Performance Analysis of Direct Torque Controlled, Inverter-fed PMSM Drive for Wire Drawing Machines

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Abstract: *Fast process times, high dynamic torque and speed control, quick accelerations to a speed-level and deceleration to zero speed again without losing tension are the major drive requirements of wire drawing machines. Permanent Magnet Synchronous Motors (PMSM) drives are fast becoming popular in various applications due to its high efficiency, power density, efficiency, high torque to inertia ratio and high reliability. The major disadvantage to its use is its cost of deployment. The paper analyses the performance of a Direct Torque Controlled (DTC) inverter-fed PMSM drive for wire drawing machines. The DTC PMSM drive offers a good dynamic performance for fast switching high torque requirement that characterizes wire-drawing machines. The simulation shows satisfactory values of torque ripples for various values of torque required.*

Keyword: *PMSM, DTC, Wire drawing.*

Nomenclature:

D_1 = diameter of wire in mm before drawing
D_2 = diameter of wire in mm after drawing
γ = Flow stress or Yield stress
γ_{ave} = Average flow stress or Yield stress
σ = Draw stress of forced tension
a = reduction in diameter or cross-sectional area of the wire
r = radius of the pulley coupled to the motor axis in meters
α = die semi-angle in degrees
A_2 = Cross sectional area of the outlet wire
μ= coulombs friction coefficient
F = Drawing force in Newton
P=Power required
ω = angular velocity in rad/sec
v = speed of draw in m/s
K = strength coefficient
n= strain-hardening exponent
ε = true strain
T = Toque in Nm;
Stator Resistance $R_s = 5.8\Omega$;
T_d= Dry Friction;
f= Frequency ;
B= Viscous Friction;
V_{dc}=Inverter DC Voltage;
L_q = Q-axis Inductance;
L_d= D-axis Inductance;
lambda_af = 0.533 wb/turns;
P = Number of poles;
J = Moment of inertia;

I. INRODUCTION

The major mechanical burden usually imposed by wire drawing machines on its drive systems is to be able to keep the tension of the wire being drawn nearly as constant as possible. The allowable tension tolerance for these machines is between 4-5% of the value of the desired [1].

PMSM drives when compared to many other types of alternating current machines is rapidly becoming the choice drives for many automotive and industrial applications. This is due to the various advantages that are associated with the configuration: high power density and efficiency, high torque to inertia ratio, and high reliability. Recent researches on rare earth magnets and also low-cost ferrite magnet PMSM have made the reduction in the cost of manufacturing PMSM possible. The continuous cost reduction of magnetic materials with high energy density and coercitivity (e.g., samarium cobalt and neodymium-boron iron) makes the ac drives based on PMSM more attractive and competitive. In very high performance applications, such as in wire drawing machines the PMSM drives are ready to meet sophisticated requirements such as fast dynamic response, high power factor and wide operating speed range. As a consequence, it is predictable that there will surely be a great increase of the use of PMSM

for several industrial applications and other various forms of applications in the future. [2-4].
Several applications of PMSM drives have been investigated. Varying from applications in electric vehicles, uses in servo motors, driving of railway vehicles, industrial drives applications such as pumps, fans blowers, compressors, centrifuges, mills, handling systems, machine tools, air conditioning systems, air conditioning systems catering equipment, coin laundry machines, auto-bank machines, automatic vending machines, money changing machines, ticketing machines, bar-code readers at supermarkets, environmental control systems, amusement park equipment etc. has also been established [5-7]. Electrical machines havean enormous influence on the reduction ofenergy consumption in most industrialized countries. The deployment of PMSM drives will obviously reduce the amount of energy consumed by many manufacturing companies due to its very high efficiency compared to the induction machines that is currently being used for most of the drives in manufacturing industries. DTC (which was developed in the 1980s by German and Japanese researchers for use in torque control of high power servo drives as an alternative to FOC) controlled AC machines offers fast dynamic response and it is quite cheaper due to the absence of costly encoder or resolvers used to sense the speed of the rotating machines. Fast process times, high torque and speed control, quick accelerations to a speed level and reverting to zero speed without losing tension, varying speed ranges and torque requirements depending on material characterizes the wire drawing machines [8] and also extruding machines, conveyors machines and many other types of machines drives used for various manufacturing operations.

II. Modeling of the PMSM

The equivalent circuits of PMSM in the d, q axes in the rotor reference frame are shown in figure 1 and 2 respectively.

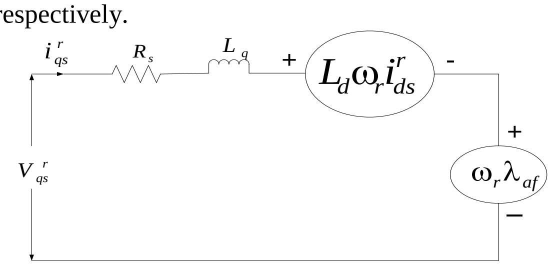

Fig. 1: Stator q-axis equivalent circuit

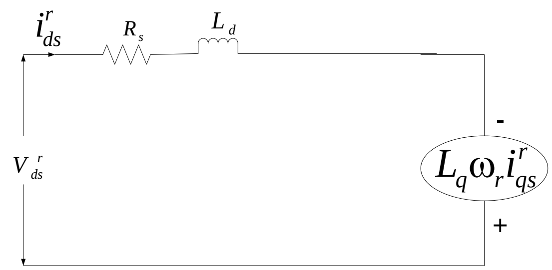

Fig. 2: Stator d-axis equivalent circuit

With the following assumptions

i. saturation and parameter changes are neglected;
ii. stator windings are balanced with the induced EMF is sinusoidal;
iii. eddy current and hysteresis losses are negligible;
iv. there are no field current dynamics; and
v. there is no cage on the rotor;

The following mathematical equations represent the modeling of an Interior Permanent Magnet Synchronous Motor taking the above assumptions into consideration [11].

$$V_{qs}^{r} = R_s i_{qs}^{r} + \rho\lambda_{qs}^{r} + \omega\lambda_{ds}^{r} \qquad (1)$$

$$V_{ds}^{r} = R_s i_{ds}^{r} + \rho\lambda_{ds}^{r} - \omega\lambda_{qs}^{r} \qquad (2)$$

$$\lambda_{qs}^{r} = L_q i_{qs}^{r}$$

$$\lambda_{ds}^{r} = L_d i_{ds}^{r} + L_m i_{fr}$$

(3)

(4)

(5)

$$\lambda_{ds}^{r} = L_d i_{ds}^{r} + L_m i_{fr} \qquad (6)$$

$$V_{qs}^{r} = R_s i_{qs}^{r} + \rho(L_q i_{qs}^{r}) + \omega_r(L_d i_{ds}^{r} + \lambda_{af})$$

$$V_{ds}^{r} = R_s i_{ds}^{r} + \rho(L_d i_{ds}^{r}) - \omega_r(L_q i_{qs}^{r}) \qquad (7)$$

$$\begin{bmatrix} V_{qs}^{r} \\ V_{ds}^{r} \end{bmatrix} = \begin{bmatrix} Rs+\rho Lq & \omega_r L_q \\ -\omega_r L_q & R_s+\rho L_d \end{bmatrix} \begin{bmatrix} i_{qs}^{r} \\ i_{ds}^{r} \end{bmatrix} + \begin{bmatrix} \omega_r\lambda_{af} \\ 0 \end{bmatrix}$$

(8)

$$T = \frac{3P}{4}\left\{\lambda_{ds}^{r} i_{qs}^{r} - \lambda_{qs}^{r} i_{ds}^{r}\right\} \qquad (9)$$

$$V_{as} = V_m \sin\omega t \qquad (10)$$

$$V_{bs} = V_m \sin(\omega t - \frac{2\pi}{3}) \qquad (11)$$

$$V_{cs} = V_m \sin(\omega t + \frac{2\pi}{3}) \qquad (12)$$

$$V_{dq0}s = KsV_{abc}s \qquad (13)$$

$$K_s = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (14)$$

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{0s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \qquad (15)$$

$$V_{qs}^{e} = V_{qs}\cos\theta_e + V_{ds}\sin\theta_e$$

(16)

$$V_{ds}^{e} = V_{ds}\cos\theta_e - V_{qs}\sin\theta_e$$

(17)

$$i_{qs}^{e} = \int \left(\frac{V_{qs}^{e}}{L_q} - \omega_e\frac{\lambda_{af}}{L_q} - \frac{R_s}{L_q}i_{qs}^{e} - \omega_e i_{ds}^{e}\frac{L_d}{Lq}\right)$$

(18)

$$i_{ds}^{e} = \int \left(\frac{V_{ds}^{e}}{L_d} - \frac{R_s}{L_q}i_{ds}^{e} - \omega_e i_{qs}^{e}\frac{L_q}{L_d}\right)$$

(19)

$$T = \frac{3P}{4}\left\{\lambda_{af}i_{qs}^{e} + (L_d - L_q)i_{qs}^{e}i_{ds}^{e}\right\}$$

(20)

$$Te = T_L + B\omega_m + J\frac{d\omega_m}{dt}$$

(21)

$$\omega_m = \frac{1}{J}\int T_e - T_L - B\omega_m$$

(22)

$$\omega_e = \frac{P}{2}\omega_m \qquad (23)$$

$$\theta_m = \int \omega_m$$

(24)

The equations above were modeled using MATLAB/SIMULINK Software

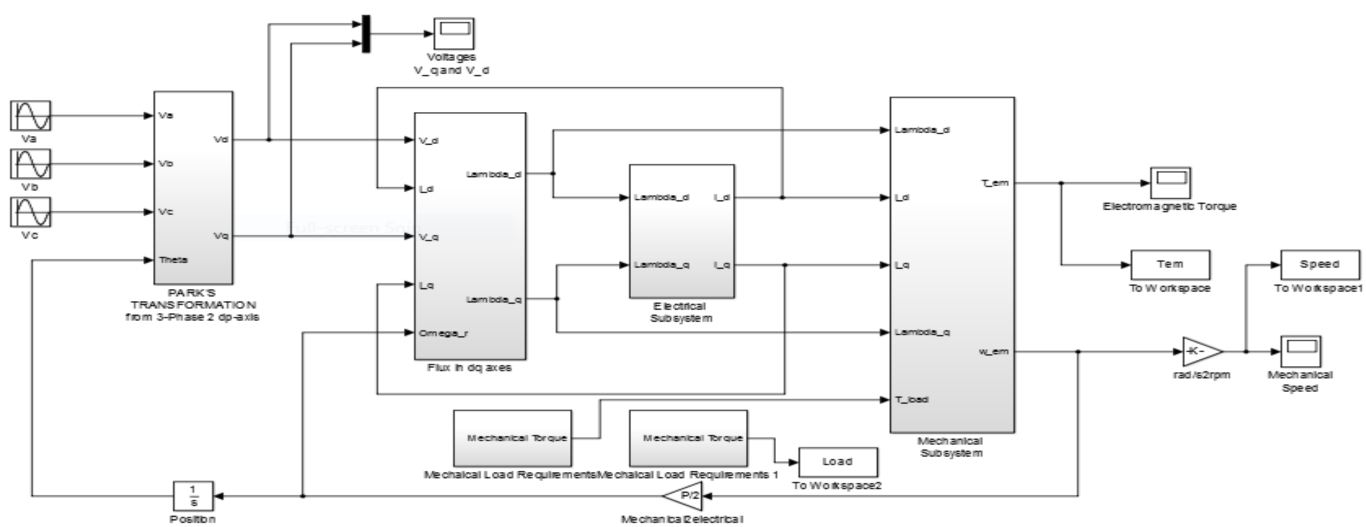

Fig. 3 Simulink screenshot of the developed PMSM model

III. Direct Torque control of the PMSM drive

The DTCmethod of vector control of AC motor drives is considered simple and robust.It has a very fast response and simple structure which makes it to be more popularly used in industrial drives [9].

Despite the disadvantages of the DTC scheme [9] which include difficulty to control torque and flux at very low speed; high current and torque ripple;

variable switching frequency behavior; high noise level at low speed; lack of direct current control, unlike FOC, DTC does not require any current regulator, coordinate transformation and PWM signals generator (as a consequence timers are not required). Despite the simplicity of the DTC scheme, it offer a very good torque control for industrial drives during transient and dynamic conditions [10]. This control scheme is proposed for manufacturing process drives due to its fast dynamic torque response which is a major torque requirement of most manufacturing drives.

A. Modeling of the DTC PMSM.

In DTC method, the control of electromagnetic torque and flux linkage is done directly and independently by using space vectors. In a PMSM, if we neglecting voltage drop due to stator resistance, variation of stator flux is directly proportional to applied stator voltage. Thus control of torque in PMSM can be achieved quickly by varying the stator flux position. DTC calculates and control stator flux linkages and torque of PMSM directly to achieve excellent transient performance [11].

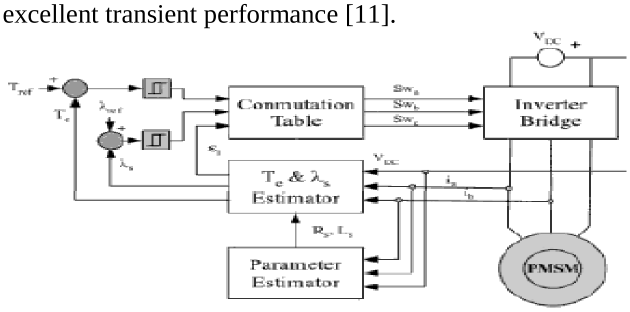

Fig. 4 Classical DTC Scheme [9]

B. Torque and flux estimator

The stator flux can be calculated using equation (3) and (5) above. The resultant stator flux is calculated using equation (25). The estimated torque can also be calculated using equation (9).

The measured values of the stator flux and torque through the estimator are compared with the set (reference) values. The error (difference) is input to a hysteresis controller which determines the switching states of the inverter. The typical DTC includes two hysteresis controllers, one for torque error correction and the other for flux linkage error correction. The hysteresis flux controller makes the stator flux rotate in a circular fashion along the reference trajectory for sine wave ac machines as shown in Fig. 4. The hysteresis torque controller tries to keep the motor torque within a pre-defined hysteresis band [12]. The flux hysteresis controller is a 2-level hysteresis controller, while the torque hysteresis controller is a 3-level hysteresis controller. The look-up table is used to determine the switching states of the inverter.

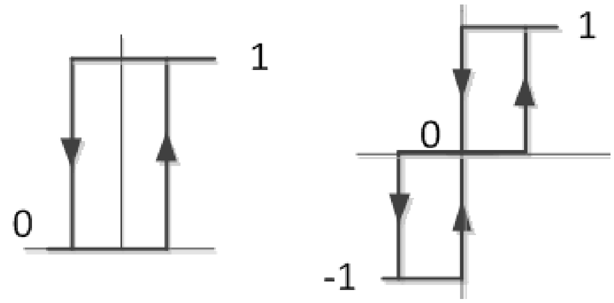

Fig. 5 Two-level and Three-level hysteresis controller [12].

Table 1. Switching vectors

H_λ	H_T	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_6	V_1	V_2	V_3	V_4

The stator flux linkage of a PMSM that is depicted in the stationary reference frame is written as:

$$|\lambda_s| = \sqrt{\lambda_{ds}^2 + \lambda_{qs}^2} \tag{25}$$

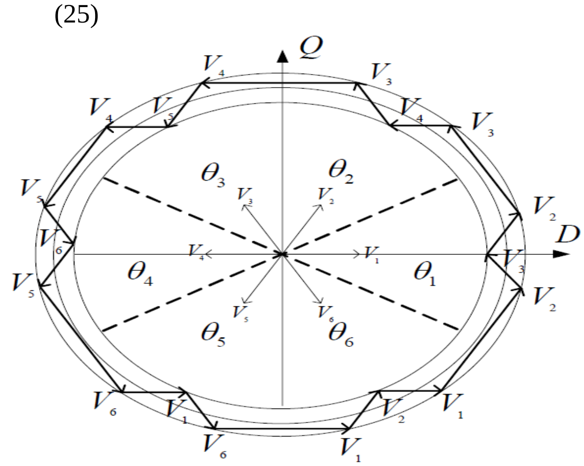

Fig. 6. Circular trajectory of stator flux linkage in the stationary dq−plane [9].

IV. Wire-drawing Machine.

The wire drawing machine is used in the wire manufacturing process to reduce the diameter of a wire to its required size. It employs a combination of a die and/or a series of dies to draw wire to a selected reduced gauge. The wire drawn is used in several applications apart from the usual electrical wires and cables for conduction of electrical current. Springs of any kind can be made from drawn wire also made from drawn wires includes paper clips, staples, spokes on wheels, wires brushes metal handles etc.

There are numerous finished products that rely on drawn wire [8].

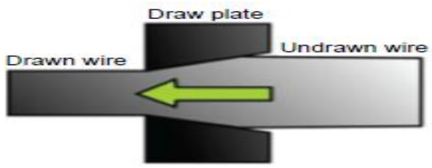

Fig.7 Wire drawing through a die [8].

Fig. 8. A wire drawing machine [8].

A. Modeling of the torque required for a wire drawing machine.

There are several methods of estimating the torque required to draw a wire from one diameter to another. The drawing force can be obtained by analytical and numerical methods based on geometry of the die and on physical properties of the work piece wire. These include the Slab method, and upper bound method, lower bound method, slip line method, Schey equation and FEA method etc [13]. For this work, the slab method was used because its fast and also gives an approximate estimate of the stress and strain values, with the following assumptions:

i. normal stress vary in only one direction of the large dimension;
ii. deformation is assumed homogeneous; and
iii. no contribution of redundant work.

$$B = \mu \cot \alpha$$

$$\gamma = K\varepsilon^n \qquad (25)$$

$$\gamma_{ave} = \frac{K\varepsilon^n}{1+n} \qquad (26)$$

$$a = 1 - \left(\frac{D_2}{D_1}\right)^2 \qquad (27)$$

$$\varepsilon = \ln \frac{1}{1-a} \qquad (28)$$

$$\sigma = \gamma_{ave}\left(\frac{1+B}{B}\right)\left[1-\left(\frac{D_2}{D_1}\right)^{2B}\right] \qquad (29)$$

$$A_2 = \pi \frac{D_2^2}{4} \qquad (30)$$

$$F = \sigma \times A_2 \qquad (31)$$

$$P = F \times v \qquad (32)$$

$$\omega = \frac{v}{r} \qquad (33)$$

$$T = \frac{P}{\omega} \qquad (34)$$

Table 2. Typical parameters values range [8]

Die semi-angle (α)	2.5^o–16^o
Coulomb friction coefficient (μ)	0–0.2
Cross-sectional area reduction (a)	0.20–0.40
Speed for non-ferrous drawing	up to 30m/s
Speed for ferrous drawing	up to 10m/s

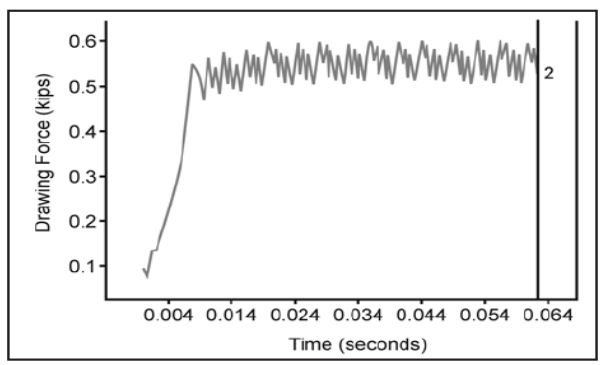

Fig. 9 Variation of Draw force with time

V. Simulation Of The Whole System

The wire drawing torque requirement was simulated in the MATLAB/Simulink environment. The profile of the torque/force required of the wire drawing machine is as shown in figure. The DTC scheme was also simulated in the MATLAB/Simulink environment.

The parameters of the PMSM drive used for the simulation is shown below:

Stator Resistance $R_s = 5.8\Omega$;
Dry Friction T_d=0;
Frequency = 50Hz;
Viscous Friction B=0;
Inverter DC Voltage V_{dc}=340;
Q-axis Inductance L_q = 0.0446H;
D-axis InductanceL_d= 0.1027H;
lambda_af = 0.533 wb/turns;
Number of poles P = 4;
Moment of inertia J = 0.0008;
Typical Values in wire drawing machines
d_1=1, d_2=0.5, μ =0.3, α =2.5, v=10, r=5, n=4, K=1000
The simulation was carried out with various values of torque required by the wire drawing machine. The flux reference was set at 0.533 wb, the hysteresis bandwidth for the flux was set at 0.005 and the hysteresis bandwidth for the torque was set at 0.12

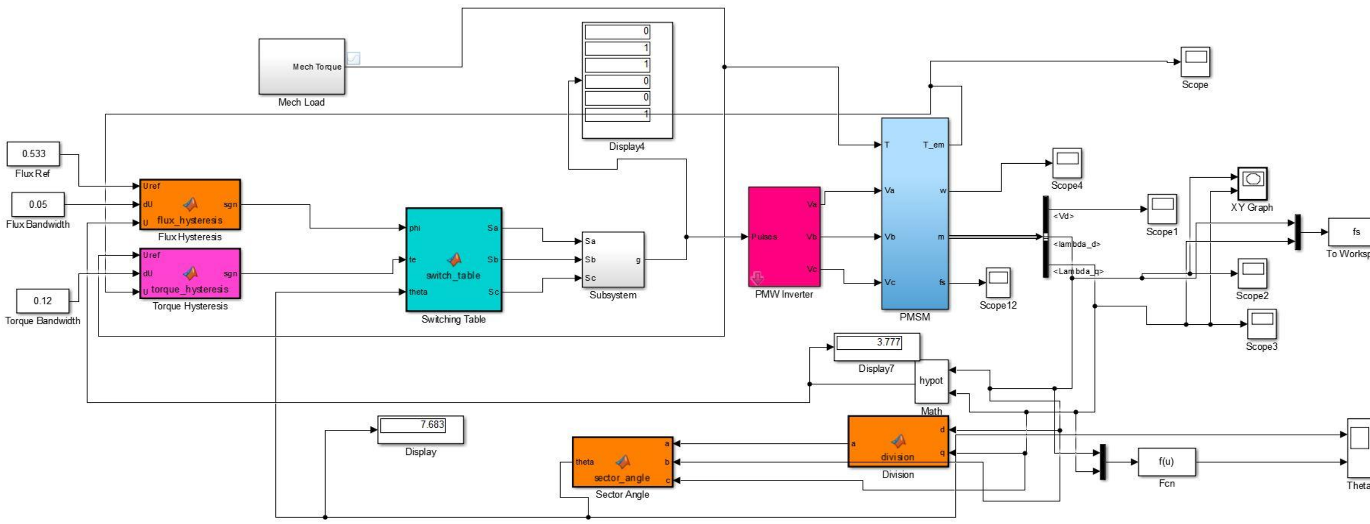

Fig. 16 MATLAB/Simulink implementation of the whole system

VI. DISCUSSION OF RESULTS

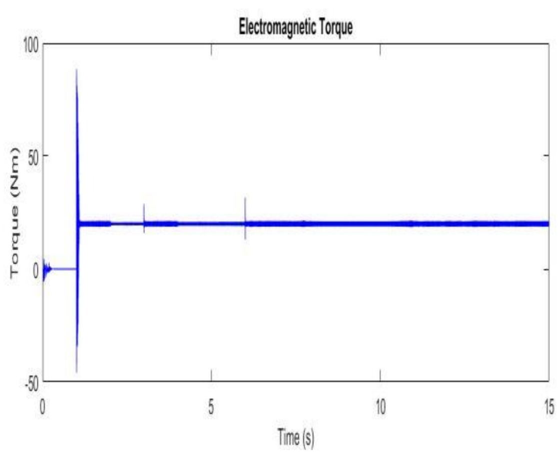

Fig. 10 Electromagnetic torque when load torque= 20Nm

The load torque at 20 N-m gives a torque ripple of 2.5 % after 4s

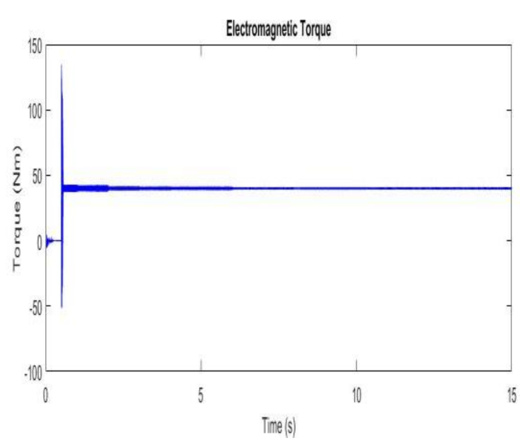

Fig. 11Electromagnetic torque when load torque= 40Nm

The load torque of 40N-m, the torque ripple was 5% between 1-2s, 3% between 2-3 s, 1.25% between 3-4s and 2.5% at 4 s above

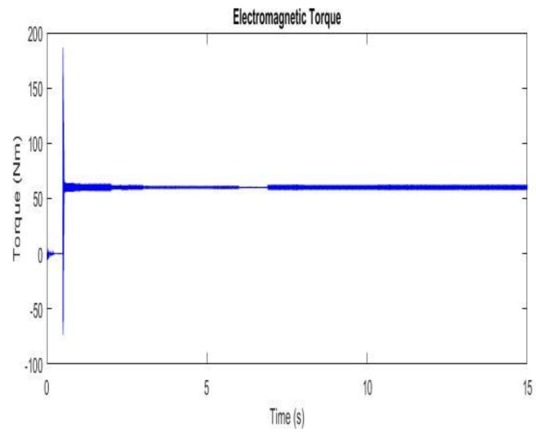

Fig. 12 Electromagnetic torque when load torque= 60Nm

At a load torque of 60N-m, the load torque ripples settles to 1.6% at 6 s

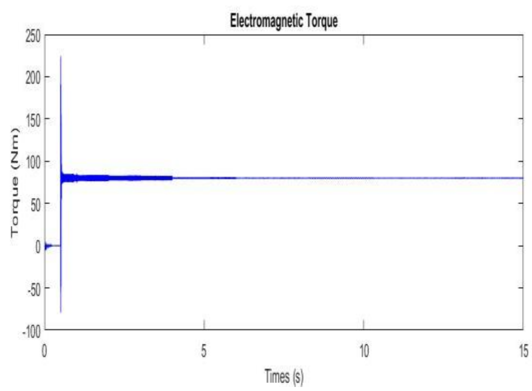

Fig. 13 Electromagnetic torque when load torque= 80Nm

The toque ripple at 80 Nm was measured as 2.5 %.

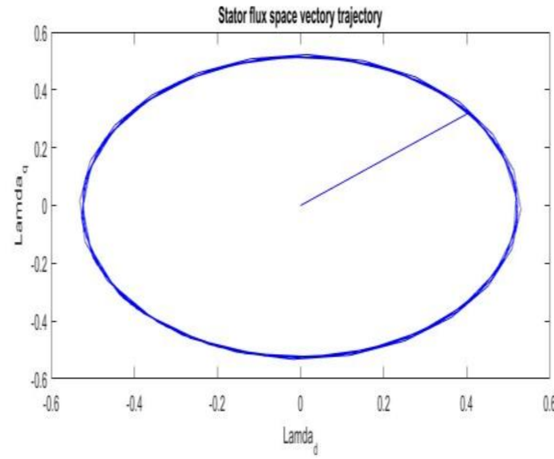

Fig. 14 Response of stator flux during steady state condition.

I. CONCLUSION

This paper was able to analyze the performance of an IPMSM drive for wire drawing machine application. The torque variation (ripple) for wire drawing machine is expected to be between 4-5% maximum. The performance of this drive shows satisfactory result.

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