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Doubly-Fed Induction Generator Technology in Clean Energy Development

Dr. Bhagwan Shree Ram
Professor, Power System Domain
SEEE, Lovely Professional University
Phagwara, Punjab, India
Email: bhagwan.24828@lpu.co.in

Dr. Narbada Prasad Gupta
Professor, Communication System Domain
SEEE, Lovely Professional University
Phagwara, Punjab, India
Email: narbada.24806@lpu.co.in

Dr. Prashant Kumar Choudhary
Asst. Professor **SEEE**
Lovely Professional University, Phagwara, Punjab, India
Email: prashnt.24788@lpu.co.in

Abstract: **Electrical engineers generally, tend to simplify the aerodynamic and mechanical parts of the system and usually stress electrical generator description; in contrast with the mechanical engineers those often overlook generator performance details. Some reported models seem to be over- parameterized, which obstructs their implementation because the parameters for the detailed description are not generally available. The cumulative worldwide wind energy conversion capacity has grown to more than 46 GW of electricity generating wind turbines that are operating in over 63 countries till 2003. Of these, over 75% have been installed in western countries. Under international agreements, the dissemination of power is supposed to be faster and 10% of the saturation level to have been achieved by the year 2025.**

1. INTRODUCTION

The literature survey has been presented regarding the state-of-the- art technology and its implementation for the analysis modeling and control strategies in the area for optimal operation of DFIG for the quality power generation. The major area of the review of literature has been highlighted as follows:

(1) The Wind plant technology

(2) The DFIG System and control strategies

(3) The Power Electronic Converters strategies and

(4) Steady state and transient state performance of energy conversion system required for DFIG systems and their evaluation for optimal operations for quality power generation.

2. THE VARIABLE SPEED PRIME MOVER USING WIND PLANT TECHNOLOGY

Modeling of Wind Turbines for predicting of power quality impact is reported in the literature. Models of wind turbines of varying complexity are presented here. Aerodynamic model of wind turbines has been developed by Wilkie, J. et al [53] which is comparatively simple model with respect to the previous complex models. The researcher had adjusted the wind speed at one point which is hub level by using of various filters in order to represent the interaction of the blades of the turbine with wind speed allocation over the rotor blade swept area. The resulting wind rotational statistics are then applied to the static power curve, represented by Cp(γ), in order to decide the driving torque. In contrast to this, an advanced approach to aerodynamic modeling, which uses a professional software package, has been presented by Bossanyi, E.A. et al in [40].

The reported drive-train models varies significantly; however, rather straightforward descriptions that frequently incorporate a soft shaft representation which dominate in the research literature. The soft shaft representation is presented, for example, by Akhmatov, V. et al in [2]. A very complex drive-train model representation that might suffer from the unavailability of system parameters is presented by Leithead, W.E. et al in [29] and by J.M., Fernandez et al in [23]. A wide range of generator model complexities can be found in the literature. Wilkie, J. at el [53] have pointed out that there is no dynamic generator model used at all, while B. N. Sh. Et al in [6] make use of a generator model with neglected stator as well as rotor dynamics. Jenkins, N. et al in [24] have utilized a generator model with neglected stator dynamics and Usaola, J. et al [52] suggested a generator model with incorporated stator and rotor dynamics. A detailed analysis of the induction machine with a particular interest in low frequency disturbances analyzed by Thiringer T. [47]. Verifications of models with practical measurements on wind turbines are rarely reported in the literature. A comparison of simulations and measurements of wind turbine responses to grid disturbances have not been found at all by the authors. A published comparison between measured and simulated impact of wind turbines during normal operation, namely the comparison of flicker impact, has been presented by Bossanyi E. A. et al in [7]. Good agreement is reported there, however, only a single result for one wind speed is presented.

The prediction of voltage fluctuations caused by variable-speed turbines is not of interest from the point of view of power quality, since variable speed wind turbines have rather low flicker emission. However, the prediction of voltage fluctuations due to fixed speed turbines is very important, since this is often one of the restrictions that sets installation limits for these turbines.

The impact of the turbines on system permanence is also dealt within the literature. The work presented by Akhmatov, V. et al in [4] describes a model connected to the power grid system of the wind generators designed for predicting both, steady-state operation impact as well as the response to grid faults had been focused. However, verification of the simulation results against field measurements is lacking. An evaluation of fault response of fixed angular speed rotated turbines and of changeable speed wind turbines connected to the doubly-fed induction generators (DFIG) is analyzed by Rodriguez J. M. et al [43]. In this research paper, conclusion and recommendations regarding an appropriate combination of the wind turbines with the power system are based on simulations. According to Carlson et. al [33] the energy production can be enhanced by 2.5 – 6.15% for a variable speed turbine comparing with it's counterpart the fixed speed wind turbines, while by D. S. Zinger et al [97] and by Z. M. Salameh [44] explained that the increase in power can be up to 37%.

The complexity of the particular models presented in the literature has been presented by Akhmatov V. in [2] to rather simple ones where the rotor speed is considered to be constant that is being presented by Petersson et al [36], depending mainly on the purpose of the study. A detailed literature study which provides a rather detailed overview of the mechanical modeling of variable speed wind turbines, is presented by Hokkanen et al [16]. The wind turbine rotor is a complex aerodynamic system and thus a sophisticated method (such as e.g. blade element theory analyzed by Heier [13]) should be applied. However, this approach is computationally rather demanding and requires detailed information on the wind turbine rotor geometry. The simplification is based on the assumption of the mechanical power captured by the wind turbine depends on the power coefficient, which is a function of the turbine blade tip speed ratio. This type of simplified model is used e.g. by Tapia et al in [49], where the aerodynamic model also includes a tower effect representation.

The mechanical part of the wind turbine system consists of a shaft and the rotor of the wind turbine itself. Most of the DFIG wind turbine models used in dynamic stability studies includes a drive train model. There are two main approaches used for modeling the drive train, so called two-mass model presented by Akhmatov in [2] and Ledesma & Usaola [52], or the frequently used lumped model approach, which assumes that all the rotating masses can be treated as one concentrated mass that is being presented by Holdsworth et al [17]. The lumped model approach may be insufficient in the case of transient analysis. The impact of the simplification of the drive train model on the accuracy of wind generator modeling is discussed in Salman and Teo [45].

3. DFIG SYSTEM AND CONTROL STRATEGIES

The saturation level of 2200 GW of wind turbine capacity installed world-wide will be reached in the 30 years from now as being presented by Herbert et al [14]. The two basic types of wind turbines used nowadays are given as follows: I. Variable speed wind turbines. And II. Fixed speed wind turbine. The research work of Salman et al [45] concludes that, it is necessary to model a DFIG and the associated control and protection circuits adequately, especially in the event of a fault. Models of the DFIG based simulation software are, in many cases, inadequate from the accuracy point of view as a result of simplifications such as neglecting the dc stator transients' components, leakage inductance saturation, mutual inductance saturation, and electromagnetic transients. This makes them unsuitable for representing the transient presentation of a DFIG accurately in the event of a grid fault. The method of symmetrical components presented by Krause et al [34] have suggested for use in the analysis of unbalanced DFIG operation when taking into account the zero-sequence components.

The dynamic model of an induction machine is usually presented by means of a so called fifth-order model that is being developed by Stanley [46], which represents Induction Machine (IM) by a system of five general differential equations of an idealized induction machine. In some power system studies, it is desirable to reduce the complexity of the system by using reduced-order models that can be obtained by assuming some of the derivatives as being equal to zero which is being compared by Thiringer [51]. For example, a third-order model of IM is obtained when we neglect the stator flux transients, as shown by Stanley [46]. The doubly fed induction generator used in variable-speed wind turbines is frequently represented by a conventional dynamic fifth-order model of IM in a two-axis d-q reference frame rotating at synchronous speed has been modeled by Akhmatov et al in [2] or in a rotor reference frame by Chellapilla and Chowdhury [9]. According to Tapia et al [49], in order to express DFIG dynamic behavior as realistically as possible, the "Quadrature-Phase Slip Ring" frame, where the stator and rotor variables are referred to their own corresponding reference frames, should be employed. A rather common DFIG model is the so-called "voltage behind reactance" reduced dynamic model presented by Holdsworth et al [17], those are widely used in the analysis of power system faults. In the case of the studies of the transient stability, it is rather common to reduce the 5th order model to a 3rd order model that is being developed by Ekanayake et al [19]. However, as concluded by Akhmatov et al in [2], using third-order models may result in too-low transient currents during disturbances, which may lead to inaccurate results, especially when the transient performance of a DFIG driven wind turbine during a grid fault is being studied. A detailed literature overview of direct and indirect coupling methods can be found in the thesis of

Kanerva S. [26]. No transient study of a wind-power generation system using the coupled field-circuit approach has yet been presented in the literature except the study of Runcos et al [44]. In thisstudy, a prototype of a 100 kW Brushless Doubly Fed Induction Generator for wind-power conversion application is investigated by means of a direct coupling method developed by Arkkio [13].

4. POWER ELECTRONIC CONTROLLER SYSTEMS

To control the current of the rotor of a DFIG by means of vector control, the reference frame has to be aligned with a flux linkage. One widespread way is to control the rotor currents with the orientation of the stator-flux being analyzed by B. Hopfensperger et al [5]. If the resistance of the stator is considered to be miniature, stator-flux orientation provides the stator voltage which is explained by L. Morel et al [27]. According to Phoenix, A.Z., [37], pure stator-voltage orientation can be done without any significant error. In this thesis stator voltage orientation has been, explained and supported by J. L. Duarte et al [22]. One way of simplifying the command of the dc-link voltage is by utilizing feedback linearization, i.e., the nonlinear dynamics of the direct current link are transformed into an equivalent linear system where linear control techniques has been applied by J. J. E. Slotline [21]. If, for example, the rotor current is controlled by a high-gain feedback, it is possible to force the system to have both slow and fast time scales, i.e., the system behaves like a singularly perturbed system. This means, that if the current control loop is high enough, it is sufficient to study the system in order to analyze the dynamic behavior of the DFIG. A stability analysis, assuming fast current dynamics, has been analyzed by M. Heller [31]. The use of doubly-fed induction machines is receiving increasing attention for wind generation has been presented by D. J. Atkinson et al [10].

Network-side frequency converter is usually represented by a simplified model, called generic control scheme based on a set of PI controllers used for obtaining two-axis voltage values depending on the required network active and reactive power values which has been elaborated by Poller M. A. in [40]. It has been observed that these models neglect the switching dynamics of the converter and an ‘ideal’ control is assumed, meaning that the converter is able to follow its demanded value at any time this has been shown by Akhmatov in [2]. A detailed model of the network- side frequency converter is presented by Pena [42], a similar approach is used by Abbey and Joos [1], where a field-oriented control aligned with the stator voltage vector position is employed. The network-side converter could also be controlled as shown by Pollanen [39]. A detailed model of the network-side vector-controlled frequency converter that uses hysteresis modulation has been presented by Akhmatov [2] and a space-vector PWM modulation is applied by Gomez and Amenedo [12]. Akhmatov [2] states a conclusion that when we study a DFIG wind turbine under network disturbances, it is necessary also to model the network-side frequency converter in detail. The author stresses that if we neglect the network-side converter model, it would affect the accuracy of the rotor current calculation as well as the dc link voltage, which are monitored by a protective system, and this could significantly affect the accuracy of the simulation. However, the majority of DFIG wind turbine studies omit the model of the grid-side converter and the dc link voltage is considered as constant, being stated by Tapia et al in [49]. A compromise solution between the detailed model of the network-side converter and constant dc link voltage consideration could be the approach presented by K. P. Kovacs [25], where a simplified dc link voltage controller is implemented. Similarly to the case of the network-side converter, the rotor-side converter can also be represented by several modeling approaches. The switching dynamics could be represented by including a PWM modulator into the model, as shown by Pena et al [42] and by et al in [49] or by using a hysteresis modulator by Chowdhurry and Chelapila [9] to control the switching of the IGBT inverter bridge.

A space vector modulated matrix converter with a stator-flux vector control has been proposed for DFIG rotor current control by Zhang et al [55]. A generic control scheme could also be applied to the rotor-side converter shown by Akhmatov in [3]. Here two series of two frequency converters, when the switching dynamics are neglected assuming that the rotor-side converter perfectly follows the reference values. The detailed explanation is presented by Poller in [40]. The rotor-side converter presented by Lei et al [28] is simplified in such a way that the converter is modeled as an ideal voltage source. An alternative control scheme to the vector control is direct torque control (DTC) has been presented by Takahasi and Nugushi [48]. The application of DTC to DFIG control and a modified DTC strategy-based controller for a DFIG wind turbine is described in detail by Gokhale et al [11]. The operation of the protection device is not clearly described but the authors use a passive crowbar that is triggered when an over-voltage in the dc link occurs, as described by Pourbeik et al [41].

5. STEADY STATE AND TRANSIENT PERFORMANCE OF ENERGY CONVERSION SYSTEM

Previous researchers have considered the transfer of harmonics from the rotor to the stator side of the DFIG, which was assumed to follow the MMF balance on both sides as shown by J. Faiz H. et al [20]. The standard equivalent circuit of an IM was modified to calculate the stator current and voltage harmonics, and frequency modulation was handled by considering the slip. It has been shown that the mechanical behavior will reflect electrically in a cage

Induction Machine, which has been explained by J. Faiz H. et al [20]. It has been observed that the consideration of the speed ripple will significantly improve the model accuracy. After a better understanding of the electromechanical interaction in the DFIG is obtained, it would be possible to improve the overall performance of the generator system by, for example, controlling the rotor side inverter. The complexities of the power network model that are used in the transient studies of a DFIG vary from very complex models to rather simple ones. A rather complex grid model, which is described and analyzed in detail by Akhmatov in [7]. A generic network model is used for transient performance assessment that is being shown by Hughes et al [15]. This model comprises a local network of a WECS and conventional power generation system connected to the main network through coupling transformers and transmission lines, where a single DFIG represents the aggregated behavior of the individual generator. The simulation models of DFIG wind turbines used for short-term voltage disturbance transient analyses (by Akhmatov et al in [10]; by Thiringer [50] and by Morren et al [32]) explained the stability transient models for the operations of the DFIG during the grid disturbances. Simulating fast transient phenomena requires the use of a small integration time step for the numerical integration and also more complex and detailed models of the generator and power electronics, as discussed by Hughes et al [18].

The use of small time steps and complex transient models results in longer simulation times in comparison with the transient stability analyses. Reactive power management has been explained by C. R. Kelber and W. Schumacher, [8]. Most of the studies are provided on the transient behavior of the DFIG under a 3-phase short-circuit fault, as presented by Salman and Teo [45]. The transient behavior of DFIG wind turbines during asymmetrical faults has been studied by simulation by Lund et al [30] and experimentally by Piekutowski et al [38]. Experimental validations of the simulation analysis performed with a full-scale laboratory setup are presented by Hogdahl [15].

6. CONCLUSION

The literature survey presented above is an important link in understanding the research work being conducted in the area of the wind plant technology, the DFIG system and control strategies, the power electronic converters strategies operations of brushless induction generator operated with wave energy conversion systems and steady state and transient performance of energy conversion system required for DFIG systems and their evaluations for optimal operations for quality power generation.

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