
Control Methods Used In Wind Energy Conversion System: A Review

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ABSTRACT

This work presents a review on the control of torque and flux of six phase induction generator in a wind energy conversion system. The control methods used for grid connected asymmetrical six-phase induction generator in variable speed wind energy conversion system (WECS) are discussed. These involve a detailed model of the six phase induction generator. The six phase induction generator consist of two sets of three phase stator windings shifted by thirty electrical degrees. Efficient control strategies are applied to the generator in order to ascertain proper regulation of the generator torque and flux, which will in turn ensure generation of quality output power from the generator. The main aim of the work is to analyze the different control methods used that ensures continuous electrical generation during loss of one to three phases on the generator or converter sides of the wind energy conversion system. From the analyses, conclusion will be made on the control method that is more suitable for regulating the torque and flux and at the same time ensuring a minimal fluctuations that occurs due to loss of phases of the generators.

Keyword: Six phase induction generator; Wind energy conversion systems; direct torque control, and field oriented control.

INTRODUCTION

The continuous increase in demand of electricity and *progressive* decline of fossil fuels with growing concerns on the global climate change has given rise to increase in production of electrical energy from renewable resources. These renewable sources include: solar, wind and tidal streams ocean (Boulouiha *et al.*, 2015; Ibrahim *et al.*, 2017). Wind energy as of 2015 has a total installed power capacity of 434.9 GW has experienced the most significant growth (Pantea *et al.*, 2019). Therefore researchers are now focused on how to ensure the continuous growth of this type of energy resources during the next decade. Different concepts of wind turbine configured with various types of generators have been developed to ensure that maximum power is been extracted and power that are of high quality are generated from the wind energy conversion system (Chinmaya & Singh 2018). The configuration of the WECS can be grouped into three classes based on the type of generator equipped with the wind turbine (Chen & Cai 2018). These classes include (Chinmaya & Singh 2019): doubly fed induction generator (DFIG) with partial scale power converter, asynchronous induction generator with full scale power converter and permanent magnet synchronous generator (PMSG) with full scale power converter (Chen & Cai 2018). Due to the

continuous increase in the rated power of the WECS (currently exceeding 10 MW), power converters in parallel configuration are now widely adopted in high power DFIG (Okedu 2016), asynchronous induction generator and PMSG (Li & Xu 2013) based WECS. Traditionally, synchronous machines were mostly utilized for power generation, however, squirrel cage induction machines is now gaining wider attention due to its numerous advantages over the squirrel cage induction generator (Chinmaya & Singh 2018).

Since the challenge recently is now to develop a means of installing a powerful and more reliable wind turbines in windier zones. Interest of researchers is now pin towards the development of offshore windfarms, which guarantee greater productivity due to the powerful and constant offshore winds (Pantea *et al.*, 2018). However, the major disadvantage of this type of generation (offshore generation) are the remoteness and *hostility* of the environment which increase the maintenance cost. Therefore, ensuring the robustness and the efficiency of the generator in use is highly recommended (Zhang *et al.*, 2011).

Three phase induction generators is the conventional machine used in WECS due to their numerous advantages, which include (Chinmaya & Singh 2019): low cost, high reliability, robustness and maintenance free operation . Multiphase induction generator with symmetrical or asymmetrical structure provides a suitable solution to increase the efficiency of the generator. Multiphase machine which has more than three stator phases has several advantages over the three phase drives which include: increased power rating, reduction in the rotor harmonic currents, reduction in the current per phase without increasing the voltage per phase, lowering the DC link current harmonics, reduced stator copper loss, power segmentation and high reliability (Hadiouche *et al.*, 2004). However, the major advantage of the multiphase induction generators is its usage in wind energy conversion system especially for offshore and on-shore grid connected power generating stations. This is so because failure of one or two phases does not drastically affect the generation of power especially when compared with three phase induction generators (Chinmaya & Singh 2018).

Multiphase generators can be developed in different configurations (6, 9, 12, 15 phase generators and also generators which are not in multiples of three four, five, seven and ten phase configurations). The asymmetrical six phase induction generator also known as dual stator winding mostly used. It is referred to as asymmetrical due to the three phase set of stator windings evenly displaced by 30° (Chinmaya & Singh 2018). The major advantage the six phase induction generator has over the conventional three phase induction generator is that, when there is fault in one to three stator phases or inverter terminals, the generator still generates electrical energy. However, power oscillations occur with the presence of these faults. This is due to the unbalances created between the stator and the rotor. Therefore, to minimize these fluctuations and ensure that the system is kept balanced, a suitable control method needs to be incorporated (Taherzadeh *et al.*, 2014).

Therefore the aim of this paper is to compare the effectiveness of the variants of field oriented control with that of direct torque control when used to control the six phase induction generator in wind energy conversion system.

Six Phase Energy Conversion Systems Topologies

Asymmetrical dual three phase induction machines with two isolated neutrals are generally preferred in six phase energy conversion system. This type of machine can be described with a set of differential equations which can be easily simplified in stationary coordinates using the vector space decomposition (VSD) approach (Gonzalez *et al.*, 2014). The VSD helps ensure that the original six dimensional space present, is been transformed into three two dimensional orthogonal subspaces. These subspaces are usually denoted as $\Gamma - S, x-y$ and $0_+ - 0_-$. of all these subspaces only the $r - s$ components contribute to the torque and flux production. The model of the asymmetrical six phase induction machine model is shown in (1). VSD was used in obtaining the model based on the following standard assumptions: negligible iron loss, magnetic saturation and space harmonics.

$$\begin{aligned}
 V_{r_s} &= (R_s + L_s \cdot \frac{d}{dt}) \cdot i_{r_s} + M \cdot \frac{d}{dt} i_{r_r} \\
 V_{s_s} &= (R_s + L_s \cdot \frac{d}{dt}) \cdot i_{s_s} + M \cdot \frac{d}{dt} i_{s_r} \\
 V_{x_s} &= (R_s + L_s \cdot \frac{d}{dt}) \cdot i_{x_s} \\
 V_{y_s} &= (R_s + L_s \cdot \frac{d}{dt}) \cdot i_{y_s} \\
 0 &= (R_r + L_r \cdot \frac{d}{dt}) i_{r_r} + \check{S}_r \cdot L_r \cdot i_{s_r} + M \cdot \frac{d}{dt} i_{r_s} + \check{S}_r \cdot M \cdot i_{s_s} \\
 0 &= (R_r + L_r \cdot \frac{d}{dt}) i_{s_r} + \check{S}_r \cdot L_r \cdot i_{r_r} + M \cdot \frac{d}{dt} i_{s_s} + \check{S}_r \cdot M \cdot i_{r_s}
 \end{aligned}
 \tag{1}$$

Where :

$L_s = L_{ls} + 3L_{ms}$, $L_r = L_{lr} + 3L_{mr}$, $M = 3L_{ms}$, \check{S}_r represents the rotor electrical speed ($\check{S}_r = p \cdot \check{S}$, $p = pole\ pair\ number$). The s an r indices denotes stator and rotor variables respectively and subscripts l and m denotes leakage and magnetizing inductance, respectively.

The performance of the machine when operating in either healthy or faulty mode can be studied using the machine model in (1). When the machine is operating in a healthy mode, only the $r - s$ components will exist. However, during the faulty operation of the machine, the additional degrees of freedom will also become available for control purposes.

Direct Torque Control of Six Phase Induction Generator in Wind Energy Conversion System

Any type of control method used for controlling the torque and the stator flux independently and simultaneously without the use of any decoupling medium is generally referred to as direct torque control. Figure 1 shows the general scheme for a DTC controller of an induction machine. This controller compares the torque and stator flux (or their estimated values) with their reference values (generally referred to as T_e^* and λ_s^*) after which their resultant errors are passed

through torque and flux controllers in order to produce the reference values of the direct and quadrature voltages (V_{sd}^* and V_{sq}^*) for the voltage source inverter. In order to minimize the errors for both the torque and stator flux, a set of three phase voltages are supplied to the stator windings via VSI. The hysteresis method of torque and flux controllers under DTC were the first generation of DTC used in literature. It was used mostly because of their quick and robust response and also because it can be easily implemented by digital processors. Nevertheless, it is characterized with high torque and flux ripples. And secondly their performances in low speeds are not desirable. Linear flux and torque controllers are introduced in order to minimize these challenges (Lascu *et al.*, 2000). The linear controller has a very good dynamic response and also can operate in a system without ripples. However, robustness of the system is not guaranteed. While a torque and flux controller that utilizes variable structure control, can guarantee control robustness, the torque ripples present in the system is significant (Fazeli *et al.*, 2010). Recently, controllers such as sliding mode control (Ayaz & Abootorabi 2018), fuzzy logic control and model predictive controller are incorporated into the direct torque control in order to ensure proper control.

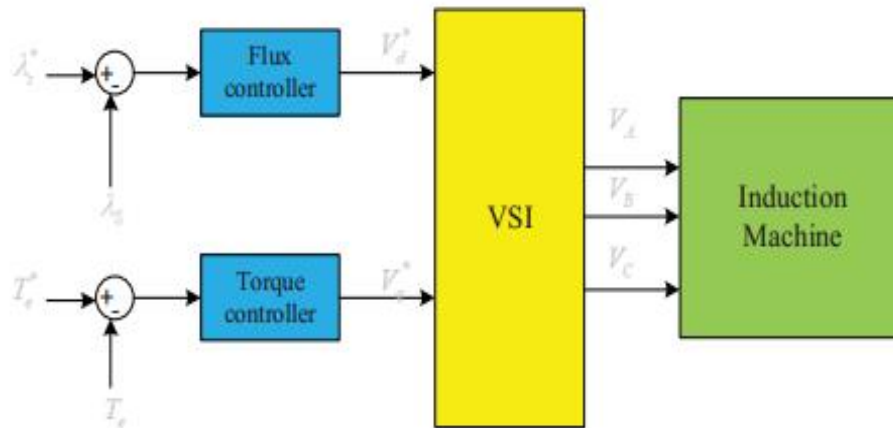


Figure 1: General Scheme of a DTC Controller

Field Oriented control of six phase induction generator in wind energy conversion system

The field orientation control are generally classified into stator flux, rotor flux and air gap flux orientations. The rotor flux orientation is simple and easy to implement. These makes it to be one of the more popular schemes used in both AC drives and wind energy systems (Datta & Ranganathan 2002). The function of the FOC is to ensure decoupled control of the rotor flux λ_r and electromagnetic torque T_e of the generator to achieve high dynamic performance. Using the rotor flux orientation, the stator current of the generator can be decomposed into a flux producing component which produces the rotor flux λ_r , and a torque producing component, which produces the torque T_e . These two components are then controlled independently.

The main issue associated with the rotor flux oriented control is to accurately determine the rotor flux angle θ_f . If the angle is obtained through the measurement of generator terminal

voltages and currents, the method is known as direct field oriented control. For the indirect field oriented control, the rotor flux angle is obtained from

$$\theta_f = \theta_r + \theta_{sl} \quad (2.5)$$

Where:

θ_r and θ_{sl} are the measured rotor position angle and calculated slip angle respectively.

Therefore the main objective of this type of control is to independently control the torque and flux. (Amimeur *et al.*, 2012) presented a field oriented control incorporated with sliding mode controller for controlling the torque and flux of the machine in a six phase wind energy conversion system. In the work a maximum power point tracking algorithm for maximizing the generated power was also employed. The FOC helps to control the flux and torque while the SMC was incorporated into the FOC to help select appropriate gains that will ensure efficient regulation for the speed flux and stator currents. However, the results obtained showed that an efficient system that will minimize the torque oscillations needs to be considered in the system. (Gonzalez-Prieto *et al.*, 2016) developed a six phase energy conversion system where six phase induction generator was used as the generator. In the work an indirect rotor field oriented control which has an outer loop and inner current loops for $d - q$ and $x - y$ currents was used to control the system in the pre-fault mode. The outer speed control loop which provides the reference of the quadrature current was used in regulating the torque. A controller was also incorporated into the system in order to minimize the imbalance that occurs in the system during the post fault mode. Nevertheless, the results obtained showed that the detection delay is higher than a fundamental cycle. (Benakcha 2018) developed a back-stepping control approach for dual stator induction generator used in wind energy conversion system. The FOC was used in the system to ensure proper control of the generator, while the back-stepping algorithm was implemented for easy control of the output variables by ensuring stability. However, it was observed that the electromagnetic torque did not properly track the reference torque.

CONCLUSION

This work has presented a review on the modelling and simulation of a six phase induction generator when used in wind energy conversion system. In wind energy conversion system, the wind turbine is connected to the grid through a six phase induction generator. It is used because of its numerous advantages over the the three phase induction generator. Nevertheless, its efficient performance depends on the type of control used in regulating the torqu and flux. For this reason, the most common types of control methods used (DTC and FOC) are discused and there drawbacks are highlighted.

Form the analyses, it is observed that the FOC is preffered over the DTC. However, efficient controllers such as model predictve controller and other predictive controllers need to be incorporated in the FOC in oreder to guarantee efficient control of the system.

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