Indirect Vector Control of Squirrel-Cage Induction Generator

Abstract

This paper presents the torque control of squirrel-cage induction generator using indirect vector control (IVC) technique. For very low-speed operations and for position type control, the use of flux sensing may not be acceptable because the devices that used to measure the air-gap flux is inaccurate in low speed. Indirect vector control is very popular in industrial applications, which doesn't rely on the measurement of the airgap flux. The indirect vector control scheme has been presented to control the torque of the generator and maintain the flux constant . The space-phasor model of the induction machine has been used in simulation. To predict the performance of the proposed system, a MATLAB/SIMULINK based study has been carried out. Simulation results are presented illustrating good control system performance.

Keywords—Induction generators; Field orientation; Modeling and simulation ; Torque control.

1.Introduction

Wind energy is one of the most important and promising source of renewable energy all over the world, mainly because it is considered to be nonpolluting and economically viable. At the same time there has been a rapid development of related wind energy technology. The control and estimation of wind energy conversion system constitute a vast subject and are more complex than those of dc drives. Induction generators with cage type rotors have been used extensively in wind power generation systems for the variable speed applications in a wide power range. Generally, variable speed wind energy conversion systems with Induction generators require both a wide operating range of speed and a fast torque response, regardless of any disturbances and uncertainties (turbine torque variation, parameters variation and un-modeled dynamics). This leads to more advanced control methods to meet the real demand. The recent advances in the area of field-oriented control along with the rapid development and cost reduction of power electronics devices and microprocessors have made variable speed wind energy conversion system an economical alternative for wind power applications. The complexity of wind energy conversion system increases substantially if high performances are demanded. The main reasons for this complexity are the need of variable frequency, the complex dynamics of ac machines, machine parameter variations etc. Various control techniques have been developed in the recent days for the control of cage induction generators.

Variable Frequency Drives are mainly classified in the following categories [1]-[7]:
Scalar Control (V/f Control) , Vector Control and Direct Torque Control (DTC).
In Scalar Control method by varying the voltage and frequency by the same ratio, flux and hence, the torque can be kept constant throughout the speed range. In vector control, it is possible to achieve high dynamic performance, equaling that of the separately excited DC motor, in variable speed AC drives[1]. Vector control or field orientation control is a method in which the machine input currents are adjusted to set a specific angle between them[2]-[3]. The key to field-oriented control is knowledge of the rotor flux position angle with respect to the stator. Methods in which rotor flux is sensed by flux sensing coils or it is calculated by machine terminal voltages or currents, are generally termed “direct vector control” (DVC) methods[4]-[5]. It is also possible to compute the angle from shaft position information, provided other motor parameters are known. This approach is generally termed “indirect vector control” (IVC). The indirect methods of Field-orientation control eliminates the need for a flux sensor or flux model but require an accurate measurement of shaft position in order to determine the precise location of the rotor flux vector[6]-[7].
In this paper the two schemes of IVC will be compared with each other. These two schemes are Indirect vector controlled induction generator without torque feedback and Indirect vector controlled induction motor with torque feedback .
The proposed schemes are described clearly and simulation results are reported to demonstrate its effectiveness.

2. Principle And Mathematical Model of Indirect Vector Control System

Figure 1 explains the fundamental principle of indirect vector control with the help of phasor diagram. The d^s-q^s axes are fixed on the stator, but the d^r-q^r axes , which are fixed on the rotor, are moving at speed ω_r. the slip angle between the Synchronously rotating axes $d^e – q^e$ and $d^r – q^r$ axis is θ_{sl} corresponding to slip frequency ω_{sl} . Since the rotor pole is directed on the d^e and ω_e=ω_r+ω_{sl} , one can write

$$\theta_e = \int \omega_e dt = \int(\omega_r + \omega_{sl})dt = \theta_r + \theta_{sl} \tag{3.3}$$

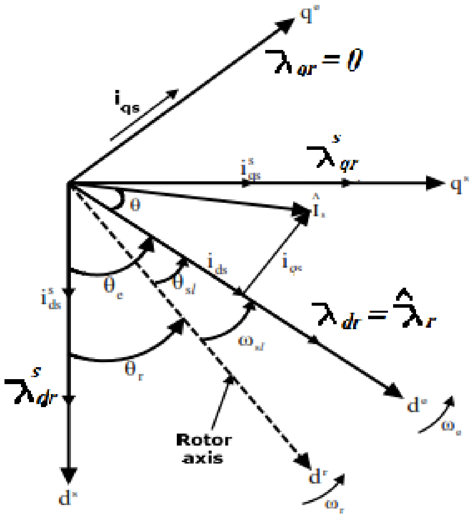


Figure .1 *Phasor diagram explaining indirect vector control*

For decoupling control, one can make a derivation of control equations of indirect vector control with help of $d^e – q^e$ dynamic model of induction machine as following[8]-[9]:

Stator qd voltage equations:

$$v_{qs} = p\lambda_{qs} + \omega_e \lambda_{ds} + R_s i_{qs} \tag{1}$$

$$v_{ds} = p\lambda_{ds} - \omega_e \lambda_{qs} + R_s i_{ds} \tag{2}$$

Rotor qd voltage equations:

$$v_{qr} = p\lambda_{qr} + (\omega_e - \omega_r)\lambda_{dr} + R_r i_{qr} = 0 \tag{3}$$

$$v_{dr} = p\lambda_{dr} - (\omega_e - \omega_r)\lambda_{qr} + R_r i_{dr} = 0 \tag{4}$$

where:

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \tag{5}$$

$$\lambda_{dr} = L_m i_{ds} + L_r i_{dr} \tag{6}$$

and

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \tag{7}$$

$$\lambda_{qr} = L_m i_{qs} + L_r i_{qr} \tag{8}$$

$$L_s = L_{ls} + L_m \tag{9}$$

$$L_r = L_{lr} + L_m \tag{10}$$

Torque equation:

$$T_{em} = \frac{3}{2}\frac{p}{2}\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \tag{11}$$

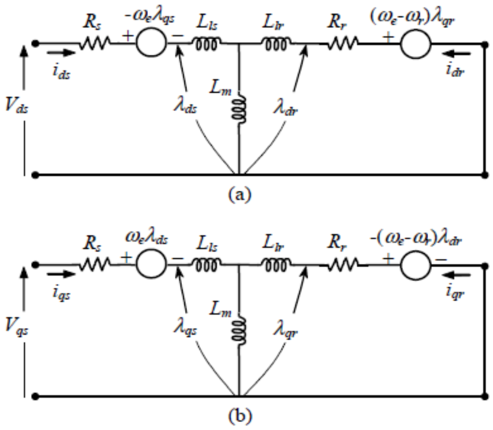


Image 1. D-Q model of an induction machine in the synchronously rotating reference frame (a) d-axis (b) q-axis

If d^e – axis is aligned with the rotor field, the q-component of the rotor field, $\lambda_{qr}^{'e}$, in the chosen reference frame would be zero [10]-[11] , that is

$$\lambda_{qr}^{'e} = L_m i_{qs}^{e} + L_r^{'} i_{qr}^{'e} = 0 \qquad \text{Wb.turn} \tag{12}$$

$$i_{qr}^{'e} = -\frac{L_m}{L_r^{'}} i_{qs}^{e} \qquad \text{A} \tag{13}$$

With $\lambda_{qr}^{'e}$ is zero , the first equation in Eq. 11 for the developed torque reduces to:

$$T_{em} = -\frac{3}{2}\frac{p}{2}\lambda_{dr}^{'e} i_{qr}^{'e} \qquad \text{N.m} \tag{14}$$

Substituting for $i_{qr}^{'e}$ using Eq. 13, Eq. 14 can be written in the desired form of:

$$T_{em} = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r^{'}}\lambda_{dr}^{'e} i_{qs}^{'e} \qquad \text{N.m} \tag{15}$$

Which shows that if the rotor flux linkage $\lambda_{dr}^{'e}$, is not disturbed, the torque can be independently controlled by adjusting the stator q component current, i_{qs}^{e} .

For $\lambda_{qr}^{'e}$ to remain unchanged at zero, $p\lambda_{qr}^{'e}$ must be zero, in which case, the q-axis voltage equation of the rotor winding with no applied rotor voltages reduces to:

$$\underbrace{v_{qr}^{'e}}_{=0} = r_r^{'} i_{qr}^{'e} + \underbrace{p\lambda_{qr}^{'e}}_{=0} + (\omega_e - \omega_r)\lambda_{dr}^{'e} \qquad \text{V} \qquad (16)$$

In other words, the slip speed must satisfy:

$$\omega_e - \omega_r = -\frac{r_r^{'} i_{qr}^{'e}}{\lambda_{dr}^{'e}} \qquad \text{elect.rad/s} \qquad (17)$$

Also, if $\lambda_{dr}^{'e}$ is to remain unchanged, $p\lambda_{dr}^{'e}$ must be zero too. Using this condition and that of $\lambda_{qr}^{'e}$ being zero in the d-axis rotor voltage equation, we will obtain the condition that $i_{dr}^{'e}$ must be zero, that is:

$$\underbrace{v_{dr}^{'e}}_{=0} = r_r^{'} i_{dr}^{'e} + \underbrace{p\lambda_{dr}^{'e}}_{=0} - \underbrace{(\omega_e - \omega_r)}_{=0}\lambda_{qr}^{'e} \qquad 18$$

And, when $i_{dr}^{'e}$ is zero, $\lambda_{dr}^{'e} = L_m i_{ds}^{e}$. Substituting this into Eq. 17 & using Eq. 13 , we obtain the following relationship between slip speed and the ratio of the stator qd current components for the d-axis for the synchronously rotating frame to be aligned with the stator field:

$$\omega_e - \omega_r = \frac{r_r^{'}}{L_r^{'}}\frac{i_{qs}^{e}}{i_{ds}^{e}} \qquad \text{elect.rad/s} \qquad 19$$

Thus, the above analysis shows that the vector control strategy can provide the same performance as is achieved from a separately excited DC machine; this is done by formulating the stator current phasor, in the two-axis synchronously rotating reference frame, to have two components: magnetizing current component and torque producing current component. The torque is the product of two. By keeping the magnetizing current component at a constant value, the generator torque is linearly proportional to the torque-producing component, which is quite similar to the control of a separately excited DC motor .

Figure .2 shows an indirect field oriented control system with torque and flux command .

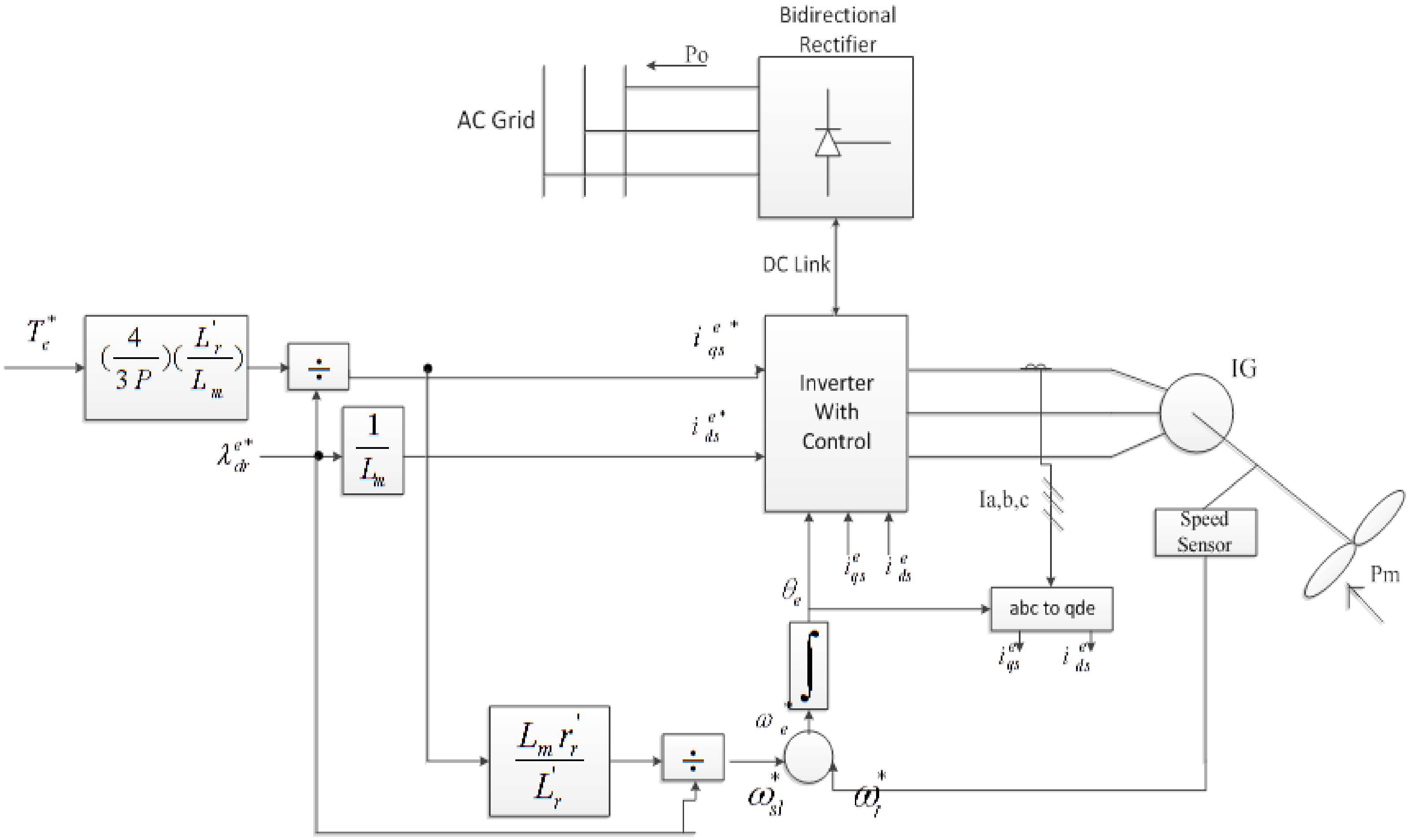


Figure 2 *indirect field oriented control system with torque and flux command .*

3. Simulation Results

Simulink is a subprogram in the MATLAB environment. It enables a system to be simulated by block diagrams and equations. Figure .3 Shows a typical block diagram of the models that can be run in Simulink. The system contains all of the equations necessary for an induction machine . Sub system #1 in Figure .3 is the controller for the model; it changes based on which model is running. Subsystem #2 in Figure .3 is the three-phase inverter block, which changes the reference voltages from the controller to the phase voltages through a PWM converter. Subsystem #3 in Figure .3 is the induction machine block, which contains all of the equations necessary for an induction machine. The block takes in the phase voltages and calculates speed, currents, fluxes, and developed torque. Subsystem #4 in Figure .3 takes the outputs of the model where the matrices are sent to the MATLAB workspace as the value listed.

The simulation has been are carried out for 3-phase, 4 pole, 15 hp, 380 v, 60 Hz. The machine parameters are Rs = 0.5814 Ω , Rr = 0.4165 Ω , Lls = 3.48 mH , Llr = 4.15 mH , Lm = 82.23 mH and the inertia (J) is 0.05 kgm^2 .

All of the simulations run with the following sequence for reference torque:

Time = [0 3 3.0001 6 6.0001 9 9.0001 12] Sec

Te $_{(\text{Reference})}$ = [-20 -20 -40 -40 -30 -30 -20 -20] N.m

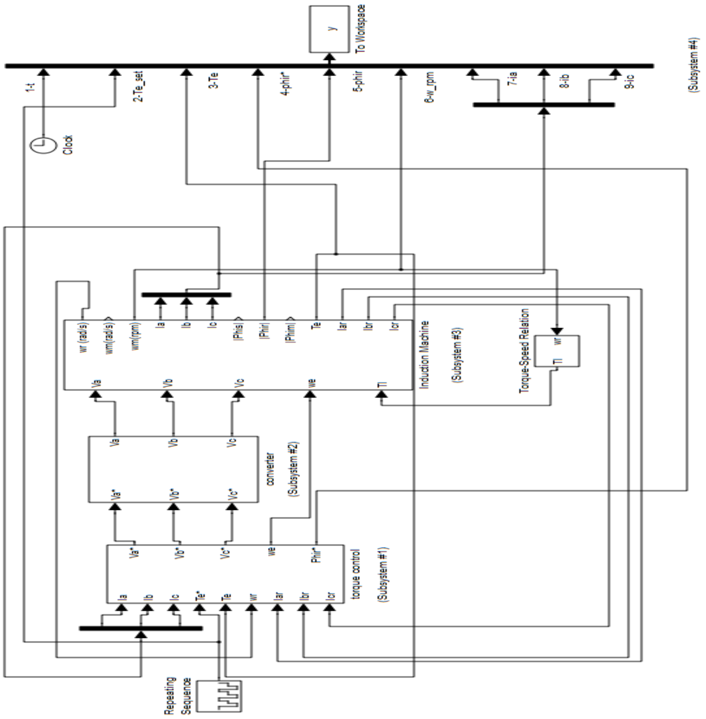
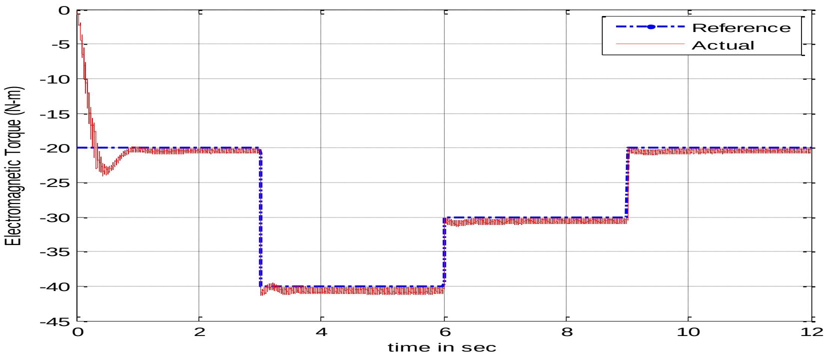


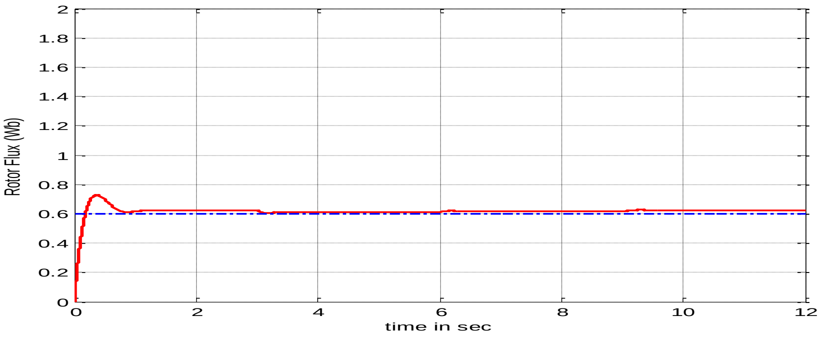
Figure .3 Shows a typical block diagram of the models

In this section, the two models of the indirect-vector torque-control system, namely, IVC model without torque feedback and IVC model with torque feedback are simulated. Both of the IVC models find the electrical speed from the speed of the shaft and the calculated slip angle. The controller imposes the restraint that the rotor flux, φ_r, is aligned with the d-axis. Since I_{qs} is directly proportional to torque, the current I_{qs} is controlled to follow the reference torque applied to the block diagram. The model without feedback uses no measurement from torque to control the torque of the generator, relying on the proportionality of and torque. The torque and flux responses of the system are shown in Figure 4a and Figure 4b respectively. The starting period is considered from time t=0-1s. Initially the torque increases linearly till 0.5 s and, goes to steady state after overcoming the rotor inertia. The torque and flux follow the reference torque and the reference flux respectively with a DC offset. Shown in Figure 4c is the speed response of the machine and in Figure 4d is the stator currents of the machine. As can be seen from those figures, when the torque increases the speed decreases and the stator current increases.

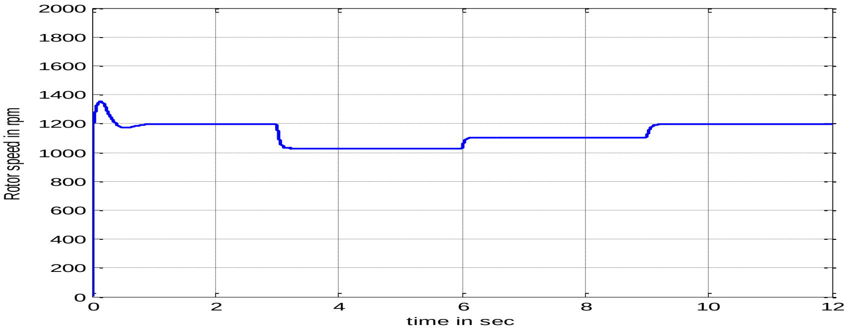
The feedback model assumes that there is a torque sensor on the shaft and therefore the reference I_{qs} is based on the difference between the reference torque and the actual torque, commanded through a PI controller. This provides significantly better response on the torque and flux as shown in Figure 5 a and Figure 5 b respectively. Except for the better torque and flux response, this system is identical to the system without feedback. Note that in this system, any change in the torque does not alter the rotor flux. Decoupling is attained and the torque follows the torque reference.



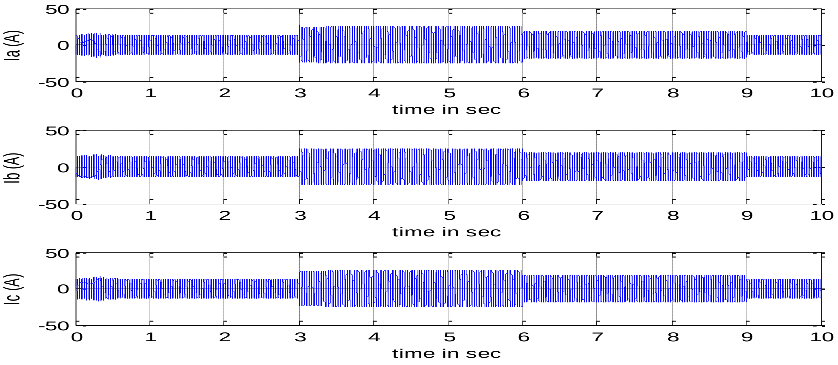
(Figure 4a) *electromagnetic torque (N.m)*



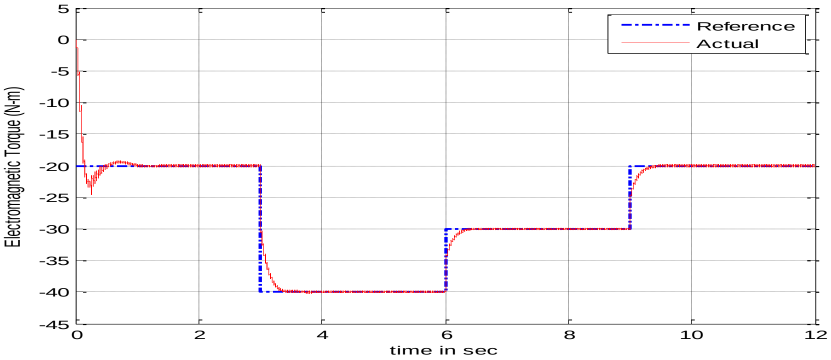
(Figure 4 b) *rotor flux (Wb)*



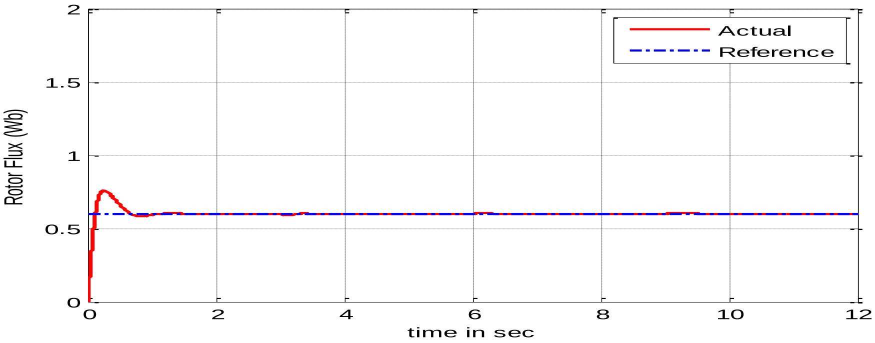
(Figure 4 c) *rotor speed (r.p.m)*



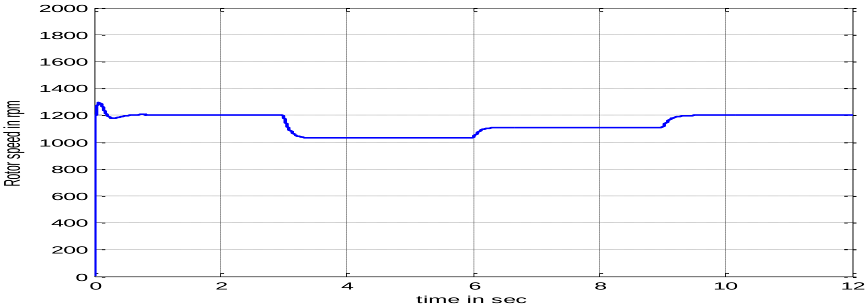
(Figure 4 d) *Stator currents* (A)
Figure. 4 *Response of IVC without torque feedback*



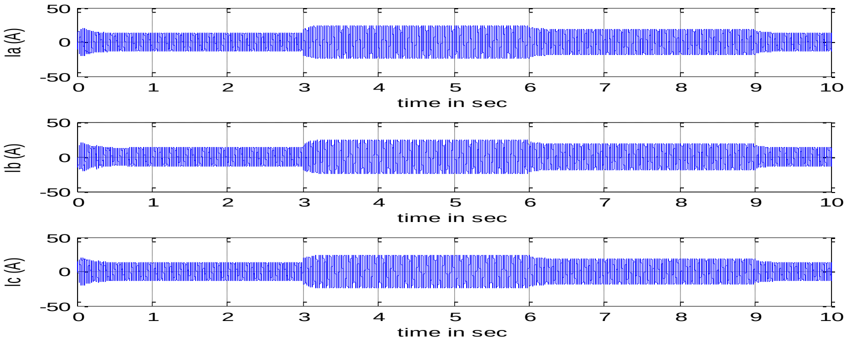
(Figure 5a) *electromagnetic torque (N.m)*



(Figure 5 b) *rotor flux(Wb)*



(Figure 5 c) *rotor speed (r.p.m)*



(Figure 5 d) *stator current(A)*

Figure 5 *Response of tuned IVC system with torque feedback*

4. Conclusions

The objective of field-oriented or vector control is to establish and maintain an angular relationship between the stator current space vector and one internal field vector, usually rotor flux or stator flux. The field oriented control assures decoupling between these vectors, and it is used to simplify the torque control of induction generators, so they can be controlled like a separately excited direct current (DC) machine. The simulation of IVC technique has been performed and the following observation could be concluded:

1- The rotor flux is kept constant even during changes in generated torque. This indicates that decoupling control of flux and torque been obtained.
2- The model without torque feedback give fast torque response with dc offset but the feedback model give torque response follows the reference torque without dc offset and with slower response.
3- The decoupling in IVC technique is conditioned by the accuracy of slip calculation. The slip calculation depends on the rotor time constant which varies continuously according to the operational conditions. Also, the IVC technique requires speed or position sensor .

5. References

1 Sandeep Goyat and Rajesh Ahuja, “Speed Control of Induction motor Using Vector or Field Oriented Control ,” International Journal of Advances in Engineering & Technolgy, July 2012, Vol. 4, Issue 1, pp 476-482

2 Rami Maher, Walid and Mohamoud Awad, “Indirect Field Oriented Control of an Induction Motor Sensing DC-link Current with PI Controller, " International Journal of Control Science and Engineering , 19-25 , 2012

3 Kroplewski, P.; Morawiec, M.; Jaderko, A.; Odeh, C. Simulation Studies of Control Systems for Doubly Fed Induction GeneratorSupplied by the Current Source Converter. Energies 2021, 14, 1254.

4 Prasad, R.M.; Mulla, M.A Mathematical Modeling and Position-Sensorless algorithm for Stator-Side Field Oriented Control of Rotor Tied DFIG in Rotor Flux Frame. IEEE Trans. Energy Convers. 2019, 35, 631-639.

5 Yahdou, A.; Djilali, A.B.; Boudjema, .; Mehedi, F. Improved Vector Control of a Counter-Rotating Wind Turbine System Using Adaptive Backstepping Sliding Mode. *J. Eur. Syst. Autom*. 2020, 53, 645-651

6 Boulaam, K.; Mekhilef, A. Output power control of a variable wind energy conversion system. Rev. Sci. Tech. Electrotechnol Energy 2017 , 62, 197-202

7 Habib, B.; Boudjema; Belaidi, A. Indirect vector control of a DFIG supplied by a two-level FSVM inverter for wind turbine system. *Majlesi J. Electron. Eng.* 2019, 15, 45-55

8 Chee-Mun Ong, “Dynamic simulation of electric machinery ,” West Lafayette, Indiana, 1998.

9 M.Godoy Simoes and Felix A. Farret “Renewable Energy Systems: Design and Analysis with Induction Generators ,” US, 2004

10 Khaled Yahia, Salah-eddine and Fateh Bechabane, "Indirect Vector Control of Induction Motor With on line Rotor resistance Identification", Asian journal of information technology, vol. 5, no. 12, pp. 1410-1415, 2006

11 R. Cardenas, and R. Pena, “Sensorless vector control of induction machines for variable speed wind energy applications,” IEEE Trans. Egy.Conv., vol. 19, no. 1, pp. 196-205, Mar. 2004.