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Review Article

A Concise Presentation of Doubly Fed Induction Generator Wind Energy Conversion Systems Challenges and Solutions

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There is increased worldwide wind power generation, a large percentage of which is grid connected. The doubly fed induction generator (DFIG) wind energy conversion system (WECS) has many merits and, as a result, large numbers have been installed to date. The DFIG WECS operation, under both steady state and fault conditions, is of great interest since it impacts on grid performance. This review paper presents a condensed look at the various applied solutions to the challenges of the DFIG WECS including maximum power point tracking, common mode voltages, subsynchronous resonance, losses, modulation, power quality, and faults both internal and from the grid. It also looks at approaches used to meet the increasingly stringent grid codes requirements for the DFIG WECS to not only ride through faults but also provide voltage support. These are aspects of the DFIG WECS that are critical for system operators and prospective investors and can also serve as an introduction for new entrants into this area of study.

1. Introduction

Wind power, projected at 500 GW at the end of 2016, is expected to supply 5% of electrical power worldwide. Growth is expected to continue, hitting 1900 GW by the end of 2020 [1]. The merits of the doubly fed induction generator (DFIG), shown in Figure 1, make it one of the most widely used generators for wind energy conversion systems (WECS). The direct drive gearless permanent magnet synchronous generator (PMSG), a newer technology, has come up to challenge its market share, but the large number of installed machines ensures the DFIG WECS cannot be overlooked in the wind industry. In addition, new projects, such as the largest wind farm in Africa at 310 MW being set up in Kenya, continue to utilize the DFIG machine.

With aerodynamic, mechanical, and electrical subsystems making up the DFIG WECS quite complex, challenges are inevitable. Wind as a prime mover only adds to these by its intermittent and uncertain nature. To complicate matters further, more stringent grid codes have been instituted due to increased wind power penetration especially as they concern fault ride through (FRT) [2, 3]. This paper seeks to present these challenges and their applied solutions. No other paper has, to the author's knowledge, tackled the issues at one go, giving an easy to understand overall picture of the DFIG WECS.

This paper is divided into five sections. Starting with an introduction in Section 1, Section 2 covers challenges faced by the DFIG WECS and Section 3 gives insight into solutions that have been applied for operation under grid faults. Section 4 presents the discussion while in Section 5 conclusions are drawn.

2. Challenges

Control and operation of the DFIG WECS present some unique challenges due to the large number of interacting subsystems which cut across different disciplines. These interactions determine the power supplied to the grid. The challenges to connection of wind power to the grid are threefold.

(a) Source Induced. The fluctuating nature of wind results in variable generation with the associated power fluctuations, voltage fluctuations, and frequency deviations. Source

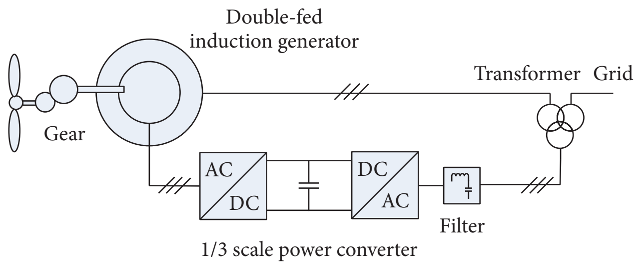

Figure 1: Configuration of a doubly fed induction generator wind energy conversion system [4].

induced fluctuations are critical on the medium-term basis in the timespan of seconds to minutes.

(b) Machine Induced. The inherent nature of the DFIG machine, as a rotating electromagnetic machine, also results in cyclical power/voltage fluctuations due to characteristics such as magnetic saturation and hysteresis. The tower also causes shadow effect as it blocks the air flows causing imbalanced forces as the rotating turbine blades come in direct line with the tower.

(c) Grid Induced. These originate from the grid system and include grid instability and transients.

Various challenges and proposed ways of handling them are given next.

2.1. Maximum Power Point Tracking (MPPT). The DFIG WECS, like any other renewable energy extraction system, seeks to maximize the extracted power by maximizing the system efficiency in a bid to shorten the installation cost return period. A shorter cost return period makes the project more appealing and competitive when viewed against the conventional energy sources [10]. This is critical considering that the maximum power extractable is limited by the strength of the renewable source which in most cases may additionally be varying. MPPT for WECS seeks to run the generator at an optimal speed relative to the wind speed as experienced by the turbine rotors. Many techniques have been proposed to achieve MPPT and include the following [10–13]:

(a) Lookup table based including power signal feedback (PSF), optimal torque (OT), and tip speed ratio (TSR) control.

(b) Nonlinear state space and state space linearization based.

(c) Neural network-fuzzy logic based.

(d) Hill climbing search (HCS) based.

(e) Hybrid hill climbing search/lookup table based including

  (i) variable step size HCS,
  (ii) dual step size HCS,
  (iii) search-remember-reuse HCS,
  (iv) modified HCS to avoid generator stall,
  (v) modified PSF to avoid generator stall,
  (vi) adaptive OT control,
  (vii) modified OT for fast tracking,
  (viii) adaptive TSR control,
  (ix) limit cycle based HCS,
  (x) disturbance injection based HCS,
  (xi) self-tuning sensorless adaptive HCS.

However, these are not without challenges, the most common being the following:

(a) There exists requirement for additional hardware such as generator speed sensor or observer and a wind speed sensor such as an anemometer. These components introduce errors such as that due to location of the anemometer on the nacelle which is at hub height and either behind the rotor for upwind machines or before the rotor for downwind machines. The anemometer thus does not cover the whole extent of the rotors with a resultant error in measured wind speed compared to the effective wind speed experienced by the rotors.

(b) The high system inertia of the wind turbine and generator does not respond fast enough in relation to wind speed changes that could be in seconds.

(c) There is the change of system parameters due to environmental changes such as air density change with seasons, aging from thermal, mechanical, or electrical system stresses, and generator loading conditions which result in changes on power converter and generator efficiencies as the load currents determine copper losses while rotational speed determines eddy current losses. As a result, no unique curve for optimal output electrical power exists and there are differences between the peaks for the input mechanical and the output electrical powers.

(d) There exist the requirements for prior knowledge of system parameter values which suffer drift.

An optimal MPPT technique should have characteristics that include adaptive tracking, self-tuning capability, simplicity of implementation, speed of convergence, and accuracy. The self-tuning sensorless adaptive HCS is the most attractive of the techniques above as in addition to exhibiting the above characteristics, it is mechanically sensorless and has minimal memory requirement.

2.2. Common Mode Voltage (CMV). CMV is voltage generated between the neutral point of the machine and the ground when pulse width modulation (PWM) technique is used in a three-phase converter. It results in shaft voltage and bearing currents which cause bearing material erosion and, consequently, bearing failure [14–16].

CMV can be reduced by the following:

(a) Appropriate selection of modulation strategy: this has the unfortunate effect of possibly increasing current harmonic output depending on the strategy adopted.

(b) Shaft grounding using earthing bushes and slip rings.

(c) Use of insulated/ceramic bearings or conductive lubricants.

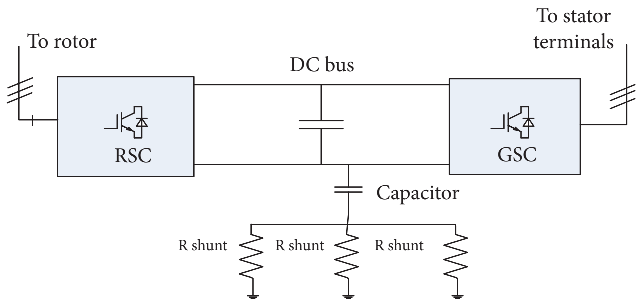

Figure 2: An RC bus filter [5].

(d) Increasing the converter voltage levels.

(e) Use of filters such as the RC bus filter whichconsists of a capacitor connected to the negative point of the DC bus on one end and to the earth on the other end through three resistors with a control that detects and supervises current circulation in the resistors [5]. This is shown in Figure 2.

2.3. Subsynchronous Resonance (SSR). This refers to resonance at subsynchronous frequencies that occurs between the mechanical parts of the DFIG and a grid system. It occurs when the DFIG is connected to a grid that is series compensated in a bid to increase system stability and power transfer capability. SSR increases as the level of series compensation in the power system increases. SSR in electrical networks appears in three ways:

(a) Torsional interactions: a situation where energy is exchanged between the grid system and the generator shaft system in an ever-increasing manner which can cause damage to the turbine-generator shaft. This is rare in wind farms as the low shaft stiffness in DFIG WECS drive train ensures low frequency torsional modes.

(b) Transient torsional amplification.

(c) Induction generator effects: when the effective stator and grid resistance at machine terminals is negative, the stator subharmonic currents interact with the rotor circuit inducing high voltages.

SSR can be damped by use of flexible AC transmission systems (FACTS) devices or intelligent control. The grid side converter (GSC) of the power electronic converter (PEC), due to its similar structure to a STATCOM, can also be controlled to damp SSR. SSR damping capability of DFIG increases with increase in wind speed [17–20].

2.4. Power Quality. The DFIG, being a rotating electrical machine and switching in the PEC, introduces harmonics and subharmonics that could result in voltage distortions at point of common coupling (PCC) to the grid. This effect increases as the number of DFIG WECS connected to the grid increases. The voltage distortions resulting from the rotor side converter (RSC) of the PEC cause increase in eddy current losses in the generator. Undesirable fluctuations in generated active and reactive power result from harmonics in rotor currents while harmonics in stator currents result in power quality deterioration at the PCC. The harmonics from the converter are reduced if the number of voltage levels is increased. As such, a three-level neutral point diode clamped (NPC) converter has fewer harmonics than a two-level back-to-back converter [15, 21, 22].

Compensation for reactive power, current and voltage harmonics, current and voltage imbalances, voltage flicker, voltage regulation, and neutral current is carried out using filters. An LCL filter is usually used to suppress the harmonics [4]. However, due to the large capacitance of the converter, the switching frequency is low necessitating use of a bulky filter [22]. Active filters are also used, some utilizing the extra capacity in RSC or GSC, for active filtering of harmonics by compensating the reactive power and harmonic currents. Hybrid filters, consisting of active and passive filters, are also an option [23–26].

2.5. Modulation. Converter switching can be modulated in different ways. Carrier based modulation is produced by triangular wave intersection with a reference modulating sinusoidal wave signal while space vector modulation (SVM) uses direct digital technique to determine the appropriate switching to be done. Sinusoidal pulse width modulation (SPWM), though simple in approach, has disadvantages as it has higher total harmonic distortion (THD) than SVM. SVM also has higher efficiency and reliability as it uses discontinuous PWM (DPWM), where switching is done only when necessary, resulting in lower converter power losses than for the continuous PWM (CPWM) applied in SPWM. DPWM, however, results in varying switching frequency which makes design of filters difficult [15, 27].

2.6. Losses in Voltage Source Converter (VSC) Components. Higher currents flow in the RSC than in the GSC. To accommodate the higher currents and ensure equal power device loading, the RSC cell has two parallel power devices for each device in the GSC cell. The semiconductor devices have conduction and switching power losses contributing to thermal losses with corresponding temperature rise. The losses reduce the efficiency of the VSC and subject the power electronics to thermal cyclic stresses. In subsynchronous mode, the most stressed device in the RSC is the insulated gate bipolar transistor (IGBT) while it is the freewheeling diode in the GSC. The reverse is true in supersynchronous mode.

Thermal cycling can be on

(a) long-term basis of periods in days or months from environmental disturbances such as wind speed and ambient temperature variations,

(b) medium-term basis of periods in minutes to seconds from speed control to attain maximum power production or pitch control to limit generated power to rated values,

(c) short-term basis with period ranging below one second from fast electrical disturbances such as grid faults, VSC switching, and load current alternation.

Thermal cycling can be reduced by circulating reactive power internally in the VSC without power factor distortion to the power system. This results in reduced thermal stresses on the semiconductor devices hence increasing their lifetime and reliability. However, the range of reactive power available for circulation in the RSC is limited by the generator reactive power capacity while in the GSC; it is limited by both the generator reactive power capacity and the DC-link voltage. Increase in converter voltage levels also decreases thermal losses [15, 28–30].

2.7. Faults. Faults can come from the DFIG WECS itself or from the grid it is connected to.

2.7.1. Faults from the Machine. Faults in the DFIG WECS occur in four main areas.

(i) Turbine Faults. These include rotor blade strikes by lightning, blade fracture due to excessive loading from wind gusts or icing as well as hydraulic system failure. Some applied solutions include lightning rods fitted on the blades as well as blades designed to stall in high winds as well as to reduce amount of ice buildup.

(ii) Gearbox Faults. Gearbox failures are rare, expected once or twice in the WECS lifetime, but they are the most costly as they usually involve replacement of the gearbox at around 10% of total cost of the WECS. In addition, they cause twice or thrice the downtime for failures by other components [31, 32]. These mechanical failures are due tothe following:

(i) manufacturing errors such as grind temper or material inclusions,

(ii) insufficient or absence of lubrication that causes surface related problems, such as

  (a) scuffing: the adhesive wear resulting in detachment and transfer of particles from meshing teeth,

  (b) micropitting: the creation of numerous surface cracks leading to surface fatigue,

(iii) fretting problems which are from small vibratory motions, especially when the WECS is parked [33].

Overheating of the lubrication oil can, in some cases, result in fires. Correct and sufficient lubrication, with lubricants of high quality and lifespan, coupled with efficient cooling for the lubricant is adequate to prevent most failures.

(iii) Generator Faults. These include

(i) open circuit in windings,

(ii) winding insulation failures leading to inter-turn winding short circuits due to overheating as a result of overload or unequal heating resulting from imbalanced voltages [34].

The integrity of the windings and the insulation is maintained by controlling operating temperatures through voltage and current regulation.

(iv) PEC Faults. These include the following:

(i) Semiconductor device failures: these include failure of the IGBTs, diodes, and bond wire connections. They result mainly from thermal cycling as the semiconductors switch on and off periodically and unevenly. Since they are made up of different materials, the different coefficients of expansion result in stresses due to expansion and compression forces [4]. Other faults include IGBT open and short circuits. An open circuit results in fluctuations in both active and reactive power outputs [35, 36]. IGBT fire-through, where a switch conducts before the time determined by the switching control system, forms an intermittent short circuit that negatively affects the terminal voltage [37].

(ii) DC-link capacitor failures: the bulky electrolytic DC-link capacitor is one of the weak links in the VSC and contributes 30% of failures in AC converters [38]. Imbalanced voltages result in active power oscillations which cause voltage fluctuations across the capacitor as well as second-order harmonic currents to flow through it. These raise the power loss and operating temperature, hence increasing the electrolytes rate of evaporation and shortening the capacitors' lifespan [39].

DC-link capacitor failure could be short circuit or open circuit. A short circuit fault results in a more severe effect on generator speed, voltage drop at PCC, reactive power absorbed as well as stator current spike, and oscillations than an open circuit fault. It makes the DC-link voltage to collapse, with currents flowing to supply the fault from both converters through the freewheeling diodes. The faults result in reduced active power output which drops to zero in case of unsuccessful fault clearance [21, 40].

(iii) Filter failures: filter failure results in degradation of power quality at PCC due to harmonics resulting from the VSC switching operations [4].

Whereas gearbox failures result in most downtime and cost, they are rare, accounting for only 5% of failures while PEC failures are most common, accounting for over 50% of all cases of DFIG WECS failures [4, 41].

2.7.2. Faults from the Power System. Faults from the power system also impact on the DFIG WECS. They include voltage sags, voltage swells, and frequency fluctuations with voltage sags being more frequent than swells. As a result, there is greater focus on low voltage ride through (LVRT) than high voltage ride through (HVRT). The major cause of voltage sags is system faults such as short circuits and faults to ground. Other causes include sudden loss of large generating units, transformers energizing, and switching in of large loads usually induction motors [11, 42–44]. However, voltage swell sometimes occurs after voltage sag due to switching

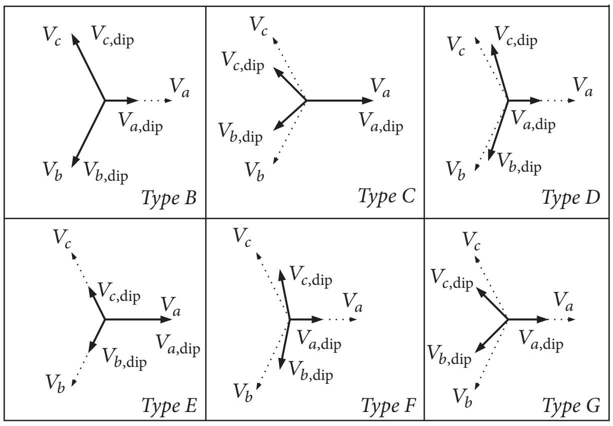

Figure 3: Fault types B to G [6].

off of large loads due to the voltage sag, reactive power overcompensation from capacitor banks, or single-phase short-term interruptions [45, 46].

(i) Types of System Faults. The five types of system faults encountered by the DFIG WECS from the grid fall into two categories [47]:

(i) Balanced/symmetrical faults: these are

  (a) three-phase,
  (b) three-phase to ground.

(ii) Unbalanced/asymmetrical faults: these are

  (a) two-phase,
  (b) two-phase to ground,
  (c) one-phase to ground.

The five types of system faults have different percentages of occurrence as given next [48]:

Type of fault	*% of total fault occurrence*
One-phase to ground fault	70–85
Two-phase faults	8–15
Two-phase to ground fault	4–10
Three-phase faults	3–5

The five types of faults are further categorized into seven types, types A–G, depending on the changes on phase-to-neutral voltage magnitudes and phase-angle jumps if any. These are as follows [47, 49, 50]:

(i) Type A is the three-phase symmetrical fault where all three-phase-to-neutral voltages show equal drop in magnitude, with no phase jump.

(ii) Types B to G are shown in Figure 3 where dotted lines indicate voltage before faults and solid lines indicate voltage after fault.

(ii) Effect of Transformers on Faults. The voltage sag is sensed at the high voltage side of the connecting transformer to the PCC. This introduces transformation to the faults resulting in a different type of fault being seen at the DFIG terminals, in some cases, depending on the type of fault and the transformer connection [51, 52]. The common transformer connection types are given in Figure 4.

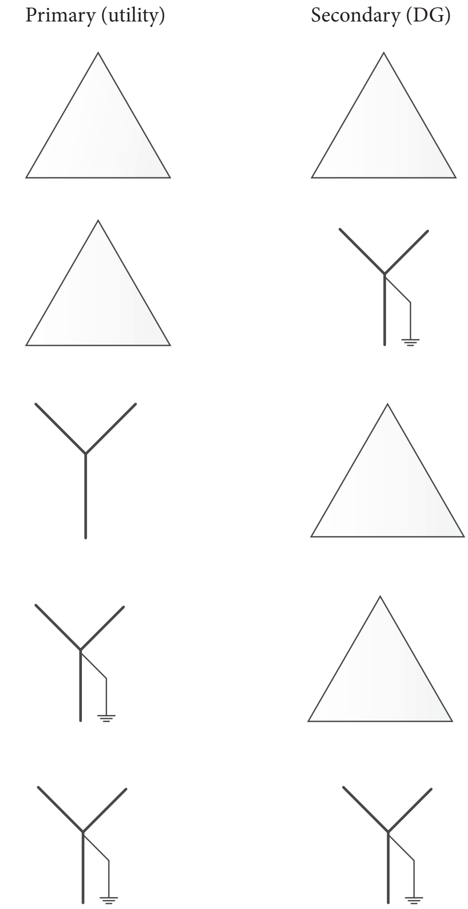

Figure 4: Interconnection transformer connections [7].

The effect of transformers on faults is given in Table 1 [6].

Fault types B and E do not appear at the generator terminals with Y-Δ connected transformer as they involve zero sequence components that are absorbed by the transformer connection. The DFIG stator isolated Y or Δ winding connection has the same effect [34, 53].

(iii) Effect of Faults on DFIG WECS. The effect of voltage sag on the generator depends on the following [12]:

(1) Type of fault: the fault components to be dealt with depend on the type of fault. Three-phase faults only involve positive sequence fault current components with a high surge value and so are more severe. The single-phase to ground and two-phase to ground faults introduce negative and zero sequence components in addition to the positive sequence components. Two-phase faults have only positive and negative sequence components.

The negative sequence voltages result in high negative sequence current components that cause double grid frequency oscillations on active power, reactive power, and

Table 1: Fault propagation inside a wind farm.

Fault	Fault at PCC (HV terminals of wind farm transformer)	Fault at wind farm transformer LV terminals with Y-Δ connection	Fault at DFIG terminals with Y-Δ connected transformer	Fault at DFIG terminals with transformer of connection type other than Y-Δ
Three-phase	Type A	Type A	Type A	Type A
Single-phase	Type B	Type C*	Type D*	Type C*
Phase to phase	Type C	Type D	Type C	Type D
Two-phase to ground	Type E	Type F	Type G	Type F

*In this case, the characteristic voltage is (1/3 + 2/3 V_{sag}) instead of being equal to V_{sag}.

electromagnetic torque resulting in stator winding and drive train lifetime reduction [7, 13, 47, 54]. The negative sequence stator flux rotates in opposite direction to the rotor and hence induces a high frequency component in the rotor winding at a frequency given by

$$\omega_e^- = \omega_s + \omega_r. \tag{1}$$

If the terminal voltage does not drop to zero, then there is also the component induced by the positive sequence stator flux which rotates at

$$\omega_e^+ = \omega_s - \omega_r, \tag{2}$$

where ω_s is stator frequency, ω_r is rotor rotational speed, ω_e is frequency of current induced in the rotor by stators' magnetic field, and the superscripts + and − represent the positive and negative sequence components, respectively [55].

(2) Phase-angle jump: a phase angle jump occurs when the X/R ratio of the fault impedance is different from that of the source impedance. X/R ratio is usually small for overhead transmission lines but big where high voltage cables are utilized. If the type of fault involves phase-angle jump, it results in higher negative sequence voltage component and consequently elevated rotor current and DC-link voltage [6].

(3) Depth of sag: this depends on distance of fault location from the generator terminals. A fault is deemed remote if it results in a voltage dip of <30%. Higher values of rotor current and DC-link voltage are experienced with increase in sag depth. The different types of faults A–G have specific depths beyond which the fault effect is most severe [47, 56].

(4) Initial point-on-wave instant of fault: the worst point-on-wave instant is when the positive and negative sequence components of stator flux are aligned in opposite directions. This results in high rotor currents because the resultant stator-forced flux is at a minimum, necessitating a large natural flux to avoid discontinuity in the stator flux trajectory since this cannot change instantaneously at the instant of fault occurrence [57].

(5) Prefault wind speed: this determines the prefault generator speed which in turn determines generator slip and resultant active power output. The d- and q-stator, RSC, and GSC currents flowing are thus obtained. The effect is critical when the machine is operating at its rated limit as the rated current is being utilized for active power generation in the stator and DC-link voltage control in the GSC. Thus, there is less reserve capacity available for generation of reactive power in both. In subsynchronous mode, power flows from the grid through the VSC to the rotor. This results in high DC-link voltage and a higher initial fault current magnitude [7].

(6) Duration of fault: longer lasting faults have greater negative effects, with voltage drops lasting longer than one second being considered as voltage interruptions. The different types of faults A–G have specific periodic durations for which the fault effect is most severe. This is the time when the current at fault recovery is farthest from prefault current [47, 53].

(7) Fault recovery process: if the voltage recovery is considered as a one-step process, large natural flux component is needed as stator-forced flux trajectory continuity must be ensured. Thus smaller natural flux components can be ensured by considering fault recovery on two or three steps. This is more realistic as the breaker phase operation is at natural zero current crossing points. Faults recovered in two steps have similar effects on the generator. The same goes for faults recovered in three steps. Smaller natural flux components increase the range of faults a generator can withstand [7, 53].

(8) Grid strength: the strength of a grid in terms of its short circuit ratio determines how severe the fault effect will be. A strong grid interconnection can withstand a higher rate of recovery, thus minimizing FRT requirement on the generator [57].

Generally rotor fault current is highest for high depth three-phase fault when the generator is delivering full power at supersynchronous speed [58].

(iv) DFIG Response to Faults. Both voltage sags and swells result in a large electromotive force being induced in the rotor circuit by the transient stator flux. This sets up a surge current in the rotor circuit which can destroy the PEC semiconductor devices as they cannot withstand currents of more than 200% of their nominal rating [45]. In addition, the low voltage at the PCC reduces the GSC capacity to transfer power to the grid as to square of the system fault voltage. This leads to excess power in the DC-link capacitor resulting in increased DC-link voltage. Protection systems are put in place to ensure the high currents do not destroy the RSC and the high voltage does not cause DC-link capacitor failure.

The rotor circuit is protected from these conditions by the passive crowbar.This is a hardware protection for the PEC.

It short-circuits the three phases of the generator rotor once triggered by the overvoltage of the DC bus voltage. Operation of the passive crowbar also sets into effect an emergency shutdown of the DFIG [5]. However, this is not ideal since DFIG needs to be kept connected to the grid.

3. Solutions to Power System Faults

Protection for DFIG has been approached in two different ways:

(i) Approaches that seek to keep the generator running and connected to the grid. This is by

(a) avoiding tripping the machine by keeping monitored parameters, that is, rotor overspeed, stator and rotor overcurrents, and rotor and DC-link overvoltage, within limits;

(b) maintaining a healthy voltage at the generator terminals irrespective of the fault and post-fault grid voltage value.

(ii) Approaches that seek to keep the generator connected so as to provide reactive power to the system at PCC and thus support the voltage.

The above approaches are implemented by one of the following:

(i) Addition of new devices at PCC such as FACTS devices like static var compensators (SVC), static synchronous compensator (STATCOM), static series compensator (SSC), and unified power flow compensator (UPFC).

(ii) Addition of new components to the DFIG stator circuit such as series dynamic braking resistor (SDBR), dynamic voltage restorer (DVR), and antiparallel thyristors.

(iii) Addition of new components to the DFIG rotor circuit such as crowbar circuit and SDBR.

(iv) Addition of new components to the PEC such as braking chopper circuit, battery energy storage system (BESS), and energy capacitor storage (ECS).

3.1. Keeping the DFIG Connected to the Grid but Not Offering Support to Grid. This is achieved by use of one or a combination of the following methods:

(a) Active Crowbar. An active crowbar consists of semiconductor switches, either IGBTs or diodes with resistors. When rotor overcurrent or high DC-link voltage is detected, and then a check of the grid voltage reveals a voltage sag or swell, the control system disconnects the RSC by blocking the firing pulses. The active crowbar circuit is then connected, rerouting the high rotor currents through additional crowbar resistances. The increased rotor circuit resistance causes the high rotor currents to decay. Once the rotor currents reach a safe level, the crowbar is deactivated and the RSC firing pulses are resumed [5]. During the period when the active crowbar is activated, the DFIG operates as a wound rotor induction generator (WRIG) with increased rotor resistance but no control over both active and reactive power output. As a result, reactive power cannot be availed for voltage support at a time when it is critically needed. Also, the DFIG when operating as a WRIG consumes reactive power, further delaying voltage recovery. To avoid this, the operation time of the crowbar circuit must be minimized by increasing the value of the crowbar resistance.

However, increasing the crowbar resistance beyond a certain point, while decreasing the current decay time, results in high voltages at the RSC terminals. These set up a charging current through the RSC diodes and the DC-link capacitor which charges up the capacitor, raising the DC-link voltage. If this voltage exceeds the set limits, it can trigger the active crowbar again after its first deactivation, thus delaying voltage recovery, or even the passive crowbar, leading to a machine shutdown. In addition to the rotor current and DC-link voltage, the values of the active crowbar resistances also influence the rotor speed and the active and reactive powers when the crowbar is active. The correct value of crowbar resistance is thus critical.

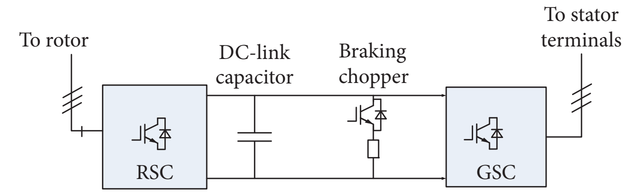

Figure 5: Power converter showing the chopper circuit [5].

(b) Braking Chopper Circuit. It consists of an IGBT with a snubber capacitor and a chopper resistor and is connected in parallel with the DC-link capacitor. It aids in keeping the DC bus voltage under the given limits during times when the active crowbar cannot control the voltage all by itself. A braking chopper dissipates excess power in the DC bus through the chopper resistor. Figure 5 shows a braking chopper circuit.

By utilizing a crowbar circuit, with or without a DC-link chopper, the DFIG machine can be kept connected during the fault by protecting it from the rotor overcurrent, rotor overvoltage, stator overcurrent, DC-link overvoltage, and rotor overspeed [59–61].

(c) Energy Storage System (ESS). The use of a braking chopper circuit is enhanced by use of an energy storage system such as a BESS [62] or ECS connected across the DC bus. The ESS stores the excess power and so avoids a DC-link overvoltage. The energy so stored is later released through the GSC to the power system when normal voltage is restored thus helping improve the power quality [13].

(d) Series Dynamic Braking Resistor (SDBR). SDBR consists of a set of three-phase resistors connected across the three phases of either the stator circuit or the rotor circuit between the rotor and the PEC. A bypass switch keeps the resistors out

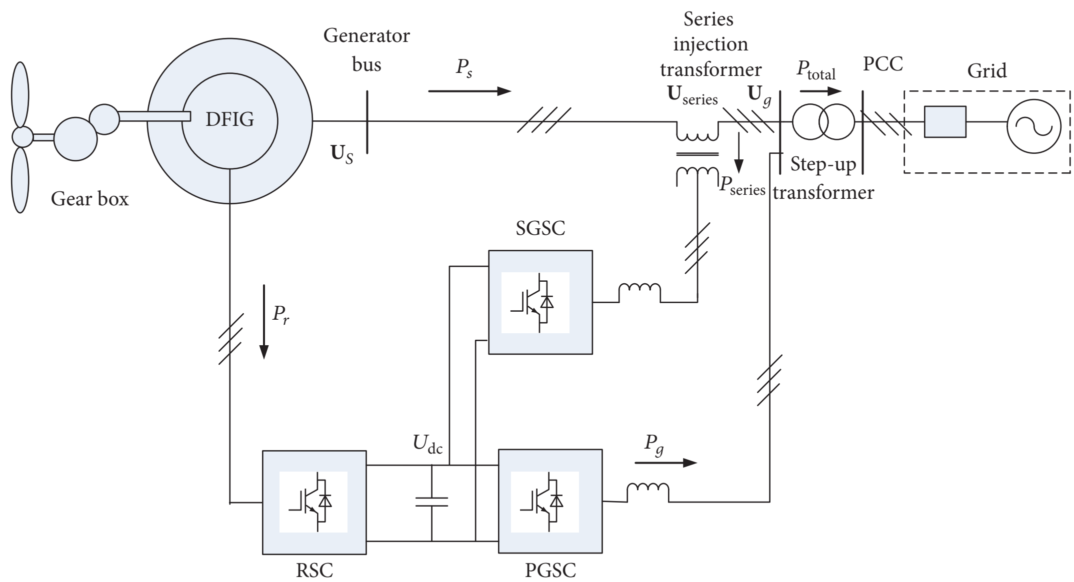

Figure 6: Configuration of a DFIG with SGSC [8].

of the circuit during normal operation and opens to insert them into the circuit during fault conditions. The resistors introduce a voltage divider action ensuring that the generator sees the normal voltage at its terminals. At the same time, the added resistance reduces fault currents. The resistors also dissipate part of the generated power thus avoiding rotor overspeed. A low value of the resistance, as well as its fast insertion once fault occurs and for a short duration as possible, leads to improved DFIG stability [13, 63–66].

(e) Dynamic Voltage Restorer (DVR). A DVR is applied in series with the stator to maintain stator terminal voltage at nominal values once fault is detected. The DFIG generates active power albeit at reduced level since MPPT is disabled. Since the export of power to the grid is curtailed, the DVR absorbs and stores or dissipates the difference between power produced by generator and power exported to grid. The power can be dissipated in its braking resistance [67, 68].

(f) Superconducting Magnetic Energy Storage (SMES). A SMES is connected to the PCC just like FACTS devices to store energy under normal operating or high voltage conditions. The energy so stored is later released to the PCC when grid energy goes down due to a fault hence maintaining the voltage at PCC. The DFIG thus does not experience the fault [69].

(g) Series Grid Side Passive Impedance Network. In these, an equivalent impedance Z_{eq} is inserted into the system on occurrence of the voltage sag to ensure the stator flux λ_s, stator current I_s and rotor current I_r, and torque T_e do not change during the sag.

$$Z_{\text{eq}} = \left(\frac{V_g}{I_s}\right) + Z_g, \tag{3}$$

where V_g is prefault equivalent electromotive force of grid, Z_g is prefault equivalent impedance of grid, and I_s is prefault equivalent stator current [70].

(h) Virtual Resistance/Inductance. In an approach similar to the series grid side passive impedance networks, a virtual resistance is introduced in the equivalent rotor circuit using a LVRT controller to decrease rotor fault currents and its decay time while a virtual inductance increases the leakage inductance of the rotor circuit with similar results. Torque oscillations are also reduced in both approaches [71, 72].

(i) Flux Damping/Demagnetization. The rotor current is controlled to counteract the dc and negative components in the stator flux that occur during a fault. To obtain the necessary current to maintain control, temporary overloading of the RSC devices to 200% is allowed [73].

(j) Supplementary Rotor Current (SRC) Controller. The SRC controller is used for the RSC to limit the magnitude of rotor current to within nominal values during faults by introducing a multiplication factor k to the effective measured RSC currents. The value of the factor depends on the fault voltage magnitude [74].

(k) Series Grid Side Converter (SGSC). A SGSC is connected to the DC bus in addition to the parallel GSC as shown in Figure 6. It is utilized to eliminate the negative sequence stator voltage, ensuring balanced stator terminal voltages even under grid network voltage imbalance [8].

3.2. Keeping the DFIG Connected to the Grid While Offering Support to Grid. Voltage control can also be achieved by reactive power injection.

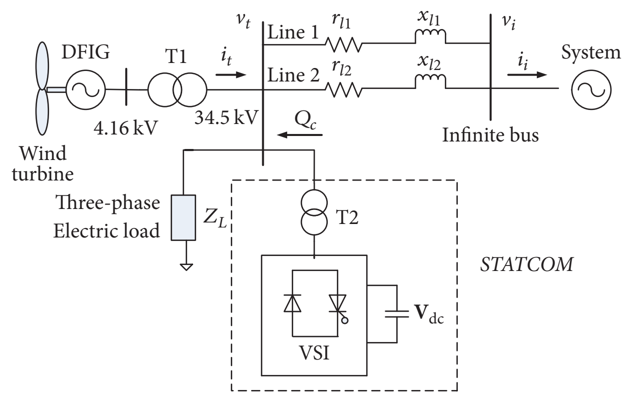

Figure 7: Single line diagram showing STATCOM connection for reactive power compensation [9].

3.2.1. From External Devices. FACTS devices are connected at the PCC to inject or absorb reactive current to keep voltage within the prescribed operational limits. They can be connected in either shunt (STATCOM, SVC), series (DVR), or hybrid manner (UPFC). This introduces the added cost of the FACTS device, maintenance costs, reduced reliability, and added control complexity [9, 66, 75–77]. Figure 7 gives an example of a STATCOM connection.

3.2.2. From DFIG. The added cost of the FACTS device can be avoided by utilizing the DFIG reactive power capacity. On fault occurrence, the reactive power output of the DFIG is given priority [78]. The reactive power output of the DFIG can be a total of up to 75% of its active power rating with around 20% of the active power rating being from the GSC [75]. This capability depends on rated rotor voltage and current limits and rated stator current limit [79, 80]. In addition to the aforementioned, the GSC reactive power capability must be considered [81]. Total reactive power generation is limited by rotor current while consumption is limited by stator current. For large slips, >0.31, reactive power generation is also limited by rotor voltage. There also are limitations imposed by magnetic flux saturation and the nonlinear relationships between junction temperature and rotor currents frequency [82].

Most grid codes require that the power factor at the PCC must be between 0.95 leading and 0.9 lagging. This cannot be met with DFIG alone once its active power production goes above 82% of nominal value. The most obvious approach is to increase the rating of the VSC [83] which results in increased reactive power production as well as faster active power response and less DC-link voltage oscillation after fault clearance. Also, the pitch angle requires very little adjustment. However, increasing the rating of the VSC comes at an added cost due to the increased rating [84]. Other approaches that avoid the increase in cost include the following:

(a) Since the generator rated power at supersynchronous speed is the sum of stator power and rotor power [85],

$$P_{\text{tot}} = P_s + P_r \tag{4}$$

at a certain point, to avoid exceeding rated power, the stator power has to decrease as the rotor power increases. At rated power, the stator supplies 0.7–0.8 p.u. while rotor produces 0.2–0.3 p.u [82]. This results in capacity which can be utilized for generating reactive power from the stator if the rating of the wind turbine is higher than that of the generator.

(b) Also, additional DFIG reactive power reserve capacity can be ensured by connecting at the PCC, FACTS devices such as mechanically switched capacitors, whose rating is just enough to ensure that the VSC injects a maximum of 10% of their rated reactive power capacity during steady state system operation. The reserve is then availed during transient states [86] while the cost of FACTS devices is minimized.

(c) In addition, whereas worst case scenarios consider the fully loaded DFIG at nominal active power output, it is only at 10% of the time that it supplies above 90% of this value. This gives additional capacity for reactive power production [85].

(d) With temporarily overloading of the converters' current outputs, but within manufacturers' limits, the IGBTs can switch up to 100% more current than the steady state rated current so long as it is operating within the safe operating area (SOA). This is usually given for a short duration of time typically 20 mS. As such, both RSC currents can be increased, thus increasing the active power, hence controlling rotor overspeed, while the increased GSC current ensures that active power is not sacrificed and so avoids DC-link overvoltage. The extra current capacity is used for reactive power generation, hence boosting total reactive power generation from the DFIG [55, 87].

(e) Using the chopper braking resistor to dissipate a larger percentage of the power from the rotor, as a result, more GSC capacity is availed for injecting reactive current to the power system [66].

(f) The GSC reactive power output is given priority over active power while the RSC also gives reactive current priority on fault occurrence. This results in improved terminal voltage. While prioritizing reactive power reduces the DFIG active power output, the healthy voltage positively affects other electrical components in the grid system ensuring they do not trip on over/undervoltage [78]. This is critical when these include other generators without FRT. To ensure reactive power output from the stator, RSC control must not be lost during the fault period.

4. Discussion

Most of the challenges resulting from the machine can be dealt with at manufacturing stage, while appropriate and timely maintenance can deal with others. The choice of an appropriate control strategy is also critical. The control system must strive to keep the thermal loading within limits and also reduce the thermal variations to ensure long lifespan especially for the electronic components. For cost effectiveness, the DFIG WECS must be used for reactive power supply during both steady and transient states especially for faults from the power system. As such, the MPPT and control strategies must incorporate this. However, coordination between the MPPT strategy and control strategy is a must if greater benefits such as reduction of component count are to be achieved. For example, the use of an MPPT strategy that requires a speed sensor minimizes the positive impact of a control strategy that does not utilize the speed sensor and vice versa.

Due to the intricate interaction between the stator and rotor circuits by magnetic flux, approaches for FRT that do not interfere with the internal setup of the DFIG WECS seem attractive. The solution must however be machine based and not at the wind farm terminals. This is as required by some grid codes such as GB 19963-2011 since FRT capability is determined based on individual machines and not on the entire wind farm. These approaches include use of SDBR and DVR on the stator circuit. However, the switching in and out of the stator side of SDBR and DVR introduces switching transients since the stator circuit carries a large percentage of the output current [88]. These voltage transients can go by up to 50% in 1–3 μS and thus introduce great stress to the DFIG windings. Future works are expected to look at reduction of switching transients where SDBR and DVR are applied for FRT.

5. Conclusion

The challenges faced in operation of the DFIG WECS which include faults from both the machine and the grid system are presented. Different approaches used to date to deal with these challenges have been explored with various MPPT and control strategies being presented. The paper has brought out issues to consider for an optimal solution which must coordinate the MPPT and control strategies and integrate FRT capabilities so as to satisfy the ever stringent grid connection codes.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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