A SURVEY ON VARIABLE-SPEED WIND TURBINE SYSTEM

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Abstract--**This paper presents a review on the main types of generator and static converters used to interface variable speed wind turbine to the electric grid. Initially the static and dynamic characteristics of wind turbines are presented. Then, different types of generators and static converters configurations are described and their main advantages and disadvantages are highlighted.**

Index terms-- **Wind Turbine, Static Converters, Generators**

I. Introduction

Global warming has been attributed to the increase of the atmospheric gases concentration produced by the burn of fossil fuel [1,2]. Wind power generation is an important alternative to mitigate this problem mainly due its smaller environmental impact and its renewable characteristic that contribute for a sustainable development [3]. Three factors have made wind power generation cost-competitive, these are: (i) the state incentives [4,5], (ii) the wind industry that have improved the aerodynamic efficiency of wind turbine, (iii) the evolution of power semiconductors and new control methodology for the variable-speed wind turbine, that allows the optimization of wind turbine performance.

Nowadays, many kinds of wind turbine systems (WTS) compete in the market. They can be gathered in two main groups [10]. The first group operates with almost constant speed "Danish concept" [26]. In this case, the generator directly couples the grid to drive train. The second one operates with variable speed; In this case, the generator does not directly couple the grid to drive train. Thereby, the rotor is permitted to rotate at any speed by introducing power electronic converters between the generator and the grid [21]. The constant speed configuration is characterized by stiff power train dynamics due to the fact that electrical generator is locked to the grid; as a result, just a small variation of the rotor shaft speed is allowed. The construction and performance of this system are very much dependent on the mechanical characteristic of the mechanical subsystems, pitch control time constant, etc. In addition, the turbulence and tower shadow induces rapidly fluctuation loads that appear as variations in the power ($P \approx v^3$). These variations are undesired for grid-connected wind turbine, since they result in mechanical stresses that decrease the lifetime of wind turbine [9,21,26] and decrease the power quality. Furthermore, with constant speed there is only one wind velocity that results in an optimum tip-speed ratio. Therefore, the wind turbine is often operated off its optimum performance, and it generally does not extract the maximum power from the wind [21,29].

Alternatively, variable speed configurations provide the ability to control the rotor speed. This allows the wind turbine system to operate constantly near to its optimum tip-speed ratio. The following advantages of variable-speed over constant-speed can be highlighted:

(i) The Annual Energy Production (AEP) increases because the turbine speed can be adjusted as a function of wind speed to maximize output power. Depending on the turbine aerodynamics and wind regime, the turbine will on average collect up to 10% more annual energy [21].
(ii) The mechanical stresses are reduced due to the compliance to the power train. The turbulence and wind shear can be absorbed, i.e., the energy is stored in the mechanical inertia of the turbine, creating a compliance that reduces the torque pulsations [24,26].
(iii) The output power variation is somewhat decoupled from the instantaneous condition present in the wind and mechanical systems. When a gust of the wind arrives at the turbine, the electrical system can continue delivering constant power to the network while the inertia of mechanical system absorbs the surplus energy by increasing rotor speed.
(iv) Power quality can be improved by reduction the power pulsations. The reduction of the power pulsation results decreases voltage deviations from its rated value in the point of common coupling (PCC). This allows increasing the penetration of the wind power in the network [24,26].
(v) The pitch control complexity can be reduced. This is because the pitch control time constant can be longer with variable speed [26].
(vi) Acoustic noises are reduced. The acoustic noise may be an important factor when sitting new wind farms near populated areas [24,26].

Although the main disadvantage of the variable-speed configuration are the additional cost and the complexity of power converters required to interface the generator and the grid, its use has been increased due the above mentioned advantages. This paper presents a review of the main configurations of variable-speed WTS, as well as control methods and their characteristics.

The remainder part of this paper is organized as following: Section II presents the wind turbine characteristics. Section III presents a brief description of the control techniques to optimize the output power. Section IV presents the main generators and converters topologies that are applied to variable speed WTS. Section V presents the control and static converter used in WTS. Finally, Section VI summarizes the main points of this paper.

II. Wind Turbines

The performance of WPS depends on the wind turbine characteristics. This section describes the types of wind turbines and presents their static and dynamic characteristics.

A. *Types of wind turbines*

There are two basic configurations of wind turbine, the horizontal axis wind turbines and the vertical axis wind turbine. In addition, the wind turbine rotor can be propelled either by drag forces or by aerodynamic lift. The horizontal or vertical based drag designs operate with low speed and high torque, which can be useful mainly for grinding grains and pumping water [7,15]. On the other hand, the horizontal and vertical based lift designs operate with high speed and low torque, as a result, they have been used for generate electricity [7].

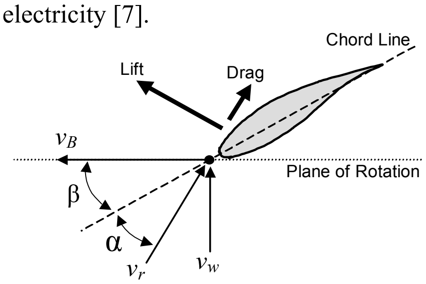

Figure 1. Definitions of lift and drag for 2-D aerodynamics.

In order to understand the basic mechanisms behind of the power generation from a wind turbine it is important to know the forces that act on the blade. The Figure 1 represents the cross section of a rotor blade (or airfoil) and shows the forces that act on it in a 2-D aerodynamics representation. The lift force (L) is produced at right angles to the relative wind velocity (v_r) while drag force (D) is aligned relative to it. The relative wind velocity is the vector resulting of the sum of the blade motion (v_B) and the wind velocity (v_w) vectors [7]. This lift force pulls the blades along its rotary path, causing thrust. The thrust produces the shaft torque. The lift force increases with the increase of the angle of attack in the normal operation region, i.e. before the airfoil reaches the region of stall behavior. In the stall region the lift force stay practically constant independently of the angle of attack. In addition, for a precise estimation of the torque generation, it is important to consider the leakage at the tip of the blades, which can be well described with a 3-D aerodynamics representation. This leakage produces a vortices system that reduces the angle of attack seen locally on the blades and consequently decreases the power extracted from the wind [6]. It is important to note that the local 2-D representation can be used to estimate the power generated on a wind turbine if the angle of attack (α) is corrected accordingly with the vortices system behind the blades. Further, when we select a profile it is important to consider the stall characteristic and the roughness sensitivity. It is also worth to mention that it is usually uneconomic to construct a wind turbine robust enough to operate at all wind speeds. Therefore, it is necessary the use a method for limiting the aerodynamic force on the wind turbine rotor. The mains limiting methods are: passive and active stall regulation [10,11,14], pitch regulation [9,10,12] and furling regulation [11]. Passive stall regulation and pitch regulation are the most used methods for medium and large WPS [10,22] while furling is used for small WPS [4].

B. *Static Characteristics*

The mechanical power extracted from the wind by a wind turbine depends on many factors [10,11,15]. A simple equation is often used to describe the torque and power characteristics of wind turbine, that is

$$p_m = 0.5\rho A c_p(\lambda) v_w^3 \quad \textbf{(w)} \tag{1}$$

where:

c_p	power coefficient;
λ	tip speed ratio (TSR) ($\frac{R\omega_w}{v_w}$);
ω_w	turbine angular speed (rad/s);
R	turbine radius (m);
ρ	air density (kg/m^3);
A	cross section area of the turbine (m^2);
v_w	wind velocity (m/s).

Figure 2 shows the block diagrams representation of this static characteristic, where β is the pitch angle.

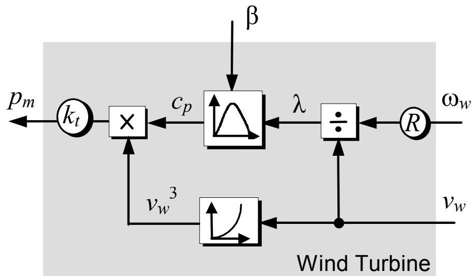

Figure 2. Static Characteristics of Wind Turbine: K_t=0.5ρA

In the equation (1), the power coefficient, $c_p(\lambda)$ depends on the aerodynamics characteristic of wind turbine, as well as the operation conditions. For a fixed pitch angle β, the power coefficient can be expressed as function of tip speed ratio λ [31,36], as shown in Figure 4. For a variable pitch angle, the power coefficient can be expressed as a two dimensional characteristic. In this case, it is function of λ and β [10]. Finally, the relationship between torque and mechanical power is given by the equation [15,16].

$$t_m = p_m \frac{R}{G\lambda v_w} \quad \text{(N.m)} \tag{2}$$

where:

G	speed-up gear ratio

Through of the torque/power characteristic of the wind turbine is possible to select the rotor speed where the efficiency and power generated are maximized [15].

C. Dynamic Models

Generally, control system design and analysis requires a reasonable dynamic model of the plant. In order to facilitate control design as well as the analysis through simulation of wind turbine system a simple dynamic model is desirable. A lumped model is presented in Figure 3. It includes two masses, and yields to a single resonant mode. The motivation to use this lumped model, is that it is simple, yet incorporating the dominating drive train mode [18,19].

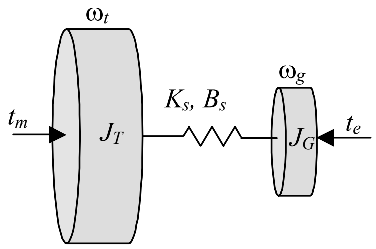

Figure 3. Simplified Wind Turbine Dynamic Model

The model is described by the following equations:

$$t_m - t = J_T \dot{\omega}_t \quad (3)$$

$$t - t_e = J_G \dot{\omega}_g \quad (4)$$

$$t = K_S \int (\omega_t - \omega_g) dt + B_S (\omega_t - \omega_g) \quad (5)$$

Where:

J_T = the wind turbine inertia,
J_G = the generator inertia,
ω_t = turbine rotational speed,
ω_g = generator rotational speed
K_s = shaft stiffness,
B_s = shaft damping,

This dynamic model has been used for physical parameter estimation based on experimental data [17,19,20,33].

Three-dimensional simulation of the dynamic behavior of WPS is presented in [52]. Its essential feature is a multi body simulation of a complete 3-D model of the wind turbine including flexible elements (for example, of the rotor and tower). The advantage in the use of this method is that the developed 3-D simulation permits a safe realistic forecast of normal operation and extreme loads. However, for the purpose of the design of static converters controllers a simpler models are preferable.

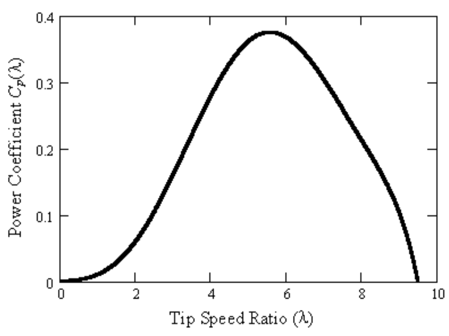

Figure 4. Power Coefficient as a Function of Tip Speed Ratio.

III. Control Strategies for Maximum Power Tracking

This section describes the main techniques that have been reported to the control of wind turbine toward the maximization the output power.

To allow the turbine to transfer a maximum fraction of available wind power for fluctuating wind velocities incident upon the turbine blades, it is desirable to maintain the tip-speed ratio at point of maximum power coefficient $c_p(\lambda)$ in the Figure 4. Based in this principle several control techniques have been developed to optimize output power for a given wind velocity. Some of these measure the wind velocity and adjust the turbine rotating speed to keep the power coefficient at its maximum value [26,35,38,50]. Other techniques employed a Maximum Power Point Tracking (MPPT) algorithm with search for the turbine rotating speed, which result in the maximum power, without measuring the wind speed [30,31,32,51]. Normally, in the MPPT the production of the reference rotating speed is based on a measurement of the power generated Therefore, since the measurement of the power generated is simpler and more accurate than the measurement of the wind velocity, the MPPT is preferred.

IV. Generators and Topologies

In this section it is presented the main configurations of generators and converters used for grid connected variable speed WPS.

A. Synchronous Generators

A synchronous generator usually consist 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.

1) *Wound Field Synchronous Generator* (WFSG)

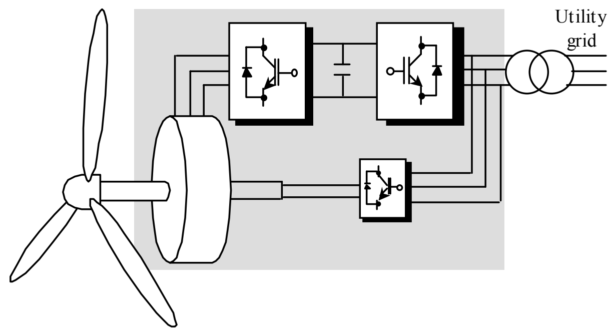

Figure 5. Variable Speed Field Winding Synchronous generator

The WPS with wound field synchronous generator is show in Figure 5. The stator winding is connected to network through a four-quadrant power converter comprised of two back-to-back PWM-VSI. The stator side converter regulates the electromagnetic torque, while the supply 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 [44].
- 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 any operation circumstances [23].
- The pole pitch of this of this generator can be smaller than that of induction machine. This could be a very important characteristic in order to obtain low speed multipole machines, eliminating the gearbox [27].

The existence of a winding circuit in the rotor may be a drawback as compared with permanent magnet synchronous generator. In addiction, to regulate the active and reactive power generated, the converter must be sized typically 1.2 times of the WPS rated power [21,23].

2) *Permanent-Magnet Synchronous Generator* (PMSG)

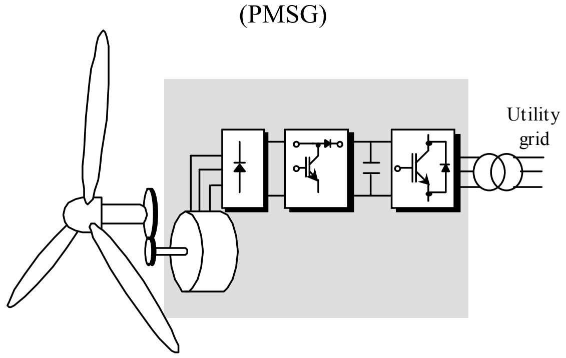

Figure 6. Permanent-Magnet Synchronous Generator with a Boost Chopper.

Figure 6 shows a WPS where a permanent magnet synchronous generator connected to a three-phase rectifier followed by boost converter [23,36,42]. In this case, the boost converter controls the electromagnet torque. The supply side converter regulates de 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 [42]. As a results this configuration have been considered for small size WPS (smaller than 50 kW)

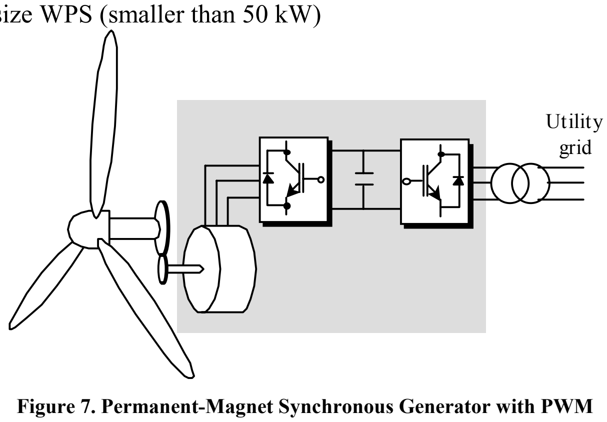

Figure 7. Permanent-Magnet Synchronous Generator with PWM converter.

Other scheme using PMSG is show in Figure 7, in the system, the PWM rectifier is placed between the generator and the DC link, and PWM inverter is connected to the network. The advantage of this system regarding the system showed in Figure 6 is the use of field orientation control (FOC) that it allow the generator to operate near its optimal working point in order to minimize the losses in the generator and power electronic circuit [30]. However, the performance is dependent on the good knowledge of the generator parameter that varies with temperature and frequency [41]. The main drawbacks, in the use of PMSG, are the cost of permanent magnet that increase the price of machine, demagnetization of the permanent magnet material and it is not possible to control the power factor of the machine [21,40].

B. *Induction Generators*

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 [21,22].

1) *Doubly Fed Induction Generator* (DFIG)

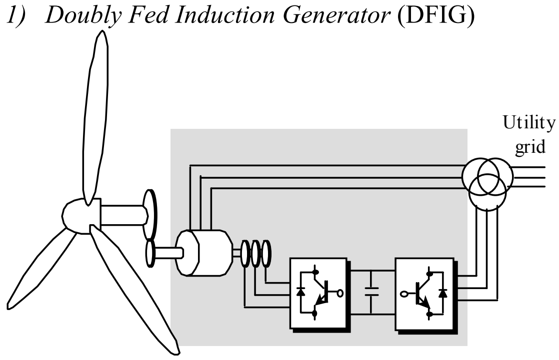

Figure 8. Doubly Fed Wound Rotor Induction Generator

The wind power system shown in Figure 8 consists of a doubly fed induction generator (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 PWM-VSI. The SCR converter can be used but they have limited performance [26]. 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 machine. On the other hand, the controller of the supply side converter regulates the DC link [23,24,38,39,62]. Compared to synchronous generator, this DFIG offers the following advantages:

- 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 [26].
- Reduced cost of the inverter filter and EMI filters, because filters rated for 0.25 p.u. total system power, and inverter harmonics represent a smaller fraction of total system harmonics [26].
- Robustness and stable response of this machine facing against external disturbance [23].

One drawback of DFIG is the use of slip rings that require periodic maintenance, especially at sea shore sites.

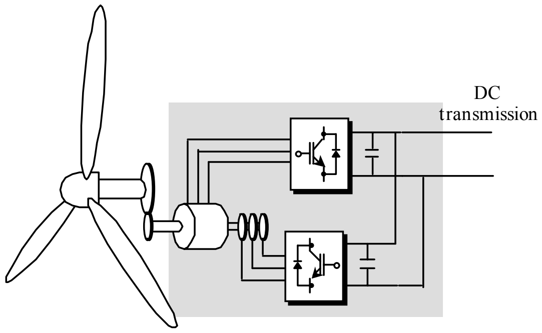

Figure 9. Variable Speed Doubly Fed Full-Controller Induction Generator

The WPS of Figure 9 shows a doubly fed full-controlled induction generator, with a dc-transmission link. This type of WPS allows to control the voltages and frequencies of the rotor and stator, consequently this system provide a higher flexibility on the control system than the conventional doubly-fed induction generator shown in Figure 8. In addition, this WPS has been considered for offshore sites, which are connecting to land gateway by submarine cables [40]. There are others method of interface the DFIG to the grid. Among them, are: (i) cycloconverter [21,34] and (ii) matrix converter [37], however they have some disadvantages over the one presented in Figure 8, those are: poor line power factor, high harmonic distortion in line and machine current for a cycloconverter and for a matrix converter, despite of eliminate the dc capacitor, this converter is more complex and its technology is less mature.

2) Squirrel Cage Induction Generator (SCIG)

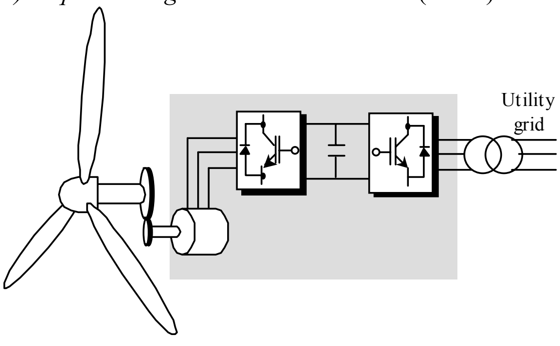

Figure 10. Variable Speed Squirrel Cage Induction Generator

A WPS with squirrel cage induction generator is show in Figure 10. The stator winding is connected to network through a four-quadrant power converter comprised of two PWM VSI connects back-to-back trough a DC link. 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. The uses of squirrel cage induction generator have some advantages:

- The squirrel cage induction machine is extremely rugged; brush less, reliable, economical and universally popular.
- Rectifier can generate programmable excitation for the generator [31].
- Fast transient response is possible [31].
- The inverter can be operated as a VAR/harmonic compensator when spare capacity is available [31].

Among the drawbacks are: (i) complex system control (FOC) whose performance is dependent on the good knowledge of the generator parameter that varies with temperature and frequency [41],(ii) the stator side converter must be oversized 30-50% with respect to rated power, in order to supply the magnetizing requirement of the machine [23].

C. Others

There are other kinds of generator used in WPS that appear in the literature, such as, Brush less Doubly-Fed Generator [23], Variable-Reluctance Generator [28] and Dual-Speed Induction generator [29]. However they not are presented in this paper because they are special types of the generator whose practical application is justified for some special case.

V. Control of Static Converters

In the early development of power converter, for WPS, three-phase diode bridge or three-phase, phase-controlled rectifier and a line/load-commutated inverter had been used. The major problems associated with these converters are: (i) poor line power factor, (ii) high harmonic distortion in line and machine current [21,31,53], (iii) poor dynamic performance. In modern designs, PWM techniques have been used due decrease of harmonic distortion and the increased controllability of the system, as well as to improve the dynamic performance.

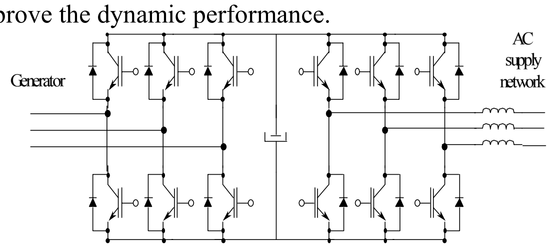

Figure 11. Back-to-Back four-quadrant PWM-VSI.

The back-to-back four-quadrant PWM-VSI, presented in Figure 11, is widely used in WPS today [22]. The PWM modulation reduces the current harmonic component in the input and output of the system. As a result, it reduces the torque pulsation on the generator and improves the output power quality, respectively [47,54,55].

Normally, a field orientation control (FOC) is preferred for control the stator/rotor side converter while the supply side converter use vector controller. As an example Figure 12 shows a block diagram of the WPS with DFIG. The supply-side converter use a vector control, with a reference frame oriented along the stator voltage vector position, enabling independent control of the active and reactive power [56-58]. On the other hand, the rotor side converter is controlled by FOC, with the *d*-axis oriented along the stator-flux vector position. In this way, a decoupled control between the electrical torque and the rotor excitation current is obtained [56,59-61].

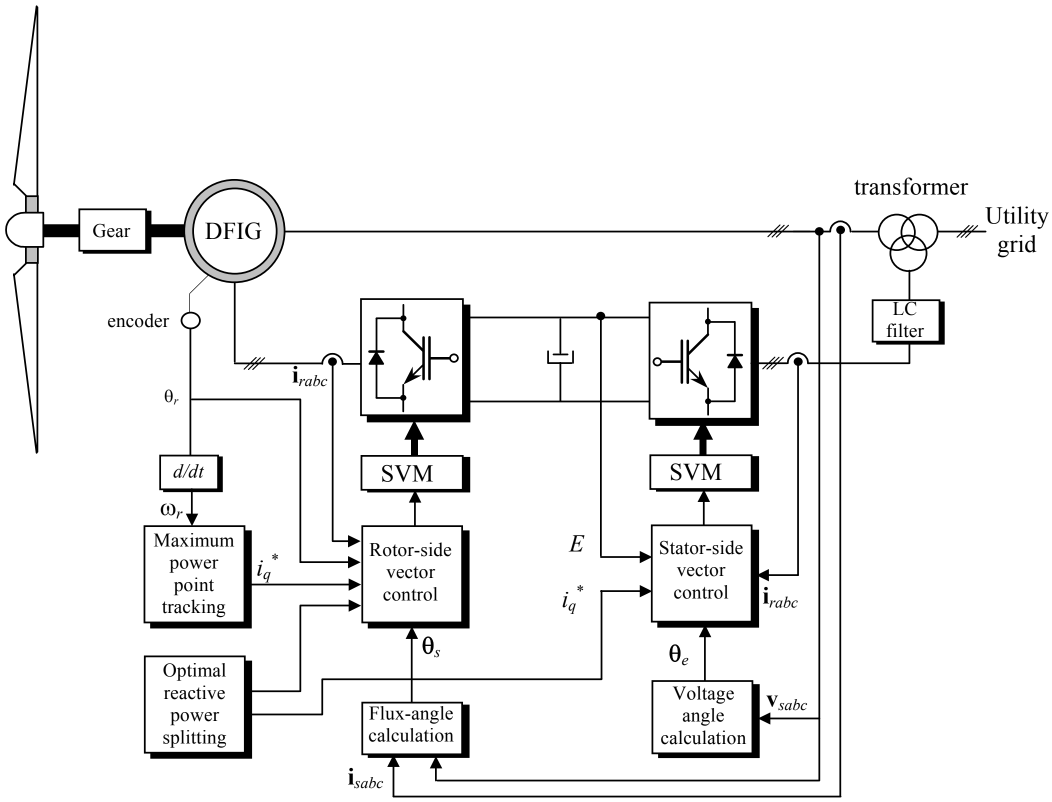

Figure 12. Vector-control structure for wind power system

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VI SUMMARY

This paper has reviewed the main variable speed WTS. All WTS require a strategy to limit the mechanical stresses. Among them the passive stall regulation and pitch regulation has been preferred for medium and large WTS, while furling for small size WTS.

The output power is maximized by adjusting the shaft speed, being MPPT is preferred because the measurement of the power is simpler than measurement of the wind velocity and it is also used in the design of the vectors controllers.

In the small and medium WTS both the SCIG and PMSG have been used while for large size WTS both DFIG and SG are preferred. The back-to-back four-quadrant PWM-VSI converter is preferred because the PWM modulation reduces the current harmonic component in the input and output of the system. As a result, it reduces the torque pulsation on the generator and allows improving the output power quality.

With the advance of power electronics technologies it is possible to optimize the WPS performance, however there still some challenge to be addressed: (i) To mitigate the uncertainty on the generator parameter, that can off-tune the FOC, (ii) To use the control of the active and reactive power of the WTS in order to support the operation of network during fault conditions and voltage disturbance.

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