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MODELLING AND CONTROL OF DOUBLY FED INDUCTION GENERATOR (DFIG) FOR WIND POWER

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Abstract: Variable speed wind turbines, with their many advantages compared to fixed speed wind turbines, is very promising technology for large scale wind farms. This report presents modelling and control strategies of variable speed doubly-fed induction generator (DFIG) based Type-3 wind turbine where the stator is connected directly to the three-phase grid and the rotor is connected to the grid through the bi-directional back-to-back AC-DC-AC converter. The goal of this project is modelling of DFIG wind turbines and study the operation and control of DFIG based wind turbines. To avoid complexity, the whole model is considered as a collection of subsystems which are modelled individually and then assembled to get wind turbine model. The complete model includes of general turbine aerodynamics, mechanical system, DFIG, current regulated power converters and the control system of wind turbine .The steady state and dynamic modelling of doubly-fed induction machine (DFIM) are discussed in this paper. And Vector control of rotor side converter is simulated in this paper assuming the grid side control is already done. The complete system is modelled and implemented in the power system simulation tool MATLAB/Simulink.

IndexTerms - Maximum power point tracking (MPPT), rotor side control (RSC), grid side control (GSC), doubly-fed induction generator (DFIG), doubly-fed induction machine (DFIM).

I. INTRODUCTION

The bulk power system was called “the largest, most complex machine ever devised by man” by Charles Steinmetz in the early 1900s, and its complexity has increased considerably since then. The basic characteristics of the power system in the 20th century were that they were comprised of 3-phase AC systems at constant voltage, synchronous AC machines (alternators) running at constant frequency for generation, and transmitted power over significant distances. Our understanding of the power system has been based on these underlying characteristics. However, in the 21st century, these characteristics no longer apply universally and our understanding of power system concepts is no longer quite as firmly entrenched.

After notable development in the field of renewable system in 21st century, modern power grid is mostly integrated with different renewable and sustainable energy sources in transmission and distribution areas. Again, necessity for a large centralized power system as a “one-size-fits-all” solution for every energy need is being questioned, and distributed generation and micro grids are gaining importance in niche applications.

In all developed and developing countries, wind power along with other renewables being interconnected and being planned for interconnection is increasing at a sharp rate. This trend is expected to continue due to increased concerns about environmental issues such as carbon emissions and global climate change, energy security in a less-than-unipolar world, and job creation in a recession environment. Out of all renewable sources, wind power has been the most successful but poses various integration challenge. Another important renewable energy i.e. solar is more practical option for residential energy production but not as popular as wind on utility scale. According to a recent survey, “Out of all the renewable energy produced in the U.S. in 2017**,** 21% came from wind, while just 7% came from solar power”.

Variable speed wind turbines which uses power electronic converters such as doubly-fed induction generator (DFIG) wind turbines and permanent magnet synchronous generator (PMSG) wind turbines, provide flexible control on rotor speed and generated power. Because of that, these turbines are more grid-friendly compared to fixed speed wind turbines. In recent time, DFIG is getting market penetration more rapidly than PMSG system which is equipped with full-rated power converters.

II. LITERATURE REVIEW

Dynamic modelling and simulation of variable speed wind turbine can be very useful in many scientific studies. For variable speed wind turbine MPPT is used to maximize power co-efficient (Cp) by controlling rotor speed indirectly as shown in Rachid El Akhrif, 2016. In Andrew O. Oduor, 2014 the relationship between power co-efficient, tip-speed ratio and pitch angle is shown and necessary constant values are evaluated. Despite various control methods, the most popular and practical control scheme of DFIGs is still field-oriented control based on PI controllers (Djamel Eddine Chouaib Belkhiat, 2013). The basic principle of vector control is to separate the component of the motor current responsible for producing the torque and the component responsible for producing the flux in such a way that they are magnetically decoupled, and then control each independently, in the same way as is done in a separately excited DC motor (Jaroslaw Guzinski, 2012). Moreover, the rotor side converter is used for improvement of performance (transient and steady state) of the DFIG (E. G. Shehata, 2013 , Zengping Wang, 2012), and the grid side converter is responsible for keeping the DC-link voltage constant at the reference value as explained in Xiaoming Yuan, 2015,Jovica V. Milanovi, 2007 and Rachid Abdessemed, 2014. In Y. H. Hu, 2016, a novel approach is proposed to extract more voltage from same DC bus by using 3rd harmonic injected PWM controlled power converters.

III. MODELLING OF ELECTRICAL SYSTEM

The typical DFIG configuration, illustrated in Fig.1consists of a wound rotor induction generator (WRIG) with the stator windings directly connected to the three-phase grid and with the rotor windings connected to a back-to-back partial scale power converter.

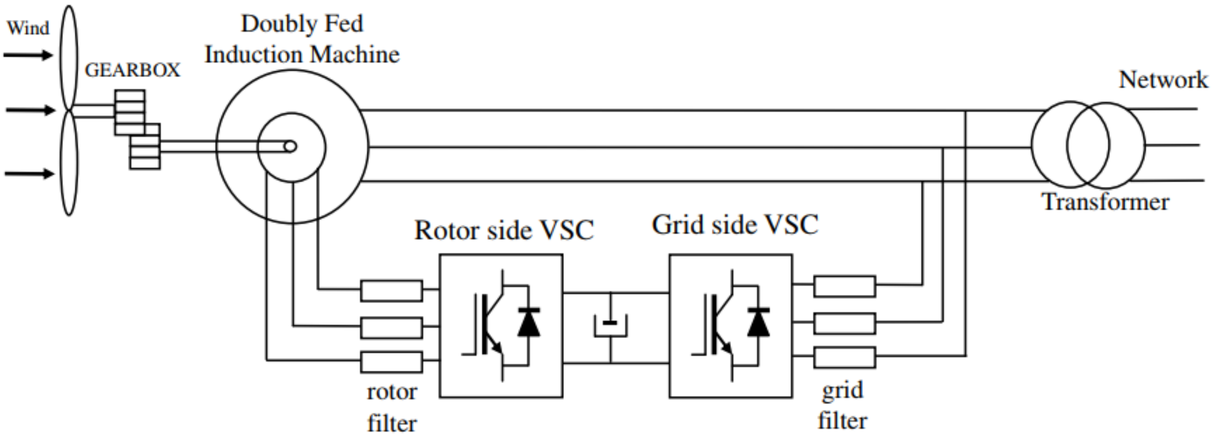


Fig 1 General configuration of DFIG based wind turbine.

DFIG system allows variable speed operation over a large but restricted range. The smaller the operational speed range the less power has to be handled by the bi-directional power converter connected to the rotor. For example, if the speed should be controllable between +/- 30%, the converter must have a rating of approximate 30% of the generator.

In order to cover a wide operating range from sub-synchronous to over synchronous speed, i.e. the DFIG is able to work as a generator in both sub synchronous (positive slip s>0) and over-synchronous (negative slip s<0) operating area, the power converter has to be able to operate with power flow in both directions. This is the reason why a back-to-back PWM (bi directional) converter configuration is used.

A. Equivalent Circuit Referring the Rotor to the Stator

In general, the equivalent circuit of Figure 1 together with the model equations (1) and (2) are used as a first step to derive the final steady state circuit of the DFIM. The fact that the stator and rotor equivalent circuits and their model equations operate at different frequencies (f_s andf_r) make them not very practical beyond analysis of the machine. Consequently, a much more practical and useful approach is to transform the equivalent circuit of Figure 1 to an equivalent circuit in which all the rotor and stator currents and voltages operate at the same frequency.

B. Referring Rotor EMF to the Stator

For that purpose, it is first necessary to find the relation between the induced *EMFs* of the stator and rotor. Hence, according to the basic form of Lenz's law:

$$E = N\frac{d\phi}{dt} \qquad (1)$$

The induced voltage E depends on the flux ϕ variation and the number of turns N. Consequently, the induced voltage $\vec{E}_s$ in the stator windings is

$$\vec{E}_s = \sqrt{2}\pi K_s N_s f_s \vec{\phi}_m \quad \text{(Vrms)} \qquad (2)$$

Where

$\vec{\phi}_m$ = Magnetizing flux

K_s = Stator winding factor; in general, slightly smaller than 1 due to the geometry of the machine

Similarly, in the rotor windings, due to the slip speed, the induced emf $\overrightarrow{E'}_{rs}$ is

$$\overrightarrow{E'}_{rs} = \sqrt{2}\pi K_r N_r f_r \vec{\phi}_m \quad \text{(Vrms)} \qquad (3)$$

where

K_r = Rotor winding factor; in general, as occurs in the stator, slightly smaller than 1 due to the geometry of the machine.

Hence, by equating Equations (2) and (3) and taking into account expression (1), the relation between the induced emf in the stator and rotor yields

$$\frac{\overrightarrow{E'}_{rs}}{\vec{E}_s} = s\frac{K_r N_r}{K_s N_s} \qquad (4)$$

We often define a constant factor, u, that relates the stator and rotor induced voltages at zero speed (s=1):

$$\frac{1}{u} = \frac{K_r N_r}{K_s N_s} \qquad (5)$$

In general and particularly also in wind energy generation applications, the machines are specially designed, in such a way that the u factor is mostly defined by the stator and rotor turns ratio:

$$\frac{K_r}{K_s} \cong 1, \Rightarrow u \cong \frac{N_s}{N_r} \qquad (6)$$

VECTOR CONTROL OF ROTOR SIDE CONVERTER

(DFIM). Control itself plays a very important role in drives and consequently also in wind turbine technology. Control of the doubly fed induction generator when generating energy in a wind turbine is necessary and unavoidable. Control maintains magnitudes of the generator, such as torque, and active and reactive power, and also magnitudes related to the grid side converter, such as the reactive power and the DC bus voltage close to their optimum values, for proper and effective energy generation. In this way, control, together with the modulator if implemented, is in charge of generating the converter switch pulses according to the desired reference values.

$$P_s = -\frac{3}{2} V_g \frac{L_m}{L_s} i_{qr} \qquad (7)$$

$$Q_s = \frac{3}{2} V_g \frac{\Psi_s}{L_s} - \frac{3}{2} V_g \frac{L_m}{L_s} i_{dr} = \frac{3}{2} V_g \frac{{V_g}^2}{\omega_s L_s} - \frac{3}{2} V_g \frac{L_m}{L_s} i_{dr} \qquad (8)$$

A. The vector control technique is also known as field oriented control.

Vector control of a grid connected DFIM is very similar to the widespread classical vector control of a squirrel cage machine. This machine is controlled in a synchronously rotating *dq* reference frame, with the *d* axis oriented along the rotor flux space vector position. The direct current is thus proportional to the rotor flux while the quadrature current is proportional to the electromagnetic torque. By controlling independently the two components of the current, a decoupled control between the torque and the rotor excitation current is obtained.

$$v_{dr} = R_r i_{dr} - \omega_r \sigma . L_r i_{qr} + \sigma . L_r \frac{d}{dt} i_{dr} + \frac{L_m}{L_s} \frac{d}{dt} \Psi_{ds} \qquad (9)$$

$$v_{qr} = R_r i_{qr} + \omega_r \sigma . L_r i_{dr} + \sigma . L_r \frac{d}{dt} i_{qr} + \omega_r \frac{L_m}{L_s} \Psi_{ds} \qquad (10)$$

In a similar way, in vector control of a DFIM, the components of the d and the q axis of the rotor current are regulated. As will be shown, if a reference frame orientated with the stator flux is used, the active and reactive power flows of the stator can be controlled independently by means of the quadrature and the direct current, respectively (Fig 2)

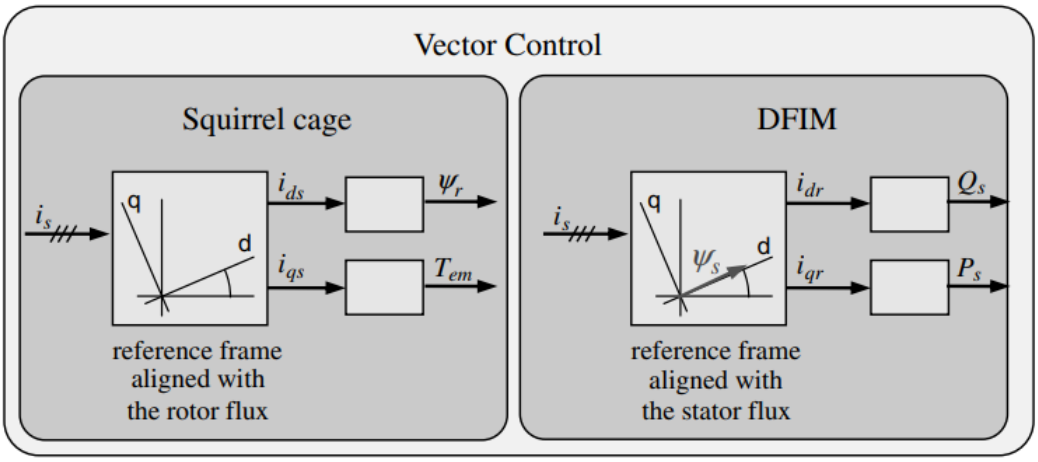


Fig 2 Comparison between the Vector Control of the squirrel cage machine and the DFIM.

Complete Control System

In previous sections the different parts of a classical vector control for a DFIM have been presented:

- Generation of the references: reference current calculations from the desired stator active and reactive powers.
- Current control loops.
- Reference frame transformations.

Figure 8.10 shows a schematic block diagram of the interconnections between all these parts.A nd depicts a control where the reference frame is oriented using the stator flux. The angle used in the transformations is thus obtained from the voltage measurements of the grid using a phase locked loop.

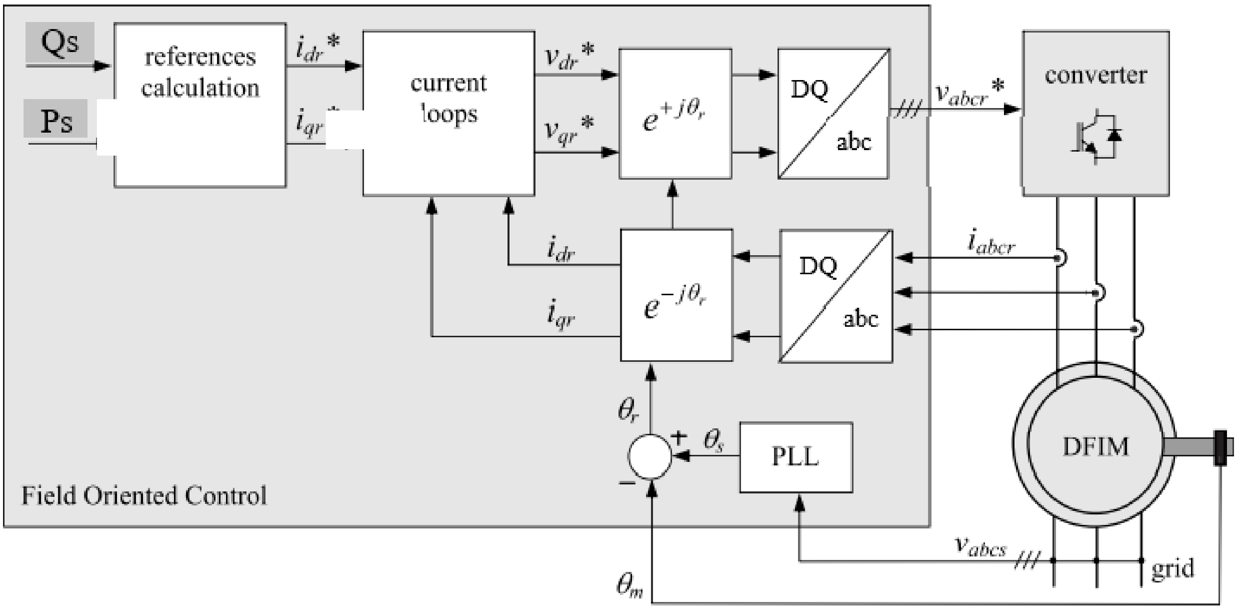


Fig 3 Schematic diagram of the vector control system.

Therefore, because of the orientation chosen, it can be seen that both rotor current components independently allow us to control the torque and reactive stator power. In this way, based on above expressions, Fig.3 illustrates the complete vector control of the DFIG.

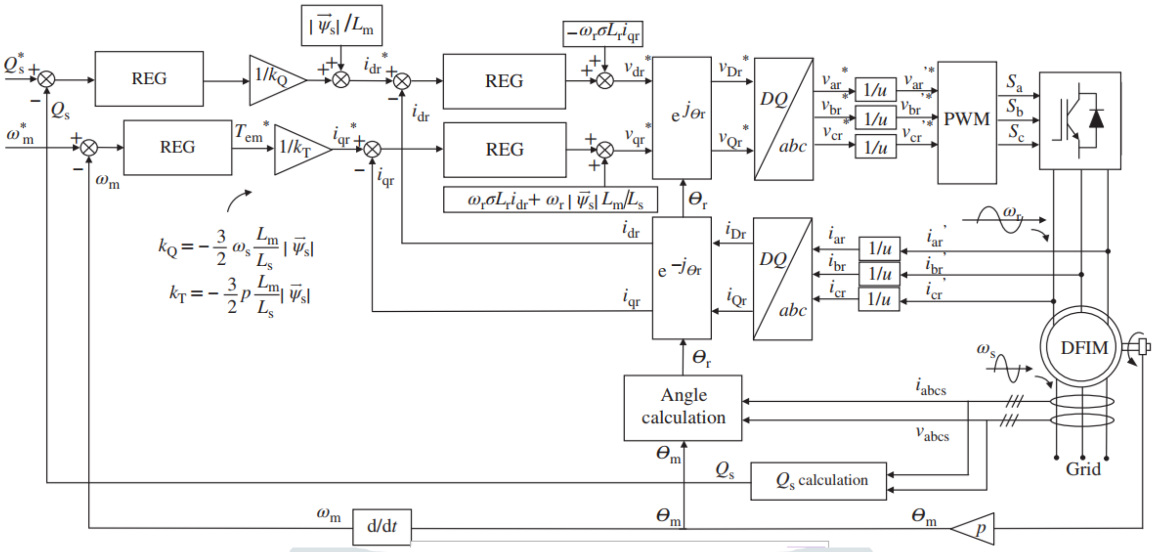
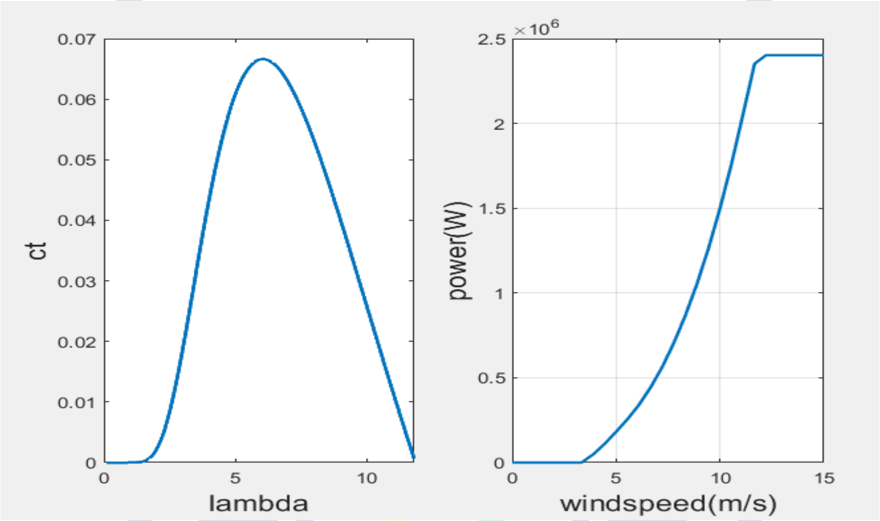


Fig4. Rotor Side Control in DFIG

SIMULATION AND RESULTS



(a) (b)

Fig 5 (a) Lambda vs Ct curve (b) wind speed vs power curve

Vector control of rotor side converter of DFIG is simulated in MATLAB/SIMULINK assuming the grid side converter is already controlled and a constant DC voltage is been given to the Rotor side converter. Two modes of DFIG have been implemented. For first 2.5 seconds we have taken the subsynchronous operation of DFIG, then after 2.5 seconds hypersynchronous operation is shown.We take the synchronous speed be 157.14 rpm.

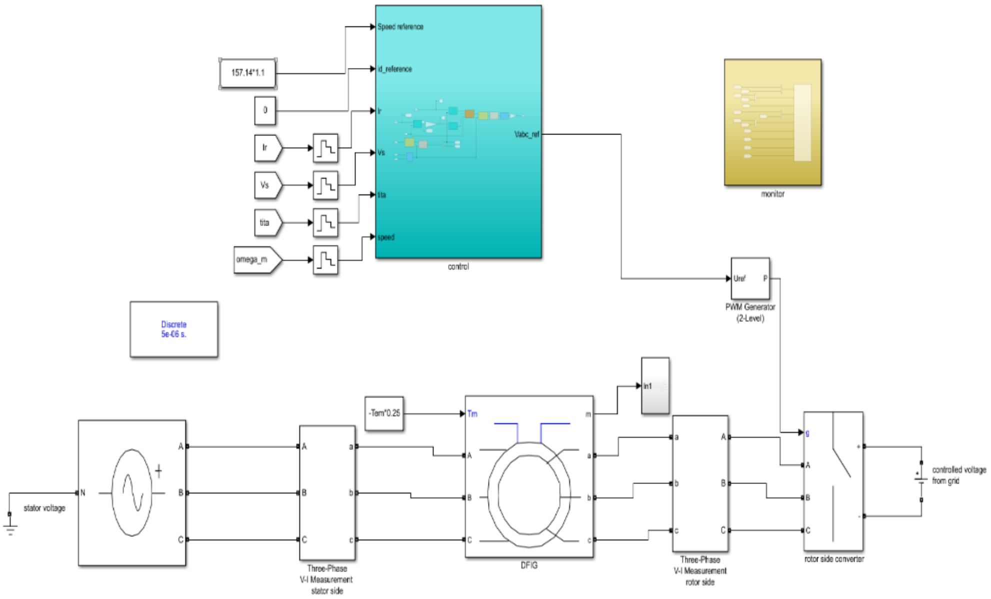


Fig 6 Simulation model of Rotor Side Control of DFIG

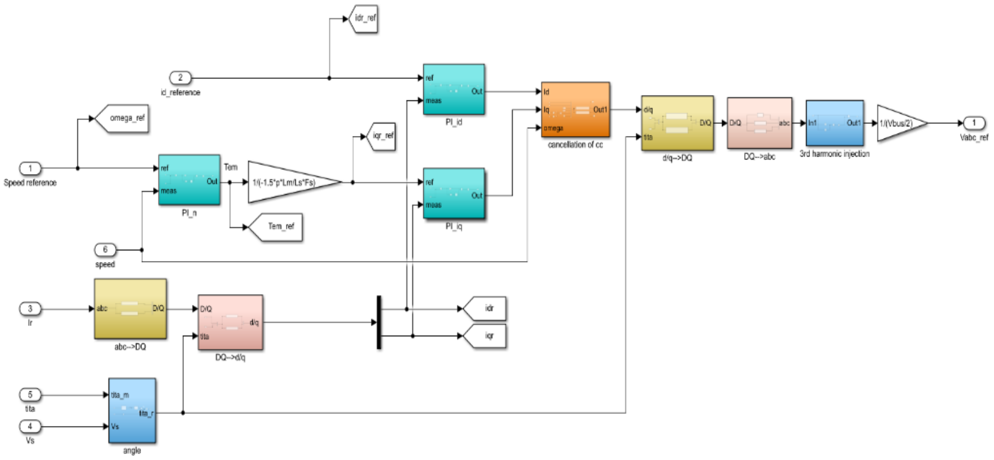


Fig 7 Rotor Side Control Block

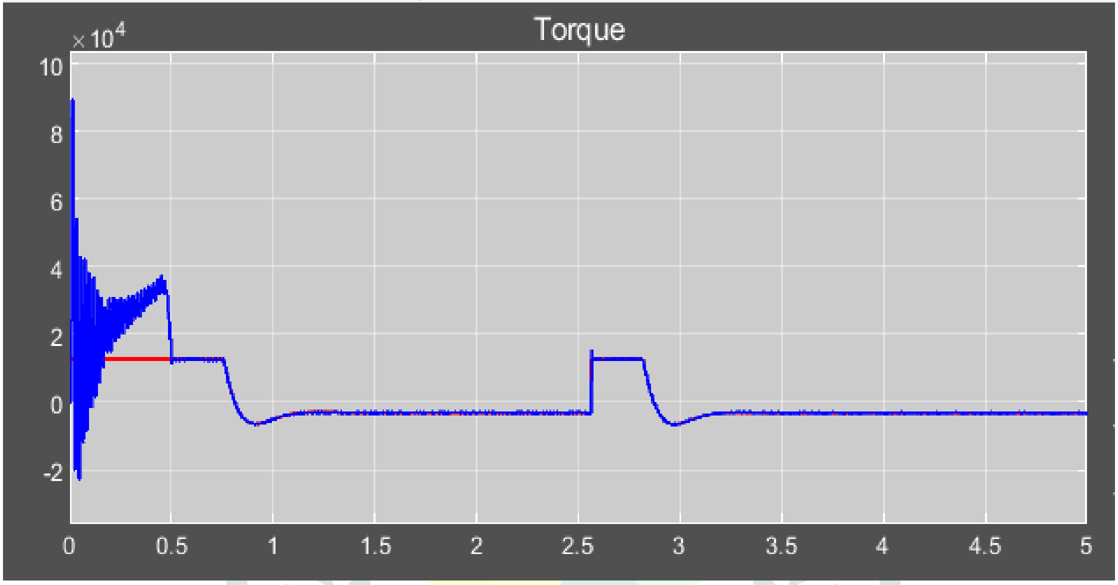


Fig 8 Speed curve

Fig 9 torque curve

In fig 8 and 9, red line represents the reference and the blue line represents the actual quantity. In fig 8, subsynchronous speed (i.e 157.14*0.9) is given for first 2.5 seconds so the actual speed curve first rises above the given speed in the transient period and then follows the reference speed. In the same way after 2.5 seconds, hypersynchronous speed (i.e 157.14*1.1) is given where we observe the step increase in the reference speed and actual speed is slowly following the reference speed.

In Fig 9, negative torque is given to the DFIG but due to variation in speed at 2.5 seconds there is some transient occurring then we can observe that actual torque id following the reference torque.

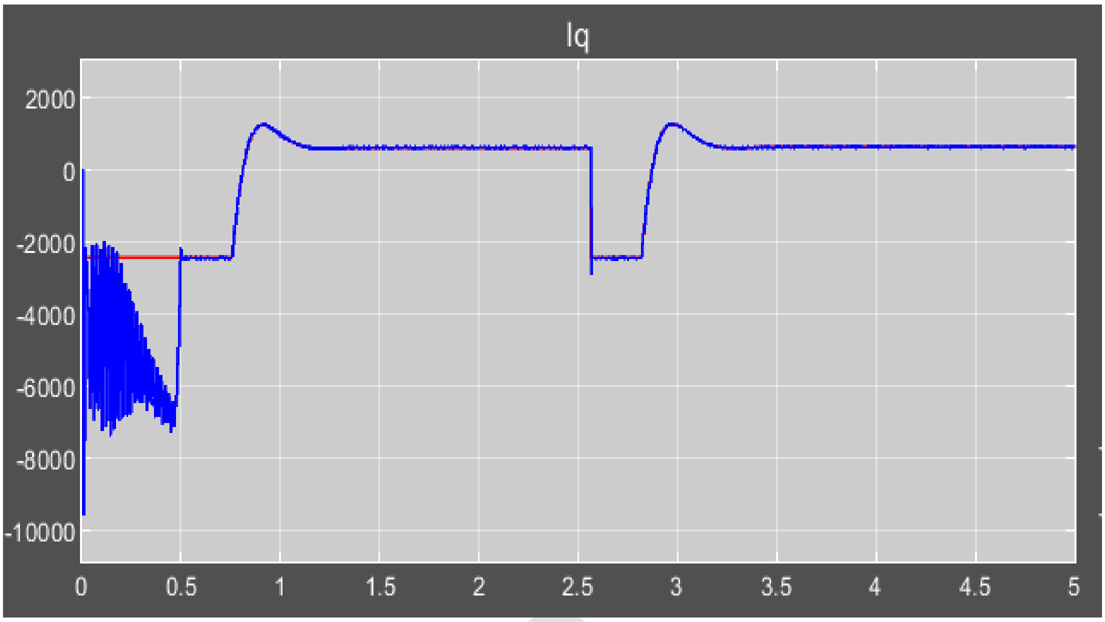


Fig 10 quadrature axis current of rotor side

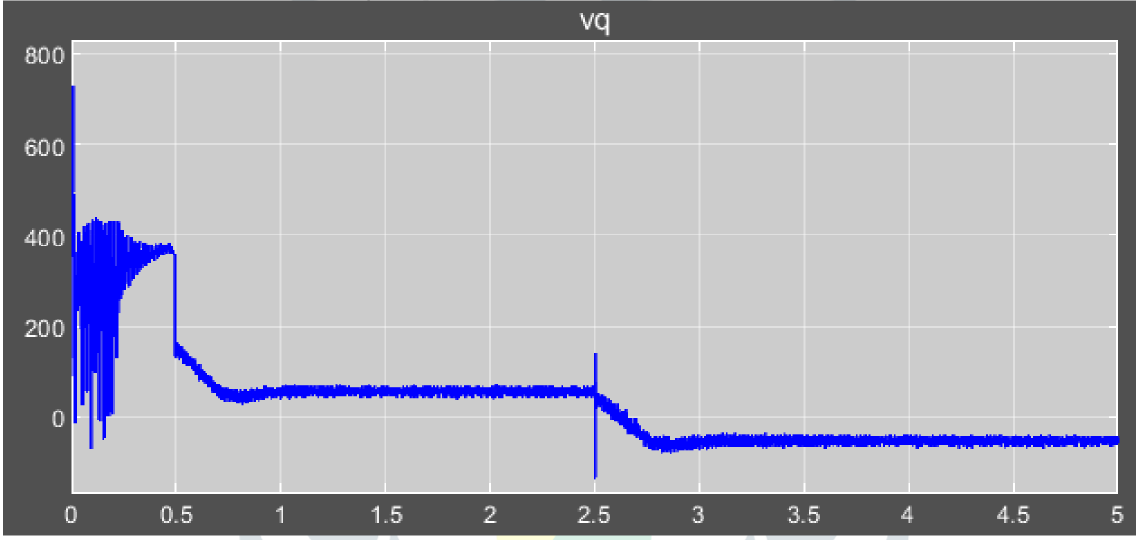


Fig 11 quadrature axis current of rotor side

Here, Iq and Vq are varied according to the torque given to the DFIG. Since, $T_{em} = -\frac{3}{2}p\frac{L_m}{L_s}\frac{V_g}{\omega_s}i_{qr}$

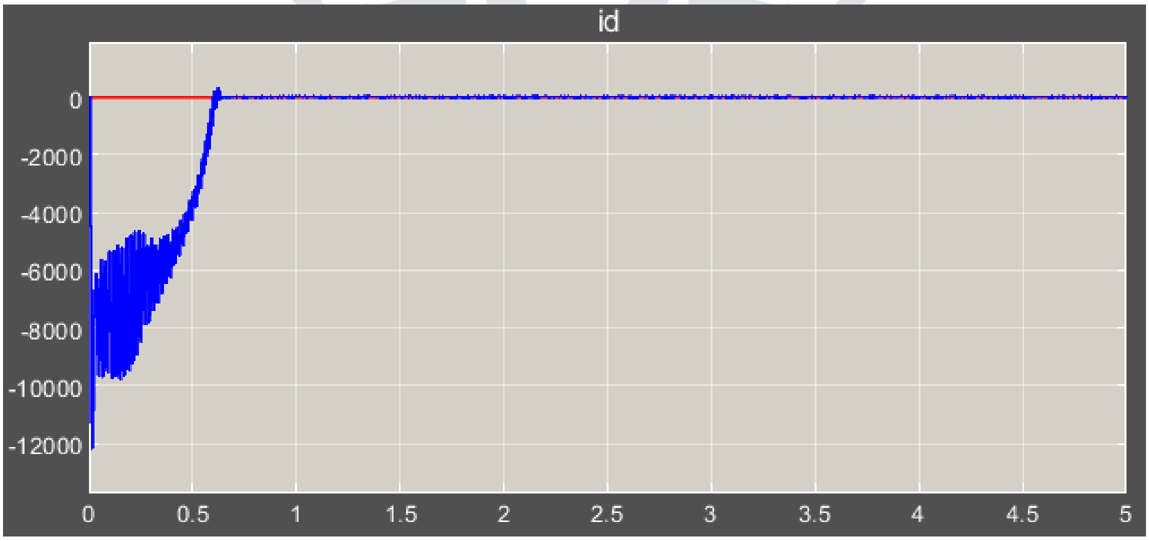


Fig 12 Direct axis current of rotor side

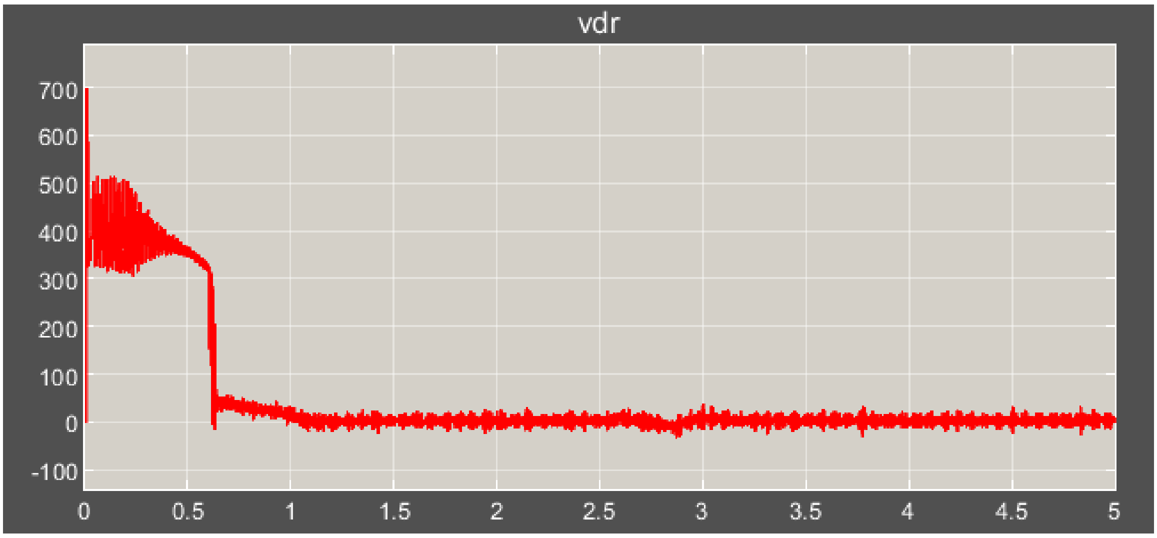


Fig13 Direct axis voltage of rotor side

Since we have set the Id reference to 0, here in fig 12 and 13 both the current and voltage waveforms reached 0 after completing the transient state.

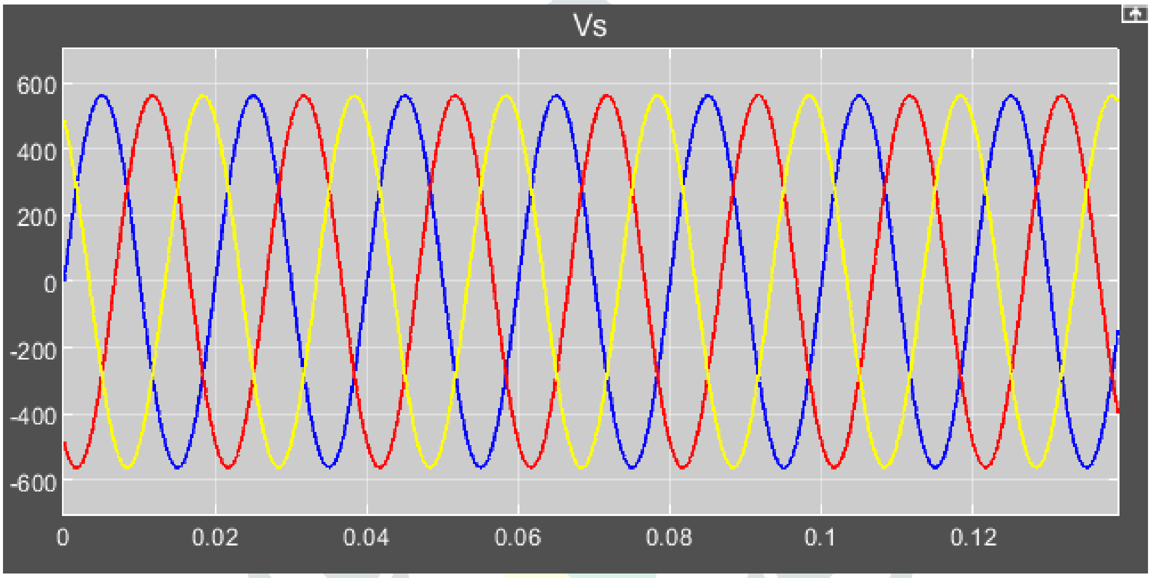


Fig 14 Stator voltage of DFIG

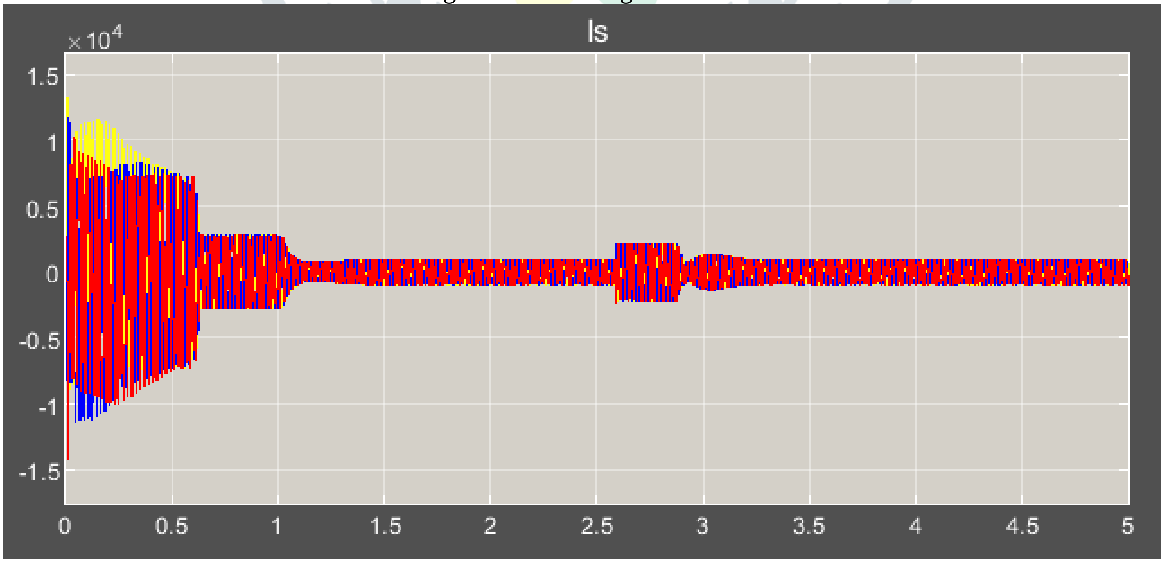


Fig 15 Stator current of DFIG

Fig 14 represents the stator voltage with frequency of 50hz. And Is in Fig 15 changes according to the torque and speed.

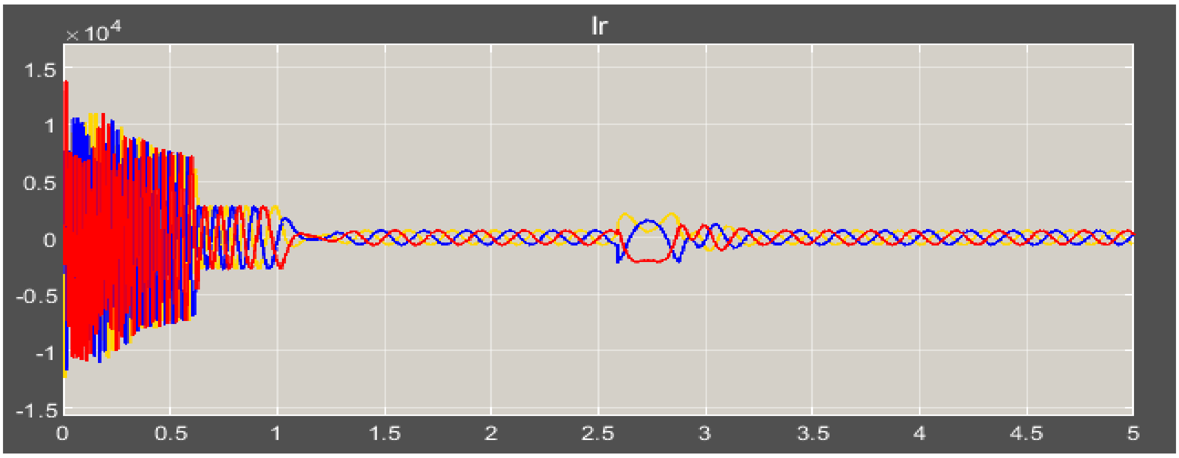


Fig 16 Rotor current of DFIG

In Fig 16, during first 2.5 seconds we observe RYB sequence as we have given sub synchronous speed; the machine receives power through rotor. And after 2.5 seconds we observe RBY sequence as we have given super synchronous speed; the machine delivers power through rotor.

CONCLUSION

A successful Wind Energy Conversion system possesses the ability to transform mechanical energy delivered by the wind into electrical energy that can be used to power any electrical grid. This project has addressed the modelling and control of variable speed type-3 wind turbine (DFIG based). The development of this model is part of an effort to develop generic manufacturer-independent wind turbine models capable of being used for power systems studies. To maintain generality, various approximations and simplifications have been used in the modelling process and despite all the simplifications, the developed time-domain model performs admirably and is able to approximate the behaviour of a real-world Wind power plant in normal condition. Aspects of the theory behind DFIG technology have also been discussed in this chapter, and the necessary mathematical foundation has been presented. The decoupling of real and reactive power control, and the extraction of maximum extractable power from the wind, are the defining aspects of DFIG technology, and a discussion of these concepts is also presented. The modelling procedure has been discussed in detail, with the salient points being the development of sub-models for the generator, converter, mechanical turbine, and pitch control, the theory behind the operation of these sub-models, and the combination of these sub-models into a complete time-domain DFIG Wind Power Plant model. Details of model parameters have been provided to allow reproduction of the results shown here. The modelling of wind turbine generators for bulk power system stability studies is the focus of intense activity in many parts of the industry. This model is expected to give realistic and correct results when used for bulk system performance studies. It is expected that these model components will continue to evolve, in terms of parameter values and structure, as experience and additional test data are obtained.

FUTURE SCOPE

This project dealt with modelling and control of Wind Energy Conversion System. Future research will be on implementing more efficient control strategies, keeping economical factor in mind.

Low-Voltage Ride-Through (LVRT) is found to be one of the biggest challenge facing wind turbine farms massive deployment; in particular, those using DFIGs. This type of generator is unfortunately sensitive to grid disturbance, in particular voltage sags. In the event of a voltage drop, turbines are required to remain connected for specific time duration before being allowed to disconnect. This requirement is to ensure that there is no generation loss for normally cleared faults. Disconnecting a wind generator too quickly could have a negative impact on the grid, particularly with large wind farms. In this context future work can be done to propose robust control strategies in order to address LVRT issues.

APPENDIX

A.1 PARAMETERS USED IN THE SIMULATION

S.NO	PARAMETER NAME	RATING
1	Rated Power	2MW
2	Rated Stator Voltage	690 V
3	Rated Stator Current	1760A
4	Stator/Rotor Turn Ratio	1/3
5	Rated Rotor Voltage	2070 V
6	Rated Frequency	50 Hz
7	Pole Numbers	4
8	Stator Resistance	2.6 mΩ
9	Rotor Resistance	2.9 mΩ
10	Stator Leakage Inductance	0.087 mH
11	Rotor Leakage Inductance	0.087 mH
12	Magnetic Inductance	2.5 mH
13	Rated Rotational Speed	1500 rpm
14	Angular Moment Of Inertia	127 Kg-m^2
15	Mechanical Damping	0.001
16	Rated Torque	12732 N-m
17	Maximum Slip	1/3

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