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Review on Power Quality Problems on-Grid Connected Wind Power System

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Abstract: This review paper focus on the effect of grid connected wind turbines on power quality issues. Special attention has been paid to voltage conditions, flicker, Fault ride-through and harmonics.
In connection with power quality, it is essential to have better focus on inverter connected wind turbines with variable rotational speed. The paper also presents concepts in variable speed wind turbines in relation to power quality with main focus on doubly fed induction generator.Various wind turbine systems with different generators and power electronic converters are assessed for controlling purposes are described, and different power quality issues are raised. Finally, the possible methods of using the power electronic technology for improving wind turbine performance in power systems to meet the main grid connection requirements are discussed. This review only focuses on assessing effects of wind turbines connected to the grid and their impact on power quality issues so that studies carried under this area should get good directions.
Key words: voltage variation, flicker, Fault ride-through, harmonics, power electronics converters, reactive power compensation

1. Introduction

1.1. Background

An increasing number of wind turbine installations and ever more wind power capacity connected to the grid have made the impact of wind turbines on voltage quality a major issue. To avoid unnecessarily conservative limits on the amount of wind power that can be connected to an electric grid, it is a necessity to be able to predict wind turbines impact on voltage quality at the Point of Common Coupling (PCC). This can only be done if the power quality parameters and characteristics of the wind turbine are known [1].
Most of power quality problems for grid connected doubly fed induction generators (DFIGs) with wind turbine include flicker, variations of voltage and injected harmonics due to switching in DFIG converters. Flicker phenomenon is the most important problem in wind power systems. [2]. Electrical flicker can be thought of as a rapidly changing system voltage that causes perceivable visual effects upon lighting systems. The voltage variation is directly related to real and reactive power variations. The amplitude of voltage fluctuation is determined by grid strength, network impedance, and phase-angle and power factor on the wind turbines [3]. Towards this, studies carried under different wind turbines connected with grids should take them in to account so as to obtain reasonable results. Many wind power plants implement power electronics converters for power compensation and control purposes. However, due to the operation of power electronic converters, they will mainly results with harmonics.The harmonic voltage and current ought to be restricted to the acceptable level for the point of wind generator link to the network. To ensure the harmonic voltage within limit, each method of obtaining harmonic current can allow only a limited contribution, as per the IEC-61400-36 guideline. Voltage harmonics are virtually always present on the utility grid. Non-linear loads, power electronic loads, rectifiers and inverters in motor drives etc., are some sources which produce harmonics [2]. The aforementioned points are areas where this review aims to focus on and further study goes over. The reactive power consumption of wind turbines consists of a constant no load demand and a requirement which varies proportionally with the output of the generator. In weak grids in particular, this results in varying voltages and poor power quality.
The term ‘weak grid’ denotes that the voltage at the point of interconnection is not “stiffly” constant. Weak grids are usually found in more remote places where the feeders are long and operated typically at a medium voltage level. In a weak grid, it is necessary to take possible voltage fluctuations into account, since there is a high probability of the standard voltage values being violated. The problem with wind turbine operating on weak grids is that the poor voltage regulation at the PCC in combination with the fluctuating nature of wind power and stochastically changing system load can produce a voltage profile at the PCC and beyond, which can adversely affect the overall power quality in the system.The voltage

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quality can be improved considerably if the wind turbines' varying reactive power consumption is provided from a dynamic compensator which supplies reactive power corresponding to the varying consumption of the induction generators [4].

Power electronics, being the technology of efficiently converting electric power, plays an important role in wind power systems. The power electronic converters are used to match the characteristics of wind turbines with the requirements of grid connections, including frequency, voltage, control of active and reactive power, harmonics, etc. [5]

This paper reviews the major areas of power quality problems in wind

1.2. Wind Energy Conversion Systems

The main components of a wind turbine system are illustrated in fig. 1.1, including a turbine rotor, a gearbox, a generator, a power electronic system, and a transformer for grid connection and fig.1.2 (a) and (b) shows the Sany's SE7715 Wind Turbine Generator (WTG) connected in Adama-II wind farm, Ethiopia. WTs capture the power from wind by means of turbine blades and convert it to mechanical power. It is important to be able to control and limit the converted mechanical power during higher wind speeds. The power limitation may be done either by stall control, active stall, or pitch control whose power curves are shown in fig. 1.3 [6]. It can be seen that the power may be smoothly limited by rotating the blades either by pitch or active stall control while the power from a stall-controlled turbine shows a small over shoot and a lower power output for higher wind speed. The common way to convert the low-speed, high-torque mechanical power to electrical power is using a gearbox and a generator with standard speed. The gearbox adapts the low speed of the turbine rotor to the high speed of the generator, though the gearbox may not be necessary for multipole generator systems.The generator converts the mechanical power into electrical power, which being fed into a grid possibly through power electronic converters, and a transformer with circuit breakers and electricity meters. The two most common types of electrical machines used in wind turbines are induction generators andsynchronous generators [7]

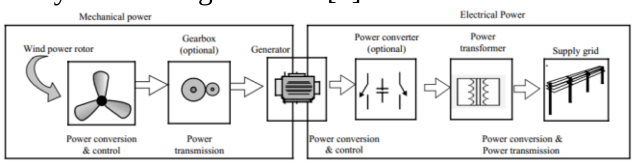
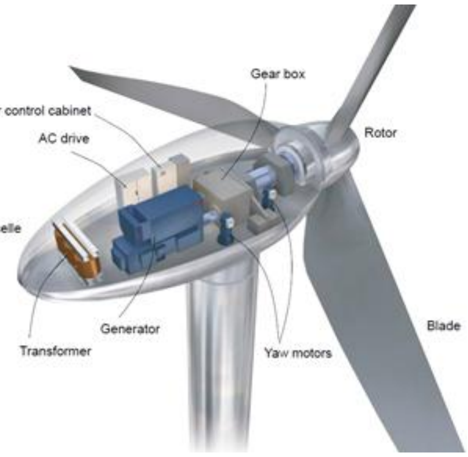
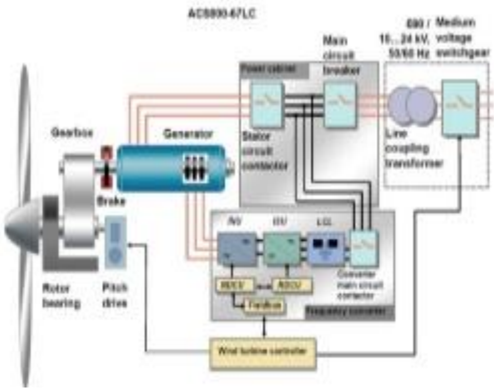


Fig.1.1Main components of a wind turbine system.



a) Components of a wind turbine converter system



b) Block diagram of the converter system

Fig.1.2. Overview of DFIG & associated controls of Adama-II wind farm [7]

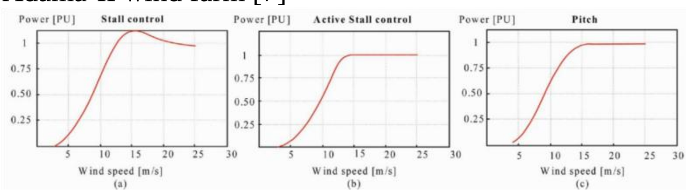


Fig.1.3. Power characteristics of fixed-speed wind turbines (a) Stall control. (b) Active stall control.(c) Pitch control [6].

1.3. Classification of the Turbines

As a general classification, wind turbines can be categorized in two groups - constant and variable speed wind turbines. The DFIG) and full-rated converter synchronous or induction machine based wind turbines belong to the category variable speed. Constant speed wind turbines use a directly grid connected squirrel cage induction generator. Due to their poor aerodynamic efficiency and limited controllability, constant speed machines are no longer the machine of choice for new installations, especially in the MW range. For purposes of deriving models for use in simulation studies, the general classification of wind turbine generators is as follows [8]

Type1-Conventional directly connected induction generator

Type2-Wound rotor induction generator with variable rotor resistance

Type3-Doubly-fed induction generator (DFIG)
Type4-Full converter machine rotor induction generator;

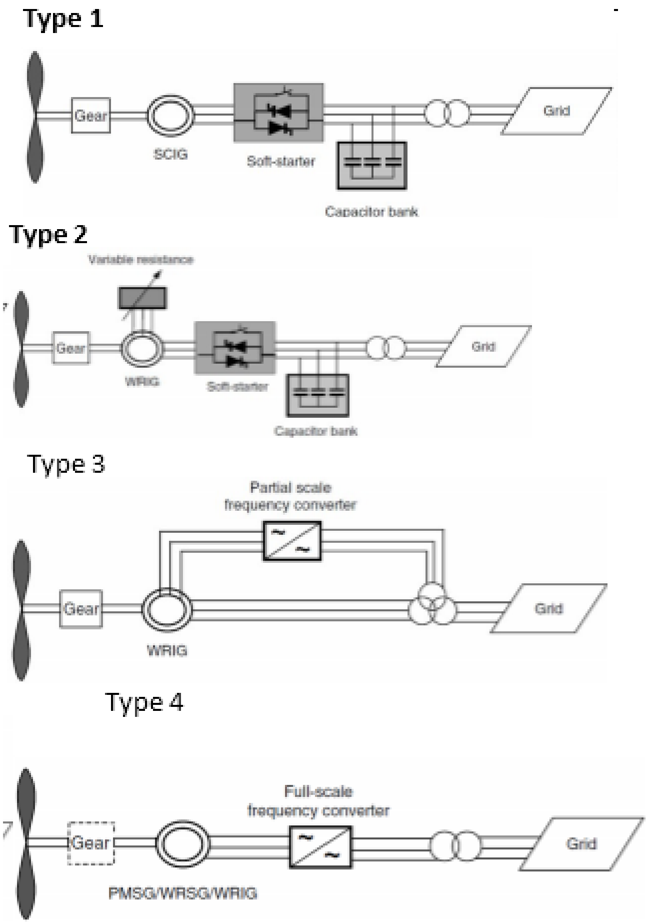


Fig.1.4. Typical wind turbine configurations. SCIG: squirrel cage induction generator; WRIG: wound, PMSG: permanent magnet synchronous generator; WRSG:wound rotor synchronous generator.

The broken line around the gearbox in the type 4 configuration indicates that there may or may not be a gearbox [9].

The type 3 wind turbine is the most widely used concept today [10]. In contrast to the type 1 and type 2 wind turbines; the wind turbine equipped with type 3 is variable speed and a fully controlled system with enhanced dynamic performance. Variable speed operation has two main advantages: (1) more energy is able to be extracted from the wind; and (2) power fluctuations are smoothed and mechanical stresses on the shaft and gearbox are reduced. The DFIG concept utilizes a wound rotor induction machine with an AC current applied to the rotor windings, thus it can be regarded as a traditional induction generator with a nonzero rotor voltage [11]. Variable speed operation is enabled by controlling the frequency of the current applied to the rotor with respect to that of the stator. The stator of the generator is directly coupled to the grid at a fixed frequency whereas the rotor is supplied via a converter at a different frequency. As such the generator is said to be “doubly-fed”. The converter, which is connected between the rotor circuit and the grid, effectively decouples the grid frequency from the rotor mechanical frequency. An advantage of DFIG is that, since the frequency converter only has to deal with the rotor power, then it needs only to be partially rated. This makes it more economical than the Type 4 wind turbine, where a fully rated converter connected between the stator and the grid is required. A speed variation of 30% around synchronous speed can be achieved with a power converter rated at 30% of nominal power [5]. Its main drawbacks are the additional protection in the case of grid faults and the use of slip rings, which makes the electrical connection to the rotor. The power converters feeding the rotor winding are usually controlled in a current regulatedPWM type, thus the stator current can be adjusted in magnitude and angle. The DFIG is controlled in a rotating d-q reference frame, with the d-axis aligned with the stator flux vector [12]. A control loop is needed to be able to control d- and q-axis currents by adjusting the pulse width-modulation indices and hence the AC-voltages of the rotor-side and grid-side converters [13]. The stator active and reactive powers of DFIG are controlled by regulating the current and the voltage in the rotor. Therefore the current and voltage of the rotor needs to be decomposed into the components related to stator active and reactive power.Thus d-components correspond to active and q-components correspond to reactive currents. At the grid-side converter, an outer control loop regulates the voltage of the intermediate DC circuit by adjusting the d-axis-current component. The reactive current of the grid-side converter can be used for sharing reactive power between the stator and the grid-side converter [14].

2. State-of-the-Art of Power Electronics for Integration and Control of Wind Turbines

A standard variable-speed wind turbine concept requires a power electronic system that is capable of adjusting the generator frequency and voltage to the grid. Power electronics have two strong features [9].

Power electronic converter systems of self-commutated type are normally adopting pulse width-modulated (PWM) control methods; the semiconductors with turn-OFF ability, such as IGBTs, are mainly used. This type of converter may transfer both active power and reactive power [16] in both directions (ac–dc or dc–ac). This means that the reactive power demand can be delivered by a PWM converter. The high-frequency switching of a PWM converter may produce harmonics and inter harmonics, which, in general, are in the range of some kilohertz. Fig. 2.1 shows a typical power electronic converter consisting of self-commutated semiconductors such as IGBTs [5].

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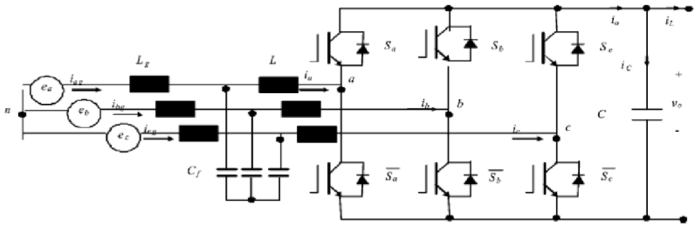


Fig. 2.1.Circuit diagram of a VSC with IGBTs.

Some major power electronic applications in variable speed wind turbines is explained hereby.

Power Electronics for Variable-Speed Wind Turbines

Variable-speed operations of wind turbine system have advantages of having less wear and tear on the tower, gearbox, and other components in the drive train. Also, variable-speed systems can increase the production of the energy and reduce the fluctuation of the power injected into the grid [5].

1) Wounded Rotor Induction Generator With Rotor Resistance Control (Dynamic Slip Control): In this scheme, by controlling the active power of the converter, it is possible to vary the rotational speed of the generator, and thus the speed of the rotor of the wind turbine.The DFIG normally uses a back-to-back converter, which consists of two bidirectional converters sharing a common dc link, one connected to the rotor and the other one to the grid. The power electronic converters for variable-speed generators have the ability to control both the active and reactive power delivered to the grid. This gives potential for optimizing the grid integration with respect to steady-state operation conditions, power quality, voltage, and angular stability. The reactive power to the grid from the generation unit can be controlled as zero or to a value required by the system operator within the converter rating limit. The control system of a variable-speed wind turbine with DFIG mainly functions to: [5]. 1) Adjust the power drawn from the wind turbine in order to track the optimum operation point;limit the power in the case of high wind speeds;

Regulate the reactive power exchanged between the wind turbine and the grid.

In a DFIG control technology, a vector control approach is adopted for the rotor controller, while two cross coupled controllers adjust the speed and power of the system.The goals of such controllers are to track the optimum operation point, limit the power in the case of high wind speeds, and control the reactive power exchanged between the wind turbine generator and the grid. The control of the grid-side converter keeps a constant dc-link voltage while injecting the active power to the grid. Internal current loops in both converters are typically using proportional–integral (PI) controllers. Most wind turbines use the pitch angle of the blades to limit the power when the turbine reaches the nominal power. Below the maximum power production, the wind turbine will vary the speed proportional to the wind speed and keep the pitch angle nearly fixed. At a very low wind, the speed of the turbine will be fixed at the maximum allowable slip to avoid overvoltage. The wind turbine control, with slow dynamic response, supervises both the pitch system of the wind turbine as well as the active power set point of the DFIG control level.

2) Wind Turbine Systems With Full Rated Power Electronic Converters:

Cage induction generators and synchronous generators may be integrated into power systems with full rated power electronic converters. The wind turbines with a full scale power converter between the generator and grid give the added technical performance. [2], [15].

3 . Maximum Wind Power Control

The power generated by a wind turbine can be expressed as

Pm=1/2ρπR2V 3Cp **2.1.**

Where ρ is the air density [kg/m3], R is the turbine rotor radius [m], V is the wind speed [m/s], and CP is the turbine power coefficient that represents the power conversion efficiency of a wind turbine. CP is a function of the tip speed ratio (TSR) designated as λ which is determined by the blade design, and the pitch angle (θ).

TSR is given by, $\lambda = R\omega_{WTR}/V$ where ω_{WTR} is the wind turbine rotor speed.

The Betz limit, CP,max(theoretical) = 16/27. In practice, it is 40%–45% [5].

Numerical approximations have also been developed to calculate Cp for given values of θ and λ as shown in equation 2.2 below [3].

$$C_p(\theta,\lambda) = 0.22\left(\frac{116}{\lambda_i} - 0.4\theta - 5.0\right)e^{\frac{-12.5}{\lambda_i}} \quad 2.2.$$

With

$$\lambda_i = \frac{1}{\frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1}} \quad 2.3.$$

The resulting C p curves are displayed in Fig.2.2.

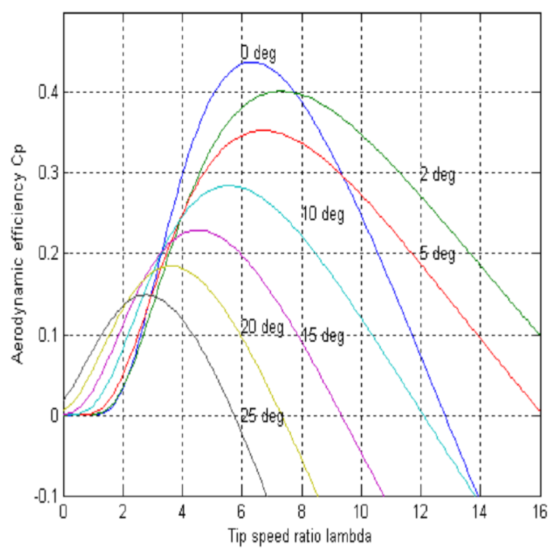


Figure 2.2 Power coefficient Cp curves as a function of tip speed ratio and pitch angle.

Normally, a variable-speed wind turbine follows the CP,max to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at the optimum TSR, λopt. An example of the relationship between the wind speed and the power generated by the wind turbine is shown in fig.2.3. As shown in the figure 2.3, the blades start to move around 4 m/s which is cut-in speed in most cases, and optimal aerodynamic efficiency is achieved up to the rated wind speed, about 15 m/s. Between the rated wind speed and cut-out speed, 25 m/s, the power delivered is limited in order to avoid overloading on the wind turbine system. Over the cut-out wind speed, the turbine has to be stopped in order to avoid damages. During the optimal efficiency wind speed range, the wind generator may be adjusted to follow the maximum power point by performing maximum power point tracking (MPPT) control for wind turbines [15].

i)*TSR Control:* Fig. 2.2 shows this kind of MPPT controller, which needs the wind speed measured by an anemometer. The controller regulates the wind turbine speed to maintain an optimal TSR [5]. However, the accurate wind speed may be difficult to obtain.

ii) *Power Signal Feedback (PSF) Control:* This control, depicted in Fig. 2.5, requires the knowledge of the maximum power curves of the turbine, which may be obtained through simulations and practical tests [5]

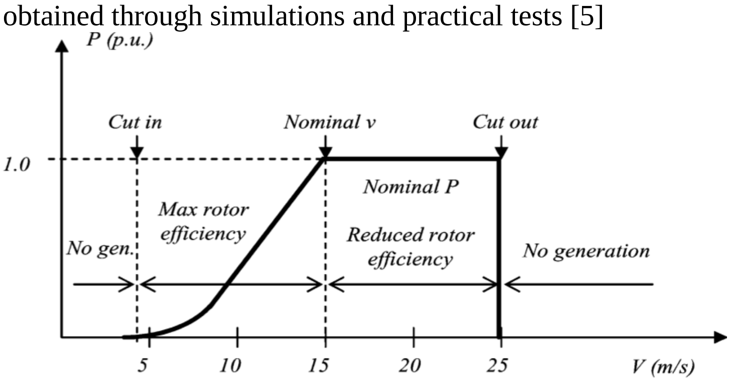


Fig. 2.3. Output power of a wind turbine as a function of the wind speed.

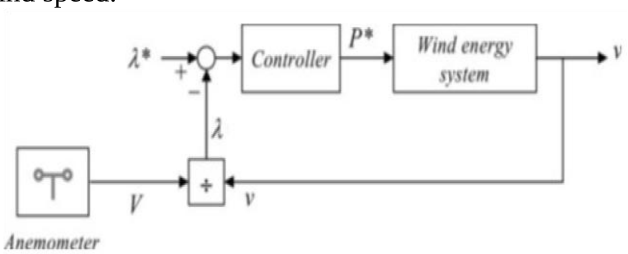


Fig. 2.4. Block diagram of the TSR

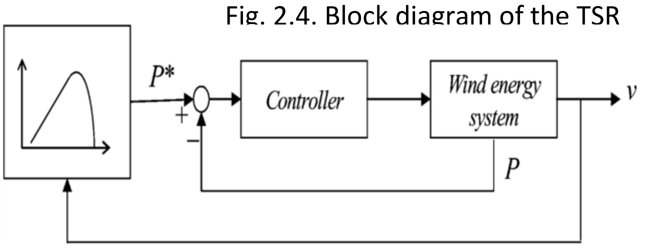


Fig. 2.5. Block diagram of the PSF control.

Pitch Control in Wind Turbines

The maximum power output in wind turbines is normally around at 15 m/s. In case the speed is higher, it would be necessary to limit the power transfer to the shaft in order to protect the system and avoid damaging in the wind turbine. Though, a power control in wind turbines is needed [18].

In the pitch control, the turbine's electronics check the power output of the turbine several times per second. When the power output is too high, a signal is sent to the blade to turn around, to pitch slightly out of the wind, and then receive less wind power. Each blade has to be able to turn around its longitudinal axis. During normal operation, the blades will pitch a fraction of degree while the rotor turns. The pitch mechanism normally uses hydraulics or electric stepper motors.

3. **Power Quality Problems and Improvement Methodologies with Power Electronic Devices***3.1.Introduction*

Large-scale integration of wind turbines may have significant impacts on the power quality and power system operation. This is mostly important when study carried over weak grids. Traditionally, wind turbines are not used to participate in frequency and voltage control. However, in recent years, attention has been increased on wind farm performance in power systems [19, 17]. Consequently, some grid codes have been redefined to specify the requirements that wind turbines must meet in order to be connected to the grid. Examples of such requirements include the capabilities of contributing to frequency and voltage control by continuously adjusting active power and reactive power supplied to the transmission system, the power regulation rate that a wind farm must provide, flicker, harmonics, etc. Some of the requirements are dealt with by power electronic technology, for example, reactive power control.

3.2. Power Quality Problems

Power quality problem is any power problem manifested in voltage, current, or frequency deviation that results in failure or malfunctioning of customer equipment which is resulted due to non-sinusoidal wave forms. Perfect power quality means that the voltage is continuous and sinusoidal having continuous amplitude and frequency and it can be represented interims of physical characteristics and properties of electricity. It is most often described interims of voltage, frequency and interruptions. The most frequent and applicable in wind turbines are:

3.2.1. Flickers

Grid-connected wind turbines may have considerable fluctuations in the output power, as the wind is a weather-dependent power source. Various references indicate that the grid suffers voltage fluctuations and flicker as the wind turbines' output power flows into the grid varies.

The flicker produced by grid-connected wind turbines during continuous operation is mainly caused by fluctuations in the output power due to wind speed variations, the wind gradient and the tower shadow effect. As a consequence an output power drop will appear three times per revolution for a three-bladed wind turbine

In order to prevent flicker emission from impairing the voltage quality, the flicker evaluation based on IEC 61000-3-7 gives guidelines for emission limits of fluctuating loads in medium-voltage and high-voltage networks. Determination of flicker emission can be done on the basis of measurement. In fact, the flicker meter specified in IEC 61000-4-15 can be used to measure flicker directly [5]. The flicker emissions may also be estimated with the coefficient and factors cf(Ψk, va) and kf (Ψk) obtained from the measurements, which are usually provided by wind turbine manufacturers [14].

Voltage variation and flicker emission of grid-connected wind turbines are related to many factors, including [3].

1) Short-circuit capacity ratio SCR = Sk /Sn, where Sk is the short-circuit capacity of the grid where the wind turbines are connected and Sn is the rated power of the wind turbine.

2) Types of wind turbines (e.g. fixed speed, variable speed).

The most important grid parameter affecting the flicker severity is the short circuit capacity (SCC). By increasing the SCC, the grid will be stronger and power quality problems will be reduced.

The grid impedance angle is so important that, if a proper value is chosen, the voltage changes from the varying active power flow will be cancelled by that from the varying reactive power flow and, therefore, the voltage fluctuations and the flicker level are reduced [3]. The determining factor is the difference between the grid impedance angle and the wind turbine power factor angle. When the difference approaches 90^0, the flicker emission is minimized. A simulation study has been carried out to investigate the flicker minimization by using reactive power compensation. The results indicate that the flicker level is significantly reduced if the angle difference (ψ-ψk) is regulated to be 90^0 by controlling the reactive power flow. The wind turbine output reactive power may be controlled to vary with the output active power so that the difference between the grid impedance angle ψk and the power factor angle ψ may approach 90^0, which leads to reduced flicker levels [5].

3.2.2. Fault Ride-Through of Induction Generators

During short-circuit fault in the power system, terminal voltage drops and short circuit current increases whose magnitude depends on the location of fault in the network. The output electrical power and the electromagnetic torque of the wind turbine will significantly reduce because of the dip in terminal voltage, whereas the mechanical input torque to the wind turbine remains the same. Consequently, the turbine and generator will accelerate, leading to increased rotor speed. On fault clearance, as the terminal voltage tends to recover, large amount of reactive power is required to re-establish the air-gap flux of the induction generator owing to large speed deviation [14]. This causes the wind generators to draw large reactive power from the grid which in turn causes additional voltage drop at the point of common coupling. This could prevent the machine terminal voltage returning quickly to the nominal value. Due to the voltage dip, the output electrical power and the electromagnetic torque of the wind turbine are significantly reduced, while the mechanical torque may be still applied on the wind turbine.Consequently, the turbine and generator will be accelerated due to the torque unbalance. The methods to achieve the target may be different. However, the main tasks are voltage recovery and speed control. Only if the voltage level is restored, the magnetic field of the generators can be re-established, and then, electromagnetic torque can be restored. Therefore, a quick recovery of voltage and re-establishment of the electromagnetic torque are crucial. The over speed of a generator may also be limited by controlling the input mechanical torque [5].

3.2.3. Harmonics

Voltage deviations from the perfect sine wave shaped 50Hz/60Hz curve give harmonics and noise. A variable speed wind turbine with a frequency converter will cause harmonic voltage in the grid, because a frequency converter generates an imperfectly sine wave shaped current. And because of the grid impedance, harmonic current will cause harmonic voltage. The amplitude of the harmonic voltage depends on the amplitude of the harmonic current and the grid impedance at the current frequency. Modern PWM frequency converters for variable speed wind turbines will typically operate with a switch frequency over 2kHz, and ideally noise will only be generated around integer multiples of switch frequency. CENELEC EN50160 gives limits on the content of harmonics up to the 40^{th}order. Standards for harmonics in the frequency range above 2 kHz, i.e. for harmonics over the 40^{th}order are not present directly in any known standard. Wind turbines without frequency converters will in generally not cause harmonic voltage problems because the generator is connected directly to the grid [1].

4. Reactive power compensation and voltage control

Reactive power compensation is the absorption or generation of reactive power to maintain efficient and reliable operation of the power system and its loads. It can be used to: (1) maintain load voltages and/or voltages of a transmission network within maximum and minimum limits, (2) increase the power transmission capability of lines while maintaining stability of the power system and (3) minimize the reactive power flow in the circuits, by compensating large reactive power consuming loads locally, and thus reduce the network losses [4]. For wind turbines with PWM converter systems, the reactive power can be controlled by the converter after modeling the system and simulating the outputs by using various soft wares like Matlab-simulink/Powersim/DigSILENT etc. Thus, these wind turbines have the possibility to control voltage by controlling the generation or consumption of reactive power. The reactive power control can be conducted by following the power system requirement to contribute to the power system voltage control; it can also be performed to minimize the possible voltage fluctuations caused by wind power fluctuations [4].

4.1.*1. Power Compensation*

Voltage stability problems may be derived from the need for reactive power of some wind turbines. This fact becomes more important during a voltage dip since in this case; the problem is to generate enough reactive power for the wind generators. Some existing solutions for transient and steady-state voltage control are as follows.

Synchronous condenser (SC), which is a synchronous machine running without a prime mover or a mechanical load [20-21]. The reactive power output of this device is controlled by the field excitation and using a voltage regulator, the SC can automatically adjust the reactive power exchange with the grid to maintain constant terminal voltage.

Static var compensator (SVC), which is a number of shunt-connected capacitors generating and reactors absorbing reactive power and whose outputs are coordinated [20, 22-23]. The term “static” indicates that the device contains no moving or rotating components. These systems use thyristor-controlled components, typically thyristor-controlled reactors (TCRs) and TSCs, also together with Mechanical Switched Capacitors (MSCs) to obtain a dynamic controller of reactive power. Normally, SVCs are connected to the collector bus that connects the wind farm to the PCC to provide a desired power factor or voltage level.The SVC can adjust the reactive power, thus to basically solve the steady-state voltage problems.

STATCOM (Static Synchronous Compensator) which is the voltage source converter controlled by the power electronics with IGBT-switches [4]. In some publications, this unit can also be termed as a static synchronous compensator [23]. As shown in Fig. 4.4, the VSC is connected to the grid to inject or absorb reactive power through an inductor X. This system is suitable to mitigate both steady state and transient events. Compared with SVCs, STATCOMs provide faster response, less disturbances, and better performance at reduced voltage levels. The STATCOM can help mitigating the flicker due to variations of reactive power absorbed by induction machine-based wind farms. Due to its faster response, when compared with a SVC, the STACOM provides a more powerful reduction of flicker. The reactive power required by the farm is evaluated and a controller drives the STATCOM inverter so as to generate the adequate quantity, making it possible to reduce drastically the reactive power flows towards the grid and therefore, the associated flicker [25]. From Fig. 4.4, if the power angle remains zero (δ=0), the active and reactive power injected to the grid by the STATCOM can be expressed as

$$P=\frac{UgUv\sin\delta}{X}=0 \tag{4.1}$$

$$Q=\frac{U_g U_v \cos\delta}{X}-\frac{U^2{}_g}{X}=\frac{U_g}{X}(U_v\text{-}U_g) \tag{4.2}$$

Consequently, the VSC acts as a reactive power generator (Q>0, capacitive behavior) if UV> Ug, and as a reactive power absorber (Q<0, inductive behavior) if UV< Ug. In practice, a small phase shift is used to compensate the VSC losses. The reactive power injected to the grid can be controlled faster than by using previous systems. The response time is limited by the switching frequency and the size of the inductor [14].

Depending on the factual demands to reactive power controllability, the compensation units can be organized with continuous control, discrete control or as a combination of those both [22]. SC and Statcoms are continuous control units. SC are characterized by relatively high running and maintenance cost because of presence of the rotating and moving parts [21], whilst Statcoms are relatively expensive feature, but with lower running cost. Reactive power control with svc can be organized in several ways, which influences on the feature cost as well.

1) As a continuous reactive power control unit using thyristor-controlled reactors, which is a relatively expensive feature.
2) As a discrete control unit with a number of thyristor- or mechanically switched capacitors and reactors, this is a relatively cheap feature.
3) As a combination of discrete and continuous units, where the cost of the feature is optimized knowing the factual demands of the reactive power demands from power stability investigations.
4) 4) In a practical solution, a number of already exciting shunt-capacitors and reactors in the near power grid can be ordered to switch on or off by the control system of the SVC for expanding its controllability and reducing the cost of the project.

5) The running cost of SVC is lower than the running cost of SC, but the continuously controlled SVC can be a more expensive feature than SC [21].

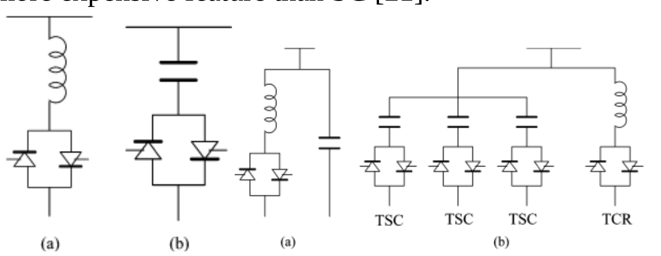


Fig. 4.2. SVC basic Fig. 4.3. Combination

components of SVCs

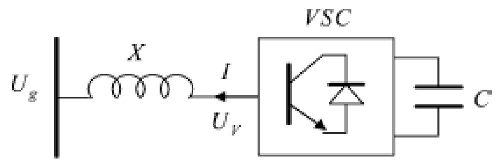
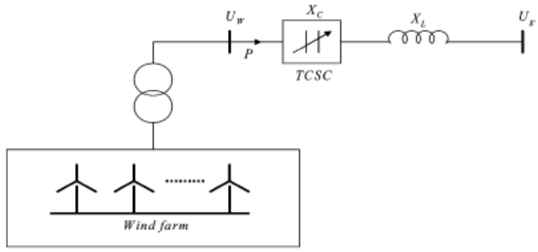
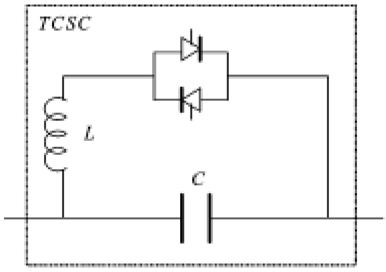


Fig. 4.4. STATCOM based on VSC connected to the PCC through an inductor.



(a)

Fig. 4.5.TCSC. (a) Wind farm connection



(b)

(b) Detail of the TCSC.

The power of TCR in fig.4.2 (a) is controlled by changing the current flow through the inductor by means of the switch. The ON-state of the thyristors can be adjusted by the firing angle. However, this device generates current harmonics due to the current waveform.

A TSC is shown in Fig. 4. 2(b), which consists of a bank of switched capacitors. Each capacitor has an individual static switch, which is similar to a TCR device, but in this case, the switching takes place when the voltage across the thyristor is zero. Consequently, this device does not produce current harmonics. However, due to the use of switching capacitors, TSC may produce voltage transients. The combinations between these components can provide good performances of compensation. For instance,TCR can be combined with fixed capacitors or with TSC, as shown in Fig. 4.3. In the first case, a TCR is used incombination with a fixed capacitor bank. This solutionis often used for subtransmission and distribution. The current harmonics may be eliminated by tuning the fixed capacitors as passive filters. The second case combines TCR and TSC in one compensator system. Hence, a continuously variable reactive power is obtained across the entire control range plus full control of both inductive and capacitive parts of the compensator [5].

5. Modelling and control of grid-connected wind turbines with DFIG

To investigate the power quality issues of grid-connected wind turbines and their interaction with the grid, a proper model of grid-connected wind turbines shall be established. The grid-connected wind turbine model simulates the dynamics of the system from the turbine rotor where the kinetic wind energy is converted to mechanical energy, to the grid connection point where the electric power is fed into it The complete grid-connected wind turbine model includes the wind speed model, the aerodynamic model of the wind turbine, the mechanical model of the transmission system, models of the electrical components, namely the generator (DFIG; PMSG; etc), PWM voltage source converters, transformer, capacitor, and the control system as shown in figure 5.1(b) [2].

Aerodynamic model, evaluates the turbine torque Tt as a function of wind speed Vv & the turbine angular speed Ωt.

Pitch system, evaluates the pitch angle dynamics as a function of pitch reference βref

Mechanical system, evaluates the generator and turbine angular speed (ωm and Ωt) as a function of turbine torque and generator torque Tem.

Electrical machine and power converters transform the generator torque into a grid current as a function of voltage grid.

Control system, evaluates the generator torque, pith angle and reactive power references as a function of wind speed and grid voltage.

Figure 5.1 shows the interaction between the different subsystems

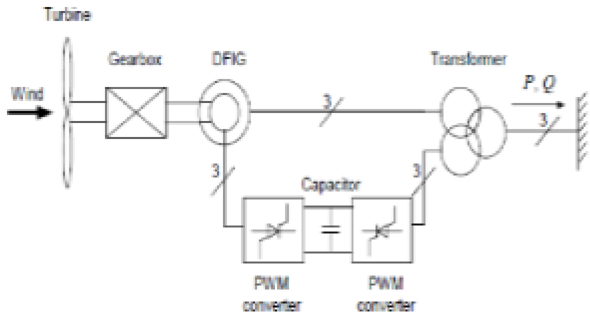
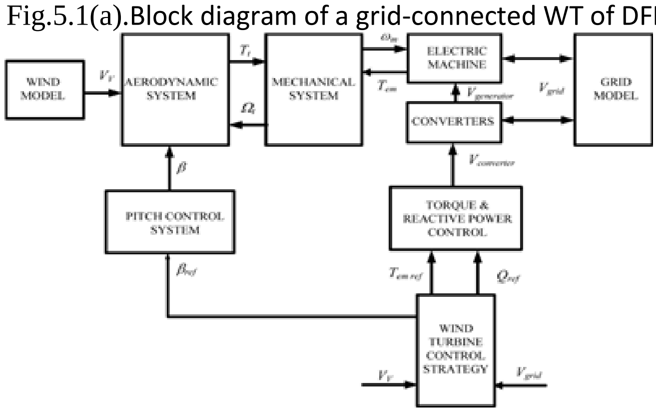


Fig.5.1(a).Block diagram of a grid-connected WT of DFIG.



b). Block scheme of a variable speed

5.1. Wind Speed Model

The output of the first block in Figure 5.1 is a wind speed sequence. This can be a sequence of measurements, but a collection of measurements will not generally cover the

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whole range of wind characteristics, such as speed range or turbulence intensity, which a wind turbine will experience. A more flexible approach is to use a wind speed model that can generate wind speed sequences with certain characteristics. Wind can be described byfour components [19]:

- an average wind speed;
- a ramp component, representing a steady increase in wind speed;
- a gust component, representing a gust;
- a component representing turbulence.

However, in most cases the average incident wind speed on swept area by the blades can be taken.

5.2. Aerodynamic model

The wind turbine rotor that extracts the energy from the wind and converts it into mechanical power is a complex aerodynamic system. A wind turbine as characterized by its aerodynamic power and aero dynamical torque may be described by the following equation:

$$P_m = \frac{1}{2}\rho\pi R^2 v_{eq}{}^3 C_p(\theta,\lambda) \qquad 5.1.$$

The corresponding aerodynamic torque can be expressed as

$$T_m = \frac{1}{2}\rho\pi R^2 v_{eq}{}^3 C_p(\theta,\lambda)/\lambda = \frac{1}{2}\rho\pi R^3 v_{eq}{}^2 C_t \qquad 5.2.$$

Where C_t is the coefficient of torque. Numerical approximations to calculate Cp for a given values of θ, where θ is the pitch angle of rotor [deg], is [3]

$$C_p(\theta,\lambda) = 0.22(\frac{116}{\lambda_i} - 0.4\theta - 5.0)e^{\frac{-12.5}{\lambda_i}} \qquad 5.3.$$

And

$$\lambda_i = \frac{1}{\frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1}} \qquad 5.4.$$

5.2.1. Maximum Power Tracking of Variable Speed Wind Turbine

In the time when the wind speed is in the range of cut-in and rated value, the maximum aerodynamic power available in the wind can be captured. The maximum power in a mass of wind can be extracted by varying the turbine speed with the varying wind speed so that at all times it is on the track of the maximum power curve [21]. For efficient wind power captured by the variable wind turbine λ =λopt, therefore, tip speed ratio can be re-written as

$$V = R\omega_{WTR}/\lambda_{opt} \qquad 5.5$$

Substituting, optimum power can be obtained as

$$P_{opt} = \frac{1}{2}\frac{\rho\pi R^5 C_p(\lambda_{opt},\theta=0)v^3}{\lambda_{opt}{}^3} \qquad 5.6$$

$$P_{opt} = k_{opt} v^3 \qquad 5.7$$

$$k_{opt} = \frac{1}{2}\frac{\rho\pi R^5 C_p(\lambda_{opt},\theta=0)}{\lambda_{opt}{}^3} \qquad 5.8$$

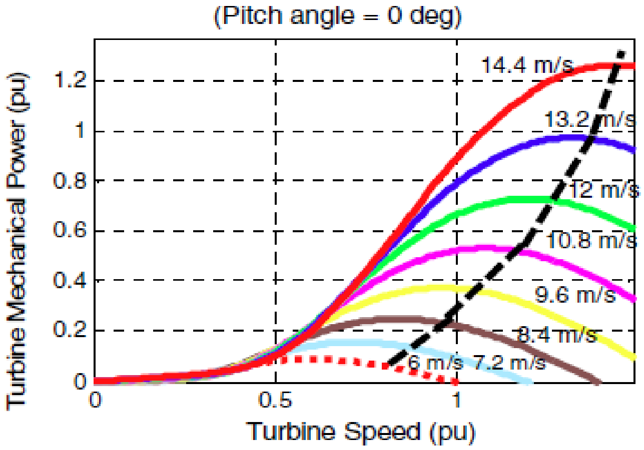

Fig. 5.2.Maximum torque tracking of a variable speed wind turbine

5.3. Rotor Model

The power in the wind providing the mechanical torque is given in equation 5.1. i.e.

$$P_W = \frac{1}{2}\rho A_r C_p(\theta,\lambda)v^3$$

Most variable-speed wind turbines are pitch controlled, and here assumption of pitch control is used in the system. The power coefficient is then a function of the tip-speed ratio λ and the pitch angle θ. A numerical approximation for the cp curve based on documentation from a particular manufacturer can be found. Issues such as the smoothing of high-frequency components over the rotor surface, and tower shadow, are less critical for variable-speed turbines because of the decoupling of electrical and mechanical behavior of power electronics. Care must be taken, however, if simulations include the bypassing of the rotor converter [9].

5.4. Modelling of the DFIG

A common used model for the DFIG is the Park model. The model in the two-phase system in the arbitrary reference frame is as follows [3], where the quantities on the rotor side are referred to the stator side.

$$u_{ds} = r_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega\psi_{qs}$$
$$u_{qs} = r_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega\psi_{ds}$$
$$u_{dr} = r_r i_{dr} + \frac{d\psi_{dr}}{dt} - (\omega-\omega_r)\psi_{qr}$$
$$u_{qr} = r_r i_{qr} + \frac{d\psi_{qr}}{dt} + (\omega-\omega_r)\psi_{dr}$$
$$\psi_{ds} = L_s i_{ds} + L_m i_{dr}$$
$$\psi_{qs} = L_s i_{qs} + L_m i_{qr}$$
$$\psi_{dr} = L_r i_{dr} + L_m i_{dr}$$
$$\psi_{qr} = L_r i_{qr} + L_m i_{qs} \qquad 5.5.$$

Where Ls=Lls+ Lm and Lr= Llr+ Lm

where Uds; Uqs; Udr; Uqr; ids, iqs, idr, iqr and ψds, ψqs, ψdr , ψqr are voltages [V], currents [A] and flux linkages [Wb] of the stator and rotor in d- and q-axis, rs and rr are the resistances of the stator and rotor windings [Ω], Ls, Lr, Lm are the stator, rotor and mutual inductances [H], Lls, Llr are the stator and rotor leakage inductances [H], w is the speed of the reference frame [rad/s], wr is the electrical angular velocity of the generator rotor [rad/s].

By calculating the apparent power and taking the real parts the following equations represent the stator-side and rotor-side active power respectively.

$$P_s = \frac{3}{2}(u_{ds}i_{ds} + u_{qs}i_{qs})$$
$$P_r = \frac{3}{2}(u_{dr}i_{dr} + u_{qr}i_{qr})$$
$$Pg = \frac{3}{2}(P_s + P_{r=}u_{ds}i_{ds} + u_{qs}i_{qs} + u_{dr}i_{dr} + u_{qr}i_{qr}) \qquad 5.6.$$

The rotor-side active power can also be found from the following equation$P_r = -sP_s$

Accordingly the imaginary parts of the apparent power represent the stator-side and rotor side reactive power respectively.

$$Q_s = \frac{3}{2}(u_{qs}i_{ds} - u_{ds}i_{qs})$$
$$Q_r = \frac{3}{2}(u_{qr}i_{dr} - u_{dr}i_{qr})$$
$$Qg = Q_s + Q_r = \frac{3}{2}\left[u_{qs}i_{ds} + u_{qr}i_{dr} - (u_{ds}i_{qs} + u_{dr}i_{qr})\right] \qquad 5.7.$$

The mutual flux between rotor and stator produces magnetic energy, which is stored in the magnetic field. This energy produces an electromagnetic torque which is calculated as

$$T_G = \frac{3}{2}PLm(i_{qs}i_{dr} - i_{ds}i_{qr}) \qquad 5.8.$$

Where P is the number of pole pairs.

An equivalent circuit may be set up by means of the voltage and flux linkage equations of the arbitrary reference frame, as shown in Fig 5.3.

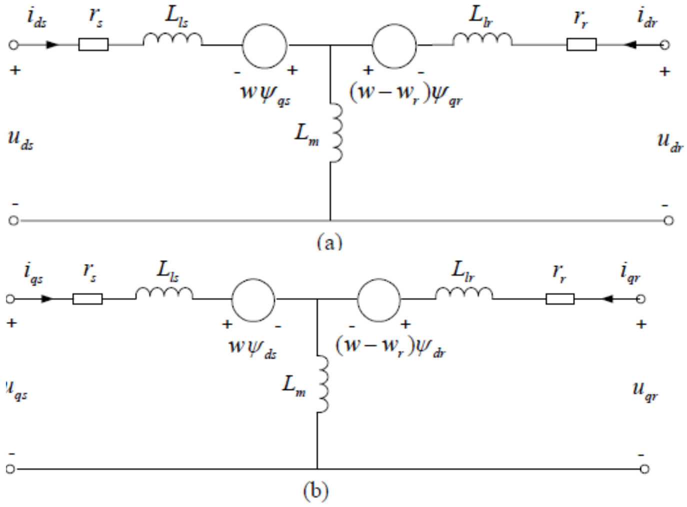

Fig. 5.3 Eqt.ckt of dq-model in arbitrary reference frame.(a) d-axis eqt. ckt; (b) q-axis eqt.ckt.

It should be emphasized that the reactive power Qg in Equation (5.7) is not necessarily equal to the reactive power fed into the grid, which is the quantity used for the load-flow solution. The value of Qg depends on the control strategy of the grid side of the power electronic converter that feeds the rotor winding, but the value for Pg does not. Even though the converter can generate or consume reactive power, it does not generate, consume or store active power, at least not for long enough to be of any interest in Power System Dynamic Simulations. The expression for Pg in Equation (5.6) gives the total active power generated by the DFIG. That means, all active power fed into the rotor winding will be drawn from the grid, and all active power drawn from the rotor winding will be fed into the grid.

5.5. DC Link model

The dc-link model describes the dc-link capacitor voltage variations as a function of the input power to the dc-link [29]. The energy stored in the dc capacitor is

$$W_{dc} = \int P_{dc}\,dt = \frac{1}{2}CV_{DC}{}^2 \qquad 5.9$$

Where C is the capacitance, Vdc is the voltage, Wdc is the stored energy, and Pdc is the input power to the dc link. The voltage and energy derivatives are. The Pdc is calculated as Pdc = Pin –Pc. Where Pin is the input power from rotor-side converter and Pc is the grid-side converter output power. The dc-link voltage varies as Pdc and is a constant when Pdc = 0.

$$\frac{dV_{dc}}{dt} = \frac{P_{dc}}{CV_{dc}}, \frac{dW_{dc}}{dt} = P_{dc} \qquad 5.10$$

5.6. Converter Model

The converter of the DFIG is modelled as a fundamental frequency voltage source. The model is only a low-

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frequency representation of the converter dynamics which does not include any switching phenomena and is not suitable for investigating high-frequency phenomena associated with power electronics.

The machine-side converters are represented as voltage sources, so the rotor voltage set points are applied directly to the rotor windings. If the frequency of the voltage is continuous, and very close to the synchronous frequency, then we can view all quantities as being in a frame where the q-axis coincides with the maximum of the terminal voltage. Then:uds= 0; uqs=us; 5.11

Where us is the stator voltage magnitude. If the stator resistance is neglected, then the electrical torque can be written as:

$$Te = -\frac{3}{2} P \frac{L_m u_s i_{qr}}{\omega s (L_{1s} + L_m)} \qquad 5.12$$

These voltages can be set depending on what current is required. The current set points can be derived from the set points for active and reactive power. The active power set point is generated by the rotor speed controller, based on the actual rotor speed value. The reactive power set point is generated by the terminal voltage or power factor controller, based on the actual value of the terminal voltage or the power factor. Both controllers will be discussed below.

The total reactive power exchanged with the grid depends not only on the control of the generator, but also on the control of the grid-side converter. The reactive and active powers of the converter are:

$$Pc = \frac{3}{2}(u_{rc} i_{rc} + u_{ic} i_{ic}), \qquad 5.13$$

$$Qc = \frac{3}{2}(u_{ic} i_{rc} - u_{rc} i_{ic}), \qquad 5.14$$

Where the subscript c stands for converter and r and i denote real and imaginary components. In these equations Pc is equal to the rotor power of the DFIG. Pr given in equation (5.6). This may be multiplied with the converter efficiency if the converter losses are to be included. The reactive power exchanged with the grid equals the sum of Qs from equation (5.7) and Qc from equation (5.14). The converter reactive power depends on the control strategy for the grid-side converter and the converter rating. If the reactive power is set to zero, the grid side of the converter operates at unity power factor [9].

5.7. Control system

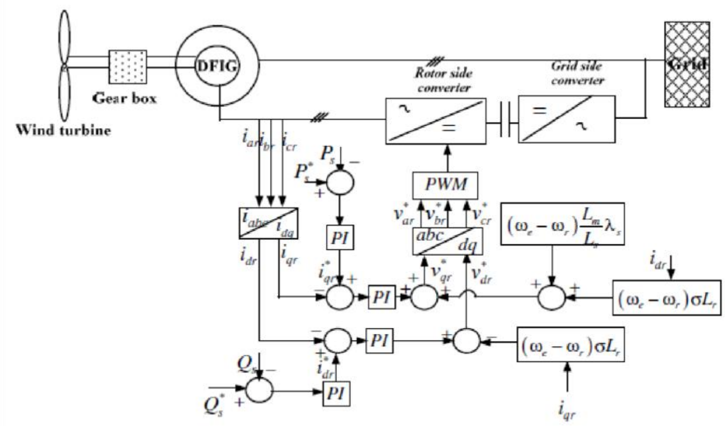
The rotor and grid side converters are so-called 'vector controlled'. The vector control method is based on the d-q transformation of the machine and system quantities. For the DFIG, if the interest is in the control of rotor currents, eq. 5.15 can be used which states the three-phase sequence of currents ia, ib and ic are converted into a two-dimensional space vector which rotates in the complexplane [27

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad 5.15$$

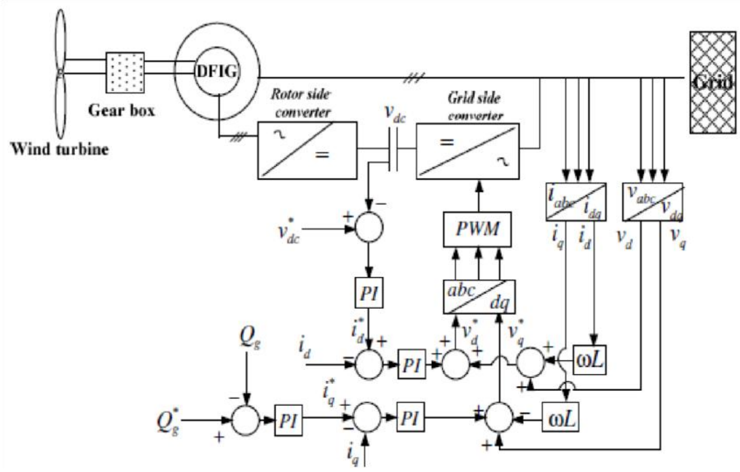
The control of the grid-side inverter is principally the same as for the rotor-side; only the reference frame is different. The control reference for the grid-side inverter control is the three-phase grid voltage which can be resolved into a stationary vector using the following transformations:

$$v_\alpha = \sqrt{3} v_{ab} + \frac{\sqrt{3}}{2} v_{bc} , \qquad v_\beta = \frac{3}{2} v_{bc} \qquad 5.16$$

The block diagram is shown in figure 5.4 (a) and (b) shows rotor and grid side control system.



a).Rotor side Controller system



b).Grid side controller system

Fig. 5.4.control system at rotor side (a) and (b) grid side

6. Conclusion and Future Trends

This review paper has focused on the power quality problems and related improvement methodologies of grid connected wind energy system in different aspects where the authors goes over for further investigations. When the type of wind turbine connected with grid varies, it was observed that there results different performances and controllability. The electrical topologies of such kind of wind turbines are get briefed. It has been shown that the wind farms consisting of different turbines may need different configurations for the best use of the technical merits. Furthermore, the possible methods of improving wind turbine performance in power systems to meet the main grid connection requirements are also touched. There exist standards mainly IEC and IEEE which requires wind farms need to meet. In connection, compensation methods for reactive power are areas touched by the paper. Through the survey, it was again observed that, out of the variable-speed operation generators, the DFIG dominates the current market for variable-speed gear-driven wind turbine systems, largely due to the fact that only the power generated in the generator rotor has to be fed through a power electronic converter system (25–30%). In future, the percentage of wind energy on many grids is expected to be a significant part, thus making wind turbines as key grid players. Therefore, these machines will require a built-in capacity to behave like power plants. Power electronic technologies as the interfaces for wind turbines and as flexible as ac transmission systems(FACTs) devices, such as STATCOM, will play a significant role in developing new state-of-the-art solutions for the future success of various new power generations installed different parts of areas and their associated control principles. It can be concluded as that, the increased number of wind turbines connected with weak grid rise power quality problems mainly in voltage fluctuation, harmonics, flicker, fault ride through, reactive power and power factor which needs to be minimized to the level of steady state operation points as per IEC, IEEE and other related standards. Reactive power consumption, harmonic distortion (current) also gets raised with increased wind turbine. Thus active power control will play a crucial role during normal operation of the power system especially in weak grid connected at most remote areas like in Ethiopia where the researcher aims for further study.

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