DFIG Based Wind Energy Conversion System For Seamless Operation During Grid Faults

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Abstract **-** Doubly Fed Induction Generator (DFIG) are widely used in wind energy generation systems because of high efficiency and independent control of active and reactive power using partial capacity converters. The proposed work concentrates on the Fault Ride Through (FRT) capability of DFIG based Wind Energy Conversion System (WECS). Here, the nine switch converter is proposed by replacing six switch converter which acts as a Grid Side Converter (GSC). The nine switch converter can provide six independent three phase output terminals. One of the three phase output terminals at the upper side are connected to the grid via interfacing inductor to realize the normal operation of GSC, while the another three phase output terminals at the lower side are connected to the neutral side of the stator windings of the DFIG to provide FRT capability. In this proposed system the control algorithms are developed to achieve the FRT capability during any kind of grid faults and to satisfy the new grid code requirements strictly. By controlling the DC link capacitor voltage, we can achieve reactive power control.

Index Terms **-** *Doubly fed induction generator (DFIG), grid faults, neutral side converter, seamless fault ride-through (seamless FRT), unbalance, wind turbine (WT).*

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I. Introduction

For centuries the winds have been used to grind grain and although present applications powered by the wind have other purposes than grinding grain, almost any wind powered machine -no matter what job it does -is still called a windmill. In the 1920´s and 1930´s, before electric wires were stretched to every community, small wind generators were used to power lights and appliances. At the instance of the growth in the world-wide infrastructure with widely distributed electrical power, the use of wind generators has been almost suspended for several decades. Among others, a consequence of the oil shock of the 1970´s is that the global energy policy of today is towards renewable energy resources and for that reason, the windmill has become its renaissance. As global energy demand is constantly rising, there is a great responsibility for society to develop the green technologies for reducing its impact on the environment. In the trend of diversifying the energy market, wind power is the most rapidly growing sector. After the oil crisis from three decades ago, wind power industry started to flourish.

Since then wind turbine technology improved rapidly and its sources of energy. Recent advancements in size and technology of wind turbines require sophisticated control systems to effectively optimize energy conversion and enhance grid integration. The wind energy conversion system is equipped with a DFIG and a back-to-back converter in the rotor circuit [1]-[3]. A control technique is presented for extracting the maximum power from the wind turbine [4].

In the conventional architecture of a DFIG, the stator windings are connected directly to the grid through a transformer and switchgear but, the rotor-side of DFIG is connected to the grid via a partially rated converter. Partially rated converter consists of Rotor Side Converter (RSC), connected between the rotor and dc link and Grid Side Converter (GSC), connected between the grid and dc link through interfacing inductors [5], [6].

Due to the presence of direct connection between the stator windings of DFIG and the grid, the grid faults will results in voltage dip at the DFIG terminals which directly affects the air-gap flux and, hence, the energy conversion process. Based upon the type of fault, dc component or combination of dc and reverse rotating ac component in the air-gap flux may be introduced due to the voltage dip at the DFIG terminals [7]. These flux components induces high voltage in the rotor windings at rotational and/or double the rotational frequency. These high-frequency voltages due the modulation index constraint cannot get limited by the RSC itself, So that it loses its current control capabilities.

The proper mitigating measures should be immediately employed, otherwise, the rotor currents can exceed the transient current rating of the RSC during the grid fault condition. Grid faults will also cause severe mechanical stress on the bearings and the gear box of WECS due to torque pulsation.

Artificial inertial response and frequency support strategies are proposed in the literature [8]–[10] for power electronics based wind farms. These studies have proposed individual wind turbine [11]–[13] and centralized control strategies [14], [15] to support system frequency during generator outages. However, their capability during grid faults is uncertain due to the converter ride-through capability during severe disturbances, as inertial response capabilities are mostly assessed as a result of generator outage events in a network.

Power utilities have compiled Fault ride through (FRT) grid code standards for wind farms, demanding additional services for network reliability and security enhancement. FRT grid code standards specify a minimum voltage profile that a wind farm should be able to ride-through [16]–[18]. Consequently, wind farms are required to stay connected beyond the defined voltage profile stipulated in published grid codes. Most of the solutions have been proposed to improve the FRT capability of the DFIG wind turbines. Common solution of the voltage dip problem is to connect a crowbar to the rotor of wind turbine. The protection technique is to limit the high current and by providing a bypass of resistors set when a voltage dip is detected and the power converter connected to the rotor is protected [19]. The main drawback of this scheme is that the DFIG consumes large amount of reactive power during grid fault. A new converter protection method, primarily based on a series dynamic resistor (SDR) is proposed [20]. This can maintain the stator voltage or rotor currents within the limits when the DFIG is being controlled to supply the reactive power to the grid during grid faults.

Furthermore, the above mentioned fault ride through techniques fails to maintain the pre-fault voltage across the stator windings of the DFIG which causes undesired electrical and mechanical transients in the system. It is necessary to keep the pre-fault voltage across the stator windings during the grid faults to obtain transient-free FRT performance. To achieve this, a dynamic voltage restorers are used as a bypass switch. Along with a specifically developed control scheme, it provides the wind generator the ability to remain connected during a voltage disturbance and, at the same time, to fulfill the demanding reactive power requirements imposed by recent grid codes. To provide the protection against dead short circuit at the DFIG terminals, the DVR should be rated for 100%.

Moreover, this technique provides an operational delay of auxiliary semiconductor switches (used to bypass the series transformer during normal condition) and hence the availability of electrical transients will be very high. Furthermore, this solution is very costly as it involves many auxiliary components. Alternately, the use of parallel grid side rectifier and series inverter at the Y-point of the stator windings is proposed and investigated during balanced faults [21]. This scheme reduces the number of passive and active components used to achieve fault-tolerant operation of DFIG effectively. However, the major drawback of this scheme is that the stator windings should have to carry the slip power during super-synchronous speed and it have an inability to ride through unbalanced faults.

The main objective of this project is to achieve seamless FRT operation in line with recent grid codes using minimum additional components and a configuration of DFIG using a nine-switch Converter.

In this proposed configuration, a traditional six-switch GSC of DFIG is replaced with a recently proposed nine-switch converter [22]–[24] to provide two independent three-phase outputs. The upper three-phase outputs are connected to grid via an interfacing inductor to realize normal GSC operation, while the Lower three-phase outputs are connected to the neutral side of the stator windings to offer series voltage compensation capability to DFIG at any kind of grid faults to improve the FRT capability. An appropriate control algorithm for the control of a nine-switch converter is developed to achieve the seamless FRT operation of DFIG. Moreover, to provide reactive current support in line with recent grid code requirements during the grid fault conditions, a coordinated reactive power controller is developed to share reactive current between GSC and RSC. It is worth noting that the proposed fault-tolerant DFIG configuration uses only three extra switches to achieve transient-free operation during any kind of grid fault.

II. SYSTEM DESCRIPTION

The schematic diagram of the proposed DFIG based wind energy conversion system for achieving seamless FRT operation is shown in fig. 1. Similar to the conventional architecture of DFIG, the stator windings are directly connected to the grid and the rotor windings are connected to grid through RSC, DC link capacitor, nine switch converter and interfacing inductor. Rotor windings of the DFIG are connected to RSC i.e., switches R1- R6 through slip rings. The RSC is connected to the DC link capacitor which can provide the DC link voltage as constant. The DVR (Dynamic Voltage Restorer) is connected across the DC link capacitor to obtain transient free performance of the system and the DBR (Dynamic Breaking Resistor) is connected across the DC link capacitor to protect the DC link capacitor from overvoltage during grid faults. These are connected to the nine switch converter i.e., switches G1- G9 which provides dual output. The upper three output-terminals of the nine switch converter are connected to grid via the interfacing inductor (L) which provides normal operation of GSC. The lower three output terminals of the nine switch converter are connected to the neutral side of the stator windings of DFIG. During normal mode of operation, the lower three switches i.e., switches G3, G6 and G9 of the nine switch converter is short circuited to form Y point in the stator windings of DFIG and the upper six switches i.e., switches G1, G2, G4, G5, G7 and G8 are used to control GSC to regulate the DC link voltage. During fault mode of operation, the lower three switches i.e., switches G3, G6 and G9 will start switching to generate the compensating voltage to maintain the pre-fault voltage across it. This operation of generating the compensating voltage is known as NSC (Neutral Side Converter) operation.

III. DFIG MODELING

A large number of papers describe the modeling of DFIGs [22]–[25]. Only the most important aspects of the modeling will be presented here. The system has been modeled and simulated in the Simulink toolbox extension of Matlab.

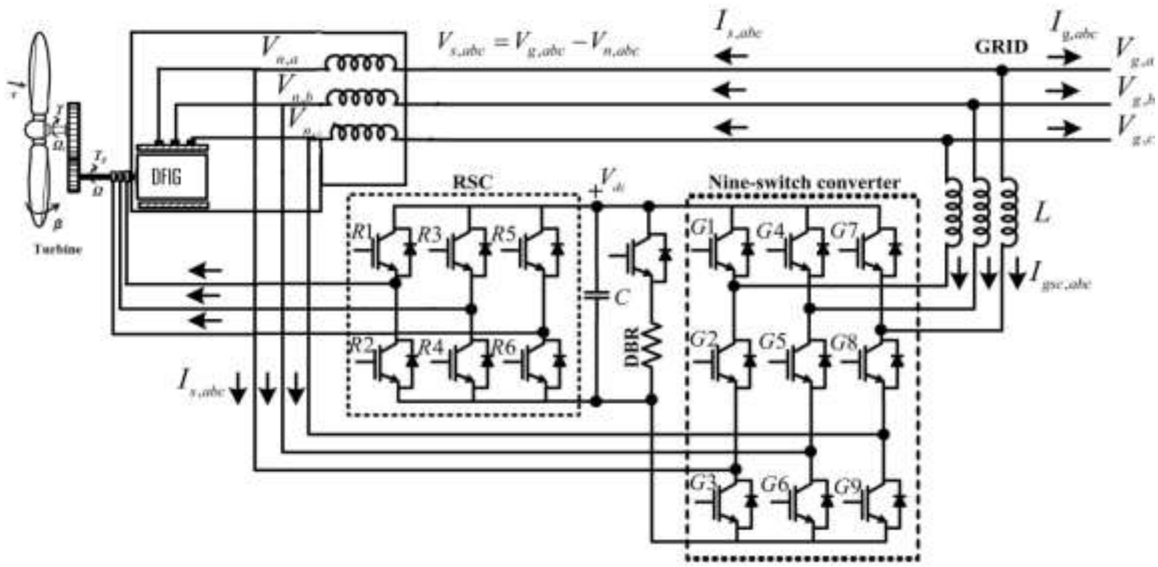

Fig. 1. Proposed DFIG based wind energy conversion system for seamless FRT during grid faults.

III. DFIG MODELING

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A d-q reference frame is chosen to model the DFIG. The model of the induction machine is based on the fifth-order two axis representation commonly known as the “Park model.” A synchronously rotating d-q reference frame is used with the direct -axis oriented along the stator flux position. In this way, decoupled control between the electrical torque and the rotor excitation current is obtained. The reference frame is rotating with the same speed as the stator voltage. When modeling the DFIG, the generator convention will be used, which means that the currents are outputs and that real power and reactive power have a positive sign when they are fed into the grid. Using the generator convention, the following set of equations results:

The stator and rotor fluxes in d-q reference frame can be written as follows:

$$\bar{\psi}_{dq,s} = \psi_{ds} + j\psi_{qs} = L_s\bar{\mathbf{I}}_{dq,s} + L_m\bar{\mathbf{I}}_{dq,r}$$
$$\bar{\psi}_{dq,r} = \psi_{dr} + j\psi_{qr} = L_r\bar{\mathbf{I}}_{dq,r} + L_m\bar{\mathbf{I}}_{dq,s}. \quad (1)$$

The stator and rotor voltages in d-q reference frame can be written as follows:

$$v_{ds} = -R_s i_{ds} - \omega_s\psi_{qs} + \frac{d\psi_{ds}}{dt}$$
$$v_{qs} = -R_s i_{qs} + \omega_s\psi_{ds} + \frac{d\psi_{qs}}{dt} \quad (2)$$

$$v_{dr} = -R_r i_{dr} - \omega_r\psi_{qr} + \frac{d\psi_{dr}}{dt}$$
$$v_{qr} = -R_r i_{qr} + \omega_r\psi_{dr} + \frac{d\psi_{qr}}{dt} \quad (3)$$

Here, v be the voltage (V), R is the resistance, i is the current (A), ω_s and ω_r are the stator and rotor electrical angular velocity (rad/s), respectively, and Ψ is the flux linkage (Vs). The indices d and q indicate the direct and quadrature axis components of the reference frame and s and r indicate stator and rotor quantities, respectively. All quantities in above equations are functions of time.

The expression for electromagnetic torque can be written as follows:

$$T_e = -\frac{\psi_{ds} L_m}{L_s} i_{qr} \quad (4)$$

The stator reactive power of the DFIG is expressed as follows

$$Q_s = \frac{v_{ds}\,\psi_{ds}}{L_{ls}} - \frac{v\,L_m}{L_{ls}} i_{dr}. \quad (5)$$

By employing the decoupled control of i_{qr} and i_{dr}, the electromagnetic torque and the stator reactive power can be controlled independently by RSC.

IV. CONTROL OF THE DFIG WIND TURBINE

The control algorithm developed for the proposed DFIG configuration is to control the RSC and the nine switch converter (GSC and NSC). This control strategy consists of two modes of operation: (1) normal mode and (2) fault mode. These modes are briefly discussed as follows:

A. Normal Mode Operation

During normal mode of operation, the DFIG is controlled to provide MPPT (Maximum Power Point Tracking) for maximum available active power by the wind turbine and user-defined reactive power.

1) *RSC Control:* During normal mode of operation, the RSC is controlled in a synchronously rotating d-q reference frame to control the electromagnetic torque and the reactive power produced by DFIG independently with d-axis aligned to stator flux vector. This electromagnetic torque and reactive power developed by DFIG is expressed in equation (4) and (5) respectively. The electromagnetic torque produced by the DFIG is proportional to i_{qr} and can be regulated by controlling v_{qr}. Similarly, the reactive power produced by the DFIG is proportional to i_{dr} and can be regulated by controlling $v_{dr.}$ The detailed control diagram for the proposed configuration of RSC is shown in fig. 2. Using a PI controller over the rotor speed, the reference q-axis rotor current (i_{qr}^*) is calculated from the reference torque command (T_e^*). The reference rotor speed command can be generated by using an appropriate MPPT algorithm. Using PI controller over reactive power supplied by DFIG, the reference d-axis rotor current (i_{dr}^*) is generated. Inorder to extract maximum power from the wind turbine, i_{qr}^* is allowed within the limits. It is limited as per

$$i_{\mathbf{dr}}^{*}{}_{,limit} = \pm\sqrt{i_{r,max}^{2} - i_{\mathbf{qr}}^{*2}} \tag{6}$$

to ensure that RSC current is within the safe limit $i_{r,max}$.

Using decoupled PI current control, the reference rotor currents i_{dr}^* and i_{qr}^* are tracked by regulating v_{dr} and v_{qr} as per equation (3). The gate signals for RSC switches (R1-R6) are generated by comparing the reference RSC voltage (v_{RSC}^*) with a triangular carrier wave using a sinusoidal PWM technique.

2) Nine Switch Converter Control: The nine witch converter control consists of two parts: (1) GSC control and (2) NSC control. The detailed schematic diagram of nine switch converter is shown in fig. 3.

The main objective of the GSC is to regulate the DC link voltage to its reference value irrespective of power flow. In synchronous reference frame theory, he voltage balance equation across interfacing inductor (L) with internal resistance (R) can be written as

$$\begin{aligned} v_{d,\mathrm{GSC}}^{*} &= Ri_{\mathbf{dg}} + L\frac{di_{\mathbf{dg}}}{dt} - \omega Li_{\mathbf{qg}} + v \\ v_{q,\mathrm{GSC}}^{*} &= Ri_{\mathbf{qg}} + L\frac{di_{\mathbf{qg}}}{dt} - \omega Li_{\mathbf{dg}} + v \end{aligned} \tag{7}$$

By aligning the d-axis of the reference frame of GSC, the active and reactive power supplied or absorbed by GSC can be written as

$$\begin{aligned} P &= \frac{3}{2}v_{\mathbf{dg}}\, i_{\mathbf{dg}} \\ Q &= \frac{3}{2}v_{\mathbf{dg}}\, i_{\mathbf{qg}} \end{aligned} \tag{8}$$

During normal mode of operation, the active power and the DC link voltage is proportional to i_{dg} and can be regulated by controlling $v_{d\ ,GSC}^*$. The reactive power is proportional to i_{qg} and a be regulated by controlling $v_{q\ ,GSC}^*$. The reference d-axis GSC current (i_{dg}^*) is generated using PI controller and the reference q-axis GSC current (i_{qg}^*) is set to be zero for normal mode of operation. By employing decoupled current control as per equation (7), the reference voltage (v^*_{GSC}) that can be generated by GSC is computed inorder to control GSC current to its reference value.

During normal steady state operation, the voltage that can be injected by the NSC at neutral side of the stator winding is zero. So that the reference voltage generated by the NSC (v^*_{GSC}) is kept to be zero. In this system, the proposed configuration is both the GSC and NSC operation can be carried out by a single nine switch converter. Both of the output terminals of the same phase in the nine-switch converter can only connect to either its upper output terminal to $+v_{dc}$ and lower output terminal to 0 V [for phase-a: G1-ON, G2-OFF, and G3-ON]. The combination where the upper output terminal needs to be connected to 0 V and lower to $+v_{dc}$ is not allowed [for phase-a: G1-ON, G2-ON, and G3-ON] as this short-circuits the dc link. Inorder to overcome these limitations, two modulating references of the same phase should share their modulation space without intersecting each other. This can be achieved by placing the reference for upper terminals always above that of the lower terminals by adding offsets to both the references. By adding the same offset to all the three phases, the adjustment of three-phase modulating reference signals in modulation space does not show any impact on the output of the converter. The reference offset voltage signals for GSC and NSC can be written as

$$\begin{aligned} v_{\mathrm{GSC},abc}^{*\prime} &= v_{\mathrm{GSC},abc}^{*} + \left[1 - \max\left(v_{\mathrm{GSC},abc}^{*}\right)\right] \\ v_{\mathrm{NSC},abc}^{*\prime} &= v_{\mathrm{NSC},abc}^{*} - \left[1 + \min\left(v_{\mathrm{NSC},abc}^{*}\right)\right]. \end{aligned} \tag{9}$$

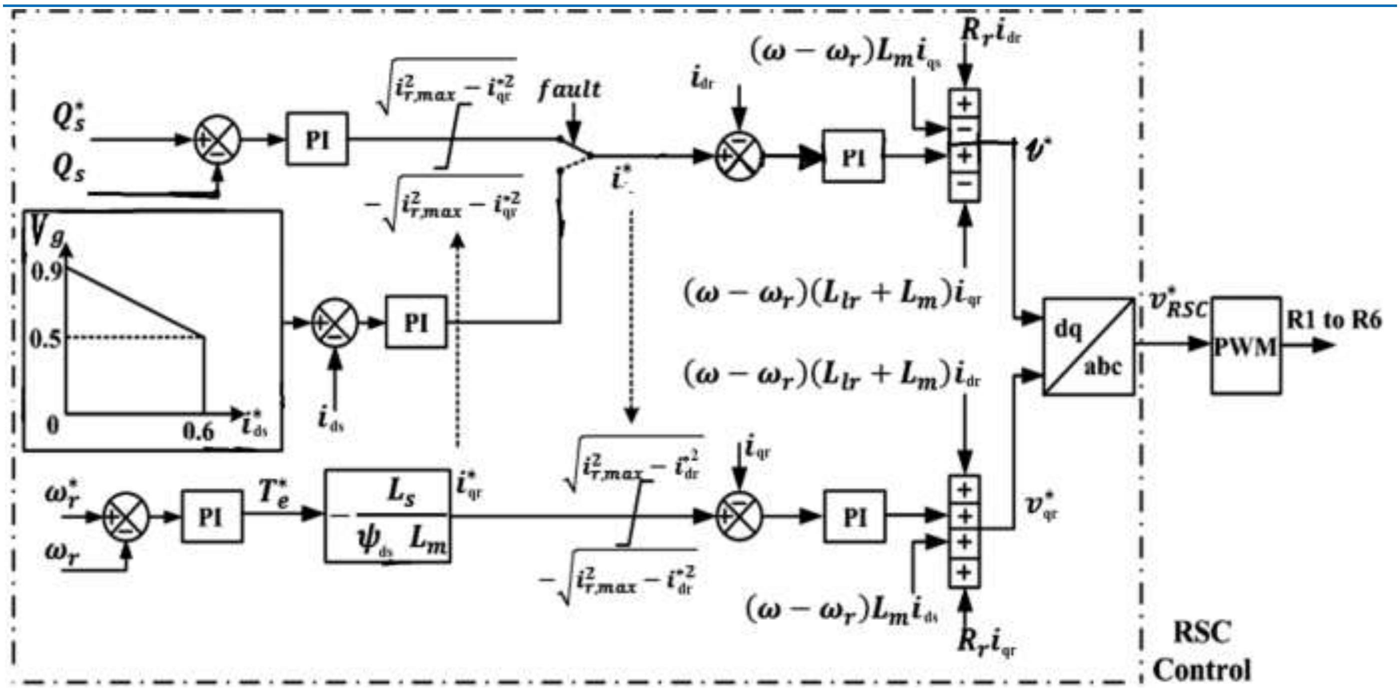

Fig. 2. RSC control

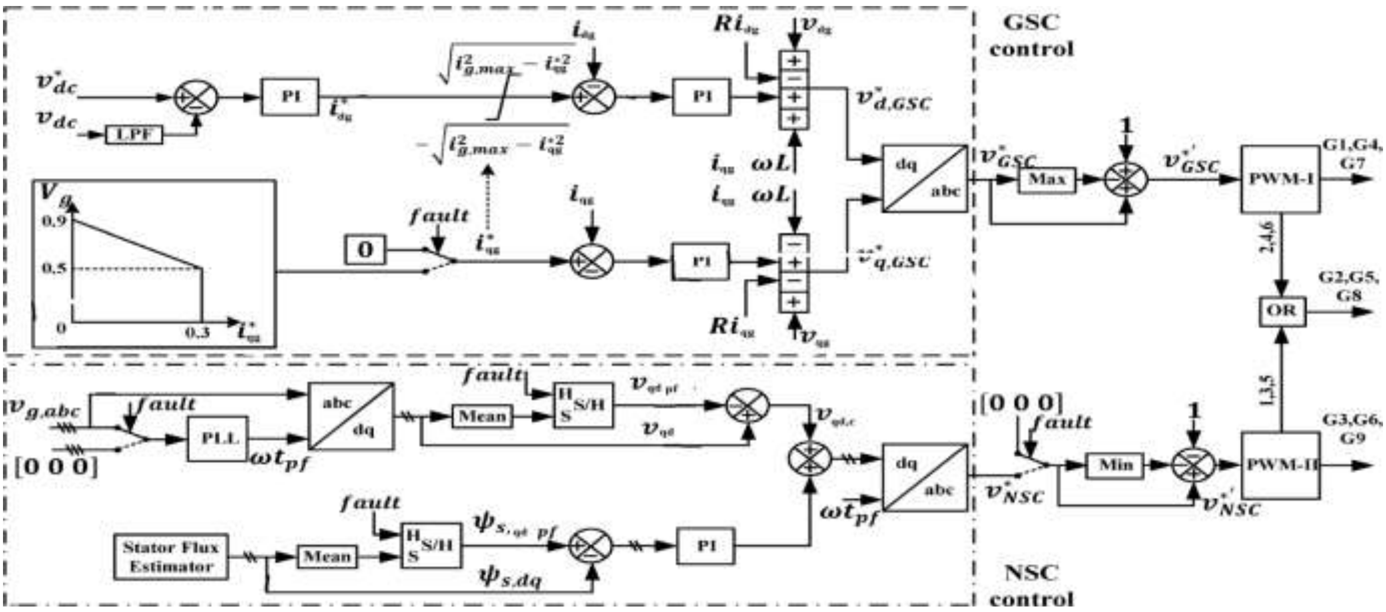

Fig. 3. Nine switch converter control

The reference offset voltage signals $v^{*/}_{GSC}$ and $V^{*/}_{NSC}$ are provided to the two individual three phase PWM generators (PWM-I and PWM-II). Thus, it can generate two sets of six PWM signals. If the GSC and NSC operations are to be achieved using two separate six-switch inverters, the PWM signals generated by PWM-I and PWM-II can be directly provided to the corresponding inverters. However, in a nine-switch inverter, the middle three switches are shared by GSC and NSC, so their gate pulses are generated by logical OŔ operation of PWM-I and PWM-II signals as shown in Fig. 4. The PWM signals generated by PWM-I is directly provided to upper three switches and the PWM signals generated by PWM-II is directly provided to lower three switches of the nine switch converter respectively.

Here, the reference voltages for NSC ($v^{*}_{NSC,abc}$) is zero. Hence ,the reference offset voltage signals($v^{*/}_{NSC,abc}$) is minus one. Therefore, the PWM signals at lower three switches will always be high. This will provide short circuits on the neutral side of the stator windings to form Y- point effectively during normal mode of operation.

B. Fault Mode Operation

This section analyzes the behavior of the generator during a fault condition. This analysis is particularly for an instantaneous voltage dip. Obviously, this is not possible in real systems. In these systems, the voltage drops with a particular level that depends on the grid fault which generates the voltage dip.

In this proposed system, during fault condition, the pre-fault voltage should be kept across the stator winding. So that the NSC should be controlled where, RSC and GSC is controlled to supply reactive current in the line with the requirement of recent grid codes. Inorder to achieve transient free operation, the grid fault should be immediately detected with least possible delay. The fault in the system can be detected by measuring the absolute error between the referee grid voltage and the actual grid voltage as follows

$$V_{\text{error}} = \left|1 - \sqrt{v_{\mathbf{dg}}^2 + v_{\mathbf{qg}}^2}\right|. \qquad (10)$$

The grid fault is detected whenever v_{error} exceeds the threshold (typically 0.1 p.u.). Once the grid fault is detected, the fault signal in Fig. 2 and 3 changes its logic from low to high. If v_{error} oscillates above and below the threshold unsymmetrical faults will be detected in the system. The fault removal is detected when the one cycle average of reduces below the threshold. The details of the actions taken by the controller of different converters during the grid fault conditions are discussed below.

1) RSC Control: During the grid fault condition, the rotor side converter has the capability to provide the required full reactive current support by using the recent grid codes provided that the NSC keeps the pre-fault voltage across the stator winding. However, if the RSC control is switched to supply full reactive current, the active current supplied by the stator has to be reduced to keep RSC switching currents below the safer limit. This leads to the over speeding of the rotor and hence, mechanical stress can be increased due to the storage of the kinetic energy produced by the WT. To reduce the negative impact of increased mechanical stress on WT's construction, the active power extraction along with reactive current supply should be maximized without exceeding the rating of any component in the system. To achieve this, the GSC and RSC will share the reactive currents required to fulfill the grid code requirements during grid faults based on their ratings. The duty of supplying two third of the reactive current (maximum 0.6 p.u.) is assigned to stator and RSC, while, one third of reactive current (maximum 0.3 p.u.) is assigned to GSC. To supply the reactive current assigned to the stator during fault condition, the i_{dr}^* is computed using the PI controller over reference stator reactive current i_{ds}^* (d-axis current is proportional to reactive power as the reference d-axis is oriented to stator flux) as shown in Fig. 3. The i_{ds}^* is calculated using

$$i_{\mathbf{ds}}^* = \begin{cases} -\frac{0.6}{0.4}(0.9 - V_g), & if\ 0.5 \le V_g \le 0.9 \\ -0.6, & if\ V_g < 0.5 \end{cases} \qquad (11)$$

In (11), v_g is the positive sequence grid voltage magnitude. It can be calculated within 20 ms to fulfill the grid code requirement. In the fault mode of operation, the priority is given to strictly satisfy the reactive current i_{dr}^* and the limit on i_{qr}^* is calculated as

$$i_{\mathbf{qr},\text{limit}}^* = \pm\sqrt{i_{r,\max}^2 - i_{\mathbf{dr}}^{*2}}. \qquad (12)$$

2) Nine Switch Converter control: During fault condition, the DBR present in the system is used to keep the dc-link voltage below the safe limit which can be comfortable to the GSC from the duty of keeping the dc-link voltage constant. Inorder to assist the RSC controller during fault condition, the GSC controller is switched to supply one third of the reactive current required to satisfy the grid codes requirement. The reference reactive current (i_{qg}^*) for the GSC during fault mode of operation is computed as per

$$i_{\mathbf{qg}}^* = \begin{cases} \frac{0.3}{0.4}(0.9 - V_g), & \text{if}\ 0.5 \le V_g \le 0.9 \\ 0.3, & \text{if}\ V_g < 0.5 \end{cases} \qquad (13)$$

and the GSC current is limited to $i_{g,max}$ by putting limits on active current (i_{dg}^*) as per

$$i_{\mathbf{dg},\text{limit}}^* = \pm\sqrt{i_{g,\max}^2 - i_{\mathbf{qg}}^{*2}}. \qquad (14)$$

During fault condition, the objective of the NSC control is to keep the pre-fault voltage across the stator winding to provide proper functioning of the RSC control. During fault condition, the logic will be high on the fault signal which activates the NSC controller as shown in Fig. 3. The compensating voltage that has been introduced by the NSC on the neutral side of the stator winding during fault condition can be computed as

$$v_{\mathbf{qd,c}} = v_{\mathbf{qd}} - v_{\mathbf{qdpf}} \qquad (15)$$

In (15), v_{qd} and v_{qdpf} are the present grid voltages and the pre-fault grid voltages computed by using pre-fault grid voltage vector angle ωt_{pf}. The pre-fault grid voltage vector angle is determined by saturating the phase-locked loop (PLL) over the grid voltage using fault signal as shown in Fig. 3. The pre-fault grid voltage v_{qdpf} are obtained by holding the samples of two cycle mean value of v_{qd} using sample and hold when fault is detected.

The compensating voltage $v_{qd,c}$ can be directly used as the reference voltages to control NSC in open-loop by converting them to stationary reference frame. Due to the absence of output filter and series injection transformer, the open-loop control can work satisfactorily for the NSC control. Such that there will be series voltage drop across the switches of the NSC which may affect the compensation. To achieve perfect compensation of the voltage dip, the switching voltage drop is added to $v_{qd,c}$ by estimating it using PI controller. This can maintain the stator flux ($\Psi_{qd,s}$) to its pre-fault value ($\Psi_{qd,spf}$) as shown in Fig. 3. The d-q axis stator flux components in Fig. 3 are estimated using (1) and (2) where, the pre-fault stator flux components are obtained by holding the samples of two cycle mean value of $\Psi_{qd,s}$ by using sample and hold when fault is detected.

V. Simulation And Results

Inorder to verify the effectiveness of the proposed DFIG wind turbine configuration and its control to achieve seamless FRT operation in line with the recent grid codes, a detailed simulation study is carried out in MATLAB. The detailed model of DFIG with six-terminal stator and the power electronics converters are developed using SIMULINK and Sim Power System tool-boxes. To
represent the actual operating conditions, it is assumed that connection, a transmission line of 25 kV to a distance of 50 km and another step-up transformer which steps up the voltage from 25 kV at Δ connection to 120 kV at Yg connection. The parameters of the DFIG-based wind turbine are shown in Table I.

Aero turbine converts energy in moving air to rotary mechanical energy in general, they required pitch control & yow control for proper operation. A mechanical interface consisting of step up gear & a suitable coupling transmits the rotary mechanical energy to an electrical generator. The electric generator will convert the received mechanical energy in to electrical energy. The electrical output from the DFIG is as shown in fig. 4.

The rotor side converter is controlled by the PI controller to control the reactive power and the electromagnetic torque present in the system. The fig.5 shows the output waveform at the DC link capacitor provided by the RSC. TABLE I

PARAMETERS OF TYPICAL WIND TURBINE`

Wind turbine specifications	
Nominal output power	1.5MW
Rated wind speed	11m/s
Operating range	6m/s to 30m/s
Generator specifications	
Rated apparent power	1.667MVA
Rated voltage	575V
Rated frequency	60Hz
Number of poles	6
Stator to rotor turns ratio	575/1975
Stator resistance	0.0023pu
Stator inductance	0.18pu
Rotor resistance referred to stator	0.0016pu
Rotor inductance referred to stator	0.16pu
Magnetizing (mutual) inductance	2.9pu
Inertia constant	0.685s
Stator winding: Accessible on neutral side.	
Others	
Coupling inductance for GSC	0.3pu
Resistance of coupling inductor	0.003pu
Nominal dc link voltage	1150V
DC bus capacitor	10mF
Reactive support by static capacitor bank at DFIG terminal	120kVAr
Dynamic breaking resistor (DBR)	0.8Ω

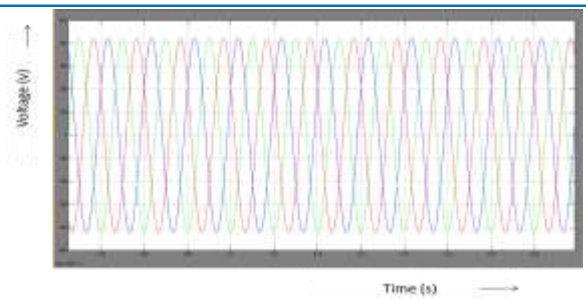

Fig. 4. Output waveform from the rotor side of DFIG

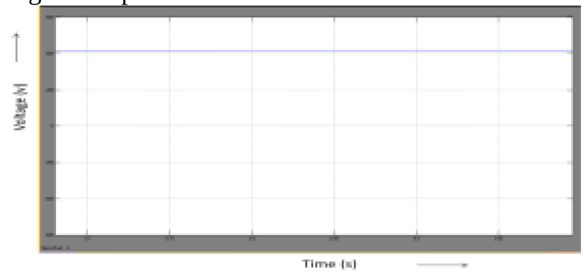

Fig. 5. Output waveform at the DC link capacitor

The grid side converter is used to control the reactive power and to control the Dc link capacitor voltage as constant. The control algorithm used to control the neutral side converter is developed for the proposed configuration to achieve seamless fault ride-through during any kind of grid faults and to strictly satisfy new grid codes requirements. The output of the nine switch converter is shown in fig. 6.

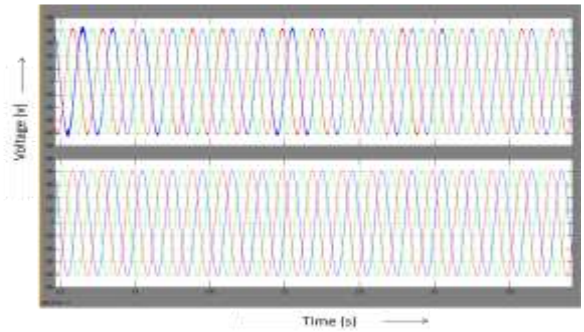

Fig. 6. Output waveform of the nine switch converter

With the aim of achieving seamless FRT operation in line with recent grid codes using minimum additional components, a DFIG using a nine-switch converter is present. In the nine switch converter, the output terminals at the neutral side of the stator windings to offer series voltage compensation capability to DFIG for riding through any kind of grid faults. An appropriate control algorithm for the control of a nine-switch converter is developed to achieve the seamless FRT operation of DFIG. Moreover, to provide reactive current support in line with recent grid code requirements during the grid fault conditions, a coordinated reactive power controller is developed to share reactive current between GSC and RSC. The output voltage of the DFIG based wind energy conversion system during fault is shown in the fig. 7.

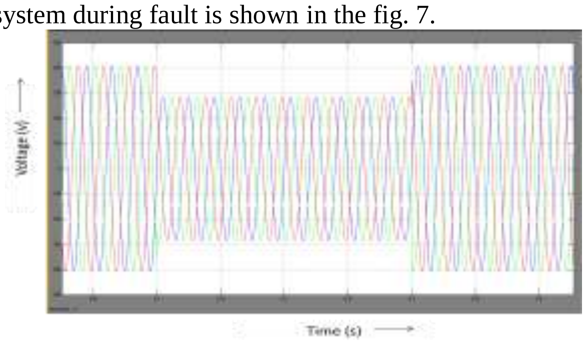

Fig. 7. Output voltage after the compensation of fault

The output voltage of the DFIG based wind energy conversion system after the compensated voltage provided by the nine switch converter is shown in fig. 8.

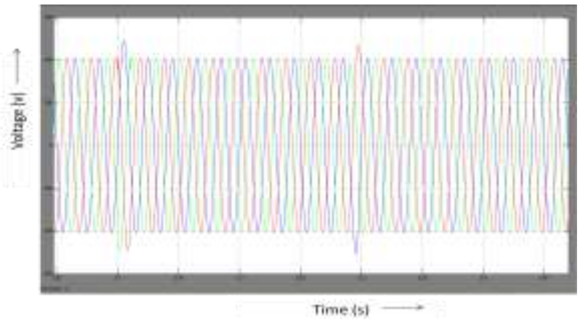

Fig. 8. Output voltage after the compensation of fault

The proposed DFIG configuration can effectively keep the pre-fault voltage across the stator winding of the DFIG during any type of fault condition to achieve transient-free FRT. It is an economic solution to achieve series voltage compensation as only three full-rated extra switches are used in the proposed solution compared with the DVR solution where a full-rated six-switch converter is required. With the proposed reactive current sharing control, the proposed fault-tolerant DFIG is able to fulfill all of the requirements of the recent grid codes. In the proposed DFIG configuration, as the compensation of grid voltage variations is achieved from the neutral side of the stator winding, there is no need for a full-rated series injection transformer as in case of the DVR solution. There is no need for an output filter for the injected voltages as the stator self-inductance will be sufficiently high. The proposed fault-tolerant DFIG seamlessly rides through any kind of grid fault as it does not involve any transfer switch (required to short circuit series injection transformer during steady-state operation in the case of DVR solution) operation during FRT.

VI.CONCLUSION

The proposed system is focused on the control strategy of a DFIG wind turbine system which equips with a nine switch inverter against severe grid faults. In order to achieve seamless fault ride-through during any kind of grid faults and strictly satisfies new grid codes requirements, an improved control strategy is proposed. Moreover, a simple demagnetization method is adopted to decrease the oscillations of the transient current both during the voltage dips and after the clearance of the faults. With the help of both control schemes, the DFIG is controllable for most of the time during voltage dips while the nine switch converter provides sufficient protection. To compensate the faulty line voltage, we have proposed a Dynamic Voltage Restorer (DVR) controller in existing DFIG wind turbine. During grid faults the NSC will absorb part of the active power generated by DFIG and pumps it to the dc link, hence, dc-link voltage tends to rise if any preventive measures are not taken. To protect the dc-link capacitor from over voltage during the grid faults, a Dynamic Braking Resistor (DBR) is connected across the dc-link capacitor. During the voltage dip resulting from the grid faults, the lower three switches also start switching to generate the compensating voltages on the neutral side of the stator winding to maintain pre-fault voltage across it. This operation of generating the compensating voltages on the neutral side of the stator winding is termed here as Neutral Side Converter (NSC) operation. Simulation results show the enhanced low voltage ride through capability of the generator with the proposed technique. In future the power quality of the wind power can be improved by adopting various control strategies using soft computing techniques such as fuzzy logic control, artificial neuro network, PSO, etc.

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