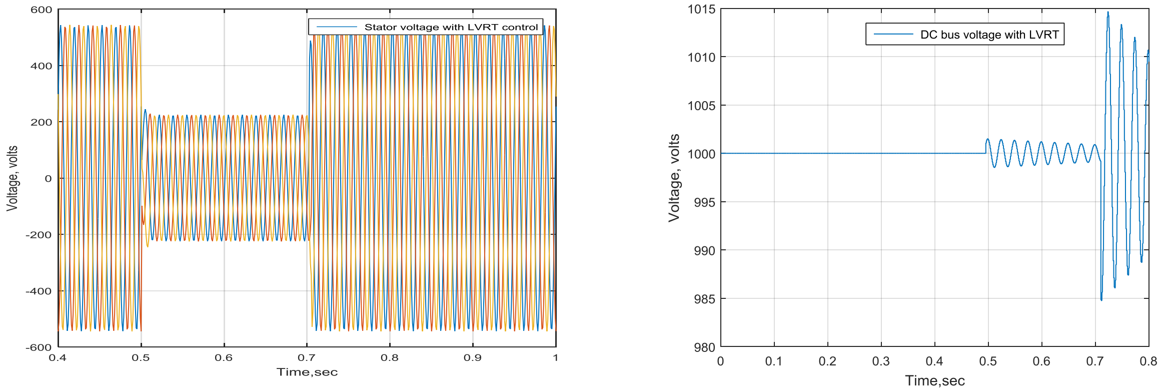

Fig.14 DFIG stator voltage and DC bus voltage during fault with LVRT control strategy

V . CONCLUSIONS

This paper presents a detailed investigation of the LVRT of grid-connected DFIGs. It provides a detailed investigation of the dynamic behaviour of DFIG-based wind turbines during different types of grid voltage sags. If this stator natural flux still exists when the subsequent grid fault occurs, the stator natural flux produced by the voltage recovery and by the next voltage sag may be superposed. This may cause the DFIG to fail to ride through the recurring faults, even with the assistance of the rotor side crowbar. As a result, the FRT strategies designed for single grid faults do not provide the best solution for the FRT of the DFIGs under recurring grid faults. This paper also presents a detailed description of the fuzzy based LVRT solutions for DFIG-based wind turbines by improving the RSC control strategies (active methods). Finally, a new rotor-side control scheme to enhance the LVRT capability of DFIGs-based wind turbines during severe grid voltage sags is proposed. The control strategy is directed at mitigating the rotor-side voltage and current shock during abnormal grid conditions, without any additional cost or reliability issues.

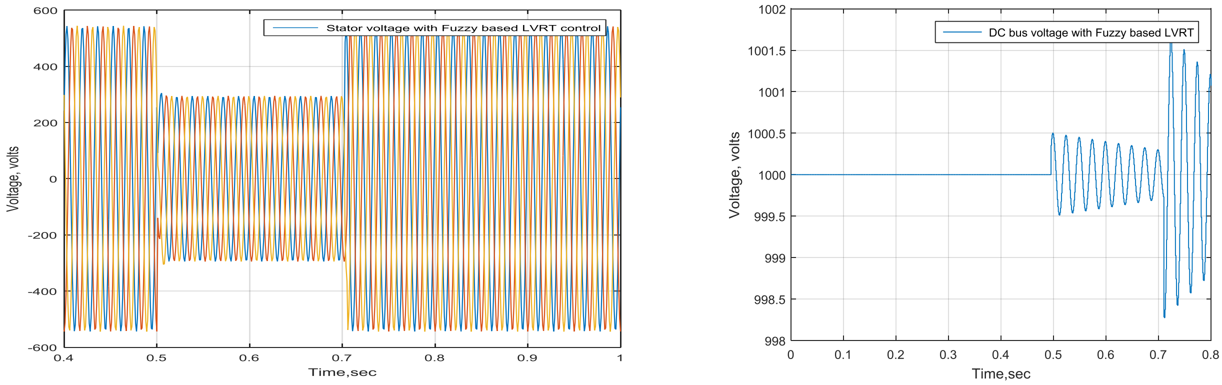

Fig.15 DFIG stator voltage and DC bus voltage during fault with Fuzzy based LVRT control strategy

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