Magnifying Steadiness & Conducting Examination of PMSM with SVPWM and PI Controller

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Abstract. A new method to improve the strength of permanent magnet synchronous machine (PMSM) is proposed in this manuscript. It utilizes the principal of space vector pulse width modulation (SVPWM) & proportional integral control (PI). The SVPWM allows the motor to have a high voltage with low harmonic distortion than the typical sinusoidal pulse width modulation. The control technique which is used in this paper is the voltage-frequency control process which depends on space vector pulse width modulation. The triggering pulses of space vector pulse width modulation inverter which is been given to the motor enables the motor to have a bigger torque at high speeds & elevated efficiency. It also increases the use of DC link voltage & low output harmonic distortion than the typical sine pulse width modulation inverter. The suggested permanent magnet synchronous machine module that involves a field-oriented control method not only links torque & flux, but also facilitates control allocation. Finally investigation of the suggested model is examined and its results are been validated by the simulation.

Keywords—Permanent Magnet Synchronous Machine, Proportional Integral Controller, Space Vector Pulse Width Modulation, Harmonic Distortion

1. Introduction
Synchronous machine have a traditional 3 phase stator winding (known as armature) and an electrical energized field winding on the rotor, through which a direct current (DC) is been given to it. Armature windings are like the stator of three phase induction motor. Permanent magnet can easily replace the electrically energized field winding. Using permanent magnet which has many advantages such as removal of brush, slip ring, and field copper loss in the field windings. The absence of field winding results into bigger efficiency and reduction in machine frame size of the motor. Permanent magnet synchronous machine is divided into two types: one is a trapezoidal type known as Brushless DC machine (BLDC) and other one is a sinusoidal type called PMSM [1]. The BLDC machine utilizes trapezoidal back emf and requires a step-by-step rectangular stator current whereas PMSM utilizes sinusoidal emf and operates via sinusoidal stator current. Some of the primary merits of permanent magnet motors are:

- Large torque ratio,
- Small torque ripple,
- Higher speed activity,
- Higher air gap flux density,
Higher torque value (fast speed and declination),
- Higher efficiency & large $\cos \varphi$.

Basically two control techniques are used in permanent magnet synchronous motor that is scalar control & vector control [2]. Simply the magnitude portion, the angular speed of the voltage present and flux are governed in scalar control. During transient condition space vectors are not been considered. So, this technique is not fit for high dynamics condition. On opposite vector control not only control the magnitude and frequency part of the motor but it also control instantaneous position of voltage, flux & current in space vector which is been needed in high dynamics condition. So through vector control we can control motor speed in both steady states as well as in transient condition also.

In squirrel cage motor voltage frequency control for PMSM is not an easy task as compared to induction motor. Some extra change in position of control loop is required which is been given by negative feedback loop from rotor speed position and active power. Field Oriented Control (FOC) is renowned vector control strategy which gives PMSM higher superiority [3]. In FOC the motor condition are changed into coordinate framework which turns motor into synchronism through flux of permanent magnet. It allows independently controlling torque & fluxing values by utilizing current feedback control circle with proportional integral control loop. By using this method we achieve constant switching frequency and low switching losses as well. Hence this technique is implemented in this manuscript.

2. Operation of PMSM

PMSM is been defined as revolving field type motor where field winding flux is been provided by permanent magnet and having no brush assembly in it. Figure 1 demonstrates basic diagram of PMSM.

![Figure 1: Basic Structure of Surface and Interior PMSM](image-url)
2.1 Equation of three phase PMSM

Equation of three phases in form of relation with voltage, current and electromotive force is shown below.

\[
\begin{bmatrix}
    v_{pa} \\
    v_{qa} \\
    v_{ra}
\end{bmatrix} = \begin{bmatrix}
    R_a + P L'_a & -1/2 P M'_a & -1/2 P M'_a \\
    1/2 P M'_a & R_a + P L'_a & -1/2 P M'_a \\
    -1/2 P M'_a & -1/2 P M'_a & R_a + P L'_a
\end{bmatrix} \begin{bmatrix}
    i_{pa} \\
    i_{qa} \\
    i_{ra}
\end{bmatrix} + \begin{bmatrix}
    e_{pa} \\
    e_{qa} \\
    e_{ra}
\end{bmatrix}
\]

Here, \(v_{pa}, v_{qa}, v_{ra}\) are the armature voltage of three phase \(p, q, r\) and \(i_{pa}, i_{qa}, i_{ra}\) are the armature current of \(p, q, r\) phase respectively. Electromotive force which has been induced in the \(p, q, r\) phase armature winding by PMSM magnetic field are \(e_{pa}, e_{qa}, e_{ra}\) respectively. \(L_a\) and \(R_a\) are mutual inductance and armature winding resistance respectively. After considering their max value it is assumed to be \(\Phi f_{pa}, \Phi f_{qa}, \Phi f_{ra}\) field magnets of \(p, q, r\) phase and stator winding which interlinks with flux to produce \(e_{pa}, e_{qa}, e_{ra}\) [4].

\[
\Phi f_{pa} = \Phi f_a \cos \theta_{re}
\]
\[
\Phi f_{qa} = \Phi f_a \cos(\theta_{re}-4/6)
\]
\[
\Phi f_{ra} = \Phi f_a \cos(\theta_{re}+4/6)
\]

Consider, \(\theta_{re}\) field magnet angle rotating in the direction of clockwise at the \(a\) phase of stator winding and \(\omega_{re}\) is the angular speed of the motor magnetic field are described as follows:

\[
\theta_{re} = -\omega_{re} \ dt
\]

So now situation, \(e_{pa}, e_{qa}, e_{ra}\) becomes:

\[
E_{pa} = P \Phi f_a = -\omega_{re} \Phi f_a \sin \theta_{re}
\]
\[
E_{qa} = P \Phi f_a = -\omega_{re} \Phi f_a \sin(\theta_{re}-4/6)
\]
\[
E_{ra} = P \Phi f_a = -\omega_{re} \Phi f_a \sin(\theta_{re}+4/6)
\]

There is also leakage inductance \(L_a\) in the armature winding and its relationship with the armature winding’s self-inductance is expressed in next equation.

\[
L'_{aa} = L_a + M'
\]

In addition, it is thought that the amount of pole pairs is \(p\) and that the rotation velocity of the desired shaft of a synchronous machine is range of \(\omega_{re}/p\) [5].

2.2 Coordinate transformation

Coordinate transformation is been defined as a process in which three phase of alternative voltage and current equation are changed into two phase of voltage and current equation. By doing this it is easier to specify two-axis dc current than two-phase AC current [6]. In order to understand the motor equation, coordinate transformation is necessary. Figure 2 shows two phase AC circuit of PMSM.

2.3 Two phase circuit mathematical equation

\[
\begin{bmatrix}
    v_{aa} \\
    v_{ja}
\end{bmatrix} = \begin{bmatrix}
    R_a + P L'_a & 0 \\
    0 & R_a + P L'_a
\end{bmatrix} \begin{bmatrix}
    i_{aa} \\
    i_{ja}
\end{bmatrix} + \begin{bmatrix}
    e_{aa} \\
    e_{ja}
\end{bmatrix}
\]
Here, $v_{αa}$, $v_{βa}$ are armature axis voltage. $i_{αa}$, $i_{βa}$ are phase armature current and $e_{αa}$, $e_{βa}$ are the speed of the motor due to rotation of the magnetic field been present in PMSM. $R_a$ is simply the winding armature resistance; $L_a$ stands simply self-induction in the armature circuit.

3. SVPWM

Space vector is a unique modulations technique of PWM used for switching inverter. In inverter there are basically 8 feasible switching states in which 6 are active vectors. In Table 1, 8 conversion pattern of PWM method is been shown. These patterns are formed by combination of 8 switching values ($U_0$ to $U_7$) reference voltage. To conduct SVPWM, voltage equation in $pqr$ reference framed is changed into static $α$, $β$ reference structure which consists of horizontal ($α$) and vertical ($β$) axis. Due to consequence 6 non zero vector and 2 zero vector are possible [7]. Considering space vector $U_{ref}$ which could be generated by 2 adjacent active vectors $T_1$ and $T_2$ for some specified time frame of ($U_α$ - ($T_1 + T_2$)), here $U_α$ is conversion period. Figure 3 shows conversion course and segment of SVPWM.
### Table 1: Conversion Design of space vector machine

| Vectors   | P+ | Q+ | R+ | P- | Q- | R- | U_PQ | U_QR | U_RP |
|-----------|----|----|----|----|----|----|------|------|------|
| U_0={000} | 0  | 0  | 0  | 1  | 1  | 1  | 0    | 0    | 0    |
| U_1={100} | 1  | 0  | 0  | 0  | 1  | 1  | +U_dc| 0    | -U_dc|
| U_2={110} | 0  | 1  | 0  | 0  | 0  | 1  | 0    | +U_dc| -U_dc|
| U_3={010} | 0  | 1  | 0  | 1  | 0  | 1  | -U_dc| +U_dc| 0    |
| U_4={011} | 0  | 1  | 1  | 1  | 0  | 0  | -U_dc| 0    | +U_dc|
| U_5={001} | 0  | 0  | 1  | 1  | 1  | 0  | 0    | -U_dc| +U_dc|
| U_6={101} | 0  | 0  | 1  | 0  | 1  | 0  | +U_dc| -U_dc| 0    |
| U_7={111} | 0  | 1  | 1  | 0  | 0  | 0  | 0    | 0    | 0    |

In space vector pulse width modulation technique there are two most important transformation used in this paper i.e. Clark transformation and Park transformation [8]. Both techniques are mainly used in SVPWM correlated to permanent magnet synchronous machine module and asynchronous machine.

#### 3.1 Clark transformation

The balance 3 phase quantities of current are changed into 2 phase balance quantities. The 3 phase quantities are changed from 3 phase coordinate system to 2 axes orthogonal stationary coordinate system using Clark transformation. Below are the subsequent equations:

\[
I_\alpha = \frac{2}{3}(I_p) - \frac{1}{3}(I_q - I_r)
\]

\[
I_\beta = \frac{2}{\sqrt{3}}(I_q - I_r)
\]

Where, \(I_p, I_q, I_r\) are 3 phase quantity of current 
\(I_\alpha\) and \(I_\beta\) stand stationary orthogonal reference form.

Here \(I_q\) is superimposed \((I_p) & I_p+I_q+I_r=0\) then \(I_r\) would change into \(I_\alpha\) & \(I_\beta\) as given below:-

\[
I_\alpha = I_p
\]

\[
I_\beta = \frac{1}{\sqrt{3}}(I_p + 2I_q)
\]
3.2 Park transformation

In Park transformation balanced 2 phase vector orthogonal stationary structure is converted into rotating orthogonal reference form.

Fundamentally 3 conditions are observed in park transformations which are as follows:-

1. \( I_p, I_q, I_r \) are coplanar to each other having 120 degree of angle between each other. 
2. \( I_\alpha \) and \( I_\beta \) (orthogonal stationary reference form) are perpendicular to each other, but with respect to 3 phase reference form.
3. Orthogonal rotating reference form, in which \( I_d \) is the angle \( \theta \) between the \( \alpha \) axis and \( I_q \) is at an angle of 90˚ to \( I_d \) next to the \( q \) axis.

Two axis stationary orthogonal reference form are changed into rotating reference form as given below:

\[
I_d = I_\alpha \cos(\theta) + I_\beta \sin(\theta) \\
I_q = I_\beta \cos(\theta) - I_\alpha \sin(\theta)
\]

(9)

(10)

At this point, \( I_d \) and \( I_q \) stand rotating reference form whereas \( I_\alpha \) and \( I_\beta \) are orthogonal stationary reference form and \( \theta \) stands angle of rotation.

4. Result & Discussion

Simulation of permanent magnet synchronous machine using space vector pulse width modulation Block & proportional integral is achieved in MATLAB & the module is been described in Fig. 4. The permanent magnet synchronous motor variables have been demonstrated as in Fig. 4 and values of variables specified in Table II.

| Variables           | Values      |
|---------------------|-------------|
| D axis coil \( (L_d) \) | 0.5 mH      |
| Q axis coil \( (L_q) \) | 0.5 mH      |
| Stator resistor \( (R_s) \) | 1.75 Ω     |
| Machine Burden \( (B) \) | 1.75e-4 wb |
| No. of Pole \( (P) \) | 4           |
| Friction Value      | 7.404e-3    |
| Magnetic Flux       | 0.1168 gcm^2 |

The motor drive framework comprises of the machine model, 3 phase IGBT inverter supplied by a 310 volt direct current supply. The triggering impulses are given by the space vector PWM function and the switching frequency is taken to 5 kilohertz. Essential important functions & proportional integral controller are incorporated into the Simulink module. To verify the model execution, unlike load burden and speed state are simulated and the outcomes are been shown in the graph.
At a point in simulation once a fix load torque and instance of same speed of 2000 rpm is been set to the motor model, then 3 phase current and electromagnetic torque are been generated with less hindrances as shown in Figure. 5. The speed and torque graph settle their values before 0.01 sec as shown in figure. 5. At 0.05 sec when a unit step of load torque is been set to the motor then also motor remains to track on his same momentum level when load is changed as shown in figure 6.

In figure 7 ramp signal is been given as a load to the motor model at 0.03 sec then also the motor continue to maintain its reference speed that is nearly equal to 2000 rpm. Stator current and electromagnetic torque slightly increases as shown in figure 7.

When continuous pulse of signal having width of 5% is been given as a load on the motor at 0.03 sec, then also speed of the motor continues at its reference speed and electromagnetic torque slightly increases as shown in figure 8.

By comparison of all three waveforms of PMSM model at different load condition, we see that whenever there is a change in load torque consequently electromagnetic torque increases but speed of the motor continuous to run at same speed and doesn’t decreases.

Figure 4: Simulink Model of PMSM with Space Vector PWM and Proportional Integral Controller
Figure 5: Graph of Permanent Magnet Synchronous Motor once Torque is fixed (i) Stator current (ii) Rotor speed (iii) Electromagnetic torque.

Fig 6: Graph of PMSM when change in torque in unit step form is been given (i) Stator current (ii) Rotor speed (iii) Electromagnetic torque.
Figure 7: Graph of Permanent Magnet Synchronous Motor once change in torque in ramp signal form is been given (i) Stator Current (ii) Rotor Speed (iii) Electromagnetic torque.

Figure 8: Graph of PMSM when change in torque in pulse generator form is been given (i) Stator Current (ii) Rotor speed (iii) Electromagnetic torque.
5. Conclusion
In the presented manuscript, the total methodology module has been examined by utilizing the Matlab software. Through simulation we directly control the entire system module that is PI regulator, IGBT inverter, and the synchronous motor. Numerical model can be effectively joined into the simulink and utilization of various tools kits simplifies simulation of huge system very easy as contrast with Spice. It is fit for indicating continuous and discrete outcomes with less simulation time and also for investigation purpose also.

From presented PWM techniques it can be seen that less convenient for digital implementation is sinusoidal PWM, because most of control processing schemes generate DC values for linear regulators instead of sinusoidal signals. The 3D-SVM is used for 4-wire systems where non symmetrical loads may occur. From presented modulation methods two dimensional (Classic) Space Vector Modulation is most suitable for symmetrical loads like 3-phase motors. It also gives largest possibilities to introduce improvements which guarantee DC link capacitors voltages balancing and additionally minimize number of switching.

Demonstration and examination of permanent magnet synchronous machine with the help of SVPWM and PI controller and its FOC under various load states are been simulated and the outcomes are shown by graph. Control techniques which are been used in this model are better in respect of speed error, switching frequency, devices loss, power quality because of lower thermal harmonic distortion of input voltage waveform and also steady switching frequency. Matlab Library is very useful for PMSM drives system since modelling of motor is very simple and result can easily be simulated and these results would be helpful for hardware implementation of motor model. In given model we can easily analyse the instantaneous & steady state value of current, speed & electromagnetic torque also.

References
[1] Bose B.K.(2002). Modern Power Electronics and AC Drives: Prentice Hall.
[2] Prasad E., Suresh B. and Raghuveer K. (2012). Field oriented control of PMSM Using SVPWM Technique. Global Journal of Advanced Engineering Technologies, vol. 1, issue 2, pp. 39-45.
[3] Adhavan B., Kuppuswamy A., Jayabaskaran.G and Jagannathan V. (2011). Field oriented control of Permanent Magnet Synchronous Motor (PMSM) using Fuzzy Logic Controller. Recent Advances in Intelligent Computational System (RAICS), IEEE, pp. 587-592.
[4] Guney I., Yuksetoguz, Serteller F. (2001). Dynamic behaviour model of permanent magnet synchronous motor fed by PWM inverter and fuzzy logic controller for stator phase current, flux and torque control of PMSM. IEEE Proceeding from Electric Machines and Drive Conference, pp. 1–5.
[5] Mustafa et al (2014). Sensorless speed control of permanent magnet synchronous machine using model reference adaptive scheme. International Journal of Emerging Trends in Engineering Research, 3(1), 24–37.
[6] Habetler T.G., Profume F, Pastorelli M.(2008). Direct torque control of induction motor machines using space vector modulation. IEEE Transaction on Industry Application, 28, 1045–1053.
[7] Khan M., Yong W, Mustafa E.(2017). Design and simulation of control technique of permanent magnet synchronous motor using space vector pulse width modulation. 4th International Conference on Mechanics and Mechatronics Research (ICMMR 2017), pp. 224-331.
[8] Busireddy H.K., Makarand M.K.L., Reddy K.R., Borghate V.B.(2019). An improved space vector pulse width modulation for nine level assymetric H-bridge three phase inverter. Arbian Journal for Science and Engineering, vol. 44, pp. 2453–2465.