Speed Control of Switched Reluctance Motor Drive Based on PID Controller

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***Abstract-* This study presents a speed control design for switched reluctance motor (SRM) drive based on PID controller. The applications of Switched Reluctance Motors (SRMs) have being increased day by day, but this type of motors represents a highly nonlinear system, therefore there are a lot of difficulties in modeling and controlling them. We have proposed a non-linear mathematical model of a four phases 8/6 poles SRM then simulated it through Simulink/Matlab facilities. The whole control mechanism consists of a hysteresis current controller to minimize the torque ripple and a PID speed controller. The control design results are then validated in real-time by Simulink/Matlab software package.**

***Index Terms*—Inductance model, Switched reluctance motor (SRM), PID Speed controller.**

I. INTRODUCTION

Switched reluctance motors (SRMs) have been the focus of many researches over the past decades. The simple mechanical construction is one of the main attractive features because it has no windings or permanent magnets on the rotor so its manufacturing cost appears to be lower compared to other motor types [1].
The power converter is the electronic commutator, controlling the phase currents to produce continuous motion. The control circuit monitors the current and position feedback to produce the correct switching signals for the power converter to match the demands placed on the drive by the user. The purpose of the power converter circuit is to provide some means of increasing and decreasing the supply of current to the phase winding [2].
The performance of the drive is observed by maintaining the turn–on (θon) angle of the converter constant and by varying the turn-off (θoff) angle [3].

II. SRM DESCRIPTION

A switched reluctance motor is a rotating electric machine where both stator and rotor have salient poles. Types of SRMs differ in the number of phases wound on the stator. Each of them has a certain number of suitable combinations of stator and rotor poles [4]. The SRM, when compared with the AC and DC machines, shows two main advantages.
1. It is a very reliable machine since each phase is largely independent physically, magnetically and electrically from the other machine phases.
2. It can achieve very high speeds because of the lack of conductors or magnets on the rotor.
However, the SRM has some limitations.

1. It must always be electronically commutated and thus cannot run directly from a DC bus or an AC line.
2. Its salient structure causes strong nonlinear magnetic characteristics, complicating its analysis and control.
3. The SRM shows strong torque ripple and noisy effects [5].

The construction of four phases with eight stator poles and six rotor poles (8/6 SRM) is shown in Fig. 1.

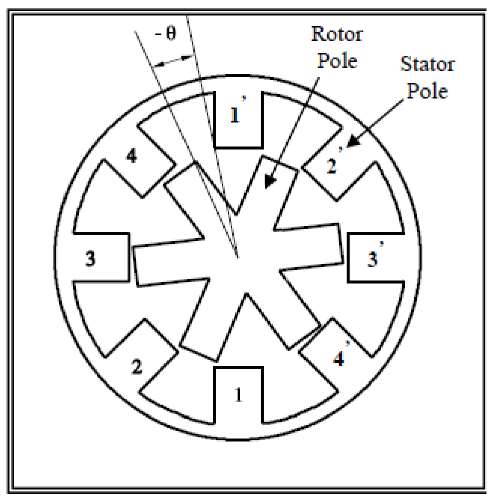


Fig.1 Construction of four phase 8/6 SRM

III. NONLINEAR DYNAMIC MODEL OF SRM

An important step in any control system design is to develop a good mathematical model, which represents the plant under various operating conditions. For simulating the dynamic characteristics of the SRM, it is essential to represent the inductance-current-position characteristics of the motor accurately. The variation of phase inductance with rotor position is expressed as a Fourier series and only the first three terms are considered. For determining the coefficients in the Fourier series, three points on the inductance current profile are used, inductance at the aligned position, unaligned position and a point in the middle of the two. In this model, the mutual

inductance of the various phases is neglected since its effect is not sensitive for the controller [3].
The voltage equation for the conducting phase is given by

$$V = Ri + L_L \frac{di}{dt} + \frac{d\lambda}{dt} \qquad (1)$$

Where,
V is the voltage applied across the windings, (V)
R is the phase resistance, (Ω)
L_L is the phase leakage inductance, (H)
$\lambda = L(i,\theta)i$, is flux linkage, (Wb.turns), where, L is the self-inductance of each phase.
The self-inductance of the stator phase A is represented by three terms in Fourier series whose coefficients depend on the current and given as [6,7]:

$$L(i,\theta_e) = L_0(i) + L_1(i)\cos\theta_e + L_2(i)\cos 2\theta_e \qquad (2)$$

Where
$\theta_e = N_r\,\theta_t =$ electrical rotor angle in radians
$N_r =$ number of rotor poles.
θ_r = mechanical rotor angle in radians.
i = phase winding current in Amp..

$$\left.\begin{aligned} L_0(i) &= \frac{1}{2}[\frac{1}{2}(L_a + L_u) + L_m] = \sum_{m=0}^{3} a_{0m} i^m \\ L_1(i) &= \frac{1}{2}(L_a - L_u) = \sum_{m=0}^{3} a_{1m} i^m \\ L_2(i) &= \frac{1}{2}[\frac{1}{2}(L_a + L_u) - L_m] = \sum_{m=0}^{3} a_{2m} i^m \end{aligned}\right\} \qquad (3)$$

where L_a is aligned position inductance, L_m is middle position inductance and L_u is unaligned position inductance. The expressions for other phase inductances are the same as Eq. (2) but shifted by 90˚ (electrical).
Equation (1) can be written as:

$$\left.\begin{aligned} V &= Ri + L_L \frac{di}{dt} + \frac{d(L(i,\theta_e)i)}{dt} \\ V &= Ri + L_L \frac{di}{dt} + L_{eq}(i,\theta_e)\frac{di}{dt} + e(i,\theta_e) \end{aligned}\right\} \qquad (4)$$

Where $L_{eq}(i,\theta_e)$ is the nonlinear equivalent inductance and
$e(i,\theta_e)$ is the speed voltage.
$L_{eq}(i,\theta_e)$ and $e(i,\theta_e)$ can be represented as respectively:

$$L_{eq}(i,\theta_e) = L_0^*(i) + L_1^*(i)\cos\theta_e + L_2^*(i)\cos 2\theta_e \qquad (5)$$

$$e(i,\theta_e) = -N_r\omega_r(L_1(i)\sin\theta_e + 2L_2(i)\sin 2\theta_e)i \qquad (6)$$

Where

$$\omega_r = \frac{d\theta_r}{dt}$$

$$\left.\begin{aligned} L_0^*(i) &= \sum_{m=0}^{3}(m+1)a_{0m} i^m \\ L_1^*(i) &= \sum_{m=0}^{3}(m+1)a_{1m} i^m \\ L_2^*(i) &= \sum_{m=0}^{3}(m+1)a_{2m} i^m \end{aligned}\right\} \qquad (7)$$

The developed torque per phase can be derived from its co-energy and is given as [7]:

$$T_{di} = -N_r i^2 (\frac{1}{2} L_1^{**}(i)\sin\theta_e + L_2^{**}(i)\sin 2\theta_e) \qquad (8)$$

Where

$$\left.\begin{aligned} L_1^{**}(i) &= \sum_{m=0}^{3}\frac{2a_{1m}}{m+2} i^m \\ L_2^{**}(i) &= \sum_{m=0}^{3}\frac{2a_{2m}}{m+2} i^m \end{aligned}\right\} \qquad (9)$$

The mechanical equation of drive system is given by,

$$T_e = \sum_{i=1}^{N} T_{di} = T_{Load} + B\omega_r + J\frac{d\omega_r}{dt} \qquad (10)$$

Where Te is the sum of the torque developed by all phases, N is the number of phases, J and B are the moment of inertia and the viscous friction coefficient, respectively and TLoad is the load torque.

IV . SRM SIMULATION MODEL

A comprehensive simulation has been constructed of a SRM system using the Matlab/Simulink software package as shown in Fig.2-b while Fig.2-a represents the power circuit , it consist of two major blocks, SRM model circuit block and drive circuit block. To show the performance of the proposed model of four phases 8/6 SRM (whose parameters are given in appendix) the model is simulated using Matlab/Simulink package, after determined the inputs (I_{ref}, θ_{off}, Sign), where Iref is the reference current, θ_{off} is the turn-off angle and Sign is the sign of the reference speed where its determine the direction of rotation.
The current dependent inductance polynomial can give as [7]:

$$\left.\begin{aligned} L_0(i) &= (7.38\times10^{-5})i^3 - (1.46\times10^{-3})i^2 + \\ &(5.63\times10^{-3})i + (5.53\times10^{-2}) \\ L_1(i) &= (1.03\times10^{-4})i^3 - (1.92\times10^{-3})i^2 + \\ &(6.53\times10^{-3})i + (5.01\times10^{-2}) \\ L_2(i) &= (3.09\times10^{-5})i^3 - (5.03\times10^{-4})i^2 + \\ &(1.18\times10^{-3})i + (8.43\times10^{-3}) \end{aligned}\right\} \qquad (11)$$

The simulation model of SRM Model block is shown in Fig. 3. The implemented simulink model of phase A is constructed using Eq. (4) as shown in Fig. 4. The simulink model of phases B, C and D is similar to the simulink model of phase A. It contains three other block, they are speed voltage block (“e” block), L_{eq} block and torque block.

The implemented simulink of speed voltage “e” block is obtained from Eq. (6) as shown in Fig. 5, the simulink model used to obtain “L_{eq}” block using Eq. (5) is shown in Fig. 6. Where L and L* blocks are used to obtain inductance polynomial using Eqs. 7 - 11. The torque computed for each phase by Eq. (8) is simulated as shown in Fig. 7. The simulink model of the drive circuit is shown in Fig.8. This figure consists of four major blocks, Matlab Function, Relay Block, modulo block and SWITCH block. Relay blocks for four phases are similar. These blocks are achieved with current switching closed loop chopping control of the converter. In chopping current controller, the current error is computed from which the switching is generated depending on its relationship to the chopping current breadth. The reference current I_{ref} will be compared to the motor phase current I. The model in Fig. 2 is simulated using Matlab/Simulink software package for testing, After assigning sign value (negative or positive) dependent on the direction of rotation (forward or reverse), the value of I_{ref} is changed from 1 to 10 and the θ_{off} is changed from 45deg to 52.5deg . Figure 9 shows the reference current–speed characteristics for different value of turn-off angles. This test on SRM model limited the appropriate values of turn-off angles that are from 45.5 deg. to 49 deg. (in commutation circuit) these values are used in the control circuit.

V. PID BASED CONTROLLER FOR SRM

A typical SRM drive system consists of the machine, a drive circuit and associated control system [8]. A complete PID type speed control based SRM drive is shown in Fig. 10. A simulation model has been constructed of the PID controller for SRM drive circuit using the Matlab/Simulink software package as shown in Fig. 11. It consists of two major controller blocks, speed-I_{ref} controller and speed-θoff controller.

(a) Speed-I_{ref} Controller Block

The reference speed N_{ref} compared with the rotor speed N is the speed error. The speed error signal is processed through PID speed controller to yield the reference current I_{ref}. The reference current I_{ref} is compared with the motor currents and the errors are used to determine the switching of the phase and main switches of any converter by current chopping controller. Figure 12 shows the construction of this block.

(b) Speed-θ_{off} Controller Block

The simulink model of speed-θ_{off} PID controller block using the Matlab/Simulink software is shown in Fig. 13, where this block is used to control the turn-off angle. The appropriate values of the parameters K_p, K_i and K_d of the speed-I_{ref} and speed-θ_{off} PID controllers may be chosen by trial and error method. The parameters K_p, K_i and K_d are shown in the appendix. Effect of each of controllers K_p, K_d and K_i on a closed loop system are summarized in Table (1) shown below.

VI. SIMULATION RESULTS OF 8/6 SRM WITH PID CONTROLLER

In this section, the simulation results are presented to verify the feasibility of the proposed overall model (including switched reluctance motor model, drive Circuit and Speed PID controller), the simulink model shown in Fig. (10), can operate at forward rotation and reverse rotation depending on the sequence of voltage pulses applied to each phase.

(a) Forward Rotation

The reference speed (N_{ref}) is chosen positive value (example N_{ref}=1500 r.p.m.) at forward rotation, therefore the sign input to the drive circuit become positive, this determines the exciting sequence of the voltage/current pulses that will be A-B-C-D , with 15˚mechanical shifting angle. The stator phase voltage and current for phase (A) are shown in Figs. 14 and 15. Figures 16 and 17 show the mechanical rotor position and mechanical rotor speed for forward rotation, under no-load conditions. Figure 18 shows the rotor speed in which at t=3.5 seconds a 3 Nm load torque step change is applied. Fig. 19 shows the response of rotor speed when reference speed change from 1500 r.p.m. to 750 r.p.m. at t=3.5 seconds.

(b) Reverse Rotation

In reverse rotation the reference speed (N_{ref}) is chosen negative value (example N_{ref}=-1500), therefore the sign input to drive circuit become negative, then the sequence of voltage and current pulses will be A-D-C-B. Figs 20 and 21 show the mechanical rotor position and mechanical rotor speed for reverse rotation, under no- load conditions. Fig 22 shows the rotor speed at reverse rotation in which at t=3.5 seconds a -3 Nm load torque step change is applied. Fig. 23 shows the mechanical rotor speed at reverse rotation in which at t=3.5 sec. reference speed change from -1500 r.p.m. to -750 r.p.m. Figs 24 shows mechanical rotor position at forward direction and Fig. 25 show the mechanical rotor speed in which the direction of rotation is changed from forward rotation to reverse rotation (N_{ref} change from 1500 r.p.m. to -1500 r.p.m.).

A simulation test is carried out to observe the response of the drive under load torque disturbance. The load torque is changed from no-load to 3 Nrn. The torque profile at no-load and at 3Nm load are shown in Fig. (26) and Fig. (27) respectively.

VII. CONCLUSIONS

In this paper a simulink model of PID based speed controller for switched reluctance motor has been implemented and tested using Matlab/simulink software package. The proposed simulink model of the four phase 8/6 switched reluctance motor has been used. The results show the promising performance of the proposed control model and prove the ability to change and reverse the speed.

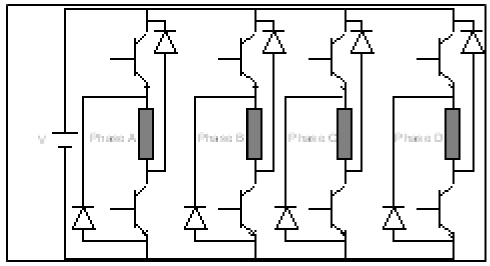
VIII. APPENDIX

The parameters of SRM are listed below.

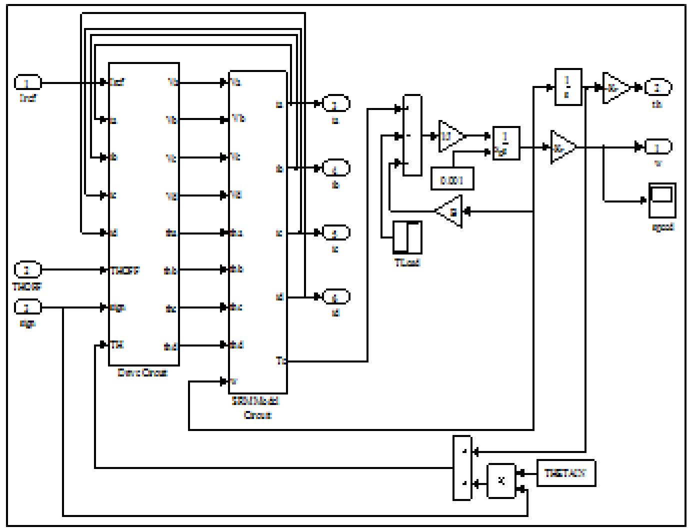
Number of stator poles (Ns) =8,

Number of rotor poles (Nr) =6,
Number of phases (P) =4,
Reference speed (N_{ref}) =±1500 r.p.m.,
DC link voltage (V_{dc})=300 V,
Stator winding resistance (R) =0.96Ω,
Leakage inductance (L_L) =1mH,
Mechanical parameters are B=0.007Kg.m^2/s/rad and J=0.02Kg.m/rad.
The PID controller parameters are listed below.

a. Speed-Iref Controller (K_p=0.012, K_i=0.01, K_d=1).
b. Speed-THOFF Controller (K_p=0.042, K_i=0.1, K_d=4).



(a)



(b)

Fig.2 (a) Schematic diagram of the power circuit and (b) The implemented simulink model of 4 phases 8/6 SRM drive

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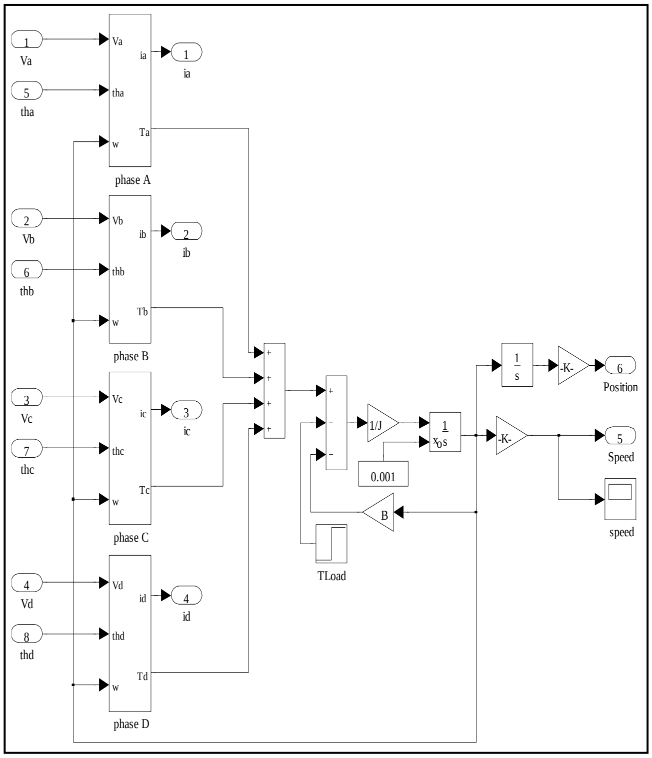


Fig.3 Simulink model of SRM model

Table (1) Effect of (K_p, K_d and K_i) on a closed loop system.

	Rise Time	***Overshoot***	***Settling Time***	***S-S Error***
K_p	Decrease	Increase	Small Change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Small Change	Decrease	Decrease	Small Change

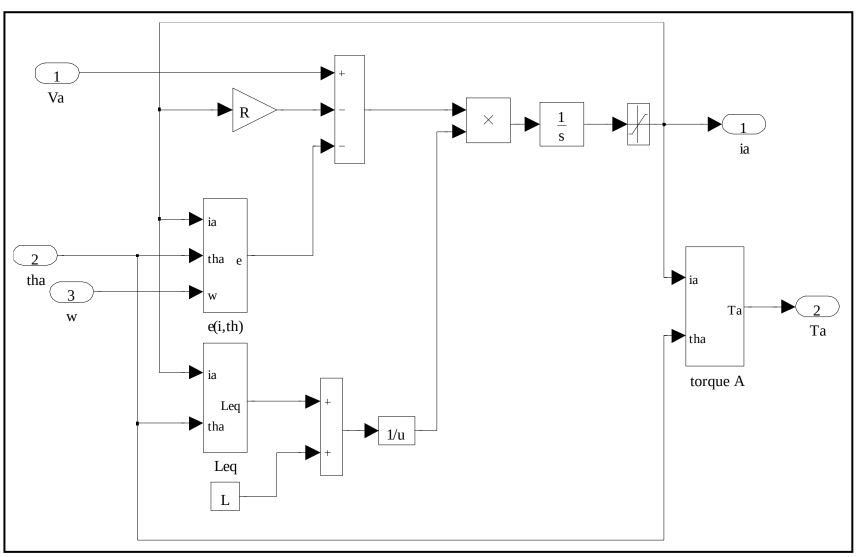


Fig.4 Simulink model of phase A

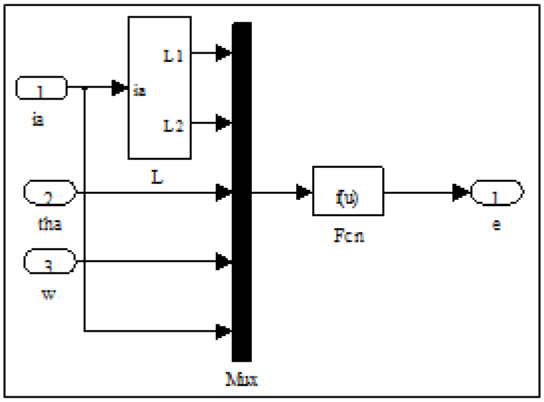


Fig.5 Simulink model of “e” block.

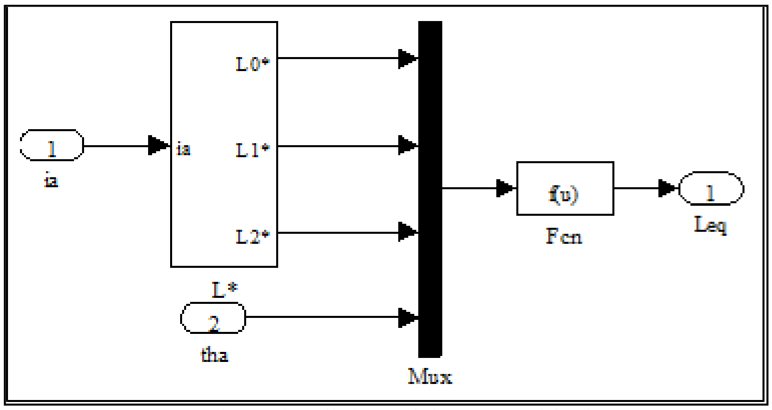


Fig.6 Simulink model of “Leq”block

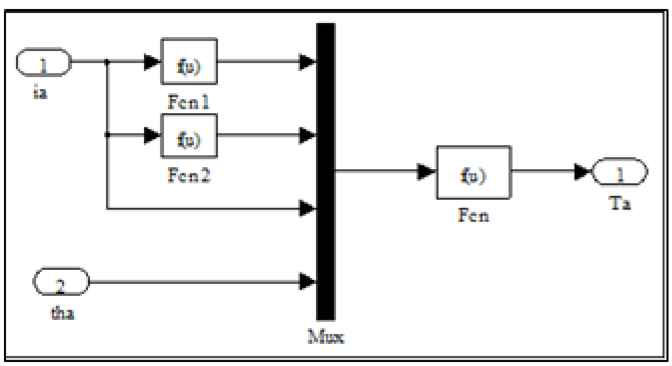


Fig.7 Simulink model of Torque block

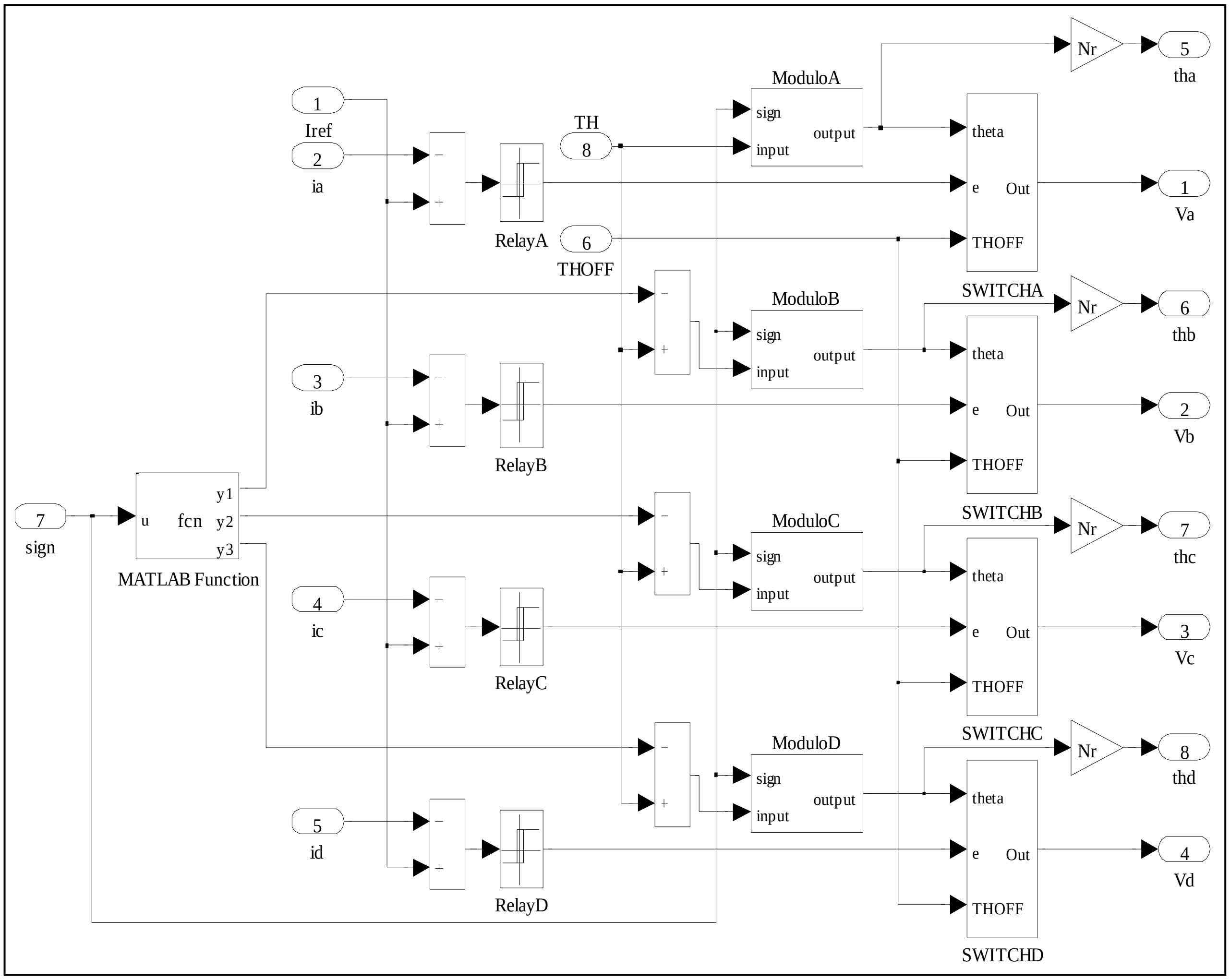


Fig.8 Simulink model of 4 phases 8/6 SRM drive Circuit.

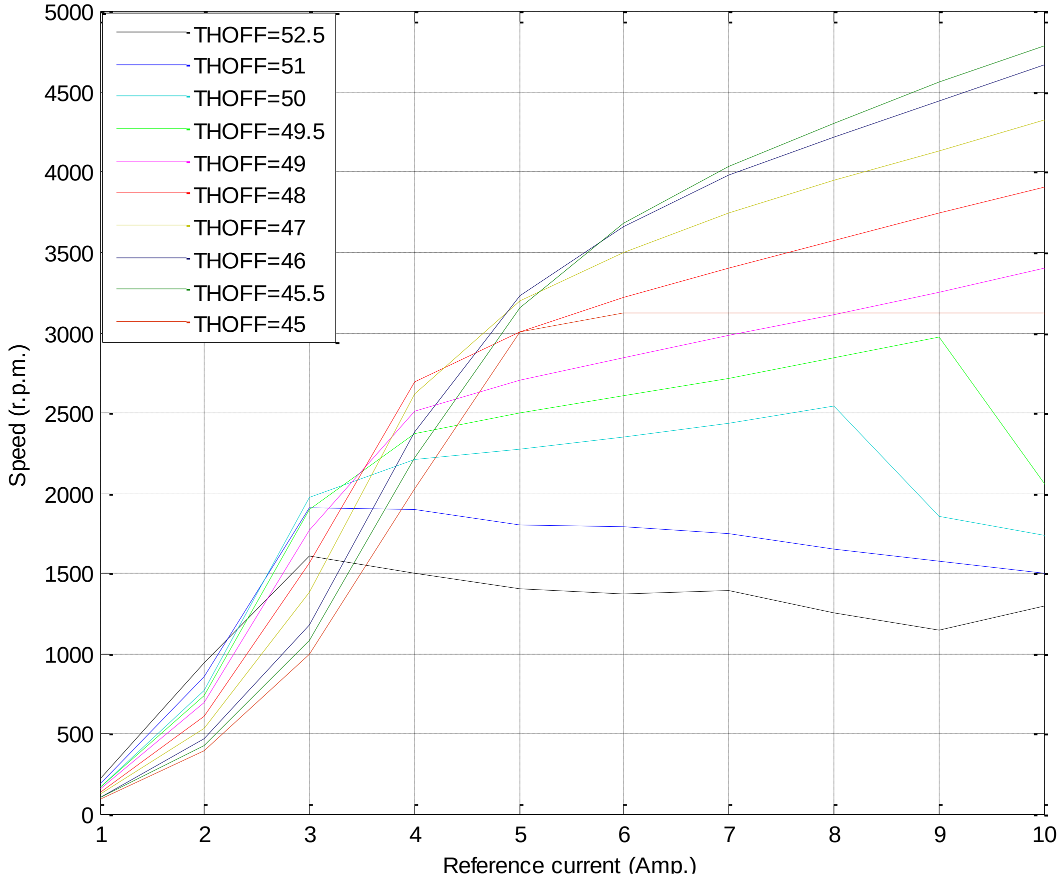


Fig.9 Reference Current–Speed characteristics

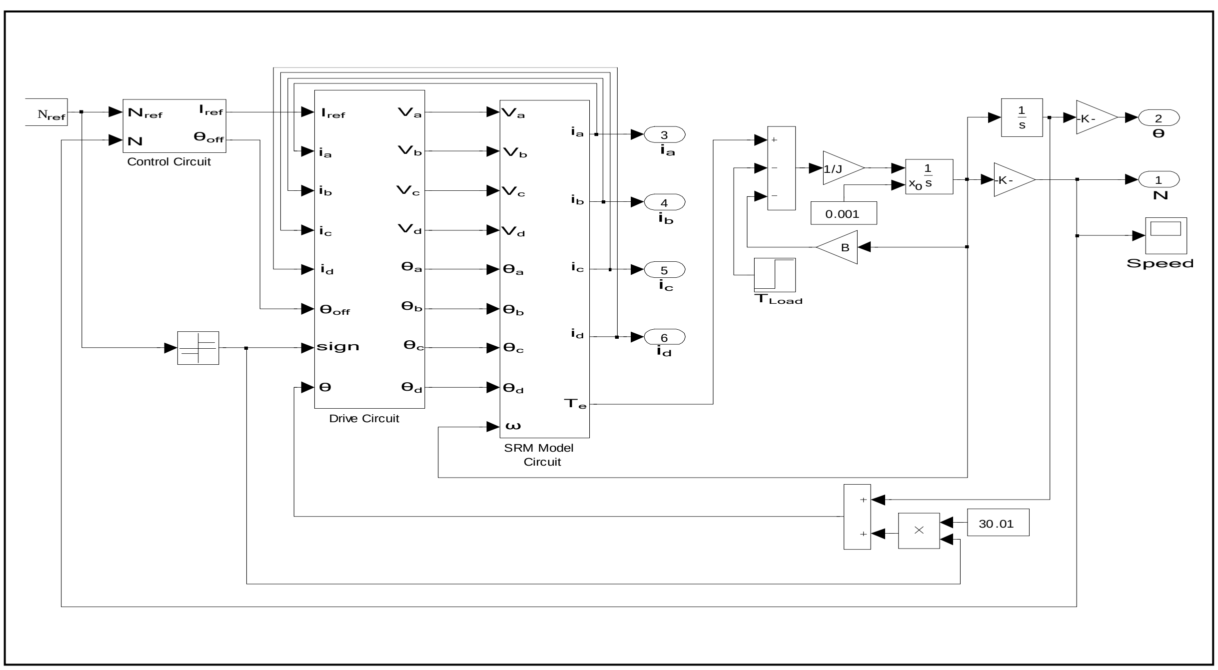


Fig.10 Simulink model of 8/6 SRM with PID controller

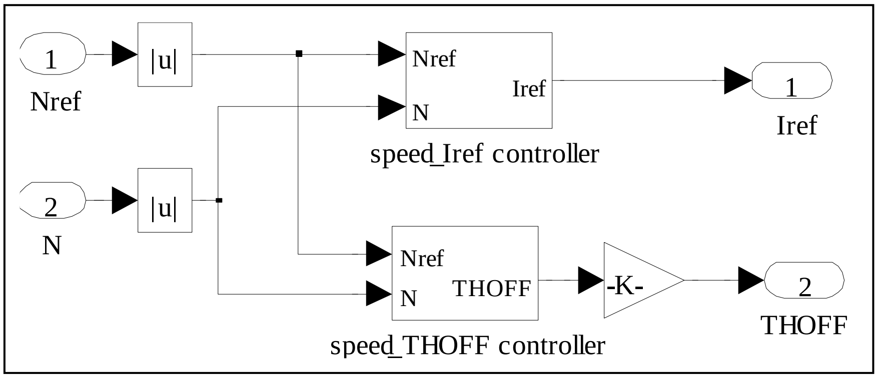


Fig.11 Simulink model of PID controller for SRM.

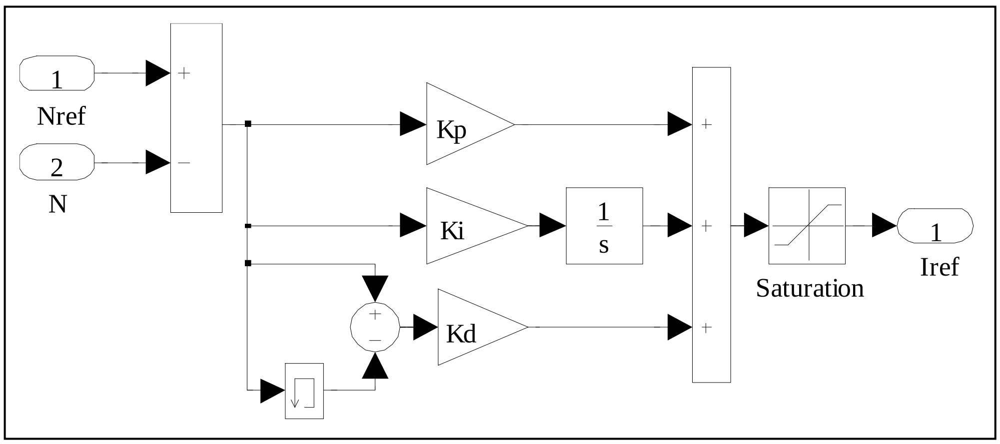


Fig.12 Simulink model of speed-Iref controller block

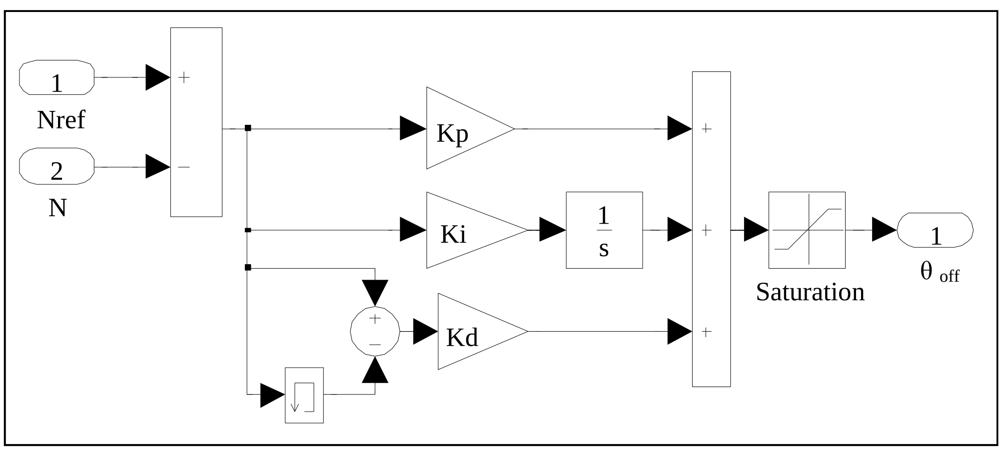
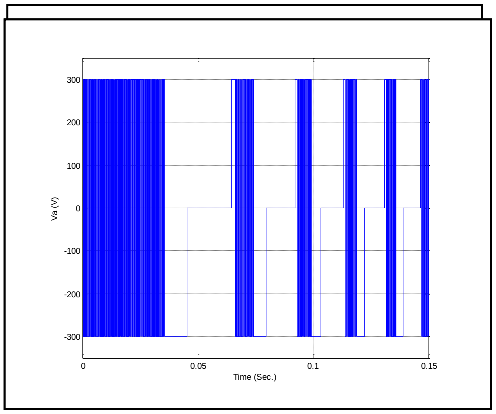
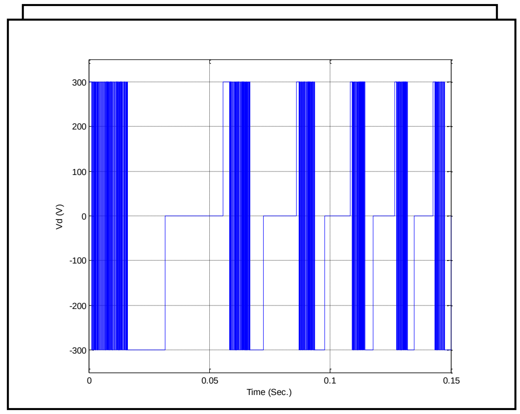


Fig.13 Simulink model of speed-θoff controller block.

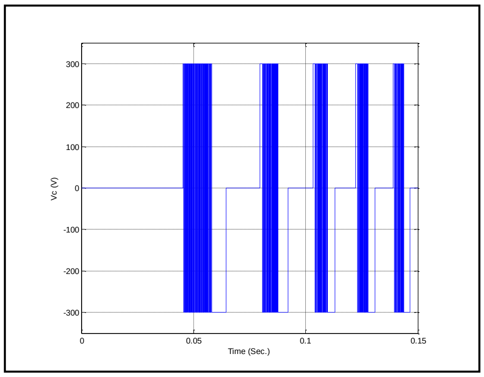
Fig.14 Motor phase voltages at forward rotation



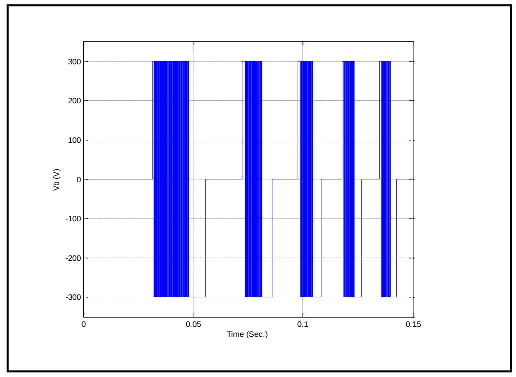
(a) Phase A



(b) Phase C



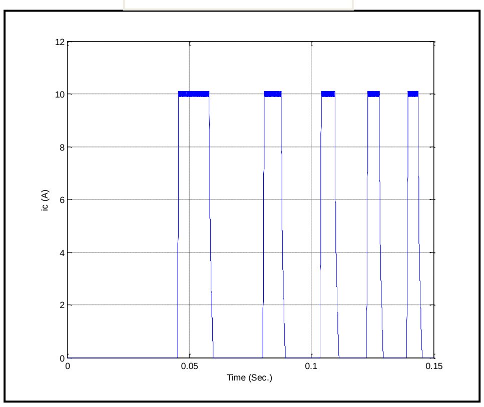
(c) Phase C

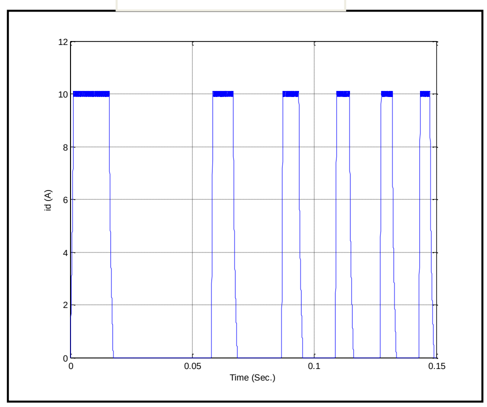


(d) Phase D

(a) Phase A

(b)Phase B





(c) Phase C

(d) Phase D

Fig.15 Motor phase current at forward rotation

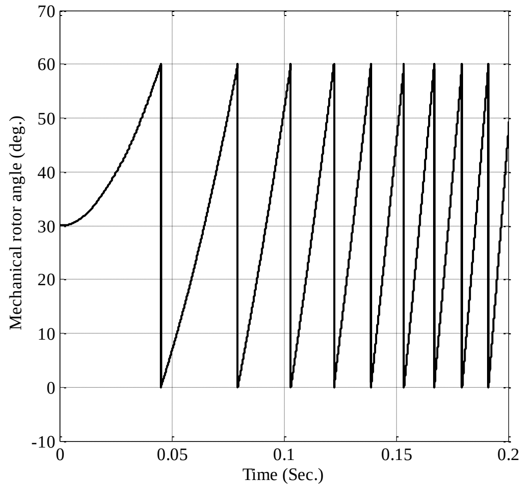


Fig.16 Mechanical rotor position at forward rotation

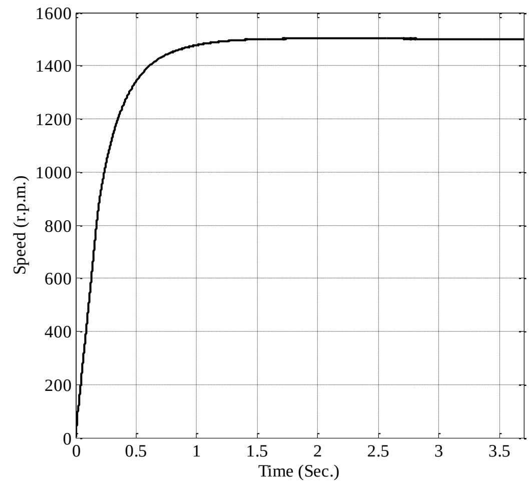


Fig.17 Mechanical rotor speed at forward rotation

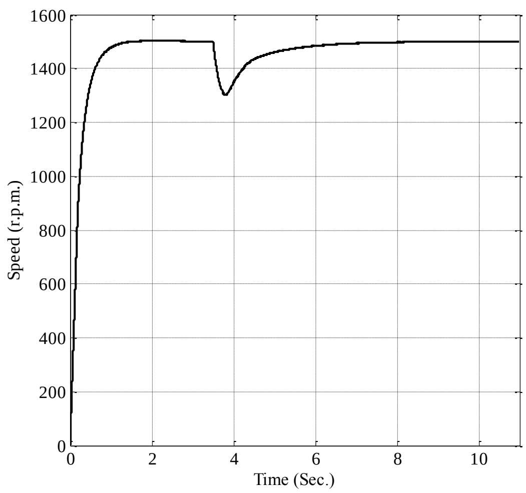


Fig.18 Rotor speed with load torque step change

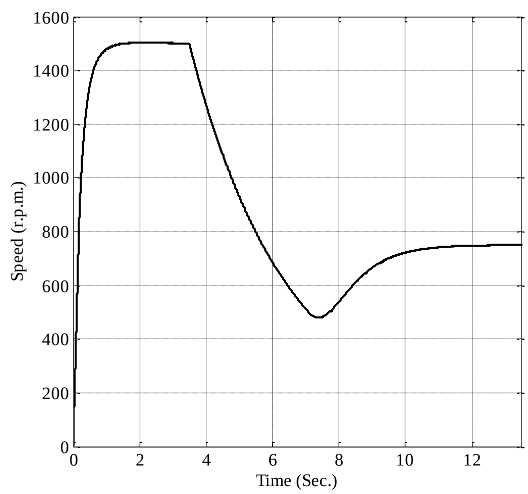


Fig.19 Rotor speed with reference speed step change

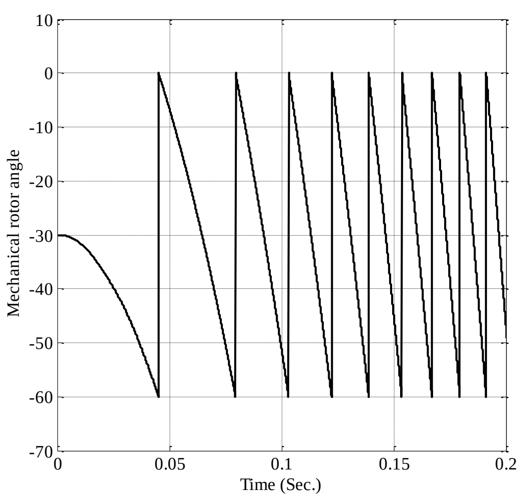


Fig.20 Mechanical rotor position at reverse rotation

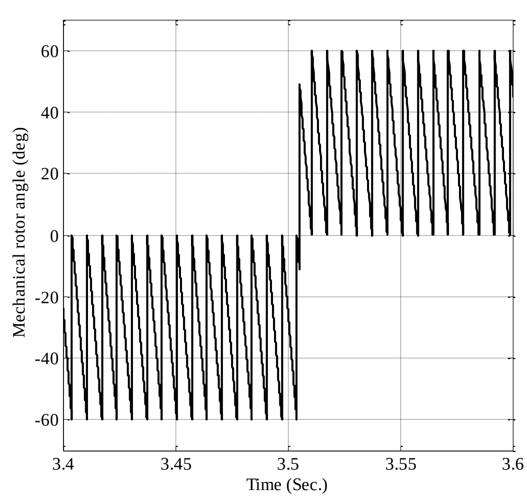


Fig.21 Mechanical rotor position at direction change.

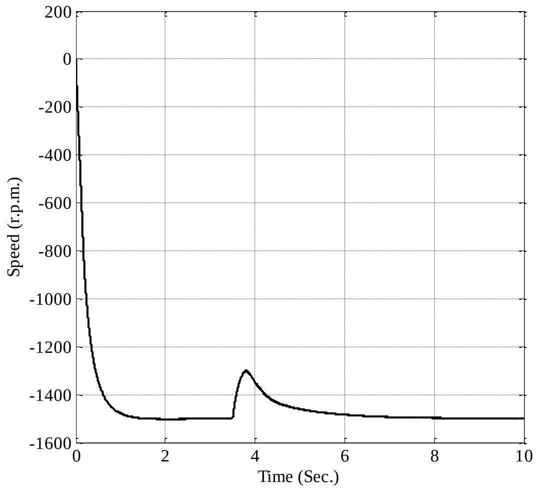


Fig. 22 Rotor speed with load torque step change

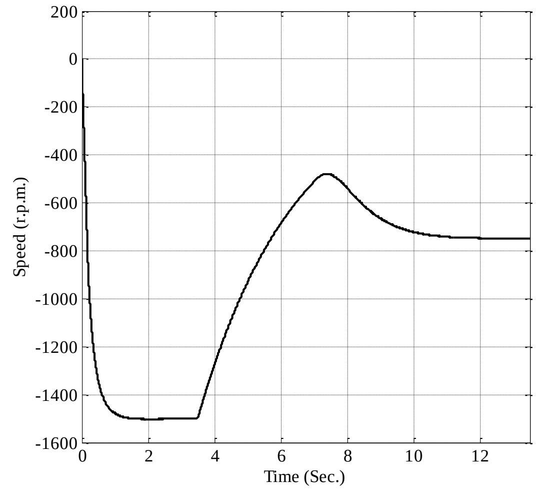


Fig.23 Rotor speed with reference speed is changed

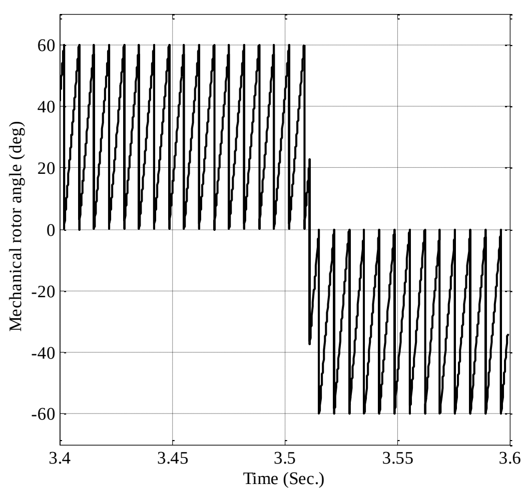


Fig.24 Mechanical rotor position at forward direction

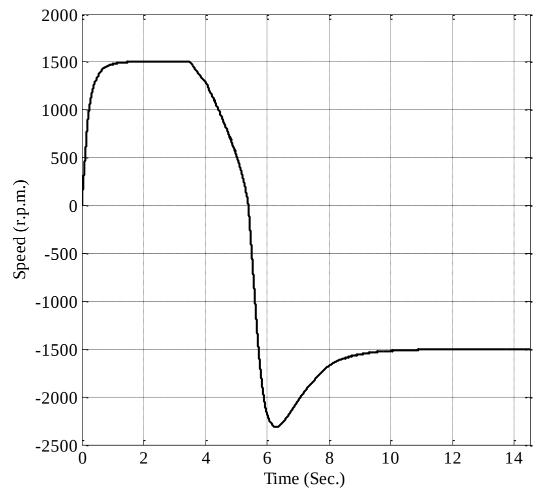


Fig. 25 Mechanical rotor speed when direction is changed

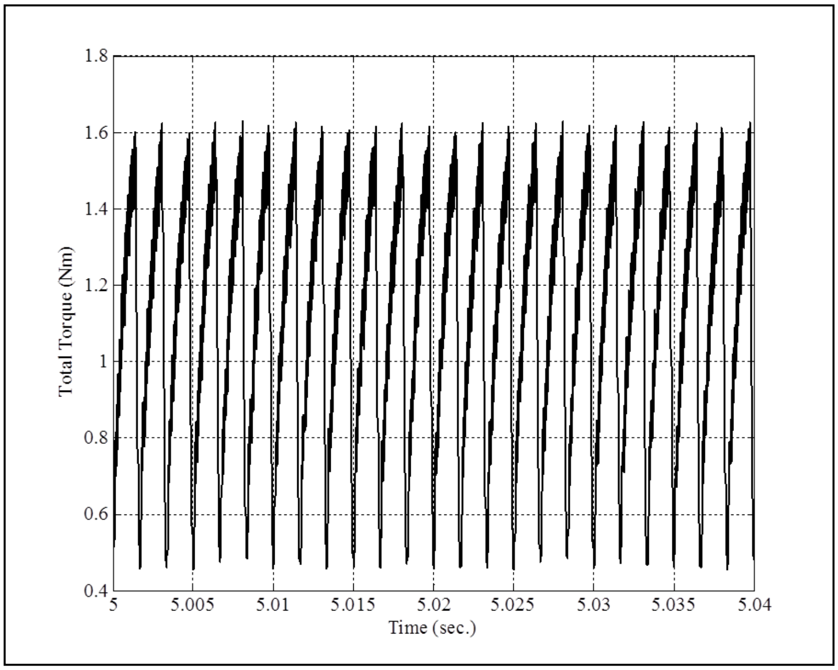


Fig. 26 Steady-state torque profile at no-load condition.

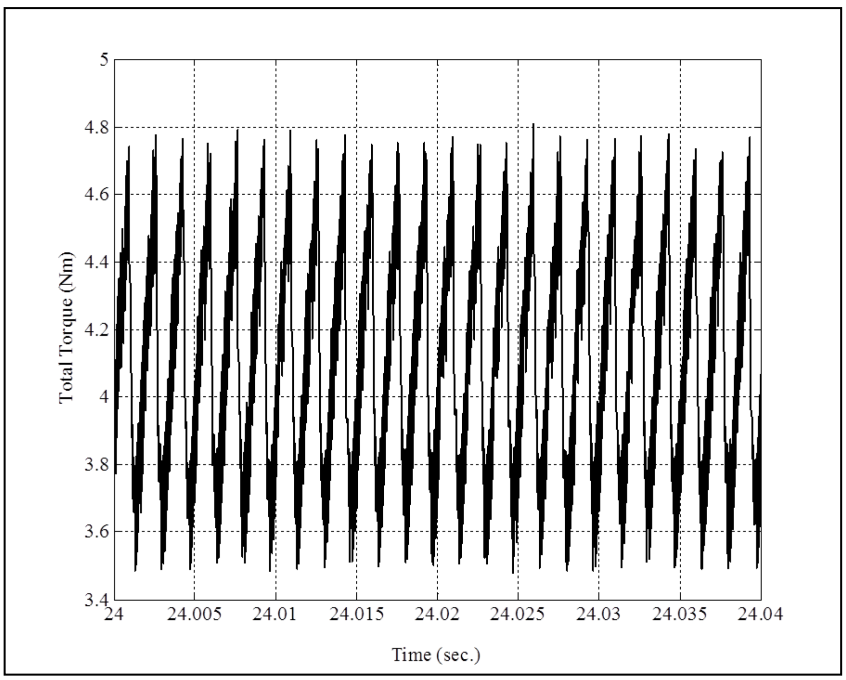


Fig. 27 Steady-state developed torque with 3N.m load torque step change