Review of different Fault Ride through (FRT) Control Strategies for a DFIG Wind Turbine

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Abstract - *This paper presents a comprehensive review of various techniques employed to enhance Fault Ride through (FRT) capability of the fixed-speed induction generators (FSIGs)-based wind turbines (WTs), which has a non- negligible 20% contribution of the existing wind energy in the world. As the FSIG-based WT System is directly connected to the Grid with no Power Electronic interfaces, terminal voltage or reactive power output may not be precisely controlled. The rising share of wind turbine energy, in the existing power system, has created new opportunities and challenges. For wind turbine energy generation doubly fed induction generators are most suitable due to their various advantages over fixed speed wind turbine systems. These generators have ability to improve stability and power quality of the existing power systems. Wind energy is the fastest growing renewable energy source. Double Fed Induction Generator, which is predominantly used nowadays in wind turbines, is very sensitive to grid disturbances and can damage the power electronic converters due to over voltage and overcurrent. Therefore, protection elements which disconnect the machine during fault are very essential. But, in such cases, the reliability of the system gets affected which is not acceptable due to the high penetration of wind energy into the grid. Fault Ride through (FRT) is a mechanism by which the wind turbine can be connected to the system during the voltage dip. This is achieved by either hardware or software implementation on the converter of rotor side and grid side which will prevent the converter from tripping and thereby provide uninterruptible operation to the DFIG during severe grid voltage faults. An analysis of different FRT control strategies has been carried out in this paper.*

Keywords - Doubly Fed Induction Generator (DFIG), Dynamic voltage restorer (DVR), Static compensator (STATCOM), Unified power flow controller (UPFC), Crowbar, Wind turbine (WT).

1. INTRODUCTION

Out of all the available renewable energy sources, wind power contributes significantly to electrical power generation. Wind is one of the most abundant renewable sources of energy in nature. The research for wind power industry started to be improved in the last century because of the oil crisis and natural resources ripening which demands additional transmission capacity and better means of maintaining system reliability. To have sustainable growth and social progress, it is necessary to meet the energy need by utilizing the renewable energy resources like wind which having tremendous environmental, social, and economic benefits.

Fortunately, the goal of reducing green-house gas emissions is aligned, to a significant extent, with the evolution and penetration of renewable energy sources (RES) [1]. The attempts to reduce the continued pollution are promising in view of the recent dramatic increase of installed wind turbines' (WTs) capacity [2–4]. However, grid integration of large WTs can pose serious adverse effects in weak or faulty grids [5]. The trend towards the integration of more WTs contributes to the increase in the fault current levels, as well as voltage reductions at the terminals of wind generators, which may lead to the disconnection of WTs and consequently affects power system stability during and after fault clearance [6–8].

Recently, many power system operators and other regions of the world have begun expanding and modifying their inter connection requirements for wind farms through technical standards, known as grid codes. One of the critical requirements concerning the grid voltage support is the low voltage ride-through (LVRT) capability, which is included in many new grid codes. Besides the LVRT requirements, some grid codes require large WTs to contribute to the voltage restoration of the power system by injecting the reactive power during the fault and the recovery period.

Earlier, simple squirrel-cage-induction generator-based wind turbines were used, which is impractical because of its fixed speed. Nowadays, the fixed speed system is replaced by variable speed system which makes use of the DFIG wind turbines. Even though DFIG can extract more power, has less mechanical stress, and has independent control of active and reactive power, it has the disadvantage of being a less stable and reliable system . DFIG machines give steady output voltage and can be directly connected to the grid. Since they are directly connected to the grid, DFIG is very sensitive to grid disturbance like voltage sag, swell, flicker and can create technical issues such as voltage stability, reactive power and fault ride through. In order to reduce the adverse effect on the power system, network operators alternate the grid code requirements.

Low Voltage ride through,is one of the major issues in power system and it is the capability of the wind turbine to stay connected to the grid,even when a severe fault occurs.This may lead to some undesired characteristics on machines,such as real and reactive power problems and falling grid code requirements.A large Emf will be induced in the rotor circuit when a fault occurs in the system,and there will be a large inrush current due to the magnetizing effect,in both stator and rotor.So,the continuous operation of DFIG wind system is essential for the reliable operation of the power system.Various control and protectin techniques for the DFIG have been anlyzed in this paper.

II. A. WIND ENERGY

In recent years wind energy is most preferable in the power system due to its less carbon emission and no depleting nature. The winds result from the large scale movements of air masses in the atmosphere. These movements of air are created by differential solar heating of the earth's atmosphere. The wind energy production technology plays a major role in the electrical system in recent days due to the increasing demand and high cost and less availability of the conventional energy sources and also the transportation cost and storage problem also the reason for the shift of the conventional energy sources to the renewable energy source. The wind energy technology uses the kinetic energy available from the wind to produce electricity by using turbine generator set. By the electromechanical conversion process the power production obtained from the wind source. At the earlier days, windmills were used for grinding grain and pumping water.

B. WIND AVAILABILITY

The wind has variable nature in the both space and time. The wind variation classified in to three types according to the time scale. First one is, the large time scale variability. In which, the variation of wind from one year to another year taken. The next one is the medium time scale. It covers the periods up to a year and usually assessed in terms of monthly variations, covering one year. So it is otherwise called as monthly variation. The third one is the short term time scale variability, covering time scales of minutes to seconds.

C. PRINCIPLE OF WIND MACHINE:

The wind machine used to provide the electrical power from the available wind power. The principle of the wind machine is the electromechanical conversion process.

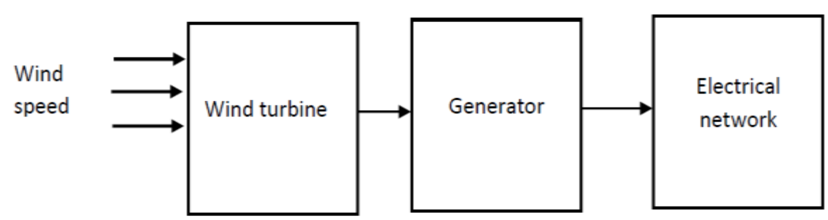

Fig. 1: Block diagram

The components present in the wind energy conversion system are the turbine, gearbox and the generator. The kinetic energy available in the moving wind strikes the blades of the turbine and produce the two types of forces namely lift force and the drag force. The lift force only used for the power conversion (kinetic energy to mechanical energy).This lift force direction is opposite to the direction of blade rotation. The lift force acts perpendicular to the wind direction.

The achieved mechanical energy from the wind turbine given to the gearbox. The gearbox used for converting the low speed high torque into the high speed low torque. The main use of gearbox is matching of the turbine rotor and the generator rotor speed. Then the mechanical power given to the generators to produce the electrical energy (mechanical to electrical energy). The generators may be synchronous or the asynchronous machines. According to the application requirements the generator type is selected. If the wind system is connected with the grid then the transformers are used to give the proper voltage level to the grid.

III. WIND ENERGY CONVERSION SYSTEM

The WECS consists of wind turbine and generator. A wind turbine is a device which is used to convert the kinetic energy present in the moving air into the mechanical energy. The wind generator used to convert the mechanical energy from the wind turbine into the electrical energy. In WECS the key technologies include wind turbine technology, power electronics technology, and system control technology.

A. WIND TURBINE TECHNOLOGY

In wind turbine technology there are many types of turbines are used based on the orientation and operation speed is controllable. The turbine rotation is parallel to the ground known as horizontal-axis wind turbines, otherwise vertical-axis turbines. In industry horizontal-axis wind turbines used because of higher wind energy conversion efficiency.

Fixed-speed wind turbines which are simple, robust, and require lower construction and maintenance cost and variable speed wind turbines. Its operation speed is fixed or constant and cannot be controlled with the different wind speed, which gives in lower energy conversion efficiency so the variable-speed wind turbines are applied in industry.

B. POWER ELECTRONICS TECHNOLOGY

The wind energy conversion system uses the generator for the conversion of the mechanical energy obtained from the wind turbine into the electrical energy. The generators used for the WECS (Wind Energy Conversion System) maybe the synchronous generator or the asynchronous generators. The asynchronous generators also called as the induction generators. The synchronous generators used for the constant speed applications and it also can be used for variable speed applications by the suitable converters. The asynchronous generators used for the variable speed applications .The classifications are

- Doubly-fed induction generator
- Squirrel-cage induction generator
- Wound-rotor synchronous generator
- Permanent magnet synchronous generator

In the DFIG WECSs, only 30% of the rated power is processed by the power converters, which greatly reduces the cost of the converters while preserving the capability to control the speed of the generator in the range of about of its rated speed. The DFIG (Doubly Fed Induction Generator) is the type of asynchronous machine. The term 'doubly fed' refers that the voltage on the stator can get the energy from the grid and the voltage on the rotor is induced by the power converter. By using DFIG we can extract maximum energy from the wind energy at low wind speeds by the optimization of the turbine speed and extract the optimum energy at gusts of wind by minimizing mechanical stresses on the turbine. The optimum energy obtained from the wind turbine is directly proportional to the wind speed. The major advantage of the DFIG is ,it can either generate or absorb reactive power by using the power electronic converters and it doesn't requires , capacitor banks as in the case of squirrel-cage induction generator. The DFIG used for the variable speed operation by the presence of the power electronic converter. The converter used for the compensation, if there is difference occurs between the mechanical and electrical frequency, which is done by injecting a rotor current with a variable frequency. The behavior of the generator at normal operation and faults are governed by the power converter and its controllers. The two type of converters presented in the power electronic converter, one is rotor-side converter and another is grid-side converter. The control mechanism of the converters are independently of each other. Their advantages are control of reactive power and to decouple active and reactive power control by independently controlling the excitation current of rotor. The DFIG has the advantage of it can be magnetized from the power grid, and magnetized from the rotor circuit also. It is also capable of generating reactive power and the generated reactive power can be delivered to the stator by the grid-side converter.

The synchronous generator consists of stator and rotor. Stator is a stationary part and the rotor is a rotating part. The selection of synchronous generator maybe WRSG (Wound Rotor Synchronous Generator).The stator of WRSG directly connected with the grid so the rotational speed of the generator fixed by the grid frequency. The rotor gets excited by direct current using slip rings and brushes or with a brushless exciter with a rotating rectifier. The main advantage of synchronous generator is, it doesn't require reactive power compensation system and no need of gearbox. By the DC supply the rotor gets excited and rotates at synchronous speed. The speed of the synchronous generator is determined by the frequency of the rotating field and by the number of pole pairs of the rotor.

IV. DOUBLY –FED INDUCTION GENERATOR

Wind turbines can either operate at fixed speed or variable speed. For a fixed speed wind turbine the generator is directly connected to the electrical grid. For a variable speed wind turbine the generator is controlled by power electronic equipment. There are several reasons for using variable-speed operation of wind turbines; among those are possibilities to reduce stresses of the mechanical structure, acoustic noise reduction and the possibility to control active and reactive power. Most of the major wind turbine manufactures are developing new larger wind turbines in the 3-to-5-MW range. These large wind turbines are all based on variable-speed operation with pitch control using a direct driven synchronous generator (without gearbox) or a doubly-fed induction generator (DFIG).

DFIG is an abbreviation for Double Fed Induction Generator, a generating principle widely used in wind turbines. It is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings. It is possible to avoid the multiphase slip ring assembly but there are problems with efficiency, cost and size. A better alternative is a brushless wound rotor doubly-fed electric machine. The Doubly-Fed Induction Generator (DFIG) with both stator and rotor windings as shown in fig. 2.

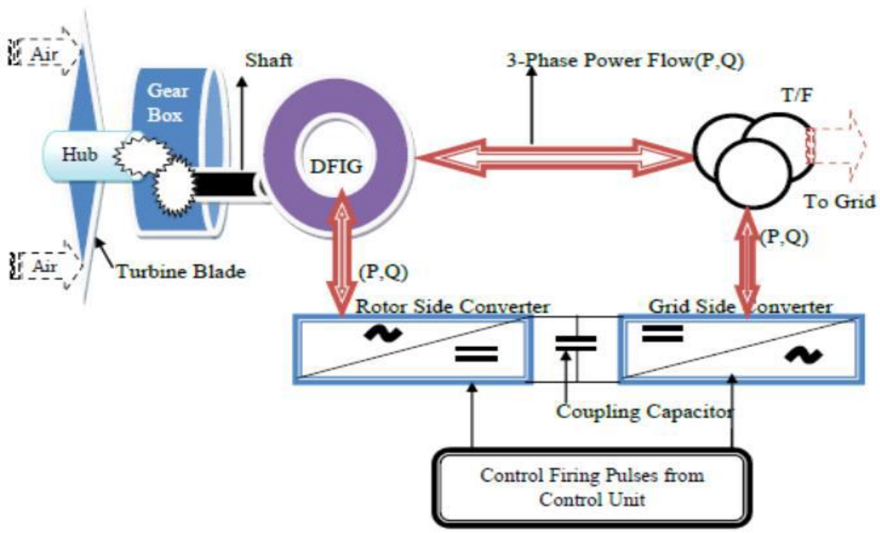

Fig. 2. Doubly-Fed Induction Generator (DFIG)

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. 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. Further, the voltage transients due to the grid disturbances (three- and two-phase voltage dips, especially) will also be magnified. In order to prevent high rotor voltages and high currents resulting from these voltages - from destroying the IGBTs and diodes of the converter, a protection circuit (called crowbar) is used.

V. GRID CODE REQUIREMENT

Due to the significant increase of wind power penetration in the power system, many countries have revised their grid code, by defining specific technical requirements for the wind farms. Grid code requirements typically refer to large wind farms, which is connected to the transmission system. Grid codes specify that wind farms must contribute to power system control, as much as conventional power generation stations and withstanding of wind system during abnormal condition. The Indian Electricity Grid Code (IEGC) provides the major technical rules to enable safe operation, maintenance, development and planning of electricity grid. The main objective of IEGC is to maintain safe and reliable operation of power system. The IEGC guideline and standards are suggested to be followed by various participants of the power grid. Indian Wind Grid Code (IWGC) has been developed only to enhance the secure operation of the wind farms and also their integration into the Indian electrical system. The Grid Codes address Fault tolerance, Reactive power/voltage control requirements, Ramp rate control and Frequency response capability.

Indian Wind Grid Code (IWGC) structure includes (1) Role of various organization and their linkages (2)Planning code for transmission system evacuating wind power (3)Connection code for wind farm (4)Operating code (5)FRT is an important feature. For the wind turbines to remain connected to the grid during the faults, various technologies have been developed to withstand the voltage dips [9]. This withstanding capability of DFIG against voltage sags is called Low Voltage Ride-Through (LVRT) or Fault Ride-Through (FRT) capability. If Fault Ride Through is not installed, generation would be susceptible to tripping when subject to a voltage dip even when connected to a healthy circuit for less than normal protection operating times.

VI. ISSUES IN DFIG CONNECTED TO GRID

A. VOLTAGE CONTROL AND POWER QUALITY

Large variations of voltage in the power systems, is one of the most common problems. Large fluctuations create voltage dips in the wind energy power generation system. Voltage control and reactive power quality can arise when there are large numbers of generators in the network for starting or stopping the generation. In the absence of proper control, a single line to ground fault, may create serious voltage fluctuation problem to other users connected to the grid and there is a chance of flickering and harmonics [10]

B. STABILITY OF THE SYSTEM AND FREQUENCY

Now a day most of the wind generation is integrated to grid and small disturbance can produce imbalance in the system. The instability occurs during the fault condition and light load condition. During the summer season the new generator would meet a significantly higher percentage than usual demand under windy conditions. This can be resolved by proper control. Current wind generation technology does not offer flexibility for balancing requirements [10]. Generators can be adjusted automatically with the variations in power, and thereby we can adjust the frequency of the system.

C. CONTINUITY AND PROTECTION

Continuity of the supply is a challenge even in case of renewable sources due to the high penetration of energy into the distribution network [10]. Wind energy is not the only source to be depended on. It must be balanced with sufficient spinning and non-spinning reserve to ensure the supply continuously. Protection would interfere with operation of other sources and equipment's connected in point of common coupling (PCC).

D. FAULT RIDE THROUGH AND GRID CODE

As the penetration of wind energy increases, the need to address the fault ride-through capability issues will also increases. The wind turbines were allowed to trip when a voltage dip occurs. During the fault ride through wind turbines are expected to remain connected to the grid both during and after a fault. Also upon voltage recovery, the wind turbines are not expected to absorb the excessive reactive power and it should match with the grid code requirements also [9,10].

VII. FAULT RIDE-THROUGH STRATEGIES FOR FSIG-BASED WTS

The FRT performance of FSIG-based wind turbines is problematic because the stator windings are directly coupled to the grid, and the induction generator consumes reactive power during and after a fault. Therefore, it fails to fulfill some of the important grid integration requirements, such as reactive power compensation or terminal voltage control. Thus, the induction generators need the external supporting devices to avoid their tripping during voltage reduction. There are many auxiliary devices reported in the literature to provide adequate dynamic voltage support and enhance the LVRT capability of WTs. The major categories of LVRT methods of FSIG- based wind turbine are depicted in Fig.3. Depending on the connection configuration, these methods can be classified into the series-connected solutions, shunt-connected solutions, and hybrid-connected solutions.

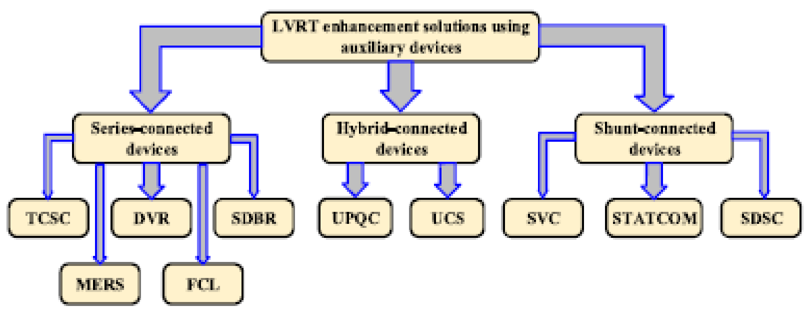

Fig.3. Classified LVRT capability enhancement methods.

i. REVIEW OF SERIES-CONNECTED SOLUTIONS

Series-connected auxiliary technologies have been successfully implemented to alleviate grid congestion, defer construction of new transmission lines, and improve system capacity. These types of technologies, as a relatively simple solution, with a smaller current injection compared to shunt-connected technologies, is effectively used to regulate voltage or limit fault current resulting significant increase in the transient and voltage stability in transmission systems. A brief explanation of series-connected solutions is presented in the following subsections.

a. THYRISTOR-CONTROLLED SERIES COMPENSATION(TCSC)

The essential principle of the TCSC is to control power flow of the gridlines, increase the dynamic stability of power transmission, and effectively limit the power oscillations [11]. Recently, the abilities of this technology have particularly been realized where in constancy in the transmission lines for delivering the huge WT generated power into the grid, lead to voltage collapse and cut off the fixed speed WT .Moreover, the ability of TCSC to limit fault current and control voltage unbalance of wind farm systems. Fig.4 illustrates a typical TCSC module installed outside the windfarm along with the basic control scheme. A TCSC consists of three components: capacitor banks C, bypass inductor L, and forward-biased thyristors T1 and T2.The function of the control block is to generate appropriate gate drive signals for the thyristors when the fault is initiated. Basically, thyristors are fired with respect to zero crossing of the line current to inject additional current into the capacitor through the bypass inductor and increase the capacitive reactance value, typically up to a factor of three times the original reactance. This way, a variable capacitive reactance can be obtained to compensate the reactive power absorbed by the induction generator, improve the fault right through of WT. This technology may be useful for wind farms located far away from the PCC, such as offshore wind farms.

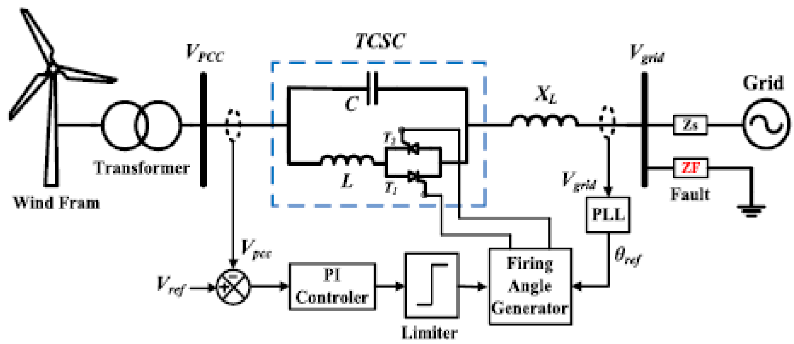

Fig.4. TCSC module installed outside the wind farm with the basic control scheme.

b. DYNAMIC VOLTAGE RESTORER(DVR)

A promising approach to effectively overcome the grid-fault- derived problems with WT generators and to enhance ride- through capability is to control the connection-point voltage by compensating voltage fluctuations during the fault. This can be accomplished by using a series-connected power electronic compensator called dynamic voltage restorer (DVR) which injects an appropriate voltage into the grid bus to keep the generator voltage constant at PCC and with the same phase as the network, as shown in Fig.5.

DVR is mainly used for the voltage sag mitigation in the point of connection. This is a series device having the same configuration of D STATCOM with a coupling transformer connected to ac mains. The main disadvantage is its cost and complexity. The VSC generates a three phase voltage which is controllable in phase and magnitude. These voltages are injected into the ac distribution system in order to maintain the load voltage at the desired volt. The DVR device is used to compensate the faulty grid voltage. The advantage of such an external protection device is the reduced complexity in the DFIG system.

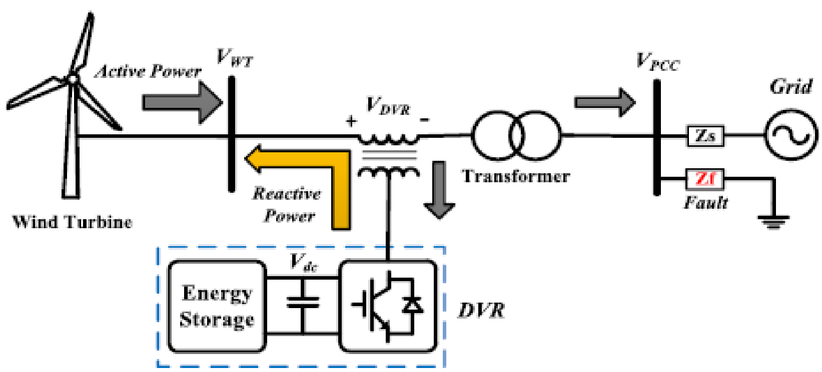

Fig.5. Principle operation of the dynamic voltage restorer and power flow during the voltage dip compensation.

c. SERIES DYNAMIC BRAKING RESISTOR(SDBR)

DBRs have been developed to contribute directly to the balance of active power between the mechanical and electrical side of the WT system during a fault, potentially reduce or eliminate the need for pitch angle control or reactive power compensation(RPC)devices [12,13]. This is performed by dynamically installing a resistor in series between the WT and the grid, in order to boost the voltage at the terminals of the generator, and there by alleviate the instability concerns on electrical torque and power during the fault period. The typical schematic layout of SDBR may in corporate one or two stages of resistor/switch units, as shown in Fig.6(a) and (b), including the static by pass switch, allowing sub-cycle response and smoothly variable control . Under normal conditions, dynamic braking resistor must be cut off by closing the bypass switch. At the beginning of the fault, the current start the passing through the resistor, R_{sh} and continue in operation in the initial postfault recovery. Once the voltage recovered above a minimum set point level and met the grid code compliance, the bypass switch is closed and the circuit is returned to its normal state. Fig.6(c) also displays a possible arrangement, using thyristor based soft-starter that is already utilized for a grid connected FSIG- based wind turbine, can enable continuous, optimized control of dynamic braking resistance. Also, ABB represented an additional feature for SDBR scheme, in which the resistors were independently controlled in each of the three phases, enhancing the scheme's performance during unbalanced fault condition.

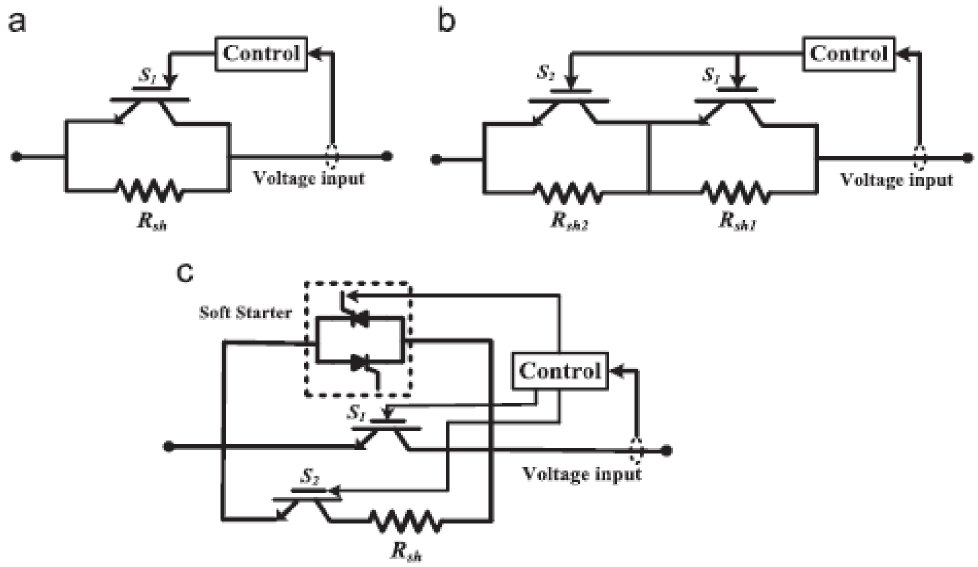

Fig.6 Various types of SDBR;(a)Single-stage scheme.(b)Two-stage switching scheme.(c)Variable resistor scheme using soft-starter.

d. MAGNETIC ENERGY RECOVERY SWITCH (MERS)

The MERS has recently been proposed as a variable series compensator between the main transformer of the wind farm and power grid to improve the LVRT capability of fixed-speed WTs by compensating the reactive power and controlling the terminal voltage of WT. The circuit configuration of the MERS is shown in Fig.7, including four reverse conductive semiconductor switches and a dc capacitor. As it is obvious from Fig.7, that it has a similar topology with respect to a single-phase full-bridge inverter with the exception that dc-link capacitor is several times smaller than that of a single-phase full bridge inverter, due to the capacitor voltage is permitted to alter considerably and to become zero during each fundamental cycle(50 or 60Hz) Moreover, this scheme possesses fewer losses compared to the PWM converters so that semiconductors in MERS are switched synchronously to the line frequency which is extremely important for high-power wind applications.

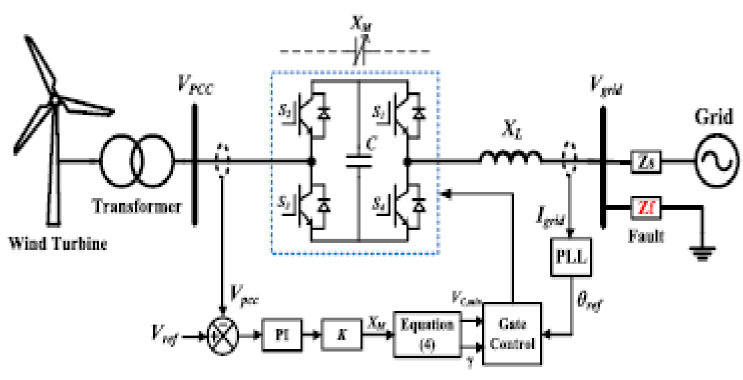

Fig. 7. Circuit configuration of the MERS for controlling the series-injected voltage.

e. FAULT CURRENT LIMITER (FCL)

The need for FCL is increased by the rising fault current levels due to integration of high penetration of WTs into the power grids. In recent years, various types of FCL such as, solid state FCL, resonant circuit, transformer coupled bridge-type fault current limiter (BFCL), and super conducting fault current limiter(SFCL) have been proposed and developed . Previous studies have proven the ability of SFCL and BFCL technology to improve LVRT capability and enhance transient stability of wind generator systems. By using these types of FCL during the fault, the stator current of induction generator has been effectively limited and the voltage reduction level of the generator terminals has been decreased ,leading to meet international grid codes. Once, the FCL is adopted in the wind farm system, the peak value of short circuit current can be limited to a level within the switchgear rating, allowing deploying of light circuit breakers.

➢ BRIDGE-TYPEFAULT CURRENT LIMITER (BFCL)

As shown in Fig. 8(a), the bridge-type FCL with discharging resistor (R_{dc}) requires the coupling transformer to be connected to the power grid. A resistor in parallel with a semiconductor switch has been connected in series with the dc reactor (L_{dc}) of the conventional bridge-type FCL, in order to control the fault current level by controlling the dc reactor current.The increase of the fault current is curbed by dc reactor without any delay. This characteristic of the bridge-type FCL suppresses the instantaneous voltage drop and it is able to improve the transient behavior of WTs in fault instant, which is the main advantage of the bridge-type FCL to other FRT enhancement techniques. Moreover, R_{dc} in the bridge-type FCL used to increase the terminal voltage of the generator, there by smoothing the electrical torque and active output power fluctuations during the fault. However, this topology needs a special and costly transformer to connect the three-phase diode bridge in series into the system, in which primary voltage rating of the transformer must be almost equal to the transmission line voltage to maintain desired level of voltage within the fault duration [14].

In [14], the authors proposed a new modified configuration of BFCL including the four-diode bridge part and shunt resistive path, shown in Fig. 8(b), in order to achieve the LVRT of fixed speed wind generator system. In normal condition, the switch must be kept closed as its gate signal S_1 is at a high level, in which line current through the dc reactor placed within the diode bridge flows in the same direction, charging the L_{dc} to the peak current. Once the fault occurs, the sudden rise of fault current would be instantaneously limited by the reactor. Hence, abrupt voltage reduction at generator terminal is prevented during the fault, providing the improved transient behavior. Once, line current in dc side i_{dc} exceeds a predefined threshold i_{th}, the IGBT switch must be turned off via sending the low level signal to S1. In this case, the diode bridge is cutoff and the line current passes through the shunt resistor R_{sh} in order to suppress fault current and consumes excess energy from the wind generator. By controlling the duration of ON and OFF periods of IGBT switch, control system provides a manageable resistor in order to control the terminal voltage of induction generator, leading to a reduction in the rotor acceleration and stabilizing the system. The controller used for the BFCL was developed in [14] and shown in Fig.9.

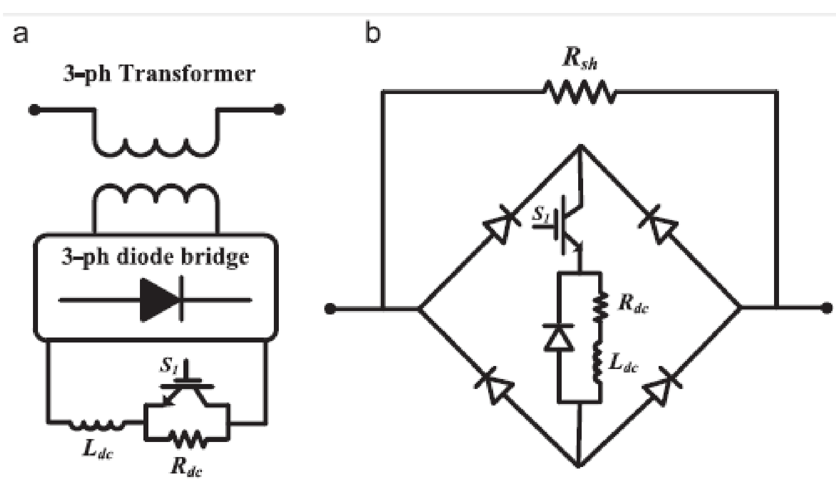

Fig. 8. Fault current limiter topology. (a) Bridge-type FCL(BFCL). (b) Modified configuration of BFCL.

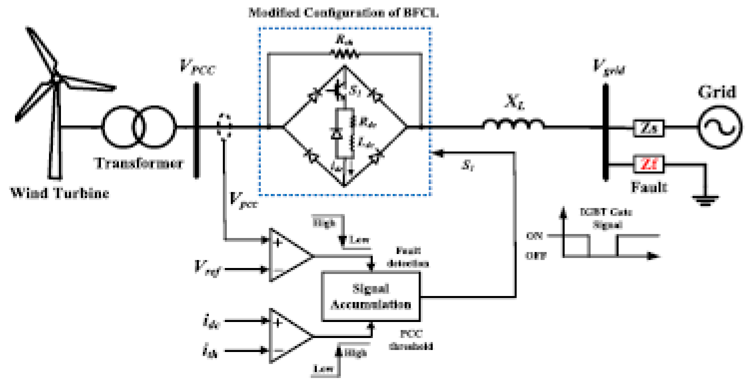

Fig. 9. Modified configuration of BFCL installed outside the wind farm with the control scheme.

➢ SUPER CONDUCTING FAULT CURRENT LIMITER (SFCL)

The SFCLs have been launched and introduced into the network to restrict prospective fault currents immediately to a manageable level by suddenly raising the resistance value. SFCL is considered as self- healing technology since it eliminates the need for any control action or human intervention due to its automatic excessive current detecting and automatic recovering from non-superconducting to superconducting states. By using the SFCL, the fault current is suppressed effectively and the voltage dip level of the WPP terminals is diminished, leading to enlarge the voltage safety margin of the LVRT curve. The first-cycle suppression of a fault current by an SFCL results in an increased transient stability of the power system carrying higher power with greater stability. This innovating device introduces an exclusive feature that cannot be obtained by conventional current limitations. Generally speaking, high temperature superconducting fault current limiters (SFCLs) have been classified into the resistive, inductive, and hybrid types. Amongst diverse SFCL devices, resistive SFCL has a simple structure with a lengthy superconductor wire inserted in series with the transmission lines. To preserve the superconductor from detrimental hotspots during the operation, the shunt resistance, R_{shunt} is essential. This parallel resistance must be contacted all over the length of the superconductor, and it regulates the controlled current to elude over- voltages likely occurring when the resistance of the super- conductor increases much quicker. With the recent breakthrough of economical second-generation high-temperature (HTS) wires, the SFCL has become more viable and is eventually expected to be at least a factor often lower in cost than presently available HTS conductor. The structure of FSIG-based WT with resistive SFCL is schematically shown in Fig.10.

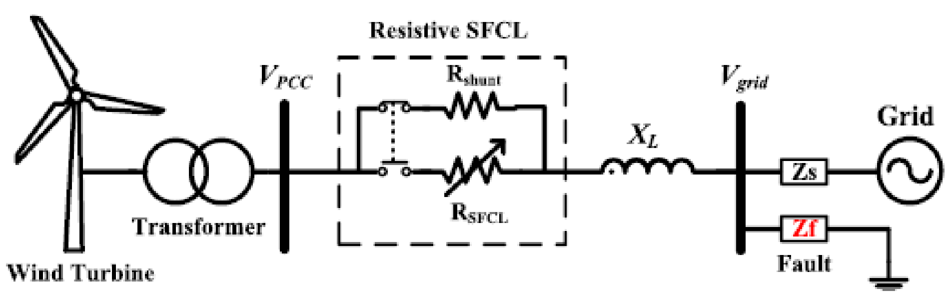

Fig. 10.The structure of FSIG-based WT with resistive SFCL

ii. REVIEW ON SHUNT-CONNECTED SOLUTIONS

Among the external topologies, the shunt-connected devices have been widely utilized to provide smooth and fast steady state and transient voltage control at point of connection. Since, the output current of these devices is adjusted to control either the nodal voltage magnitude or reactive power injected at the voltage terminal, the shunt-connected topology proved to be the most effective solution in the wind power application in order to fulfill the recent international grid codes. A brief explanation of shunt- connected solutions is presented in following subsections.

a. STATIC VAR COMPENSATOR(SVC)

Thyristor-controlled SVCs have been applied for voltage support of critical loads, reactive power compensation, and transient stability improvement in electric power transmission systems. The SVC is a combination of a thyristor- controlled reactor (TCR) with a thyristor-switched capacitor (TSC) or MSC as one compensator system which is practically connected to the PCC bus(or the wind turbine terminals) in order to provide fast voltage support and fulfill LVRT of WTs with induction generators. Based on new grid codes, this is a supplementary feature now for wind turbines to supply variable reactive power depending on network demand and actual voltage level, while the crucial problem of SVC is to inject an uncontrollable reactive current dependently on the grid voltage. Thus, the current injected by the SVC reduces linearly with the voltage sag and consequently the injected reactive power diminishes quadratically. The basic control of the SVC shown in Fig. 11 as a PI controller to control the firing angle of the thyristors of the TCR and TSC, keeping VPCC at 1pu during and immediately after the fault. A Fuzzy controller was designed for the SVC to significantly prove an improved dynamic response in terms of overshoot and settling time as compared to a conventional PI controller.

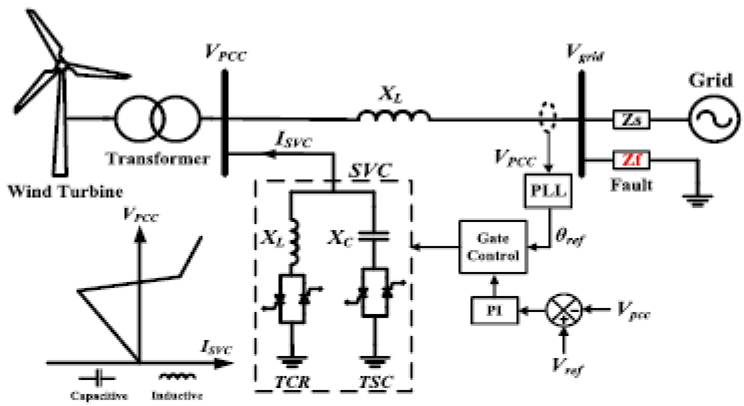

Fig. 11. Shunt compensation system for wind driven induction generator using SVC along with the basic control system.

b. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

STATCOM derived from SVC is the most widely used FACTS device. . The main attraction of STATCOM is the independent voltage control. The STATCOM configuration consists of a VSC, a dc energy storage device; and a coupling transformer connected in shunt with the ac system. The STATCOM can continuously and independently provides a controllable reactive current in response to voltage reduction, supporting the stability of grid voltage. The prospect of the STATCOM application in the wind power system has emerged in the1990s, where its significant contribution was power quality improvement during normal operation. The most important component of STATCOM is the modular voltage source converter (VSC), equipped with insulated gate bipolar transistors (IGBTs) that are controlled by pulse width modulation (PWM).Fig.12 displays the basic STATCOM which can be used in LVRT capability for fixed-speed wind turbines. It is connected to the grid to inject or absorb reactive power through a three-phase transformer. This system is appropriate to alleviate the effects of both steady-state and transient con- tangencies

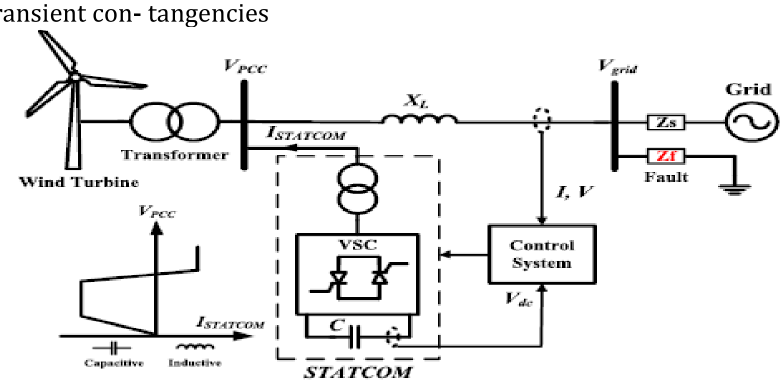

Fig. 12. The structure of the FSIG-based WT along with STATCOM connected to wind turbine terminal.

c. SUPER CONDUCTING DYNAMIC SYNCHRONOUS CONDENSER (SDSC)

One possible solution of integrating large-scale wind farm in power system is the superconducting dynamic synchronous condenser (SDSC) shown in Fig.13, so that rotor windings entailed of HTS wires. Compared with a conventional synchronous condenser, SDSCs provide up to 45% more dynamic reactive compensation in order to boost the bus voltage during a severe fault situation with power losses and maintenance. Since, SDSC machine has a relatively low synchronous reactance relatively low compared to other synchronous machines with the same rating, allowing the machine to respond significantly to transient changes in voltage by injecting or absorbing reactive power. The SDSCs are able to perform with a very high field current (upto2.0pu) for a long period of time, allowing the machine to release the reactive power up to three-times rated output during a transient low-voltage event. Thus, the SDSC can assist a wind farm to meet the interconnection agreement with the utility by providing voltage regulation and improving stability of a power system.

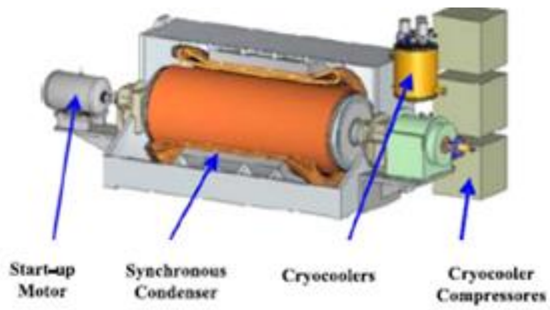

Fig.13. Structure of the SDCS

iii. REVIEW ON HYBRID-CONNECTED SOLUTIONS

Reactive power and voltage compensation using series–shunt (hybrid) topologies has been one of the effective techniques in improving the LVRT capability of the large scale of the wind farm level at the point of common coupling. The unified power quality conditioner (UPQC) demonstrates there may be a possible solution to the technical grid integration problems coming from the wind- driven FSIG. Fundamentally, UPQC which is an integration of series and shunt VSC have been commonly studied by many researchers as the ultimate device to improve voltage sag, voltage unbalance, harmonics, dynamic active and reactive power regulation and also the application of the UPQC systems to enhance low voltage ride-through capability of the FSIG-based wind turbine. The series VSC provides the lack of voltage to prevent over-speeding of the FSIG while the shunt VSC injects additional VAR required during the voltage reduction. However, the capital cost involved in the installation of this device is higher than any other solutions devices because of its use of two converters. A novel combination of resistive SFCL and UPQC illustrated in Fig.14, in order to improve power quality problems and fulfill grid code requirements. The SFCL not only reduce the volt-ampere rating of the UPQC, thereby reducing the installation cost, but also aid the LVRT capability of the wind turbine and improves dynamic performance of the induction generator for additional support.

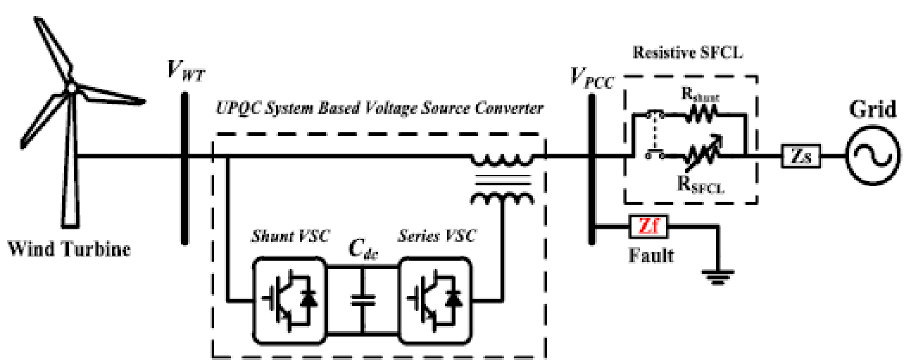

Fig. 14. The structure of the proposed system: FSIG-based wind turbine with UPQC and SFCL connected to the grid.

Moreover, the feasibility of resistive SFCL incorporated in series with the dc-link inductance of the UPQC based on a current source converter is to limit excessive current in the event of the generator side fault (see Fig. 15) and increase voltage level at the generator terminal leading to compliance with international grid codes.

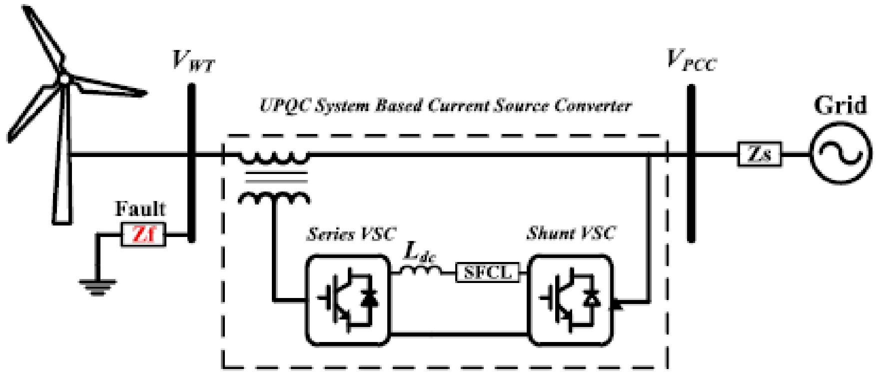

Fig. 15. The structure of the proposed system: FSIG-based wind turbine with current source UPQC and SFCL connected to the dc link.

A topology based on combined shunt and series grid interface configuration, namely, unified compensation system (UCS) to improve FRT capability for FSIG wind turbines. The system structure depicted in Fig.16 utilizes one converter to provide both series and shunt compensation. In normal operation, the UCS operates like a STATCOM and supports voltage or reactive power regulation through the shunt connection. In faulty conditions, the UCS instantaneously switches from the shunt to the series grid connection, compensates the voltage, and maintains the stator voltage at its rated value.

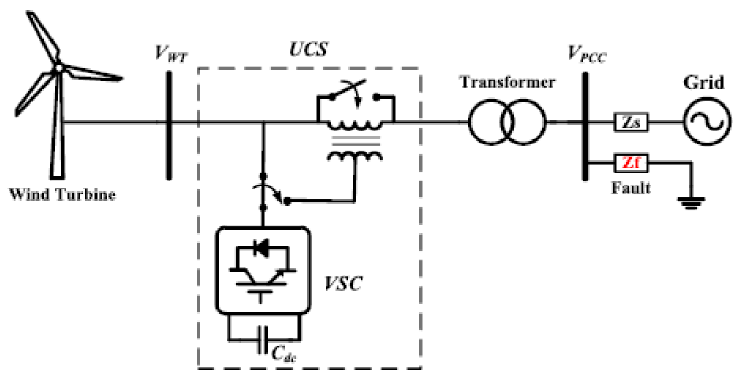

Fig. 16. Configuration of unified compensation system (UCS) connected to wind turbine terminal

iv. CROWBAR METHOD

Crowbar method is the conventional method to enhance the LVRT capability of the wind turbines. During voltage dip, the rotor circuit is disconnected and the DFIG run as squirrel cage induction motor. The crowbar consists of the resistors and switches shown in fig17. The user can control the switching by adjusting the triggering. By adjusting the value of crowbar resistance, operation of crowbar may differ. The main aim is to reduce the rotor voltage by means of providing an additional path to the rotor current and DFIG stay connected to grid. It is the simplest method and has the advantage of low cost. The main problem is its high short circuit current at the time of RSC thereby drawing more reactive power from the network[15].There are different methods to improve the stability and continuity namely passive crowbar ,active crowbar and stator crowbar. Among these Passive crowbar techniques has an outstanding performance.

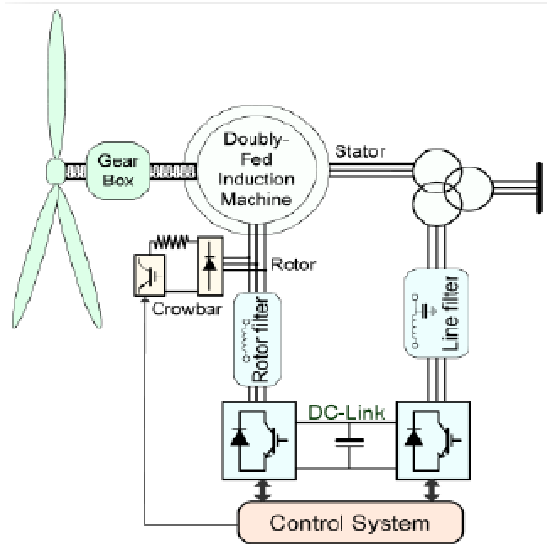

Fig .17. Crowbar circuit

v. DC CHOPPER

DC chopper is also known as braking resistance which is connected in parallel with the dc link capacitor to limit the over voltage and current during abnormal condition. Schematic of this method is shown in figure18.The dc-link brake chopper shorts the dc-link through a power resistor when the dc-link voltage exceeds a fixed threshold level. The brake is used to maintain the dc-link voltage when transient rotor over current occurs. There are six anti parallel diodes in the rotor-side converter that are highly rated to withstand short-circuit currents. The brake chopper works on a hysteresis band, i.e., the turn-OFF voltage is set below the turn-ON threshold value.

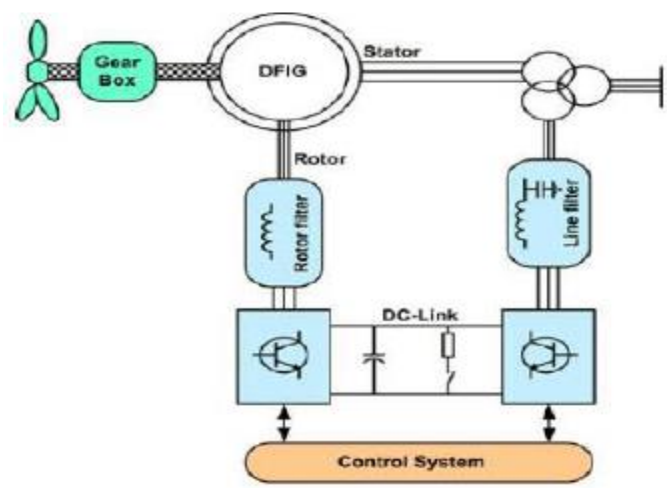

Fig. 18. dc chopper circuit

vi. NON LINEAR CONTROL

Nonlinear control schemes which are used to improve the LVRT characteristics may not effectively mitigate the serious voltage variations .Nature of instability can be identified by the DFIG model analysis and eigen value tracking. Lyapunov based control is widely used for removing the effects of stator dynamics and rotor current dynamics through rotor control voltage. This helps to improve rotor dynamics and LVRT capability.

vii. CURRENT FEED BACK TECHNIQUE

a) REVERSE CURRENT TRACKING

During the fault time an EMF is induced which exceeds the maximum output voltage of rotor side converter .Over current will flow through rotor side and DFIG will cause serious issues. The rotor current is controlled to track the stator current in the reverse direction. There by limiting the rotor current in a certain range with restricted RSC output voltage. No need of flux linkage or sequence component separation. This method reduces the fault current with little torque oscillation.

b) STATOR CURRENT FEED BACK

The proposed technique aims to reduce the rotor currents by changing the RSC control instead of installing additional hardware protection like a crowbar in the wind turbine system. When a fault affects the generator the measured and transformed stator currents are fed back as reference for the rotor current controller (stator currents in stator flux orientation).The objective is to reduce stator current oscillations and thus reduce the rotor currents as well.

viii. TUNED DAMPING CONTROLLER

By using bacterial foraging technique with coordinated tuning of the damping controller the stability of DFIG system is improved. Damping controller using auxiliary signal for speed deviation is used in the angle control which results in damping out of low frequency variations.

ix. TWO DEGREES OF FREEDOM INTERNAL MODEL CONTROL

Internal model control take the power limit characteristics of the DFIG back to back converter. The design of IMC consider power, voltage and speed of response limitation of power electronic converter. IMC improves the system stability.

x. FLUX LINKAGE TRACKING

LVRT control strategy based on flux linkage tracking is designed for RSC to suppress the rotor current during grid faults. The basic principle of the control strategy is that, when a grid fault is detected, the rotor flux linkage is controlled to track a reduced fraction of the changing stator flux linkage by altering the output rotor voltage of the RSC. As long as the difference between ψs and ψr is kept small enough, the rotor current will be restricted within the maximum current allowed. This method suppress rotor current with smaller torque oscillations, suitable for industrial applications.

XI. WITH DIFFERENT STORAGE SYSTEM

a) UNINTERRUPTABLE SUPPLY (UPS)

The fly wheel based energy storage system to get uninterruptable supply is used in standalone operation of DFIG. When main supply is cut off, a fixed frequency and amplitude of the output voltage is obtained. The Output voltage can be controlled by the synchronization of actual voltage vector with reference vector in the synchronous rotating polar frame of reference. By using ups the voltage control is improved.

b) SUPER CAPACITOR STORAGE

The LVRT improvement can also be achieved by using storage elements. Super Capacitors use the nickel chromium battery that has been used for small wind power generation. By using this, The DC link capacitor voltage of DFIG can be controlled and the limit if over current can be reduced.

c) SUPER CONDUCTING MAGNETIC ENERGY (SMES)

SMES Stores energy in the form of DC that creates a dc magnetic field. At cryogenic temperature the conductor carrying current behaves like a super conductor with zero resistive drops. During grid fault SMES provide the stored energy. The advantage of using SMES is that The transient stability of the system can be improved by using PI and Fuzzy based systems. Limitation due to overvoltage that stress the SMES coil. The disadvantage is that the stress in the SMES coil increases during over voltage.

CONCLUSION

This paper presented the comprehensive review of the state-of- the-art developments for LVRT capability improvement of WTs based on fixed-speed wind turbines, which is relatively a new concept in maintaining voltage profile of the wind power generation. Low Voltage Ride Through is an important feature for wind turbine systems to full fill the grid code requirements. Different methods for LVRT have been studied in this paper. Then, all reviewed methodologies were categorized into three main groups, i.e., series-connected solutions, shunt-connected solutions, and hybrid-connected solutions; discussing the performance of the LVRT schemes including their advantages and limitations in details. It is found that the overall cost and control complexity of the SFCL and UPQC schemes are higher than other types of LVRT technologies. On the other hand, the SDBR and BFCL methods were relatively the cheapest and simplest control structure among other LVRT solutions from economic feasibility point of view. Crowbar method is a conventional method with low cost but draws more reactive power. From the above analysis Low Voltage Ride Through is an important feature for wind turbine systems to full fill grid code requirements. DFIG is sensitive to grid voltage variations. To overcome this, suitable control must be implemented to protect the converter from tripping during grid voltage faults. High current transients cause voltage fluctuations, rotor current, torque variations and dc link voltage fluctuation. DFIG with energy storage system and FACTS devices are common now days. But this increase cost and complexity of the system. Various types of modifications are done in flux tracking and current feedback technique gives good performance characteristics. Further research should be focused on the control strategy which improves the LVRT with reduced cost and complexity with good reactive power support during fault.

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