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Grid Stability and Control in DFIG Wind Turbines using Dynamic Voltage Restorer

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The development of wind power in India began in the 1990s, and has significantly increased in the last few years.India has the fifth largest installed wind power capacity in the world.As of 31 Jan 2013 the installed capacity of wind power in India was 18551.7 MW, mainly spread across Tamil Nadu (7134 MW), Gujarat (2,884 MW), &Maharashtra (2310.70 MW)whichare leading the top. All across the world, the demand for electricity from renewable energies is constantly growing. To meet this demand, wind farms must be as operable as conventional power plants and better integrated into the grid control mechanism. Our wind power plants should actively support the grid, fulfilling all necessary requirements and ensuring reliable energy supplies even during breakdowns. Wind power plants feed the grid with controlled reactive power. This allows for a constant voltage control, sustaining the line voltage. Even at temporary voltage dips the wind power plant remains connected to the grid and helps to keep it stable. If any frequency fluctuations occur the effective power of our wind turbines should automatically adjust according to the needs.

Keywords: *Renewable Energy (RE),Wind Turbine Generator(WTG),Wind Power Plant(WPP),Doubly Fed Induction Generator (DFIG),Dynamic Voltage Restorer*

1.0 INTRODUCTION

The wind is abundant almost in any part of the world. Its existence in nature caused by uneven heating on the surface of the earth as well as the earth's rotation means that the wind resources will always be available. The increased amount of power from decentralized renewable energy systems, as especially wind energy systems, requires ambitious grid code requirements to maintain a stable and safe operation of the energy network. The actual grid codes stipulate that wind farms should contribute to power system control like frequency and voltage control to behave similar to conventional power stations. For operation during grid voltage faults, it becomes clear that grid codes prescribe that wind turbines must stay connected to the grid and should support the grid by generating reactive power to support and restore quickly the grid voltage after the fault. In this paper, the application of a DVR that is connected to a wind-turbine-driven DFIG to allow uninterruptible fault ride through of voltage dips fulfilling the grid code requirements is investigated. The DVR can compensate the faulty line voltage, while the DFIG wind turbine can continue its nominal operation as demanded in actual grid codes. Here, asymmetrical faults are investigated and simulation results under transient grid voltage dips on a 2 MW DFIG is presented. The results consist with the detailed analysis of DFIG behavior with and without activation of DVR control for better understanding.

2.0 GRID ABNORMALITIES

Grid protection encompasses measures to protect against excessively high currents and voltages.

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Grid abnormalities are predominantly caused by grid short circuits, rapid auto-reclosure changes in grid voltage and frequency fluctuations as shown in Figure 1.

Single-phase, two-phase and three-phase grid short-circuits in the direct vicinity of the generator are almost identical to generator short-circuits. Grid short-circuits some distance from the generator cause currents to flow across the transformer and conductor impedances that lie between the short-circuit and generator [2]. The rapid auto-reclosure familiar to electricity supply companies, in which grid sections become separated fromthe energy supply for approximately 100 to 500 ms, because of the connection between the wind power plant and consumers, lead to a brief unintentional period in which the system operates in isolation. As a state of equilibrium does not exist between power supply and consumption, voltage and frequency will drift away from the grid values.

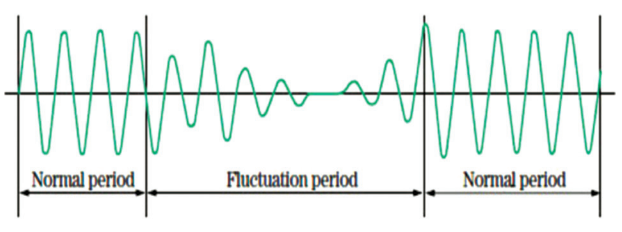

FIG.1 VOLTAGE FLUCTUATIONS IN SYSTEM

Because of the connection between direct coupled asynchronous generators and variable speed power converter supply systems, it is possible for the asynchronous generator to go over to the consumer or motor mode during the interruption [1]. In this situation individual plant regulation systems greatly influence the behavior of turbines and the network as a whole. Changes in grid voltage within the normal range do not cause any dominating torque levels. In grids supplied via power converters, rapid grid frequency fluctuations can lead to significant loading of the drive and generator of wind turbines.

2.1 Frequency Response

System frequency is a continuously changing variable that is determined and controlled by the second-by-second balance between system demand and total generation. If demand is greater than generation, the frequency falls while if generation is greater than demand, the frequency rises. National Grid has a license obligation to control frequency within the limits specified in the 'Electricity Supply Regulations', i.e. ±1% of nominal system frequency (50 Hz) save in abnormal or exceptional circumstances. National Grid must therefore ensure that sufficient generation and / or demand is held in automatic readiness to manage all credible circumstances that might result in frequency variations. There are two types of Frequency Response Dynamic and Non Dynamic Response. Dynamic Frequency Response is a continuously provided service used to manage the normal second by second changes on the system. While Non Dynamic Frequency Response is usually a discrete service triggered at a defined frequency deviation.

3.0 REGENERATION TECHNOLOGY

The conventional ways of generating electricity using non-renewable resources such as coal, natural gas, oil and so on, have great impacts on the environment as it contributes vast quantities of carbon dioxide to the earth's atmosphere which in turn will cause the temperature of the earth's surface to increase, known as the greenhouse effect. Hence, with the advances in science and technology, ways of generating electricity using renewable energy resources such as the wind are developed. Single WTG has limited capacity, much less than a conventional power generator, a wind power plant normally consists of many WTGs connected together by overhead lines or cables. Their power output is collected and transmitted to the grid through an alternating current (AC) or direct current (DC) line, after voltage step-up at the substation in the WPP. Some WPPs now have a capacity comparable to that of conventional power generators. As the penetration of renewable generation such as wind energy increases, the need to address the fault ride through capability issues will become more critical. Hitherto, the wind turbines were allowed to trip when a voltage dip occurs.

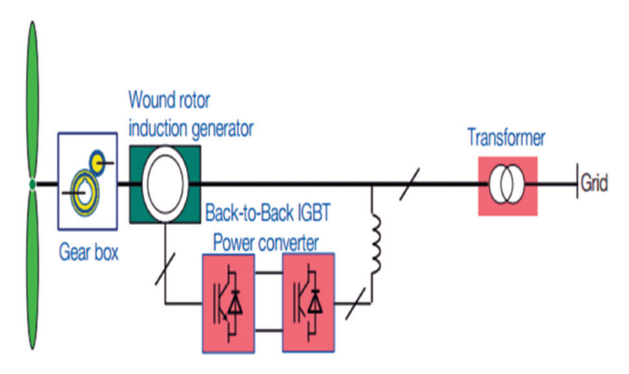

FIG. 2 SCHEMATIC OF DFIG CONNECTED TO GRID

Among the WTG's, turbines using the doubly fed induction generator (DFIG) are dominant due to its variable-speed operation and separately controllable active and reactive power as shown in Figure.2. But the reaction of DFIGs to grid voltage disturbances is sensitive, for symmetrical and unsymmetrical voltage dips, and requires additional protection for the rotor side power electronic converter. Conventionally, a resistive network called crowbar is connected in case of rotor over currents. But the machine draws a high short circuit current when the crowbar is activated [8], resulting in a large amount of reactive power drawn from the power network, which is not acceptable when considering actual grid code requirements. Thus, other protection methods have to be investigated to ride-through grid faults safely and fulfill the grid codes.

3.1 Induction generator

An induction generator is mechanically and electrically similar to a polyphone induction motor. Induction generators produce electrical power when their shaft is rotated faster than the synchronous frequency of the equivalent induction motor. They are often used in wind turbines and some micro hydro installations due to their ability to produce useful power at varying rotor speeds. IG is not self-exciting, meaning they require an external supply to produce a rotating magnetic flux. The external supply can be supplied from the electrical grid or from the generator itself, once it starts producing power. They are commonly used in the wind turbine electric generation due to its reduced unit cost, brushless rotor construction, ruggedness, and ease of maintenance. Moreover, induction generators have several characteristics over the synchronous generator [3]. The speed of the asynchronous generator will vary according to the turning force (moment, or torque) applied to it. In real life, the difference between the rotational speed at peak power and at idle is very small approximately 1 percent. This is commonly referred as the generator's slip which is the difference between the synchronous speed of the induction generator and the actual speed of the rotor.

3.2 Control Scheme

A wind turbine power plant operates in a range of two characteristic wind speed values referred to as Cut in wind speed and Cut out wind speed. The turbine starts to produce power at Cut in wind speed usually between 4 to 5 m/s. Below this speed, the turbine does not generate power. The turbine is stopped at Cut out wind speed usually at 25 m/s to reduce load and prevent damage to blades. They are designed to yield maximum power at wind speeds that lies usually between 12 to 15 m/s. It would not be economical to design turbines at strong winds, as they are too rare. However, in case of stronger winds, it is necessary to waste part of the excess energy to avoid damage on the wind turbine [5]. Thus, the wind turbine needs some sort of automatic control for the protection and operation of wind turbine. The functional capabilities of the control system includes controlling the automatic startup, altering the blade pitch mechanism, shutting down when needed in the normal and abnormal condition plus obtaining information on the status of operation, wind speed, direction and power production for monitoring purpose.

4. DOUBLE FED INDUCTION GENERATOR (DFIG)

In the last 15 years, the use of doubly fed induction machines in modern variable-speed wind turbines has increased rapidly. A doubly fed induction machine is a wound-rotor doubly-fed electric machine and has several advantages over a conventional induction machine in wind power applications.

First, as the rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances

Second, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. A variable speed wind turbine utilizes the available wind resource more efficiently than a fixed speed wind turbine, especially during light wind conditions.

Third, the cost of the converter is low when compared with other variable speed solutions because only a fraction of the mechanical power, typically 25-30%, is fed to the grid through the converter, the rest being fed to grid directly from the stator [6].

The efficiency of the DFIG is very good for the same reason According to new grid code requirements, wind turbines must remain connected to the grid during grid disturbances. Moreover, they must also contribute to voltage support during and after grid faults. The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis current vector control or direct torque control (DTC). DTC has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.

4.1 DFIG Controlled Operation

The doubly-fed generator rotors are typically wound with 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus in the typical ± 30% operational speed range around the synchronous speed, the rated current of the converter is accordingly lower which leads to a lower cost of the converter. The drawback is that controlled operation outside the operational speed range is impossible because of the higher than rated rotor voltage. The crowbar system is essential to avoid the disconnection of the doubly fed induction wind generators from the network during faults. The most common way to avoid high induced currents in the rotor side converter (RSC) is the use of a crowbar system. Wind turbines based on DFIG have the stator windings connected directly to the grid, making the rotor winding susceptible to high currents induced during grid faults. The rotor windings are connected to the grid via a back-to-back converter, which is very sensitive to over-currents [4]. The crowbar will short-circuit the rotor windings through a resistance when excessive currents or voltages are detected. In order to be able to continue the operation as quickly as possible an active crowbar has to be used [7]. The active crowbar can remove the rotor short in a controlled way and thus the rotor side converter can be started only after 20-60 ms from the start of the grid disturbance. Thus it is possible to generate reactive current to the grid during the rest of the voltage dip and in this way help the grid to recover from the fault. As a general rule, the activation and the deactivation of the crowbar system is based only on the DC-link voltage level of the back-to-back converters.

4.2 Fault Ride throughSolutions

The rapid development of power electronics has made that the old devices for controlling voltage based on capacitors and reactors have been replaced by Flexible AC Transmission Systems (FACTS). New wind turbines have integrated different systems to withstand voltage dips, however the old wind turbines have to install different FACTS to overcome dips. The main solutions are installed either in each turbine or in the point of common coupling. The FACTS used in wind systems can be divided into three categories depending on their connection .Series device, such as the Dynamic Voltage Restorer (DVR). Shunt device, such as Static Voltage Compensator (SVC) and Static Compensator (STATCOM) and Series-shunt device they are a combination of a series and parallel FACTS. In wind system Unified Power-Quality Conditioner (UPQC) are used.

5. DYNAMIC VOLTAGE RESTORER

Dynamic Voltage Restorer is a series compensator, which works inserting a voltage of magnitude and frequency necessary. DVR consists of medium voltage switchgear, a coupling transformer, filters, rectifier, inverter, energy source and control and protection system. DVR can inject or absorb real and reactive power independently by an external storage system without reactors and capacitors. If the storage system is a capacitor bank, during normal operation it will be charging, and when a swell or voltage sag is detected this capacitor will discharge to maintain load voltage supply injecting or absorbing reactive power.Thisis called as Dynamic Voltage Restorer (DVR) in the literature as their primary application is to compensate for voltage sags and swells [7]. However, the control techniques are different. DVR is expected to respond fast (less than 1/4 cycle) and thus employs PWM converters using IGBT or IGCT devices. Typically, DVRs are made of modular design with rating of 2 MVA or 5 MVA. They have been installed in substations of voltage rating from 11 kV to 69 kV.Power circuit of DVR as shown in Figure 3 consists of four components described below.

5.1 Voltage Source Converter (VSC)

The function of an inverter system in DVR is used to convert the DC voltage supplied by the energy storage device into an AC voltage. Voltage source converter (VSC) of low voltage and high current with step up injection transformer is used for this purpose in the DVR compensation technique. Generally Pulse-Width Modulated Voltage Source converter (PWMVSC) is used. There are two basic three phase inverter topologies, the popular two-level inverter and the multilevel inverters have recently emerged as an attractive alternative to PWM schemes so that the losses associated with fast switching can be eliminated. The implementation of the PWM in the two level inverter is simpler and its cost is cheaper than a multilevel inverter.

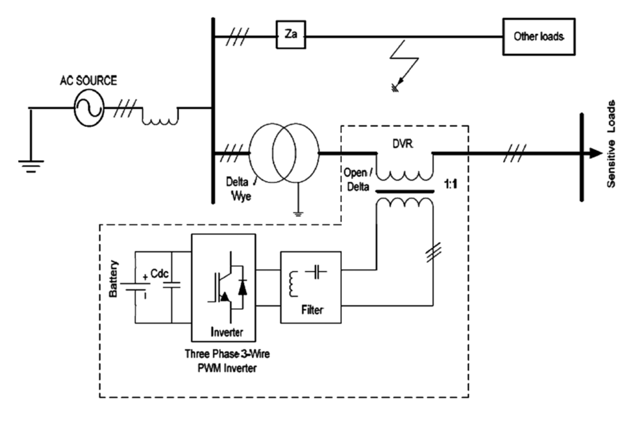

FIG. 3 POWER CIRCUIT OF DYNAMIC VOLTAGE RESTORER

5.2 Boost or Injection Transformers

In a three-phase system, either three single-phase transformer units or one three phase transformer unit canbe used for voltage injection purpose .The injection transformer comprises of two sidevoltages namely the high voltage side and low voltage side. Normally the high voltage side of the injectiontransformer is connected in series to the distribution system while power circuit of the DVR can be connected atthe low voltage side. The basic function of the injection transformer is to increase the voltage supplied by thefiltered VSC output to the desired level while isolating the DVR circuit from the distribution network [6]. Thetransformer winding ratio is pre-determined according to the voltage required in the secondary side of thetransformer generally this is kept equal to the supply voltage to allow the DVR to compensate for full voltagesag. A higher transformer winding ratio will increase the primary side current, which willadversely affect the performance of the power electronic devices connected in the VSC. The DVR performance is totally depending on therating of the injection transformer, since it limits the maximum compensation ability of the DVR.Multilevel inverter topologycan used in DVR allowing the direct connection of the DVR to the distribution system without using injectiontransformer. The three single phase transformers connection used in the three-phase DVR can be configured either indelta/open or star/open connection. In case of unbalance fault in the highvoltage side, the zero sequence current flowing almost zero, if the distribution transformer connection in Δ-Ywith the grounded neutral. As such connection, the DVR is only mitigating the positive and negative sequencecomponents.

5.3 Passive Filters

Basically filter unit consists of inductor (L) and capacitor (C). In DVR, filters are used to convert the inverted PWM waveform into a sinusoidal waveform. This can be achieved by eliminating the unwanted harmonic components generated by the VSC action. Higher orders harmonic components distort the compensated output voltage. The unnecessary switching harmonics generated by the VSC must be removed from the injected voltage waveform in order to maintain an acceptable Total Harmonics Distortion (THD) level. The switching frequencies of the VSCare usually up to several kHz for medium power level. The passive filters can be placed either in the high voltage or in low voltage side winding of the series injection transformer. If the filter is installed at the low voltage side it has the advantage of being closer to the harmonic source thus high order harmonic currents are avoided to penetrate into the series injection transformer. Harmonics currents will circulate into the series injection transformer if the filtering scheme is placed at the high voltage.

5.4 Energy Storage

The DVR needs real power for compensation purposes during voltage disturbances in the distributionsystem. In this case the real power of the DVR must be supplied by energy storage when the voltagedisturbances exit. The energy storage such as a battery is responsible to supply an energy source in DC form. Energy storage consists of two types form. One using stored energy to supply the delivered power and the otherhaving no significant internal energy storage but instead energy is taken from the faulted grid supply during thesags. A shunt–converter or the rectifier is the main sources of the directenergy storage which is supplied to DVR. The application of the energy storage inDVR is depending on the designed rating required and total cost is also must be considered. Flywheels, batteries, superconducting magnetic energy storage (SMES) and super capacitors can be usedas energy storage devices. Lead acid batteries are popular among the others owing to its high response during charging anddischarging. Flywheel Energy Storage as a preferred energy storage device, the system utilizes a single AC/AC powerconverter for the grid interface as opposed to a more conventional AC/DC/AC converter, leading to higherpower density and increased system reliability [5]. However the suitable of the type of energy storage depend on the DVR designed in term rated power and thetotal cost factor. The DVR has two operating modeslike Standby mode also termed as short circuit operation (SCO) mode where the voltage injected has zero magnitude. Secondly boost mode when the DVR injects a required voltage of appropriate magnitude and phase to restore the pre-fault load bus voltage.

6.0 MODE OF OPERATION

The control and protection of a DVR designed to compensate voltage sags must consider the following functional requirements.

- When the supply voltage is normal, the DVR operates in a standby mode with zero voltage injection. However if the energy storage device say batteries is to be charged, then the DVR can operate in a self-charging control mode.

- When a voltage sag/swell occurs, the DVR needs to inject three single phase voltages in synchronism with the supply in a very short time. Each phase of the injected voltage can be controlled independently in magnitude and phase. However, zero sequence voltage can be eliminated in situations where it has no effect. The DVR draws active power from the energy source and supplies this along with the reactive power required to the load.
- If there is a fault on the downstream of the DVR, the converter is by-passed temporarily using thyristor switches to protect the DVR against over currents. The threshold is determined by the current ratings of the DVR.

Typically, a DVR may be designed to protect a sensitive load against 35% of three phase voltage sags or 50% of the single phase sag. The duration of the sag could be 200 ms. The DVR can compensate higher voltage sags lasting for shorter durations or allow longer durations up to 500 ms for smaller voltage sags. The response time could be as small as 1 ms.

7.0 MODELING OF CASE STUDY

The investigated wind turbine system, as shown in Figure 4, consists of the basic components like the turbine, a gear, a DFIG, and a back-to-back voltage source converter with a dc link. A dc chopper to limit the dc voltage across the dc capacitor and a crowbar are included. The back-to-back converter consists of a RSC and a LSC, connected to the grid by a line filter to reduce the harmonics caused by the converter. A DVR is included to protect the wind turbine from voltage disturbances. Due to the short period of time of voltage disturbances, the dynamics of the mechanical part of the turbine will be neglected and the mechanical torque brought in by the wind is assumed to be constant. The findings of the section enhance the understanding of rotor over currents during symmetrical grid voltage dip, only if the RSC can provide a sufficient voltage level, controllability of rotor currents can be obtained. If the rotor voltage exceeds the converter voltage, high currents will flow through the diodes into the dc-link capacitor, damaging the insulated gate bipolar transistor (IGBT) or the dc capacitor.

7.1 Crowbar Protection

To protect the RSC from tripping due to over currents in the rotor circuit or overvoltage in the dc link during grid voltage dips, a crowbar is installed in conventional DFIG wind turbines, which is a resistive network that is connected to the rotor windings of the DFIG. The crowbar limits the voltages and provides a safe route for the currents by bypassing the rotor by a set of resistors. When the crowbar is activated, the RSCs pulses are disabled and the machine behaves like a squirrel cage induction machine directly coupled to the grid.The magnetization of the machine that was provided by the RSC in nominal condition is lost and the machine absorbs a large amount of reactive power from the stator, and thus from the network [8] which can further reduces the voltagelevel and is not allowed in actual grid codes.

Triggering of the crowbar circuit also means high stressto the mechanical components of the system as the shaft and the gear. Anyway, to compare a conventional DFIG wind turbine system protected by a crowbar circuit, simulation results including crowbar protection are studied. Therefore, the crowbar resistance is designed here.If the rotor phase voltage across the crowbar rises above the maximum converter voltage and high currents will flow through the anti-parallel diodes of the converter.A crowbar resistance of Rcrowbar = 0.3 Ω is used in the simulations. There are approaches limiting the operation time of the crowbar to return to normal DFIG operation with active and reactive power control as soon as possible by injecting a demagnetizing current using a threshold control.

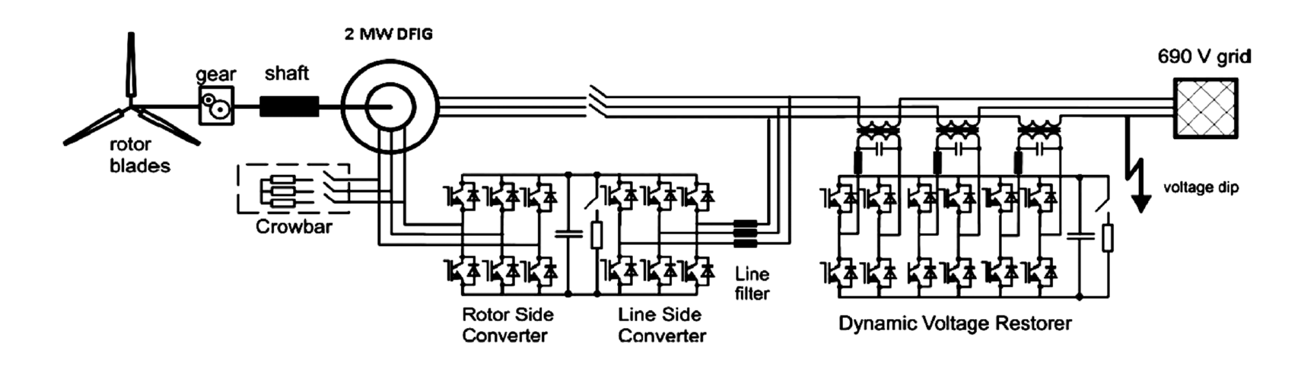

FIG.4 SCHEMATIC DIAGRAM OF DFIG WIND TURBINE SYSTEM WITH DVR

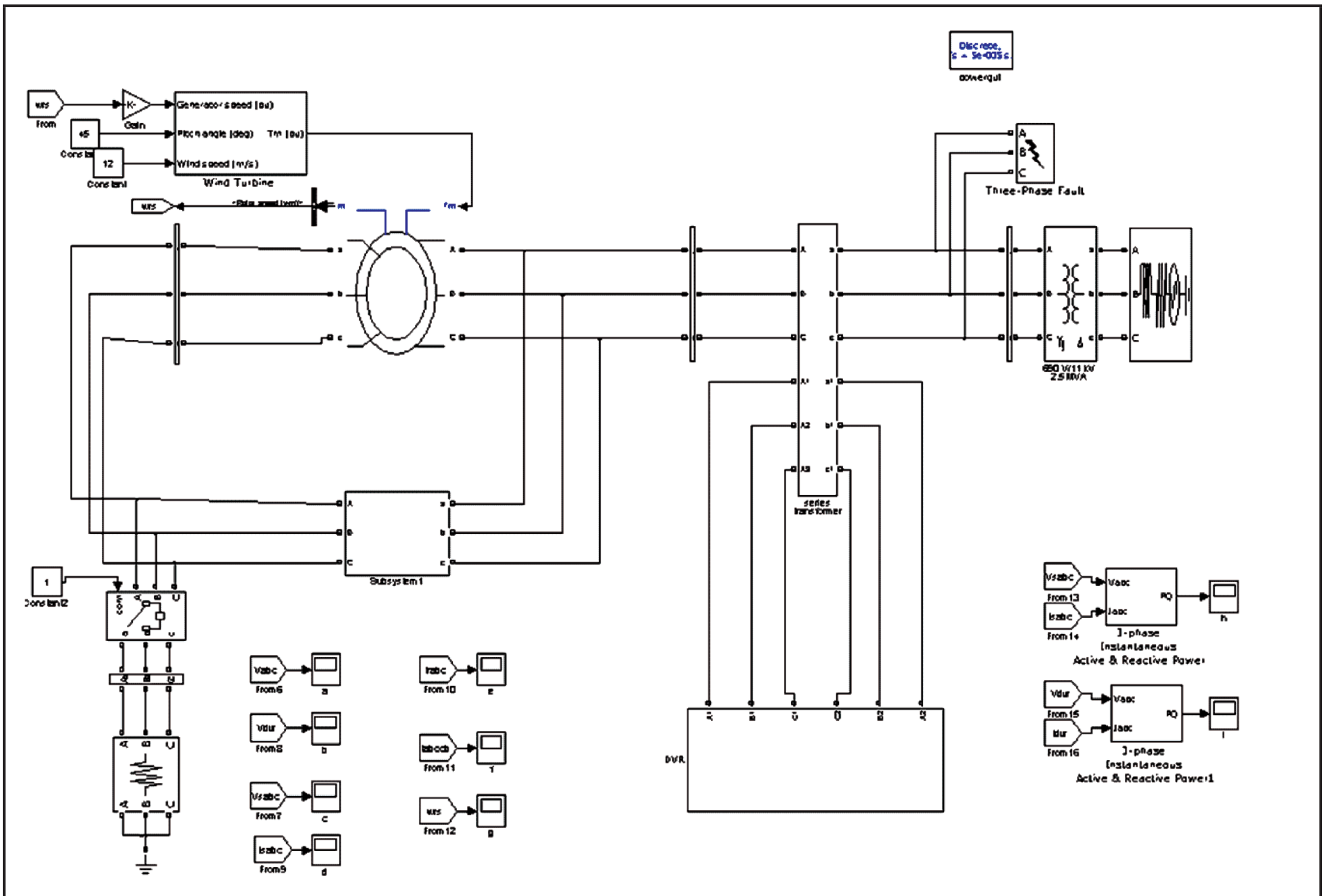

FIG.5 BLOCK DIAGRAM OF A DFIG WIND TURBINE WITH CROWBAR/DVR PROTECTION

7.2 Simulation Study

Simulation results for a 2 MW wind turbine under an asymmetrical two-phase grid fault show the effectiveness of the proposed technique in comparison to the low-voltage ride through of the DFIG using a crowbar where continuous reactive power production is problematic. The simulation parameters are as per Table 1. The system performance of the DFIG is protected by the conventional passive crowbar, and protected by the DVR during a two-phase 37 % voltage dip of 100 ms duration istaken in Figure 5.

The DFIG reacts with high stator currents I_s , and thus, high rotor currents are induced in the rotor circuit. When the rotor currents exceed the maximum level, the crowbar is triggered to protect the RSC from over currents I_{RSC}.When the voltage level has been reestablished and transients have decayed, the crowbar can be deactivated. When the RSC is in operation, the machine magnetization is provided by the rotor, but when the crowbar is triggered, the RSC is disabled and the machine excitation is shifted to the stator. Thus, reactive power control cannot be provided during the voltage dip, which is not acceptable when considering the grid codes. The machine

TABLE 1

SIMULATION/SIMULINK PARAMETER

Symbol	Quantity	Value
Uline	Low voltage level (Ph-Ph,rms)	690V
Ws	Line angular frequency	2π 50Hz
PDFIG	Wind turbine rated power	2 MW
I	Stator to rotor transmission ratio	1
N	Rated mechanical speed	1800 r/min
Lh	Mutual Inductance	3.7 Mh
Rs	Stator resistance	10 mΩ
R Crowbar	Crowbar Resistance	0.3 Ω

cannot generate enough torque so that the rotor accelerates, which can lead to disconnection of the turbine due to over speed. In this case the DVR is not activated in the simulations. Note that a communication between DVR and DFIG is necessary. The DVR power to compensate the voltage dip is shown in simulation. It becomes clear that the active and reactive power that cannot be fed into the faulty grid during grid fault must be consumed by the DVR.When the wind turbine system is protected by the DVR, the voltage dip can almost be compensated. The DFIG response is much less critical, which means that lower stator over currents and rotor over currents are produced so that the crowbar does not have to be triggered. Although the stator voltage dip is fairly well-compensated, a slight distortion in the stator currents (dc components), and thus, disturbed rotor currents can be observed as per results in Figure 6 & Figure 7. Anyway, the RSC remains in operation and can control stator active and reactive power independently. Thus, the speed is kept constant and a reactive power production (Qs = 0.5Mvar) during grid fault as demanded in grid codes is performed.

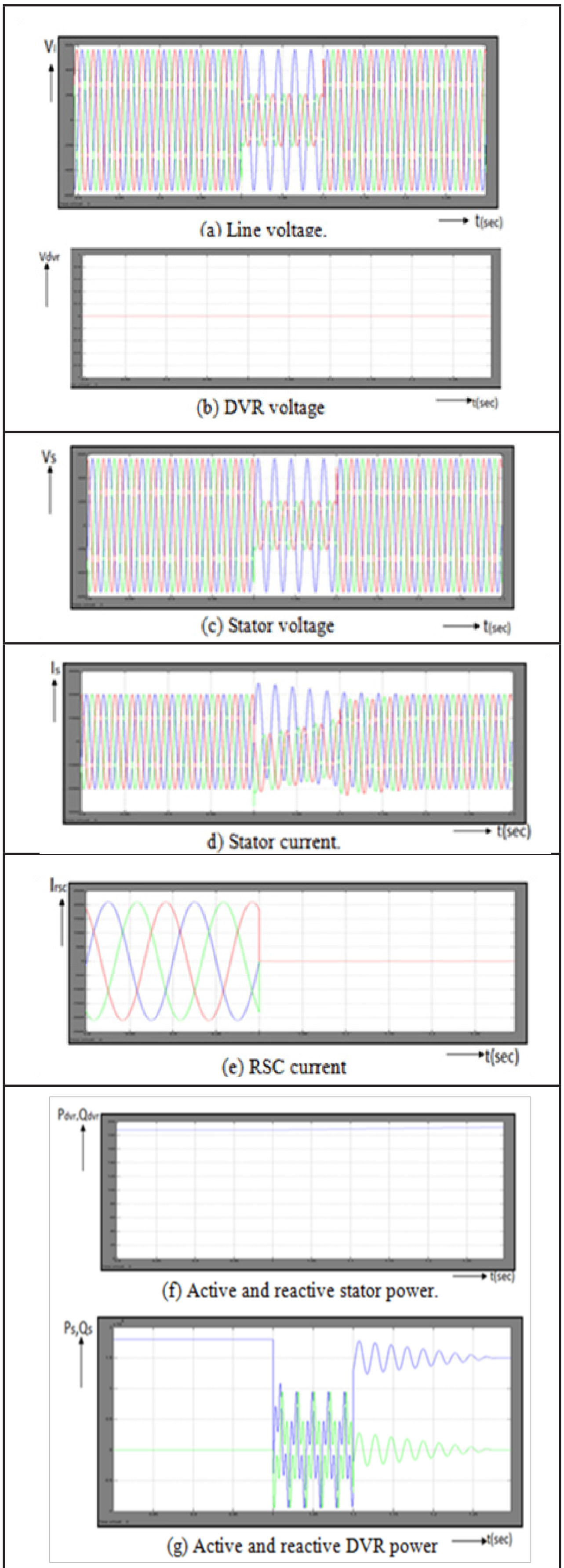

FIG. 6 SIMULATION OF DFIG PERFORMANCE WITH CROWBAR PROTECTION DURING 37 % TWO-PHASE VOLTAGE DIP.

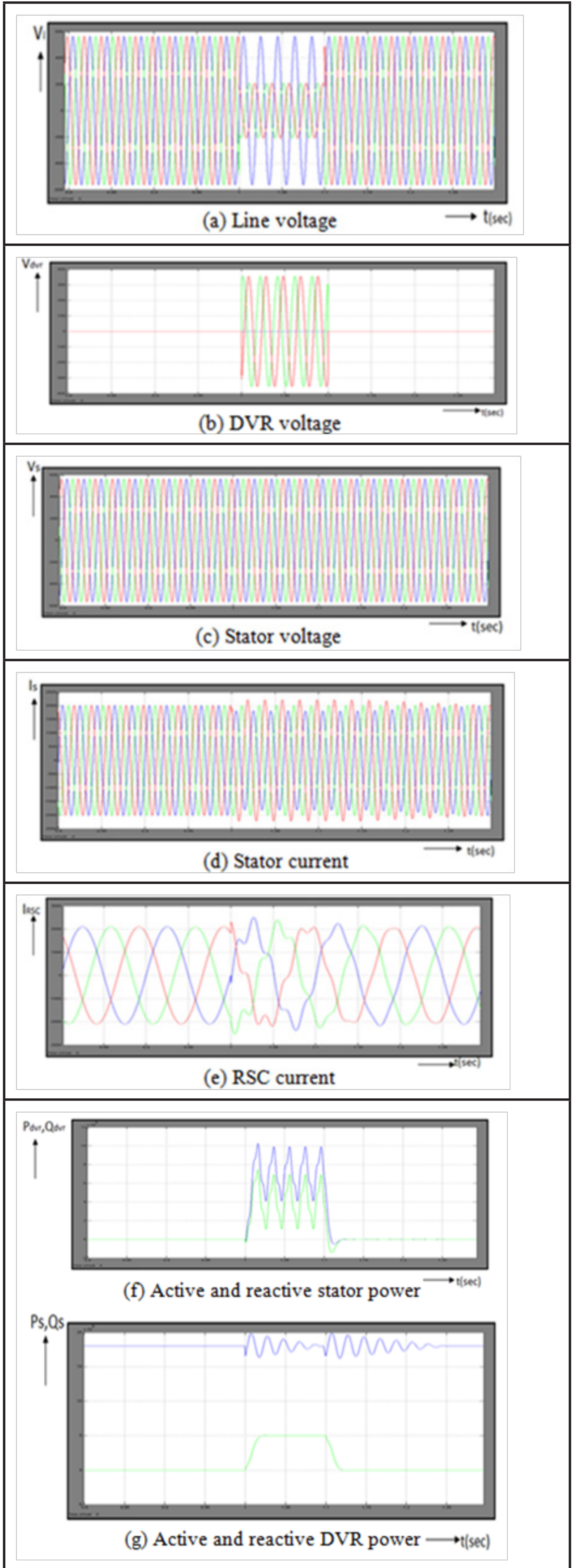

FIG.7 SIMULATION OF DFIG PERFORMANCE WITH DVR PROTECTION DURING 37 % TWO-PHASE VOLTAGE DIPS (WITHOUT CROWBAR)

8.0 CONCLUSION

DFIG based wind turbine systems are heavily stressed during grid faults. To guarantee grid connectivity even at zero grid voltage in accordance with utility requirements special measures are necessary. Wind turbines equipped with rotor crowbar and DC-link chopper are able to stay on grid and limit currents and voltages below the threshold values. Simulations have shown that DFIG equipped with crowbar is able to ride through grid disturbances but cannot provide reactive power control. The application of a DVR connected to a wind-turbine-driven DFIG to allow uninterruptible fault ride-through of grid voltage faults is investigated. The DVR can compensate the faulty line voltage, while the DFIG wind turbine can continue its nominal operation and fulfill any grid code requirement without the need for additional protection methods. The DVR can be used to protect already installed wind turbines that do not provide sufficient fault ride-through behavior or to protect any distributed load in a micro grid. Simulation results for a 2 MW wind turbine under an asymmetrical two-phase grid fault show the effectiveness of the proposed technique in comparison to the low-voltage ride through of the DFIG using a crowbar where continuous reactive power production is problematic.

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