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Enhancing Stability & Performance Analysis of PMSM Using SVPWM & PI Controller

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Abstract— **This paper presents the enhancing stability & performance analysis of permanent magnet synchronous motor (PMSM) using space vector PWM & PI controller. Usually, a proportional-integral (PI) controller is used as a speed controller for a Permanent Magnet Synchronous Motor (PMSM) in high performance drive system despite the existence of many modern nonlinear control techniques. However, a PI controller is sensitive to speed changes, load disturbances and parameters variation without continuous tuning of its gains. The conventional approach to these issues is to tune the proportional and integral gains manually by observing the response of the system. The tuning of the PI parameters must be made on-line and automatic in order to avoid tedious tasks in manual control. The SVPWM inverter enables to feed the motor with a higher voltage with low harmonic distortions than the conventional sinusoidal PWM inverter. The control strategy of the inverter is the voltage / frequency control method, which is based on the space-vector modulation technique. The SVPWM inverter enables to feed the motor with a higher voltage with low harmonic distortions than the conventional PWM inverter. The SVPWM allows to having a higher torque at high speeds, and a higher efficiency. The SVPWM inverter is used to offer 15% increase in the dc-link voltage utilization and low output harmonic distortions compared with the conventional sinusoidal PWM inverter. The proposed PMSM drive system involving the field-oriented control scheme not only decouples the torque and flux which provides faster response but also makes the control task easy. The performance of the proposed model is simulated. The advantages of the proposed model are confirmed by the simulation results.**

Index Terms— Permanent Magnet Synchronous Motor, Proportional-Integral Controller, SVPWM, Harmonic distortions.

I. Introduction

Recently, an increased interest in application of permanent magnet synchronous motors (PMSM) in speed controlled drives has been observed. This is stimulated mainly by:

- Development of modern high switching frequency semiconductor power devices (as for example IGBT modules of 5-th generation)
- New rare earth magnetic materials as samarium-cobalt (Sm-Co) or neodymium-iron boron (Nd-Fe-B).
- Specialized digital signal processor (DSP) for AC drive applications with integrated PWM function, A/D converters as well as processing of encoder signals (e.g ADMC401, TMS320FL24XX, TMS320FL28XX).

Synchronous motors with an electrically excited rotor winding have a conventional three phase stator winding (called armature) and an electrically excited field winding on

the rotor, which carries a DC current. The armature winding is similar to the stator of induction motor. The electrically excited field winding can be replaced by permanent magnet (PM). The use of permanent magnets has many advantages including the elimination of brushes, slip rings, and rotor copper losses in the field winding. It leads to higher efficiency. Additionally since the copper and iron losses are concentrated in the stator, cooling of machines through the stator is more effective. The lack of field winding and higher efficiency results in reduction of the machine frame size and higher power/weight ratio.

Generally, the permanent magnet AC machines can be classified into two types: trapezoidal type called “brushless DC machine” (BLDCM) and sinusoidal type called permanent magnet synchronous machine (PMSM). The BLDC machines operate with trapezoidal back electromagnetic force (EMF) and require rectangular stator phase current. The PMSM’s generate sinusoidal EMF and operate with sinusoidal stator phase current.

Among the main advantage of PM machines are :

• High air gap flux density,
• Higher power/weight ratio,
• Large torque/inertia ratio,
• Small torque ripple,
• High speed operation,
• High torque capability (quick acceleration and deceleration),
• High efficiency and high cos φ (low expense for the power supply),
• Compact design.

Recently the PMSM are also used as adjustable speed drives in variety of application such as fans, pumps, compressors, blowers. Another area is automotive application as an alternative drive in hybrid mode with classical engine. The power of offered synchronous motors is in the range several kW to MW.

The main requirements for high performance PWM inverter-fed PMSM drive can be formulated as follows:

• Operation with and without mechanical motion sensor,
• Fast flux and torque response,
• Available maximum output torque in wide range of speed operation region,
• Constant switching frequency,
• Uni-polar voltage PWM,
• Low flux and torque ripples,

- Robustness to parameters variation,
- Four quadrant operation.

The PMSM control methods can be divided into *scalar* and *vector control*. According to, in scalar control, which based on a relation valid for steady states, only the magnitude and frequency (angular speed) of voltage, currents, and flux linkage space vectors are controlled. Thus, the control system does not act on space vector position during transient. Therefore, this control is dedicated for application, where high dynamics is not demanded. Contrary, in vector control, which is based on relation valid for dynamics states, not just magnitude and frequency (angular speed), but also instantaneous position of voltage, current and flux space vectors are controlled. Thus, the control system adjusts the position of the space vectors and guarantee their correct orientation for both steady states and transients.
The scalar constant V/Hz control for PMSM without damper winding (squire cage) is not simple as for induction motor. It requires additional stabilization control loop, which can be provide by feedback from: rotor velocity perturbation, active power or DC-link current perturbation.
The most popular vector control method known as field oriented control (FOC) gives the permanent magnet synchronous motor high performance. In this method the motor equation are transformed in a coordinate system that rotates in synchronism with permanent magnet flux. It allows separately and indirectly control flux and torque quantities by using current control loop with PI controllers like in well known DC machine control.
The space vector pulse width modulation with PI controller in PMSM allows achieving fixed switching frequency, considerably reduce switching losses as well as torque and current ripples. Also requirement of very fast sampling time is eliminated. Therefore, this new method is subject of this paper.

II. PMSM

A permanent magnet synchronous motor is a revolving-field type where the field magnet rotates to assume the brushless with a synchronous motor which uses a permanent magnet for the field magnet. Figure 2.1 shows the structure of cylindrical shape.

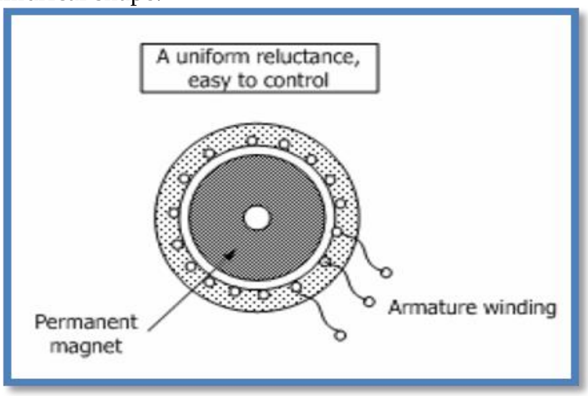

Fig 2.1: Structure of surface permanent magnet synchronous motor

2.1 Representation of three-phase AC circuit equation

Figure 2.2 is the equivalent circuit of 3 phase cylindrical permanent magnet synchronous motor. The circuit equation of the relation of voltage, current and impedance from the equivalent circuit becomes.

$$\begin{bmatrix} v_{ua} \\ v_{va} \\ v_{wa} \end{bmatrix} = \begin{bmatrix} R_a + PL'_a & -\frac{1}{2}PM'_a & -\frac{1}{2}PM'_a \\ -\frac{1}{2}PM'_a & R_a + PL'_a & -\frac{1}{2}PM'_a \\ -\frac{1}{2}PM'_a & -\frac{1}{2}PM'_a & R_a + PL'_a \end{bmatrix} \begin{bmatrix} i_{ua} \\ i_{va} \\ i_{wa} \end{bmatrix} + \begin{bmatrix} e_{ua} \\ e_{va} \\ e_{wa} \end{bmatrix}$$

Here, v_{ua} , v_{va} , v_{wa} are the armature voltage of *u*,*v*,*w* phase. i_{ua}, i_{va}, i_{wa} are the armature current of *u*,*v*,*w* phase. e_{ua} , e_{va} , e_{wa} are a speed electromotive force which is induced in the *u*,*v*,*w* phase armature winding by permanent magnet magnetic field. R_a is the armature winding resistance. L_a is self-inductance of the armature winding. M_a is a mutual inductance between armature winding. *P*(= *d dt*) is a differential operator. When the maximum value is assumed to be φ_{fua} ,φ_{fva} ,φ_{fwa} field magnets of *u*,*v*,*w* phase armature winding interlinkage fluxes to generate e_{ua} , e_{va} , e_{wa} becomes.

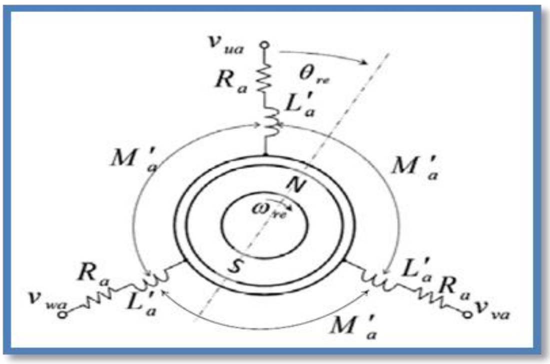

Fig 2.2: The equivalent circuit of three-phase cylindrical permanent magnet synchronous motor

$$\phi_{fua} = \Phi'_{fa} \cos \theta_{re}$$
$$\phi_{fva} = \Phi'_{fa} \cos (\theta_{re} - 2 \quad / 3) \qquad (1)$$
$$\phi_{fwa} = \Phi'_{fa} \cos (\theta_{re} + 2 \quad / 3)$$

Here, θ_{re} is an angle of the field magnet taken clockwise based on *u* phase of armature winding (electrical angle), and ω_{re} the angular velocity of the magnetic field (electrical angle) are express as follow:

$$\theta_{re} = \qquad _{re}\, dt \qquad (2)$$

In this case, e_{ua} , e_{va} , e_{wa} becomes:

$$e_{ua} = P\phi_{fua} = -\omega_{re}\, \Phi'_{fa} \sin \theta_{re}$$
$$e_{va} = P\phi_{fva} = -\omega_{re}\, \Phi'_{fa} \sin (\theta_{re} - 2 \quad / 3) \qquad (3)$$
$$e_{wa} = P\phi_{fwa} = -\omega_{re}\, \Phi'_{fa} \sin (\theta_{re} + 2 \quad / 3)$$

In the armature winding, there is also a leakage inductance l_a and its relation with the self-inductance of the armature winding is express in the next equation.

$$L'_{aaa} = l + M' \qquad (4)$$

Furthermore, the number of pole pairs is assumed to be *p* , the rotation speed ω_{rm} of the output shaft of a synchronous motor (mechanical angle) is ω_{re} / p .

2.2 Coordinate transformation

As for the grasp of the control system characteristic deriving the control method, it is easier when it is represented by 2 phase than to be represented by 3 phase alternative current and voltage. Moreover, it is simple to represent 2 axis direct current than 2 phase alternative current. To change the view of the motor this way, it is necessary to change the coordinate view, this is called coordinate transformation.

2.3 Two phase circuit equation

I. $(\alpha - \beta)$ circuit equation coordinate system. The circuit equation of $(\alpha - \beta)$ from 3 phase alternative current through the coordinate transformation is showed equation (5).

$$\begin{bmatrix} v_{\alpha a} \\ v_{\beta a} \end{bmatrix} = \begin{bmatrix} R_a + PL_a & 0 \\ 0 & R_a + PL_a \end{bmatrix} \begin{bmatrix} i_{\alpha a} \\ i_{\beta a} \end{bmatrix} + \begin{bmatrix} e_{\alpha a} \\ e_{\beta a} \end{bmatrix}$$

Figure 2.3 shows the equivalent circuit.

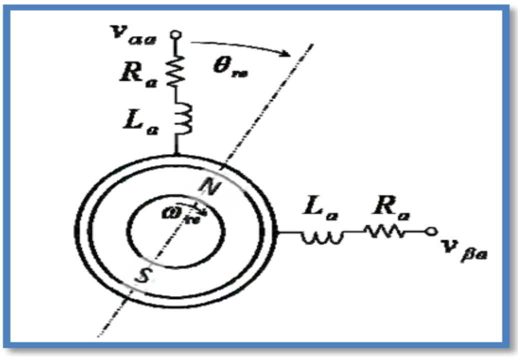

Fig 2.3: The equivalent circuit 2 phase alternative current

Here, $v\alpha_a$, $v\beta_a$ are axis armature voltage, $i\alpha_a$, $i\beta_a$ are phase armature current, $e\alpha_a$, $e\beta_a$, are the speed electromotive force induced by phase armature windings of the field permanent magnet. R_a is armature winding resistance, L_a is self-inductance of the armature winding, *a R* is the same as equation (1), L_a is represented in next equation using l_{aa}, M'_a of equation (1).

III. Space Vector Pulse Width Modulation

Space vector modulation is a one of the advanced pulse width modulation (PWM) technique used for inverter switching. Usually there are eight possible switching states in an inverter. In these six are active vectors. This PWM technique approximates the reference voltage Vref by a combination of the eight switching patterns (V0 to V7) are described in the Fig. 3.1 with the switching patterns and output voltages of a three-phase power inverter in Table 1. To implement the space vector PWM, the voltage equations in the abc reference frame can be transformed into the stationary α, β reference frame that consists of the horizontal (α) and vertical (β) axes, as a result, six non-zero vectors and two zero vectors are possible.

The required space vector $V\,ref$ can be generated using two neighboring active vectors $V1$ and $V2$ for a time period of $t1$ and $t2$ respectively along with null vectors for a time period of $(T\,s - (t1 + t2))$, where $T\,s$ is the switching period.

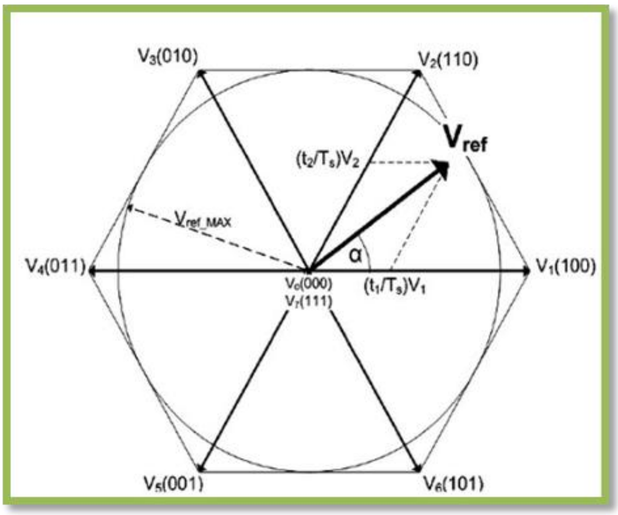

Fig. 3.1: Switching vectors and sectors

Table 1: Switching Patterns of SVM

Vector	A+	B+	C+	A-	B-	C-	V_{AB}	V_{BC}	V_{CA}
V_0={000}	0	0	0	1	1	1	0	0	0
V_1={100}	1	0	0	0	1	1	$+V_{dc}$	0	$-V_{dc}$
V_2={110}	1	1	0	0	0	1	0	$+V_{dc}$	$-V_{dc}$
V_3={010}	0	1	0	1	0	1	$-V_{dc}$	$+V_{dc}$	0
V_4={011}	0	1	1	1	0	0	$-V_{dc}$	0	$+V_{dc}$
V_5={001}	0	0	1	1	1	0	0	$-V_{dc}$	$+V_{dc}$
V_6={101}	0	0	1	0	1	0	$+V_{dc}$	$-V_{dc}$	0
V_7={111}	0	1	1	0	0	0	0	0	0

IV. Simulation & Results

The simulation of PMSM with SVPWM & PI controller is done in MATLAB/Simulink and the model is given in figure 4.1. The motor has been modelled as in figure 4.1 using the parameters given in Table 2.

TABLE II. MOTOR PARAMETERS

Parameter	Value
d axis inductance (L_d)	0.4 mH
q axis inductance (L_q)	0.4 mH
Stator Resistance (R_s)	1.74 Ω
Motor Inertia (J)	1.74e-4 wb
Number of Poles (P)	4
Friction Factor	7.403e-5
Flux linkage established by magnet	0.1167 gcm^2

The drive system consists of the motor model, three phase inverter fed by a 310 V dc supply. The firing pulses are provided by the SVPWM block and the switching frequency is taken as 5 kHz. Necessary transformation blocks and PI controllers are included in the simulation model. To check the model performance, different load and speed conditions are simulated and the results are given.

When a constant load torque and constant reference speed of 2000 rpm is given the three phase currents generated are sinusoidal with minimum distortions, in figure 4.3. The torque and speed curves settle at their reference values before 0.01s, in figure 4.3. When a step change in load torque is given at 0.05s, the three phase currents shows the change in magnitude of current with change in torque (figure 4.4) and the motor continues to run at the given reference speed even after the change in load as in figure 4.3.

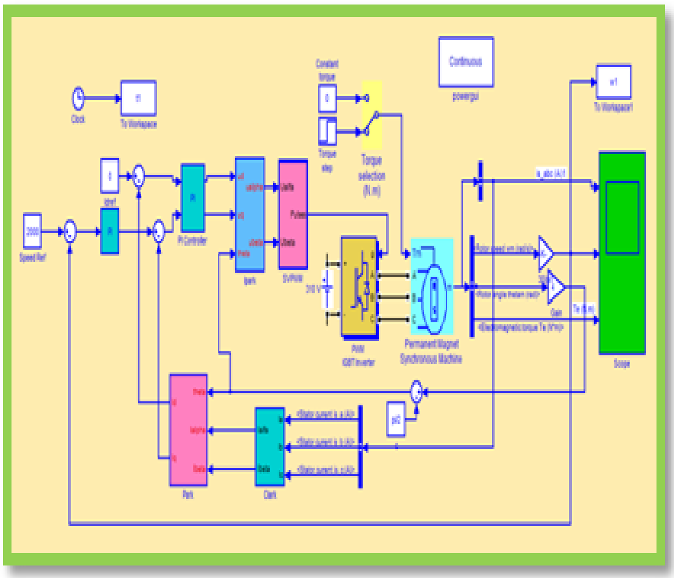

Figure 4.1: MATLAB/SIMULINK model of PMSM with SVPWM & PI Controller

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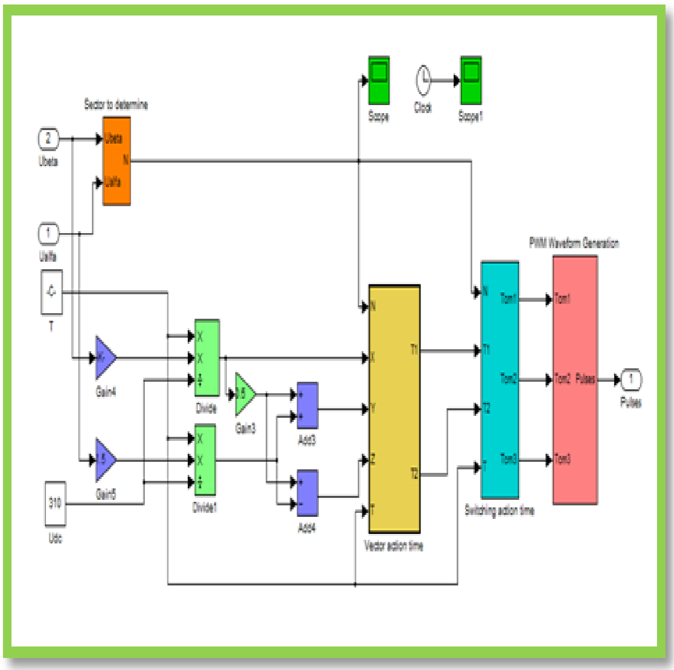

Figure 4.2: MATLAB/SIMULINK model of SVPWM.

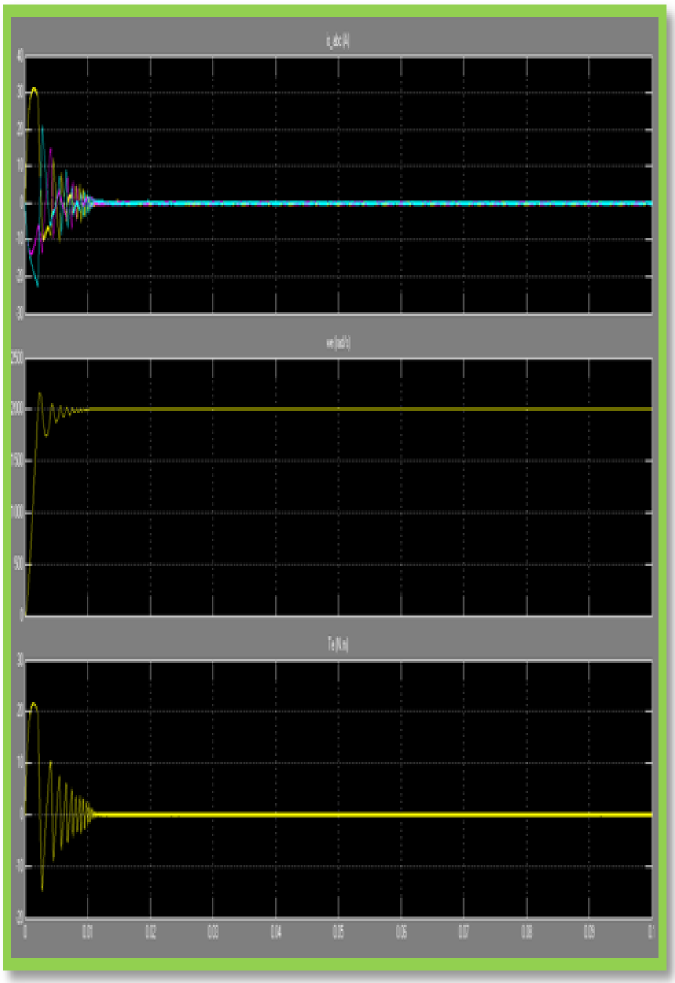

Figure 4.3: Waveform of PMSM when torque is constant (i) Current of Stator (ii) Rotor Speed (iii) Electromagnetic Torque.

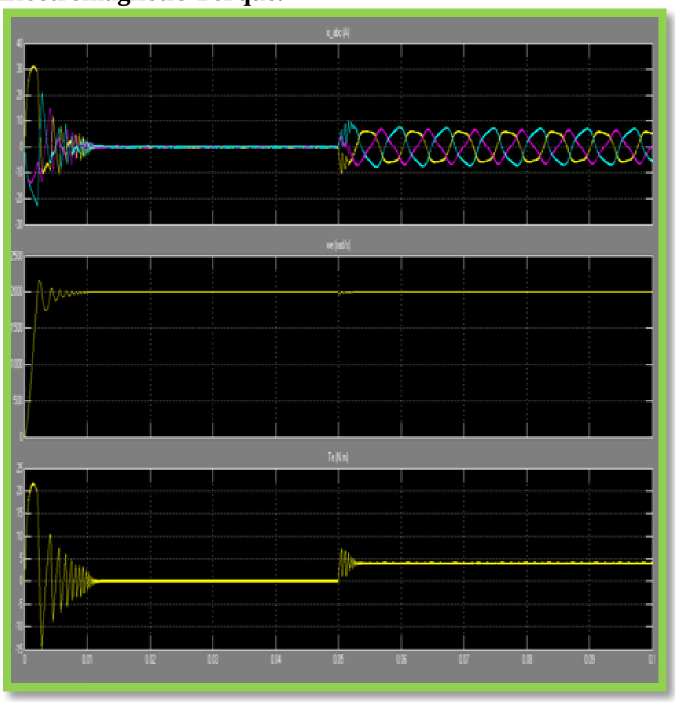

Figure 4.4: Waveform of PMSM when change in torque (i) Current of Stator (ii) Rotor Speed (iii) Electromagnetic Torque.

V. Conclusion

In this paper, the complete system has been simulated using the software package Matlab/Simulink. The simulation encompasses the entire system: the controller, the inverter, and the machine. Mathematical models can be easily incorporated in the simulation and the presence of numerous tool boxes and support guides simplifies the simulation of large system compared to Spice. Simulink is capable of showing real time results with reduced simulation time and debugging.

The modelling and analysis of PMSM using space vector pulse width modulation and proportional integral controller and its field oriented control under different load conditions are simulated and the results are analysed. This control schemes in terms of switching frequency, device losses, power quality, speed error and current control ability are better because of having constant switching frequency and lower THD of the input voltage waveforms. MATLAB/Simulink library provides easy modeling of PMSM drives and the simulated results will be helpful in hardware implementation of the drive. The transient and steady state values of current, speed and torque curves are analysed. The three phase currents show less distortion and torque curves have very little ripples. Thus SVPWM technique has the advantage of less overshoot, lower torque pulsation and quick response.

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