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Evaluation of PI and Fuzzy Logic Controllers for a Wind Energy Conversion System Based on a Doubly Fed Induction Generator

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Abstract:

The purpose of this research is to analyze the wind turbine generator design for a doubly fed induction generator wind turbine generator with variable speed. The wind energy conversion system uses a variety of generator topologies, such as DC generators, synchronous generators, and induction generators. Most commonly utilized for WECS are the Permanent Magnet Synchronous Generator and the Doubly Fed Induction Generator. However, DFIG turned out to be more favourable than PMSG in terms of cost, converter size, and the production of energy in sizable wind farms. In this paper, PI controller and fuzzy logic controller are used to regulate the stator side converter and rotor side converter for the regulation of active and reactive power. DFIG's whole mathematical modelling is carried out employing.

Keywords: Doubly fed induction generator (DFIG), Voltage source converter (VSC), Wind energy conversion system (WECS), Rotor side converter (RSC), Grid side converter (GSC), PI controllers, Static compensator (STATCOM), Voltage-oriented control (VOC), Pulse width modulation (PWM).

Introduction Due to increase in global warming and devastating contamination of the world's environment there is an increase in the use of non-conventional resources to fulfil the energy needs of the society which includes solar cells, wind turbines, hydro power and biomass etc. There are many engineers and several institutes working for making the optimal utilization of all these non-conventional energy sources possible. Wind energy is one of the alternative forms of energy that has played an important role in the history of civilization. In earlier generation, non-conventional energy resources were not used in large scale production due to lack of technology. But now wind turbine technology has emerged out with an exponential growth in the generation of power. The wind power has its own importance because of the various advancements and improved performance of several Wind Energy Conversion Systems (WECS). Most of the global energy is being increasingly generated by modern wind power systems. Germany is among the biggest wind power markets. Along with Germany there are many countries like US, Spain, France, Denmark, China and India as well which considers wind energy as a serious alternate for generation of electricity. During 1980, the world's installed wind capacity was almost 13 MW .59.024 GW of wind power was in operation by the end of 2005. By the end of 2006, the total

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installed capacity of wind turbines has reached 74.150 GW with an annual growth of approximately 23.8%. This installed capacity increased 93.926 GW and 121.188 GW in end of 2007 and 2008 respectively with annual growth of approximately 26 %. It is expected that by the end of 2012 and 2017 and as updated on 4th June 2019 the total installed wind power capacity has reached to 597 GW all over the world. Also in India, Wind power generation capacity has increased in recent years. As seen from the data of 31 March 2019 the total installed wind power capacity was 336.625 GW [1]. The total wind farms are grown to 443 in India. Thus, India has the fourth largest installed wind power capacity in the world. Wind power capacity is mainly spread across the South, West, North and East regions. There are a number of options available for the selection of wind power installation. Because of this a major focus is kept on wind power conversion systems in the current paper.

Mathematical modelling of DFIG

Firstly, the Kinetic Energy of the wind is transformed into the mechanical energy in the rotor turbine blades. The kinetic energy of the wind can be expressed as:

$$K.E = \frac{1}{2} m v^2$$

Where 'm' is the mass of the air stream moving with velocity 'v'. If A= area of the rotor blades swept due to exposed wind stream, and ρ is the density of air in kg/ 3 m,ϑ is the volume of air available to the rotor and thickness = wind velocity. This K.E can also be expressed in

$$K.E = \frac{1}{2} \rho A v^3.$$

On further calculation we have the mechanical power developed in the turbine which is expressed by:

$$P_m = \frac{1}{2} \rho A v^3$$

The actual power produced by the rotor by using a power coefficient Cp which is defined as the ratio of mechanical power of the rotor blades to the wind power. Thus, the maximum power that can be extracted is calculated by the equation:

$$P_m = \frac{1}{2} \rho A C p v^3$$

The voltage equations used in modelling DFIG is obtained from the equivalent circuit of DFIG. The voltage differential equations for stator and rotor coils in vector form is expressed as:

$$\bar{V}_s = \bar{i}_s R_s + \frac{d\bar{\phi}_s}{dt}$$

$$\bar{V}_r = \bar{i}_r R_r + \frac{d\bar{\phi}_r}{dt}$$

The methodology used in the control of DFIG involves the use of Clarke and park transformation to convert the three-phase rotating reference frame quantities into Two phase stationary reference frame using Clarke's transformation and then to two phase stationary reference frame by using Park Transformation. For Modelling of DFIG, we need to transform the above equation from three phase to two phase components and subsequently rotating all the variables into a synchronous rotating reference frame (d-q) oriented along the stator flux. [6] Using this transformation concept the dynamic model of WRIM is developed in a synchronously rotating reference frame and stationary reference frame as well. The final voltage and flux linkage equations that represent the dynamic model of induction machine in stationary reference frame (α-β) for stator and rotor are given below:

$$v_{\alpha s} = r_s i_{\alpha s} + \frac{d}{dt}(\varphi_{\alpha s})$$

$$v_{\beta s} = r_s i_{\beta s} + \frac{d}{dt}(\varphi_{\beta s})$$

$$\varphi_{\alpha s} = L_s i_{\alpha s} + L_m i_{\alpha r}$$

$$\varphi_{\beta s} = L_s i_{\beta s} + L_m i_{\beta r}$$

$$v_{\alpha r} = r_r i_{\alpha r} + \frac{d}{dt}\varphi_{\alpha r} + \omega_r \varphi_{\beta r}$$

$$v_{\beta r} = r_r i_{\beta r} + \frac{d}{dt}\varphi_{\beta r} - \omega_r \varphi_{\alpha r}$$

$$\varphi_{\alpha r} = L_r i_{\alpha s} + L_m i_{\alpha s} \quad \text{and} \quad \varphi_{\beta r} = L_r i_{\beta s} + L_m i_{\beta s}$$

The model of DFIG expressed in d-q reference frame rotating at synchronous speed is derived by considering the axis position as shown in Fig. 1.

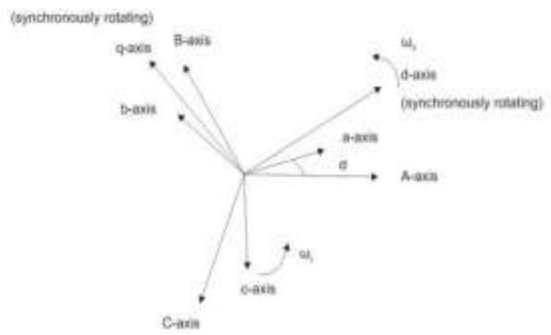

Fig. 1. Reference system used in DFIG

The equivalent circuit representation of dynamic model of induction machine in synchronous reference frame is shown in fig.

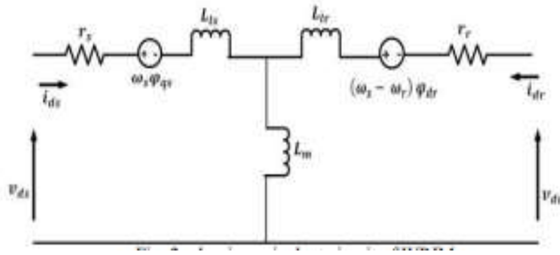

Fig. 2. d-axis equivalent circuit of WRIM

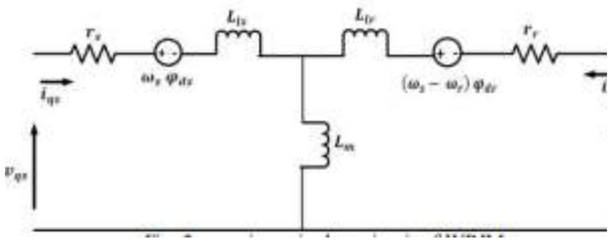

Fig. 3. q-axis equivalent circuit of WRIM

The rotor and stator equations when combined gives the equivalent circuit. Therefore, we have the following DFIG equivalent circuit and equations describing the behaviours of DFIG in rotating reference frame oriented along stator flux [7] as:

$$\bar{V}_{s,dq} = \bar{i}_s R_{s,dq} + \frac{d\bar{\phi}_{s,dq}}{dt} + j\omega_s \phi_{s,dq}$$

$$\bar{V}_{r,dq} = \bar{i}_r R_{r,dq} + \frac{d\bar{\phi}_{r,dq}}{dt} + j(\omega_s - \omega_r)\phi_{r,dq}$$

Where, $\bar{\phi}_{r,dq} = L_r i_{r,dq} + L_m i_{s,dq}$ an $\bar{\phi}_{r,dq} = L_r i_{r,dq} + L_m i_{s,dq}$.

The stator and stator referred rotor self-inductance are equal to their magnetizing inductance and respective leakage inductance and is given as:

$$L_s = L_m + L_{ls}$$
$$L_r = L_m + L_{lr}$$

Where the d-q are the axis of stator flux reference system , , , s dq s dq , , V i ϕ s dq —– are the stator voltage, current and flux vector. , , , r dq r dq , , V i ϕ r dq —– are the rotor voltage, current and flux vector. s r ωω and are the stator flux reference system and rotor electrical speed. The final equation representing the stator and rotor active and reactive powers for the DFIG are given by:

$$P_s = \frac{3}{2}(V_{ds} i_{ds} + V_{qs} i_{qs})$$

$$Q_s = \frac{3}{2}(V_{qs} i_{ds} - V_{ds} i_{qs})$$

$$P_r = \frac{3}{2}(V_{dr} i_{dr} + V_{qr} i_{qr})$$

$$Q_r = \frac{3}{2}(V_{qr} i_{dr} - V_{dr} i_{qr})$$

In this proposed model we aim at controlling the above active and reactive power using Rotor side control and Grid side control. The DFIG model includes the rotor side converter and stator side converter whose control strategy is discussed in the below section.

Control strategy

A. Rotor Side Control

RSC's main purpose is to extract maximum energy with independent control of active and reactive power. RSC is controlled in voltage-oriented reference frame. Active and reactive power are controlled by direct and quadrature axis rotor currents (idr and iqr) respectively. The rotor side control was developed using the PI controller equivalent steady-state circuit using the pulse-width modulation technique. The three phase currents are decomposed into their d and q components in this control structure. Such components are compared with the reference signal and the error signal is transmitted through a proportional integral (PI) producing the d and q components.

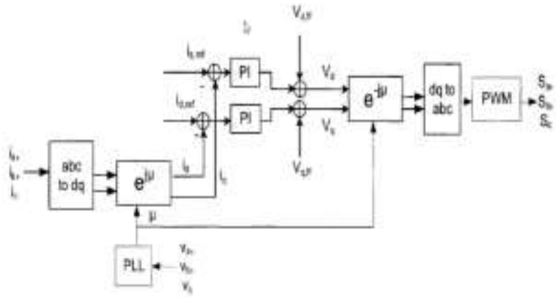

Fig. 4. PWM linear feedback current control scheme

B. Grid side converter control

The grid side controller's main objective is to keep a steady DC-link voltage independent of the rotor energy flow value and path. The rotating reference axis dq is aligned along the grid voltage to power the grid side converter. The line side converter control consists of d and q current references generated using the dc voltage error and the reactive power references, followed by a hysteresis current control block for generation of the gating signaIs. Again, for grid voltage synchronization and proper conversion to dq components, a PLL is needed.

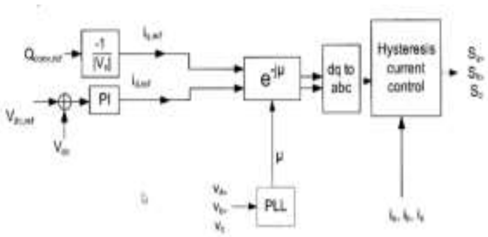

Fig. 5. Grid side converter control for regulation of dc voltage and supply of reactive power

The control of both the Rotor and stator is done by two separate controllers, one is PI Controller and the Second is the Fuzzy Logic Controller.

Simulation results

The proposed Fuzzy Logic control model is implemented in MATLAB/SIMULINK and Fuzzy Logic Toolbox. The simulated model of DFIG is rated at 2MW with a nominal bus voltage 690V.The wind speed is assumed to be 12m/sec with Rs=Rr=0.0029ohm; Ls=Lr=0.0026H; Lm=0.0025H; J=135Kg; no.of pole pairs=2 as the machine parameters .The model is tested for load transient and fluctuation in wind speed at various instants i.e. at t= 0.25 sec ,t=2 sec, t=4sec and t=6 sec respectively and its transient performance is analyzed at these instants.

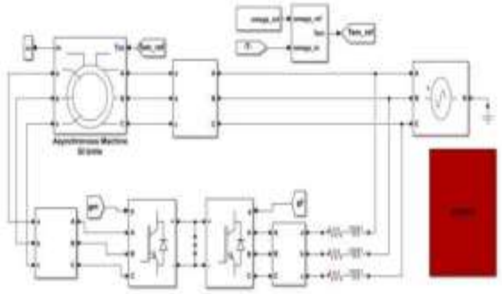

Fig. 6. Simulink diagram of doubly fed induction generator

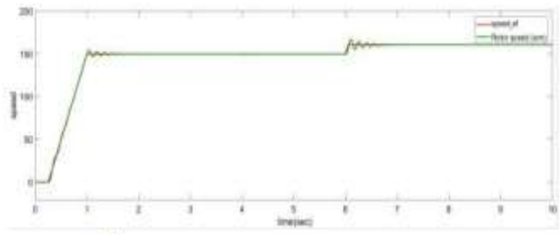

Fig. 7. Rotor speed tracking using PI controller

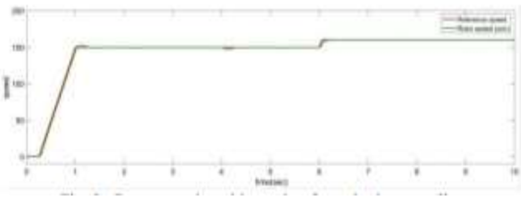

Fig. 8. Rotor speed tracking using fuzzy logic controller

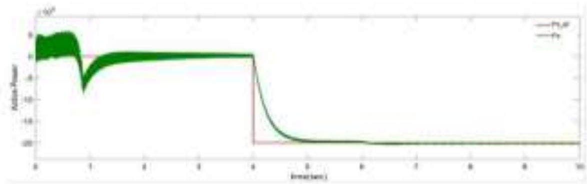

Fig. 9. Active power of stator using PI Controller

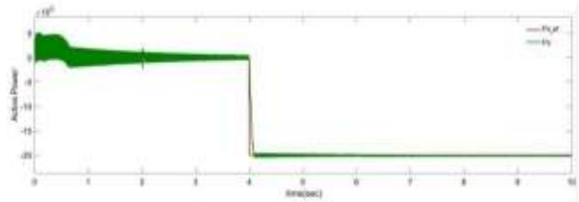

Fig. 10. Active power of stator using Fuzzy Logic Controller

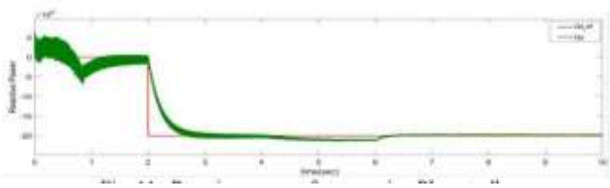

Fig. 11. Reactive power of stator using PI controlled

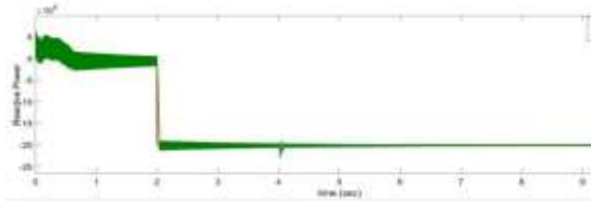

Fig. 12. Reactive power of stator using fuzzy controller

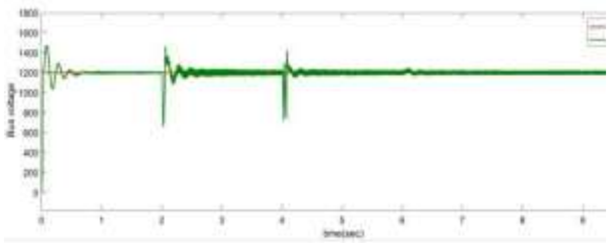

Fig. 13. DC link bus voltage for PI Controller

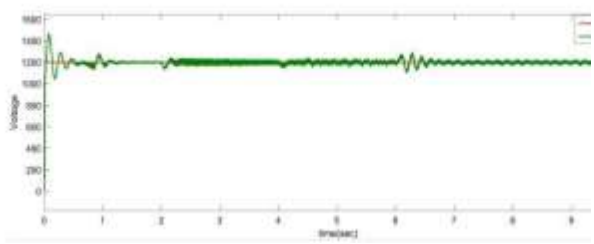

Fig. 14. DC link bus voltage for fuzzy logic Controller

Conclusion

The dynamic models of the Doubly Fed Induction Generator are studied and analysed in various reference frames as a clear understanding is needed for the development of control algorithms for stand-alone WECS based on DFIG. Two control algorithms are implemented to achieve the desired goal which involve the use of the PI controller and the Fuzzy logic controller and evaluate their transient output performance is analysed during sudden load transients and wind speed changes. Vector control technique is used for the control of Rotor side converter and stator side converter. Vector control technique is used for the control of Rotor side and stator side converter. The results show the importance of the control strategy, and both controllers were used to obtain the results. The performance of the proposed model is compared in terms of current, voltage, power Quality, Torque, Active power and Reactive Power. As a result, we can conclude that fuzzy logic controller shows a better performance than with the use of conventional PI controller specially at lower wind speed.

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