

نهج موحد لتصميم جهاز التحكم PI في مجال دلتا للتحكم غير المباشر في محرك حثي

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الخلاصة

توفر معلمات النظام الديناميكي باستخدام مشغل دلتا الوقت المتقطع إطاراً موحداً للنمذجة والتحليل والتحكم مما يؤدي إلى نتائج زمنية مستمرة من الوقت المتقطع عند درجة عالية لأخذ العينات. إن التحكم غير المباشر بالمجال (IFOC) لمحرك الحث ثلاثي الطور المرتكز على عاكس المصدر الحالي (CSI) شائع بالنسبة لتطبيقات الجهد المتوسط بسبب مزاياه من حيث بساطة الدائرة والقدرة على عكس الطاقة وحماية أفضل للدائرة القصيرة على العاكس من مصدر الجهد. في هذا البحث، تم اقتراح جهاز تحكم غير مباشر بالمجال يتغذى على عاكس المصدر الحالي عالي الأداء بناءً على التحكم في تعديل عرض النبضة (PWM) باستخدام حلقة التباطؤ. في هذا النهج، تم تنفيذ كل من وحدة تحكم التدفق وعزم الدوران في معلمات مشغل دلتا باستخدام ماتلاب / سميولينك. لقد لوحظ أنه في وقت أخذ العينات دلتا = 0.1 ثانية، يتم تعيين خصائص استجابة عامل دلتا لنظرائه المستمرين في الوقت على أساس واحد إلى واحد. إنه يعرض فائدة الطريقة المقترحة التي تقضي تماماً على وجود طبولوجيا التحكم الرقمي القائمة على مشغل النبوة للتحكم الحركي القائم على التحكم غير المباشر في المجال.

A unified approach for PI controller design in delta domain for indirect field-oriented control of induction motor drive

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Submitted: 17/01/2019

Revised: 13/09/2019

Accepted: 16/10/2019

ABSTRACT

The parameterization of the dynamic system using discrete time delta operator provides a unified framework for modeling, analysis, and control leading to continuous time results from its discrete time description at high sampling limit. Indirect field oriented control (IFOC) of three-phase induction motor based on current source inverter (CSI) is popular for medium voltage applications because of its advantages of simpler circuit, power reversal capacity, and a better short circuit protection over voltage source inverter. In this paper, a high performance CSI fed IFOC is proposed based on closed loop Pulse Width Modulation (PWM) control using AC hysteresis. In this approach, both the flux and torque controller are implemented in delta operator parameterization using MATLAB/Simulink. It has been seen that, at the sampling time $\Delta=0.1$ second, the delta operator response characteristics map to its continuous time counterparts on one to one basis. It exhibits the usefulness of the proposed method, which completely eliminates the existence of shift operator based digital control topologies for IFOC based induction motor control.

Keywords: delta operator; indirect field orientated control; PI controller.

INTRODUCTION

An induction motor (IM) is designed to operate from a three-phase source of alternating voltage, that is, a type of asynchronous AC motor. High reliability, relatively simple, rugged structure, low cost, wide speed range, high efficiencies, and robustness are the parameters that make this kind of motor advantageous. For the development of the electrical drives, induction machine is considered as the execution element for all related aspects like starting, braking, speed reversal, and speed change. Due to the rapid improvements in power electronics and drives, the induction motor becomes the major component for high performance applications. The researchers have devoted quality time for the control of induction motor throughout the decades (Bimal K Bose, 2002; Goyat et al., 2012; Ohnishi T et al., 1988). The mathematical model of IM constitutes both the electromagnetic and mechanical system for the study of steady state and transient condition of induction motor drives. As modern IM drives (R. N. Andriamalala et al., 2008) are fed from the converters, the machine model is done in a manner so that it can comply with the applied input voltage and current for the necessary operation of the inverters. Pulse Width Modulation (PWM) control technique uses the voltage and frequency as a variable in order to drive the induction motor machines. The indirect field oriented control

using Current Source Inverter technology (CSI) may be an alternative for medium voltage applications as shown in Zen Guo et al. (2016). The scalar control of induction motor that results in a sluggish response of the system has been presented in Lorenz R.D et al. (1992). To meet the high standards of performance set by dc drives, variable speed AC drives employing induction motors and the field-oriented control method (P. H. Zhang et al., 2006) have been developed in recent years. Besides the scalar control, an alternative approach in the form of indirect rotor flux orientation control is made where the motor control is done using the concept of synchronously rotating reference frames. In case of field-oriented control, the flux and the torque are decoupled to provide fast dynamic response as well as good steady state performance. Independent control of the torque and flux of the complex dynamic of the motor using decoupling technique has been introduced in early 1970s (Blaschke et al., 1972). Thus, a good performance with parameter insensitive property can only be possible by applying sophisticated control techniques.

For the development of control system, mathematical modeling plays very important role. The discrete time systems can be obtained by sampling continuous time systems. The shift operator parameterizations are commonly used to represent the sampled systems. At fast sampling limit, the shift operator parameterization fails to provide meaningful information and, therefore, calls for delta operator modeling, which is popularized by Middleton and Goodwin (R. H. Middleton et al., 1990). The delta operator parameterized system converges to its corresponding continuous-time counterpart providing a unified framework in system studies. P. Sarkar *et al.* (2001) demonstrated the unified controller design method in the complex delta domain. Nowadays, the application of delta operator is seen for the designing of adaptive I-PD control in Tsuyoshi Shiota1 et al. (2013). The delta operator based PI observer is designed by John Cortes-Romero *et al.* (2013) for active disturbance rejection control of induction motor. The application for delta operator for output feedback control of T-S Fuzzy systems with time varying delays is seen in Hongyi Li et al. (2015).

This paper presents an indirect field-oriented control (IFOC) of induction motor (IM) drive using the PI controller designed in delta domain. The performance of PI controller, which is applied in three-phase IM drive system, is investigated in this paper. The theoretical principle, numerical simulation procedures, and the results of these methods are discussed and compared with results obtained using the PI controller in continuous time domain and discrete time domain.

DYNAMIC MODELING OF INDUCTION MOTOR

A. Basic Model

The dynamic equivalent circuit of the investigated Induction Motor in the synchronous reference frame is given by Figure 1(a) & Figure 1(b).

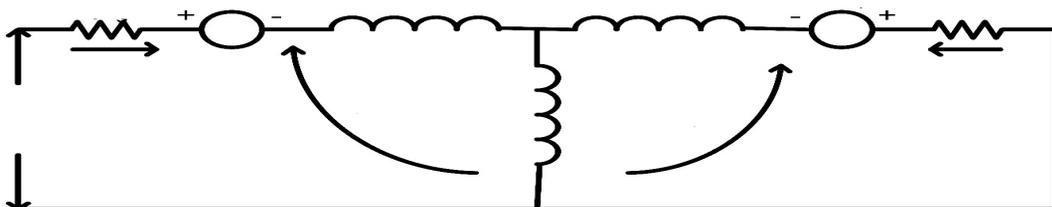


Fig. 1(a). Dynamic equivalent circuit of induction motor in d-axis.

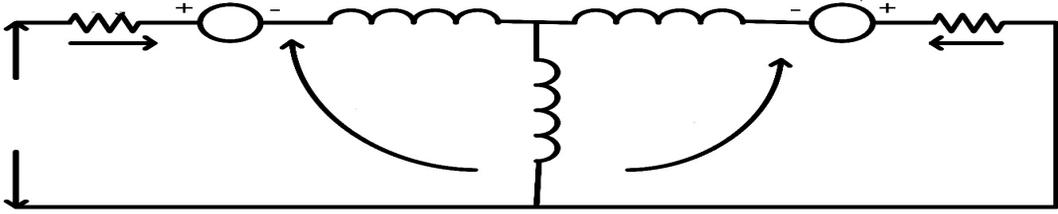


Fig. 1(b). Dynamic equivalent circuit of induction motor in q-axis.

The fifth-order (d-q) model of an induction motor (M. Ouhrouche et al., 2006) established in the synchronous reference frame rotating at speed ω_e is given by

$$\frac{d}{dt} \begin{bmatrix} I_{sd} \\ I_{sq} \\ \psi_{rd} \\ \psi_{rq} \\ \omega_r \end{bmatrix} = \begin{bmatrix} -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma \tau_r}\right)I_{sd} + \omega_e I_{sq} + \frac{L_m}{\sigma L_s L_r \zeta_r} \psi_{rd} + \frac{L_m \omega_r}{\sigma L_s L_r} \psi_{rq} \\ -\omega_e I_{sd} - \left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma \tau_r}\right)I_{sq} - \frac{L_m \omega_r}{\sigma L_s L_r} \psi_{rd} + \frac{L_m}{\sigma L_s L_r \zeta_r} \psi_{rq} \\ \frac{L_m}{\tau_r} I_{sd} - \frac{1}{\tau_r} \psi_{rd} + (\omega_e - \omega_r) \psi_{rq} \\ \frac{L_m}{\tau_r} I_{sq} - \frac{1}{\tau_r} \psi_{rq} - (\omega_e - \omega_r) \psi_{rd} \\ \frac{p^2 L_m (I_{sq} \psi_{rd} - I_{sd} \psi_{rq})}{J L_r} - \frac{F}{J} \omega_r - \frac{p}{J} T_l \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} V_{sd} \\ \frac{1}{\sigma L_s} V_{sq} \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

In equation (1), $\sigma = \frac{L_m^2}{(1 - L_s L_r)}$ is the coefficient of dispersion and the rotor electrical constant is defined as $\tau_r = \frac{L_r}{R_r}$.

As the control scheme emphasizes the rotor dynamics (rotor flux position calculation), rotor circuit analysis is done from the mathematical model equations of induction motor drives for the necessary implementation of the control scheme.

Now, under the scheme of rotor flux control from the synchronously revolving reference frame, the d-axis is made to align with respect to the rotor flux vector to produce the stator d-axis current component. This stator d-axis current component is responsible for controlling the field of rotor circuit, which results in the q-axes component becoming zero ($\psi_{rq} = 0$) and the d-axis component. $\psi_{rd} = \psi_r$. Therefore, in the rotor flux field coordinate, the induction motor can be represented by the following model.

$$\frac{d}{dt} \begin{bmatrix} I_{sd} \\ I_{sq} \\ \psi_r \\ \omega_r \end{bmatrix} = \begin{bmatrix} -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma \tau_r}\right)I_{sd} + \omega_e I_{sq} + \frac{L_m}{\sigma L_s L_r \zeta_r} \psi_r \\ -\omega_e I_{sd} - \left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma \tau_r}\right)I_{sq} - \frac{L_m \omega_r}{\sigma L_s L_r} \psi_r \\ \frac{L_m}{\tau_r} I_{sd} - \frac{1}{\tau_r} \psi_r \\ \frac{p^2 L_m (I_{sq} \psi_r)}{J L_r} - \frac{F}{J} \omega_r - \frac{p}{J} T_l \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_s} V_{sd} \\ \frac{1}{\sigma L_s} V_{sq} \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

$$T_e = \frac{pL_m\psi_r}{L_r} I_{sd} \quad (3)$$

$$\psi_r = \frac{L_m}{(1 + s\tau_r)} I_{sd} \quad (4)$$

$$\omega_{sl} = \omega_e - \omega_r \quad (5)$$

In the case of rotor field reference frame, all stator variables are to be converted into *abc* reference frame using a simple transformation given by

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta_e & -\sin\theta_e & 0 \\ \cos(\theta_e - 2\pi/3) & -\sin(\theta_e - 2\pi/3) & 0 \\ \cos(\theta_e + 2\pi/3) & -\sin(\theta_e + 2\pi/3) & 0 \end{bmatrix} \begin{bmatrix} x_d \\ x_q \end{bmatrix} \quad (6)$$

$$\theta_e = \int (\omega_r + \frac{L_m I_{sq}}{\tau_r \psi_r}) dt \quad (7)$$

The meanings of the notations in the above derivations are given below.

I_{sd} is the current phasor in stator d-axes of synchronously rotating reference frame.

I_{sq} is the current phasor in stator q-axes of synchronously rotating reference frame. ψ_{rd} is the rotor flux phasor in the d axes and ψ_{rq} is the rotor flux phasor in the q axes. ω_{sl} is the slip speed, T_l is the load torque, and θ_e is the displacement of rotor flux.

F = Coefficient of friction

J = Moment of Inertia

P = Number of poles

T_r = Rotor time constant

R_s = Stator resistance

L_s = Stator inductance

L_r = Rotor inductance

L_m = Mutual inductance between the rotor and stator

B. Coordinate Transformation

The three-phase quantities of AC motors can be analyzed in terms of complex space vectors and equivalent to two-phase α , β co-ordinate frame. They can be further transformed into time invariant two-phase rotating d, q

reference frame. Clarke transformation is used to convert the three-phase a, b, c quantities into equivalent two-phase α , β quantities. Park transformation is used to convert the space vectors into time invariant rotating d, q frame. The different transformation techniques in matrix form are given below:

1. Clarke transformation (a,b,c to α , β projection):

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (8)$$

2. Park Transformation (α , β to d, q projection):

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (9)$$

3. Inverse Park transformation (d, q to α , β projection):

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (10)$$

4. Inverse Clarke transformation (α , β to a,b,c projection):

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -1/2 & \sqrt{3}/2 & 0 \\ -1/2 & -\sqrt{3}/2 & 0 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (11)$$

where θ is the rotor position angle.

CLOSED LOOP PWM CONTROL USING AC HYSTERESIS

Vector control scheme requires the use of proper voltage control mechanism via the use of inverter switching phenomena. This need is fulfilled using PWM control methods. The PWM control method is further categorized into closed or open loop control strategy. The use of such a scheme for inverter logic helps getting the desired voltage at desired frequency by selectively choosing the firing angle of the trigger circuit.

This paper is considered under the current control scheme via the AC hysteresis current controlling principle. According to the principle of AC hysteresis current controller, it can be used to act on independent three-phase systems or can be used for current phasor error compensation by using a coordinated control of respective stator components of current. It works on a feedback closed loop mechanism. At the output side of the motor, current signals are compared to those of the input reference signals. Hence, a corrected output is provided at the motor terminals that follows with the vector control principles.

The hysteresis band is taken as a reference for the switching conditions leading to the inverter action only because phenomena speed and torque of the motor change accordingly. With proper switching, the harmonic content at the output is significantly reduced to supply pure AC content. The hysteresis band stated above follows a tolerance limit of

2W of each (a, b, c) of three-phase systems to provide the necessary frequency of output for the current in each phase. It is one the most reliable and hence has a simple operating principle. Generally, the motor is connected in star winding pattern, and necessary mathematical model is derived for connection between motor terminals and CSI.

Equations related to the connection of the inverter model to the three terminals of the three phase stator circuits are given as

$$V_{as} = 2/3V_{AG} - 1/3V_{BG} - 1/3V_{CG} \quad (12)$$

$$V_{bs} = 1/3V_{AG} + 2/3V_{BG} - 1/3V_{CG} \quad (13)$$

$$V_{cs} = 1/3V_{AG} - 1/3V_{BG} + 2/3V_{CG} \quad (14)$$

where V_{as} , V_{bs} and V_{cs} are, respectively, inverter induced stator voltage across a, b, and c phases of stator, whereas V_{AG} , V_{BG} and V_{CG} represent corresponding phases to ground voltage of individual phasor. From the Simulink model, a constant DC source of 200 V is provided along with ground at 0 V, and corresponding phases are selected depending upon the principle of AC hysteresis current controller.

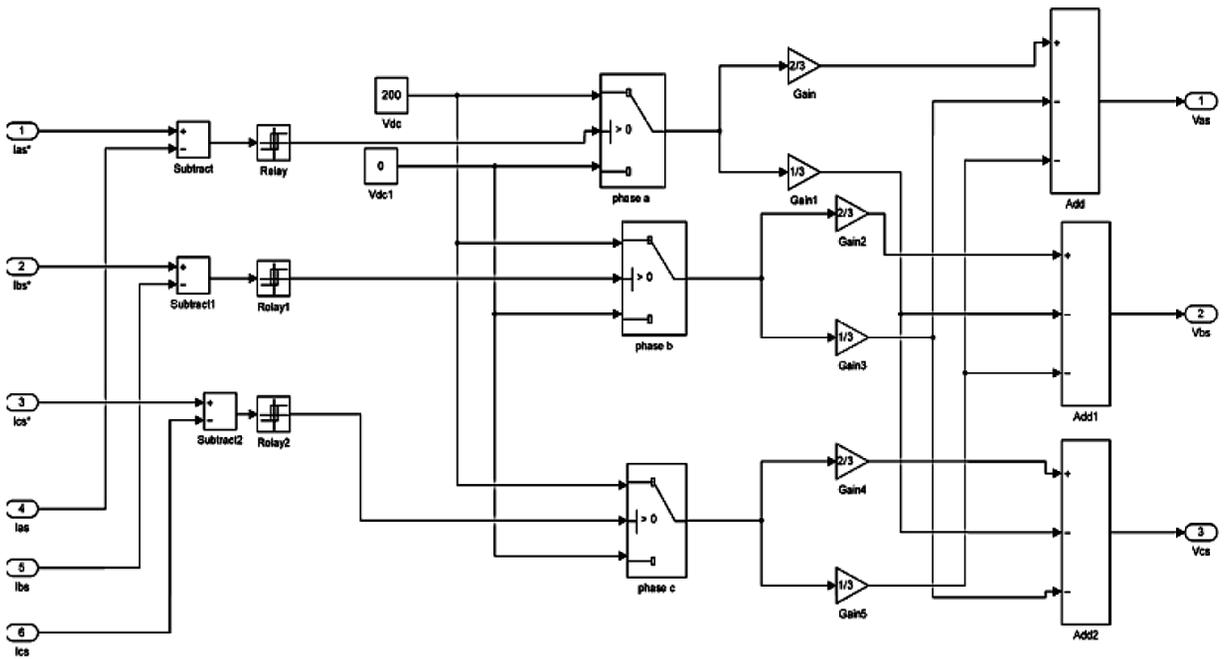


Fig. 2. Simulink representation of CSI inverter.

CONTROLLER DESIGN IN DELTA DOMAIN

A. Definition of Delta Operator

Definition of Delta Operator

The delta operator is defined as

$$\delta = \frac{q - 1}{\Delta} \quad (15)$$

where Δ is the sampling period and q is the forward shift operator. Operating δ on a signal $x(t)$ gives

$$\delta x(t) = \frac{x(t + \Delta) - x(t)}{\Delta} \quad (16)$$

At fast sampling limit, when $\Delta \rightarrow 0$,

$$\lim_{\Delta \rightarrow 0} \delta x(t) = \frac{d}{dt} x(t) \quad (17)$$

B. Discrete Speed and Current Control

The IFOC scheme described above is implemented in both continuous and discrete-time environment. In this paper, discrete-time control using delta operator is considered. There is one speed controller for velocity control and two current controllers for torque control as per the block diagram stated earlier. The feedback signals from the current and position sensors are discretized through ADC to implement digital control scheme using delta operator.

C. δ -operator based discretization

The definition of delta operator is given in (15). The corresponding complex domain operator γ is related to z as

$$\gamma = \frac{z - 1}{\Delta} \quad (18)$$

The discrete-time control scheme based on delta operator is obtained as

$$\gamma^{-1} = \frac{\Delta z^{-1}}{1 - z^{-1}} \quad (19)$$

INDIRECT FIELD-ORIENTED CONTROL OF INDUCTION MOTOR

Indirect field-oriented control is the control of both the phase and amplitude of stator voltage and current space vector of Induction Motor at the same time. In this method, by using Park and Clarke transform, three-phase stator currents are converted into space vector form. The main objective of vector control is to control the torque and flux separately. Both the torque and flux are controlled separately using PI controller. The reference current for flux component is taken as zero, and the reference current for torque component is derived from the drive speed controller. There exists one speed control loop that controls the output speed of motor in respect of the input reference speed, and it generates the appropriate torque signal for necessary production of stator q-axis current. The flux component of current is kept constant. Furthermore, the same is controlled via the PI control and thereby results in the production of stator d-axis current component.

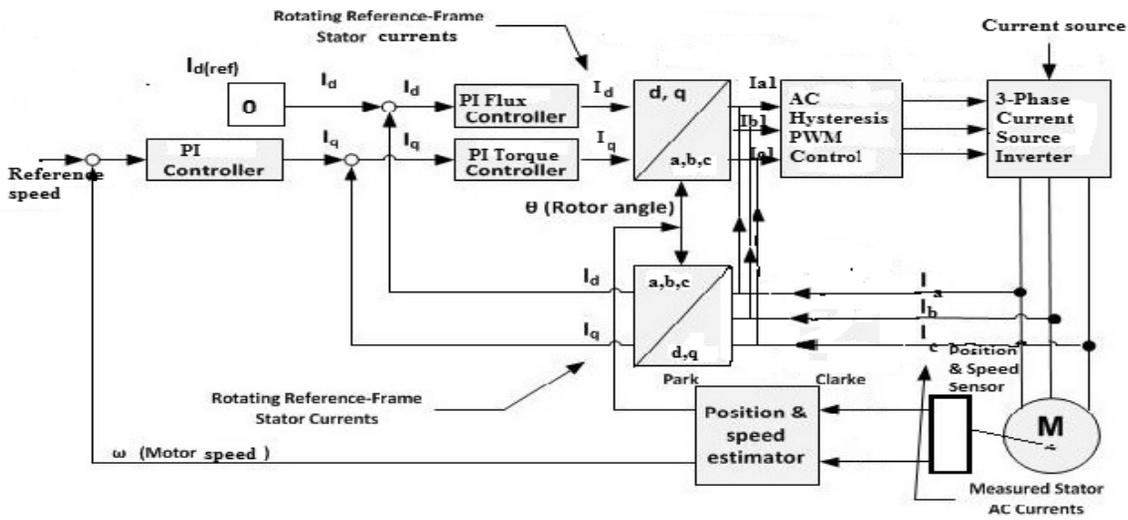


Fig. 3. Indirect field-oriented control scheme of IM.

The controller output is the reference voltage signal, which is used in the AC hysteresis PWM control block to operate the 3-phase current source inverter. The block diagram of IFOC is given in Figure 3. The steps to perform the proposed vector control are described below:

Step 1: Measure the motor quantities (phase currents and voltages).

Step 2: Transform the above stator current quantities into 2-phase systems (d, q) using Park transformation.

Step 3: Measure the rotor position angle from the position sensor.

Step 4: The torque and flux producing components of stator currents are controlled separately.

Step 5: The reference speed signal of the speed controller is set, which gives the reference current output for torque component.

Step 6: Reference Current space vector is transformed into 3-phase (a, b, c) system using inverse Park transform.

Step 7: AC hysteresis PWM control is used to operate current source inverter to drive the IM.

SIMULINK BLOCK DIAGRAM OF DIFFERENT SUBSECTIONS

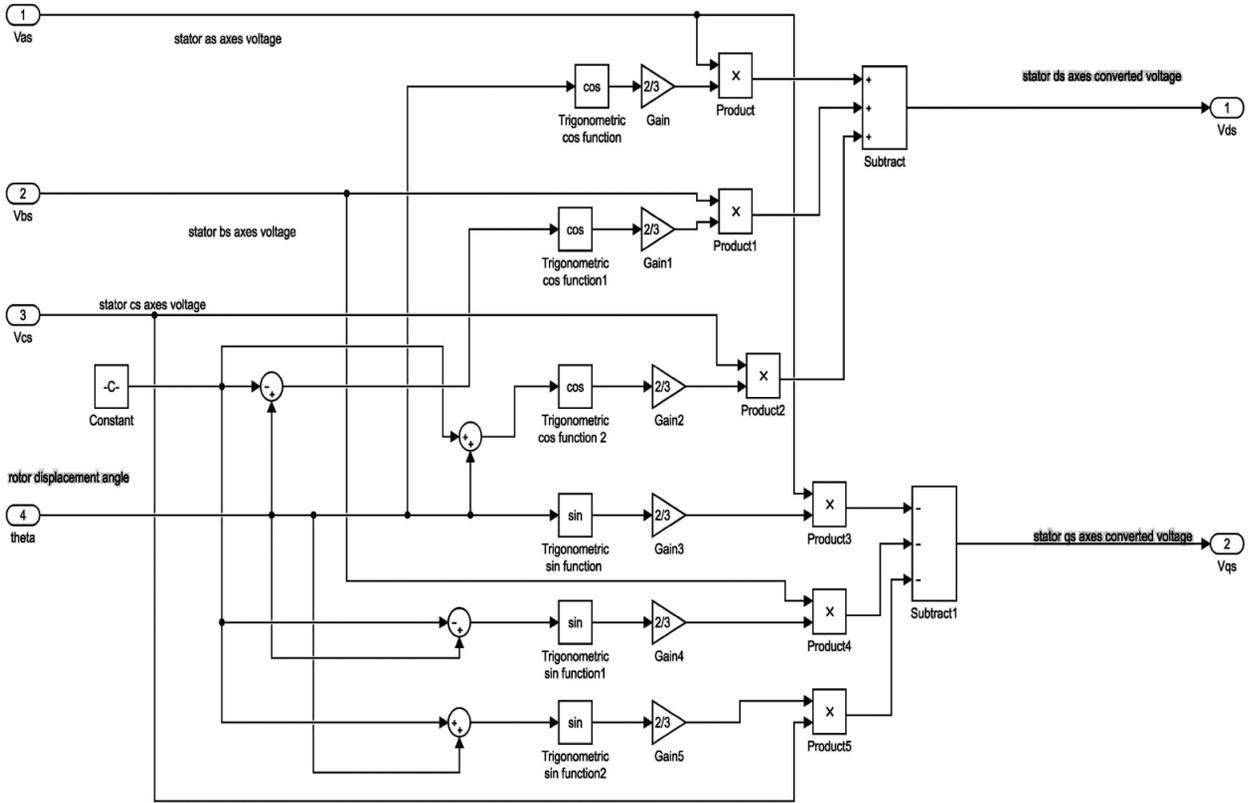


Fig. 4. Simulink model of abc-dq coordinate transformation.

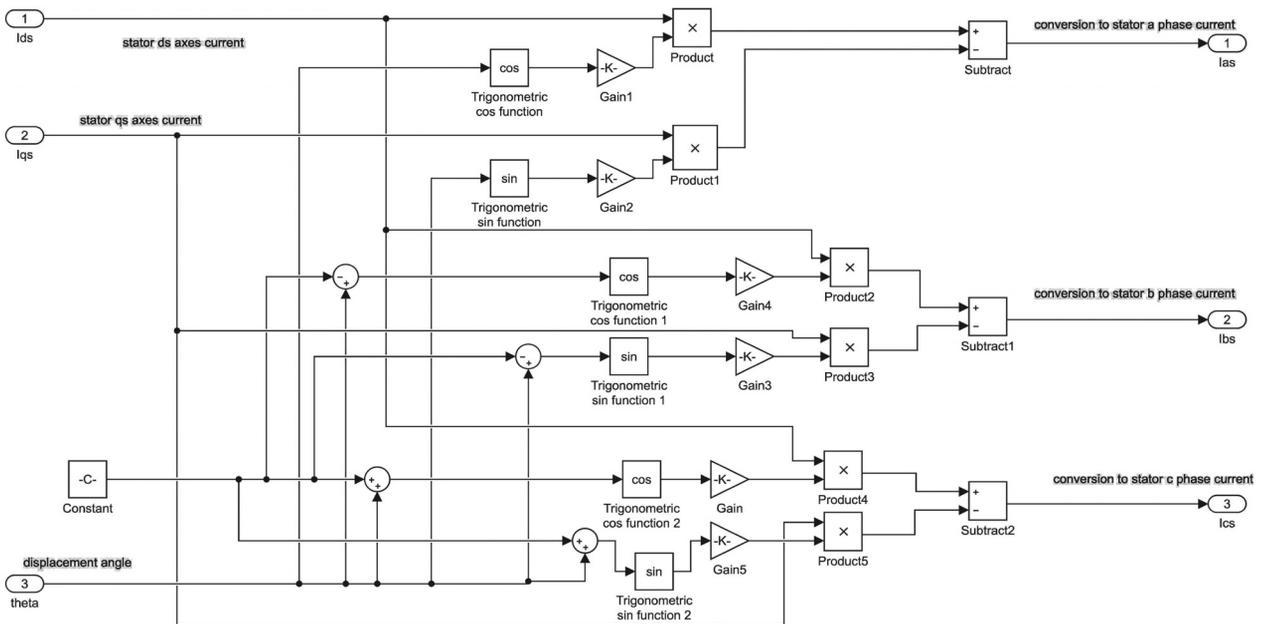


Fig. 5. Simulink model of dq-abc coordinate transformation.

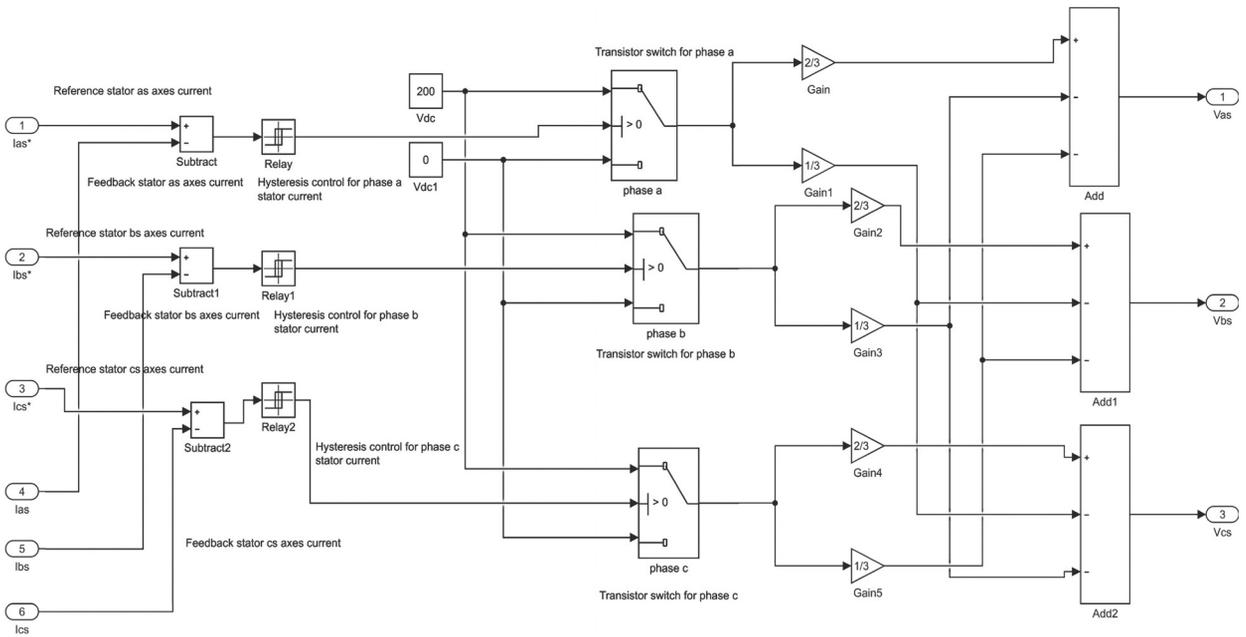


Fig. 6. Simulink model of AC hysteresis-controlled CSI inverter.

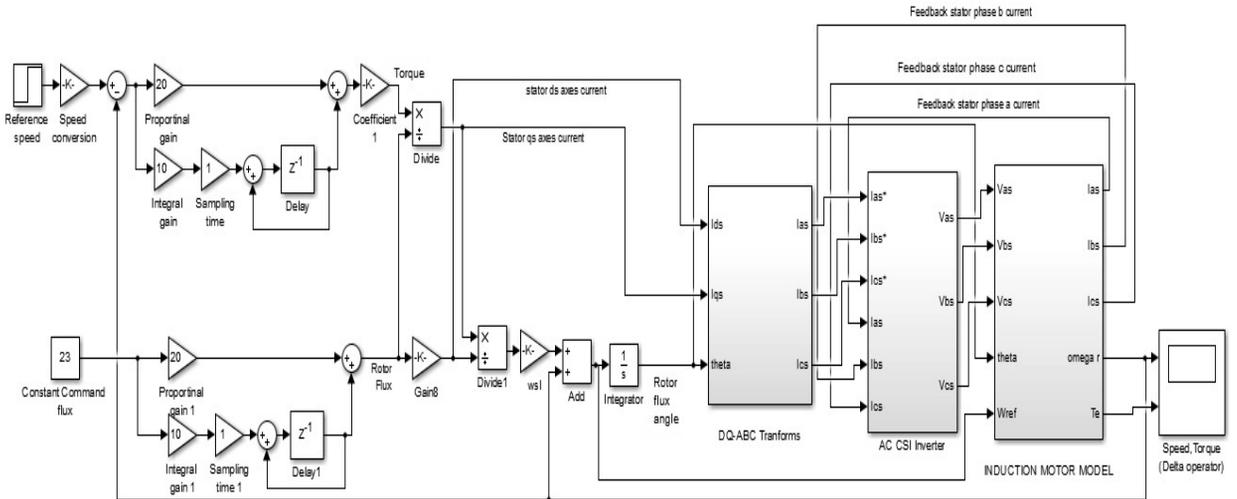


Fig. 7. Simulink model of PI speed controller in delta domain for 3-phase Induction motor.

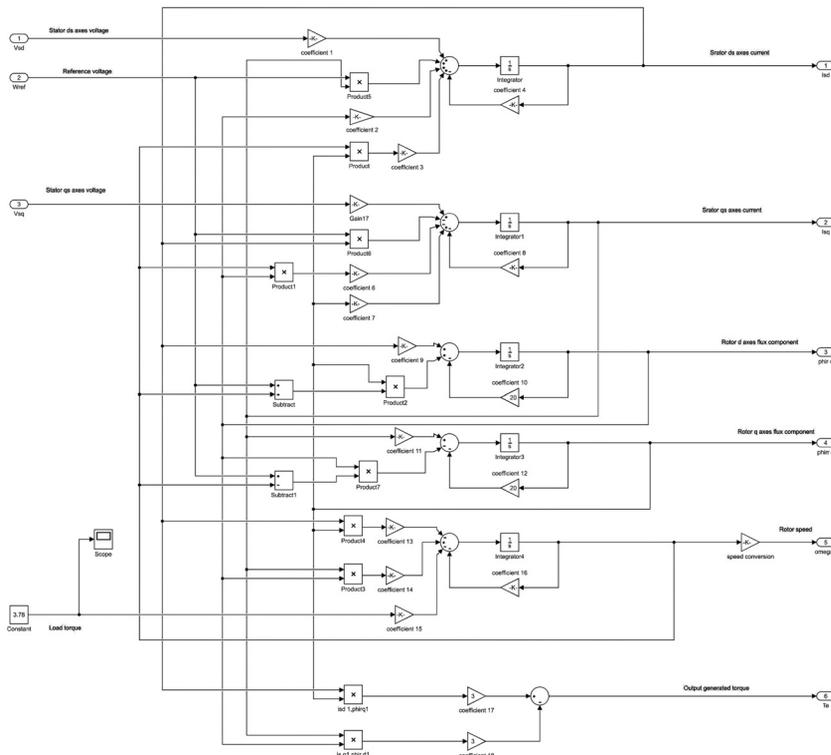


Fig. 8. Simulink model of 3-phase induction motor established in the synchronous reference frame rotating.

SIMULATION AND RESULT ANALYSIS

A 3-phase induction motor with the following parameters is taken as the model, and simulation using the Matlab/Simulink platform is done to get the outputs.

Parameter selection for 3-phase Induction Motor is given in Table 1.

Table 1. Specifications of 3-phase Induction Motor.

Parameter	Values
Rs (Stator Resistance)	1.40 ohm
Rr (Rotor Resistance)	1.40 ohm
Ls (Stator Inductance)	0.302 H
Lr (Rotor Inductance)	0.080 H
Lm (Magnetizing Inductance)	0.120 H
f_r (Rotor frequency)	3.14 rad/sec
J (Moment of Inertia)	0.001180 kg-m ²
P (No. of Rotor poles)	4
Sampling interval (Δ)	0.1sec
B (Viscous Friction)	0.050 kg-m ² /sec
Voltage, Frequency, Phase, Pole, Type	230 V/50 Hz/3phase/4 pole/Squirrel Cage

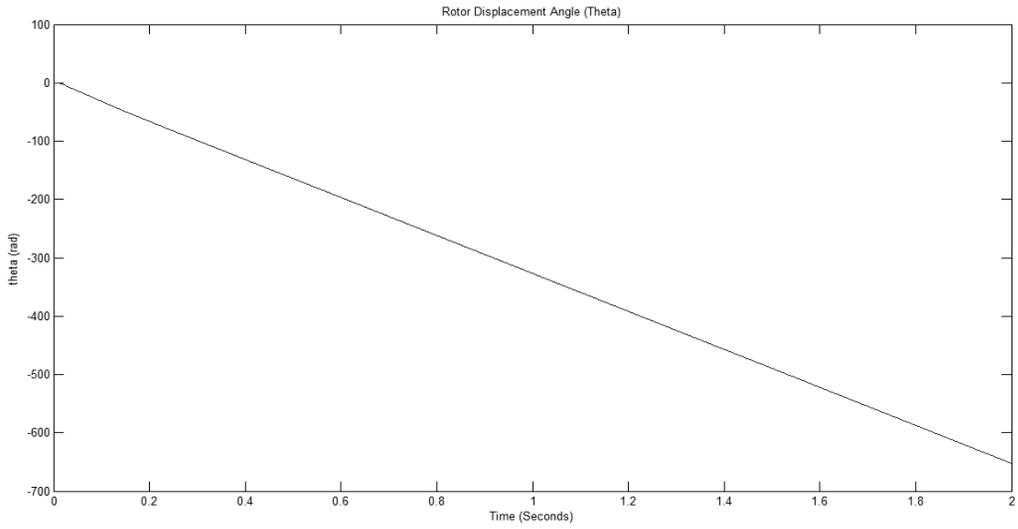


Fig. 9. Rotor displacement angle.

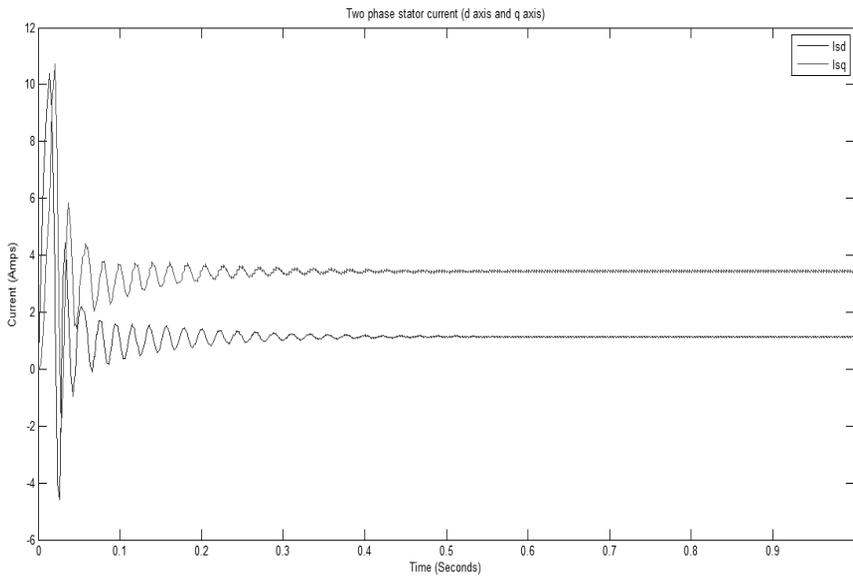


Fig. 10. Two-phase stator current (d-axis and q-axis).

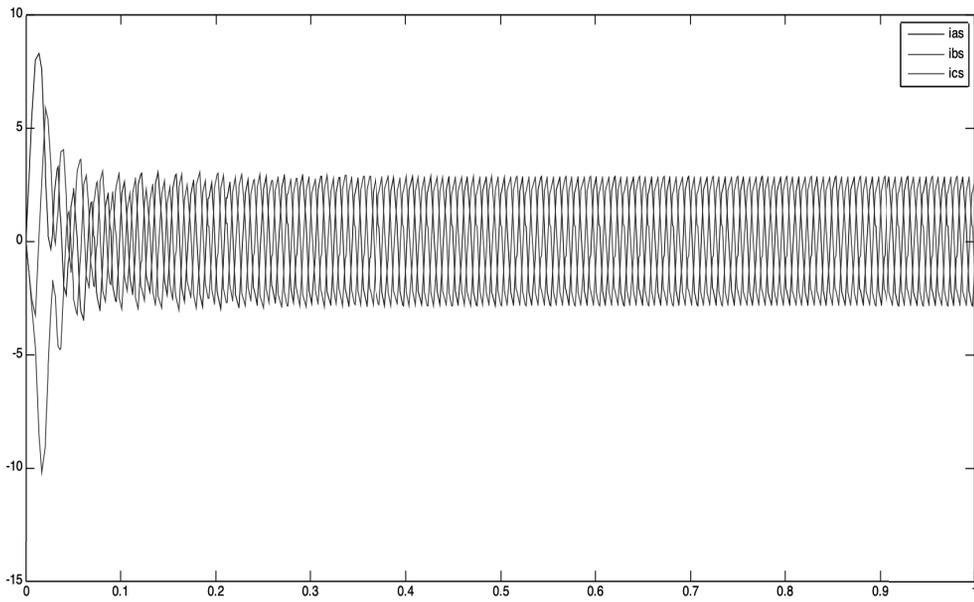


Fig. 11. Three-phase stator current.

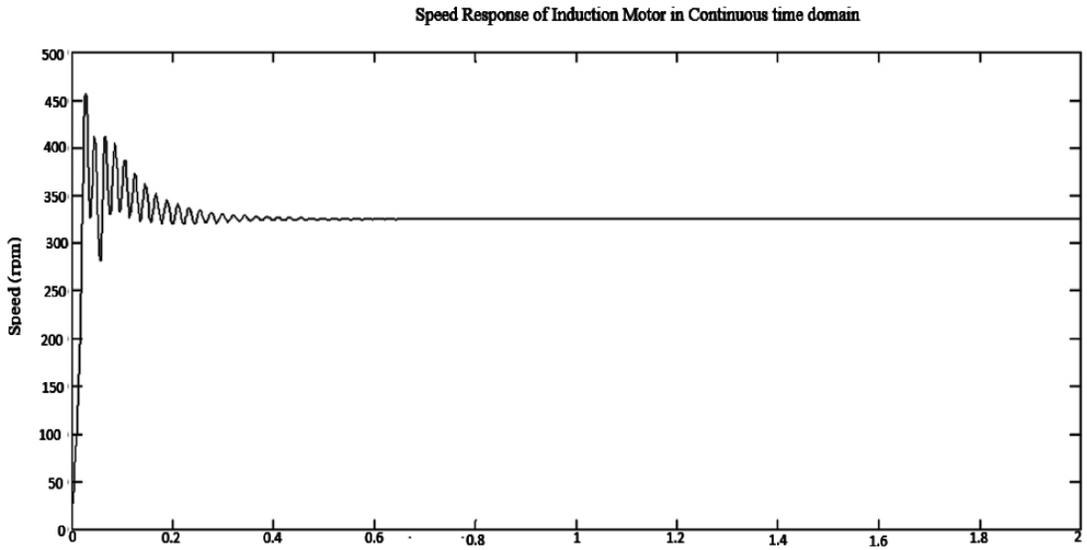


Fig. 12. Speed response of Induction motor in continuous time domain.

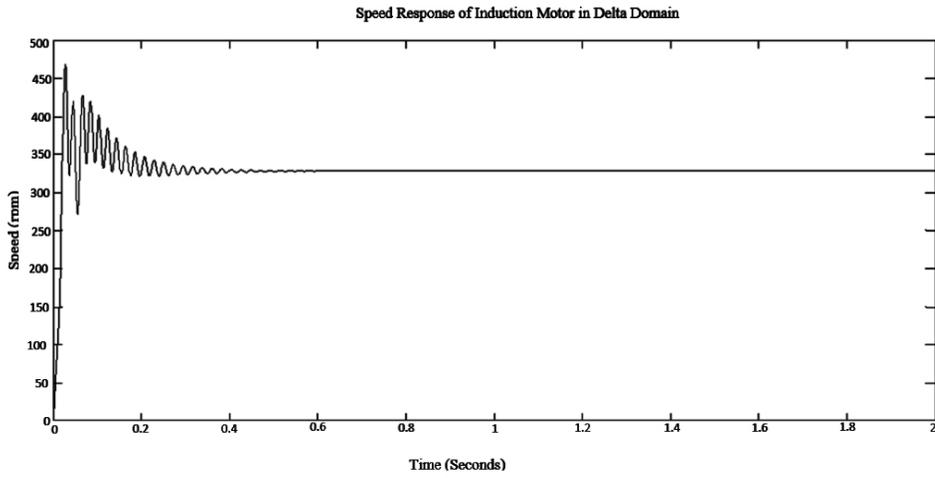


Fig. 13. Speed response of Induction Motor in delta domain.

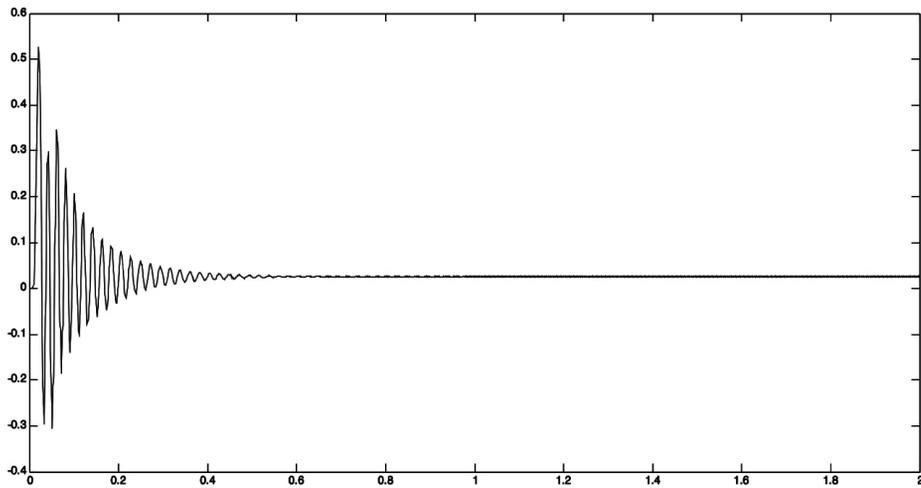


Fig. 14. Torque response in continuous time domain.

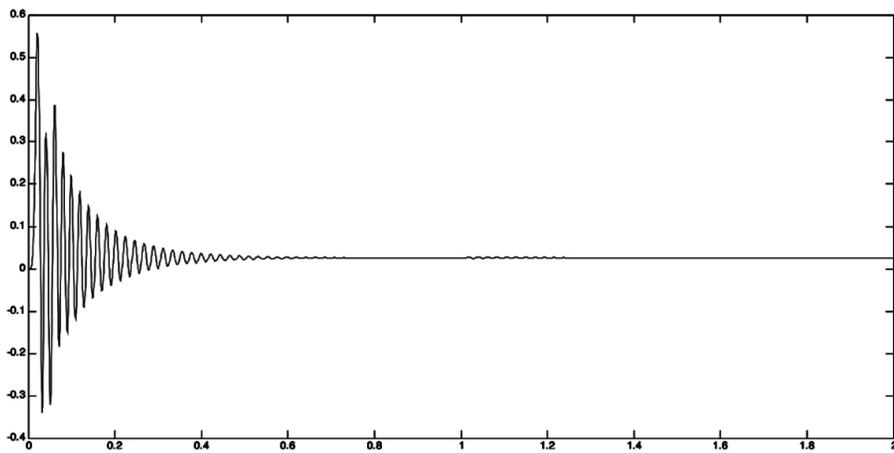


Fig. 15. Torque response in delta domain.

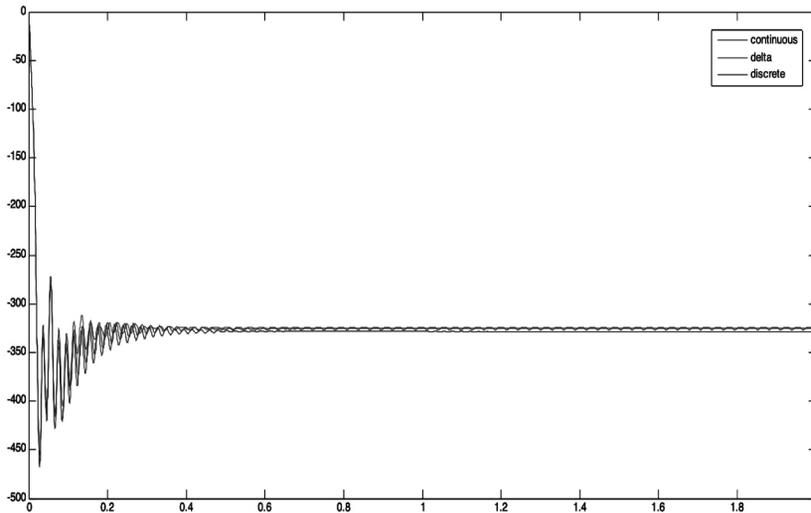


Fig. 16. Comparison of speed response in continuous, discrete, and delta domain.

The reference speed for the above experimental work is taken as 350 rad/sec for the necessary analysis of output speed response. The rated torque is fixed to 3.78 N-m. Figure 9 shows that the angular rotor position varies almost linearly even with slight change of speed. Two-phase stator currents in d-q axes are shown in Figure 10. Upon analysis, it is found that the current component I_{ds} tends to saturate near the zero value, whereas I_{qs} has a significant value above zero for necessary torque and speed control of the drives. Figure 11 shows the stator three-phase currents that show that, even with slight distortion in the output speed of rotor, it still maintains the sinusoidal nature of the current. The speed response using PI controller in continuous time control mode is shown in Figure 12. From Figure 12 it is observed that there is frequent overshoot from time $t=0.03$ sec to $t=0.5$ sec after which the transients are stabilized and speed response is constant for the entire time frame without any disturbance. The nature of the output is the same in Figure 13 by using PI controller designed in Delta domain. It is observed that the torque is stabilized after $t=0.04$ seconds in using PI controller designed in continuous time as well as delta domain. In Figure 16, a comparative study of speed response in continuous time, discrete time, and delta domain is demonstrated. In this work, it has been focused on the design of controllers in the delta domain. Delta domain approach is to get the continuous time result from the discrete time data. When the sampling time is very less or close to zero, the discrete time result approaches to continuous time result and that is clearly observed from this graph, and superiority of the delta operator parameterized approach is proved.

CONCLUSIONS

In this paper, the problem of PI controller design in discrete delta domain has been considered for speed control of induction motor drive using IFOC mode. The method uses the concept of AC Hysteresis CSI mode inverter control for controlling the speed of IM drives. The simulation structure of the induction motor model in rotating reference frame is established. The output of the motor current signals is compared with the input reference signals, and the error signal is used for required transistor switching to maintain the desired motor output speed. Both the PI flux controller and PI torque controller are developed in delta domain and implemented using MATLAB/Simulink. The simulation results have been compared with both the discrete shift domain and continuous time domain. It has been shown that the delta operator implementation converges exactly to the continuous time transient response of the

induction motor at different operational mode at sampling time, $\Delta = 0.1$ seconds, while there remains some steady state error in discrete shift representation. Simulation results show that the delta operator based control scheme has good dynamic performance and stability leading to a viable alternative to the analog and discrete shift operator based control schemes.

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