Performance Analysis of Permanent Magnet Synchronous Motor

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***Abstract*— The permanent magnet synchronous motors (PMSM) became more plausible being used in traction applications due to their high torque to weight ratio properties and extensive flux weakening properties to extend the constant power region to obtain maximum speed of PMSM drives. This paper presents the close loop control technique which is field oriented control (FOC) for a salient pole PMSM drives using a proportional-integral-derivative (PID) controller as a speed controller. An imposing model of FOC with flux weakening control is submitted to inspect the performance of PMSM drives on top of a extensive range of speed which includes both constant torque region and constant power region. A space vector pulse width modulated (SVPWM) three phase voltage source inverter (VSI) fed PMSM drive is simulated in MATLAB/Simulink. The maximum speed which happens in flux weakening zone is detected that it depends on the PMSM motor parameters. It is ahead condescended by the result obtained from simulation of PMSM drive under examination.**

***Keywords*— FOC, PMSM, Field-Weakening region, SVPWM**

I. INTRODUCTION

The permanent magnet synchronous motors (PMSM) presently get too plausible due to their transcendent properties like high torque to weight ratio, high flux density, high power factor, low noise, smaller volume and size, longer life, and superior dynamic performance. The PMSMs are widely used with the current controlled voltage source inverter (VSI) for industrial and traction applications because of their excellent properties. In industrial applications, servo motors demand constant torque region and in traction applications, both constant torque and constant power region are necessary. Due to these properties, PMSM drive is also chartered for aircraft and vehicular applications where its high credibility is a most crucial feature.

In the close loop speed control, PMSM uses two advanced execution speed control techniques. These are vector control, also known as field oriented control, and direct torque control. These two control techniques are invented for asynchronous motor drives which are also suitable for PMSM control. The DTC chooses a appropriate voltage based on a predetermined switching table to get the desire torque. But, due to its initial execution and poor speed operation, this technique is not used these days. Now, FOC is used due to their wonderful dynamic performance for PMSM. In FOC, stator current is splitted into flux generating (d-axis current) and torque generating (q-axis current) component for getting the disunited control of PMSM drives.

In the literature, papers have dealt with direct torque control and field oriented control with flux weakening control for PMSM drives. Poonam Jayal and G. Bhuvaneswari [1] have experimentally presented the control of PMSM drive using FOC and field weakening control. They investigated the PMSM drive from few hundred speed to 3500 rpm speed. They used PI controller as speed controller which give satisfactory results. Dongyun Lu and Narayan C. kar proposed extensive groupage and overviews of flux weakening control Strategy for PMSMs. Several control algorithms have been examined in this paper with advantage and disadvantage that help explorer to select suitable flux weakening control algorithm for traction applications. S. Dwivedi and Bhim Singh [3] presents a comparative idea with verification of two close loop control techniques which are vector control (FOC) and direct torque control (DTC). They investigated these two techniques for PMSM drives experimentally and observed that DTC gives best control strategies for control of speed of PMSM drive. J. O. Estima and A. J. Marques [4] presents a comparative work regarding PMSM drives for without any fault and fault operating conditions. During inverter faults condition, the stator phase current stops being sinusoidal and directing to beating torque which affects machine performance but power factor improve. V. R. Jevremovic [5] has proposed a simple but robust closed-loop flux weakening regulator for PMSM. The important features of this regulator is that it is single gain and it is independent of motor parameters. it operates satisfactory in both regions and provides expansion of PMSM speed range.

Leopold Sepulchre [6] has presented a control algorithm for flux weakening strategy in d-q frame for PMSM drive which enables to drive these machines without depending upon the speed of drives. A algorithm is proposed to figure out the current references in the stator reference frame for salient poles PMSM.

This paper presents a complete modeling and implementing of FOC for PMSM drive and also utilizing flux weakening control to obtain speed above base speed. Drive design is tested using MATLAB/SIMULINK for FOC implemented PMSM drive in constant torque and flux weakening regions.

II. MODELING AND FOC OF PMSM DRIVE

The air-gap flux in a PMSM is constant until no current is provided through the stator side in d-axis. With the help of d-axis stator current, the air gap flux magnitude can be modified to achieve maximum speed of PMSM drive in constant power regions.

A. Mathematical Modeling of the PMSM

The mathematical modeling of PMSM is derived by supposing no saturation, sinusoidal electromotive force, zero constant and varriable losses. The stator voltage equations for a PMSM in the synchronously revolving reference frame (d-q reference frame) are as follows:

$$V_{sd} = i_{sd}R_s + L_s\frac{di_{sd}}{dt} - L_s w_e i_{sq} \quad (1)$$

$$V_{sq} = i_s q R_s + L_s\frac{di_{sq}}{dt} + L_s w_e i_{sd} + \lambda_m w_e \quad (2)$$

Where, V_{sd} and V_{sq} are direct(d) and quadrature(q) axis stator voltage components. i_{sd} and i_{sq} are d-q axis stator current components. R_s and L_s are stator per phase resistance and inductance. w_e is electrical rotor speed. λ_m is permanent magnet flux linkage

The torque evolved by the PMSM is given as:

$$T_e = \frac{3}{2}\times\frac{P}{2}\lambda_m i_{sq} = k_T i_{sq} \quad (3)$$

Where,

P = Number of pole

K_T = torque constant

The evolved torque is equilibration through load torque, accelerating torque and damping torque of the system and this mechanical equation can be showed as:

$$T_e - T_L = J\frac{dw_m}{dt} + Bw_m \quad (4)$$

where,

T_e = Electromagnetic Torque

T_L = Load Torque

J = Moment of inertia

B = Damping Coefficient

w_m = Mechanical Rotor speed in rad/sec

B. Field-oriented control strategy of PMSM

The determination of the position of field flux is the origin of FOC. In Field oriented control, the stator current is transmuted to synchronously revolving reference frame i.e. d-q reference frame. The stator current is splitted into two components i_d and i_q. The d-axis component (i_d) is responsive for flux production while q-axis current (i_q) is responsible for torque production. The idea of splitting the stator current is utilised to control the flux and torque for speed control similar as dc motor. Therefore, when this FOC technique is carried out, it permits an substantive control of the produced torque and field flux to achieve better dynamic performance. The block diagram of Field-oriented controlled PMSM is demonstrated in the figure 1.

III. FLUX WEAKENING STRATEGY OF PMSM

The advanced PMSM drives become too plausible in industrial and traction applications day by day. Therefore enhancing the speed range of PMSM drive is necessary and this is done only with the help of flux weakening control strategy.

A. Limitations of Flux-weakening Control

The voltage limit V_{max} that the voltage source inverter (VSI) can able to supply the PMSM as input is extented by DC link voltage and space vector PWM (SVPWM) strategy. The maximum stator current I_{max} is also decided by the VSI rating and machine thermal ratings. Let V_{max} and I_{max} are the maximum inverter output per phase voltage and current respectively. Therefore, the limits of voltage and current which also limitation on maximum attainable speed of PMSM drive are given as follows:

$$i^2_{sd} + i^2_{sq} \le I^2_{max} \quad (5)$$

$$v^2_{sd} + v^2_{sq} \le V^2_{max} \quad (6)$$

Here, $V_{max} = 0.577\ V_{dc}$ (for space vector PWM)

B. Description of Flux Weakening Control

The flux weakening control is carried out by introducing negative d-axis current into stator to reduce the rotor flux. Due to this negative current, q-axis component of stator current reduces inevitably. Thus electromagnetic torque get reduced. The block diagram of Flux-weakening control of PMSM is demonstrated in the figure 2.

This control strategy is introduced by the introduction of outer external loop. In the flux weakening control, if the voltage exceed the limitation of voltage ($V_{max} = 0.577V_{dc}$) then the flux Weakening controller feels the error of the voltage and inject negative d-axis current. At the speed below reference speed below reference speed, the output voltage magnitude of the current regulation is generally less than V_{max}. Therefore, the flux weakening algorithm is not operated.

The maximum speed that a PMSM can be achieved at no load, in the flux weakening zone, is calculated from equations (1) and (2) is given by :

$$w_{mn}(\max) = \frac{\sqrt{v_{sn}^2 - (i_{sn}R_{sn})^2}}{1 + L_{sn}i_{sn}} \quad (7)$$

where, w_{mn} is the per unit speed, v_{sn} is the per unit stator phase voltage, R_{sn} and L_{sn} are the per unit per phase resistance and inductance respectively.

IV. PMSM DRIVE SYSTEM DESCRIPTION

The figure 1 shows the complete basic building block of field Oriented control of PMSM drive using Flux weakening control. The drive consists of PID controller as speed controller, space vector PWM (SVPWM), the PMSM and three phase VSI to supply the PMSM drive system. This system is functioning for constant torque and constant power zone.

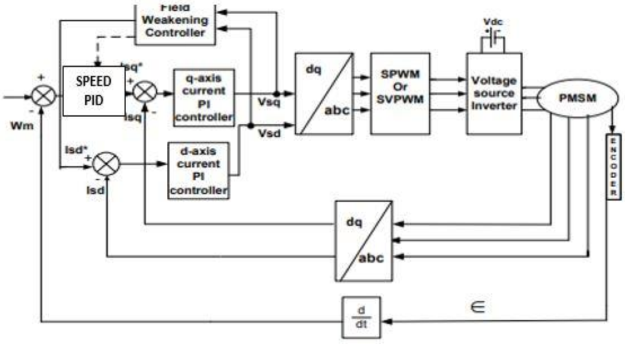


figure 1 Block diagram of Field oriented controlled PMSM

In this close loop system, the time constant of system are designed such that the internal current loop responds faster than external speed loop. The figure 2 shows the block diagram of Flux-weakening controller for PMSM drive system. When speed is greater than rated speed, flux weakening controller operates and inject negative d-axis current which invariably reduces q-axis current. Hence electromagnetic torque reduces. The maximum speed that can a PMSM drive system attained is achieved in this region.

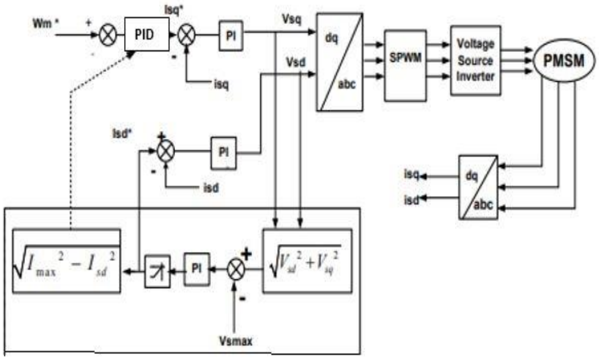


fig. 2. Block diagram of Flux-weakening control of PMSM

V. MAXIMUM ATTAINABLE SPEED IN FLUX WEAKENING REGION

The PMSM parameters utilised for simulation are given in table-I and are utilised for investigative calculation.

TABLE-I
PARAMETERS OF PMSM MOTOR

Base power (P_{base})	750 watts
No. of poles	2
Base speed	3000 rpm
Base torque (T_{base})	2.39 Nm
Base current (I_{base})	2.19 A
Per phase stator resistance (R_s)	0.6 Ohm
Per phase stator inductance (L_s)	0.002 H
Inertia constant (J)	0.00015 kg-m^2
Torque constant (K_T)	0.59Nm/A_{rms}
PM flux linkage (λ_{pm})	0.8 Wb
Phase to phase supply voltage (V_{LL}) (Ideal supply source)	230 Volts RMS
DC voltage (V_{DC})	321 Volts

From the above values, analytical calculation can be done as follows:

Base voltage (V_{base}) = $P_{base}/3\times I_{base}$ = 114.115 volts

Base speed (w_{base}) = P_{base}/T_{base}= 313.81 rad/sec

Base Impedance (Z_{base}) = V_{base}/I_{base} = 52.13 Ohms

Base inductance (L_{base}) = 0.166 H

Per unit phase resistance (R_{sn}) = R_s/Z_{base} = 0.0155

Per unit phase inductance (L_{sn}) = L_s/L_{base} = 0.0126

Per phase stator voltage (V_s) = $0.577V_{dc}/1.414$ = 130.97

Per unit stator voltage (V_{sn}) = V_s/V_{base} = 1.147

After putting these values in equation (7), the maximum attainable speed by PMSM drive in field weakening region can be given as:

$$w(max) = 1.162$$

For a base speed of 3000 rpm, the utmost speed of the PMSM drive, in rpm, becomes

$$N = 1.162\times3000 = 3485 \text{ rpm}$$

VI. SIMULATION AND RESULTS

The accomplished model of field-oriented controlled PMSM drive system is developed in MATLAB/SIMULINK environment to emulate the deportment of the drive with PID controller. Figure 3 shows the simulated model of the field-oriented controlled PMSM drive system. The transient, steady state response and dynamic response above base speed for this PMSM drive have been investigated for several operational circumstances.

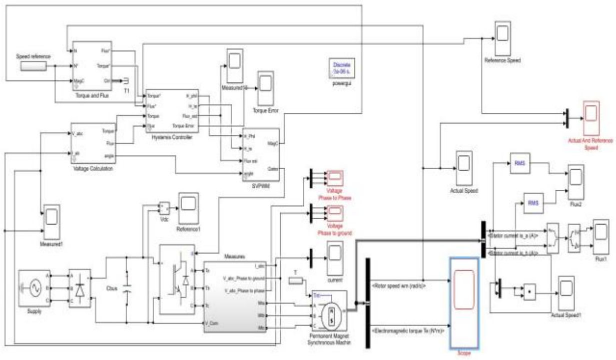
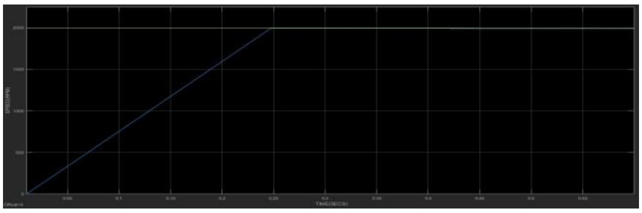


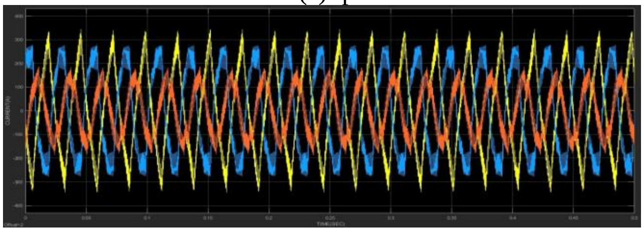
figure 3. MATLAB/Simulink Model of Field Oriented controlled PMSM drive

(i). Starting Response of the PMSM drive (below base speed)

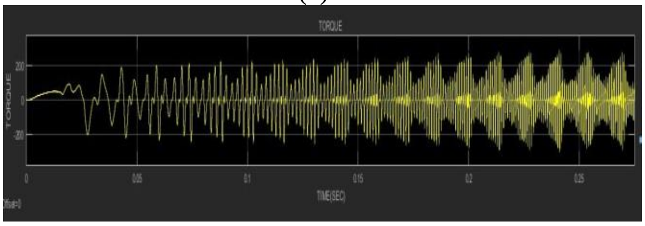
Figure 4(a) demonstrates the simulated result of the rotor speed of Field oriented controlled (FOC) PMSM drive. From the figure, it is observed that the PMSM drive reaches at a speed of 2000 rpm standstill in 0.24 sec with load torque 0.4 p.u. without any undershoot or overshoot. figure 4(b) and 4(c) shows the simulated results of the three phase stator current and the torque during this Operating condition.



4(a)Speed



4(b)Current

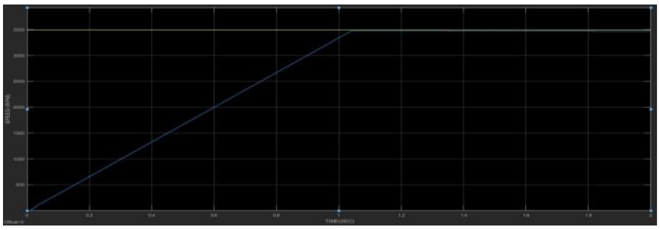


4(c) Torque

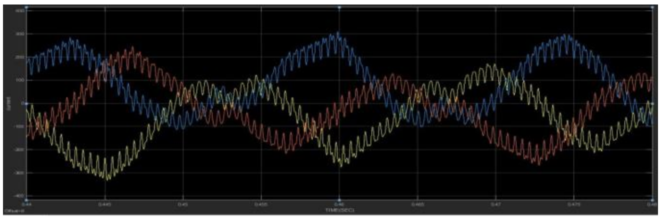
figure 4. Transient response of the PMSM drive below base speed

(ii) Dynamic Response of the PMSM Drive (Above Base Speed)

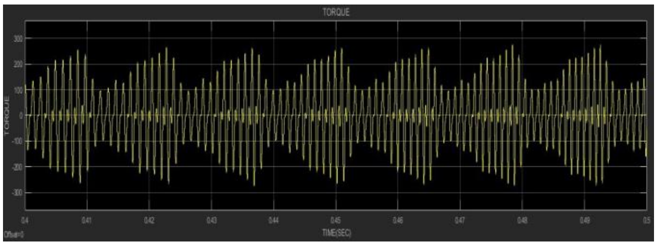
Figure 5(a) demonstrates the simulated result of the utmost attainable speed of the PMSM drive with flux-weakening control. For this, the reference speed is modified to 3490 rpm. Then, the motor reaches at its maximum attainable speed of 3490 rpm in 1.05 sec at load torque 0.4 p.u. with slight overshoot. Since this Operation performed under flux-weakening region, the electromagnetic torque capability reduces but machine delivers its constant power.



5(a) Speed



5(b) Current

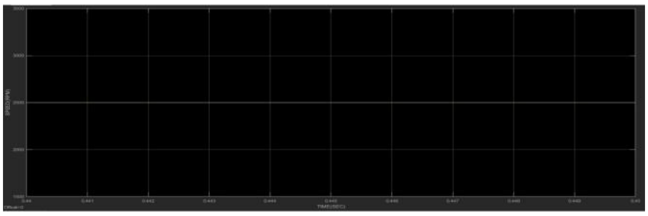


5(c) Torque

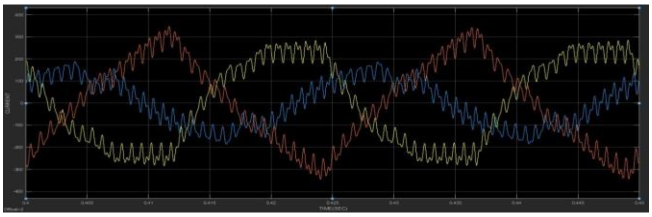
figure 5. Response of the PMSM drive above base speed

(iii) Steady State Response of the PMSM Drive (Below Base speed)

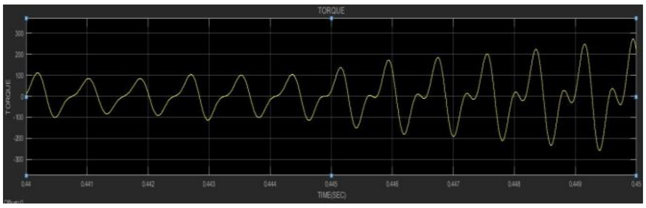
Figure 6 demonstrates the simulated results of the speed of the speed of the PMSM drive, the three phase stator current and the torque for steady state Operation with load torque 0.4 p.u.



6(a) Speed



6(b) Current



6(c) Torque

Figure 6. Steady state response of the PMSM drive

VI. CONCLUSIONS

The Permanent Magnet Synchronous Motor drives gaining more and more popularity in the varriable speed field due to their enhanced controllability, high torque to weight ratio, and better dynamic performance. This paper presents an attempt to unfold the excellent performance of PMSM drive which is controlled by field oriented control (FOC) technique using field weakening control for wide speed Operation. In this work, a proportional-integral-derivative controller (PID) is proposed as speed controller to improve the speed performance of PMSM drives. The PMSM drive has been examined under different operational circumstances such as starting, steady state and by changing reference speed for a broad range of speed operation. The performance of the proposed control is inspected through MATLAB/SIMULATION which showed that the drive is working nicely in the constant torque and constant power zones.

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