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MODERN CONTROL ASPECTS IN DOUBLY FED INDUCTION GENERATOR BASED POWER SYSTEMS: A REVIEW

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ABSTRACT: Doubly fed induction generators (DFIG) based wind turbine is an emerging technology, which becomes increasingly popular due to its various advantages over fixed speed generator systems. A DFIG based wind turbine has an ability to generate maximum power with varying and adjustable speed, ability to control active and reactive power by the integration of electronic power converters, low power rating of cost converter components, and so on. This study presents an overview and literature survey over past few decades on the different problems associated due to penetration of WT-DFIG in the power system and control aspects of DFIG.

Keywords: DFIG, Battery Storage System, Wind Turbine

I.INTRODUCTION

World's largest sum of electricity generation contributed by non-renewable sources of fuel such as coal, gas and oil. These fuels emit lots of CO2 other harmful gases to the atmosphere and their residues in the water, which raised global warming issues of earth health problems of human and wild-life issues[7]. According to FatihBirol, Chief Economist, International Energy Agency of the Organisation for Economic Cooperation and Development (IEA), world electricity demand is projected to double between 2000 and 2030, growing at an annual rate of 2.4%. This is faster than any other energy demand. Total share of electric energy consumption rises from 18% in 2000 to 22% in 2030. Electricity demand growth is strongest in developing countries, where demand will climb by over 4% per year over the projected period, which gets more than triple by 2030. Consequently, the electric energy demand in developing countries will rise global electricity share from 27% in 2000 to 43% in 2030[2]. Non-renewable resources also depreciating in reserve each year and not long-lasting. Their purchasing cost increasing day by day and it would become unaffordable to developing countries. So, these countries have to face unbalance between demand and blackouts. Some developed countries also have faced some blackouts in the past. This harms drastically their economy. Hence cost, availability and environmental pollution and health issues become the limiting factor for these fuels. No, doubt we can go for nuclear fusion (H+H =He + abundant source of energy but nobody knows when we able control it?) and nuclear fission (Pl and Uranium on splits as chain reaction gives a large amount of heat energy and harmful radiating residues which is the major cause of health problems for any country as already faced by Japan and Russia) .The earth disturbances, human population and atmospheric are still limiting factors for nuclear fission. In present scenario to cope up the demand of electricity, we must have to divert for another solution. So, solution of this critical situation would be provided by the natural resources. These resources characterized as renewable energy resources such as Wind, solar, hydro, Geo and Bio-gas. In past few decades there is a lot of research findings to capture these energies and new technologies being listed by researches [1-3]. Out of these resources wind energy conversion systems (WECS) becomes so much popular in the world. There are some other limiting factors related to other natural resources such as for solar energy costlier solar cell and long-lasting storage battery technologies, required large area for 1MW plant ,maintenance problems after atmospheric conditions and need more man power. Secondly, hot air fed turbine technologies based power plants based on solar energy constrained by atmospheric conditions, availability of day light and need to keep up large amount of hot sand reserve at night. Other natural resources and their limiting factors are as follows:

- A biomass plant emits harmful gases during energy conversion and it takes more energy to harvest biomass crops than it ever produces after.
- Hydropower dams can damage the surrounding aquatic ecosystem and can permanently alter some species' behavior. Also, a siltation can permanently damage the dam and leave it non-operational.
- For Geothermal costs of drilling are extremely high and choice of a good site would take a lot of time.

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Out of the above natural sources wind energy conversion systems include less conversion equipment, land need, less maintenance, direct coupling of wind turbine to generator shaft. There So many WECS technologies available classified as: fixed speed and variable speed WECS. Fixed speed employed Squirrel Cage Induction Generator(SCIG) as mechanical to electricity conversion element with soft starter technology simple to construct but may affect steady state stability of power system under unbalanced conditions such as gust in wind, voltage dip in the bus bar voltage , and Need a stiff power grid and not tolerated by weak Grid [1-6].Variable speed WECS employed mainly two technologies such as SCIG in which Capacitor bank and soft-starter are replaced by a full scale converter. It requires 100% rating of power stability equipment (FACTS for power factor correction) as that of generator rating. It gives still less effective steady state stability measures as constrained by high cost of converter[1,4,5]. Second technology of variable WECS is Doubly Fed Induction Generator (DFIG) based wind power to electricity conversion element as shown in fig. 1. This technology becomes so much popular and opted by maximum number of countries in the world. There are following advantages listed for DFIG based WECS [4-6]:

- Converter system provides reactive power compensation and smooth grid integration.
- The market shareof DFIG systems (75%) many times the any other types of WECS.
- Around 86% patents are on controlling of DFIG. Woodward filed 10 patent applications in the same field in year 2010, as it has no previous record of Intellectual Property activity.
- Converter Rating is only 25%-30% inDFIG as compared to 100 % of total nominal power of the generator.
- Stator feeds the remaining 70%-75% of total power directly into the grid.
- Wider range of variable speed of approximately ± 30% around synchronous speed.

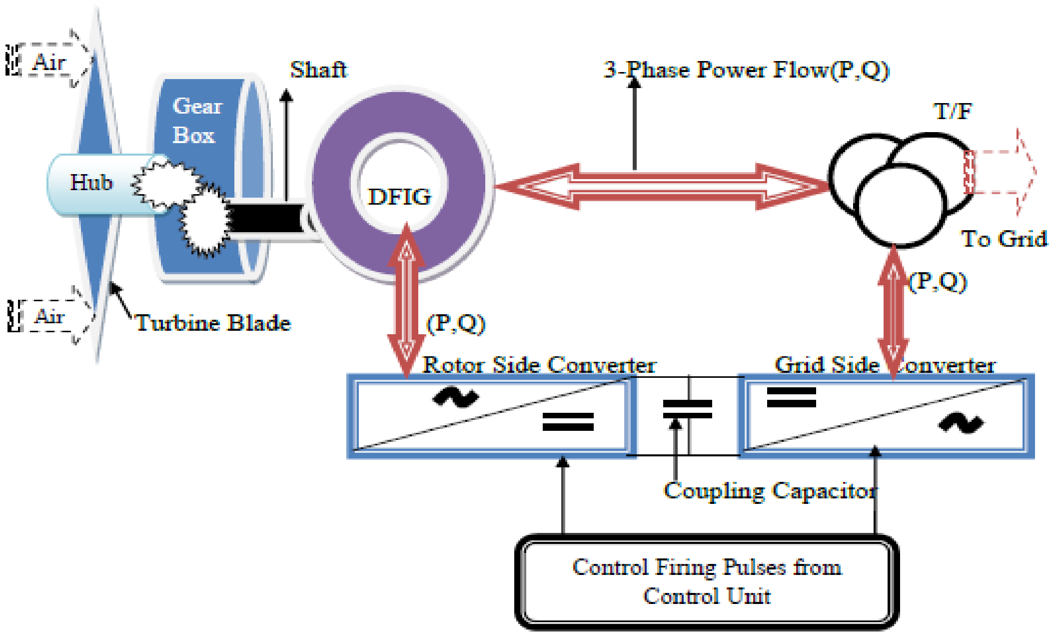

Fig. 1DFIG with power converter.

In the present scenario due to penetration of large number of DFIG based WECS and interconnection to main grids gives rise to new steady state stability challenges for the researchers and scientists due to some power regulating issues under unbalance conditions such as Voltage sags or faults which occur in the network makes performance poor, fault ride-through(FRT), Low voltage ride through (LVRT) capabilities of DFIGWTs under transient periods, Inter area oscillations in long distance transmission to keep up constant output power to grid and to extract maximum power from continually fluctuating power, Sub-synchronous resonance (SSR) occurred in series compensated electrical networks becomes new area of research with DFIGWTs connected to series compensated networks, Large oscillations of the DC-link voltage cannot be avoided as the grid side converter controller was not optimized, Suitable choice of Insulated gate bipolar transistor (IGBT for converter equipment) thermal impedances, Small-Signal Stability Problems and steady state problems. Some other issues are also taken as research finding by the researchers such as converter's battery energy system optimization (BES), stator's harmonic current control, Direct torque control, amplitude frequency control, load frequency control, open loop rotor control, Control based inertia contributed by DFIG, Hysteresis-Based Current Regulators and Dynamic Stability control using FACTS. This paper gives an overview on the some emerging issues related with DFIG based WECS taken by the researchers in past and novel technologies

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proposed by them. There are around thousands of research IEEE activities (Research Publications) on DFIG control aspects during past few decades. Fig. 2 shows the major IEEE's IP Activities on DFIG in approximation.

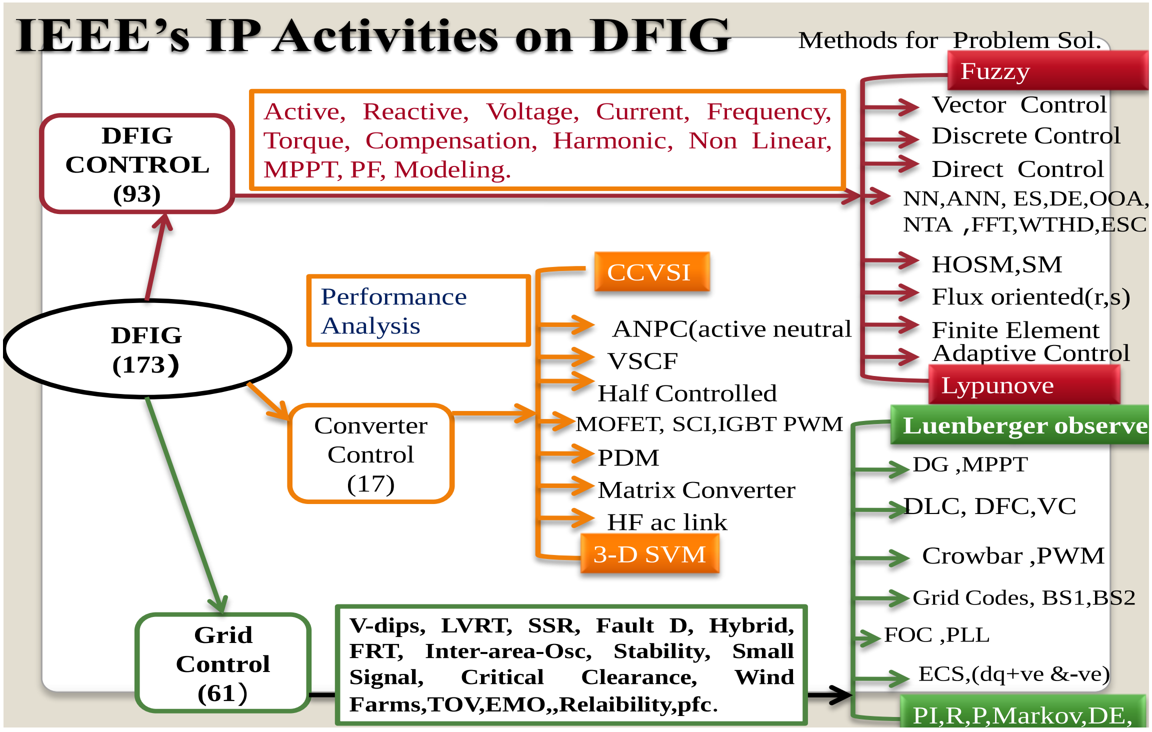

Fig. 2 IEEE's IP Activities on DFIG

II. EMERGING ISSUES AND THEIR CONTROL MEASURES OF DFIG BASED WECS

The Emerging Issues and their Control of DFIG based WECS are shown in the above fig.2 and described one by one as follows:

(a) Coordinated control of frequency regulation capability.

A (DFIG)-based WECS not provide frequency response because of the decoupling between the output power and the grid frequency. Power reserve margin also problem for DFIG because of the maximum power point tracking (MPPT) operation. [8] presented a novel frequency regulation by DFIG-based wind turbines to coordinate inertial control, rotor speed control and pitch angle control, under low and high wind speed variations.

(b) Battery Control Operation (BESS)

[9] presented a new based on battery energy storage system (BESS) and tried to reduce the power fluctuations on the grid for uncertain wind conditions and also, compared with an existing control strategies like the maximum power point extraction at unity power factor condition of the DFIG.[10] presented the modified rotor side of DFIG with DC link capacitor is replaced with the BES. The co-ordinated tuning of the associated controllers using bacterial foraging technique (based on eigen-value) to damp out power oscillations.Furthermore, an evolutionary iterative particle swarm optimization (PSO) approach for the optimal wind-battery coordination in a power system was proposed in [11], [12].

(c) Stator Current Harmonic Control

[13] proposed a sixth-order resonant circuit to eliminate negative sequence 5^{th} harmonic and positive sequence 7^{th} harmonics currents from fundamental component of stator current. A stator current harmonic control loop is added to the conventional rotor current control loop for harmonic suppression. The affects of voltage harmonics from the grid on the DFIG are also have been discussed in [14]–[17]. Resonant controllers have been widely used in harmonic control and unbalanced control for both DFIG and power converter systems [17], [18]–[25]. The use of resonant circuits aims to achieve high bandwidth at certain frequencies and also eliminate current harmonics in the three-phase

power converter systems [16]–[20] and the DFIG [17] during grid voltage distortion. In [22]–[24], the resonant controllers are used to keep the current output balanced during a grid voltage imbalance.

(d) Fault Ride Through

A grid fault posed an overload condition to DFIG when it trying to stabilize the wind farm. This would check the fault ride through capability of the DFIG. [26] Proposed the dc-link chopper-controlled braking resistor with the supplementary rotor current (SRC) control of the rotor side converter of the DFIG and series dynamic braking resistor (SDBR) connected to the stator of the DFIG. [27,28] a study focused on stabilizing FSWT without using any FACTS device. A series dynamic braking resistor (SDBR) was used to improve the FRT of large wind farms composed of IGs in [29], while in [30] the SDBR was connected to the rotor side converter of the DFIG to improve its Fault Ride Through capability. A superconducting fault current limiter (SFCL) [31], passive resistance network [32], and series anti-parellelthyristors [33] connected to the stator side of a grid connected DFIG. [34] proposed a new control strategy using a dc-chopper inserted into the dc-link circuit of the DFIG and a small value of SDBR connected in series in the stator of the DFIG, the former of which acts as a damping load to suppress the dc-link voltage during a grid fault.

(e) Regulation of active/reactive power

[35] DFIG is a electromechanical device and is modelled as non-linear system with rotor voltages and blade pitch angle as its inputs, active and reactive powers as its outputs, and aerodynamic and mechanical parameters as its uncertainties. A controller was developed that is capable of maximising the active power in themaximum power tracking (MPT) mode, regulating the active power in the power regulation (PR) mode for simultaneously adjusting the reactive power to achieve a desired power factor. For MPPT adaptive controls [35–38] and fuzzy methodologies [39–41] were proposed despite not knowing the Cp-surface. In [42] developed a non-linear controller that simultaneously enables control of the active power in both the MPT and PR modes with aerodynamic and mechanical parameters were known. [43] presented a dynamic model of BDFIG with two machines' rotor electromechanically interconnected. The method used to extract maximum power at any given wind speed is to implement maximum power point tracking (MPPT) algorithm based on the various control strategies for the VSR have been discussed in [44-46]. It has been demonstrated in [43] that the proposed BDFIG system can be used for the large off-shore wind energy application with reduced system maintenance cost. [47] proposed a model-based predictive controller for a power control of DFIG and internal mode controller [48], [49] have satisfactory performance when compared with the response of PI, but it is difficult to implement one due to the formulation of a predictive functional controller and the internal mode controller. Fuzzy based DFIG power control can be realized [50, 51].

(f) Voltage Unbalance Control

[52] Wind energy is often installed in rural, remote areas characterized by weak, unbalanced power transmission grids. Voltage unbalance factor (VUF) is defined as the negative sequence magnitude divided by the positive sequence magnitude. The control topology is fairly standard (based on stator-voltage-oriented *dq*vector control is used. This orientation can be called "grid flux oriented" control [52]. [53] implemented new rotor current control scheme which consists of a proportional–integral (PI) regulator and a harmonic resonant (R) to suppress 5^{th} and 7^{th} harmonics. The steady-state and transient response of DFIG-based wind power generation systemunder balanced [53]–[56] and unbalanced [57]–[64] grid voltage conditions have been well understood. [61] and [62] proposed proportional–integral (PI). plus resonant tuned at twice the grid frequency current controllers for both grid- and rotor-side converters. For instance, standards IEEE-519–1992 [65] and ER G5/4–1 [66] have, respectively, recommended different practices and requirements for harmonic control in electrical power systems. As indicated in [67] and [68-69], the presence of harmonics in the supply system results in torque pulsations and increased copper and iron losses in electrical machines. [70] presented a feedback/feedforward nonlinear controller for DFIG. The mechanical and electrical parts of the wind turbines are considered separately in most of the current literature: [71]–[88] considered only the mechanical part, while [96]–[103] considered only the electrical part, focusing mostly on the DFIGs. [104] considered both these parts, its controller was designed to maximize wind energy conversion, as opposed to achieving power regulation (i.e., only operate in the MPT mode).

(g) Direct Torque Control

Direct power control (DPC) was based on the principles of direct torque control [105], [106]. The DPC applied to the DFIG power control has been presented in [107]–[109]. This strategy calculates the rotor voltage space vector based on stator flux estimated and power errors. An alternative to DPC is power error vector control [110]. This strategy is less complex and obtains results similar to those of direct control of power. A anti-jamming control has been proposed by [111] to improve the controller performance. The predictive control is an alternative control technique that was applied in machine drives and inverters [112], [113]. Some investigations like long-range predictive control [114], general predictive control [112], and model predictive control [115]–[117] were applied to the induction motor drives.

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A predictive DPC for DFIG was presented in [118]. [119] DTC control is achieved with the grid voltages, rotor currents, and rotor position. The most widely used control techniques for the RSC are the field-oriented control (FOC) [120] and the direct control techniques such as direct torque control (DTC), [121], [122] and direct power control (DPC) [123], [124]. However, switching frequency control can be performed using predictive control [125]. The grid-side converter (GsC) can also be controlled by FOC [120], [126], [127] or direct control techniques like the DPC in [128]. As grid connection is performed only with RsC control in the DFIG-based wind system, the GsC will not be detailed in this paper [129]. [130] presented a control strategy based on the direct control of a virtual torque for grid connection and on a DTC for running process, with the same DTC switching table like in [131], but no PI regulator is used and only grid voltage, rotor current, and rotor position measurements are needed. The application of variable structure control (VSC) techniques to the electrical drives and wind energy generation [132–136].

(h) Open loop rotor position: Sensor less control algorithm

The sensor less rotor position estimation schemes under open-loop category either employ a voltage integrator (for the flux estimation) [138–139] or depend on inverse trigonometric computations. in real time [140] or recursive procedures [141–142]. Some of the techniques suffer from saturation in the integration stage or at other levels of the process which results in poor performance when the machine operates at a synchronous speed [138–140] or influence of machine parameter variations [141]. Flux estimation based on a recursive approach was proposed in [142–145], where the stator flux magnetising current instead of the stator flux components is estimated using re-computation. There are several position-sensorless methods proposed in [146]–[161]. There are major challenges in designing a position sensorless for a doubly fed wound-rotor induction machine.

(i) Magnitude and Frequency Control

A magnitude and frequency control (MFC) strategy has been proposed for the doubly fed induction generator (DFIG)[162] . Flux magnitude and angle control (FMAC) were discussed in [163–166]. In order to get the rotor speed and position information, an accurate position encoder will be equipped or a sensor less algorithm will be applied [167, 168].These methods increase the system complexity. Another useful control strategy is based on the direct power control (DPC) [169, 170]. Although the proposed MFC scheme has some benefits, the system dynamic response was not idea as shown in the previous section. The parameters of the PI control can be optimised or advanced control methods can be used in future to improve the system performance.

(j) Control based inertia contributed by DFIG

The paper [171] designed a supplementary control of adjusting pitch compensation and maximum active power order to the converter in order to improve inertial response during the transient for the DFIG. An approach was introduced is proposed in [172]. The technique was based on changing the DFIG torque set point based on the derivative of system frequency. This technique, however, has limitations. The work carried out in [173-174] advocates a similar approach and proposes a supplementary control which provides a response to the natural inertial response. The primary frequency control based on deviation of grid frequency is proposed in [175]. A similar concept together with a scheme to provide frequency response by de-loading the wind turbine is proposed in [176] and [177]. The work reported in [178] identifies the peak and duration of maximum active power that can be extracted for a commercially available GE 3.6 MW wind turbine. The work also addresses the possibility of varying the wind turbine physical parameters. The control concept presented in [179] aims to provide incremental energy equivalent to a synchronous generator with inertia constant of 3.5 MWs/MVA. According to [180], wind turbine frequency response is limited to a short time period. Proposed the idea of coordination with conventional generation units by feeding an additional signal based on participation factors. The work carried out in [181] addresses governor regulation, current control limits of the converter, and auxiliary loop parameters while investigating frequency response from DFIG based wind plants.

(k) Hysteresis-Based Current Regulators

[182] proposed an enhanced hysteresis-based current regulators in the field-oriented vector control with PI controller of doubly fed induction generator (DFIG) wind turbines. However, its performance depends on the accurate estimation of the machine parameters and it suffers from a complex control structure[182]. In[183], [184] Consequently, the system formulation is only valid around a specific operating condition and the response will deviate if the operation point varies. The nominal condition, e.g., voltage sag/swell conditions requested in modern grid codes [185]. Nonlinear control approaches, such as direct torque/power control (DTC/DPC) methods, have been addressed in [186]–[187]. Modified methods have been proposed to overcome these problems [189]–[193], but extra drawbacks were introduced, such as the inclusion of additional PI controllers [190], [191], reduced robustness to the machine parameters variations [189]–[191], and complex online calculation requirements [192], [193]. Based on the same

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principle used in DTC/DPC, have suggested replacing the conventional PI current regulator with a nonlinear predictive current regulator [194].

(l) Dynamic Stability Using FACT Devices

[195] Proposed a damping controller of the STATCOM is designed by using modal control theory to contribute effective .The analyzed results of stability improvement of power systems using STATCOMs and the damping controller design STATCOMs were presented in [196-197].System modeling and controller design for fast load voltage regulation and mitigation of voltage flicker using a STATCOM were demonstrated in [198]. A new D-STATCOM control algorithm enabling separate control of positive- and negative-sequence currents was proposed in [199]. [200] investigated the dynamic performance of a STATCOM and a static synchronous series compensator (SSSC). The dynamic performance of the nonlinear system with an optimized STATCOM controller was evaluated under a three-phase fault condition [201]. Discussed and compared different control techniques such as PSS, static VAR compensator (SVC) and STATCOM for damping undesirable inter-area oscillations in power systems were carried out and a method of PI control for a STATCOM was compared and contrasted with various feedback control strategies, and a linear optimal control based on LQR control [202-203]. ASTATCOM based on a current-source inverter (CSI) was proposed in [204]. The integrated STATCOM/BESS was and performance of the different FACTS/BESS combinations was compared and provided experimental verification of the proposed controls on a scaled STATCOM/BESS system [205]. A combination of SVC and STATCOM technology on a connected transmission system with IGs in a wind farm was discussed [206].

III.RESEARCH GAPS FOUND IN THE LITERATURE

Research gaps found in the above literature are as follows[8-206]:

- Need to explore system behavior and control strategies with the simulation models as well as experimentally. Need to enhance the system stability over wide range of rotor speed variations by adding position sensor.
- Need to construct a simulation model to theoretically examining the performance of IG connected to grid not only for voltage fluctuations but also for steady state and transient stability aspects in more fast and efficient manner.
- Need to develop a technique measurements of harmonics and to study the effect of harmonics introduced by cycloconverter on the performance of DFIG connected to grid.
- Need to optimize active power requirements of DFIG to enhance the efficiency of the system
- DFIG provide wide control on active, reactive and efficiency but these factors are required to compared on the merge of high cost of power electronics equipment.
- The Dynamic model of DFIG was only limited to theoretical assumptions of sinusoidal mechanical variations, effect on the protection devices were not shown, Need to develop a mathematical model to study nonlinear behavior to predict actual mechanical vibrations and its effect on protection devices.
- Fuzzy logic and neural network based controllers, as well as state-estimation based controllers, could be employed to incorporate the interaction between the various control objectives DFIG -WECS.
- For a variable-speed wind turbine, the control and protection of the converter and generator systems must be included in a model and a detailed model is required.
- For development of wind turbine standard generalized dynamic models to embed in the power system usual numerical tools to be used.
- Robust control is missing as leakage inductance of rotor was neglected in the literature and need to consider the effect of variations in the rotor leakage inductance on the performance of the DFIG under unbalance voltage conditions. Also rebalancing of network voltage after unbalance condition should be explored with control strategy.
- Inappropriate data available and rough observations about load variations cause inaccurate results. Need to develop control strategy to remove uncertainty of compensation capacitance requirements during voltage fluctuations. Need to develop models of DFIG based on variational differential equations .
- To enhance controller response new techniques based on fuzzy or NN need to be implement which gives better parametric variation for Robust control.
- Need to develop more realistic simulink models by connecting wind farm , conventional power plant and FACTS devices to same grid. A parametric variation and robust control strategies will help to demonstrate stability issues.
- As rotor nonlinear fluctuations effects are well demonstrated with the help of HOSM technique but it opens new research interest to develop new controller strategies are to reduce the DFIG power generated fluctuations.
- Control techniques based on simple dq for torque, reactive power, and dc-link voltage are analyzed for balanced and unbalanced faults ride-through performance and advanced controller part was not considered. However, this

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model given a very good control performance, but performance study not explored to large wind farm connected to grid.

- Study gives demonstrated a better understanding of IGBT life time measurements converters but still need to develop new controller to minimize overall losses occurred in the DFIG based wind farms.
- Although the proposed MFC scheme has some benefits, the system dynamic response was not idea as shown in the previous section. The parameters of the PI control can be optimised or advanced control methods can be used in future to improve the system performance.

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Appendix-A

DFIG CONTROL

- NN-Neural Network
- ANN-Artificial NN
- ES- Evolutionary Strategy
- DE- Differential Evolution Algorithm
- OOA,-Online Optimization Algorithm
- NTA –Newton Type Algorithm.
- FFT- Fast Fourier Transform
- WTHD-Weighted Third Harmonic Distortion.
- ESC-Extreme seeking control Algorithm
- HOSM- High Order Sliding Mode
- SM- Sliding Mode
- Active neutral-point-clamped (ANPC)
- VSCF-Variable speed constant freq.
- 3-D SVM- 3-Dimensional space vector modulation
- PDM-Pulse density modulation

GRID CONTROL

- DG –Distributed Generation Protection
- MPPT –Maximal Power Point Tracking
- BS1,BS2-Battery Source Scheme 1 and 2
- FOC – Field Oriented Control
- PLL-Phase Locked Loop Controller
- DFC,-Direct Frequency control
- VC- Vector control
- ECS Energy Capacitor systems
- (dq+ve &-ve)
- PI- Proportional Integral
- R- Harmonic Resonant
- Markov
- DE-Differential Evaluation