A REVIEW: DOUBLY FED INDUCTION GENERATOR WIND ENERGY CONVERSION SYSTEMS DEFIES AND SOLUTIONS

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Abstract: There is augmented global wind power generation, a huge percentage of which is grid connected. The doubly fed induction generator (DFIG) wind energy conversion system (WECS) has lots of merits and, as a consequence, large numbers have been installed to date. The doubly fed induction generator wind energy conversion system operation, under both fault and steady state conditions, is of huge curiosity since it impacts on grid recital. This review research paper presents a strong look at the a variety of applied solutions to the defies of the doubly fed induction generator wind energy conversion system together with maximum power point tracking, common mode voltages, sub-synchronous resonance, modulation, losses, power quality, and faults both internal and from the grid. It also looks at move towards used to meet the more and more stringent grid codes necessities for the doubly fed induction generator wind energy conversion system to not only ride through faults but also offer voltage support. These are features of the doubly fed induction generator wind energy conversion system that are serious for system operators and prospective financiers and can also dole out as an introduction for novel entrants into this study area.

Keyword: Doubly Fed Induction Generator (DFIG), Wind Energy Conversion Systems (WECS), Maximum Power Point Tracking (MPPT).

1. Introduction

Wind power, projected at 500GW at the end of year 2016, is anticipated to supply 5% of electrical power global. Growth is anticipated to persist, hitting 1900GW by the end of year 2020 [1]. The advantages of the DFIG, shown in Figure 1 and make it one of the main broadly used generators for WECS. The direct drive gearless PMSG (permanent magnet synchronous generator), a latest technology, has come up to defy its market share, but the huge number of installed machines makes sure the doubly fed induction generator wind energy conversion system cannot be over looked in the wind industry. Additionally, novel assignments, for instance the biggest wind farm in Africa (310 MW) being set up in Kenya, continue to make use of the doubly fed induction generator (DFIG) machine. With mechanical, aerodynamic and electrical sub-systems making up the doubly fed induction generator wind energy conversion system relatively difficult, defies are inevitable. Wind energy as a prime mover adds to these by its irregular and uncertain in nature. To obscure matters further more stringent grid codes have been instituted due to augmented wind energy power penetration especially as they apprehension fault ride throughout FRT [2, 3]. This research review paper looks for to present these defy and their applied results.

This research paper is alienated into five parts or sections. Starting with an introduction in Section 1, Section 2 covers defy or challenges faced by the doubly fed induction generator wind energy conversion system and Section 3 provides insight into results that have been applied for operation under grid faults condition. Section 4 gives the discussion while in Section 5 conclusions are presented.

2. Challenges

Control and operation of the doubly fed induction generator wind energy conversion system present a few inimitable challenges because of the huge number of interacting subsystems which cut across various disciplines. These dealings conclude the power supplied to the grid. The defies to connection of wind power to the grid are three-fold.

a) *Source Induced*. The unpredictable nature of wind consequences in uneven generation with the associated voltage fluctuations, power fluctuations, and frequency deviations. Source induced fluctuations are decisive on medium-term basis in the time span of seconds to minutes.

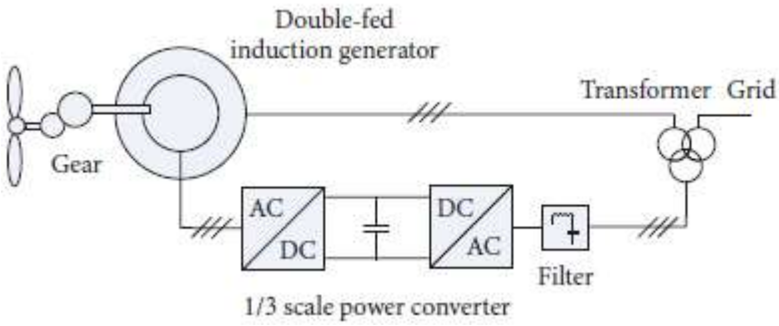

Figure 1: DFIG WECS Configuration [4].

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

c) *Grid Induced*. These instigate from the grid system and consist of grid instability and transients.

A variety of challenges and proposed ways of managing them are given next.

2.1. Maximum Power Point Tracking (MPPT)

The doubly fed induction generator wind energy conversion system, like any additional renewable energy withdrawal system, looks for to maximize the extracted power by maximizing the system effectiveness in a bid to cut down the installation cost return period. A shorter price return period makes the project or assignment more appealing and competitive when viewed in opposition to the conventional energy sources [10]. This is decisive thinking that the maximum power extractable is limited by the strength of the renewable energy source which in mainly cases may furthermore be varying. Maximum Power Point Tracking for wind energy conversion system looks for to run the generator or alternator at an optimal speed compared with wind speed as experienced by the rotor of turbine. Many methods have been suggested to attain MPPT and include the following [10–13]:

a) Look-up table based together with 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.

Though, these are not without challenges, the most general being the following:

(a) There exists prerequisite for additional hardware such as generator or alternator speed sensor or observer and a wind speed sensor such as an anemometer. These parts initiate errors such as that because of location of the anemo-meter on the nacelle which is at hub height and either at the back the rotor for up-wind machines or earlier than 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 react fast adequate in relation to wind speed varies that could be in seconds.

(c) There is the alter of system parameters because of environmental changes for instance air density change with seasons, aging from thermal, mechanical system and electrical system stresses, and generator loading states which outcome in changes on power converter and generator capabilities as the load currents determines copper losses while rotational speed decides eddy current losses. Accordingly, no inimitable curve for optimal output electrical power exists and there are disparities amid the peaks for the mechanical input and the electrical powers output.

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

An optimal Maximum Power Point Tracking technique should have traits that include adaptive self-tuning, tracking capability, speed of convergence, simplicity of implementation 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)

Common Mode Voltage (CMV) is voltage generated amid the neutral point of the machine and the ground when pulse width modulation method is used in a 3-phase converter. It consequences in bearing currents and shaft voltage which cause bearing material erosion and, consequently, bearing failure [14-16].

CMV can be reduced by the following:

(a) Suitable selection of modulation policy: this has the inopportune effect of possibly augmenting current harmonic outcome depending on the strategy adopted.
(b) Shaft grounding using earthing bushes and slip rings.
(c) Use of insulated/ceramic bearings or conductive lubricants.
(d) Increasing the converter voltage levels.
(e) Use of filters such as the RC bus filter which consists of a capacitor connected to the negative point of the DC bus on one end and to the earth on another end through 3-resistors with a control that senses and oversees current circulation in the resistors [5]. This is shown in Figure 2.

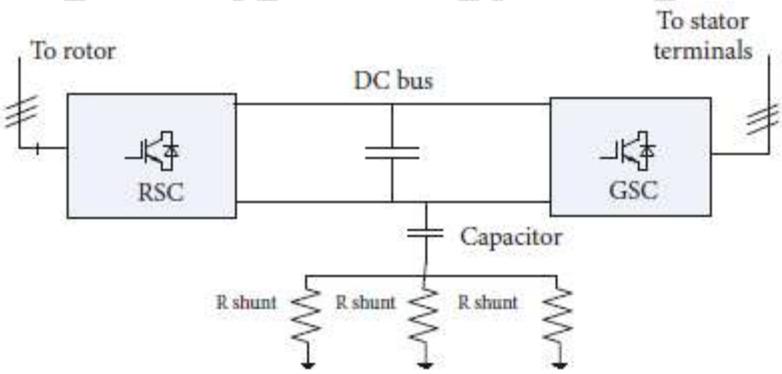

Figure 2: An RC bus filter [5].

2.3. Sub-synchronous Resonance (SSR)

This refers to resonance at sub-synchronous frequencies that occurs between the mechanical parts of the DFIG and a grid system. It happens when the DFIG is connected to a grid that is series compensated in a bid to increase system stability and power transfer capability. Sub-synchronous Resonance augments as the level of series compensation in the power system augments. SSR in electrical networks appears in three ways:

(a) Torsional interactions: a circumstance where energy is replaced amid the grid system and the generator shaft system in an ever-augmenting way which can cause damage to the turbine-generator shaft. This is unusual in wind farms as the low shaft firmness in doubly fed induction generator (DFIG) wind energy conversion system (WECS) drive train makes sure 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 sub harmonic currents interact with the rotor circuit inducing high voltages.

Sub-synchronous Resonance can be damped by use of flexible A.C. transmission systems (FACTS) devices or intelligent control. The GSC (Grid Side Converter) of the PEC (Power Electronic Converter), because of its similar structure to a STATCOM, can too be controlled to damp Sub-synchronous Resonance. Sub-synchronous Resonance damping capability of doubly fed induction generator augments with augment in wind speed [17–20].

2.4. Power Quality

The DFIG, being a rotating electrical machine and switching in the PEC, introduces harmonics and sub harmonics that could result in voltage distortions at point of common coupling (PCC) to the grid. This effect augments as the number of doubly fed induction generator wind energy conversion system attached to the grid augments. The voltage distortions outcomes from the rotor side converter (RSC) of the Power Electronic Converter cause augment in eddy current losses in the generator. Unwanted fluctuations in generated active and reactive power outcome from harmonics in rotor currents although harmonics in stator currents outcome in power quality weakening at the PCC. The harmonics from the converter are diminished if the number of voltage levels is augmented. As such, a 3-level neutral-point- diode clamped (NPC) converter has less harmonics than a 2-level back-to-back converter [15, 21, 22].

Compensation for current, reactive power and voltage harmonics, voltage imbalances and current, voltage regulation, voltage flicker, and neutral current is carried out using filters. An LCL filter is generally employed to suppress the harmonics [4]. On the other hand, because of the huge capacitance of the converter, the switching frequency is low necessitating employ of a bulky filter [22]. Active filters are too employed, some utilizing the additional capacity in GSC or RSC, for active filtering of harmonics by compensating the harmonic currents and reactive power. Hybrid filters, consisting of passive and active filters, are too a choice [23–26].

2.5. Modulation

Converter switching is able to be modulated in various ways. Carrier based modulation is generated by triangular wave intersection with a reference modulating sine wave signal though space vector modulation (SVM) employs direct digital method to decide the suitable switching to be done. Sinusoidal pulse width modulation (SPWM), while simple in approach, has demerits as it has high THD than SVM. Space vector modulation also has higher effectiveness and dependability as it employs discontinuous pulse width modulation (DPWM), where switching is done only when essential, resulting in lower converter power losses than for the continuous pulse width modulation (CPWM) applied in Sinusoidal pulse width modulation. Discontinuous pulse width modulation, on the other hand, results in diverging switching frequency which makes design of filters complicated [15, 27].

2.6. Losses in Voltage Source Converter (VSC) Components

Higher currents flow in the rotor side converter (RSC) than in the grid side converter (GSC). To lodge the higher currents and make sure equal power device loading, the rotor side converter cell has two parallel power devices for every device in the grid side converter cell. The semiconductor devices have conduction along with switching power losses contributing to thermal losses with corresponding temperature increase. The losses diminish the effectiveness of the Voltage Source Converter and subject the power electronics to thermal cyclic stresses. In sub-synchronous 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 super-synchronous mode.

Thermal cycling can be on:

(a) Long-term base of periods in months or days from environmental disturbances for instance wind speed and ambient temperature distinctions,

(b) Medium-term base of periods in minutes to seconds from speed control to achieve maximum power production or pitch control to limit produced power to rated values,

(c) Short-term base with period ranging beneath one second from fast electrical disturbances for instance grid faults, Voltage Source Converter switching, and load current alternation.

Thermal cycling can be diminished by circulating reactive power inside in the Voltage Source Converter without power factor deformation to the power system. This outcome in diminish thermal stresses on the semiconductor devices hence increasing their life span and dependability. On the other hand, the variety of reactive power available for circulation in the rotor side converter is limited by the generator reactive power capacity while in the grid side converter; it is limited by in cooperation the generator reactive power capacity and the D.C.-link voltage. Augment in converter voltage levels also diminishes thermal losses [15, 28–30].

2.7. Faults

Faults can come from the Doubly Fed Induction Generator Wind Energy Conversion System itself or from the grid it is connected to.

2.7.1. Faults from the Machine

Faults in the doubly fed induction generator wind energy conversion system arise in four main regions.

(i) *Turbine Faults*: These contain rotor blade strikes by lightning, blade fracture because of too much loading from wind squalls or icing in addition to hydraulic system malfunction. A few applied solutions contain lightning rods fitted on the blades in addition to blades designed to stall in high winds in addition to to diminish amount of ice buildup.

(ii) *Gearbox Faults*: Gearbox malfunctions are uncommon, supposed once or twice in the wind energy conversion system life span, but they are the most expensive as they generally engross substitution of the gearbox at around 10 percent of total expenditure of the WECS. Additionally, they cause twice or thrice the down-time for malfunctions by other components [31, 32].

These mechanical malfunctions are because of the following:

i. Manufacturing errors for instance grind temper or material inclusions,
ii. Insufficient or absence of lubrication that causes surface related problems, such as
   (a) Scuffing: the adhesive wear ensuing in detachment and relocate of particles from meshing teeth,
   (b) Micro-pitting: the creation of numerous surface cracks leading to surface fatigue,
iii. Fretting troubles which are from little vibratory motions, especially when the Wind Energy Conversion System is parked [33].

Over-heating of the lubrication oil can, in a few cases, outcome in fires. Accurate and adequate lubrication, with lubricants of high quality and lifespan, coupled with proficient cooling for the lubricant is sufficient to prevent most malfunctions.

(iii) *Generator Fault:* These include
   (a) Open circuit in windings,
   (b) Winding insulation malfunctions leading to inter-turn winding short circuits because of over-heating consequently of overload or unequal heating ensuing from imbalanced voltages [34].

The honesty of the windings and the insulation is sustained by managing operating temperatures throughout current and voltage regulation.

(iv) *PEC Faults:* These include the following:

(a) Semiconductor device failures: these include failure of the IGBTs, diodes, and bond wire connections. The outcome mainly from thermal cycling as the semiconductors switch on and off periodically and unequally. As they are made up of diverse materials, the diverse coefficients of expansion outcome in stresses because of expansion and compression forces [4]. Other faults include IGBT open and short circuits. An open circuit outcomes in fluctuations in both reactive and active power outputs [35, 36]. Insulated-gate bipolar transistor (IGBT) fire-through, where a switch conducts before the time decided by the switching control system, forms an intermittent short circuit that negatively influences the terminal voltage [37].

(b) 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 potentials outcome in active power oscillations which cause potential fluctuations across the capacitor in addition to second-order harmonic currents to flow through it. These hoist the power loss and operating temperature, therefore escalating the electrolytes rate of evaporation and shortening the capacitors' life-span [39].

D.C.-link capacitor breakdown could be open circuit or short circuit. A short circuit fault outcomes in a more harsh effect on generator speed, potential drop at PCC, reactive power absorbed in addition to stator current spike, and oscillations than an open-circuit fault. It makes the D.C.-link potential to collapse, with currents flowing to supply the fault from both converters throughout the free-wheeling diodes. The faults outcome in diminished active power output which drops to zero in case of ineffective fault clearance [21, 40].

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

While gearbox breakdowns outcome in most downtime and price, they are rare, accounting for only 5 percent of malfunctions while PEC failures are most general, accounting for over 50 percent of all cases of Doubly Fed Induction Generator Wind Energy Conversion System failures [4, 41].

2.7.2. Faults from the Power System

Faults from the power system also impact on the Doubly Fed Induction Generator Wind Energy Conversion System (DFIG WECS). They contain voltage sags, potential swells, and frequency fluctuations with voltage sags being more recurrent than swells. Consequently, there is better focus on LVRT than HVRT. The main cause of voltage sags is system faults for instance short-circuits and faults to ground. Other causes contain rapid loss of large generating units, transformers energizing and, switching in of great loads generally induction motors [11, 42–44]. On the other hand, voltage swell for a moment occurs after voltage sag because of switching off of large loads because of the voltage sag, reactive power over-compensation from capacitor banks, or 1-Ø short-term interruptions [45, 46].

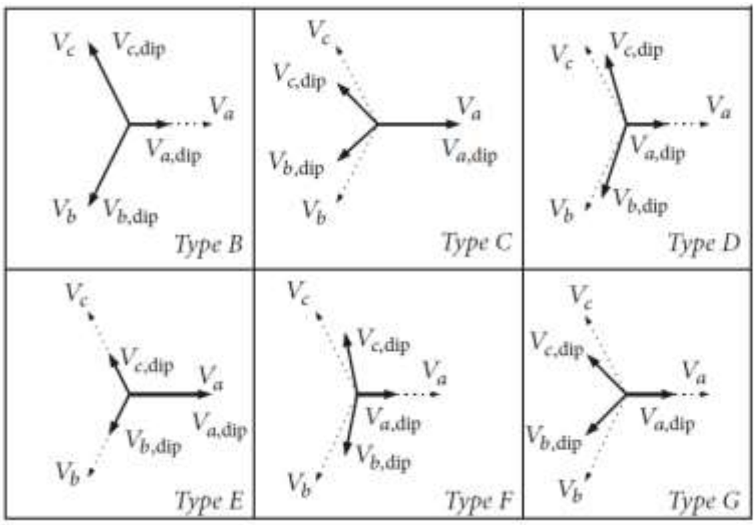

Figure 3: Fault types B to G [6].

(i) *Types of System Faults:* The five kinds or types of system faults encountered by the Doubly Fed Induction Generator Wind Energy Conversion System from the grid fall into two categories [47]:

(a) Balanced/symmetrical faults: these are-
- 3-phase,
- 3-phase to ground.

(b) Unbalanced/asymmetrical faults: these are-
- 2-phase,
- 2-phase to ground,
- 1-phase to ground.

The five kinds of system faults have different percentages of incidence as given next [48]:

Table 1: Types of system faults and percentages of occurrence

Type of fault	***% of total fault occurrence***
One-phase to ground fault	70–85
Two-phase faults	08–15
Two-phase to ground fault	04–10
Three-phase faults	03–05

The five kinds of faults are additional classified into seven kinds, types A–G, and depending on alters on phase-to-neutral potential magnitudes and phase angle jumps if any. These are as follows [47, 49, 50]:

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

(b) 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 potential sag is sensed at the high potential side of the connecting transformer to the PCC. This initiates transformation to the faults ensuing in a different kind of fault being seen at the Double Fed Induction Generator terminals, in a few cases, depending on kind or type of fault and the transformer connection [51, 52]. The ordinary transformer connection types are given in Figure 4.

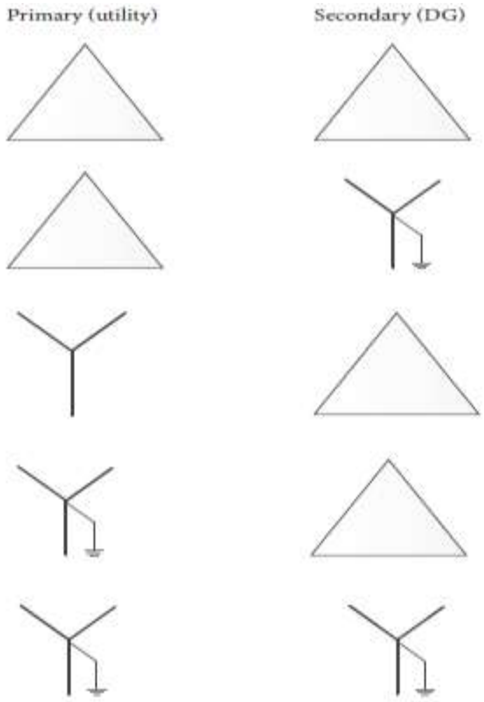

Figure 4: Interconnection transformer connections [7].

The effect of transformers on faults is given in Table 2 [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 potential sag on the generator depends on the following [12]:

1) Type or kind of fault: The fault components to be dealt with depend on the kind or type of fault. 3-phase faults only engage +ve sequence fault-current components with a high-surge value and so are harsher. The 1-Ø to ground and 2-Ø to ground faults initiate -ve and zero sequence components as well as the +ve sequence components. 2-Ø faults have only +ve and -ve sequence components.

   The -ve sequence potentials outcome in high -ve sequence current components that cause double grid frequency oscillations on reactive power, active power, and electro-magnetic torque ensuing in stator winding and drive train life span diminution [7, 13, 47, 54].

Table 2: 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 (3-Ø)	Type A	Type A	Type A	Type A
Single Phase (1-Ø)	Type B	Type C#	Type D#	Type C#
Phase(Ø) to Phase(Ø)	Type C	Type D	Type C	Type D
2-Ø 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}.

The -ve sequence stator flux rotates in reverse direction to the rotor and therefore induces a high frequency component in rotor winding at a frequency given by

$$\omega_e^- = \omega_s + \omega_r \qquad (1)$$

If the terminal potential doesn't drop to zero, then there is also the component induced by the +ve sequence stator flux which rotates at

$$\omega_e^+ = \omega_s - \omega_r \qquad (2)$$

Where ω_s is stator frequency, ω_r is rotor rotational speed, ω_e is frequency of current induced in the rotor by stator's 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 kind or type of fault engages phase-angle jump, it outcomes in higher -ve sequence voltage component and consequently elevated rotor current and D.C.-link voltage [6].

3) Depth of sag: This depends on distance of fault site from the generator terminals. A fault is deemed distant if it outcomes 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 sub-synchronous 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 super-synchronous 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. 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 Doubly Fed Induction Generator (DFIG) has been approached in two different modes:

(i) Approaches that look for to keep the generator running and attached to the grid. This is by:
   (a) Avoiding tripping the machine by keeping monitored parameters, that is, rotor over speed, stator and rotor over currents, and rotor and DC-link overvoltage, within limits;
   (b) Sustaining a healthy potential at the generator terminals irrespective of the fault and post-fault grid potential value.

(ii) Approaches that look for to keep the generator attached so as to offer reactive power to the system at point of common coupling and thus support the voltage.

The above approaches are implemented by one of the following:

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

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

(iii) Addition of new components to the Doubly Fed Induction Generator rotor circuit such as crowbar circuit and series dynamic braking resistor (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 Doubly Fed Induction Generator Connected to the Grid but Not Offering Support to Grid.

This is achieved by use of one or a combination of the following methods:

(i) *Active Crowbar*: An active crowbar contains of semiconductor switches, either insulated-gate bipolar transistor (IGBT) or diodes with resistors. When rotor over current 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 attached, rerouting the high rotor currents through extra crowbar resistances. The augmented rotor circuit resistance causes the high rotor currents to decompose. Once the rotor currents attain a safe level, the crowbar is disabled and the RSC firing pulses are continued [5]. Throughout the period when the active crowbar is activated, the Doubly Fed Induction Generator operates as a wound rotor induction generator (WRIG) with augmented rotor resistance but no control over both reactive and active power outcome and output. Accordingly, reactive power can't be availed for potential support at a time when it is seriously needed. Also, the Doubly Fed Induction Generator when operating as a wound rotor induction generator consumes reactive power, further delaying potential recovery. To evade this, the operation time of the crowbar circuit must be diminished by rising the value of the crowbar resistance.

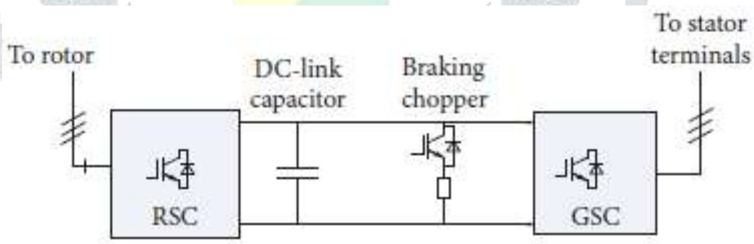

Figure 5: Chopper circuit Power converter [5]

On the other hand, augmenting the crowbar resistance away from a certain point, while diminishing the current decay time, outcomes in high potential at the RSC terminals. These setup a charging current through the RSC diodes and the D.C.-link capacitor which charges-up the capacitor, hoisting the D.C.-link potential. If this potential surpasses the set limits, it can trigger the active crowbar once more after its first deactivation, thus delaying potential recovery, or still the passive crowbar, leading to a machine shut down. As well as the rotor current and D.C.-link potential, the values of the active crowbar resistances also influence the rotor speed and the reactive and active powers when the crowbar is active. The accurate value of crowbar resistance is thus serious.

(ii) *Braking Chopper Circuit*: It contains of an insulated-gate bipolar transistor (IGBT) with a snubber capacitor and a chopper resistor and is attached in parallel with the D.C.-link capacitor. It assists in keeping the D.C. bus potential under the given limits during times when the active crowbar can't control the potential all by itself. A braking chopper dissipates surplus power in the D.C. 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 over current, rotor overvoltage, stator over current, DC-link overvoltage, and rotor over speed [59–61].

(iii) *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 D.C. bus. The Energy Storage System stores the surplus power and so evades a D.C.-link over voltage. The energy so stored is later released through the grid side converter to the power system when normal potential is reinstated thus helping get better the power quality [13].

(iv) *Series Dynamic Braking Resistor (SDBR)*: Series Dynamic Braking Resistor contains of a set of 3-phase resistors attached across the 3-phases of either the stator circuit or the rotor circuit amid the rotor and the Power Electronic Converter. A bypass switch remains the resistors out of the circuit during regular process and opens to place in them into the circuit throughout fault conditions. The resistors initiate a potential divider action ensuring that the generator sees the regular potential at its terminals. Simultaneously, the added resistance diminishes fault currents. The resistors also disperse part of the generated power thus evading rotor over speed. A low value of the resistance, in addition to its fast inclusion once fault happens and for a short duration as probable, leads to get better Doubly Fed Induction Generator stability [13, 63–66].

(v) *Dynamic Voltage Restorer (DVR)*: A Dynamic Voltage Restorer is applied in series with the stator to sustain stator terminal potential at nominal values once fault is spotted. The Doubly Fed Induction Generator generates active power albeit at diminished level since Maximum power point tracking is disabled. Since the export of power to the grid is restrained, the Dynamic Voltage Restorer absorbs and accumulates or dissipates the dissimilarity between power produced by generator and power exported to grid. The power can be dispersed in its braking resistance [67, 68].

(vi) *Superconducting Magnetic Energy Storage (SMES)*: A Superconducting Magnetic Energy Storage is attached to the Point of Common Coupling just like FACTS devices to store energy under normal operating or high voltage conditions. The energy so accumulated is afterward released to the point of common coupling when grid energy goes down due to a fault hence maintaining the voltage at point of common coupling. The Doubly Fed Induction Generator thus does not experience the fault [69].

(vii) *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.

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

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].

(viii) *Virtual Resistance/Inductance:* In an approach alike to the series grid side passive impedance networks, a virtual resistance is initiated in the equivalent rotor circuit using a Low Voltage Ride-Through (LVRT) controller to diminish rotor fault currents and its decay time whereas a virtual inductance augments the leakage inductance of the rotor circuit with analogous outcomes. Torque oscillations are also diminished in both approaches [71, 72].

(ix) *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 attain the essential current to sustain control, temporary overloading of the RSC devices to 200% is allowed [73].

(x) *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 worth of the factor depends on the fault potential magnitude [74].

(xi) *Series Grid Side Converter (SGSC)*. A Series Grid Side Converter is attached to the D.C. bus as well as the parallel GSC as given away in Figure 6. It is utilized to remove the -ve sequence stator voltage, ensuring balanced stator terminal potentials even under grid network potential imbalance [8].

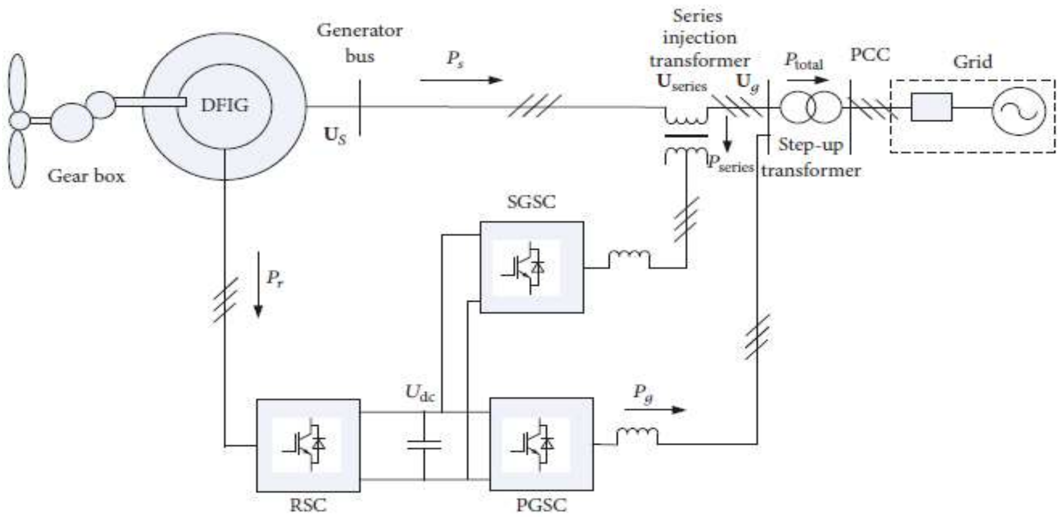

Figure 6: Configuration of a Doubly Fed Induction Generator with SGSC [8]

3.2. Keeping the DFIG Attached to Grid While Offering Support to Grid

Potential control can also be attained by reactive power injection.

3.2.1. From External Devices

FACTS devices are attached at the point of common coupling to insert or absorb reactive current to keep potential inside the prescribed operational limits. They can be attached in either shunt (STATCOM, SVC) or series (DVR), or hybrid manner (UPFC). This initiates the added price of the FACTS device, maintenance prices, diminished reliability, and added control intricacy [9, 66, 75–77]. Figure 7 gives an example of a STATCOM connection.

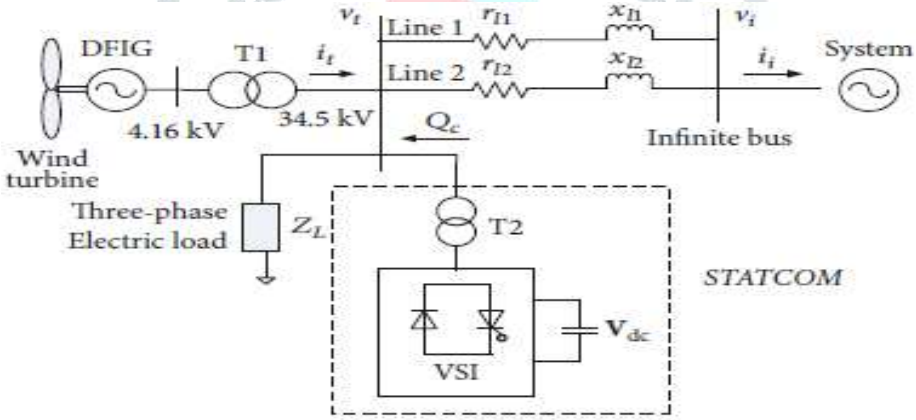

Figure 7: Single line diagram of STATCOM connection for reactive power compensation [9]

3.2.2. From DFIG

The added price of the Flexible Alternating Current Transmission System (FACTS) device can be evaded by utilizing the Doubly Fed Induction Generator reactive power capacity. On fault occurrence, the reactive power output of the Doubly Fed Induction Generator is given priority [78].The reactive power output of the DFIG can be a total of up to 75 percent of its active power rating with around 20 percent of the active power rating being from the GSC [75]. This ability depends on rated rotor potential and rated stator current limit and current limits [79, 80]. As well as the aforesaid, the GSC reactive power ability must be considered [81]. Total reactive power generation is limited by rotor current whereas expenditure is limited by stator current. For large slips, >0.31, reactive power generation is also limited by rotor potential. There also are limitations inflicted by magnetic flux saturation and the non-linear relation-ships amid junction temperature and rotor currents frequency [82].

Most grid codes necessitate that the power factor at the point of common coupling must be amid 0.9 lagging and 0.95 leading. This cannot be met with Doubly Fed Induction Generator 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, augmenting the rating of the VSC comes at an added price because of the augmented rating [84]. Additional approaches that evade the augment in price include the following:

(i) Since the generator rated power at super-synchronous speed is the sum of stator power and rotor power [85], at a certain point, to avoid exceeding rated power, the stator power has to diminish as the rotor power augments. At rated power, the stator supplies 0.7–0.8 p.u. while rotor produces 0.2–0.3 p.u [82]. This outcome in ability which can be employed for generating reactive power from the stator if the rating of the wind turbine is higher than that of the alternator or generator.

$$P_{Tot} = P_s + P_r \quad (4)$$

(ii) Also, further Doubly Fed Induction Generator reactive power store capacity can be guaranteed by linking at the Point of Common Coupling (PCC), Flexible Alternating Current Transmission System (FACTS) devices for instance mechanically switched capacitors, whose rating is just adequate to guarantee that the VSC inserts a maximum of 10% of their rated reactive power capacity during steady state system process. The preserve is then availed for the period of transient states [86] while the price of FACTS devices is reduced.

(iii) Additionally, while worst case situations consider the fully loaded Doubly Fed Induction Generator at nominal active power outcome, it is only at 10 percent of the time that it supplies above 90 percent of this worth. This gives extra capacity for reactive power production [85].

(iv) With provisionally overloading of the converter's current outputs, but within manufacturers' limits, the IGBTs can switch up to 100 percent more current than the steady state rated current so long as it is processing inside the safe operating area (SOA). This is generally given for a short period of time typically 20 micro seconds. As such, both RSC currents can be increased, thus increasing the active power, hence controlling rotor over speed, while the increased GSC current ensures that active power is not sacrificed and so avoids DC-link overvoltage. The additional current capacity is employed for reactive power generation, therefore boosting total reactive power generation from the Doubly Fed Induction Generator [55, 87].

(v) 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].

(vi) 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/under voltage [78]. This is serious when these comprise other generators without FRT. To make sure reactive power output or outcome from the stator, RSC control must not be gone during the fault period or duration.

4. Discussion

Most of confronts ensuing from the machine can be dealt with at manufacturing stage, whereas suitable and timely maintenance can deal with others. The option of a suitable control policy is also serious. The control system must strive to remain the thermal loading inside limits and also diminish the thermal variations to make sure long lifetime duration especially for the electronic parts. For price efficacy, the Doubly Fed Induction Generator Wind Energy Conversion System must be employed for reactive power supply during both transient states and steady especially for faults from the power system. As such, the Maximum Power Point Tracking (MPPT) and control policies must incorporate this. On the other hand, coordination amid the Maximum Power Point Tracking (MPPT) policy and control policy is a must if better profits for instance diminution of component count is to be attained. For instance, the use of a Maximum Power Point Tracking (MPPT) policy that necessitates a speed sensor minimizes the positive impact of a control policy that doesn't utilize the speed sensor and vice versa.

Because of the complicated interaction amid the stator and rotor circuits by magnetic flux, move towards for FRT that don't get in the way with the internal set-up of the Doubly Fed Induction Generator Wind Energy Conversion System seem attractive. The result must though be machine based and not at the wind farm terminals. This is as necessitated by some grid codes for instance GB 19963-2011 since FRT capability is decided based on individual machines and not on the whole wind farm. These approaches comprise use of Series Dynamic Braking Resistor and dynamic voltage restorer on the stator circuit. However, the switching out and in of the stator side of Series Dynamic Braking Resistor and dynamic voltage restorer initiates switching transients as the stator circuit carries a huge 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. Prospect efforts are supposed to look at diminution of switching transients where Series Dynamic Braking Resistor and dynamic voltage restorer 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 systems are presented. Several approaches employed to date to deal with these confronts have been explored with various Maximum Power Point Tracking (MPPT) and control policies being presented. The research paper has brought out matters to consider for an optimal result which must coordinate the Maximum Power Point Tracking (MPPT) and control policies and integrate FRT capabilities so as to gratify the ever stringent grid connection codes.

References

[1] http://www.wwindea.org/wwea-half-year-report-worldwindwind-capacity-reached-456-gw.

[2] K. E. Okedu and U. Roland, "Low voltage ride–through methods for DFIG VSWT," *Journal of Emerging Trends in Engineering and Applied Sciences*, vol. 5, no. 8, pp. 221–226, 2014.

[3] D. A. Rivkin, L. D. Anderson, and L. Silk, *Wind Turbine Control Systems*, Jones Bartlett Learning, USA, 2013.

[4] F. Blaabjerg, M. Liserre, and K. Ma, "Power electronics converters for wind turbine systems," *IEEE Transactions on Industry Applications*, vol. 48, no. 2, pp. 708–719, 2012.

[5] Ingeteam, "Power converter training manual," http://www.ingeteam.com/, 2014.

[6] M. Mohseni, S. M. Islam, and M. A. S. Masoum, "Impacts of symmetrical and asymmetrical voltage sags on DFIG–based wind turbines considering phase–angle jump, voltage recovery, and sag parameters," *IEEE Transactions on Power Electronics*, vol. 26, no. 5, pp. 1587–1598, 2011.

[7] V. P. Mahadanaarachchi, *Fault analysis and protection of doubly fed induction generator–based wind farms, [MSc. thesis]*, Oklahoma State University, 2009.

[8] J. Yao, H. Li, Z. Chen et al., "Enhanced control of a DFIG-based wind-power generation system with series grid-side converter under unbalanced grid voltage conditions," *IEEE Transactions on Power Electronics*, vol. 28, no. 7, pp. 3167–3181, 2013.

[9] W. Qiao, G. K. Venayagamoorthy, and R. G. Harley, "Real–time implementation of a STATCOM on a wind farm equipped with doubly fed induction generators," *IEEE Transactions on Industry Applications*, vol. 45, no. 1, pp. 98–107, 2009.

[10] S. M. R. Kazmi, H. Goto, H.-J. Guo, and O. Ichinokura, "Review and critical analysis of the research papers published till date on maximum power point tracking in wind energy conversion system," in *Proceedings of the 2010 2nd IEEE Energy Conversion Congress and Exposition, ECCE 2010*, pp. 4075–4082, September 2010.

[11] M. A. Abdullah, A. H. M. Yatim, C. W. Tan, and R. Saidur, "A review of maximum power point tracking algorithms for wind energy systems," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 5, pp. 3220–3227, 2012.

[12] B. Wu, Y. Lang, N. Zargari, and S. Kouro, *Power Conversion And Control of Wind Energy Systems*, John Wiley Sons, Inc, New Jersey, NJ, USA, 2011.

[13] O. P. Mahela and A. G. Shaik, "Comprehensive overview of grid inter faced wind energy generation systems," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 260–281, 2016.

[14] B. R Uckert and W. Hofmann, "Commutation strategy for minimized common mode voltage using direct power control," in *Proceedings of the 27thAnnual IEEE Applied Power Electronics Conference and Exposition (APEC '12)*, pp. 106–112, February 2012.

[15] M. Z. Sujod, "Harmonics and common mode voltage in a DFIG with two–level and three–level NPC converter using standard PWM techniques," in *Proceedings of the 39th Annual Conference of the IEEE Industrial Electronics Society (IECON '13)*, pp. 1650–1655, November 2013.

[16] A. M. Garcia, D. G. Holmes, and T. A. Lipo, "Reduction of bearing currents in doubly fed induction generators," in *Proceedings of The 41st IAS Annual Meeting Conference of the IEEE*, pp. 84–89, October 2006.

[17] S. O. Faried, I. Unal, D. Rai, and J. Mahseredjian, "Utilizing DFIG–based wind farms for damping sub-synchronous resonance in nearby turbine–generators," *IEEE Transactions on Power Systems*, vol. 28, no. 1, pp. 452–459, 2012.

[18] C. Zhu, M. Hu, and Z. Wu, "Parameters impact on the performance of a double–fed induction generator–based wind turbine for sub-synchronous resonance control," *IET Renewable Power Generation*, vol. 6, no. 2, pp. 92–98, 2012.

[19] L. Fan and Z. Miao, "Mitigating SSR using DFIG–based wind generation," *IEEE Transactions on Sustainable Energy*, vol. 3, no. 3, pp. 349–358, 2012.

[20] D. Muthumuni, "Investigating possible induction generator effects due to sub–synchronous resonances," https://hvdc.ca/uploads/ck/files/Application_Note_-_Investigating_Possible_Induction_Generator_Effects_Due_to_SSR_-no_background_colour.pdf

[21] S. Heir, *Grid Integration of Wind Energy Conversion Systems*, John Wiley Sons Ltd, 2nd edition, 2006.

[22] P. Zhan, W. Lin, J. Wen, M. Yao, and N. Li, "Design of LCL filters for the back–to–back converter in a doubly fed induction generator," in *Proceedings of the 2012 IEEE Innovative Smart Grid Technologies - Asia, ISGT Asia*, pp. 1–6,May 2012.

[23] F. K. A. Lima, M. A. N. Nunes, E. E. C. Morais, J. L.Dantas, and C. G. C. Branco, "A new proposal for DFIG grid–side converter as double-tuned hybrid filter to improve the power quality," in *Proceedings of the 39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013*, pp. 1472–1477,November 2013.

[24] N. P. Gupta, P. Gupta, and D. Masand, "Power quality improvement using hybrid active power filter for a DFIG based wind energy conversion system," in *Proceedings of the 3rd Nirma University International Conference on Engineering (NUiCONE'12)*, pp. 1–6, December 2012.

[25] B. Singh, K. Al-Haddad, and A. Chandra, "A review of active filters for power quality improvement," *IEEE Transactions on Industrial Electronics*, vol. 46, no. 5, pp. 960–971, 1999.

[26] M. Boutoubat, L. Mokrani, and M. Machmoum, "Control of a wind energy conversion system equipped by a DFIG for active power generation and power quality improvement," *Renewable Energy*, vol. 50, pp. 378–386, 2013.

[27] A. Mudlapur, A. Raju, and U. Rao, "Evaluation of different PWM techniques for two level inverter in grid connected WECS," in *Proceedings of the 2013 2nd International Conference on Advances in Computing, Communications and Informatics (ICACCI '13)*, pp. 1753–1758,August 2013.

[28] D. Zhou, F. Blaabjerg, M. Lau, and M. Tonnes, “Thermal behavior optimization in multi-MW wind power converter by reactive power circulation,” *IEEE Transactions on Industry Applications*, vol. 50, no. 1, pp. 433–440, 2014.
[29] J. Zhang, G. Chen, and X. Cai, “Thermal smooth control for Multi–MW parallel wind power converter,” in *Proceedings of the 2013 IEEE International Conference of IEEE Region 10 (TENCON ’13)*, pp. 1–4,October 2013.
[30] K. Ma, M. Liserre, F. Blaabjerg, and T. Kerekes, “Thermal loading and lifetime estimation for power device considering mission profiles in wind power converter,” *IEEE Transactions on Power Electronics*, vol. 30, no. 2, pp. 590–602, 2015.
[31] J. Puigcorbe and A. De-Beaumont, “Wind Turbine Gearbox Reliability: the impact of rotor support, 2010,” http://www.renewableenergyworld.com/articles/print/volume-13/issue-3/wind-power/wind-turbine-gearbox-reliability.html.
[32] A. M. Ragheb and M. Ragheb, “Wind Turbine Gearbox Technologies, 2011,” http://www.intechopen.com/books/ fundamental-and-advancedtopics-in-wind-power.
[33] Wind Power Engineering [Online], http://www.windpowerengineering. com/design/mechanical/gearboxes/gears-gearboxes-101/.
[34] W. Qiao and R. G. Harley, “Improved control of DFIG wind turbines for operation with unbalanced network voltages,” in *Proceedings of the 2008 IEEE Industry Applications Society Annual Meeting (IAS ’08)*, pp. 1–7, October 2008.
[35] S. Karimi, A. Gaillard, P. Poure, and S. Saadate, “FPGA–based real–time power converter failure diagnosis for wind energy conversion systems,” *IEEE Transactions on Industrial Electronics*, vol. 55, no. 12, pp. 4299–4308, 2008.
[36] M. Shahbazi, M. R. Zolghadri, P. Poure, and S. Saadate, “Wind energy conversion system based on DFIG with open switch fault tolerant six–legs AC-DC–AC converter,” in *Proceedings of the 2013 IEEE International Conference on Industrial Technology (ICIT ’13)*, pp. 1656–1661, February 2013.
[37] A. F. Abdou, A. Abu-Siada, and H. R. Pota, “Application of STATCOM to improve the LVRT of DFIG during RSC fire–through fault,” in *Proceedings of the 2012 22nd Australasian Universities Power Engineering Conference: “Green Smart Grid Systems” (AUPEC ’12)*, pp. 1–6, September 2012.
[38] E. Giraldo and A. Garces, “An adaptive control strategy for a wind energy conversion system based on PWM-CSC and PMSG,” *IEEE Transactions on Power Systems*, vol. 29, no. 3, pp. 1446–1453, 2014.
[39] C. Liu, D. Xu, N. Zhu, F. Blaabjerg, and M. Chen, “DC–voltage fluctuation elimination through a DC–capacitor current control for DFIG converters under unbalanced grid voltage conditions,” *IEEE Transactions on Power Electronics*, vol. 28, no. 7, pp. 3206–3218, 2013.
[40] A. M. S. Yunus, A. Abu-Siada, and M. A. S. Masoum, “Impact of DC-link fault on the dynamic performance of DFIG,” in *Proceedings of the 2012 IEEE Power and Energy Society General Meeting, (PES ’12)*, pp. 1–6, July 2012.
[41] A. Bonanomi, “Powerful analysis of wind turbine gearboxes, 2014,” http://www.powertransmissionworld.com/ powerful-analysis-of-wind-turbine-gearboxes/.
[42] N. Cherfia, D. Kerdoun, and A. Boumassata, “Sliding mode control indirect strategy of the active and reactive power for the wind turbine DFIG,” in *Proceedings of the Conference International des Energies Renewables (CIER ’13)*, Sousse, Tunisie, 2013.
[43] D. Zhiyong and L. Wei, “Adaptive estimation of three–phase grid voltage parameters under unbalanced faults and harmonic disturbances,” *IEEE Transactions on Power Electronics*, vol. 32, no. 7, pp. 5613–5627, 2017.
[44] Z. Dai, W. Lin, and H. Lin, “Estimation of single–phase grid voltage parameters with zero steady–state error,” *IEEE Transactions on Power Electronics*, vol. 31, no. 5, pp. 3867–3879, 2016.
[45] Z. Zheng, G. Yang, and H. Geng, “High voltage ride–through control strategy of grid-side converter for DFIG–based WECS,” in *Proceedings of the 39th Annual Conference of the IEEE Industrial Electronics Society (IECON ’13)*, pp. 5282–5287, November 2013.
[46] C. Feltes, S. Engelhardt, J. Kretschmann, J. Fortmann, F. Koch, and I. Erlich, “High voltage ride-through of DFIG-based wind turbines,” in *Proceedings of the IEEE Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21stCentury*, pp. 1–8, IEEE, Pittsburgh, Pa, USA, July 2008.
[47] A. Rolan, J. Pedra, and F. C´orcoles, “Detailed study of DFIG based wind turbines to overcome the most severe grid faults,” *International Journal of Electrical Power and Energy Systems*, vol. 62, pp. 868–878, 2014.
[48] A. Yousef, *Wind turbines level energy storage for low voltage ride through (LVRT) support, [MSc. thesis]*, The University of Wisconsin, Milwaukee, Wis, USA, 2012.
[49] M. H. J. Bollen, *Understanding Power Quality Problems: Voltage Sags And Interruptions*, IEEE Press, New York, NY, USA, 2000.
[50] R. Prasad, *Low voltage ride–through capability for matrix converters fed adjustable–speed induction machine drives for industrial and wind appliances [Ph.D. thesis]*, University of Minnesota, Minnesota, Minn, USA, 2011.
[51] G. Abad, J. Lopez, M. Rodriguez, L. Marroyo, and G. Iwanski, *Doubly Fed Induction Machine: Modeling and Control for Wind Energy Generation*, John Wiley & Sons, 2011.
[52] R. Teodorescu,M. Liserre, andP. Rodriquez, *Grid Converters for Photovoltaic and Wind Power systems*, John Wiley & Sons Ltd, 2011.
[53] A. RolAn, F. COrcoles, and J. Pedra, “Doubly fed induction generator subject to symmetrical voltage sags,” *IEEE Transactions on Energy Conversion*, vol. 26, no. 4, pp. 1219–1229, 2011.
[54] J. J. Justo, F. Mwasilu, and J.-W. Jung, “Doubly-fed induction generator based wind turbines: a comprehensive review of fault ride–through strategies,” *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 447–467, 2015.
[55] J.Morneau, *A comparative evaluation of low voltage ride through solutions in wind turbines using doubly fed induction generators, [MSc. thesis]*, McGill University, Montreal, Canada, 2008.
[56] G. JoOs, “Wind turbine generator low voltage ride through requirements and solutions,” in *Proceedings of the IEEE Power and Energy Society 2008 General Meeting: Conversion and Delivery of Electrical Energy in the 21st Century*, pp. 1–7, July 2008.

[57] Y. M. Alsmadi, L. Xu, F. Blaabjerg, A. P. Ortega, and A. Wang, "Comprehensive analysis of the dynamic behavior of grid–connected DFIG-based wind turbines under LVRT conditions," in *Proceedings of the 7th Annual IEEE Energy Conversion Congress and Exposition, (ECCE '15)*, pp. 4178–4187, September 2015.
[58] D. Campos-Gaona, E. L. Moreno-Goytia, and O. Anaya-Lara, "Fault ride–through improvement of DFIG-WT by integrating a two–degrees–of–freedom internal model control," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 3, pp. 1133–1145, 2013.
[59] K. E. Okedu, *Low Voltage Ride through Enhancement of Grid Connected Wind Farms: Augmentation of Variable Speed Wind Turbines Fault Ride through (FRT) Capability*, LAP Lambert Academic Publishing, 2012.
[60] V. Akhmatov, "Variable–speed wind turbines with doubly–fed induction generators Part IV: uninterrupted operation features at grid faults with converter control coordination," *Wind Engineering*, vol. 27, no. 6, pp. 519–529, 2003.
[61] V. Akhmatov, "Variable–speed wind turbines with doubly–fed induction generators part III: model with the back–to–back converters,"*Wind Engineering*, vol. 27, no. 2, pp. 79–91, 2003.
[62] Ch. Laxmi, K. S. Latha, and Dr. Himani, "Improving the low voltage ride through capability of wind generator system using crowbar and battery energy storage system," *International Journal of Engineering Science Invention*, vol. 1, no. 7, pp. 14–19, 2013.
[63] Q. Liu, L. Yu, and G. Wu, "Comparison of control strategy for double–fed induction generator (DFIG)," in *Proceedings of the 3rd International Conference on Measuring Technology and Mechatronics Automation*, pp. 741–744, January 2011.
[64] K. E. Okedu, S. M. Muyeen, R. Takahashi, and J. Tamura, "Application of SDBR with DFIG to augment wind farm fault ride through," in *Proceedings of the 2011 International Conference on Electrical Machines and Systems, (ICEMS '11)*, August 2011.
[65] K. E.Okedu, S.M.Muyeen, R. Takahashi, and J.Tamura, "Effectiveness of current-controlled voltage source converter excited doubly fed induction generator for wind farm stabilization," *Electric Power Components and Systems*, vol. 40, no. 5, pp. 556–574, 2012.
[66] M. Nasiri, J. Milimonfared, and S. H. Fathi, "A review of low–voltage ride–through enhancement methods for permanent magnet synchronous generator based wind turbines," *Renewable and Sustainable Energy Reviews*, vol. 47, pp. 399–415, 2015.
[67] A. O. Ibrahim, T. H. Nguyen, D.-C. Lee, and S.-C. Kim, "A fault ride–through technique of DFIG wind turbine systems using dynamic voltage restorers," *IEEE Transactions on Energy Conversion*, vol. 26, no. 3, pp. 871–882, 2011.
[68] A.Moghadasi, A. Sarwat, and J. M.Guerrero, "A comprehensive review of low–voltage–ride–through methods for fixed–speed wind power generators," *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 823–839, 2016.
[69] A. M. S. Yunus, M. A. S. Masoum, and A. Abu-Siada, "Application of SMES to enhance the dynamic performance of DFIG during voltage sag and swell," *IEEE Transactions on Applied Superconductivity*, vol. 22, no. 4, 2012.
[70] X. Yan, G. Venkataramanan, P. S. Flannery, Y. Wang, Q. Dong, and B. Zhang, "Voltage–sag tolerance of DFIG wind turbine with a series grid side passive–impedance network," *IEEE Transactions on Energy Conversion*, vol. 25, no. 4, pp. 1048–1056, 2010.
[71] S. Hu, X. Lin, Y. Kang, and X. Zou, "An improved low–voltage ride–through control strategy of doubly fed induction generator during grid faults," *IEEE Transactions on Power Electronics*, vol. 26, no. 12, pp. 3653–3665, 2011.
[72] D. Zhu, X. Zou, Y. Kang, L. Deng, and Q. Huang, "Inductance–simulating control for DFIG–based wind turbine to ride–through grid faults," in *Proceedings of the 31st Annual IEEE Applied Power Electronics Conference and Exposition, (APEC '16)*, pp. 3521–3525,March 2016.
[73] D. Xiang, L. Ran, P. J. Tavner, and S. Yang, "Control of a doubly fed induction generator in a wind turbine during grid fault ride–through," *IEEE Transactions on Energy Conversion*, vol. 21, no. 3, pp. 652–662, 2006.
[74] K. E. Okedu, S. M.Muyeen, R. Takahashi, and J. Tamura, "Wind farms fault ride through using DFIG with new protection scheme," *IEEE Transactions on Sustainable Energy*, vol. 3, no. 2, pp. 242–254, 2012.
[75] K. E. Okedu, "A Study of wind farm stabilization using DFIG or STATCOM considering grid requirements," *Journal of Engineering Science and Technology Review*, vol. 3, no. 1, pp. 200–209, 2010.
[76] A. J. Prabhakar, *Application of STATCOM for improved dynamic performance of wind farms in a power grid, [MSc. thesis]*, Missouri University of Science and Technology, 2008.
[77] K. R. Padiyar, *FACTS Controllers in Power Transmission And Distribution*, New Age International Publishers, New Delhi, India, 2007.
[78] S. Foster, L. Xu, and B. Fox, "Coordinated reactive power control for facilitating fault ride through of doubly fed induction generator-and fixed speed induction generator–based wind farms," *IET Renewable Power Generation*, vol. 4, no. 2, pp. 128–138, 2010.
[79] S. N. Singh, J. Otergaard, and B. Singh, "Reactive power capability of unified DFIG for wind power generation," in *Proceedings of the IEEE PES General Meeting, (PES '10)*, pp. 1–7, July 2010.
[80] J. Zhao, X. Li, J. Hao, and J. Lu, "Reactive power control of wind farm made up with doubly fed induction generators in distribution system," *Electric Power Systems Research*, vol. 80, no. 6, pp. 698–706, 2010.
[81] J. Tian, C. Su, and Z. Chen, "Reactive power capability of the wind turbine with Doubly Fed Induction Generator," in *Proceedings of the 39th Annual Conference of the IEEE Industrial Electronics Society, (IECON '13)*, pp. 5312–5317,November 2013.
[82] S. Engelhardt, I. Erlich, C. Feltes, J. Kretschmann, and F. Shewarega, "Reactive power capability of wind turbines based on doubly fed induction generators," *IEEE Transactions on Energy Conversion*, vol. 26, no. 1, pp. 364–372, 2011.
[83] A. M. Kassem, K. M. Hasaneen, and A. M. Yousef, "Dynamic modeling and robust power control of DFIG driven by wind turbine at infinite grid," *International Journal of Electrical Power and Energy Systems*, vol. 44, no. 1, pp. 375–382, 2013.

[84] K. E. Okedu, "Impact of power converter size on variable speed wind turbine," *Pacific Journal of Science and Technology*, vol. 13, no. 1, pp. 176–181, 2012.
[85] B. Pokharel, *Modeling, control and analysis of a doubly fed induction generator based wind turbine system with voltage regulation, [MSc. thesis]*, Tennessee Technological University, 2011.
[86] J. M. Garcia, *Voltage control in wind power plants with doubly fed generators [Ph.D. thesis]*, Aalborg University, 2010.
[87] M.Mohseni and S. M. Islam, "Transient control of DFIG-based wind power plants in compliance with the Australian grid code," *IEEE Transactions on Power Electronics*, vol. 27, no. 6, pp. 2813–2824, 2012.
[88] S. Sharma, J. P. Mishra, and S. Datta, "Sliding mode power control of a DFIG based variable speed wind energy conversion system," in *Proceedings of the 2015Annual IEEE India Conference (INDICON)*, pp. 1–6, New Delhi, India, December 2015.