SENSORLESS FIELD ORIENTED CONTROL OF AC INDUCTION MOTOR USING PI, PD & PID CONTROLLERS

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Master of Technology in Marine Engineering and Management

By

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CERTIFICATE

This is to certify that the dissertation entitled “**SENSORLESS FIELD ORIENTATION CONTROL OF AC INDUCTION MOTOR USING PI, PD & PID CONTROLLERS”** submitted by NIKHIL JOHN ANTONY to Indian Maritime University Kolkata Campus for the completion of the degree in Master of Technology in Marine Engineering and Management, is an authentic work carried out by him under our supervision and guidance. The contents of this dissertation, in full or in parts have not been submitted to any other institute or University for the award of any degree or diploma.

The Project has been carried out at Indian Maritime University Kolkata Campus.

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Nikhil John Antony
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LIST OF SYMBOLS AND ABBREVIATIONS

The key symbols/notations used in the dissertation are given below:

d-q	Synchronous rotating reference frame direct and quadrature axes
α-β	Stationary reference frame direct and quadrature axes
p	Number of poles of induction motor
N_s	Synchronous speed of induction motor
N_r	Rotor speed of induction motor
S	Slip speed of induction motor
s	Sampling time
f	Frequency of supply to induction motor
$I_{a,b,c}$	Instantaneous three-phase supply current
I_m	Amplitude of supply current
L_r	Rotor inductance of induction motor
L_s	Stator inductance of induction motor
L_m	Magnetizing inductance of induction motor
Ψ_r	Rotor flux linkage of induction motor
Ψ_s	Stator Flux linkage of induction motor
$\Psi_{\alpha r}$	Rotor flux linkage in α - axis
$\Psi_{\alpha s}$	Stator flux linkage in α - axis
$\Psi_{\beta s}$	Stator flux linkage in β - axis
$\Psi_{\beta r}$	Rotor flux linkage in β - axis
Ψ_{dr}	Rotor flux linkage in d - axis

Ψ_{qr}	Stator flux linkage in q - axis
I_d	Current in d - axis/Flux component
I_q	Current in q - axis/Torque component
i_{qs}	Stator current in q - axis
i_{ds}	Stator current in d - axis
$i_{\beta s}$	Stator current in β - axis
$i_{\beta r}$	Rotor current in β - axis
$i_{\alpha s}$	Stator current in α - axis
$i_{\alpha r}$	Rotor current in α - axis
i_{sdref}	Stator reference current in d - axis
i_{sqref}	Stator reference current in q - axis
V_d	Voltage in d - axis
V_q	Voltage in q - axis
ω_{eslip}	Electrical rotor slip speed
ω_m	Mechanical speed of rotor
ω_r	Rotor speed
R_r	Rotor resistance of induction motor
R_s	Stator resistance of induction motor
T_e	Developed Torque (Nm)
T_i	Integral reset time
T_d	Derivative reset time
K_p	Proportional component
K_i	Integral component

K_d	Derivative component

The list of key abbreviations in the dissertation are given below:

AC	Alternating Current
DC	Direct Current
MOSFETS	Metal Oxide Silicon Field Effect Transistors
IGBT	Insulated Gate Bipolar Transistors
PWM	Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
FOC	Field Orientation Control
IFOC	Indirect Field Orientation Control
DFOC	Direct Field Orientation Control
ADC	Analog Digital Converter
ANN	Artificial Neural Network
IIR	Infinite Impulse Response
PI	Proportional Integral Controller
PD	Proportional Derivative Controller
PID	Proportional Integral Derivative Controller

ABSTRACT

This dissertation focuses on the effective utilization and feasibility of field-oriented control of AC induction motor using PI, PD and PID controller without any physical sensors. The speed, torque and position in this scheme are estimated, analyzed and simulated with the help of motor control block-set in MATLAB/Simulink for a (10HP, squirrel cage induction motor). Separately excited dc motors due to their simplicity has been used extensively in numerous applications for high performance application. Induction motors have been used to replace separately excited dc motor because they are rugged, cheaper, lighter, lesser maintenance and has lower moment of inertia. With the FOC vector approach, the control of the induction motor behaves similar to that of a separately excited dc motor. The torque and flux components in the d-q rotating reference frame can be independently controlled with the help of unit vectors.

Based on how the field angle is used to determine the unit vector, the vector control scheme is classified into two, direct vector control using the measured field angle and indirect vector control using the evaluated field angle. The direct vector control is efficient but is also complex and reduces the reliability of the system especially for high-speed drives. The indirect vector-controlled induction motor drives primarily involve the decoupling of the stator current into the torque and flux producing component but it still faces the challenge that the motor parameters variate with temperature resulting in estimation error of speed in steady state and transient state. To overcome this drawback, flux observers are utilized to have better parameter variation effects and also speed accuracy.

The dynamic performance of PI, PD and PID control techniques has been presented without speed sensors which improves the mechanical robustness, design space and reducing the overall cost.

CHAPTER 1. INTRODUCTION

1.1 Background

The induction motor had been introduced and pioneered in the year 1888 by the father of scalar energy, Nikola Tesla. After numerous years of effort and determination, he succeeded in building an AC machine that was brushless and provided a contactless mechanism that helped eliminate sparks caused by brushes in DC machines. His early development had marked the 21st-century advancement in the field and had provided a standard and incisive perception for broad utilization of three-phase generations and distribution systems. The use of squirrel cage induction motors had been extensively increased over the year owing to their standout advantages like high reliability, reduced maintenance, cost effective, compactness, and robustness.

Power electronics enables the efficient utilization of variable speed drives in both DC and AC motor machines. It provides a better understanding of the design, control, and conversion of power in its electrical form. From mercury-arc valves to semiconductor switching devices such as diodes, thyristors, power MOSFET, and IGBT as shown the vast development and enhancement in the field of power electronics. PWM techniques have been used to reduce the power delivered by an electrical signal by chopping it into different parts. It has been used to mass-produce multiple supplies for induction machines. The scalar method using the voltage/frequency (v/f) ratio is kept constant to manipulate the flux produced. The dynamic response of flux and torque of v/f drives are non-desirable compared to the vector control even though the v/f control is simple and has been used widely. The rise and expansion of vector control for induction motors has been able to adverse with DC machines in high dynamic performance applications.

1.2 Literature Review

Numerous analyses, research, documentation, and results have been evaluated and published using MATLAB/Simulink for the effective and efficient speed control of induction operating both scalar and vector methods. Robert H. Park had conceptualized a unique transformation used widely in the analysis and study of both synchronous and asynchronous motors. His novelty involved the ability to transform the linear differential equation from a time-variant system to another linear time-invariant system in related machines. His contribution paved the way to many researchers in the 20th century [1].

J.G Ziegler and N.B Nichols had set the foundations of unique sets of unit measurement for all the major controllers and formulas for the three main principle control effects through analysis and examinations were proposed for each effect. With the formulas obtained, enabled the controllers' settings to be evaluated through experiments. Their work has assisted researches in adjusting of existing controller applications and in the design of new installations [2]. K.C. Hause and C.H Thomas had studied the performance of symmetrical induction machinery and demonstrated the dynamic capabilities of two as well as three-phase machines in both balanced as well as unbalanced operations. The simulations had been obtained from the equations that better described the symmetrical induction machine in an arbitrary reference frame. These simulations had been useful for further studying the performance of induction motors with power electronic switching devices [3].

The vector control concept had been initially introduced by K. Hasse and F. Blashcke were able to assimilate the decoupled control of both the flux component as well as torque component in induction machines. K. Hasse had proposed the indirect FOC through his work on the dynamic speed controller drives with squirrel cage AC machines [4]. F. Blaschke proposed the direct FOC through his novelty in which he had introduced the concept of field orientation applied to new transvector machines. Both their works were instrumental for further development/advancement in AC drives to compete with DC drives [5]. R. Lee, P. Pillay, and R. Harley had presented the compelling equations of the reference frames to wield the simulations of induction motors when used in direct and quadrature axis theory [6].

E.Y.Y. Ho and P.C. Sen had proposed that the decoupling control of the induction motors by utilizing different schemes with respect to airgap, stator and rotor flux had been developed. The relationship between the slip frequency as well as torque in terms of the transient and steady state of each scheme were simulated and compared [7]. H.W. Van Der Broeck, H.C. Skudelny and G.V. Stanke through their novelty showed that the space vector representation results in lower current harmonics and higher modulation index. This was carried out with the aid of 8086 microprocessors and its performances were analyzed and reported. The main objective of the work was to show that the space vector concept with derived switching time for PWM voltage source in comparison with the SPWM [8].

G.C. Verghese and S.R. Sanders had examined real time simulation of estimation (flux observers) in field orientation of motor equations without the use of feedback of any corrective estimation errors. They proposed corrective feedback to the flux estimation and also reduced the level of sensitivity of the estimation to motor parameter variations [9]. C. Schauder used an effective model reference adaptive system for the speed estimation of induction motor from measured terminal voltages and currents were described and was further used as feedback in the vector control system and hence obtained a moderate bandwidth speed control without any physically mounted transducers/sensors. It was performed on a 30HP laboratory drive and respective usage was verified [10]. R. Krishnan and A.S Bharadwaj had reviewed the parameter that influences the sensitivity of indirect FOC induction motor. They illustrated the importance of parameter sensitivity and compensation study with respect to efficient motor and power inverter usage [11].

H. Tajima and H. Yoichi had demonstrated a estimation method for the speed of induction machine and its influence to a flux observer which was based on FOC scheme. With the implementation of digital signal processing and experiments showing that the speed sensor-less field-oriented control system invokes with stability and robustness for rotor resistance variations [12]. H. Kubota and K. Matsuse had verified and presented through experimentation a unique methodology of speed estimation of the motor and the rotor resistance of the induction machine by the key components on the field current to overcome the change in rotor resistance that results in estimation errors of the induction motor. [13]. F.Z. Peng and T. Fukao had illustrated a new approach to estimation the speed of induction motor from measured terminal voltages and current for sensor-less measurement of vector control through simulations and experiments. The feedback in the IFOC was the estimated speed obtained. The introduced technique was simpler and rugged to variations of motor parameters and was not dependent on the information of the stator resistance values neither was it affected stator resistance thermal variations. Thus, the method achieved speed control with wider bandwidths [14].

Robert. D Lorenzo and et al had emphasized on the importance of basic control system requirements, torque control principle for field orientation, the current and magnetized flux control of induction motor, using FOC scheme [15]. R.B Giménez had illustrated and developed in his research a unique vector control method of induction drive without the utilization of speed or position sensor and demonstrated that the dynamic performance of sensor-less control to that of sensor-based vector drives [16]. G.C. Souza, B.K. Bose and J.G. Cleland had proposed, emphasized and described the importance and utilization of fuzzy logic controller upon line efficiency control from IFOC especially the speed control subsystem. The theoretical development was made possible on a TMS320C25 digital signal processor. The paper aimed at the improvement of adjustable speed drive systems efficiency for energy saving, cooling system operations and the importance of tackling environmental pollution [17].

Z.V Lakparampil, K.A Fathima and V.T Ranganathan described the detailed equations for the dynamic behavior of induction motors in synchronous rotating reference frame with respect to designs of gain and time constant of multiple controllers which were tested and simulated using digital signal processing and Insulated Gate Bipolar Transistor as power inverter with a scheme using a 40HP prototype drive [18]. D.W. Novotny and T.A. Lipo in their book had emphasized the great change in numerous industrial applications with the aid of electrical drive systems. Their book represented in detail the variable forms of the equations describing AC machines and further incorporated in inverter models in dynamics states. It also showed the dynamic analysis of vector-controlled technique with equations [19]. L. Baghli, H. Razik, and A. Rezzoug had proposed an alternative to fuzzy logic controller with the introduction of neural networks in the rotor FOC of induction motor. The experimental results on position control and speed control under loads were analyzed and studied and have been compared with classic PI controllers for the neural act to behave like that of a fuzzy logic controller [20].

H. Tajima, G. Guidi and H. Umida had performed and investigated a model based, speed sensorless field-oriented control of induction motor through simulation and experimentation. Mainly focusing on the speed, stator resistance and rotor resistance estimator, thus making it suitable for all round inverters [21]. J. Holtz and J. Quan in their novelty emphasized the importance of offsets components in the obtained feedback signals, various distortions due to the non-linearity of the switching states of the inverters and also the sensitivity of the system which are considered in the performance of vector-controlled induction motor drives without speed sensors which are fairly poor at lower speeds. Their experiments demonstrated smooth steady state operations and high dynamic performance at low speeds by integrating precise estimations and using corrective offsets for the distortion and sensitivity of the system [22].

K. Zhou and D. Wang had performed an inclusive analytical finding between the SVPWM and carrier-based PWM mainly with modulation signals, sector of the space vector, switching patterns, distribution of zero-sequence signals was established for load types. The implementation of both the SVPWM and carrier-based PWM in a closed loop feedback inverter [23]. A. Miloudi and A. Draou had designed a gain PI controller to simulate the performance of speed control and rotor resistance estimation which were compared to a standard PI controller which showed good results without overshooting [24].

M. Hinkkanen in his novelty involves the flux estimation for sensorless induction motor drives using linearized model of speed adaptive full order flux observers which was utilized in determining the observers gain and speed adaptive gain. Through experimental results had showed stable operations for a wide range of speed using an flux observer and method of varying the speed-adaptive gains in field-weaking regions [25] E.D. Mitonikas and A.N. Safacas had proposed an improved sensorless vector control scheme for an induction motor drive with enhanced closed loop estimation of stator flux to obtain precise stator flux estimation on a dynamic model of AC motor. Model Reference Adaptive System was used for rotor speed estimation(observer). The agenda of the paper was to propose a unique method to attain precise flux and speed control for broader areas of utilization even with low frequency [26].

A. Iqbal, A. Lamine and I. Ashra had emphasized the importance of voltage and frequency supplied to induction drives from 3 phase VSI in their work. They developed and illustrated the step-by-step modelling of SVPWM using

MATLAB/Simulink with respect to voltage source inverters [27]. D.P. Marcetic and S.N. Vukosavic worked mainly on demonstrating the phase angle difference between spectral components of few selected signals which are with in the speed estimators that would be used for rotor resistance with help of computer aided simulation and experiments which was carried out under a variety of conditions to approve the utilization of their proposed rotor resistance technique [28].

R. Bojoi, P. Guglielmi, and G.M. Pellegrino had presented a sensorless IFOC method of the three-phase induction motor for low cost applications with algorithm based on a flux observer for robustness and simplicity and also had illustrated experimental results for a induction motor drive of 0.5 KW for a primary pump in modern industrial applications [29]. K.S Gaeid, H.W Ping and H.A.F Mohamed had illustrated a well-built Simulink block model of induction motor by comparing the torque, voltage and current waveforms respectively in the motor frames in order to resolve the issues faced in the mathematical reference frame transformation and thus are able to predict the motor parameter performance using software only [30].

A.A Ansari and D.M Deshpande had represented a hybrid model that was inclusive of model ranging from simple equivalent circuit to the more complex d-q and abc model. The simulation of an induction motor was simulated based on mathematical modelling and the steady state performance using Matlab and three phase induction motor using Simulink [31]. S. Sikarwar and A.Barve had emphasized on the importance of the usage of both the discrete PI and PID controllers in high applications of non-linear systems like electric motor drives. The proposed method was implemented for better reliability and performance of the induction machine. [32]

H. Haq, M.H. Imran, H.I. Okumus and M. Habibullah had used a squirrel cage induction motor for the speed control in the FOC scheme with PI controllers and showed that the step response was fast, robust and achieved high performance [33] J.R Manepalli and C.V.N Raja had integrated the use of classical Ziegler-Nichols method and genetic algorithm optimization for the speed control of induction motor with PI and PID controllers [34]. S.T. Nyugen and et al presented a unique real time speed estimation for three-phase induction motor in IFOC technique with ANN with an error-based scheme to implement a neural network. The simulations showed that the value of the estimated speed tracked with respect to the given speed and resulted in minuet error as long as the sampling time introduced is small, accordingly implemented the corrective rate for the neural network [35].

1.2 Aim

The dissertation illustrates the development of a model-based indirect FOC with speed, position, and torque control for an AC induction motor using motor control block sets. The sensor-less FOC will be implemented using three types of closed loop feedback controllers for the control system such as PI, PD, and PID for speed, current, and position control in order to compare and analyze them, select the appropriate algorithm for the AC motor. A Simulink model of the AC induction motor will be illustrated emphasizing on the key factors that's have been used to simulate the respective controllers chosen to better understand their effective integration into the model.

1.3 Limitations

This dissertation will mainly focus on the software simulation of the induction motor and will not implement any type of hardware implementation but the development of hardware with AI implementation and microprocessors will be considered as future scope of work with unlimited advanced possibilities.

CHAPTER 2. THEORY/ALGORITHM

2.1 Induction Motor

AC induction motors are extensively used in both large well as small scale industrial, commercial and residential applications due to their ruggedness, reliability, feasibility, and higher efficiency as compared to DC motors. It prominently stands out as a self-starting motor with no brushes and commutators, reduces the chance of sparks or losses, and hence provides more efficiency as there are no frictional losses and can endure even in harsh environments. It can operate at different loads and at different speeds, to drive the mechanical load due to its wide option of speed control it offers.

The electric AC current in the rotor are responsible to provide the necessary torque through the principle of electro-magnetic induction created by the rotating magnetic flux in stator winding. The stator that has the rotating magnetic field would create the flux, thus resulting it to rotate. But due to the lag tendency of flux current between the rotor and stator, the rotor would never reach its synchronous speed. Using this principle, the speed control of induction motor has come a long way of advancement and enhancement.

The rotating magnetic field created at the stator passes through the airgap present between the stator and rotor and it cut the stationary conductor in the rotor and thus results in an induced emf in the stationary conductors due to the popular faraday’s law, which clearly states that there would be an induced emf in a conductor, because of the relative motion between the magnetic flux and the conductor. Due to the relative motion, it opposes the change and makes the relative motion zero as per the Lenz law which depends on the law of energy conservation and also the Newton’s third law. The rotor conductor would rotate in the direction as that of the rotating magnetic field and for the efficiency of the induction motor drive, it must follow the condition that the slip speed should always be less than synchronous speed.

Hence, when the slip is said to be zero, there is no relative motion and thus there will be no induced emf and which in turn does not oppose the change or follow the Lenz law, thus no rotation of the rotors. It is vital to follow the principles of induction motor for higher performances. Due to induced emf in the rotor, it also creates a current as it is short circuited in induction motor, thus a flux will be produced in the presence of the current in the rotor. This interaction between the rotor flux and magnetics flux creates torque. To overcome the lack of self-starting torque and drawbacks in single-phase induction motor, the use of three-phase induction motor are preferred widely in the advancement and rise of power electronics and demands in various industries. The basic three-phase supplying current are represented in an induction motor as I_a, I_b, I_c which are:

$$I_a=I_m \cos\omega_b t \tag{1}$$

$$I_b=I_m \cos(\omega_b t - {}^{2\pi}/_{3}) \tag{2}$$

$$I_c=I_m \cos(\omega_b t+ {}^{2\pi}/_{3}) \tag{3}$$

2.2 Field Orientation Control

FOC has been a popular technique used to control the speed and current of AC induction motors. It exuberates excellent control capabilities over full speed torque, zero torque and various speed ranges. The basic concept of the FOC technique are used to determine the rotor angle to decouple the flux component (I_q) and magnetized torque component (I_d).

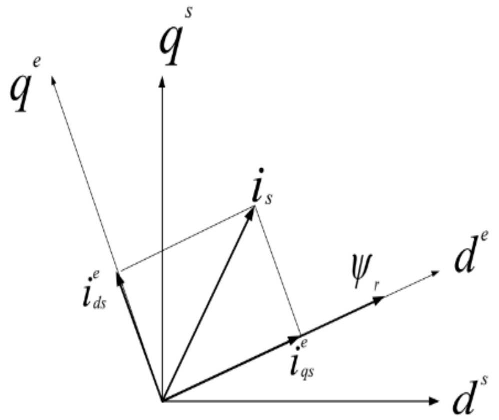

Figure 1. The decoupling between torque and flux rotor in FOC

The instantaneous stator currents obtained with respect to the stationary reference frame are transformed into a rotating reference frame that are signified and aligned with vectors to produce the desired current components in the d-axis and q-axis. Field oriented control scheme to work requires the transformation of coordinate axes of stator current from stationary frame to rotating frame of reference. Likewise, the FOC algorithm requires the real-time feedback information of the current and position angle of the rotor in the induction motor. Most, traction-based applications such as conveyors, elevators, cranes, electric vehicles, etc. have used torque control that enables the motor control system to follow a specific reference frame. In the speed control, it follows a specific speed reference estimation and also incorporates a reference of toque for the torque control which forms an inner subsystem. For the position angle control, the position is obtained from the speed controller present in the inner subsystem. The sensor-less FOC technique has been used to provide the precise estimated feedbacks, unlike the sensor-based FOC technique.

2.2.1 Sensor-less FOC Algorithm

The sensor-less FOC algorithm has been better understood from the coordinate reference transformation process which is illustrated in the figure (). AC motor mainly involves the manipulation of the stator while in FOC, an input current that is sinusoidal is applied to the stator. The signals which are time-variant hence enabling a magnetic flux in the rotating frame to be generated.

The transformation of these coordinates enables the segregation of the current producing component which are responsible for the magnetized flux of the rotor and the torque.

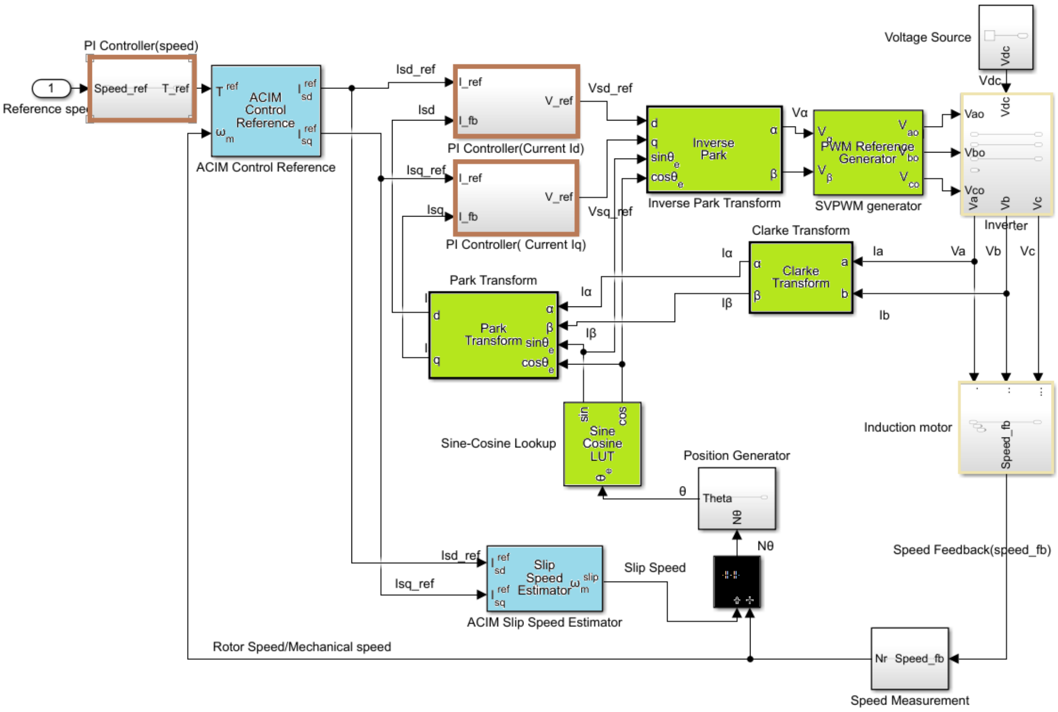

Figure 2. Simple block diagram of Sensor-less FOC scheme

2.2.2 Controlling Direct and Quadrature Current

The direct and quadrature current are proportional to the magnetic field generated by the stator of the induction motor and the magnetic fields are proportional to the current flowing through the coils of the induction motor. This desired current is controlled by the voltage source applied to the phases of the induction motor, enabling better control from the signal to the variable to control.

The Iq and Id are present in the rotating frame of reference or also known as the d-q frame, they represent the time variant current in the stator frame of reference also known as the α-β frame, which is the reference frame of the control signal.

As the reference frame is rotating from the perspective of the stator, the required stator current are known to be sinusoidal for a constant speed. Hence instead of controlling the sinusoidal current in the stator frame, they can be transformed using the Park transformation into the rotating reference frame, thus turning them into a constant speed thus making it simpler to control. Hence, we come to the relation that current in q-axis is directly proportional to the torque of the motor as shown below;

$$T_e = K_m * I_q \tag{4}$$

The sensor-less FOC algorithm for AC induction machines could be examined by the following steps:

a. Measurement of phase current

The instantaneous currents (I_a,I_b,I_c) are transformed using the Clark's transformation (I_α-I_β) are measured in the stationary frame of reference as I_α and I_β respectively.

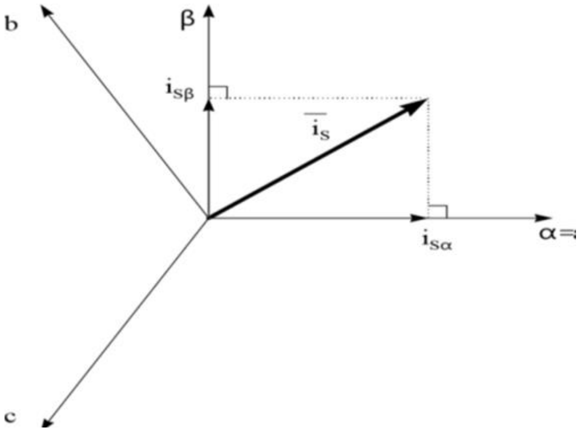

Figure 3. Representation of phase currents from abc to α-β axes

The Clarks transformation converts the stator phase current to a fixed/stationary reference frame. By measuring only two stator phase currents (I_a & I_b) and the third phase current could be determined by the assimilation of all three currents are equal to zero.

$$I_a + I_b + I_c = 0 \tag{5}$$

$$I_\alpha = I_a \tag{6}$$

$$I_\beta = \frac{I_a + 2I_b}{\sqrt{3}} \tag{7}$$

b. Transforms current from fixed reference frame to rotating reference frame

By using the popular Park's transformation, the phase currents are easily transformed from its stationary to rotating reference frame by using simple algorithmic equations as shown below;

$$I_d = I_\alpha \cos\theta + I_\beta \sin\theta \quad (8)$$

$$I_q = - I_\alpha \sin\theta + I_\beta \cos\theta \quad (9)$$

The Park transformation converts two orthogonal vectors on a fixed/stationary reference frame into two orthogonal vectors on a rotating/rotor reference frame.

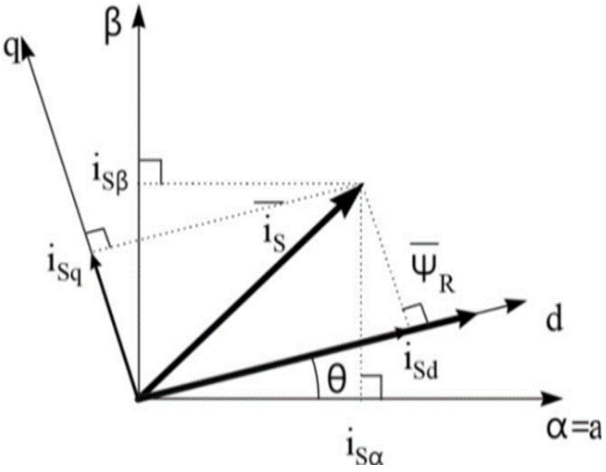

Figure 4. Representation of phase currents from α-β to d-q axes

To perform the park transformation, the necessary inputs required are the output from the Clark transformation (I_α I_β) and the estimated angle of the rotor (θ) which are determined using a flux observer in the model. The sensor less position estimation of the angle of the rotor are vital for the transformation of the current (I_α,I_β) from the stationary reference frame to the rotating reference frame, the resulting currents are responsible for the generation of magnetized flux (I_d) and torque (I_q).

c. Applying the current control algorithm

For the effective utilization and conceptualization of the algorithm in the closed loop system, the controller needs to be well controlled to constant levels such that I_d=0 and I_q=T_e/K_m from equation (6), a PI, PD and PID controller are used to illustrate the objective of the dissertation and to determine the best approach for precise feedback.

The specific controllers used such as PI, PD and PID are provided with the speed error between the reference speed and rotor speed and to also compensate the torque and flux in the system.

d. Transform the output from controller into stationary reference frames.

The voltage outputs (V_d & V_q) from the PI/PD/PID controllers are in the synchronous coordinate that needs to be applied to reach the desired set point, since the control signal can only be applied in the stator coordinate, the need to convert the them arises and this is carried out by the inverse park transformation. The Inverse Park transformation are essential to calculate the equivalent input voltages from the rotating reference frame to fixed reference frame.

The outputs of PI/PD/PID controllers which are the voltages (V_d, V_q) in the d and q coordinate are evaluated in the rotating reference frame and are transformed back to stationary reference frame producing the Vα and Vβ. Both the park and inverse park uses simple and basic trigonometric transformation from one reference frame to another accordingly.

$$V_\alpha = V_d\cos\theta - V_q\sin\theta \qquad (10)$$

$$V_\beta = V_d\sin\theta + V_q\cos\theta \qquad (11)$$

2.2.3 Estimators

Flux observers (position estimation) are used in AC induction machines to estimate the precise synchronous speed, electrical position, rotor magnetic flux and electromechanical torque for the effective performance of field-oriented control for the voltage and current in the stationary frame of reference. It does this in-order to estimate the state based on the given input and output of the system in which the input are the 3-phase current from equation () and the rotor speed which can be obtained from equation(). The use of sensor-less flux observers is to eliminate the need for sensor and thus reducing the cost and maintenance requirement.

$$i_{dr} = \frac{L_M}{L_r}(\, i_{mr} - i_{ds}) \qquad (12)$$

$$\omega_e = \omega_r + \frac{R_r}{L_r} * \frac{i_{qs}}{i_{mr}} \qquad (13)$$

Torque estimator are used to estimate the appropriate electromechanical torque and power for FOC of AC induction motor. To enable it, both the torque and speed at the output, the resultant feedback values of d - q axis currents and speed are given as inputs respectively and are represented in eq(15,16). In terms of PU parameters, it initial is converted to SI units and converter back after computation.

$$T_e = \frac{3}{2} p \left(\frac{L_m}{L_r}\right) \Psi_{dr} * i_{qs} \qquad (14)$$

$$P = T_e * \omega_e \qquad (15)$$

Slip speed estimator are used in the estimation of mechanical slip speed from the difference between the synchronous speed and rotor speed of the induction motor by evaluating the d and q reference currents and output the estimated corresponding stator currents. For FOC of induction motor, the slip speed value is determined by

$$\Psi_{dr} = \frac{L_r}{R_r} \qquad (16)$$

$$\omega_{eslip} = \frac{L_m * i_{sqref}}{\tau_r * \Psi_{dr}} \qquad (17)$$

$$\Psi_{dr} = L_m * I_{ds} \qquad (18)$$

Rotor Flux are kept constant and the d-axis are aligned to the rotor flux reference frame, results in the relation given in eq (19)

Control reference

It is responsible to compute the phase voltage output from the duty cycle of 0-1 range input and also the inverter DC voltage and provides results in the three phase voltages.

2.2.4 Space Vector Pulse Width Modulation

The output of Inverse Park transformation (Vα and Vβ) are fed into a popular modulation method called the space-vector modulation technique. It converts the stationary stator reference frame signal to desired signals to efficiently run the power inverter used followed by the AC induction motor.

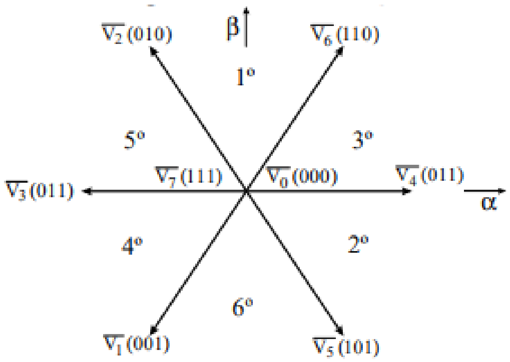

Figure 5. Sector and vector representations in SVPWM

The primary objective of the SVPWM modulation is to give rise to appropriate PWM controlled signals so that a vector unit with any or specific angles can be produced. In the SVPWM method, a three-phase two-level inverter can be simplified to drive eight switching states in which the inverter has six critical active states (1-6) and two specific zero states (0 and 7). The switching sequence are performed in the inverter with the help of MOSFETS, IGBT which enables the switching with respect to the bandwidth with several thousand times per second, hence precisely control the power delivered to the 3-phase induction motor with the concept of pulse width modulation (PWM) to obtain an accurate current sine wave at the desired frequency to the motor.

2.3 Ziegler-Nichols Method

Ziegler-Nichols's method are widely used for both open loop and closed loop system when motor parameters are unavailable and is determined experimentally and be even used when the motor parameters are known for a dynamic system with repeated iterations. By determining the delay time and time constant, the gain parameter for the motor can be calculated and manipulated for a finer result. This method is typically used for first order system with delays.

Table 1. Zeigler-Nichols's Method for Closed loop response system

Type of controllers	Proportional gain	T_i	T_d
Proportional controller	T / L	Infinite	Zero
Proportional integral controller	0.9	L / 0.3	Zero
Proportional integral derivative controller	1.2* T/L	2*L	0.5*L

2.4 PI/PD/PID controllers for current, speed and position control

The PI/PD/PID controller are a set of control loop for feedback mechanism which are responsible to correct the error signals between the measured variable and its reference signal values. Induction motor control process, a total of three PI controllers are used with each responsible for its unique function. One for the I_d component producing the magnetic flux, another for the I_q component for torque generation and the last for the speed of the motor.

PI controller known as proportional and integral controller will take up the responsibility and the operation of eliminating mainly steady state errors and multiple forced oscillations but with the introduction of the integral component will also slow the response of the speed and the overall stability of the system.

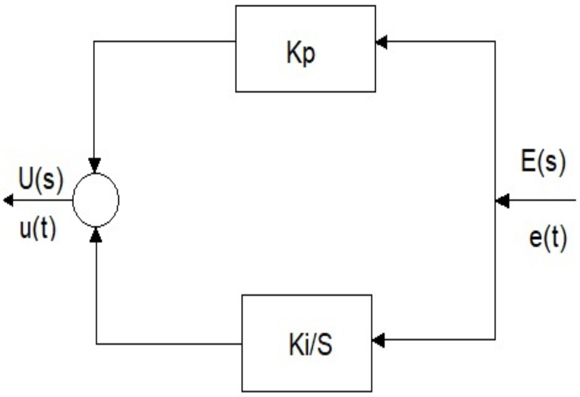

Figure 6. Simple PI controller block diagram

PI controllers are unable to predict the error that can be the error in the future for an effective feedback and in-turn decreases the speed of the response. It overcome this drawback, the proportional with derivative (PD) is proposed which has the ability to predict the status of the error in the near future and also increases the speed of the response.

Controller equation in time domain:

$$PI = K_p + K_i \int dt \tag{19}$$

Controller equation in frequency domain:

$$PI = K_p + \frac{K_i}{s} \tag{20}$$

The PI controllers enables and improves damping, nullifies offset (zero offset) and no steady state error. It is mainly used in industrial applications that doesn’t emphasis on the speed of the response and used when large vibrational disturbances, noises and delays in the system.

Steps taken for setting PI controller:

1. Initially set the K_p and K_i to zero

2. Gradually increase the $K_{p\ \text{until}}$ the step response oscillates.

3. Set K_p to the last stable values.

4. Increase K_i until the steady state error disappears fast enough while avoiding oscillation.

Table 2.Parameter influence of PI controller

Type of controller	Overshoot value	Rise time value	Settling time value	Steady state error value
PI	↓	↓	↓	×

PD also known as proportional and derivative controller are used in a control system to obtain precision and improve the overall performance of the system it is utilized in. It provides an efficient system with respect to change in output to change in error signal. The derivative control enhances the sensitivity in order to provide corrective measure in advance, thus improving the stability of the overall system without affecting the steady state error. The system filtration is carried out by high pass filter (IIR). The main concerning problems faced are the calibration offsets and to eliminate steady state error.

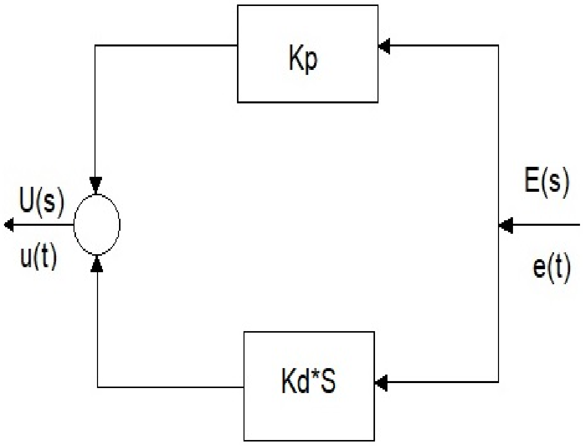

Figure 7. Simple PD controller block diagram

Control equation in time domain:

$$PD = K_p + K_d \frac{d}{dt} \quad (21)$$

Control equation in frequency domain:

$$PD = K_p + K_d * s \quad (22)$$

Steps taken for setting PD controller:

1. Initially set the K_p and K_d to zero.

2. Gradually increase K_p until the step response oscillates.

3. Gradually increase K_d until the oscillations stops.

4. Repeat 2-3 until oscillations cannot be stopped by K_d.

5. Set K_p and K_d to the last stable values.

Table 3. Parameter influence of PD controller

Type of controller	Overshoot	Rise time	Settling time	Bandwidth
PD	↓	↓	↓	↑

PID popularly known as proportional, integral and derivative controller are widely used in numerous control-based applications because it reduces the vast number of parameters in a system to be tuned and it does so by providing the necessary control signals that are directly proportional to the error between the resulting output and the reference signal and integrate the error signal and finally derivates the error signal in a closed loop system. The system filtration could be carried out by either high or low depending upon the cut-off frequency.

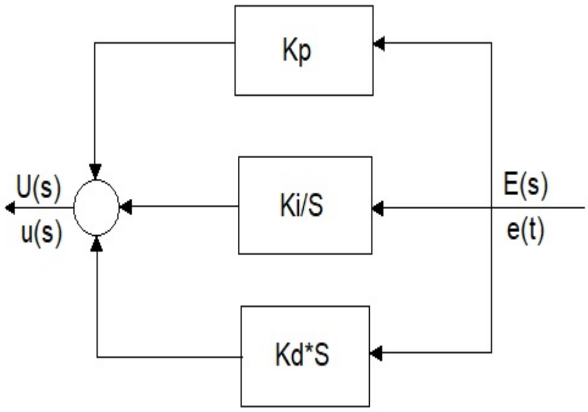

Figure 8. Simple PID controller block diagram

Control equation in time domain:

$$PD = K_p + K_i \int dt + K_d \, dt \qquad (23)$$

Control equation in frequency domain:

$$PID = K_p + \frac{K_i}{s} + K_d{*}s \qquad (24)$$

Steps taken for setting PID controller:

1. Initially set the K_p, K_i and K_d to zero.

2. Gradually increase the K_p until step response oscillates.

3. Gradually increase the K_d until oscillations stops.

4. Repeat 2-3 until oscillations cannot be stopped by K_d.

5. Finally set the K_p and K_d values to the last stable value.

6. Increase K_i until the steady state error disappears fast enough while avoiding oscillation.

Table 4. Parameter influence of PID controller

Type of controller	Overshoot value	Rise time value	Settling time value	Steady state error value
PID	↓	↓	↓	×

3. SIMULATIONS/RESULTS/DISCUSSION

3.1 Model

The model of sensor-less FOC of AC induction motor was implemented on MATLAB/Simulink. The model does not have any hardware implementation and are purely based on software simulation. The induction motor parameters used are given below.

Table 5. Induction motor parameters

Motor type	10HP, 460V,60Hz,1765 rpm
Rotor resistance (R_r)	0.451 (ohm)
Stator resistance (R_s)	0.68373 (ohm)
Rotor Inductance (L_r)	0.0041525 H
Stator Inductance (L_s)	0.0041525 H
Mutual Inductance (L_m)	0.14862
Number of pole (p)	2
Inertia(J)	0.05 kgm^2
Damping coefficient	0.0153

3.2 Field Oriented Control

The field-oriented control implementation in Simulink are designed using motor control block-set. The model mainly consists of 3 primary blocks such as Speed control, current control and inverter and motor model.

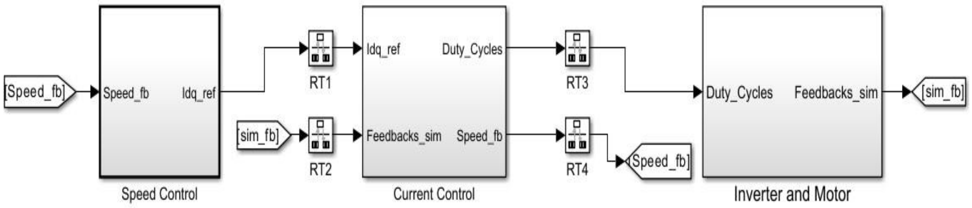

Figure 9. Simplified representation of Sensor-less FOC scheme model

3.3 Simulation & Results of PI controller in FOC model

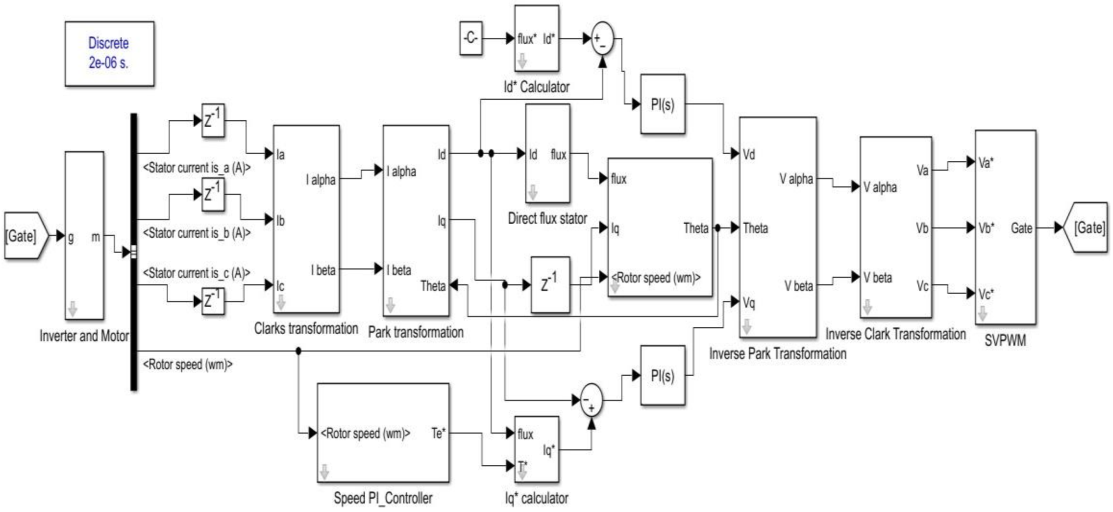

Figure 10. PI controllers for direct and quadrature current control

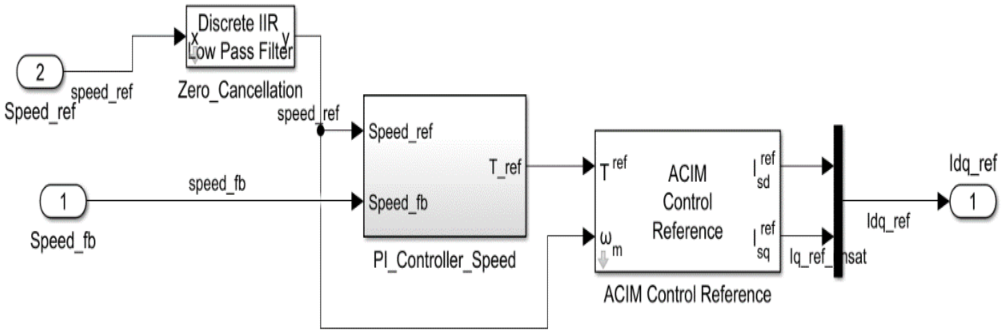

Figure 11. PI controller for speed in FOC model

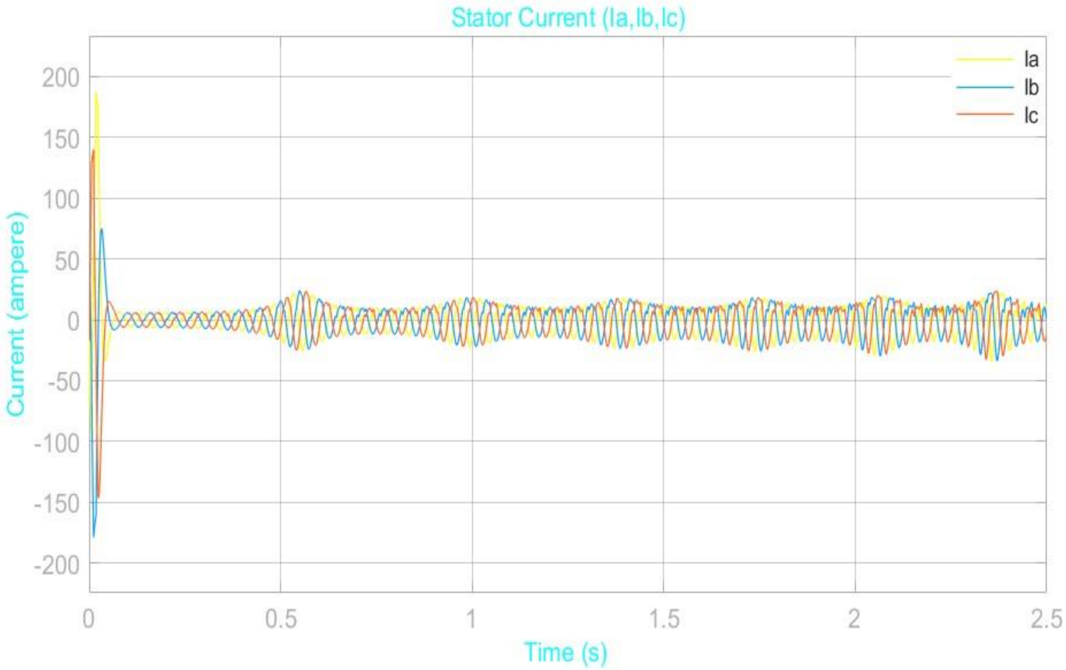

Figure 12. Results of stator currents from PI controller in sensor-less FOC model

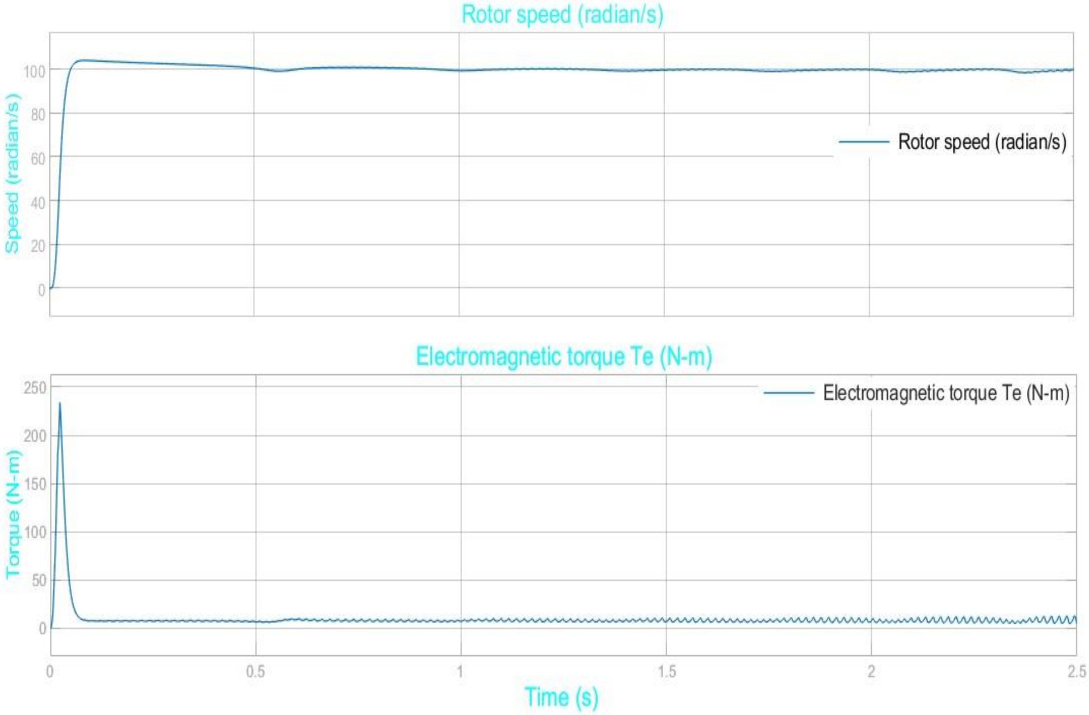

Figure 13. Results of Rotor speed and Torque from PI controller in FOC model

3.4 Simulation & Results of PD controller in FOC model

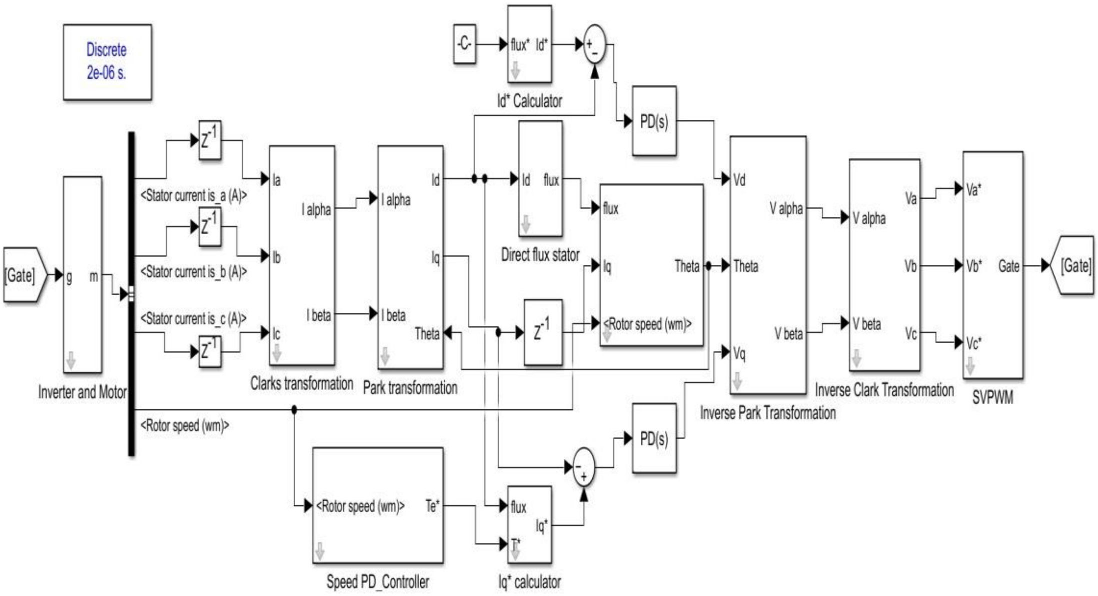

Figure 14. PD controllers for direct and quadrature current control

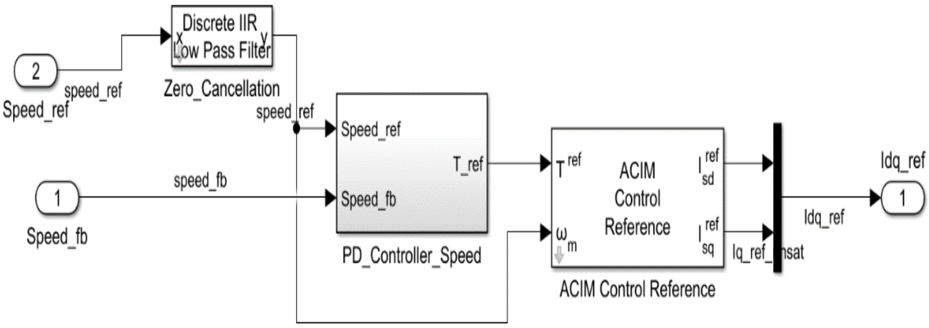

Figure 15. PD controller for speed in FOC model

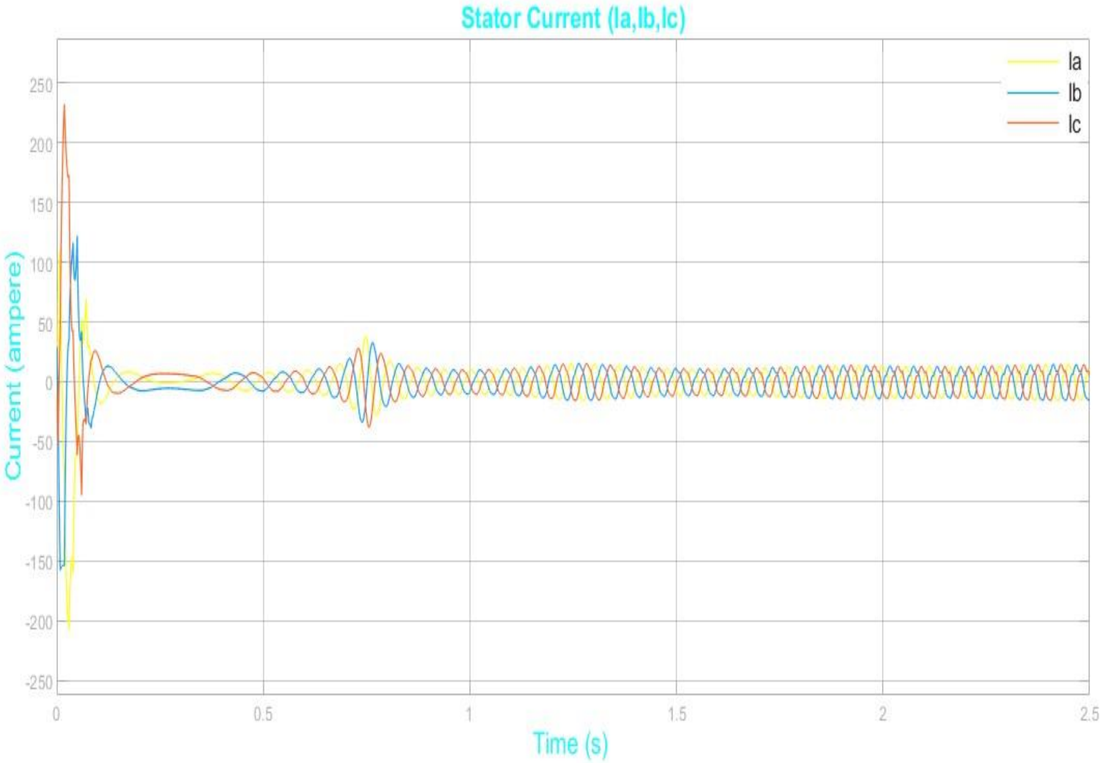

Figure 16. Result of stator currents from PD controller in sensor-less FOC model

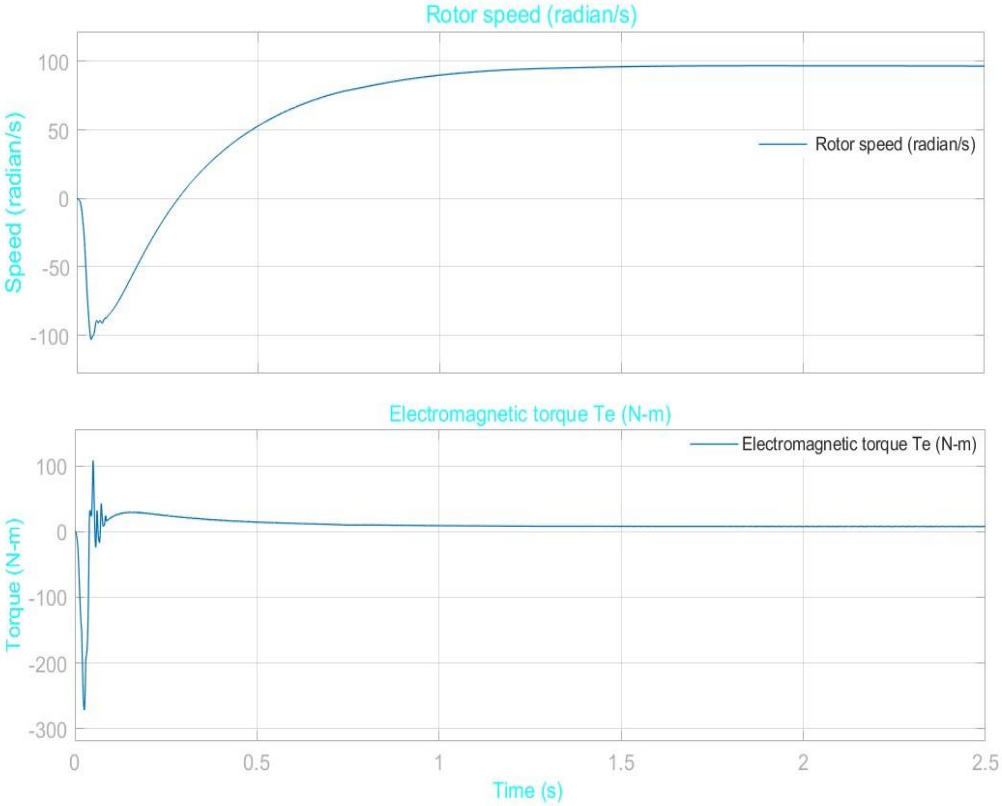

Figure 17. Results of Rotor speed and Torque from PD controller in FOC model

3.5 Simulation & Results of PID controller in FOC model

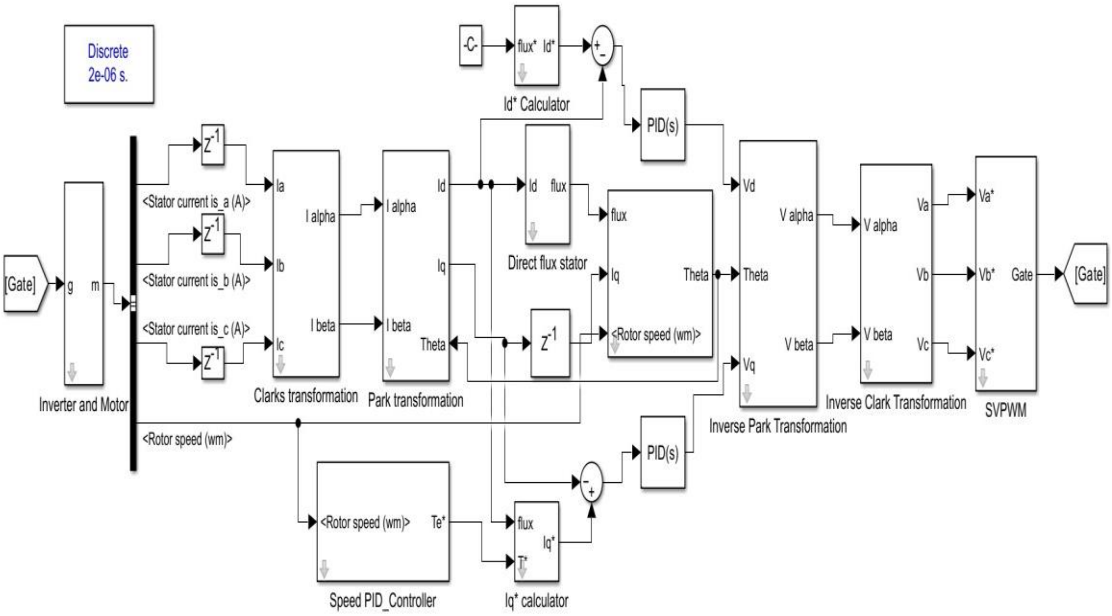

Figure 18. PID controllers for direct and quadrature current control

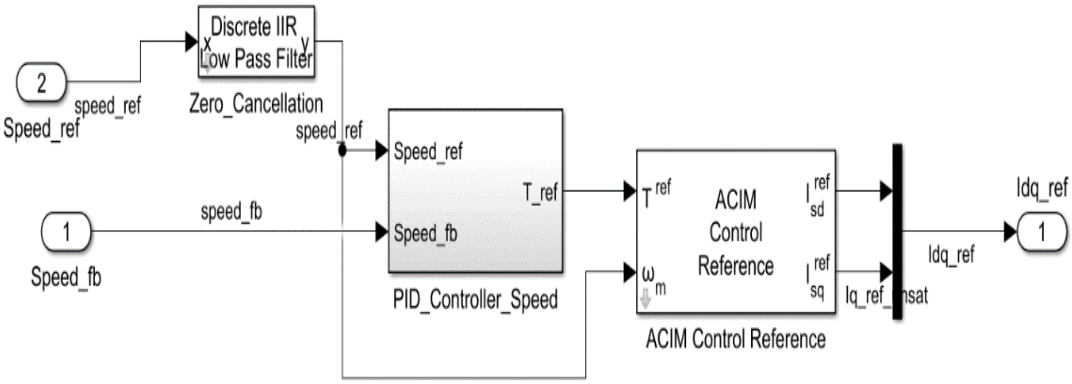

Figure 19. PID controller for speed in FOC model

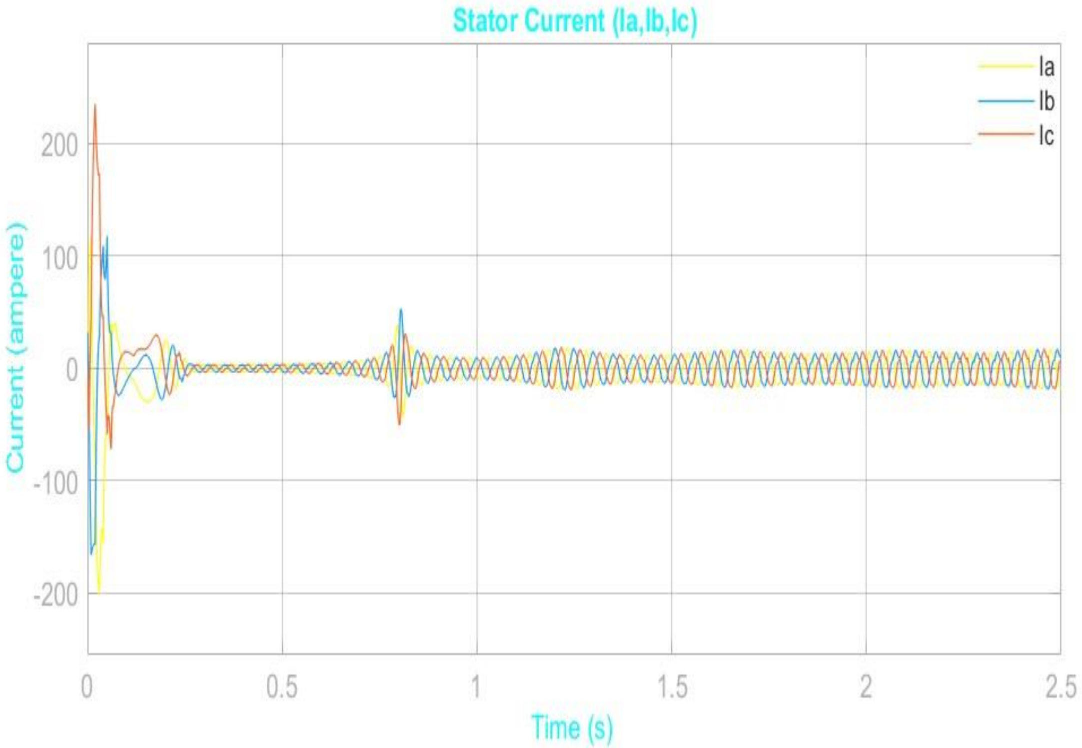

Figure 20. Results of stator currents from PID controller for sensor-less FOC model

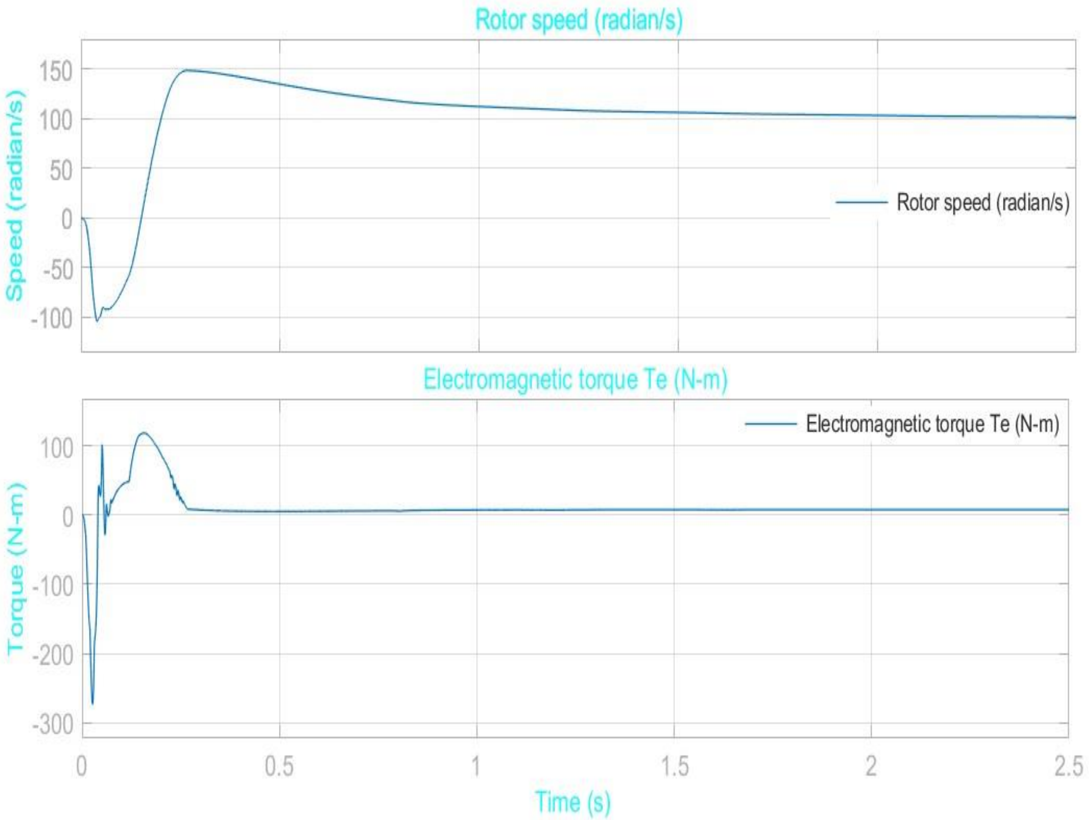

Figure 21. Results of Rotor speed and Torque from PID controller in sensor-less FOC model

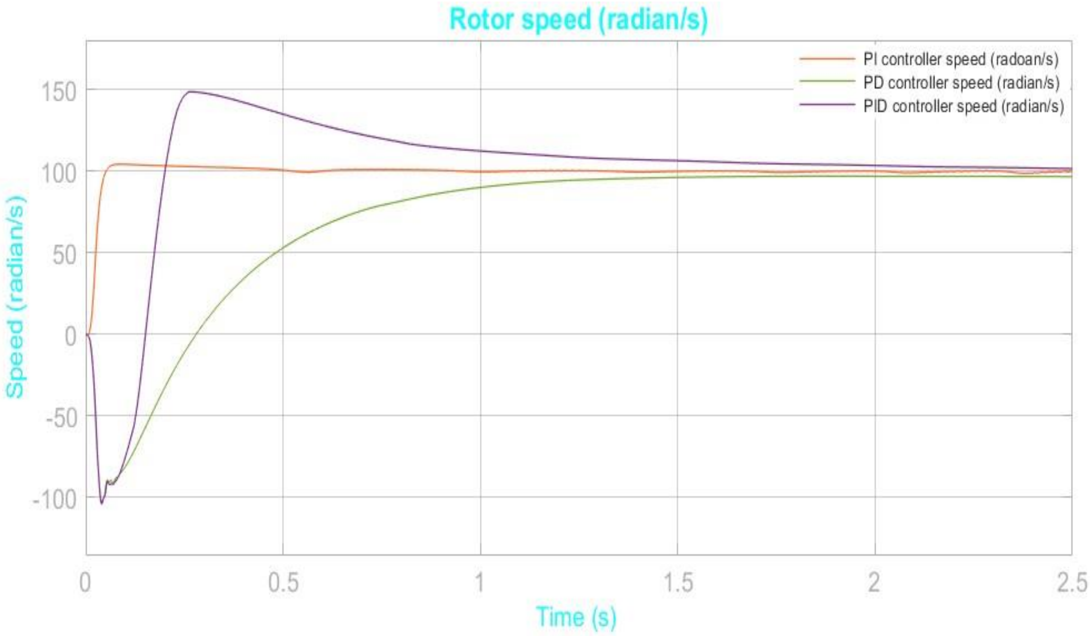

Figure 22. Results of PI vs PD vs PID controller of speed in FOC model

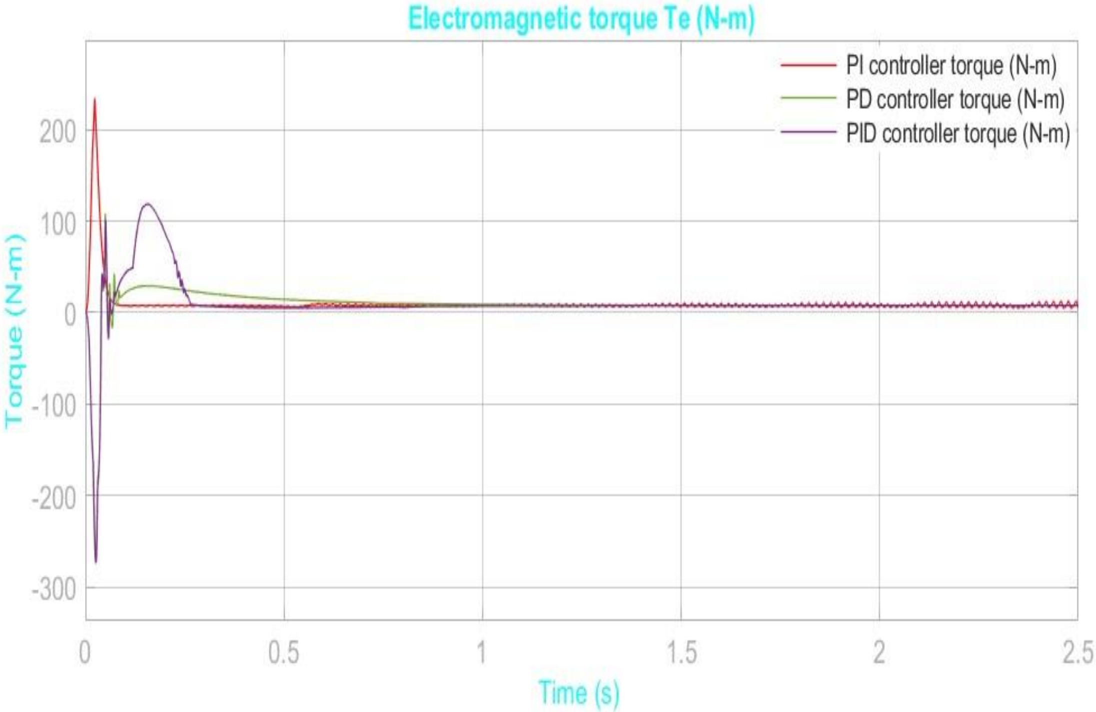

Figure 23. Results of PI vs PD vs PID controller of torque in FOC model

Comparative analysis:

The results of speed controller using PI/PD and PID have been illustrated and from the graph the PI controller shows a better result than the PD and PID controller as the derivative controller cannot precisely determine the change in error to provide a faster and efficient response while the PID controller is more desirable in term of direct and quadrature current as it is able provide a smoother, stable and desired output. The derivative will not reach set point at a faster rate due to the add additional noise in the system over time.

Table 6. PI Controller values used in FOC model

Type of controller used	Speed	Direct and quadrature current value
Proportional value	40	5000
Integral value	50	200

Table 7. PD Controller values used in FOC model

Type of controller used	Speed	Direct and quadrature current value
Proportional value	44	3800
Derivative value	12	100

Table 8. PID Controller values used in FOC model

Type of controller used	Speed	Direct and quadrature current value
Proportional value	60.5	4250
Integral value	67.5	415
Derivative value	13.75	73

4. CONCLUSION

The study of discrete PI, PD, PID controller are reviewed in the sensor-less FOC of AC three-phase induction motors. The motor-based model is investigated with sensor-less FOC for AC induction motor. The PI, PD, PID controllers each were simulated in the motor-based model that controlled the current in the motor to produce the specific torque.

The sensor-less FOC scheme is utilized by using 3 types of controllers such as PI, PD and PID controllers designed with the help of Ziegler-Nichols tuning method. The results are obtained and verified from the simulations and its respective MATLAB coding. The speed, position and current in the FOC scheme are controlled by 3 controllers in total. From the simulations obtained PI controller are more effective than PD and PID controllers as it minimizes rise time, overshoot and settling time using the Ziegler-Nichols method.

The effective benefit of derivative controller cannot be achieved in power electronics and the FOC scheme as it causes additional unwanted noise to the system over a time period, thus it is uncontrollable as it will continue to oscillate repeatedly and not reach its set point. Even though, the integral controller in the system causes a concern, this is overcome with the use of Anti windup and rest algorithm to adjust the output of the current. From the results obtained, the PI controller is preferred more than the PD and PID controller for the speed, position and current control of AC induction motor.

4.1. Future scope

- Utilization of advanced hybrid AI implementation for accurate estimations in-order to reduce cost and manpower, even overcome harsh environments with fuzzy logic controllers, Artificial neural networks, digital signal processing etc.
- Introduction of advanced power electronic semiconductor for refined inverter outputs and real time simulations to determine power quality issues such as noise and vibration through motor conditioning and harmonic analysis.
- Safety consideration of the system from excessive voltage situations for implementation in real time system

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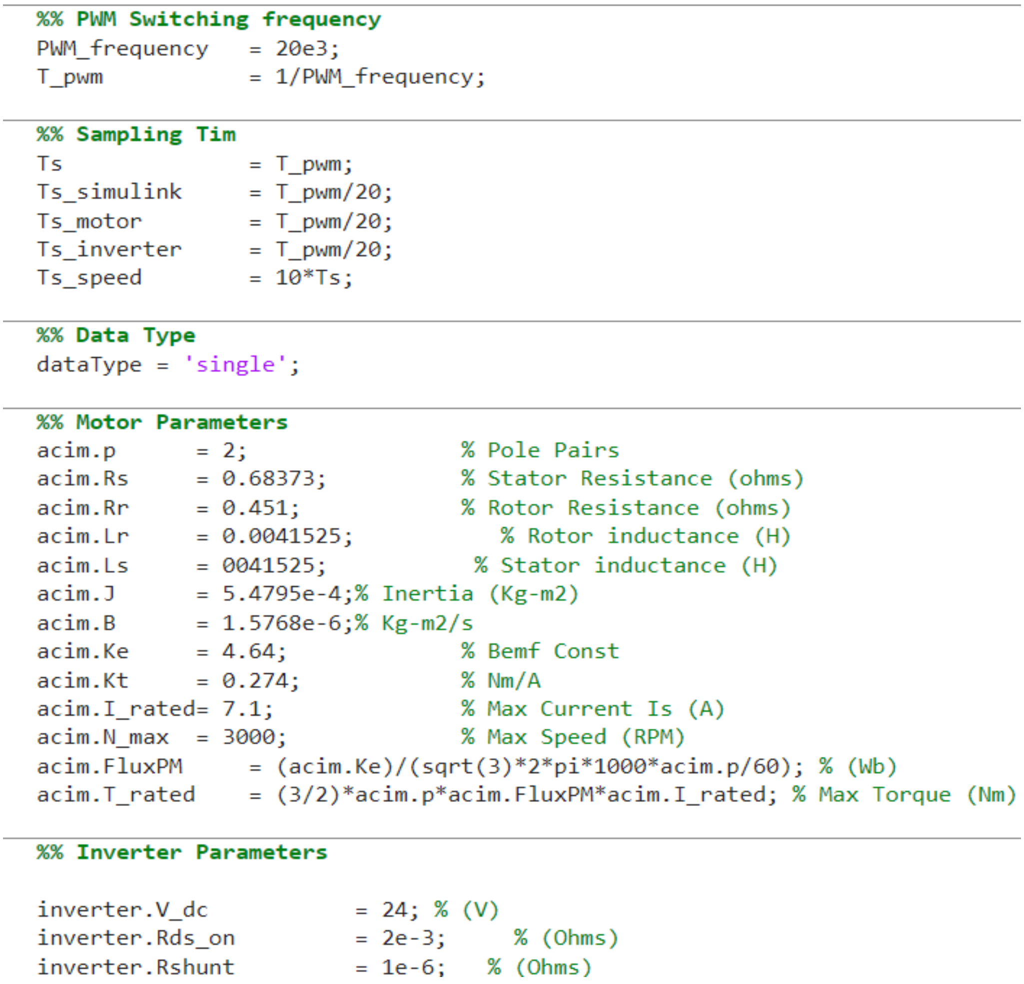
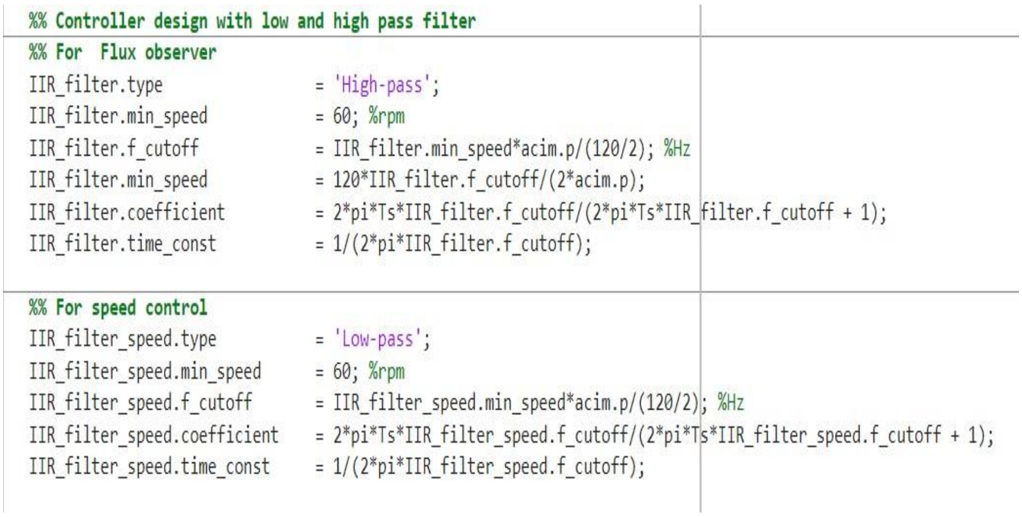
APPENDIX

C- MATLAB FFT Script



```
%% PWM Switching frequency
PWM_frequency    = 20e3;
T_pwm            = 1/PWM_frequency;

%% Sampling Tim
Ts               = T_pwm;
Ts_simulink      = T_pwm/20;
Ts_motor         = T_pwm/20;
Ts_inverter      = T_pwm/20;
Ts_speed         = 10*Ts;

%% Data Type
dataType = 'single';

%% Motor Parameters
acim.p       = 2;               % Pole Pairs
acim.Rs      = 0.68373;         % Stator Resistance (ohms)
acim.Rr      = 0.451;           % Rotor Resistance (ohms)
acim.Lr      = 0.0041525;          % Rotor inductance (H)
acim.Ls      = 0041525;          % Stator inductance (H)
acim.J       = 5.4795e-4;% Inertia (Kg-m2)
acim.B       = 1.5768e-6;% Kg-m2/s
acim.Ke      = 4.64;            % Bemf Const
acim.Kt      = 0.274;           % Nm/A
acim.I_rated= 7.1;              % Max Current Is (A)
acim.N_max   = 3000;            % Max Speed (RPM)
acim.FluxPM      = (acim.Ke)/(sqrt(3)*2*pi*1000*acim.p/60); % (Wb)
acim.T_rated     = (3/2)*acim.p*acim.FluxPM*acim.I_rated; % Max Torque (Nm)

%% Inverter Parameters

inverter.V_dc             = 24; % (V)
inverter.Rds_on           = 2e-3;     % (Ohms)
inverter.Rshunt           = 1e-6;   % (Ohms)
```

IRR Filter Script



```
%% Controller design with low and high pass filter
%% For  Flux observer
IIR_filter.type                = 'High-pass';
IIR_filter.min_speed           = 60; %rpm
IIR_filter.f_cutoff            = IIR_filter.min_speed*acim.p/(120/2); %Hz
IIR_filter.min_speed           = 120*IIR_filter.f_cutoff/(2*acim.p);
IIR_filter.coefficient         = 2*pi*Ts*IIR_filter.f_cutoff/(2*pi*Ts*IIR_filter.f_cutoff + 1);
IIR_filter.time_const          = 1/(2*pi*IIR_filter.f_cutoff);

%% For speed control
IIR_filter_speed.type          = 'Low-pass';
IIR_filter_speed.min_speed     = 60; %rpm
IIR_filter_speed.f_cutoff      = IIR_filter_speed.min_speed*acim.p/(120/2); %Hz
IIR_filter_speed.coefficient   = 2*pi*Ts*IIR_filter_speed.f_cutoff/(2*pi*Ts*IIR_filter_speed.f_cutoff + 1);
IIR_filter_speed.time_const    = 1/(2*pi*IIR_filter_speed.f_cutoff);
```