Power control of induction generator using P-I controllers for wind power applications

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Abstract—— **A line excited cage generator system, with PI control for efficiency optimization and performance enhancement, is discussed in this paper. A squirrel cage induction generator driven by a prime mover feeds the power to a utility grid through two double side pulse width modulated converter system. The generation control system uses three PI controllers. The first PI controller tracks the generator speed with the reference speed for maximum power extraction. The second PI controller controls the direct axis current for reactive power control. The third PI controller provides control of quadrature axis current for active power control. The fourth PI controller is used to maintain the dc link voltage constant. The performance of the PI controlled variable speed wind energy conversion system is evaluated through simulation study in MATLAB. Closed loop speed response of the generator with PI controller show fast speed response can be obtained with well designed PI controllers.**

Keywords- ***squirrel cage induction generator, indirect vector control, PI controller, PWM converter, wind energy generation.***

I. INTRODUCTION

The global electrical energy consumption is rising and there is steady increase of the demand on power generation. The existing conventional energy sources are depleting. So, alternative energy source investment is becoming more important these days. Wind electrical power systems are recently getting lot of attention, because they are most cost competitive, environmentally clean and safe renewable source. Of course, the main drawback of wind power is that its availability is somewhat statistical in nature. So it must be supplemented by additional sources to supply the demand curve. In the most preliminary type of wind electrical power system, a fixed speed wind turbine drives an induction generator, directly connected the grid. This system has a number of drawbacks, however. The reactive power and, therefore, the grid voltage level cannot be controlled; the blade rotation causes power and voltage variations [1].

Most of these drawbacks are avoided, when variable-speed wind turbines are used. The power production of variable speed turbines is higher than for fixed speed turbines, as they can rotate at the optimal rotational speed for each wind speed. Noise at low wind speeds is reduced. Other advantages of variable speed wind turbines are reduced mechanical stresses, reduced torque and power pulsations, and improved power quality [2].

The disadvantage of the variable speed turbine is a more complex electrical system, requiring power electronic converters to make the variable speed operation possible. But, the evolution of power semiconductors and variable frequency drive technology has aided the acceptance of variable speed wind generation systems. In spite of additional cost of converters and control, the total energy capture in a variable speed wind turbine system is larger and therefore the lifecycle cost is lower than with fixed speed system.

The advantages of cage induction machines are well known. These machines are relatively inexpensive, robust, and require low maintenance. When induction machines are operated using vector control techniques, fast dynamic response and accurate torque control are obtained. All of these characteristics are advantageous in variable speed wind energy conversion systems (WECS). Squirrel cage generators with shunt passive or active VAR (volt ampere reactive) generators was proposed in [3], which generate constant frequency power through a diode rectifier and line commutated thyristor inverter. Operation of several self excited induction generators connected to a common bus is analyzed in [4]. The control systems for the operation of indirect rotor flux oriented vector controlled induction machines for variable speed wind energy applications are discussed in [5]-[7]. Sensorless vector control scheme suitable to operate cage induction generator is discussed in [5]. In [6] cage induction machine is considered and a fuzzy control system is used to drive the WECS to the point of maximum energy capture for a given wind velocity.

The induction machine is connected to the utility using back to-back converters. In this paper a variable speed wind turbine driven squirrel cage induction generator system with two double sided PWM converters is described. PI control is used to optimize efficiency and enhance performance. The control algorithms are evaluated by MATLAB simulation study.

II. INDUCTION GENERATOR ELECTRICAL MODEL

The basic configuration of a line excited induction generator is sketched in fig.1. Normally the stator is interfaced with the grid through back-to-back PWM inverter configuration. The operating principle of a line excited induction generator can be analyzed using the classic theory of rotating fields and the well-known d-q model, as well as three-to-two and two-to-three axes transformations.

In order to deal with the machine dynamic behavior both the stator and rotor variables are referred to synchronously rotating reference frame in the developed model. When aiming to express the induction machine electrical model in the above mentioned reference frame , it is first necessary to perform the Clark's

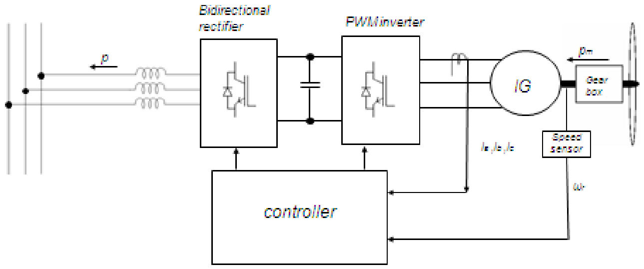


Fig.-1

transformation from the three phase to the d-q current and voltage systems through the following equation

$$\begin{bmatrix} V_{qs}{}^{s} \\ V_{ds}{}^{s} \\ V_{0s}{}^{s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta-120) & \cos(\theta+120) \\ \sin\theta & \sin(\theta-120) & \sin(\theta+120) \\ 0.5 & 0.5 & 0.5 \end{bmatrix}\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \qquad ...(1)$$

It is convenient to set $\theta=0$, i.e. ‘ q_s’ aligned with ‘a_s’ axis. Ignoring zero sequence components we get

$$V_{qs}{}^{s} = V_{as} \qquad …….. (2)$$

$$V_{ds}{}^{s} = -\frac{1}{\sqrt{3}}V_{bs} + \frac{1}{\sqrt{3}}V_{cs} \qquad ……. (3)$$

The general convention applied in this model is similar to that of the motor convention, i.e. the stator currents are positive when flowing towards the machine and real power and reactive power are positive when fed from the grid. The

The equations describing the asynchronous machine in terms of phase variables were derived to develop the model with all rotor variables referred to stator. The equations were then transformed into d-q axis reference frame with axes rotating at synchronous speed using transformations as given above. When deriving the model the q-axis was assumed to be 90^{o} ahead of the d-axis in the direction of rotation, and the d-axis was chosen such that it coincides with the maximum of the stator flux. Therefore V_{qs} equals the terminal voltage and V_{ds} equal to zero.

Stator voltages:

$$V_{qs} = R_s\, i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega_e \Psi_{ds} \qquad …… (4)$$

$$V_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt} - \omega_e \Psi_{qs} \qquad ……. (5)$$

Rotor voltages:

$$V_{qr} = R_r\, i_{qr} + \frac{d\Psi_{qr}}{dt} + (\omega_e\text{-}\omega_r)\, \Psi_{dr} \qquad …….(6)$$

$$V_{dr} = R_r\, i_{dr} + \frac{d\Psi_{dr}}{dt} - (\omega_e\text{-}\omega_r)\, \Psi_{qr} \qquad …. (7)$$

The flux linkages in these equations were calculated from:

$$\Psi_{qs} = L_s\, i_{qs} + L_m\, i_{qr}\,, \qquad \Psi_{qr} = L_r\, i_{qr} + L_m\, i_{qs}$$

$$\Psi_{ds} = L_s\, i_{ds} + L_m\, i_{ds}\,, \qquad \Psi_{dr} = L_r\, i_{dr} + L_m\, i_{ds}$$

machine is given as The final mathematical model for the squirrel cage induction

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} R_s + sL_s & -\omega_e L_s & sL_m & -\omega_e L_m \\ \omega_e L_s & R_s + sL_s & \omega_e L_m & sL_m \\ sL_m & -(\omega_e - \omega_r)L_m & R_r + sL_r & -(\omega_e - \omega_r)L_r \\ (\omega_e - \omega_r)L_m & sL_m & (\omega_e - \omega_r)L_r & R_r + sL_r \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \qquad …….(8)$$

where ‘s’ is the laplace operator and ‘ω_r’ is the rotor electrical speed.

For a singly fed machine as the cage motor $V_{qr} = V_{dr} = 0$

The machine dynamics is given as

$$T_e + T_{turbine} = J\frac{d\omega_m}{dt} + B\omega_m \qquad …. (10)$$

$$T_e = \frac{3}{2}\frac{P}{2}L_m(i_{qs}i_{dr} - i_{ds}i_{qr}) \qquad ….(11)$$

The active and reactive power of the generator is given as

$$p = V_{ds}i_{ds} + V_{qs}i_{qs} \qquad …..(12)$$

$$q = V_{qs}i_{ds} - V_{ds}i_{qs} \qquad ….. (13)$$

III. CONTROL STRUCTURE

The key feature of field oriented control is to keep the magnetizing current at a constant rated value. Thus the torque producing component of current can be adjusted according to the active power demand with a better dynamic response as in Fig.-2. With this assumption the mathematical formulation can be written as

$$\omega_{sl} = \frac{R_r}{L_r}\frac{i_{qs}}{i_{ds}} \qquad ….. (14)$$

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\psi_{dr}i_{qs} \qquad ….. (15)$$

where ω_{sl} is the slip speed and ψ_{dr} is the d-axis rotor flux linkage.The basic configuration of the drive consists of a line excited squirrel cage induction generator interfaced with the grid through a back-to-back PWM inverter. The inverters are voltage controlled bidirectional voltage source inverters having a dc link between them. The rotor speed is fed back by a speed sensor which is then added with the slip speed to get the synchronous speed which is further integrated to get the angular displacement θ_e from which the unit vectors are generated.

The controller PI-1 keeps the rotor speed in track with the reference speed such that maximum power can be captured from the wind by the wind turbine. The controller PI-2 controls the direct axis rotor current such that the rotor magnetizing flux remains constant to get better dynamic response. The controller PI-3 controls the quadrature axis current such that the given active power demand can be met. The controller PI-4 is used to keep the dc link voltage constant.

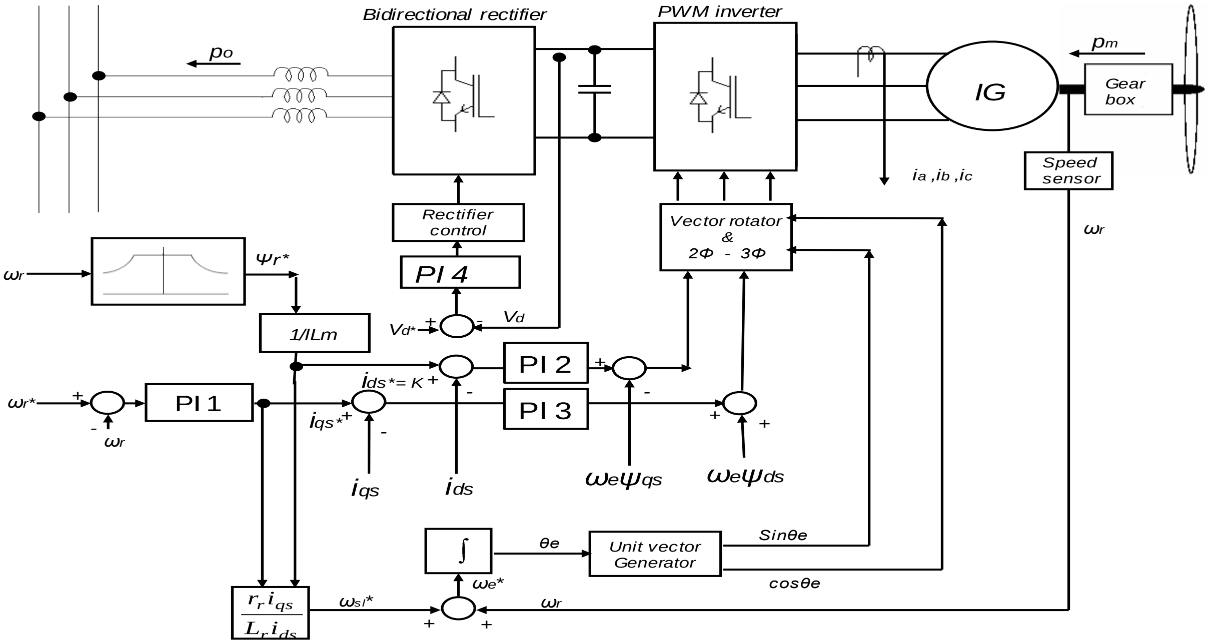


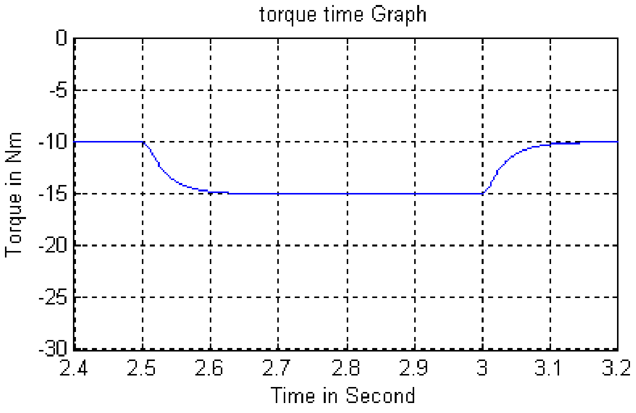
Fig-2

The PI controllers were initially tuned by using Zeigler- Nicholas P-I-D tuning rule. Then they were further adjusted to get optimum results.

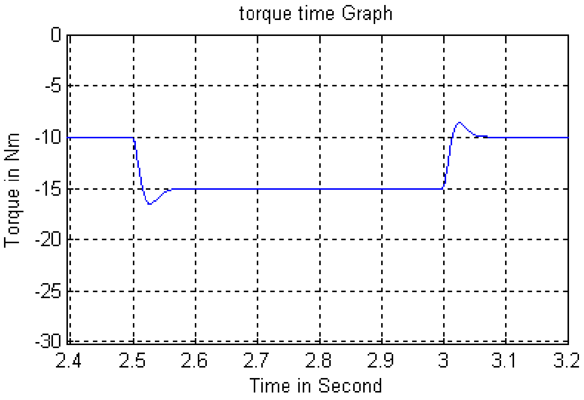
IV. RESULTS AND DISCUSSION

The drive system was simulated with PI controllers with different operating conditions such as step change in the reference speed and some sample results are presented in the following section.

A step change command for torque is given at t = 2.5sec. which continues for 0.5sec. and again returns to the previous value. In openloop the machine takes around 0.13sec. to achieve steady state but with pi control it takes approximately 0.05 sec. to achieve steady state which can be seen clearly in fig.- 3.. Thus with PI controllers the active power, reactive power and line current values change for a very short transient time or else remain constant thus improving the stability of the system. The results in the following sections shows the improved performance of the generator system.

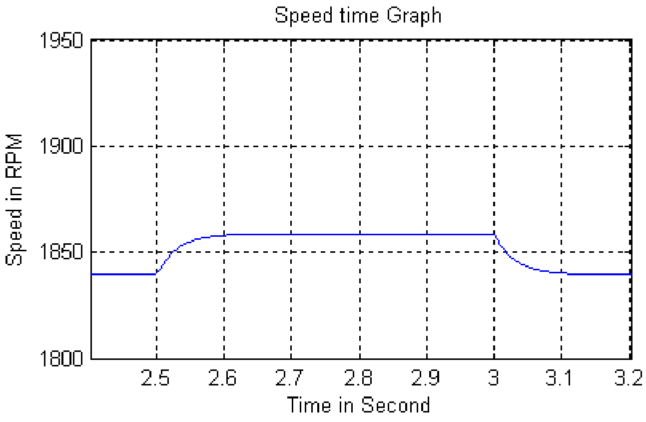


(a)



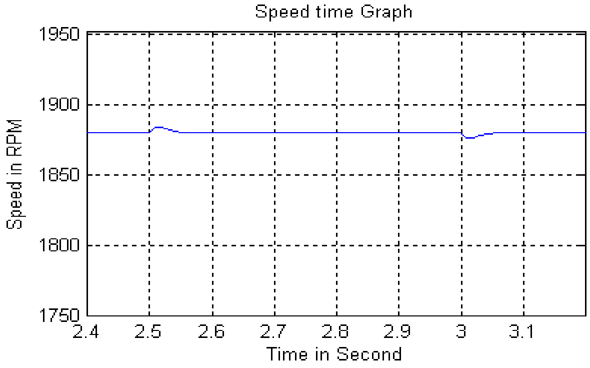
(b)

Fig-3 simulated torque response due to step change of turbine torque (a) open loop (b) PI

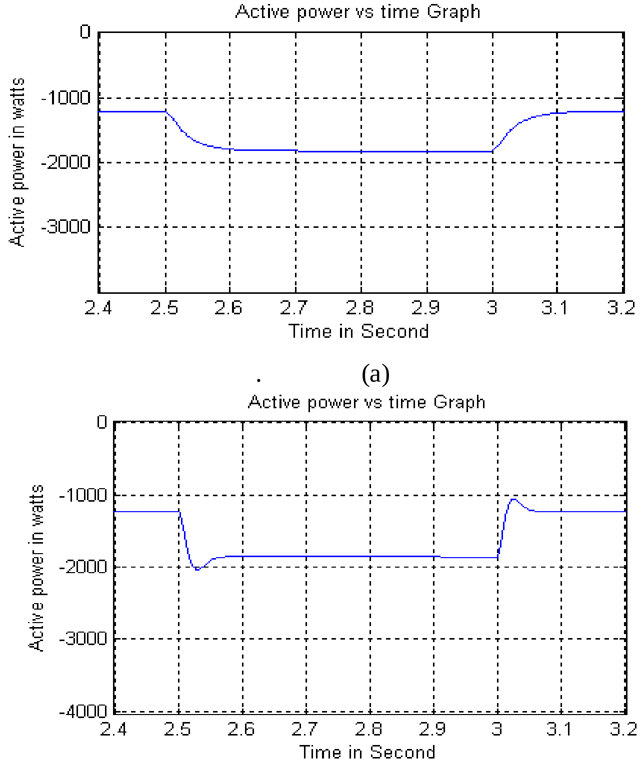


(a)

Fig-4 Simulated speed response of the drive system due to step change in turbine torque (a) open loop (b) pi



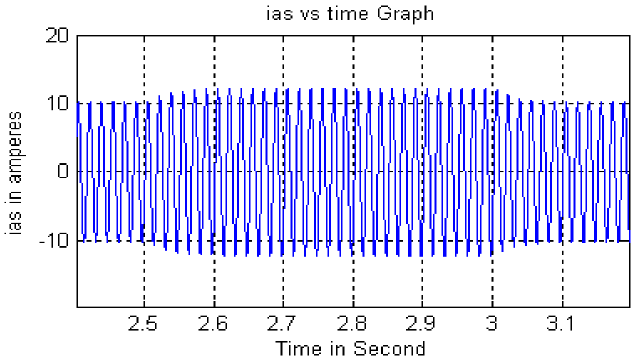
(b)



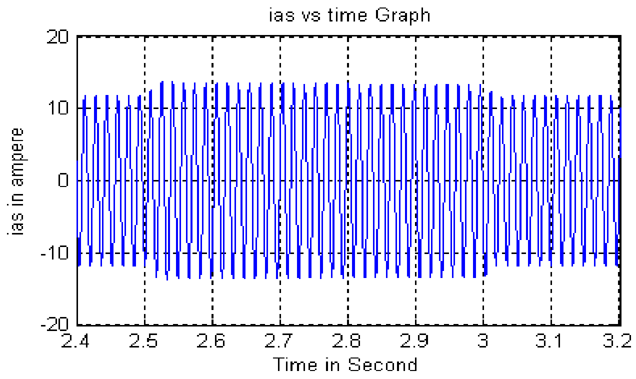
(a)

(b)

Fig-5 simulated active power response due to step change of turbine torque (a) open loop (b) PI



(a)



(b)

Fig-6 simulated torque response due to step change of turbine torque (a) open loop (b) PI

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