Research Issues in DFIG Based Wind Energy System

R. Rajasekaran and M. Mekala

Abstract—**Among different renewable energy sources, Wind energy is the most imperative energy source in power system. The development of grid connected wind energy conversion system expands, its grid connectivity issues has additionally been expanded. A portion of the issues are incorporates, for example, the regulation of voltage at Point of Common Coupling (PCC), reactive power absorption and injection, voltage sag and swell and etc. The Doubly Fed Induction Generator (DFIG) is most broadly utilized as a part of wind energy conversion system. DFIGs are extremely sensitive to grid voltage disturbances. With expanded entrance of wind energy as a renewable energy source the wind turbine should be connected to the grid during transient conditions like grid faults. The Fault Ride-Through (FRT) or Low Voltage Ride Through (LVRT) capability of wind turbines during grid faults is one of the core requirements to ensure stability in the power grid during transients and fault conditions. In this paper consists of various grid connectivity issues and research areas of wind energy conversion system and also the various control schemes for improving the LVRT system. These several techniques are used to improve the LVRT capability and limit the fault current to avoid the disconnection of DFIG from the grid under fault conditions for enhancement of stability and the performance of wind turbine.**

***Index Terms*—Wind energy, Doubly Fed Induction Generator (DFIG), Fault Ride Through (FRT) or Low Voltage Ride Through (LVRT) capability, Grid Connectivity Technical Issues.**

Review Paper
DOI: 10.7251/ELS1822040R

I. Introduction

Renewable energy sources are including sun powered, wind, tidal, small Hydro, geothermal, denied determined fuel and fuel cell energies is supportable, reusable and earth benevolent and clean. With the expanding lack in petroleum products, and contamination issues renewable energy source has turned into an essential energy source on the planet [1]. The National Action Plan on Climate Change (NAPCC) was shaped in 2008 for environmental change control, has likewise considered part of renewable energy source in all out energy creation of India. NAPCC has additionally set an objective to expand the renewable energy source share in all out energy generation up to 15 percent till year 2020, which unmistakably demonstrates India‘s dedication towards a manageable improvement [2]. Under the Ministry of Non Renewable Energy (MNRE) program has done different alteration with respect to impetuses, plans and strategies for wind energy [3].

The Indian policy support for wind energy has driven India and it positioned fifth with biggest introduced wind power capacity. The aggregate introduced control limit was 19,565 MW on June 30, 2013 and now India is simply behind USA, China, Spain and Germany. Worldwide introduced wind control limit demonstrates India‘s better execution in wind energy. The aggregate introduced wind control limit in India had achieved 17.9 GW in August 2012.A fast development in wind control establishment has been estimated in southern and western states in India. A requirement for around 350-360 GW of aggregate energy age limit was accounted for by the Central Electricity Authority in its National Electricity Plan (2012) by the year 2022 [2],[3]. So among the different renewable energy sources wind energy is the quickest developing and most encouraging renewable energy source [4]-[11].

Wind Energy Conversion System (WECS) create power by utilizing the energy of wind to drive an electrical generator. The change of the kinetic energy of the approaching air stream into the electrical energy [12]. It happens in two stages: the extraction device, i.e., the wind turbine rotor catches the wind power movement by means of aerodynamically designed blades, and converts it into rotating mechanical energy, which drives the generator rotor. The electrical generator at that point changes over this rotating mechanical power into electrical power. A gear box might be utilized to coordinate the rotational speed of the wind turbine rotor with one that is fitting for the generator. The electrical power is then exchanged to the grid through a transformer. The association of the wind turbine to the system is conceivable at various levels of voltage [13] [14]. Power electronic converters can likewise be utilized for upgraded control extraction and variable speed operation of the wind turbine. The real parts of an average wind energy transformation system incorporate a wind turbine, generator, and interconnection mechanical assembly control systems.

II. Grid Code Requirements for Wind Turbines

The operation and grid connection requirements for wind turbines vary between utilities around the world, but some trends are common to most of them. A few of these requirements are summarized as follows [15], [16].

Manuscript received 18 December 2017. Received in revised form 19 April 2018 and 23 May 2018. Accepted for publication 5 June 2018.

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A. Voltage and Frequency Operating Ranges

The wind turbines are required to stay connected to the grid and work within typical grid voltage and frequency ranges. Transmission level voltages are usually considered to be 115 kV and above. Lower voltages such as 66 kV and 33 kV are usually considered sub-transmission voltages. Voltages under33 kV are usually used for distribution. Voltages over 230 kV are viewed as additional high voltage and require diverse outlines contrasted with hardware utilized at bring down voltages.

The recurrence of the electrical system fluctuates by nation. The most electric power is produced at either 50 or 60 Hz. All the generating equipments in the electric system are designed to operate within very strict frequency margins. Grid codes specify that all generating plants should be able to operate continuously between a frequency range around the nominal frequency of the grid, usually between 49.5 to 50.5 Hz (for 50 Hz systems such as in Europe), and to operate for different periods of time when lower/higher frequencies down/up to a minimum/maximum limit, typically 47.5 and 52 Hz.

B. Reactive Power Control and Voltage Regulation

Wind farms are required to control their output reactive power in order to maintain the reactive power balance and the power factor at the Point Common Coupling (PCC) within the desired range. Grid codes additionally requires each wind turbine to control its own terminal voltage to steady an incentive by methods for an Automatic Voltage Regulator (AVR).

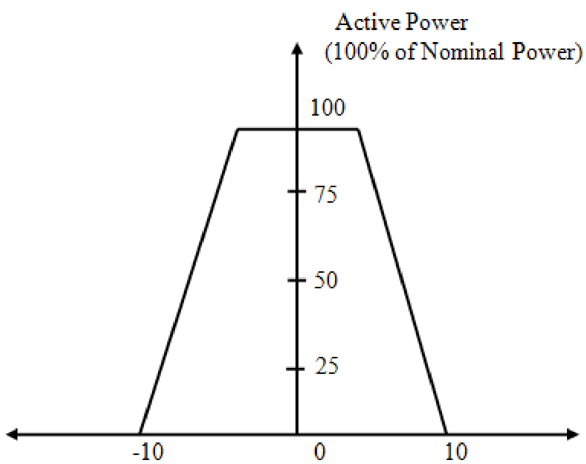

Fig.1. Typical reactive power limiting curve for wind generator.

The Voltage is closely related to the reactive power consequently wind turbines with the ability of controlling reactive power can support and regulate the PCC local system voltage.

C. Active Power and Frequency Control

Grid codes requires wind farms to provide a certain control of the output active power in order to ensure a stable frequency in the power system. Active power control requirements for supporting and stabilizing the system frequency refer to the ability of wind farms to regulate their power output to a defined level either by disconnecting turbines or by pitch control action for the case of variable speed wind turbines.

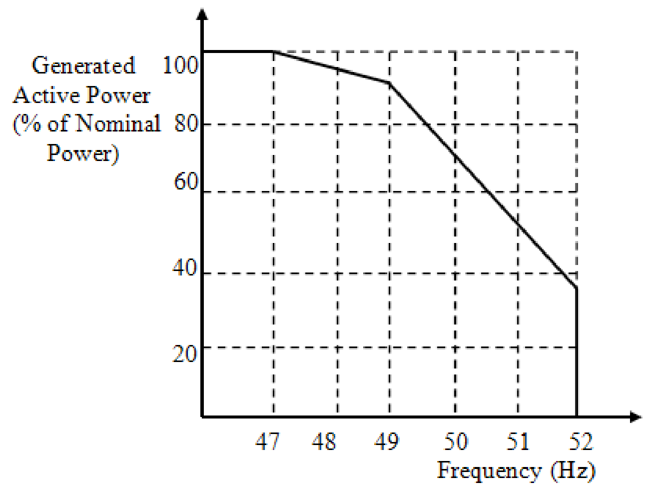

Fig. 2. Typical frequency controlled regulation of active power.

D. Low-Voltage Ride-Through (LVRT)

During grid faults, wind turbines are required to stay connected to the grid for a specific amount of time before being allowed to disconnect. Moreover, wind turbines are required to support the grid voltage during both symmetrical and asymmetrical grid voltage sags by means of reactive power compensation.

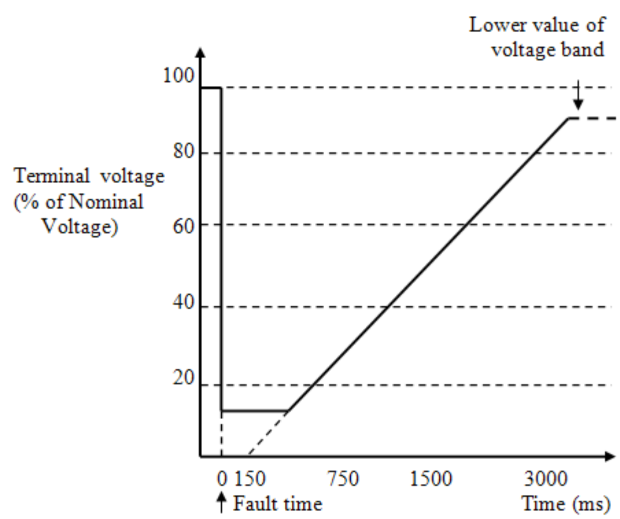

Fig. 3. Typical fault ride-through capability of a wind power generator.

The functional operation of LVRT is based on the comparison of the characteristic with that of the terminal voltage. The FRT requirements under voltage dip is one of the main focuses of the grid codes and also include fast active and reactive power restoration to the pre-fault values, after the system voltage returns to its normal operation levels.

E. High-Voltage Ride-Through (HVRT)

HVRT grid code states that wind turbines should be capable to stay connected to the power grid for a specific amount of time in the event the grid voltage goes above its upper limit value. With the rapid increase of large offshore wind farms, a new problem associated with the response of wind turbines to temporary overvoltage arises due to load shedding or unbalanced faults. Under this condition current may flow from the grid into dc link.

F. Power Quality Capability

Wind farms are required to deliver power with a desired quality by maintaining constant voltage or current harmonics within desired range. Flicker is another voltage quality issue on wind power generation associated with the electric grid. Fluctuations in the system voltage affect the power quality of grid connected wind turbine.

G. Wind Power Plants Modeling and Verification

Grid codes require that wind power plants must be modeled and controlled to meet the connection requirements. Wind farm owners/developers must provide models and system data to enable the system operator to investigate by simulations the interaction between the wind farm and the power system.

H. Communications and External Control

Grid codes require wind farm operators to provide the capability to connect and disconnect the wind turbines remotely. Furthermore, wind farm operators must provide signals corresponding to a number of parameters which are important for the system operators to enable proper operation of the power system. Communication and external control can be affected by harmonics. Harmonic disturbances are a phenomenon associated with the distortion of the fundamental sine wave and are produced by nonlinearity of electrical equipment.

III. Types of Generators Used in Wind Turbine System

Any types of three-phase generator can connect to with a wind turbine. Several different types of generators which are used in wind turbines are as follows. Asynchronous (induction) generator and synchronous generator. Squirrel cage induction generator (SCIG) and wound rotor induction generator (WRIG) are comes under asynchronous generators. Wound rotor generator (WRSG) and permanent magnet generator (PMSG) are comes under synchronous generator [17], [18].

A. Asynchronous Generator

a. *Squirrel Cage Induction Generator (SCIG)*

The fixed speed concept is used in this type of wind turbine. In this configuration the Squirrel Cage Induction Motor is directly connected to the wind through a transformer is shown in the Fig. 4. A capacitor bank is here for reactive power compensation and soft starter is used for smooth grid connection. The main disadvantage it does not support any speed control [17].

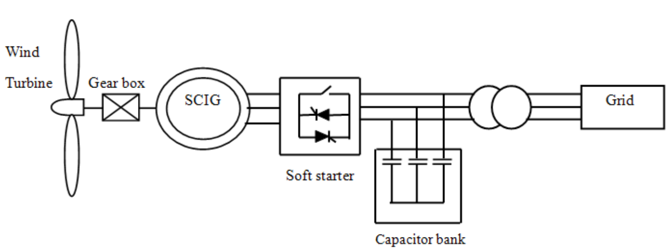

Fig. 4. SCIG wind turbine.

b. Wound rotor induction generator (WRIG)

The variable speed concept is used in this type .In this type of turbine Wound Rotor Induction Generator is directly connected to the grid as shown in Fig. 5.

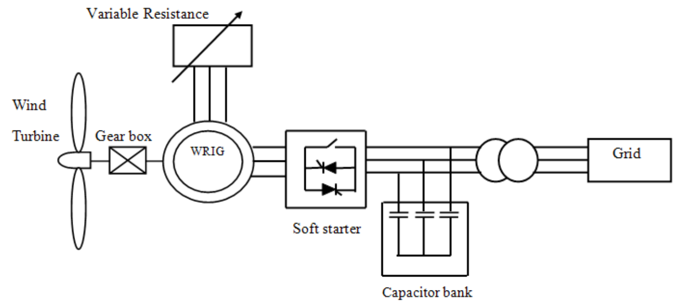

Fig. 5. WRIG wind turbine.

The variable rotor resistance is for controlling slip and power output of the generator. The soft starter used here for reduce inrush current and reactive power compensator is used to eliminate the reactive power demand. The disadvantages are speed range is limited, poor control of active and reactive power, the slip power is dissipated in the variable resistance as losses [18].

B. Synchronous Generator:

1) Wound Rotor Generator

Turbine with wound rotor connected to the grid is shown in figure 6.This configuration neither requires soft starter nor a reactive power comparator. The partial scale frequency converter used in this system will perform reactive power compensation as well as smooth grid connection. The wide range of dynamic speed control is depend on the size of frequency converter. The main disadvantage in the case of grid fault is it requires additional protection and uses slip rings, this makes electrical connection to the rotor.

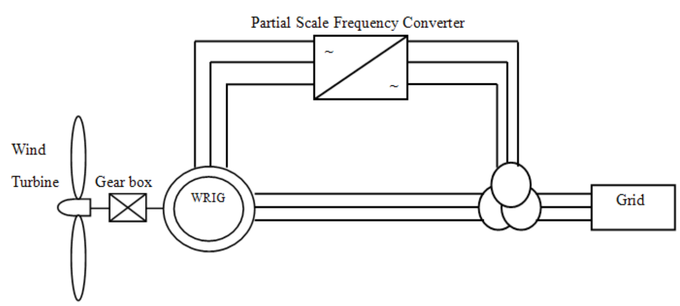

Fig. 6. WRIG wind turbine.

2) Permanent Magnet Generator

The generator is connected to the grid via full scale frequency converter. The frequency converter helps to control both the active and reactive power delivered by the generator to grid.

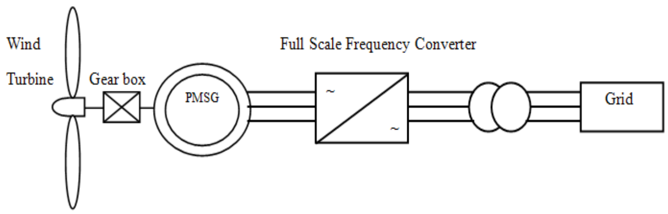

Fig. 7. PMSG wind turbine.

3) Doubly Fed Induction Generator

In order to satisfy the modern grid codes, the grid turbine system have the capability of reactive power support. Doubly fed induction generator based wind turbine system has more advantages than others [19]-[25].

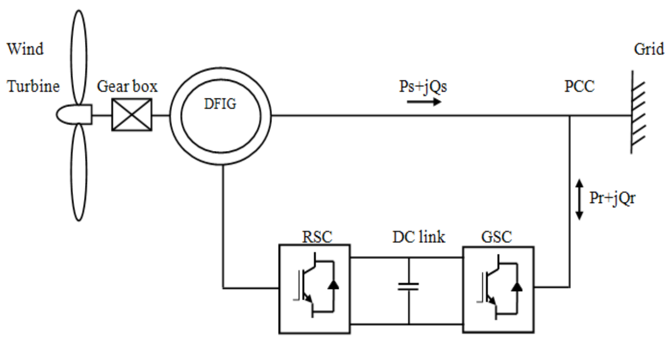

Fig. 8. Doubly Fed Induction Generator wind turbine.

DFIG wind turbine delivers power through the stator and rotor of the generator, the reactive power can be provided in two sides. Reactive power can be supported either through grid side converter or through rotor side converter. The stator part of the turbine is directly connected to the grid and the rotor is interfaced through a crowbar and a power converter [19]. The voltage to the stator part is applied from the grid and the voltage to the rotor is induced by the power converter. The doubly fed induction machine can be operated in generating mode in both sub-synchronous and super-synchronous modes [20].

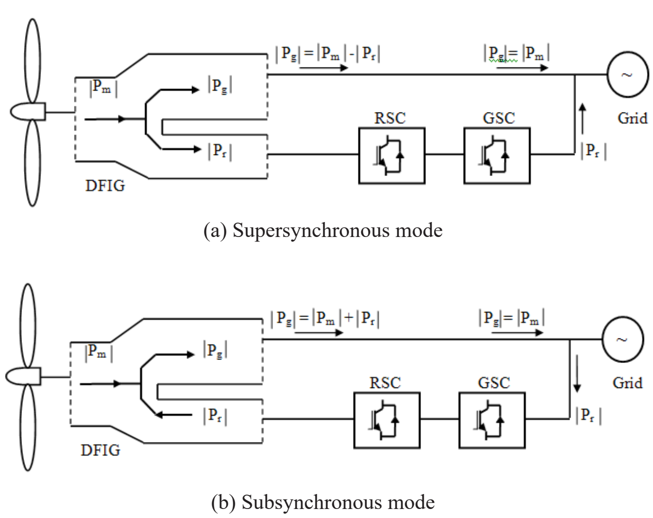

Fig. 9. Operating modes of DFIG.

The power is delivered from the rotor through the power converter to the grid if the generator is operates above synchronous speed (super synchronous speed). If the generator is operates below synchronous speed (sub synchronous speed), then the power is delivered from the grid through the power converter to the rotor The power converter controls both the active and reactive power flow, the DC voltage of link capacitor between the grid and DFIG wind turbine by feeding the pulse width modules to the converters. A crowbar is implemented between the generator and converter to prevent short circuit in the wind energy system [19].Which may result in high current and high voltage. The RSC converter controls the flux of the DFIG wind turbine, which operates at the slip frequency that depends on the rotor speed of the generator. According to the maximum active and reactive power control capability of converter, the power rating of the RSC is determined. So DFIGs are widely used in modern WTs due to their power control capability, variable speed operation, low converter cost, and reduced power loss [20]-[25].

IV. Grid Connected Technical Issue on DFIG Based Wind Turbine

Doubly-Fed Induction Generator (DFIG) Wind Turbine (WT) can be affected by power system faults and requires crowbar protection. When the crowbar is triggered, the rotor is short circuited over the crowbar impedance, the DFIG operates as a Squirrel-cage Induction Generator (SCIG) that tends to drain large amount of reactive power from the grid during fault, potentially causing a voltage drop [26]. In this paper, the problem is many number of controllers are used that leads to the increase cost and complex design.

Novel active crowbar protection (NACB_P) system was designed to enhance the FRT capability. The problem in this is Capacitor is used in the protection circuit is to eliminate the ripples generated in the rotor current [27]. The problem is Overvoltage on DC link capacitor affect the converter during fault conditions.

The PI controller is used to enhance the low voltage ride through (LVRT) capability of doubly fed induction generator (DFIG) by means of STATCOM [28]. In this paper the problem is additional device needed for voltage sag compensation. STATCOM supports only for reactive power compensation.

A Fuzzy Logic Controlled Series Variable Resistor (FLC-SVR) used for transient stability enhancement of the grid co-nnected wind farms [29].The problem is when using of series variable resistor (SVR) it dissipates the large amount of energy that leads to losses.

Rotor Current-based Model Reference Adaptive System (MRAS) sensor less vector control provided for RSC. GTO-based thyristor controlled stator current limiter and dc chopper are used [30]. The problem is the control technique leads to complex design and also increase the installation cost.

Inductive and resistive Superconducting Fault Current Limiter(SFCL) are installed in series with the dc transmission line, and once the fault is detected, the current-limiting inductance or resistance will be activated to limit the fault current for Robustness improvement of a VSC-HVDC system with wind plants against DC fault [31]. The problem in this paper is it will leads to reactive power absorption and the fluctuations in the power.

Resistive-type Superconducting Fault Current Limiter (SFCL) connected in series with the DFIG rotor winding to limit the peak values of the fault rotor current, dc-link voltage [32]. It will leads to a complex design and it does not provide reactive power compensation are the problem associated in this paper.

A new controller approach for Unified Power Flow Controller (UPFC) is proposed to improve the LVRT capability. The shunt and series converters of the UPFC are controlled using a Hysteresis Current Controller (HCC) and Proportional Integral Controllers (PI) [33]. The major problem is: UPFC is a complex power electronic device developed to control and optimize the power flow in electrical power Transmission systems.

Study of the LVRT of grid-connected DFIG-based wind turbines including the crowbar. The back to back converter is used to control the reactive power from the power grid. The DFIG are very sensitive to grid faults and it will affect the converters [34]. It provides only about investigation of transient characteristics and the dynamic behavior of DFIG. The author does not consider about the problems generated in the DFIG based wind turbine system.

It proposes a modified flux-coupling-type Superconducting Fault Current Limiter (SFCL) is suggested to improve the Fault Ride-through (FRT) capability of DFIG [35]. Problem is the SFCL is used at different locations it increases the cost and produce switching harmonics.

The SFCL is used to limit the fault current, compensate the terminal voltage drop. The power fluctuation is suppressed by the Superconducting Magnetic Energy Storage (SMES) [36]. Problem is Combined operation of SFCL and SMES provide the Complex Controller design.

Improving the Fault Ride-Through Capability of DFIG Based Wind Turbine Using Superconducting Fault Current Limiter (SFCL). The SFCL is used to reduce fault current level at the stator side and to improve FRT capability of the system [37]. It does not limit the rotor short circuit current in the DFIG based wind turbine is one of the problem in the proposed method.

The wind turbine current controllers need to be designed to eliminate the impact of grid voltage harmonics, especially low-order harmonics. This paper proposes a stator current harmonic suppression method using a sixth-order resonant controller to eliminate negative sequence fifth- and positive sequence seventh-order current harmonics. A stator current harmonic control loop is added to the conventional rotor current control loop for harmonic suppression [38]. The author does not consider about the voltage compensation and reactive power compensation.

The studies on Doubly Fed Induction Generator (DFIG) based wind farm integrated with one superconducting fault current limiter (SFCL) based passive voltage compensator and one transient voltage control (TVC) based active voltage compensator is used for transient voltage stability improvement [39]. Problem is the resistive type of SFCL work is based on the choosing of resistance value.Due to large amount energy consumption affect the voltage compensation.

This describes an experimental investigation of an alternative FRT approach using a brake chopper circuit across the converter dc link to ensure that the dc-link voltage remains under control during a fault. DFIG systems employs a rotor circuit crowbar to protect the rotor converter during a fault [40]. The additional chopper circuit is used that leads to additional components and switching stress.

V. Role of Control Schemes in Performance of Wind Turbine

A. Control of Rotor Side Converter (RSC):

In normal operation, the control scheme of the RSC is illustrated in Fig. 10. In order to decouple the electromagnetic torque and the rotor excitation current, the induction generator is controlled in the stator-flux oriented reference frame, which is a Synchronously rotating reference frame, with its -axis oriented along the stator-flux vector position (the stator-flux vector is calculated using us) [41]. The typical proportional-integral (PI) controllers are used for regulation in the rotor speed and reactive power (outer) control loops as well as the rotor current (inner) control loops.

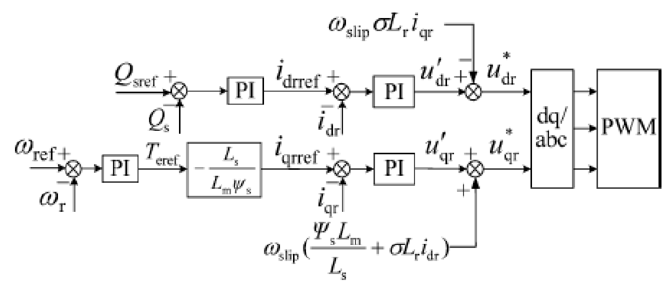

Fig. 10. Control scheme of the RSC during normal operation.

When a short-term low-voltage fault occurs, the incoming power from the wind and the power flowing into the grid are imbalanced instantaneously, resulting in the transient excessive currents in the rotor and stator circuits. Therefore from the energy balance point of view, the key point of suppressing the over-currents in the rotor and stator circuits is to reduce the imbalanced energy flowing through the DFIG WT system. When at least one of the monitored parameters, including the rotor current, stator current, DC-link voltage, and grid voltage, exceeds its respective protection setting due to the grid fault, LVRT control strategy will be triggered in [43]. With this control strategy, the rotor side controller will increase the generator rotor speed by reducing the generator torque to zero during the fault, in order to absorb and convert the incoming energy from the wind into the kinetic energy in the WT inertia. The increased kinetic energy can be transformed and released into the grid after the fault clearance. The control scheme of the RSC against grid faults is illustrated in Fig. 11.

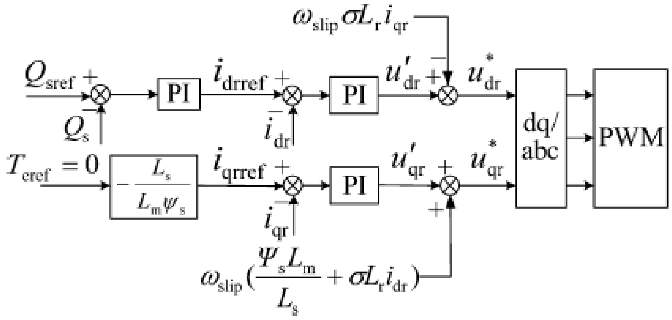

Fig. 11. Control scheme of the RSC during grid faults.

B. Control of Grid Side Converter (GSC)

In Fig. 12. shows the control scheme of the GSC in normal operation, where u_a and i_L are the grid-side converter voltage vector and the grid-side inductor current vector, respectively. In order to obtain the independent control of active and reactive power flowing between the grid and the GSC, the converter control operates in the grid-voltage oriented reference frame, which is a synchronously rotating reference frame, with its d-axis oriented along the grid-voltage vector position [41]. Similarly, the typical PI controllers are used for regulation in the DC-link voltage (outer) control loop and the grid side inductor current (inner) control loops.

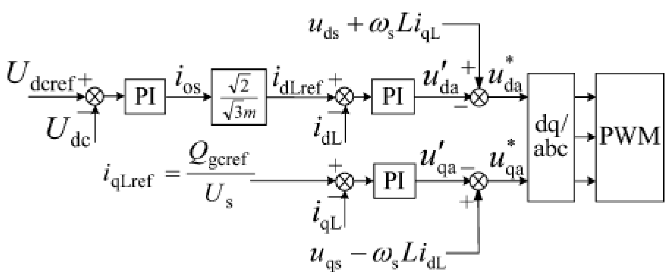

Fig. 12. Control diagram of the GSC in normal operation.

In normal operation, when the power flowing through the grid and rotor side converters is balanced i_{os} is equal to i_{or}, so the DC-link voltage is constant. When the grid voltage dips, i_{os} may not be equal to i_{od} due to the instantaneous unbalanced power flow between the grid and rotor side converters, and therefore the DC-link voltage may fluctuate. In order to reduce the fluctuation of the DC-link voltage, the item (P_r/u_{ds}) reflecting the instantaneous variation of the output power of the rotor side controller is directly set as the reference of the during the grid fault [42]. However, the stator voltage may reduce to zero during the grid fault. This will introduce an extremely high transient value of i_{dL}. The detailed control scheme of the GSC during the grid fault is shown in Fig. 13.

In this paper [43], when the rotor current, stator current, DC-link voltage, or grid voltage exceeds its respective relay setting due to the grid voltage dip, the term (P_r/U_{dc}) describing i_{or} is represented as a disturbance to compensate the instantaneous rotor power in the control scheme.

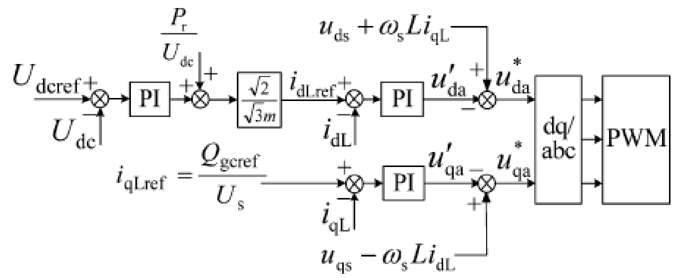

Fig. 13. Control scheme of the grid side converter during a grid fault.

VI. Possible Solutions

There are various possible solutions are available to avoid the problems in DFIG based wind turbine. These techniques can be splited into two categories by Adding external hardware to the conventional DFIG and using different control scheme with conventional DFIG.

A. Adding the Crowbar

The first solution to add LVRT capability to the DFIG is using crowbar resistance. In this solution, a set of three resistors are activated to be connected to the rotor upon the fault occurrence to bypass the RSC furthermore the gating signals for RSC and GSC are turned off. However, the control of the active and reactive powers is lost during the crowbar operation and the DFIG operates as a squirrel cage induction generator which absorbs reactive power from the grid leading to worst voltage dip situation. The position of the crowbar resistance is shown in Fig. 14.

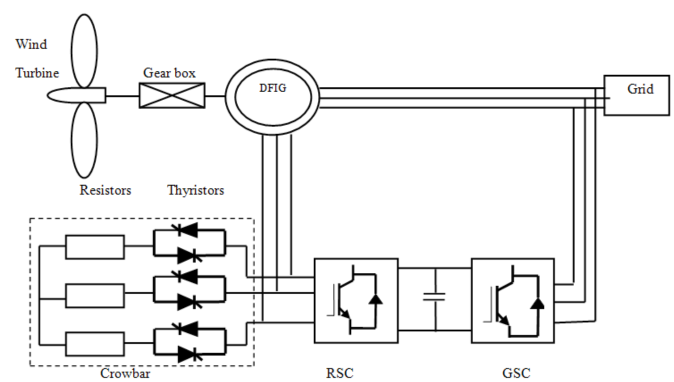

Fig. 14. DFIG with Crowbar.

B. Dynamic Voltage Restorer (DVR)

Another solution for adding LVRT capability for DFIG is using DVR in series with the DFIG to compensate the low voltage of the grid is shown in Fig. 15. The DVR consists of a battery, a three phase inverter, a filter and an injection transformer. The DVR has a great advantage of enabling DFIG to work in almost normal condition under symmetrical and asymmetrical faults.

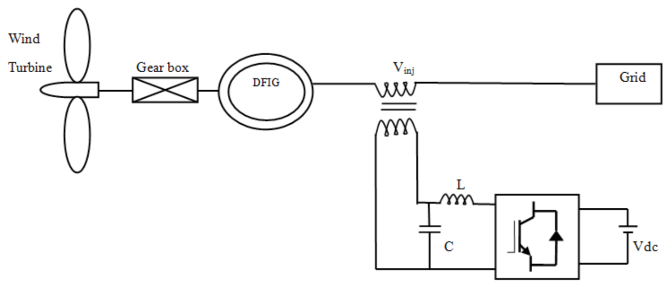

Fig. 15. Applying DVR to DFIG.

C. Superconducting Fault Current Limiter (SFCL) and Superconducting Magnetic Energy Storage (SMES)

Another solution is to connect a Superconducting Fault Current Limiter (SFCL) and Superconducting Magnetic Energy Storage (SMES) unit with the PCC to improve the dynamic performance of a wind energy conversion system equipped with DFIG during low voltage. The SMES circuit is composed of capacitor, DC chopper, and superconducting coil with inductance (LSC) shown in Fig 16. During the fault condition on stator side, SFCL is connected between the DFIG and grid to decrease the fault current and avoid the voltage drop. The SMES is connected in the DFIG based wind energy conversion system for avoiding the power fluctuations.

The SFCL is operates only if the current exceeds a threshold level. The SMES is used to eliminate the unbalanced kinetic energy after the operation of the SFCL, so that the remaining power fluctuation can be suppressed.

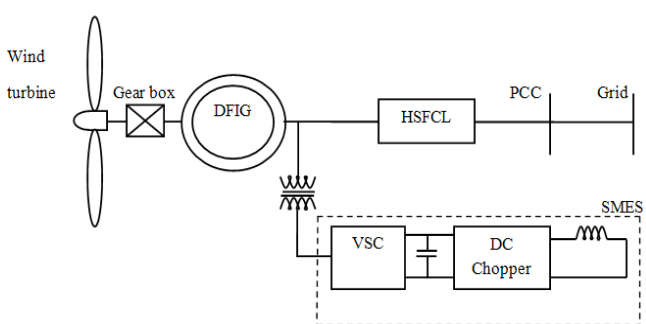

Fig. 16. Applying SMES to DFIG.

D. Chopper Circuit

Another solution controls the DC link voltage by adding a chopper circuit to the capacitor to release the excess energy from the capacitor besides overrating the diodes of the RSC to handle the high fault current.

E. Active and Passive Compensators

Another solution is using active and passive compensators are used. In this technique, a damping resistor in series with the stator (passive compensator) is used in addition to changing the mode of control of RSC to active ride-through compensator mode (active compensator). In active compensator mode the RSC uses the d and q components of the rotor currents to suppress the oscillations in the stator flux and limit the rotor current. Furthermore, a nonlinear control of the GSC has been used to contain the DC-link voltage within its safe limits.

VII. Conclusion

This paper has reviewed on major grid code requirements of DFIG based wind turbine. Among the various grid code requirements the Fault Ride-Through (FRT) or Low Voltage Ride Through (LVRT) capability of wind turbines is one of the core requirements to ensure stability in the power grid during transients and fault conditions. In this paper discussed about the various types of generators used in the wind energy conversion system. As a result DFIG has the better performance and has the more advantages compared to other generators. Then the literature review on various papers and the technical issues on DFIG based wind turbine system are provided.

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