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# Modeling and Simulation of Chopper Controlled Slip Ring Induction Motor

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**Abstract—***Dynamic model of the induction motor can be used as a teaching tool in electric machines and power electronics courses in academic as well as research institutions. Dynamic simulation helps in the pre-testing of drive systems. Pre-testing is conducted by researchers in academia as well as by engineers in industry. Electric machine simulation technique began more than 80 years ago at M.I.T. Since then it continues to advance with technology. Dynamic model takes into account the instantaneous effects of varying voltages or currents, stator frequency and torque disturbance. The dynamic modelling of chopper controlled slip ring induction motor drive is performed. The non-linear differential equations describing the system in arbitrary reference frame and synchronous reference frame are solved by using simulation software package. The torque-speed responses of the drive are simulated with arbitrary and synchronous reference frames for different load torques and duty cycles. Also, the waveforms showing the conversion from three phase to two phase reference frame are shown. The speed and torque responses obtained for different duty cycles and load torques with different reference frames gives satisfactory results.*

## 1. INTRODUCTION

AC motors are the most widely used electric motors in industry. They run at essentially constant speed from no load to full load i.e. they are used in constant speed application. The speed is frequency dependent and as such these motors are not easily adapted to speed control. The AC motors exhibits a number of advantages: they are lightweight, ruggedness, and have low maintenance cost as compared with DC motors so are more economical. AC motors require control of voltage, current and frequency for variable speed applications.

Because of ease of control three phase induction motors are mostly applied in adjustable speed drives than three phase synchronous motors. There are two types of induction motors: squirrel cage induction motors and slip ring (wound rotor) induction motors.

Due to the recent advancements in technology, the AC drives are becoming more popular. Drives systems are used in applications such as pumps, fans, textile and paper mills, subway transportation and electric vehicle, home appliances, cement and steel mills, robotics and servos etc.

## 2. ROTOR VOLTAGE CONTROL

This speed control technique is employed only to slip ring induction motors.

### 2.1. Static Rotor-Resistance Control

In a slip ring induction motor, an external three phase balanced variable resistor can be inserted in the rotor circuit as shown in the Fig. 1.

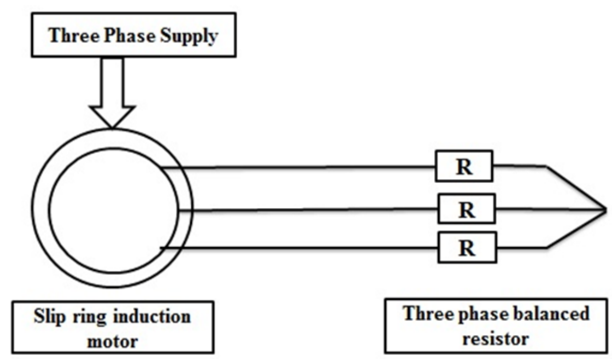


**Fig. 1: Block Diagram of Speed Control by Static Rotor Resistance Method.**

By varying the rotor circuit resistances, the developed torque can be varied. Although this method increases the starting torque and limits the starting current, this is an inefficient method since there would be imbalances in voltages and currents if the resistances in the rotor circuit are not equal and also efficiency is reduced at low speeds.

### 2.2. Chopper controlled method

Because of the losses in the three phase rotor resistor, the external three phase balanced resistor is replaced by a three phase diode rectifier, resistor (R) and Gate Turn off Thyristor

(GTO) or an Insulated Gate Bipolar Transistor (IGBT) which acts as a DC converter switch as shown in Fig. 2.

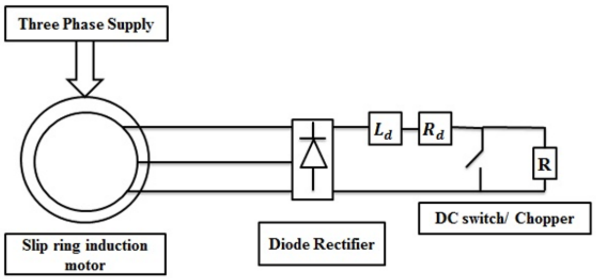


**Fig. 2: Block diagram of Chopper Controlled Method.**

This is an open loop control scheme extensively used in industry because of its simplicity and inexpensiveness. The inductor $L_d$ is used to smoothen the DC current. The IGBT allows the effective rotor circuit resistance to be varied for the speed control of slip ring induction motor. Diode rectifier converts slip-frequency input power to DC at its output terminals.

When the chopper is conducting i.e. during time $T_{on}$ resistance R (external resistance) gets short circuited and effective resistance in the rotor circuit is $R_d$ (smoothing inductor resistance). When chopper is off i.e. during time $T_{off}$ effective resistance in the rotor circuit is $R+R_d$. Hence for total time $T=T_{on}+T_{off}$ the effective value of rotor resistance is

$$R_{eff} = \frac{R_d T_{on} + (R+R_d)T_{off}}{T_{on}+T_{off}} \tag{1}$$

$$R_{eff} = R_d + R\frac{T_{off}}{T} \tag{2}$$

$$R_{eff} = R_d + R(1-d) \tag{3}$$

Where $d = \frac{T_{on}}{T}$ is the duty cycle of the chopper. Thus by varying the on time $T_{on}$, the rotor resistance can be varied.

## 3. DYNAMIC MODELING OF SLIP RING INDUCTION MOTOR

The transient behaviour of high performance and adjustable speed drive is taken into consideration in dynamic model. An AC machine's dynamic performance is complex as there is continuous change of coupling coefficients between the stator and rotor phases with the change of rotor position. Differential equations with time varying mutual inductances are used to describe the machine model but it leads to complexity of the model.

In the 1920s R.H. Park, proposed a new theory of machine analysis to solve the problem of time varying parameters. He replaced the variables (flux linkages, voltages and currents) associated with the stator windings of a machine with fictitious windings variables rotating with the rotor at synchronous speed. Thus with a transformation called the Park's transformation, he showed that all time varying inductances in the voltage equations due to an electric circuit in relative motion and varying magnetic reluctances can be eliminated. Later in 1930s H.C. Stanley proved that time varying inductances due to an electric circuit in relative motion can be eliminated by transforming the rotor variables to fictitious stationary windings variables. G. Kron also proposed a transformation of both rotor and stator variables to a reference frame which moves at synchronous speed that moves with rotating magnetic field. D.S. Brereton further proposed a transformation of stator variables to a reference frame which is rotating that is fixed on the rotor. Later, Krause and Thomas showed that the stator and rotor reference frame can be referred to a common reference frame which may rotate at any speed (arbitrary reference) to eliminate the time varying inductances.

### 3.1. Axes Transformation

The three phase stationary reference frame variables are first transformed to two phase stationary reference frame variables and then after that they are transformed to synchronously rotating reference frame or arbitrary reference frame variables and vice-versa.

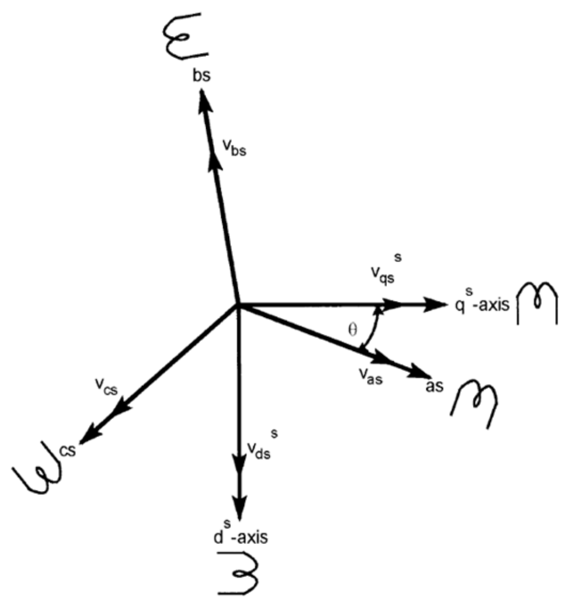


**Fig. 3: Three phase to two phase transformation in stationary reference frame. [6]**

The matrix equation representing the two phase voltages $V_{ds}^s$ and $V_{qs}^s$ in terms of three phase voltages $V_{as}$ , $V_{bs}$ , $V_{cs}$ in stationary reference frame of a three phase induction motor is as follows

$$\begin{bmatrix} V_{qs}^s \\ V_{ds}^s \\ V_{os}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta-120^o) & \cos(\theta+120^o) \\ \sin\theta & \sin(\theta-120^o) & \sin(\theta+120^o) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \quad (4)$$

$V_{os}^s$ is the zero sequence component which may or may not be considered. Here voltage is taken as the variable. For convenience $\theta$ is set to zero so that the $q^s$-axis is aligned with the as-axis. By neglecting the zero sequence component, the transformation relations that convert the voltages on three phase stationary reference frame (as-bs-cs) into two phase stationary reference frame ($d^s$-$q^s$) can be obtained as

$$V_{qs}^s = V_{as} \quad (5)$$

$$V_{ds}^s = -\frac{1}{\sqrt{3}}V_{bs} + \frac{1}{\sqrt{3}}V_{cs} \quad (6)$$

The relations that convert the voltages on stationary reference frame ($d^s$-$q^s$) into synchronously rotating reference frame ($d^e$-$q^e$) are as follows.

$$V_{qs} = V_{qs}^s \cos\theta_e - V_{ds}^s \sin\theta_e \quad (7)$$

$$V_{ds} = V_{qs}^s \sin\theta_e + V_{ds}^s \cos\theta_e \quad (8)$$

Where $\theta_e = w_e t$, $w_e$ is the synchronous speed of the motor in rad/sec. For arbitrary reference frame ($d^c$-$q^c$) replace $\theta_e$ as $\theta_c = w_c t$ and $w_e = w_c$ where $w_c$ is arbitrary speed in rad/sec that is revolving at the same angular speed as that of the sinusoidal variable.

### 3.2. Equations describing the modeling of the proposed motor drive

The stator circuit equations in synchronously rotating reference frame can be written as

$$V_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + w_e\varphi_{ds} \quad (9)$$

$$V_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - w_e\varphi_{qs} \quad (10)$$

Here $\varphi_{ds}$ and $\varphi_{qs}$ are the d-axis and q-axis stator flux linkages, $i_{ds}$ and $i_{qs}$ are the d-axis and q-axis stator currents respectively. Since the rotor moves at speed $w_r$, the d-q axes which is fixed on the rotor move at a speed $w_e$-$w_r$ relative to the synchronously rotating reference frame.

The rotor circuit equations in synchronously rotating reference frame can be written as

$$V_{qr} = R_r i_{qr} + \frac{d\varphi_{qr}}{dt} + (w_e - w_r)\varphi_{dr} \quad (11)$$

$$V_{dr} = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} - (w_e - w_r)\varphi_{qr} \quad (12)$$

$\varphi_{dr}$ and $\varphi_{qr}$ are the d-axis and q-axis rotor flux linkages, $i_{dr}$ and $i_{qr}$ are the d-axis and q-axis rotor currents respectively.

The flux linkage expressions in terms of currents are as follows

$$\varphi_{qs} = L_s i_{qs} + L_m i_{qr} \quad (13)$$

$$\varphi_{ds} = L_s i_{ds} + L_m i_{dr} \quad (14)$$

$$\varphi_{qr} = L_r i_{qr} + L_m i_{qs} \quad (15)$$

$$\varphi_{dr} = L_r i_{dr} + L_m i_{ds} \quad (16)$$

$$\varphi_{qm} = L_m (i_{qs} + i_{qr}) \quad (17)$$

$$\varphi_{dm} = L_m (i_{ds} + i_{dr}) \quad (18)$$

$L_s$ and $L_r$ are the stator and rotor self-inductance respectively. $L_m$ is the magnetizing inductance. $R_s$ and $R_r$ are the stator and rotor resistance respectively. By combining the above equations from (9) to (18) the electrical transient model in matrix form in terms of voltages and currents in synchronously rotating reference frame of an induction motor can be written as

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + sL_s & w_e L_s & sL_m & w_e L_m \\ -w_e L_s & R_s + sL_s & -w_e L_m & sL_m \\ sL_m & (w_e - w_r)L_m & R_r + sL_r & (w_e - w_r)L_r \\ -(w_e - w_r)L_m & sL_m & -(w_e - w_r)L_r & R_r + sL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (19)$$

Here, s is the Laplace operator. Similarly, the electrical transient model in matrix form in terms of voltages and currents in arbitrary reference frame can be written as

$$\begin{bmatrix} V_{qs}^c \\ V_{ds}^c \\ V_{qr}^c \\ V_{dr}^c \end{bmatrix} = \begin{bmatrix} R_s + sL_s & w_c L_s & sL_m & w_c L_m \\ -w_c L_s & R_s + sL_s & -w_c L_m & sL_m \\ sL_m & (w_c - w_r)L_m & R_r + sL_r & (w_c - w_r)L_r \\ -(w_c - w_r)L_m & sL_m & -(w_c - w_r)L_r & R_r + sL_r \end{bmatrix} \begin{bmatrix} i_{qs}^c \\ i_{ds}^c \\ i_{qr}^c \\ i_{dr}^c \end{bmatrix} \quad (20)$$

The chopper control scheme for speed control of slip ring induction motor is shown in Fig. 2. The voltage equation for the chopper circuit by neglecting stator and rotor leakage inductance is expressed as

$$v_{dc} = sL_d i_{dc} + R_d i_{dc} + R(1-d)i_{dc} \quad (21)$$

$V_{dc}$ is the output mean voltage of the diode rectifier and $i_{dc}$ is the instantaneous current through the DC link. As the diode rectifier voltage is converted to synchronously rotating reference frame, the instantaneous value of q-axis coincides with the maximum value of rotor phase voltage [3]. Thus the rotor d-axis and q-axis voltage for the chopper controlled slip ring induction motor becomes

$$V_{dr} = 0 \quad (22)$$

$$V_{qr} = V_m \quad (23)$$

$V_m$ is the peak phase voltage. The output voltage of the rotor rectifier becomes by using equation (23)

$$v_{dc} = \frac{3\sqrt{3}}{\pi} V_m = \frac{3\sqrt{3}}{\pi} V_{qr} \quad (24)$$

For balance condition, by neglecting the losses in the rectifier circuit, the instantaneous power on the AC side becomes equal to power on the DC side of the rectifier.

$$\frac{3}{2} V_{qr} i_{qr} = -v_{dc} i_{dc} \quad (25)$$

Combining equations (24) and (25)

$$i_{dc} = -0.906 i_{qr} \quad (26)$$

Here $i_{qr}$ is the q-axis rotor current fed to the diode rectifier. The negative sign implies the input power to the rotor. Substituting equations (26) and (24) in (21)

$$V_{qr} = -0.55 i_{qr} [R_d + R(1-d)] - 0.55 s L_d i_{qr} \quad (27)$$

Now substituting equations (22) and (27) in (19) and rearranging them for the chopper controlled slip ring induction motor that is required for computer simulation, the modified electrical transient model in matrix form in terms of voltages and currents in synchronously rotating reference frame can be written as

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + sL_s & w_e L_s & sL_m & w_e L_m \\ -w_e L_s & R_s + sL_s & -w_e L_m & sL_m \\ sL_m & (w_e - w_r) L_m & R_{tr} + sL_{tr} & (w_e - w_r) L_r \\ -(w_e - w_r) L_m & sL_m & -(w_e - w_r) L_r & R_r + sL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (28)$$

Similarly in arbitrary reference frame by substituting equations (22) and (27) in (20)

$$\begin{bmatrix} V_{qs}^c \\ V_{ds}^c \\ V_{qr}^c \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + sL_s & w_c L_s & sL_m & w_c L_m \\ -w_c L_s & R_s + sL_s & -w_c L_m & sL_m \\ sL_m & (w_c - w_r) L_m & R_{tr} + sL_{tr} & (w_c - w_r) L_r \\ -(w_c - w_r) L_m & sL_m & -(w_c - w_r) L_r & R_r + sL_r \end{bmatrix} \begin{bmatrix} i_{qs}^c \\ i_{ds}^c \\ i_{qr}^c \\ i_{dr}^c \end{bmatrix} \quad (29)$$

$$R_{tr} = R_r + 0.55[R_d + R(1-d)]$$

$$L_{tr} = L_r + 0.55 L_d$$

Also the q-axis rotor flux linkage becomes

$$\varphi_{qr} = L_{tr} i_{qr} + L_m i_{qs} \quad (30)$$

The developed electromagnetic torque for a (P) pole, three phase induction motor is expressed as

$$T_e = \frac{3}{2} L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (31)$$

The motor speed (rad/sec) is obtained from

$$T_e = T_l + J \frac{2}{P} \frac{dw_r}{dt} \quad (32)$$

$$w_r = \int \frac{P}{2} \frac{1}{J} (T_e - T_l) \quad (33)$$

Where J is the moment of inertia $(Kgm^2)$ and $T_l$ is the mechanical load torque in Nm.

## 4. SIMULATION RESULTS AND DISCUSSION

The simulation is conducted by using Matlab simulation software package having the drive parameters [3]

380V, 3.5A, 50Hz, 1440 rpm, $R_s = R_r = 2.4\Omega$, $P = 4$, $L_s = L_r = 0.332\text{H}$, $J = 0.06 kgm^2/\text{sec}$.

The parameters can be found by standard test methods. The results obtained thus are described for both arbitrary and synchronously rotating reference frame. Here, the arbitrary reference frame speed is 314rps and 157rps for synchronously rotating reference frame.

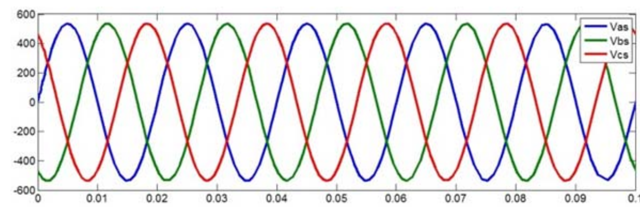


**Fig. 4: Waveform showing three phase voltages.**

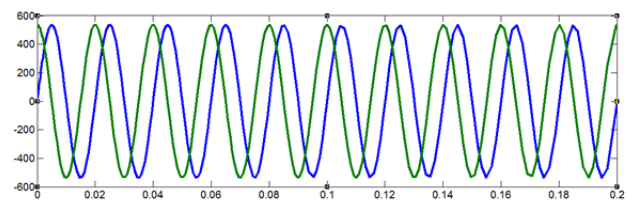

**Fig. 5: Waveform showing two phase voltages.**

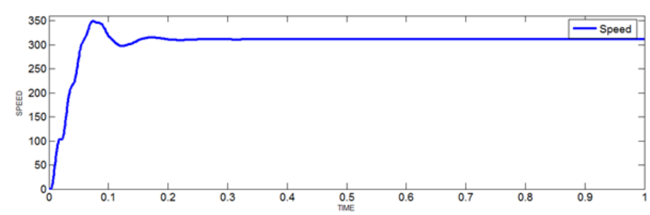


**Fig. 6: Speed vs time plot for 0.85 duty cycle and 10Nm load torque in arbitrary reference frame.**

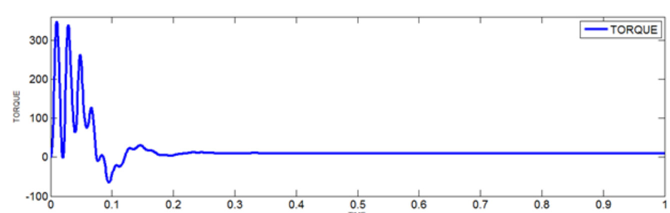


**Fig. 7: Torque vs time plot for 0.85 duty cycle and 10Nm load torque in arbitrary reference frame.**

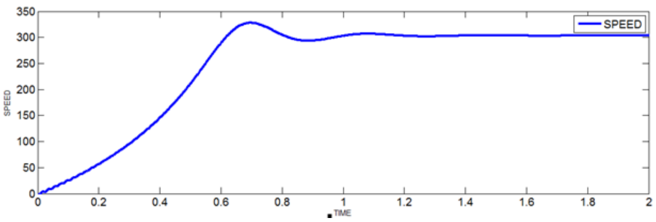


**Fig. 8: Speed vs time plot for 0.50 duty cycle and 5Nm load torque in arbitrary reference frame.**

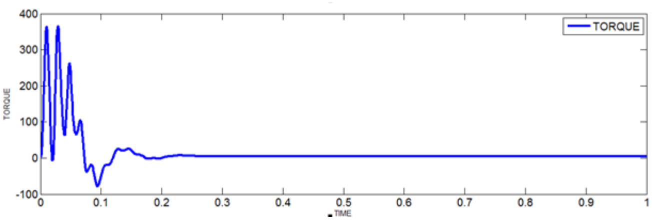


**Fig. 9: Torque vs time plot for 0.50 duty cycle and 5Nm load torque in arbitrary reference frame.**

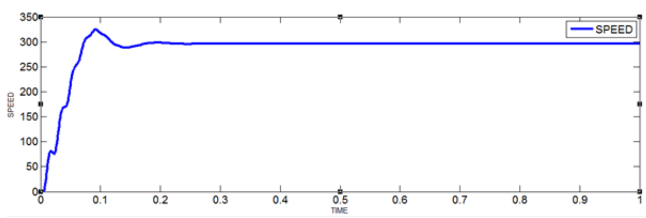


**Fig. 10: Speed vs time plot for 0.85 duty cycle and 50Nm load torque in arbitrary reference frame.**

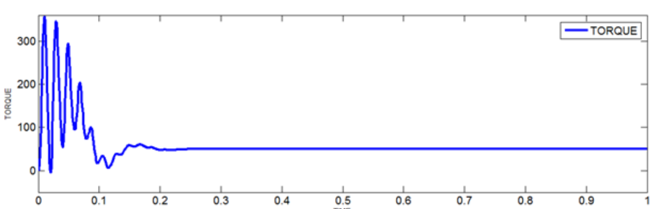


**Fig. 11: Torque vs time plot for 0.85 duty cycle and 50Nm load torque in arbitrary reference frame.**

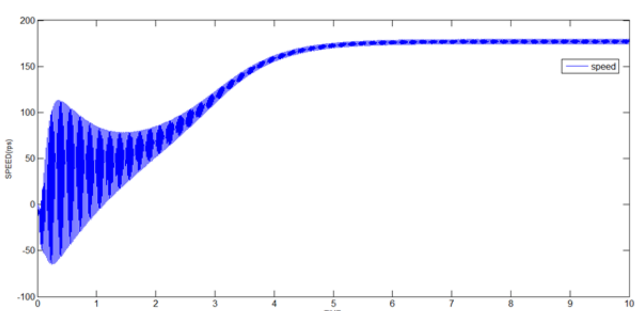


**Fig. 12: Speed vs time plot for 0.85 duty cycle and 10Nm load torque in synchronous reference frame.**

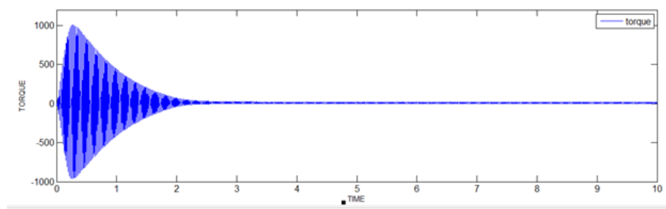


**Fig. 13: Torque vs time plot for 0.85 duty cycle and 10Nm load torque in synchronous reference frame.**

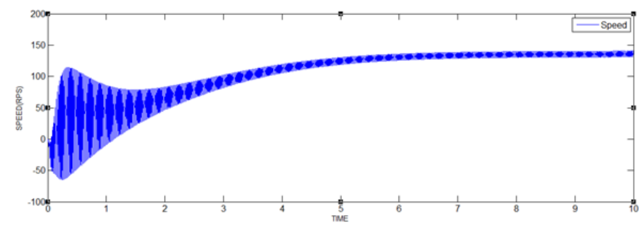


**Fig. 14: Speed vs time plot for 0.50 duty cycle and 5Nm load torque in synchronous reference frame.**

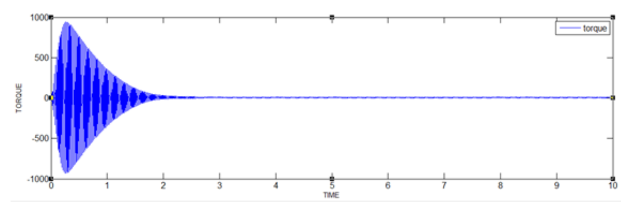


**Fig. 15: Torque vs time plot for 0.50 duty cycle and 5Nm load torque in synchronous reference frame.**

## 5. CONCLUSION

Chopper controlled slip ring induction motor offers many advantages such as fast response and smooth control, less maintenance and compact size of the system. Here an open loop chopper controlled slip ring induction motor is successfully simulated both in the arbitrary and the synchronous reference frame to predict the performance of the drive system both in steady state and dynamic state. Both synchronous and arbitrary reference frame model gives satisfactory results in terms of change in speed with different duty cycles and load torques.

## 6. ACKNOWLEDGEMENTS

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## REFERENCES


[1] Anand Bellure, Dr. M.S Aspalli, “Dynamic d-q Model of Induction Motor Using Simulink”, International Journal of Engineering Trends and Technology (IJETT), Volume 24, Number 5, June 2015

[2] P N H Phanindra Kumar, D M Deshpande, Manisha Dubey, “Modeling of Vector Controlled Induction Motor in Different Reference Frames”, International Journal of Innovative Research in Science, Engineering and Technology, Volume 3, Special Issue 3, March 2014

[3] Hilmi F. Ameen, “Computer Simulation and Mathematical Modelling of Static Rotor Resistance Chopper Control of WRIM by Reference Frame Theory”, Procedia Computer Science 3 (2011) 1009–1017

[4] N. S. Wani and M. Ramamoorty, “Chopper Controlled Slip Ring Induction Motor”, IEEE Transactions on Industrial Electronics and Control Instrumentation, Vol. IECT- 24, No. 2, May 1977

[5] Aleck W. Leedy, “Simulink / MATLAB Dynamic Induction Motor Model for Use as a Teaching and Research Tool”, International Journal of Soft Computing and Engineering (IJSCE) ISSN: 2231-2307, Volume-3, Issue-4, September, 2013

[6] Bimal K. Bose, “Modern Power Electronics And AC Drives”, Prentice Hall PTR, 2002

[7] R. Krishnan, “Electric Motor Drives-Modeling, Analysis, and Control”, Prentice Hall, 2001

[8] Paul C. Krause, Oleg Wasynczuk, Scott D. Sudhoff, “Analysis of Electric Machinery and Drive Systems”, Second Edition

[9] S.K Pillai, “A first course on Electrical Drives”, Second Edition, Wiley Eastern Limited, 1989

[10] Dr. P.S. Bimbhra, “Power Electronics”, Fourth Edition, Khanna Publisher’s, 2011