Modeling of Hysteresis Motor

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Abstract:- Hysteresis motor is similar to permanent magnet synchronous motor. Magnetic property of rotor material plays very much important role on performance of motor. This motor posses smooth vibration free operation, lower noise, constant torque etc and having wider applications in sound producing, sound recording instrument, teleprinter, hairdryer, gyroscope etc. Hysteresis motor particularly used in application have smooth starting torque. Hysteresis motors are limited to small size by the difficulty of controlling rotor losses caused by imperfections in the stator mmf wave. This paper presents principle, mathematical analysis and MATLAB/simulink implementation of 3-phase Hysteresis motor in arbitrary reference frame. The reference frame theory has been used to derive mathematical modeling of hysteresis motor and dynamic model gives steady state and transient state behaviour of Hysteresis motor.

Keywords:- Hysteresis motor, Gyroscope, MATLAB/Simulink etc.

Nomenclature-

T_s = Starting torque (N-m)
φ_s = stator flux (Wb)
φ_r = rotor flux (Wb)
α = Angle between stator flux and rotor flux (degree)
P_e = Eddy current loss (W)
P_h = Hysteresis loss (W)
B = Remanence (Tesla)
H_C = Co-ercivity (KA/m)
V_{qs} = Voltage of q -axis winding (V)
V_{ds} = Voltage of d-axis winding (V)
i_{qs} = q axis stator currents (A)
i_{ds} = d axis stator currents (A)
R_q = stator q axis resistance (Ω)
R_d = stator d axis resistance (Ω)
λ_{qs} = stator q axis flux linkage (Wb-t)
λ_{ds} = stator d axis flux linkage (Wb-t)

I.   INTRODUCTION

Hysteresis motor is a special type of synchronous motor with uniform air gap and there is no D.C. excitation in the rotor. The mechanical torque of this motor is produced by the virtue of hysteresis and eddy currents. This torque induced in the hardened steel rotor by the action of rotating m.m.f of the stator winding. Hysteresis motor operates at synchronous speed. The rotor of hysteresis motor has no winding, no teeth rather than ferromagnetic material is used. The rotor is placed within a slotted stator carrying distributed windings. It is designed in a manner to produce a sinusoidal space distribution of flux. When the stator is energized from a three-phase supply, synchronously revolving field is produced. The revolving stator flux magnetizes the rotor. The rotating field is approximately constant in space wave form and rotating at synchronous speed[1]. Hysteresis motors are exciter less synchronous machines, which have found wide applications in sub fractional horse power ratings. These motors have some favourite features such as constant torque, low start-up current and noiseless operation. However, low efficiency and low power factor are common deficiencies of the hysteresis motors, which should be rectified using more suitable rotor substance and having accuracy in design considerations as possible. In general, magnetic property of the rotor material has the most important and plays a key role in the hysteresis motors performance. Hysteresis motor has wide application in sound producing equipment, sound recording instrument, gyroscope teleprinter, hair dryer, refrigerator etc[2].

Tomotsugu Kubota, Genjiro Wakui, Minoru Itagaki[3] described in past years rotor ring of Hysteresis motor is made is up of Alnico material which have various disadvantages to overcome disadvantages like larger dimension, rigid grinding, rare earth material, the rotor ring is made up of Fe–Cr–Co magnet steel with magnetic anisotropy is applied for hysteresis rotor ring. J. Rizk, A. Hellany and M. Nagrial[4] discussed the rotor of a hysteresis motor is a cylindrical tube of high hysteresis loss permanent magnet material without windings or slots made up of 36% cobalt steel with neodymium. Magnetic properties of hysteresis material plays very much important role in performance of hysteresis motor. Joyashree Das, Dr. Rup Narayan Ray[6] explained hysteresis motor made up of high temperature superconducting material posses higher current density, flux density. This motor is easily affected by air gap and structure dimension variation[6]. Air gap plays important role in flux distribution in hysteresis ring and influences on output torque efficiency and novel rotor design to improve dynamic performance of hysteresis motor is presented by Mohammad Modarres and Byung-il Kwon[7]. Comparisons of magnetic properties for Fe-36% Cobalt, Alnico, Fe-Cr-Co and Fe- Cr-Ni-Mo-C help us to choose the best material for the hysteresis motor in different applications. Fe-Cr-Ni-Mo-C alloys goes to saturation , higher permeability, lower magnetic field intensity. The output power of a hysteresis motor depends on the volume of the rotor ring and area of hysteresis loop proportionally. For a given output power, due to less area of the hysteresis loop, greater hysteresis material volume is required for the hysteresis motor, in which Fe-Cr-Ni-Mo-C alloy is used. Teymoor Ghanbari, Ahmad Darabi, Mohsen Sanati Moghadam presented comparison of various magnetic material with hysteresis delay angle permeability magnetic flux density and electromagnetic characteristics of Fe-Cr-Ni-Mo-C material[9]. Mouliswararao reddy, L.V suresh discussed dynamic modeling of hysteresis motor in MATLAB/Simulink by using reference frame theory[14]. Addition to this Omer M, Awed Badeeb investigated dynamic performance of hysteresis motor by using MATLAB/simulink[15].

This paper presents dynamic modeling of hysteresis motor. The structure of this paper is organized as section-II deals with working principle of hysteresis motor. Section- III describe basic mathematical analysis of hysteresis motor. Section- IV describes dynamic modeling of motor by using reference frame theory. Section –V deals with simulink model of 3-phase hysteresis motor in arbitrary reference frame. Section- VI and VII deals with simulation results and conclusion with future scope.

II. WORKING PRINCIPLE OF HYSTERESIS MOTOR

Hysteresis motor is named due to the net mechanical torque is the combination of eddy current torque and hysteresis torque, when motor runs at synchronous speed torque due to eddy current losses vanish and torque due to hysteresis loss is remaining. The stator of the hysteresis motor has slots which accommodates the copper windings that can be single or poly-phase. These kinds of windings are used to create the magnetic rotating field that drags the rotor. The rotor is made up of hard iron material with a high degree of magnetic hysteresis. Due to high value of coercivity (normally 8 to16 kA/m, with large hysteresis loop) the hysteresis loss is high. This is the main region for large AC loss in the rotor of the hysteresis motor. In this case motor shaft is made up of paramagnetic material. The hysteresis ring is affected by the rotational hysteresis causes by the stator windings and the direction of the magnetization of each element of the ring is different from that of the magnetic field or magnetic flux density. That is to say, the thicker the hysteresis ring becomes the larger the rotational hysteresis increases and to make matters worse, the output of the thicker ring motor becomes less than that of thin rotor motor[1].
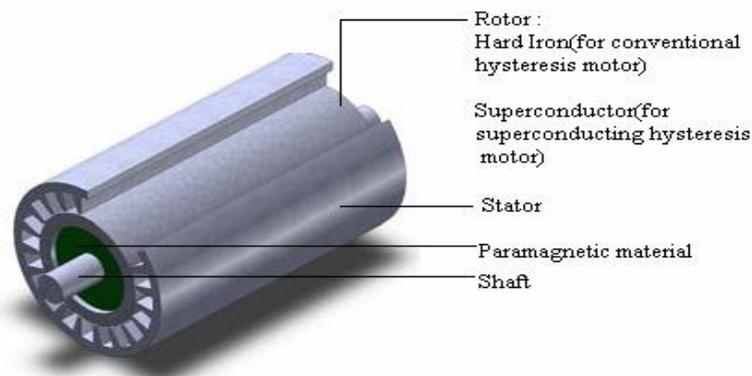
Fig.1: Hysteresis motor layout

Due to hysteresis effect, the axis of magnetization of rotor will lag behind the axis of stator field by hysteresis lag angle α as shown in fig 2. If the rotor is stationary, the starting torque is produced. It is given by

$$T_s = \varphi_s \varphi_r \sin \alpha \tag{1}$$

where φ_s = stator flux.

φ_r = rotor flux.

α = angle between stator flux and rotor flux.
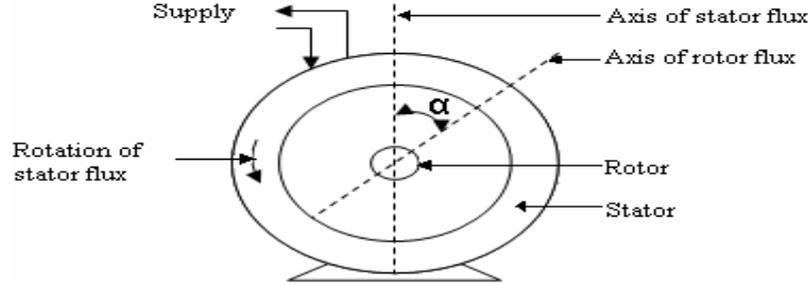
Fig. 2: Hysteresis motor.

Then rotor accelerates to synchronous speed with a uniform torque. Now φ_s and φ_r are constant. When the rotor accelerates, the lag angle α remains constant since the angle α depends upon the hysteresis loop of the rotor. The torque is independent of the rate at which the loop is traversed. Therefore a constant torque is developed from standstill to synchronous speed[10]. After reaching synchronism, the motor continues to run at synchronous speed and adjusts its torque angle to develop the load torque. When the stator field moved forward, due to high residual magnetism (i.e. retentivity) the rotor pole strength remains maintained. So higher the retentivity, higher is the hysteresis torque. The hysteresis torque is independent of the rotor speed. The high retentivity ensures the continuous magnetic locking between stator and rotor. Due to principle of magnetic locking, the motor either rotates at synchronous speed or not at all. Only hysteresis torque is present which keeps rotor running at synchronous speed[2]. Hysteresis motor is a type of synchronous machine which has found wide applications as small scale machines. Due to its simple structure, this motor is being used in various fields such as

- Navigation, chemical, weaving, and military industries
- Magnetic ribbons in recorders, hard disks, clocks and other precision equipment [1] [2].

III.   MATHEMATICAL ANALYSIS

Initially, the electromagnetic torque is developed by a hysteresis motor by virtue of the eddy-current loss and the hysteresis loss. The eddy-current loss can be given by

$$P_e = K_e B^2 f_2^2 \tag{2}$$

Where, K_e is a constant, f_2 is frequency of eddy-current, and B is flux density.

In terms of slip s, the rotor frequency f_2 is related to the stator supply frequency f by

$$f_2 = sf \tag{3}$$

Thus (2) and (3) yield

$$P_e = K_e B^2 s^2 f^2 \tag{4}$$

The torque due to eddy current is given by

$$T_e = \frac{P_e}{sw_s} = \frac{K_e B^2 s^2 f^2}{sw_s} = K_1 s \tag{5}$$

where $K_1 = \frac{K_e B^2 f^2}{w_s}$

So, $Te \propto s$ all other parameters are constant.

It is clear from Eq. (5) that when the rotor rotates at synchronous speed, the slip becomes zero and torque due to eddy current component vanishes. It only helps to start.

The hysteresis-loss is given by:

$$P_h = K_h B^{1.6} f_2 = K_h B^{1.6} sf \tag{6}$$

Where, K_h is an another constant.

The corresponding torque is given by:

$$T_e = \frac{P_h}{sw_s} = \frac{K_h B^{1.6} sf}{sw_s} = K_2 s = \text{constant} \tag{7}$$

It is clear from Eq. (7) that the hysteresis component is constant at all the rotor speed.

Hysteresis losses are produced in the rotor of a hysteresis motor is proportional to the area of hysteresis loop. These losses are dissipated as heat in the rotor.

Let us assume that the hysteresis loss per revolution is E_h joules and that the field rotates at N_s revolution per minute. The energy dissipated in the rotor per minute is

$$W = N_s E_h \tag{8}$$

The corresponding power (dissipated as heat) is

$$P_s = \frac{W}{t} = \frac{N_s E_h}{t} \tag{9}$$

However, the power dissipated in the rotor can only come from the mechanical power used to drive the rotor. This power is given by

$$P_h = \frac{2\pi N_s}{60} T_h \tag{10}$$

Thus (9) and (10) yield

$$\frac{2\pi N_s}{60} T_h = \frac{N_s E_h}{t}$$

Hence $T_h = \frac{E_h}{2\pi}$ (11)

Where, T_h is torque exerted on the rotor [N-m] and E_h is hysteresis energy dissipated in rotor [J][2].

IV. DYNAMIC MODELING OF HYSTERESIS MOTOR

The dynamic modelling of hysteresis motor is carried out by using reference frame theory .The dynamic model of the Hysteresis Machine (HM) is derived using a two-phase motor in direct and quadrature axes. This approach is done because of the conceptual simplicity obtained with only one set of two windings on the stator. The rotor has no windings, only magnets. The magnets are modelled as a current source or a flux linkage source, concentrating all its flux linkages along only one axis. The flux linkages of the stator q and d axis windings are derived from first principles. The physical modeling of the machine is developed from which the circuit model is derived. Constant inductance for windings is obtained by a transformation to the rotor by replacing the stator windings with a fictitious set of d-q windings rotating at the electrical speed of the rotor. The equivalence between the three-phase machine and its model using a set of two-phase windings is derived and this approach is suitable for extending it to model an *n* phase machine where *n* is greater than 2, with a two-phase machine. The transformation from the two-phase to the three-phase variables of voltages, currents, or flux linkages is derived in a generalized way. Derivations for electromagnetic torque involving the currents and flux linkages are obtained[13].
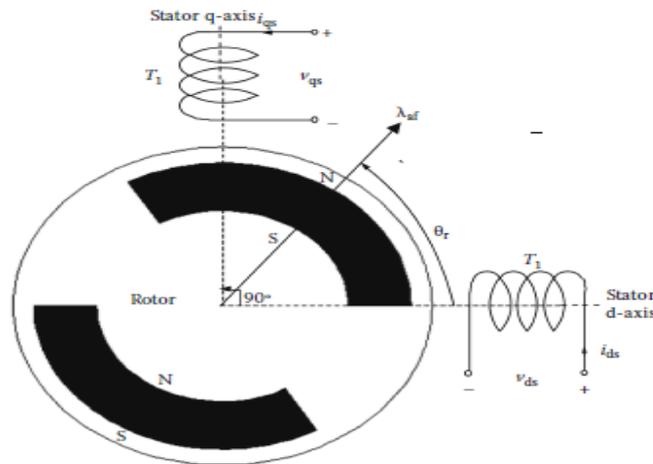
Fig. 3: A two-phase Hysteresis Motor

The windings are displaced in space by 90 electrical degrees and the rotor axis is at an angle θ_r from the stator d axis winding. It is assumed that the q-axis leads the d-axis to a counter clockwise direction of rotation of the rotor. The d- and q-axes stator voltages are derived as the sum of the resistive voltage drops and the derivative of the flux linkages in the respective windings as

$$V_{qs} = R_q \, i_{qs} + p \, \lambda_{qs} \tag{12}$$
$$V_{ds} = R_d \, i_{ds} + p \, \lambda_{ds} \tag{13}$$

Where- p is the differential operator, d/dt

V_{qs} and V_{ds} are the voltages of q axis and d axis windings

i_{qs} and i_{ds} are the q axis and d axis stator currents

R_q and R_d are the stator q axis and d axis resistances

λ_{qs} and λ_{ds} are the stator q axis and d axis flux linkage

The flux linkage of stator winding can be written as the sum of flux linkage due to their own excitation , mutual flux linkage from other winding current and magnet source. The q and d stator flux linkages are written as

$$\lambda_{qs} = L_{qq}\,i_{qs} + L_{qd}\,i_{ds} + \lambda_{af}\,\sin\theta_r \tag{14}$$

$$\lambda_{ds} = L_{dq}\,i_{qs} + L_{qd}\,i_{ds} + \lambda_{af}\,\cos\theta_r \tag{15}$$

Where θ_r is the instantaneous rotor position. The windings are balanced and their resistance are equal and denoted as $R_q = R_d = R_s$.The q and d axis stator voltages can be written as

$$V_{qs} = R_s i_{qs} + i_{qs}pL_{qs} + L_{qq}pi_{qs} + L_{qd}pi_{ds} + i_{ds}pL_{qd} + \lambda_{af}\,p\sin\theta_r \tag{16}$$

$$V_{ds} = R_s i_{ds} + i_{qs}pL_{qd} + L_{qd}pi_{qs} + L_{dd}pi_{ds} + i_{ds}pL_{dd} + \lambda_{af}\,p\cos\theta_r \tag{17}$$

L_{qq} and L_{dd} are the self-inductances of q and q axis windings respectively. The mutual inductances between any two windings are denoted by L with subscript where first subscript denotes the windings at which the emf is measured due the current in other winding indicated by second subscript.

Substituting the self- and mutual inductances in terms of the rotor position into the stator voltage equations. The final machine equations then are

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = R_s \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} L_1 + L_2\cos\theta_r & -L_2\sin2\theta_r \\ -L_2\sin2\theta_r & L_1 - L_2\cos2\theta_r \end{bmatrix} d/dt \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + 2\omega_r \begin{bmatrix} -\sin\theta_r & -\cos2\theta_r \\ -\cos2\theta_r & \sin2\theta_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} +$$
$$\lambda_{af}\,\omega_r \begin{bmatrix} \cos\theta_r \\ -\sin\theta_r \end{bmatrix} \tag{18}$$

The third term exists because of saliency, i.e., when $L_q \neq L_d$. In surface mount magnet machines, the inductances are equal and, therefore, L_2 is zero and the third term in the above equation vanishes. Also disappearing in the matrix's second term are the position dependent terms, resulting in a simple expression for surface mounted magnet machines in stator reference frames. It is then given by

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = R_s \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} L_1 & 0 \\ 0 & L_2 \end{bmatrix} d/dt \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \omega_r\,\lambda_{af} \begin{bmatrix} \cos\theta_r \\ -\sin\theta_r \end{bmatrix} \tag{19}$$

A. *Electromagnetic Torque*

The electromagnetic torque is given by

$$T_e = (3/2)\,(P/2)[\,\lambda_{af} + (L_d - L_q)i_{dr}]i_{qr} \tag{20}$$

B. *Transformation to Rotor Reference Frames*

The model is constructed according to the equations has been simulated by using MATLAB/SIMULINK. A 3-phase source is applied to Hysteresis Motor and equations are given by

$$V_a = \sqrt{2}\;V_{rms}\,\sin(\omega t) \tag{21}$$

$$V_b = \sqrt{2}\;V_{rms}\,\sin(\omega t - \tfrac{2\pi}{3}) \tag{22}$$

$$V_c = \sqrt{2}\;V_{rms}\,\sin(\omega t + \tfrac{2\pi}{3}) \tag{23}$$

The three-phase voltages are transferred to a synchronously reference frame in only two phase (d-q axis transformation). This can be done by using following equations

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - 120) & \sin(\theta_r - 120) & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r + 120) & 1 \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} \tag{24}$$

Conversion of dq axis to abc

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \tfrac{2}{3} \begin{bmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{25}$$

V. SIMULATION OF HYSTERESIS MOTOR

The discussed dynamic model of hysteresis motor is simulated in MATLAB/Simulink having rating are given in Table-I. The machine parameter are stator resistance R_s= 1.2ohm, B = 4.6752e-5 kg/m², J = 2.0095e-5 N-ms, rotor resistance R_r= 2.035ohm, direct axis inductance (L_d) = 7.8e-3 H, quadrature axis inductance(L_q) = 7.8e-3 H, these parameters are used in given modelling of Hysteresis motor.

TABLE-I MACHINE RATING

Rated phase voltage(V)	220V
Rated frequency(Hz)	50
Number of poles	4
Rated speed(rpm)	1500

As shown in fig.4 hysteresis motor is supplied by 3-phase balanced supply of 220V, 50Hz. It includes Hysteresis motor subsystem block which consist of computation of abc-dq axis, dq-abc axis transformation, torque calculation, direct and quadrature current calculation and finally measurement of all parameters.
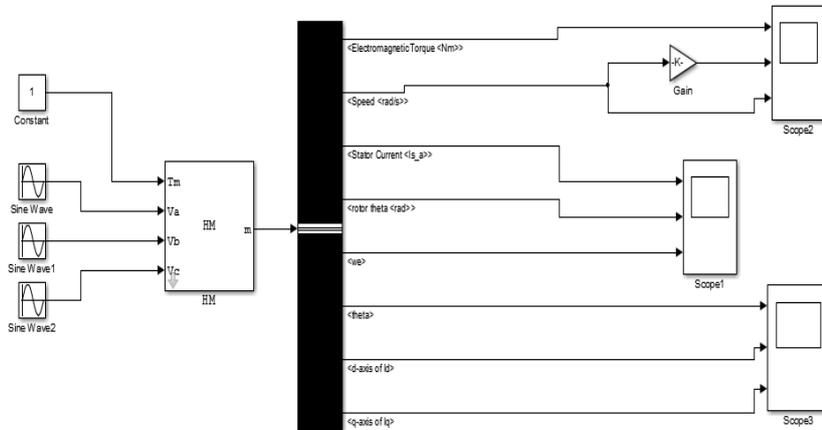
Fig. 4: Simulink model of 3-phase Hysteresis Motor

Fig.5 shows detail simulink model of 3-phase Hysteresis motor. Voltage , Current and torque equation and transformation matrix are used to implement the model of hysteresis motor. abc to dq block transforms three phase voltage into 2 phase voltage. The id and iq calculation block gives current in direct and quadrature axis whereas torque calculation block gives electromagnetic torque by using equation (20). Measurement block measure all parameters such as current, torque, speed and rotor position.
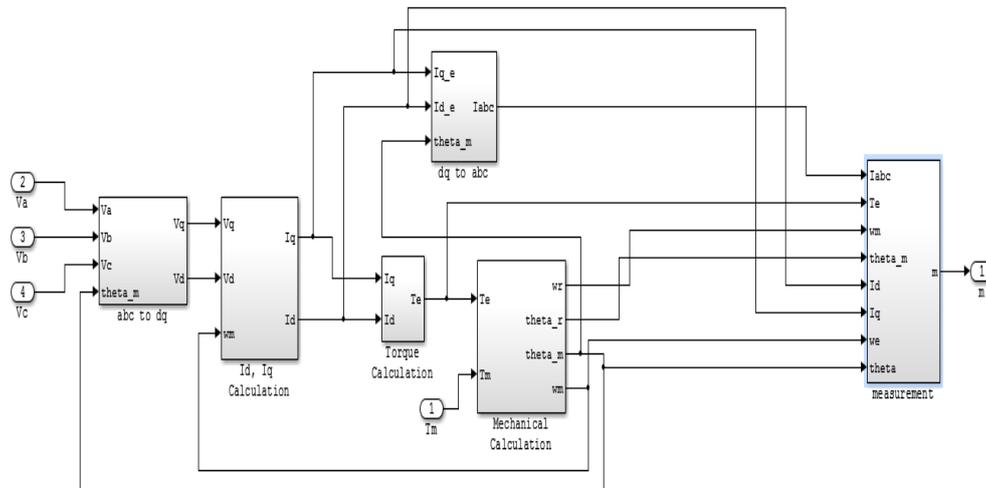
Fig. 5: Simulink Model of 3- Phase Hysteresis Motor

VI.   RESULTS AND DISCUSSION

The developed MATLAB model of 3-phase hysteresis motor gives following results in terms of current, voltage, torque and speed etc. Fig. 6 shows the electromagnetic torque and speed characteristics with respect to time and fig. 7 shows stator current and rotor theta. The variation of torque during starting is observed which occurs due to inrush current. Steady state torque is attained after 0.2 sec. The developed instantaneous

electromagnetic torque is comprised of average asynchronous torque and pulsating torque. The average asynchronous torque combines the hysteresis torque, eddy current torque and magnet brake torque. Because of the presence of permanent magnet acting as a constant current source in the rotor, there is a pulsating torque superimposed on the average asynchronous torque. During period of synchronization the torque pulsation dies out and turns into the synchronous torque.
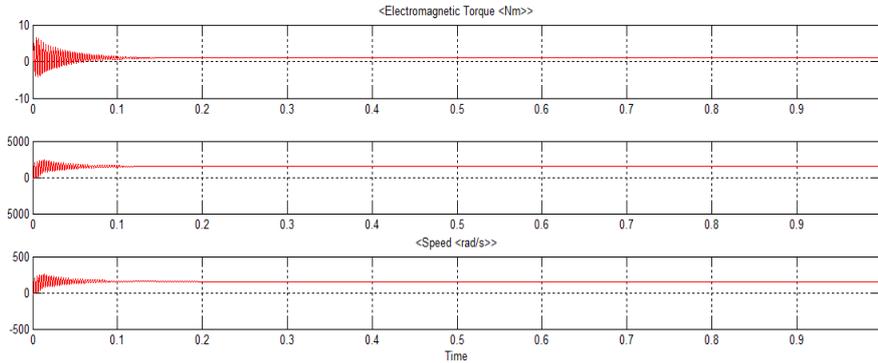
Fig. 6: Electromagnetic torque and speed of Hysteresis motor
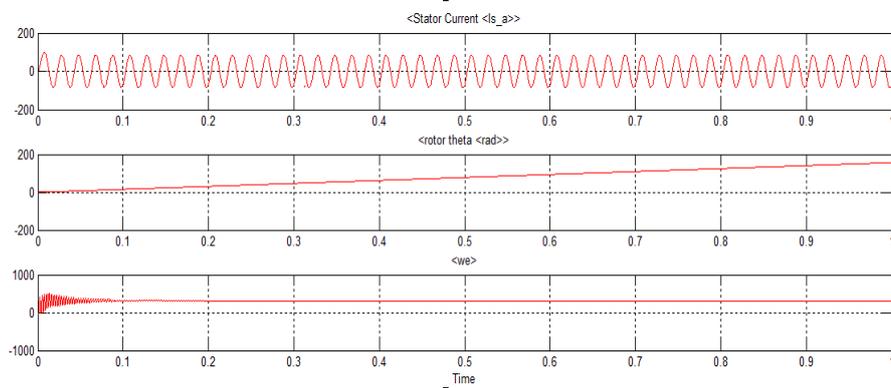
Fig. 7:. Stator current, rotor theta and we of Hysteresis motor

In Hysteresis motor as load changes suddenly rotor tries to oscillates about new position is called hunting causes surge in current and power. Here at no load condition rotor position is shown. At starting of hysteresis motor the inrush current flows through motor which lasts for few cycles and disappears as motor attains the steady state speed. The constant no load steady state stator current is observed. Fig. 8 shows q axis and d axis current. The inrush current lasts for 0.2 sec due to which small overshoot is observed.
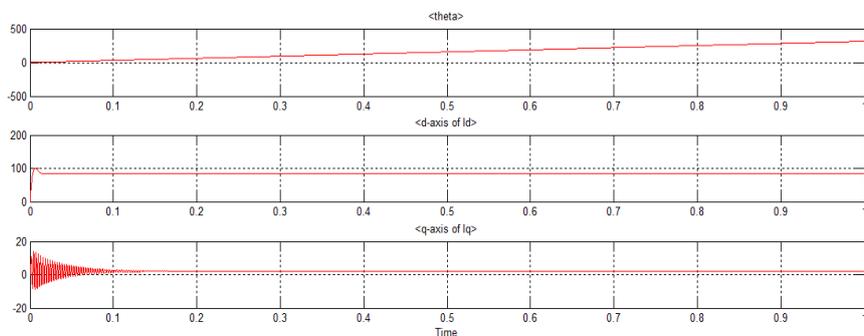
Fig. 8: Rotor position and d-axis and q-axis current of motor

VII. CONCLUSION

Hysteresis motors are self starting brushless synchronous motors which are being used widely due to their interesting features such as smooth vibration free operation, constant torque, lower maintenance, small size etc. The hysteresis loops of the material used in the rotor and their influences on the parameters of the equivalent circuit are necessary to be taken into consideration adequately for better performance of hysteresis

motor. These motors are widely used in recorders, hard disks, home appliances, clocks, electric valves, navigation, military , chemical and weaving industries etc.

This paper presents an investigation of the dynamic performance of a three-phase hysteresis motor fed from a three-phase balanced power supply. A mathematical model similar to those representing conventional machines has been adopted to reflect the hysteresis motor operation. This paper proposes principle, mathematical analysis and dynamic modeling of 3-phase hysteresis motor by using reference frame theory. The results indicate smooth operation of motor at synchronous speed.

The implemented 3-phase hysteresis motor can be used in machine tool design application. By changing rotor material performance of hysteresis motor can be observed. As load changes on motor, rotor oscillates about new equilibrium position causes hunting in hysteresis motor which in turn causes temperature rise, mechanical stresses surge in current and power etc. To avoid hunting damper winding and flywheels are used.

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