Design Of A Permanent Magnet Synchronous Machine For The Electric Power Steering

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Abstract:-This paper presents a design of PMSM for Electric power Steering which are widely being applied in automotive application. **Automotive control systems are complex systems involving multidisciplinary knowledge. Permanent magnet synchronous machines are known as a good candidate for *Electric power Steering* due to their unique merits. However they have two major drawbacks i.e. high cost and small speed range. In this paper an optimal design of a permanent magnet machine is presented. A reduction of permanent magnet material for a constant torque and an extension in speed and torque ranges are chosen as the optimization aims. For this purpose the analytical model of the permanent magnet synchronous machine is derived.**

***Keywords— Electric power Steering*, Permanent magnet synchronous machine. Permanent magnet material, MOEFET Inverter circuit, clock signal generator, address generator, EPROM.**

I. INTRODUCTION:-

Electric power steering (EPS) is an advanced steering system that uses an electric motor to provide steering assist. It eliminates the need for a hydraulic power steering pump, hoses, hydraulic fluid, drive belt and pulley on the engine, therefore the total system is lighter than a comparable hydraulic system through the use of compact system units Also, since EPS is an on-demand system that operates only when the steering wheel is turned, the fuel efficiency of vehicle equipped with such system is up to 3% better than that of automotive equipped with an equivalent-output hydraulic system. As a result, electric power steering is more energy efficient and environmentally compatible. This motivates the great increase of EPS-equipped automotive recently.

Due to factors such as high power density and efficiency, maintenance, and extremely wide operating speed range, permanent magnet synchronous motors (PMSM) are the subject of development for automotive applications. For effective drives of PMSM, the power converter and controller are also effectively developed and integrated as the PMSM drive system. As these electrical components are being given much weight on the system, the complexity of automotive control system is rapidly increasing. Electric Power Steering(EPS) systems like Fig.1 have attracted much attention for their advantages with respect to improved fuel consumption(saving 3~6%, reduction of weight 3~5kg) and have been widely adopted as automotive power steering equipment in recent years. The permanent magnetic field Direct Current(DC) motors are widely used for EPS system, but nowadays many engineers are trying to adopt the Permanent Magnet Synchronous Motor(PMSM). It is because the fact that motor vibration and torque fluctuations are directly transferred through the steering wheel to the hands of the driver must be considered. It is most important to drive the motor with minimum fluctuations so that manufacturers have become aware of the torque fluctuations requirement to be 1~3% of rated torque. This motor for EPS has the following operating requirements: generating torque at standstill, reversing its rotation abruptly, and small fluctuations in torque during operation, and very low vibration and noise.

Fig.1. Column typed EPS system and PMSM

II. METHODOLOGY:-

A)PERMANENT MAGNET MACHINE DESIGN:--

Interior typed permanent magnet (IPM) machines are proposed in different configurations; among them the machine with tangential magnet poles enjoys many features including structural simplicity, mechanical robustness, good flux weakening capability and wide speed range. These features made it a preferred choice for many researchers and manufacturers. Therefore this configuration of IPM machines is also chosen in this paper for design optimization. A one pole pitch cross sectional view of a 6-pole IPM machine with tangential magnet configuration is shown in Fig.A1. The figure mainly details the rotor configuration and dimensions as the stator is usually the same as stator of an induction machine and is not the focus of the present design optimization.

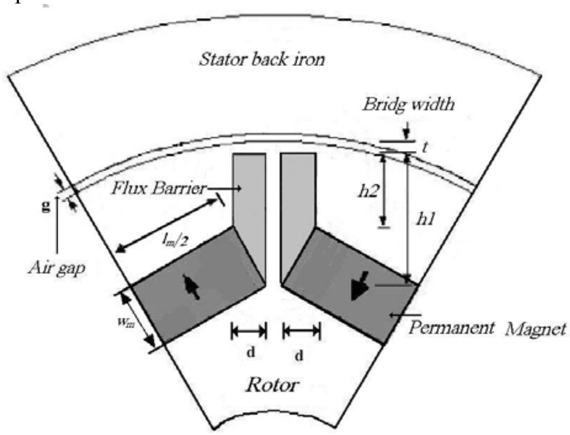

Fig.A1 One pole pitch cross section of IPM Machine

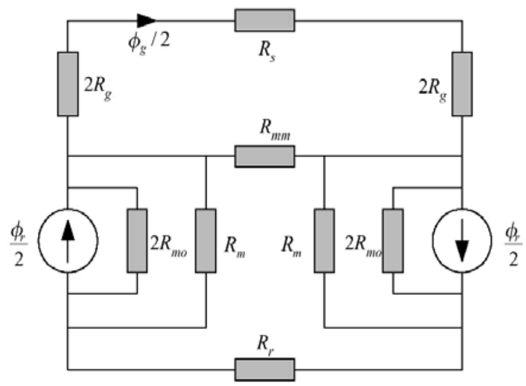

Fig. A2 Magnetic equivalent circuit of PMSM

A pair of half magnet poles, two flux barriers, stator and rotor cores and air gap can be seen in Fig. A1. A magnetic model and an electrical model of the machine are recalled in this section to calculate parameters and variables of the machine needed for a design optimization.

A1. Magnetic Model:-

Magnetic equivalent circuit of one pole pitch of IPM machine is shown in Fig. A2. A detailed magnetic equivalent circuit of the motor in Fig. A1 can be used to obtain an average air gap flux density as [5]:

$$B_g = \frac{C_\Phi}{1+\beta(1+2\eta+4\lambda)} B_r \quad (1)$$

where *Br* is remanence of the magnet, *CΦ =Am/Ag* is the flux concentration factor and *Ag* and *Am* are the cross-sectional areas per pole of the air gap and magnet respectively. The magnetic reluctances of stator and rotor cores are ignored for the sake of simplicity. The values of parameters in

(1) are given by:

$$\beta = \frac{\mu_{rec} K_C g C_\Phi}{w_m} \quad (2)$$

$$\eta = \frac{w_1(h_1+h_2)}{4d\mu_{rec} l_m} \quad (3)$$

$$\lambda \cong \frac{1+\frac{1}{\beta}+2\eta}{2\frac{A_m}{A_{mm}}\frac{B_r}{B_s}-4} \quad (4)$$

where *g* is the air gap length, *KC* is the Carter coefficient, μrec is relative recoil permeability and *Amm=t.l* represents the cross-sectional area of the iron bridge above the nonmagnetic barriers with *t* and *l* being the bridge width and motor stack length, respectively. Also *lm* and wm denote the magnet length and width; and *h*1 and *h*2 represent the inner and the outer flux barrier heights respectively, while *Bs* is a limit of the leakage flux density in the bridge due to saturation. Using *Bg* from (1) in connection with (2)-(4), the maximum value of first harmonic of PM flux linkage is obtained as [5]:

$$\psi_M = \frac{4Dl}{\pi}\left(\frac{K_{w1}N_{ph}}{P}\right) B_g \sin\left(\frac{\alpha\pi}{2}\right) \quad (5)$$

where *Kw1* is the winding factor, *Nph* is the winding turns per phase and *P* is the number of pole pairs and α is a pole-arc to pole pitch ratio. Also *D* is the inner diameter of the stator. The *d*-axis and *q*-axis inductances are given by:

$$L_d = \frac{3\mu_0 Dl}{g}\left(\frac{K_{w1}N_{ph}}{P}\right)^2 \frac{\pi}{8} K_d \quad (6)$$

$$L_q = \frac{3\mu_0 Dl}{g}\left(\frac{K_{w1}N_{ph}}{P}\right)^2 \frac{\pi}{8} K_q \quad (7)$$

where K_d and K_q are defined as:

$$K_d = \left(\alpha - \frac{\sin(\alpha\pi)}{\pi}\right) + \frac{g}{g_e}\left(1-\alpha+\frac{\sin(\alpha\pi)}{\pi}\right) \quad (8)$$

$$K_q = \left(\alpha + \frac{\sin(\alpha\pi)}{\pi}\right) + \frac{g}{g_e}\left(1-\alpha-\frac{\sin(\alpha\pi)}{\pi}\right) \quad (9)$$

and *ge* denotes an effective air gap and is given by:

$$g_e = K_C g \tag{10}$$

with μr being the relative permeability of PM.

A2. Electrical Model:-

A conventional *d-q* electrical model of the machine in asynchronously rotating reference frame can be used in design optimization and evaluation. In this model the flux distribution in the air gap is assumed to be sinusoidal and the iron loss and magnetic saturation are not considered. The motor vector diagram is shown in Fig. A. Voltage equations are expressed as follows:

$$V\sin(\delta) = i_d R_1 + \omega i_q L_q \tag{11}$$

$$V\cos(\delta) = i_q R_1 - \omega i_d L_d + E_f \tag{12}$$

The motor torque is then obtained as:

$$T = \frac{3P}{2}\left(\psi_M + \left(L_d - L_q\right)i_d\right)i_q \tag{13}$$

where *id* and *iq* are the *d*-axis and *q*-axis components of the stator current vector *Is*. Thus the magnitude of *Is* is given by:

$$I_s = \sqrt{i_d^2 + i_q^2} \tag{14}$$

Since an IPM motor torque depends on the stator current

vector components as well as the motor parameters, the design optimization is carried out under the condition of maximum torque per Ampere control. This condition can be as obtained from (11) and (12) as follows [06]:

$$i_d = \Gamma - \sqrt{\left(\Gamma^2 + \frac{I_s^2}{2}\right)} \tag{15}$$

$$i_q = \sqrt{I_s^2 - i_d^2} \tag{16}$$

Where

$$\Gamma = \frac{\psi_M}{4L_d}(\rho - 1) \tag{17}$$

$$\rho = \frac{L_q}{L_d} \tag{18}$$

Flux linkage and inductances can be normalized as follows:

$$\psi_M^* = \sqrt{\left(L_q i_q^*\right)^2 + \left(\psi_M + L_d i_d^*\right)^2}, \quad L^* = \frac{\psi_M^*}{I_{\max}}$$

$$L_{dn} = \frac{L_d}{L^*}, \quad L_{qn} = \frac{L_q}{L^*}, \quad \psi_{Mn} = \frac{\psi_M}{\psi_M^*}$$

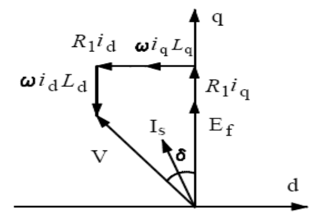

Fig.A Vector diagram of PMSM

A3. Permanent Magnet Materials:--

The property of a permanent magnet of the selection of the proper materials is very important in the design of permanent magnet synchronous machine.

Fig. A3 shows the demagnetization segment of the B-H curve where the permanent magnet is usually designed to operate. The maximum flux density Br corresponding to point A' will be available initially if the magnet is short circuited with steel keepers (no air gap). When the magnet is installed in the machine, the air gap will have some demagnetization effect and the operating point B' will corresponds to the no load line shown in the fig. The slope of the no load line (w.r.t. H axis) will be smaller with higher air gap. With current flowing in the stator winding, the magnetic axis (d^e) armature reaction effect can have a further demagnetization effect, which will further reduce the air gap flow density. A load line corresponding to worst case demagnetization, which may be due to a starting, transient, or machine fault condition is also shown in fig.A3. Once the operating point reaches D and the demagnetization effect is removed the magnet will recover along the recoil line, which has approximately the same slop as the original B-H curve near H=0. In a subsequent operation, the stable operating point will be determined by the intersection of the load line and the recoil line. The magnet is therefore, permanently demagnetized at low load operation. Corresponding to the vertical distance between A and A'. The worst case demagnetization point is therefore vitally important for machine performance and should be closely controlled. Alternatively, if the material of the permanent magnet is selected to have a straight line demagnetization curve, the recoil line will coincide with the demagnetization line irrespective of the worst case demagnetization point. (i.e. permanent demagnetization will be negligible).

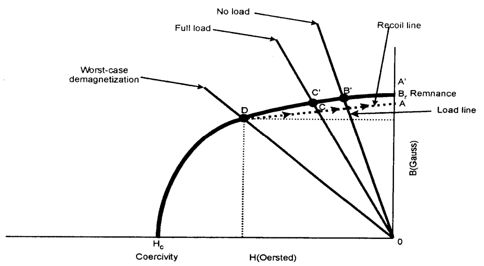

Fig .A3 PM Materials characteristics

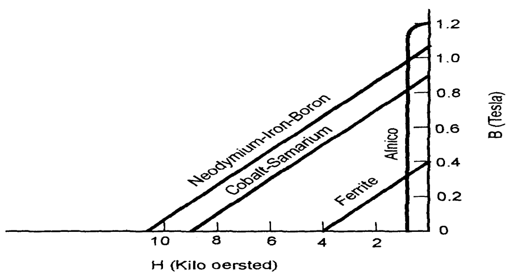

Fig. A4 Permanent Magnet characteristics

Fig. A4 shows the characteristics of several possible PM materials. A lines has high service temperature good thermal stability and high flow density, but the disadvantage is low coercive force coupled with squarish B-H characteristics, which means the permanent demagnetization high so that it is practically unsuitable for a PM machine. Barium and strontium ferrites are widely used as permanent magnets. Ferrite has the advantages of low cost and plentiful supply of low material. They are also easy to produce and their process is suited for high volume, as well as moderately high service temperature (400^{0}C). The magnet has a practically linear demagnetization curve, but its remnance (Br) is low. Therefore, the volume and weight of the machine tends to be high. The cobalt samarium (COSM) magnet is made of iron, nickel, cobalt and rare Earth Samarium. It has the advantages of high remnance, high energy density defined by (BHmax) and linear demagnetization characteristics. The service temperature can be as high as 300^{0}C and the temperature stability (% changes in B/^{0}C) is very good. (-0.03 %). But the material is very expensive because of an inadequate supply of samarium. The Neodymium iron boron (Nd-fe-B) magnet has the highest energy density, high remnance and very good coercively (HC). The disadvantage are low service temperature (150^{0}C) and susceptibility to oxidation unless protected by a coating. Besides the temperature stability (-0.13%) is interior to that of a COSM magnet. The material is expensive compared to ferrite, but because of higher energy density the machine weight is reduced. The application of Nd-fe-B magnets is growing in PM machines.

B) EPS SYSTEM DESIGN:-

According to the motor mounted location, the EPS system can be divided into three types, which are a column assist type, a pinion assist type, and a rack assist type, respectively. There is serious noise request in the column assist type since the type is closest to drivers than other two types. Oppositely, the column assist type is farthest to the engine and chassis than other two types. The request of water and heat proof can be reduced. The pinion assist type is better than the column assist type in shock and noise. An advantage of the rack assist type is that the assist motor can be mounted on any locations of the rack. Therefore, the rack assist type has the elasticity of mechanism integration in chassis. In applications, the column assist type is popular and small power nowadays. For this reason, this research is based on the column assist type.

B.1 EPS hardware system structure

Figure 2 shows the hardware structure of the EPS system. Two sensors which are an angle sensor and a speed sensor are applied to detect the steering wheel angle and the vehicle speed, respectively. The two sensors return feedback signals real-time to the EPS controller for the assist strategy analysis. Through the closed-loop control of the assist motor, the assist motor can provide desired output torque. Thus, the produced motor torque combines with the driver torque to drive the rack.

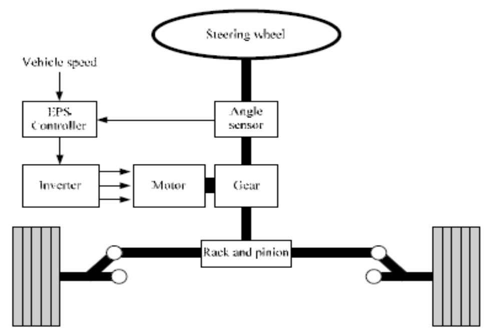

Figure B1 EPS hardware structure

B.2 EPS System model

An EPS dynamic model can be represented as Fig. B2. According to the Newton motion law, the dynamic equations of an EPS system can be represented as Eq. (1)-(3) [3].

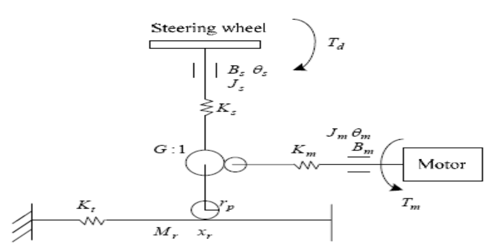

Figure:B2 EPS dynamic model

$$J_s \frac{d^2\theta_s}{dt^2} + B_s \frac{d\theta_s}{dt} + K_s\left(\theta_s - \frac{x_r}{r_p}\right) = T_d \qquad (1)$$

$$M_r \frac{d^2x_r}{dt^2} + B_r \frac{dx_r}{dt} + K_t x_r = \frac{K_s}{r_p}\left(\theta_s - \frac{x_r}{r_p}\right) + \frac{GK_m}{r_p}\left(\theta_m - \frac{Gx_r}{r_p}\right) \qquad (2)$$

$$J_m \frac{d^2\theta_m}{dt^2} + B_m \frac{d\theta_m}{dt} + K_m\left(\theta_m - \frac{Gx_r}{r_p}\right) = T_m \qquad (3)$$

where *dT* is the driver torque, θ is the steering wheel angle, *rp* is the radius of the pinion. *Js* and *Jm* are the rotational moment of inertia of the column steering and the motor, respectively. *Bs* , *Br* , and *Bm* are the viscous damping coefficient of the column steering, the rack, and the motor, respectively. *Ks* , *Kt* , and *Km* are the torsion bar stiffness, the spring stiffness, and the motor shaft stiffness. *xr* is the rack position. *Mr* is the mass of the rack. *Tm* is the motor torque, θ *m* is the motor angle, and *G* is the motor gear ratio. Note that *Kt xr* in (2) is the automatic return torque of the front tires while a car is turning. While the steering wheel angle is under 180, the automatic return torque is almost linear to the steering wheel angle.

C) MOTOR DRIVE DESIGN:-

Permanent magnet synchronous motor is used here with three stator windings for the motor operation. Three supply voltages are obtained with the help of three phase MOSFET bridge inverters. MOSFET bridges are fed with fixed dc voltage which is obtained by rectifying ac voltage available from ac mains with the help of Diode Bridge. Shunt capacitor filter is used for filtering purpose. Operation of the MOSFET Bridge is controlled by the control circuit. Gating pulses required to turn the MOSFET On are obtained from the control circuit. By controlling the frequency of the gating pulses frequency of the output from MOSFET Bridge is controlled. Control circuit consists of clock generator counter and EPROM. First data required to generate gating pulses is calculated and is stored in EPROM. This data is outputted at the output of the EPROM by generating the address of the memory location with the help of 4 bit binary ripple counter. Clock input required for the operation of the counter is generated using IC 555 in a stable mode. Frequency of the gating signals coming out of EPROM is dependent on the frequency with which addressing is done which is turn dependent on the clock frequency. Thus by varying the clock frequency of gating signal is varied. If frequency of gating signal is varied, then the MOSFET bridge output frequency is also varied. Thus we obtain variable frequency output.Gating signal outputted by EPROM can not be directly applied to MOSFET Bridge as they are very weak. So isolator and driver circuit is used. Necessary isolation of low power control circuit from high power bridge circuit is obtained by using opt isolator.

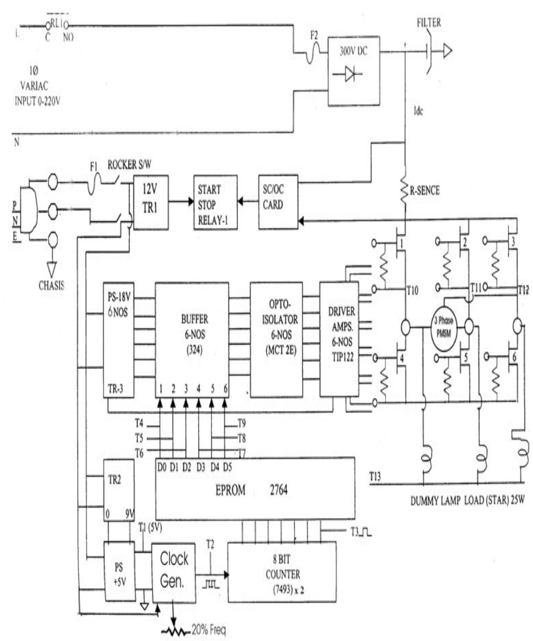

Fig.C1 Block Diagram of permanent magnet synchronous motor Drive

III. RESULT ANALYSIS:

Test Point Waveforms:

The waveforms at various points in the control circuit and power circuit are shown in the fig.

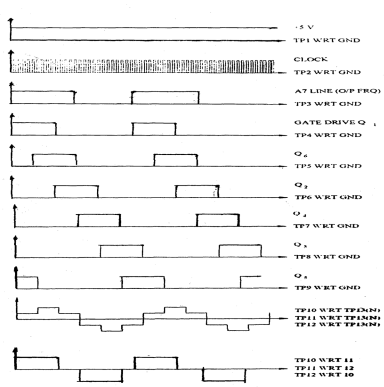

Fig. 5.1 Waveforms at various Test Points

Observation Tables:

Table No.1: Variation in the speed of the motor as a function of inverter frequency

Sr. No.	Time (m.s.)	Frequency (Hz)	Expected Speed (rpm)	Measured Speed (rpm)	Voltage (Volts)
1	30	33.3	999	1010	265
2	25	40	1200	1226	270
3	22	45.4	1362	1380	270
4	20	50	1500	1520	270
5	18	55.5	1665	1682	270
6	17	59	1770	1790	270

Table No.2: Variation in the speed of the motor as a function of load at constant frequency of 33.3 Hz

Sr.No.	Load (gm)	Expected Speed (rpm)	Measured Speed (rpm)	Voltage (volts)
1	500	999	1010	270
2	100	999	1010	270
3	150	999	1010	270
4	200	999	1010	270
5	250	999	1010	270
6	300	999	1010	270

Table No.3: Variation in the speed of the motor as a function of load at constant frequency of 50 Hz.

Sr.No.	Load (gm)	Expected Speed (rpm)	Measured Speed (rpm)	Voltage (Volt)
1	500	1500	1520	270
2	1000	1500	1520	270
3	1500	1500	1520	270
4	2000	1500	1520	270
5	2500	1500	1520	270
6	3000	1500	1520	270

Result Table:

Table 1:

Sr. No.	Load (gm)	Frequency (Hz)	Speed (rpm)	Torque (N-m)	Output Power(W)
1	500	33.3	1010	0.14715	15.55
2	1000	33.3	1010	0.2943	31.12
3	1500	33.3	1010	0.4414	46.68
4	2000	33.3	1010	0.5886	62.19
5	2500	33.3	1010	0.7357	77.81

Table 2:

Sr. No.	Load (gm)	Frequency (Hz)	Speed (rpm)	Torque (N-m)	Output Power (W)
1	500	50	1520	0.14715	23.47
2	1000	50	1520	0.2943	46.84
3	1500	50	1520	0.4414	70.25
4	2000	50	1520	0.5886	93.68
5	2500	50	1520	0.7357	117.1
6	3000	50	1520	0.8829	140.5

Table 3:

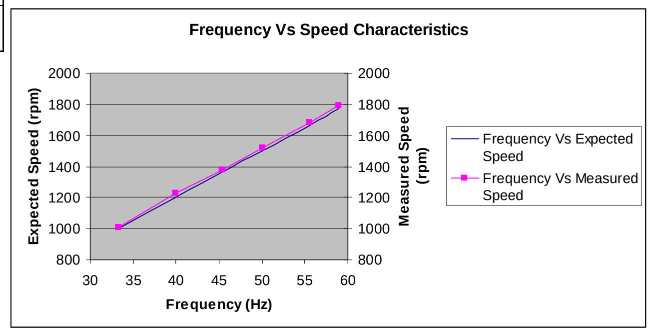

Fig. Frequency Vs Speed characteristics

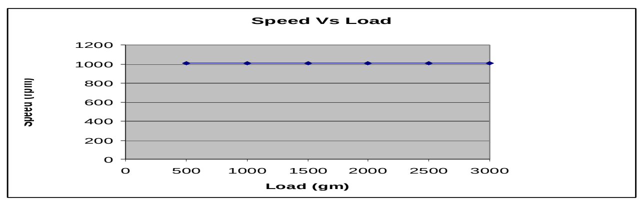

Fig. Speed Vs Load Characteristics at Constant Frequency = 33.3 Hz

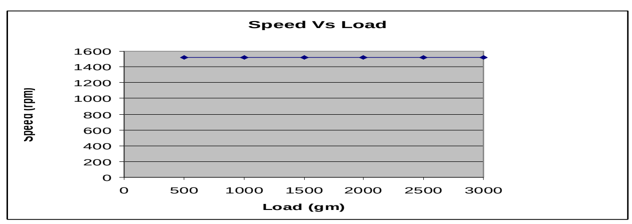

Fig. Speed Vs Load Characteristics at Constant Frequency = 50 Hz

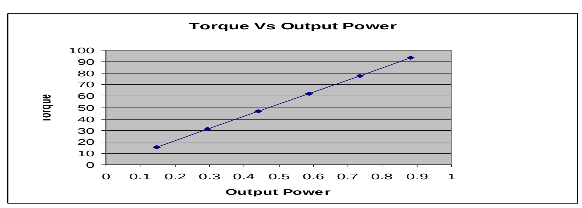

Fig. Torque Vs Output Power at frequency 33.3 Hz

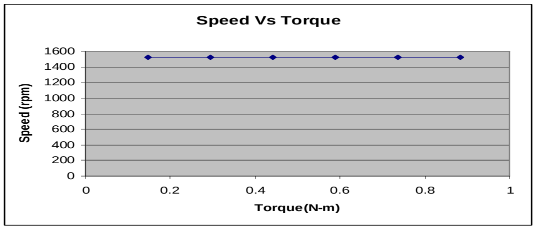

Fig. Speed Vs Torque at Constant Frequency = 50 Hz

III. CONCLUSION:-

In this paper an optimal design of a permanent magnet machine has been presented. A reduction in the permanent magnet material for a constant torque and an extension in the constant power region have been chosen as the optimization aims. For this purpose the analytical model of the permanent magnet synchronous machine has been derived.. It was seen that with the same developed torque the magnet volume decrease about 9% and also the power speed characteristic was going to be better that typical machine. In this paper Design of permanent magnet synchronous machine gives constant torque in the result table. Hence This machine is suitable for Electric power steering (EPS) used in automotive application.

V) REFERENCES:-

[1] M. Zeraoulia, and *et al*, "Electric motor drive selection issues for HEV propulsion systems: A comparative study," *IEEE Trans. Vehicular Tech.,* vol. 55, pp.1756-1763, Nov. 2006.
[2] L. Chang, "Comparison of ac drives for electric vehicles- A report on experts' opinion survey," IEEE AES Systems Magz. pp.7-10, Aug. 1994.
[3] C. Mi, "Analytical design of permanent-magnet traction-drive motors,"IEEE Trans. Magn., vol. 42,pp. 1861-1866, July, 2006.
[4] S. Wu, L. Song, and S. Cui, "Study on improving the performance of permanent magnet wheel motor for the electric vehicle application," IEEE Trans. Magn., vol. 43, pp. 438-442, Jan 2007.
[5] C.C. Hwang, S.M. Chang, C.T. Pan, T.Y. Chang, "Estimation of Parameters of Interior Permanent Magnet Synchronous Motors," *J. Magnetism and Magnetic Materials*, pp. 600–603, 2002.
[6] S. Vaez-Zadeh, A.R. Ghasemi, "Design Optimization of Permanent magnet Synchronous Motors for High Torque Capability and Low Magnet Volume," Electric Power Systems Research, Vol.74, pp. 307- 313, Mar. 2005.
[7] S. Vaez-Zadeh, M. Tavakkoli, 'Optimal design of permanent magnet synchronous motor from two points of view: Infinite maximum speed and extended constant torque region," in Proc. 11th Iranian electrical engineering conf., ICEE, Shiraz, May 2003, vol. 4, pp. 231-239. (in Persian).
[8] J. Song, K. Boo, H. S. Kim, J. Lee, and S. Hong, *Model development and control methodology of a new electric power steering system*, Proc. Inst. Mech. Eng. Part D-J. Automob. Eng., vol. 218, pp. 967-975, 2004.

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