

Chapter 2

Literature Review

2.1 Introduction

Electrical power is the most widely used source of energy for our homes, workplaces, and industries. Population and industrial growth have led to significant increases in power consumption over the past three decades. Natural resources like coal, petroleum, and gas which drive our power plants, industries, and vehicles for many decades are becoming depleted at a very fast rate. This serious issue has motivated nations across the world to think about alternative forms of energy which utilize inexhaustible natural resources. Wind plants have benefited from steady advances in technology made over past 15 years. Much of the advancement has been made in the components dealing with grid integration, the electrical machine, power converters, and control capability. The days of the simple induction machine with soft start are long gone. We are now able to control the real and reactive power of the machine, limit power output, and control voltage and speed [1]. There is a lot of research going on around the world in this area, and technology is being developed that offers great deal of capability. It requires an understanding of power systems, machines, and applications of power electronic converters and control schemes put together on a common platform. Unlike a conventional power plant that uses synchronous generators, a wind turbine can operate as fixed speed or variable speed. In a fixed speed wind turbine, the stator of the generator is directly connected to the grid. However, in a variable speed wind turbine, the machine is controlled and connected to the power grid through a power electronic converter. There are various reasons for using a variable speed wind turbine [2, 3]:

- More power is achieved from the variable speed generator in comparison with its constant speed counterpart system.
- Reactive power compensator and soft starter system could be omitted because of power electronic devices existence.
- Simple pitch control is available with a feasible cost.

- Mechanical stresses are reduced by absorbing and reducing torque pulsations in variable speed.
- Torque pulsation reduction improves power quality by eliminating power variation and reducing flickers.
- Maximum power point tracking systems are employable, which improve variable speed systems efficiency.
- Acoustic noise is also reduced by working at a lower speed in lower wind gusts.

The use of renewable energy sources for electric power generation is gaining importance in order to reduce global warming and environmental pollution, this is in addition to meeting the escalating power demand of the consumers. Generally, wind power generation uses either fixed speed or variable speed turbines, the main configurations of generators and converters used for grid connected variable speed wind power system (WPS) are presented in the following sections.

2.2 Synchronous Generators Driven by a Fixed Speed Turbine

A synchronous generator usually consists of a stator holding a set of three-phase windings, which supplies the external load, and a rotor that provides a source of magnetic field. The rotor may be supplied either from permanent magnetic or from a direct current flowing in a wound field.

2.2.1 Wound Field Synchronous Generator Driven by a Wind Turbine

The stator winding is connected to network through a four-quadrant power converter comprised of two back-to-back sinusoidal PWM. The machine side converter regulates the electromagnetic torque, while the grid side converter regulates the real and reactive power delivered by the WPS to the utility. The wound field synchronous generator has some advantages that are

The efficiency of this machine is usually high because it employs the whole stator current for the electromagnetic torque production [4].

The main benefit of the employment of wound field synchronous generator with salient pole is that it allows the direct control of the power factor of the machine, consequently the stator current may be minimized at any operation circumstances.

The existence of a winding circuit in the rotor may be a drawback as compared with permanent magnet synchronous generator. In addition, to regulate the active and reactive power generated, the converter must be sized typically 1.2 times of the WPS rated power [5].

2.2.2 Permanent Magnet Synchronous Generator (PMSG) Driven by a Wind Turbine

Many configuration schemes using a permanent magnet synchronous generator for power generation had been adopted. In one of them, a permanent magnet synchronous generator was connected to a three-phase rectifier followed by boost converter. In this case, the boost converter controls the electromagnet torque. The supply side converter regulates DC link voltage as well as control the input power factor. One drawback of this configuration is the use of diode rectifier that increases the current amplitude and distortion of the PMSG [6]. As a result, this configuration has been considered for small size wind power system (WPS) (smaller than 50 kW).

In another scheme using PMSG, the PWM rectifier is placed between the generator and the DC link, while another PWM inverter is connected to the network. The advantage of this system regarding the use of field-orientation control (FOC) is that it allows the generator to operate near its optimal working point in order to minimize the losses in the generator and power electronic circuit. However, the performance is dependent on the good knowledge of the generator parameter that varies with temperature and frequency. The main drawbacks, in the use of PMSG, are the cost of permanent magnet that increases the price of machine, demagnetization of the permanent magnet material, and it is not possible to control the power factor of the machine [7].

2.3 Induction Generators Driven by a Variable Speed Wind Turbine

The AC generator type that has most often been used in wind turbines is the induction generator. There are two kinds of induction generator used in wind turbines that are squirrel-cage and wound rotor.

2.3.1 Squirrel-Cage Induction Generator (SCIG) Driven by a Wind Turbine

Three-phase squirrel-cage induction generators are usually implemented in standalone power systems that employ renewable energy resources, like hydropower and wind energy. This is due to the advantages of these generators over conventional synchronous generators. The main advantages are reduced unit cost, absence of a separate DC source for excitation, ruggedness, brushless rotor construction, and ease of maintenance. A three-phase induction machine can be operated as a self-excited induction generator if its rotor is externally driven at a suitable speed,

and a three-phase capacitor bank of a sufficient value is connected across its stator terminals. The stator winding in this generation system is connected to the grid through a four-quadrant power converter comprised of two PWM VSI connects back-to-back through a DC link voltage, this can be shown in Fig. 2.1.

The control system of the stator side converter regulates the electromagnetic torque and supplies the reactive power to maintain the machine magnetized. The supply side converter regulates the real and reactive power delivered from the system to the utility and regulates the DC link, but the uses of SCIG have some drawbacks as following [8]:

Complex system control, whose performance is dependent on the good knowledge of the generator parameter that varies with magnetic saturation, temperature, and frequency.

The stator side converter must be oversized 30–50% with respect to rated power, in order to supply the magnetizing requirement of the machine.

2.3.2 *Doubly Fed Induction Generator (DFIG) Driven by a Wind Turbine*

The wind power system shown in Fig. 2.2 consists of a DFIG, where the stator winding is directly connected to the network and the rotor winding is connected to the network through a four-quadrant power converter comprised of two back-to-back sinusoidal PWM. The thyristor converter can be used, but they have limited performance.

Usually, the controller of the rotor side converter regulates the electromagnetic torque and supplies part of the reactive power to maintain the magnetization of the

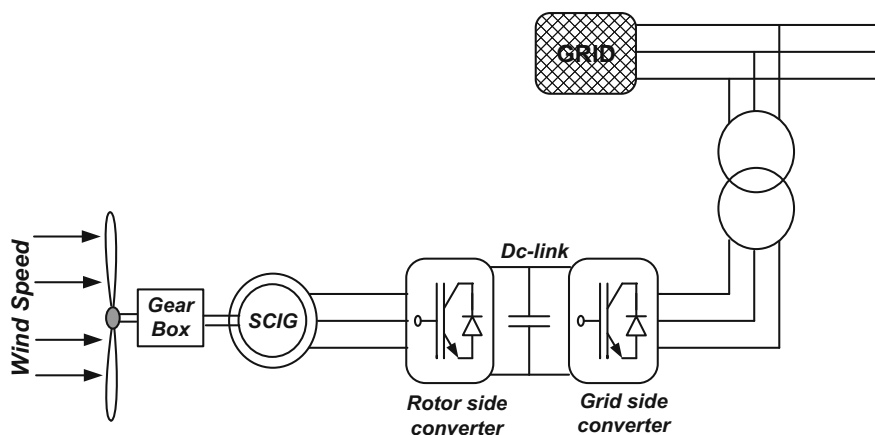


Fig. 2.1 Squirrel-cage induction generator (SCIG) driven by a wind turbine

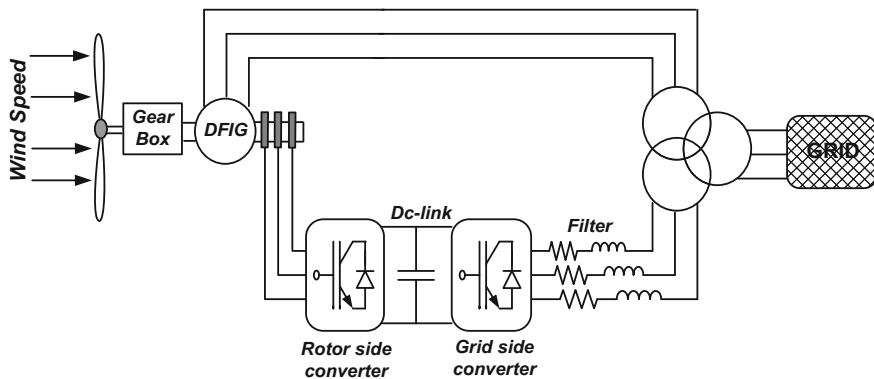


Fig. 2.2 Doubly Fed wound rotor induction generator driven by a wind turbine

machine. On the other hand, the controller of the grid side converter regulates the DC link voltage [9]. Compared to synchronous generator, this DFIG offers the following advantages [10]:

- Reduced inverter cost, because inverter rating typically 25% of the total system power. This is because the converters only need to control the slip power of the rotor.
- Reduced cost of the inverter filter, because filters rated for 0.25 p.u. total system power, and inverter harmonics represent a smaller fraction of total system harmonics.
- Robustness and stable response of this machine facing against external disturbances.

2.3.2.1 Operation Modes

DFIGs have two dedicated operating modes [11] as follows:

1. Operation mode, in which generator rotor rotates at a speed above the synchronous speed and is called supersynchronous mode. In this mode, slip is negative, and both stator and rotor windings deliver power to the grid.
2. Operation mode, in which generator operates under synchronous speed and is called as the subsynchronous mode. In this mode, slip is positive, and stator winding delivers power to both the grid and the rotor winding. Total obtained power from stator winding does not exceed the producible power in supersynchronous mode with respect to smaller rotational speed in this mode.

2.4 Modeling of a Wind Turbine-Generator System

The modeling of a wind turbine-generator system consists of the aerodynamic modeling, the drive train system modeling, the DFIG modeling, and the power converter modeling. Hence, this part of the study will only focus on the modeling of such system.

2.4.1 *Aerodynamic Modeling*

In [12], Tao sun deduced the maximum energy that a wind turbine system can extract from the air system under ideal conditions. In [13], the authors derived the relationship between the mechanical power input and the wind speed passing through a turbine rotor plane, which can be expressed by the power coefficient of the turbine. There are three most commonly used methods to simulate the power coefficient which is provided by the wind turbine manufacturer. The first two methods are given in Refs. [12, 14, 15]. The third method is the lookup table method and given in Refs. [16, 17]. There are two other methods to approximate the power efficiency curve, but they are not commonly used. Interested readers can find them in [18, 19].

2.4.2 *Drive Train Modeling*

For the drive train system modeling, the work in Ref. [20] elaborately explained the reduced mass conversion method and compared a six-mass model with reduced mass models for transient stability analysis. In [21], Stavros A. Papathanassiou used a six-mass drive train model to analyze the transient processes during faults and other disturbances. In [22], three different drive train models and different power electronic converter topologies were considered to study the harmonic assessment. Reference [23] compared the transient stabilities of a three-mass model, a two-mass model, and a one-mass model. In addition, the effects of different bending flexibilities, blade and hub inertias on the transient stabilities of large wind turbines were also analyzed. In [24], a three-mass model, which took into account the shaft flexibility and blade flexibility in the structural dynamics, was developed and then used to derive a two-mass model. In [20, 25], the authors concluded that a two-mass drive train model was sufficient for transient stability analysis of wind turbine-generator systems. Besides, the two-mass model is widely used in Refs. [26–31]. Other references, such as [15, 32–34] focused their study on the generator control and modeling, where the drive train system was simply expressed by single mass models.

2.4.3 DFIG Modeling

The Doubly Fed induction machines can be categorized into four types. These types are the standard Doubly-Fed induction machine, the cascaded Doubly-Fed induction machine, the single-frame cascaded Doubly-Fed induction machine and the brushless Doubly-Fed induction machine [35]. However, only the standard type and brushless type of Doubly-Fed induction machines have been applied in wind turbine-generator systems. In Ref. [36], the authors developed the brushless Doubly-Fed induction generator by employing two cascaded induction machines to eliminate the brushes and copper rings and used a closed-loop stator flux-oriented control scheme to achieve active and reactive power control. In [37], Yongchang Zhang proposed a direct power control (DPC) strategy for cascaded brushless Doubly Fed induction generators which featured quick dynamic responses and excellent steady-state performances. The DFIG model can be expressed in the stationary stator reference frame, the reference frame rotating at rotor speed, and the synchronously rotating reference frame. In [33, 38], the authors adopted the synchronously rotating reference frame in order to simplify the controller design because of the fact that all the currents and voltages expressed under this reference frame will be of a DC nature. While, in [9], both stator and rotor variables were referred to their corresponding natural reference frames, and the machine model expressed in such reference frame is called the “Quadrature-Phase Slip-Ring” model.

The DFIG model can usually be expressed by reduced order models, which can yield a third-order model by neglecting the derivative terms of the stator flux and first-order model by neglecting both the derivative terms of the stator flux and rotor flux [39]. But in [38], the authors proposed an enhanced third-order model which considered the DC-components of the stator currents and gave a comparison between a full-order model and the proposed model for wind ramp conditions. Alvaro Luna, in [40], deduced a new reduced third-order model by ignoring the stator resistances and inductances through applying the Laplace transformation and compared the proposed model with a full-order model for transient analysis.

There are many references which made the comparison between the full-order model and reduced order models [41–43]. In [44], the authors even considered the saturated conditions and made a detailed comparison among these unsaturated and saturated full-order models and reduced order models. Pablo Ledesma, in [45], compared a third-order model with a full-order model in two extreme operation points under short-circuit fault conditions. These points are subsynchronous speed and supersynchronous speed, respectively. As known, the difference between the model of a squirrel-cage induction generator and a Doubly-Fed induction generator is the rotor input. Hence, the simplified models of squirrel-cage induction generators may be helpful for understanding the reduced order models of DFIGs. Interested readers can find them in [46, 47].

2.4.4 Power Converter Modeling

The traditional power converter used in wind turbine-generator systems is a back-to-back two-level PWM converter. The three-phase voltage source PWM converter model can be expressed in the abc reference frame and the d-q synchronous reference frame which is deduced for control purposes. The mathematical model based on space vectors expressed in the abc reference frame was derived in [48]. In [49–51], the authors showed the detailed work about the transformation of a PWM converter model from the abc reference frame to the d-q synchronous reference frame. For wind turbine applications, some researchers simplified the power converter model by employing an equivalent AC voltage source that generates the fundamental frequency [34]. In [52], José R. Rodríguez gave the detailed description for the working principles, control strategies and made comparisons for three-phase voltage source and current source PWM converters.

2.5 Control Strategies for a Wind Turbine-Generator System

The control schemes for a wind turbine-generator system include the pitch angle control, maximum power point tracking control, and the DFIG control. The traditional control techniques and advanced control techniques for wind turbine-generator systems are reviewed in this section.

2.5.1 Pitch Angle Control

The pitch angle control is a mechanical method of controlling the blade angle of the wind turbine when the captured wind power exceeds its rated value or wind speed exceeds its rated value. In this way, pitch angle control is enabled to limit the maximum output power to be equal to the rated power, and thus protect the generator when the wind speed experiences gusts. The pitch angle controller is only activated at high wind speeds.

There are numerous pitch angle regulation techniques described in the literature [5, 53–58]. The conventional pitch angle control usually uses PI controllers [5, 53, 54]. However, several advanced pitch control strategies were proposed. A new approach for the pitch angle control, which worked well for unstable and noisy circumstance, was presented in [55]. Besides, a fuzzy logic pitch angle controller was developed in [56], which did not need much knowledge about the system.

Furthermore, a pitch angle controller using a generalized predictive control was presented in [57], whose strategy was based on the average wind speed and the standard deviation of the wind speed. Another pitch control scheme was proposed

in [58], in which a self-tuning regulator adaptive controller that incorporated a hybrid controller of a linear quadratic Gaussian neuro controller and a linear parameter estimator was developed for the pitch angle control. In [59], the authors only applied a fuzzy logic pitch angle controller in a wind turbine-generator system to achieve the maximum power point tracking control and power control.

2.5.2 Maximum Power Point Tracking Control

In order to achieve the maximum power point tracking (MPPT) control, some control schemes have been presented. The maximum power point tracking control can be mainly divided into two types. They are the conventional control schemes and intelligent control schemes.

2.5.2.1 Conventional Control Schemes

The conventional control schemes can also be divided into current mode control and speed mode control, which depends on the setting of reference values. The reference values are the active power and electromagnetic torque for current mode control [60–62] and the rotational speed for the speed mode control [63]. In [64], the author compared these two control strategies for dynamic transient analysis and concluded that the current mode control has slow response with simple construction, while the speed mode control has fast response with complex construction. The discussions and limitations of these two control schemes were presented in [65].

In fact, the wind speeds in above conventional control schemes need to be exactly measured. However, the anemometer cannot precisely measure the wind speed because of the flow distortion, complex terrain, and tower shadow influence [66]. Hence, some studies on maximum wind energy tracking without wind velocity measurement had been developed in [67, 68].

2.5.2.2 Intelligent Control

The intelligent control strategies usually apply the hill-climbing control and the fuzzy logic control to the maximum power point tracking control. The traditional hill-climbing control uses a fixed-step speed disturbance optimal control method to determine the speed, perturbation size, and direction according to the changes in the power before and after sampling [69]. However, this control method is usually slow in speed because the step disturbance is fixed. Therefore, some improved hill-climbing control methods were proposed. For example, a method of using variable-step wind energy perturbation method to control the captured wind power was analyzed in [65]. Another advanced hill-climbing searching method with an

online training process, which can search for the maximum wind turbine power at variable wind speeds, even without the need for knowledge of wind turbine characteristics, wind speed, and turbine rotor speed, was developed in [70]. Fuzzy logic control-based MPPT strategies have the advantages of having robust speed control against wind gusts and turbine oscillatory torque, having superior dynamic, and steady performances, and being independent of the turbine parameters and air density; see [66, 71].

2.5.2.3 Other Control Strategies

In [72], the authors presented a novel adaptive MPPT control scheme in which the wind speed was estimated by the output power and the efficiency of the generator, and the maximum efficiency was estimated by the maximum tip-speed ratio tracker. A novel MPPT strategy that was based on directly adjusting the DC/DC converter duty cycle according to the results of comparisons between successively monitored wind turbine output powers was proposed in [73], in which there was no requirement for the knowledge of wind turbine characteristic and measurements of the wind speed.

2.5.3 DFIG Control

Control of the DFIG is more complicated than the control of a squirrel-cage induction generator, because the DFIG can operate at subsynchronous speed and supersynchronous speed by regulating the rotor terminal voltages. Through the years, many researchers have presented various types of DFIG control strategies, such as field-oriented control, direct torque/power control, predictive control, sensorless control, and nonlinear control.

2.5.3.1 Field-Oriented Control

Field-oriented control (FOC) or vector control is commonly used in DFIG controls due to its ability of controlling the motor speed more efficiently, and the low economic cost to build an FOC system. Field-oriented control also provides the ability of separately controlling the active and reactive power of the generator. Currently, there are mainly two types of field-oriented control in DFIG, which are stator voltage-oriented control and stator flux-oriented control, respectively. The stator flux-oriented control is widely used in the DFIG control designs [26, 9], in which the q -axis current component is used for active power control and the d -axis component is used for reactive power control.

While for the stator voltage-oriented control, the situation is on the contrary [74, 75], the d -axis component is used for active power control and the q -axis

current component is used for reactive power control. In [76], the author compared real and reactive power control for a DFIG-based wind turbine system using stator voltage- and stator flux-oriented control, respectively, and the simulation results illustrated same performances.

2.5.3.2 Direct Torque/Power Control

Recently, a new technique for directly control of the induction motors' torque or power was developed, which included direct torque control (DTC) and direct power control (DPC). Direct torque control scheme was first developed and presented by I. Takahashi and T. Noguchi [77, 78]. Based on the principles of DTC for electrical machines, direct power control for a three-phase PWM converter was introduced in [79].

Direct torque control techniques do not require current regulators, coordinate transformations, specific modulations, and current control loops [80]. Thus, direct torque control has the ability of directly controlling the rotor flux linkage magnitude and generator torque through properly selecting the inverter switching states [10]. To show the advantages of DTC, the comparison between the field-oriented control and direct torque control was made in [81]. Direct torque control using space vector modulation technology was presented in [82]. In [83, 84], the authors applied basic direct torque control to a Doubly-Fed induction generator. Direct torque control which was achieved without PI controller and only required the knowledge of grid voltages, rotor currents, and rotor position as was proposed in [48, 80]. Z. Liu, in [85, 86], proposed a novel direct torque control scheme which was developed based on the control of the rotor power factor.

Direct power control has the merits of being simple, requiring fewer sensors, having low computational complexity, fast transient response, and low machine model dependency compared with direct torque control [87]. In [88], the comparison between field-oriented control and direct power control for a PWM rectifier was presented, and the simulation results showed that the virtual-flux-based direct power control was superior to the [86] voltage-based direct power control and field-oriented control. In [89, 90], the authors used direct power control in a DFIG-based wind turbine system under unbalanced grid voltage conditions. A new direct power control, which was based on the stator flux and only needed the stator resistance values of the machine parameters, was proposed in [91].

2.5.3.3 Other Control Strategies

In recent years, increasing attention is being paid to the application of predictive control in the field of the DFIG-based wind turbine-generator systems [92–94]. Several predictive direct power control strategies were studied and compared for AC/DC converters in [95].

Sensorless operation is important for wind applications due to the need for low cost and high reliability particularly for wind turbines which are usually installed in harsh environment [96]. There are many studies worked on the sensorless control; see Refs. [97–102]. Sensorless control is usually achieved by estimating the rotor position, so that there is no need for the rotor position encoder. A common way used for the estimation of parameters without taking any feedback is the use of model reference adaptive system (MRAS) observer as used in [100–102].

Moreover, direct torque/power control strategies can be considered as “sensorless type” control techniques because direct torque/power control could obtain a good dynamic control of the torque/power without any mechanical transducers on the machine shaft [81]. A nonlinear control approach, which used the nonlinear static and dynamic state feedback controllers with a wind speed estimator in a wind turbine-generator system, was proposed in [25].

2.6 Power Converter Topologies for a Wind Turbine-Generator System

Power electronics, being the technology of efficiently converting electric power, plays an important role in wind power systems. In recent years, the multi-level converters and matrix converters became main solutions for medium voltage drives. In this section, the application of multi-level converters and matrix converters in wind turbine-generator systems is reviewed.

2.6.1 Multi-level Converters

Compared with traditional two-level converters, multi-level converters have many advantages, such as more sinusoidal output voltage waveforms, lower total harmonic distortion (THD), reduced filter size and cost, reduced switching losses in the IGBTs, lower dv/dt [103, 104]. This is due to the fact that the output voltages can be formed using more than two voltage levels.

Generally speaking, multi-level converters can be classified into three categories [105]:

- Neutral-point-clamped (NPC) converters.
- Flying capacitor converters.
- Cascaded H-bridge (CHB) converters.

Multi-level neutral-point-clamped converters are most widely used in wind turbine-generator systems. In [106], three-level NPC converters were applied in PMSG-based wind turbine systems with field-oriented control. In [107], the author used a three-level neutral-point-clamped PWM converter to drive a permanent magnet synchronous generator, in which a space vector modulated direct power

control, was applied. In [108], a new application of the predictive direct power control was presented for a Doubly-Fed induction machine equipping with three-level NPC converters, in which constant switching frequency technology was achieved. In [109], the active and passive components of a NPC converter, such as insulated-gate bipolar-transistors, free-wheeling diodes, clamping diodes, grid filters, DC-bus capacitors, were designed for a wind turbine system equipped with a squirrel-cage induction generator. A comparison between traditional two-level converters and three-level NPC converters for a wind power system was made [110]. In [111, 112], the authors made comparisons between the neutral-point-clamped converters, flying capacitor converters, and cascaded H-bridge converters for wind power generation. The application of cascaded H-bridge converters in wind turbine-generator systems was developed in recent years; interested readers can find them in [113, 114].

2.6.2 Matrix Converters

The matrix converter concept, which was first introduced by A. Alesina and M. G. B. Venturini [86], has become increasingly attractive for wind power applications. When compared with back-to-back two-level converters, matrix converters have some significant advantages, such as sinusoidal input and output currents, absence of a Dc-link capacitor, fewer IGBT switches, simple and compact power circuit, operation with unity power factor for any load, and regeneration capability [115, 116].

Numerous works have been published for the application of matrix converters in wind turbine-generator systems. The application of a matrix converter for power control of a DFIG-based wind turbine system can be found in [117]. In [118], a wind turbine system, which was composed by a SCIG and a matrix converter, was presented. For the applications of PMSG-based wind turbine systems, one can easily find them in [119].

2.7 DFIG Grid Synchronization

DFIG should be synchronized with grid before connection in order to have minimum impact on power system. But only a few authors studied the DFIG grid connection control [120].

Due to the universality of vector control (VC), it has also been extended to the grid synchronization process. In general, a cascaded structure using four PIs (two for outer stator voltage loop and two for inner rotor current loop) is used to achieve the equality of amplitude, frequency, and phase [121, 122], which requires the information of stator voltage, grid voltage, rotor current, and rotor position. To reduce the complexity and tuning work, a single loop stator voltage oriented direct

voltage control strategy is proposed in [123], which reduces the control loops by half by using two PIs only and eliminates the use of rotor current. As a result, the demand on the computation power and the number of parameters for tuning is reduced. Although smooth grid synchronization is achieved by using VC, the tuning effort of PI is still necessary.

In [124], DTC method is used for grid synchronization and normal condition but using PI controller beside hysteresis one, variable switching frequency and noticeable torque ripples are its disadvantages.

The main goal of successful synchronization is to reduce stresses on the electrical and mechanical components of the wind turbine. Also, it helps in preventing power system disturbance due to stator-grid connection. The mechanical stress is caused by heavy transient torque at the start-up, and the electrical stress is due to huge heavy start-up currents. The mechanical stress can damage the gearbox, shaft, and the rotor of the machine while electrical stress can damage the insulation, and winding of the stator and the rotor over a period of time [124].

In [125], the rotor current is controlled for grid synchronization. Having noticeable differences between stator and grid voltages because of voltage feedback lack is the main drawback of this method. Reference [80] presents Direct Virtual Torque Control (DVTC) that is achieved without PI controller and requires only the measurement grid voltage, rotor current, and rotor position. But, because of using hysteresis controller, switching frequency is variable and ripples of the flux and torque are high.

Wind Driven Doubly Fed Induction Generator

Grid Synchronization and Control

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A.E.H.A.

2018, XIX, 96 p. 54 illus., 40 illus. in color., Hardcover

ISBN: 978-3-319-70107-3