Speed Control of Permanent Magnet Synchronous Motor Using SVPWM Vector Control

Doaa AL-Mansory[1], Issa Ahmed Abed[2], Diyah AL-Thammer[3]
{doaasalihnaser@gmail.com[1], issaahmedabed@stu.edu.iq[2], diyahpower@stu.edu.iq[3]}

Engineering Technical College, Southern Technical University, Iraq[1,2,3]

Abstract. This article discusses how to regulate the speed of a Permanent Magnet Synchronous Motor (PMSM). Depending on the field-oriented control principle, which is among the most often used AC motor drives accessible in the industry, a new approach to regulating the PMSM using pulse width modulation of space vectors (SVPWM) is suggested. The entire framework is designed on the MATLAB /Simulink platform (vector control). The whole system, using the speed loop outside and the interior current loop, using two control loops are simulated based on synchronous motor speeds using power electronics and microelectronic technology have advanced. The AC servo device for PMSM is applied based on control methods that are used more often.

Keywords: PMSM, SVPWM, field-oriented control, controlling vector.

1 Introduction

In many industrial applications, the ability to control the speed of electric motors is necessary, just like robots, computer numerical control (CNC), traction engines, air conditioning, pumping systems, etc. Permanent magnet synchronous motors (PMSM) have been widely used recently increasing, substituting the Induction motor due to the requirement for greater efficiency and smaller size in an application, for example, vehicles and appliances for homes [1, 2]. This machine is now commonly used in servo systems with high-efficiency applications such as actuators in robotics and aerospace, as no external excites are provided to the rotor, reduction of damages, and highly effective PMSM. There are primarily two types of PMSM drive in the industry, one shows the distribution of sinusoidal flux in a PMSM, while the other is the distribution of trapezoidal change in a brushless DC machine [3]. Due to complexity compared to field-oriented induction motor drive control, PMSM drives are usually favored in servo systems. The principle of vector control is used in this work to achieve a linear transient response, along with decoupled regulation of the transient response of the AC three-phase unit, such as the separately excited DC motor [4, 5]. The vector control-based proportional-integral (PI) control method (field-oriented control) is widespread and useful for the regulation of PMSM with an accurate mathematical model [6]. PMSM vector control was performed using the space vector pulse width modulation (SVPWM) inverter output voltage methods generation rather than a traditional sinusoidal modulation of the width of the pulse. The flux (i_d) as well as Torque (i_q) of the system, it is possible to function independently in the same period in this scheme [7]. The SVPWM technology ensures optimum voltage of DC input utilization and less harmonic distortion. Multilevel inverters and two-level inverters are usually known as an inverter. In contrast to the two-level inverters, one of the benefits of multilevel

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inverters is decreased harmonic distortion. Sometimes known as the control of decoupling or vectors, the field-oriented rule came in late 1960; the research field of ac drives was prominently developed in 1980 to resolve the challenges of synchronous motor drive and induction inverter-fed oscillating flux and torque response. Numerous authors have modelled and simulated such a drive. The author in [8] described the modeling and simulation of a PMSM drive system that depends on FOC. The work in [9] presented a MATLAB/Simulink implementation of a vector-controlled PMSM drive utilizing the SVPWM method.

This paper is structured it is as follows: the PMSM basic mathematical model developed in Section II. The suggested methodology of vector control is provided in Section III. Section IV describes the implementation of the SVPWM algorithm on a systematic basis. Design of two-level inverter in section V. Results of the simulation for section VI are discussed Section VII contains the conclusion.

2 Proposed System

The magnetic field is a permanent magnet. The field is excited by permanent magnets that produce sinusoidal back EMF in a synchronous motor, which is one form of AC synchronous motor. It uses a permanent magnet to generate a magnetic field. The d-q rotor reference frame principle was used to construct the motor axis. In this model, a speed and current closed-loop control method have been used, with the SVPWM formula in the inner loop that accounts for the strong coupling, time-varying, as well as non-linearity properties, and also the PI speed controller with the outer loop to improve robustness and anti-interference efficiency.

2.1 Mathematical Model of PMSM

Generally, the wound rotor synchronous motor's stator is quite similar to the permanent magnet synchronous motor's stator. The main difference is that the high-performance permanent magnet PMSM rotor is constructed from new magnetic materials of rare earth with high levels of surface or rotor conductivity. The winding of the three-phase stator creates through the air gap, a rotating magnetic field. The relationship in the space between the stator and the electromagnetic field of the rotor generates electromagnetic Torque that drives the synchronization of the rotor. The following ones are the assumption in the derivation process is made [10], [11]:

- Saturation and variance of parameters are ignored.
- Stator windings are balanced with sinusoidal mediated EMF.
- The loss of eddy current and hysteresis is negligible.
- No current field dynamics are available.

PMSM stator voltage equations can be written as a rotating reference frame in d, q with the assumptions as follows [12],[13],[14],[15],[16],[17],[18],[19],[20]:

$$V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \tag{1}$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \tag{2}$$

Where, V_q and $V_d$the stator voltage is the d, q reference frame, i_d and i_q are the d, q rotating reference frame stator current in, λ_d and λ_q are the d, q axis stator flux relation, R_s is the winding resistance of the stator as a result of the permanent magnets., the flux linkage may be used to express as a flux linkage λ_f. ρ: operator $\frac{d}{dt}$. Flux Linkages equations:

$$\lambda_q = L_q i_q \tag{3}$$

$$\lambda_d = L_d i_d + \lambda_f \tag{4}$$

Where L_q and L_d the inductance of the d and q axis stator and the rotor permanent magnet flux is λ_f. Substituting eqn. (3), eqn. (4) in eqn .(1), and eqn. (2) we get the voltage as:

$$V_q = R_s i_q + \omega_r\left(L_d i_d + \lambda_f\right) + \rho L_q i_q \tag{5}$$

$$V_d = R_s i_d - \omega_r L_q i_q + \rho\left(L_d i_d + \lambda_f\right) \tag{6}$$

And we arranged them in matrix format we get:

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{bmatrix} \tag{7}$$

In the above equation, ω_r is the rotor electrical speed, where ω_m is the mechanical rotor velocity in rad/sec,

$$\omega_m = \omega_r \left(\frac{2}{p}\right) \tag{8}$$

The formula of electromagnetic Torque generated can be written as:

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\left[\lambda_f i_q + \left(L_d - L_q\right) i_d i_q\right] \tag{9}$$

If, P, the number of poles. By setting i_d equal to zero and $L_d = L_q$ at in type Surface Permanent Magnet Synchronous Motor (SPMSM). The torque equation is as follows:

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right) \lambda_f i_q \tag{10}$$

The mechanical equation of Torque for modeling of PMSM express the relationship between the electromagnetic Torque T_e , load torqueT_l, and electrical speed ω_r as follows, the mechanical Torque equation:

$$T_e = T_l + B\omega_m + J\frac{d\omega_m}{dt} \tag{11}$$

Solving the mechanical velocity of the rotor from the equation:

$$\omega_m = \int \left(\frac{T_e - T_l - B\omega_m}{J}\right) dt \tag{12}$$

J the inertia of the rotor, B the value of the coefficient of viscous friction, and T_l the Torque of the load.

2.2 Park and Clarke Transformations

The amounts of AC motors in the three phases can be evaluated in two-phase equivalent rules αβ coordinate frame for complex space vectors. They can be converted further into a relation of two-phase rotating dq reference time frame invariant. The PMSM dynamic performance in the reference frame, dq it can be used to describe the features of the transient and steady-state. The transformation of Clark is used to convert the quantities of three-phase abc into equivalent amounts of two stages of αβ quantity as in eqn. (12). To transform the space vectors αβ frame into a rotating frame that is time-invariant dq frame in eqn. (13), Park converting is used. The various techniques of transformation are explained below in matrix form:

1) Transformation by Clark (abc-to-αβ):

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{13}$$

2) Transformation of Park (αβ-to-dq):

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{14}$$

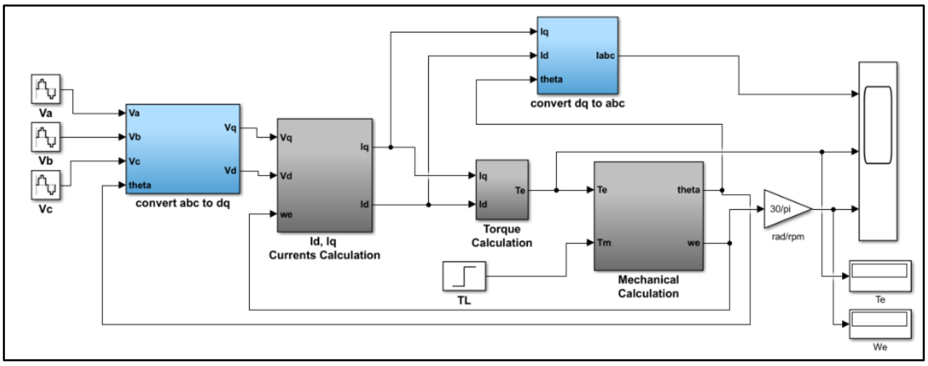

Figure 1. a) the Implementation of PMSM, MATLAB/Simulink program Simulink model with drive circuit; b) Simulink model of PMSM drive circuit

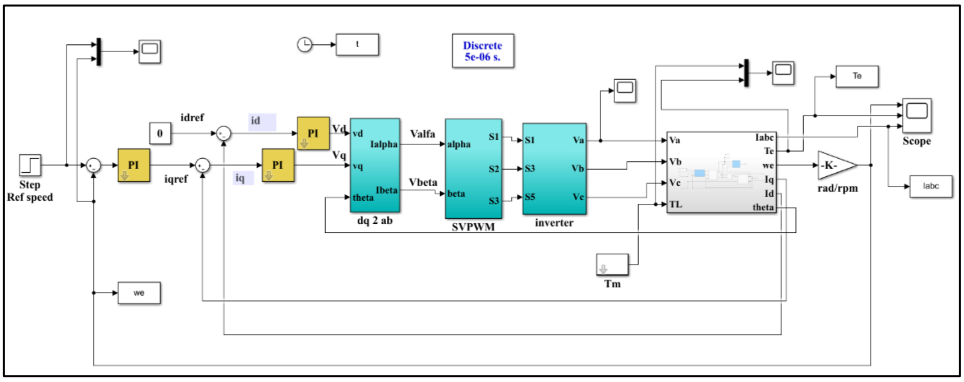

Figure 2. Simulink model of PMSM drive circuit.

3 Vector Control Theory for PMSM

The system of method of vector control is an intelligent method of regulating the drive to PMSM, using the field-oriented concept to regulate magnetic circuit controls of the space vector. Utilizing Park and Clarke transforms, with two orthogonal elements i_{sq} andi_{sd}, 3-phase currents of stators are converted into two-phase currents. The regulation of vectors is supposed to separately control torque and flux. Here, i_{sq} is it the component creating Torque, and i_{sd} is the component making flux [21]-[22]. Therefore, there are two distinct loops for control:

1. Velocity loop: the outer circle that regulates the motor speed and produces the reference signal for the current controller with the q-axis.
2. The Current loop: the inner circle was the motor that governs the motor's flux and Torque.

For a motor drive system with maximum speed range, the speed control loop consists of a motor, an inverter, a controller that measures the discrepancy between the speed of reference and real velocity that produces an error that is fed to the controller of the PI. For the motion control system, PI controllers are commonly used. They include a proportional gain, which has results proportional to the failure input and integration for a step-change in information to make the steady-state error zero.

4 Space Vector Technique of Pulse Width Modulation

Modulation of Space vector pulse width (SVPWM) is a digital adjustment method that aims to produce, on average, PWM load line voltages equal to the reference load line [23]. In reality, SVPWM is just an algorithm for modulation that transforms the reference from control to phase voltage (phase to neutral) should be applied to the specified PWM modulation times/duty-cycles. In the power electronics and drive systems industry, these methods of PWM switching have usually been employed. The purpose of the pulse width is modulated to provide an inverter-regulated voltage output after the output voltage's harmonic content is reduced. One of the different forms of modulation techniques is Space Vector Modulation Techniques. However, SVPWM is becoming a primary method of realizing PWM due to the benefits, including.

- Lower current ripple power.
- Better use of buses.
- Lower order harmonics, along with its output voltage power, can be removed or minimized.

The inverter can have eight space vector outputs depending on the eight possible switching combinations, of which six are active vectors (V1-V6), and two zero vectors (V0 and V7). As in the case of a regular hexagon, six sectors compose the space vector path. A maximum reachable voltage is the circle radius, i.e. $(1/\sqrt{3})$ Vdc, as seen by Fig. 3. The distance of 60 degrees between any two non-zero vectors adjacent to them. In the SVPWM approach, the reference voltage ($Vref$) is a vector created through switching between one and two nearest zero vectors active space vectors, representing the three-phase AC voltage [24].

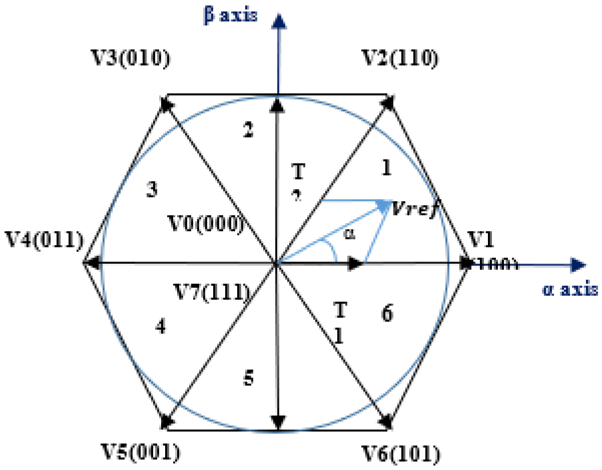

Figure 3. Basic switching vectors and six sectors for SVPWM [24].

Step1: The sector can be determined according to the relationship between Vα, Vβ in each sector, and$Vref$. Sector judgment model the following technique is used to determine the sector it is based on the expression voltage $\alpha - \beta$ coordinate for control implementation as follows: [25]

When, $V_\beta > 0$, After that, A=1, else A=0 (15)

$\sqrt{3}\ V_\alpha - V_\beta > 0$, After that, B=1, else B=0 (16)

$-\sqrt{3}\ V_\alpha - V_\beta > 0$, After that, C=1, else C=0 (17)

V_α ,V_β , they first converted from 3-phase to 2-phase stationary frame voltage.
Determination $V\alpha$ and Vβ from Clark's transformation as this:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{18}$$

Then determine$|\overline{V_{ref}}|$, and angle α from **Fig. 4:**

$$|\overline{V_{ref}}| = \sqrt{{V_\alpha}^2 + {V_\beta}^2} \qquad ; \alpha = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) = 2\pi f t \tag{19}$$

Where (f) is the fundamental frequency

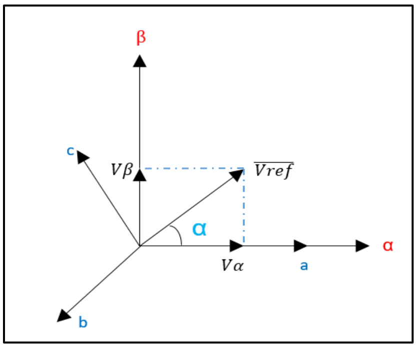

Figure 4. Reference Voltage of SVPWM for PMSM.

Step2: Vector estimation switching period T1, T2

T1 and T2 The operating time of the current sector's corresponding voltage vector. You can measure the active time as follows:

$$X = \sqrt{3}\,\frac{T}{V_{dc}}\,V_\beta \tag{20}$$

$$Y = \frac{3}{2}\,\frac{T}{V_{dc}}\left(V_\alpha + \frac{1}{\sqrt{3}}\,V_\beta\right) \tag{21}$$

$$Z = \frac{3}{2}\,\frac{T}{V_{dc}}\left(\frac{1}{\sqrt{3}}\,V_\beta - V_\alpha\right) \tag{22}$$

Where T denotes the total amount of time spent switching. It will now determine the operation time based on the data in Table 1.

Table 1. Assessment of T1 and T2 for SVPWM.

The No. sector	1	2	3	4	5	6
T1	-z	Y	X	Z	-y	-x
T2	x	Z	-y	-x	-z	Y

Step3: Determining the points for vector switching, the switch of the voltage vectors, the PWM symmetrical series, can be used. it can measure the vector switching points as follows:

$$T_a = \frac{T_0}{4} \tag{23}$$

$$T_b = \frac{T_0}{4} + \frac{T_1}{2} \tag{24}$$

$$T_c = \frac{T_0}{4} + \frac{T_1}{2} + \frac{T_2}{2} \tag{25}$$

Where T is the whole time period. In the current sector, T1 and T2 are the voltage vector's operating times. Where $T_0 = T - T_1 - T_2$.

Now, the points for vector switching Tcm1, Tcm2, and Tcm3 can be discovered in Table 2.

Table 2. Switching with Points vector

	Sector					
Point switching vector	1	2	3	4	5	6
Tcm1	Ta	Tb	Tc	Tc	Tb	Ta
Tcm2	Tb	Ta	Ta	Tb	Tc	Tc
Tcm3	Tc	Tc	Tb	Ta	Ta	Tb

Step 4: created PWM puls

Now, pulses of PWM can be generated by comparing Tcm1, Tcm2, and Tcm3 with Isosceles' triangle wave. To receive PWM2, PWM4, PWM6, it can be set on NOT service on PWM1, PWM3, and PWM5. The PWM waveform symmetrical space vector, which is used in 3-phase VSI. Below is the procedure for the design of the SVPWM method. The switching frequency (fs) of the SVPWM used in this control is (5 kHz), and the sampling time (Ts) is (0.0002 sec), and the dc input voltage is 200v.

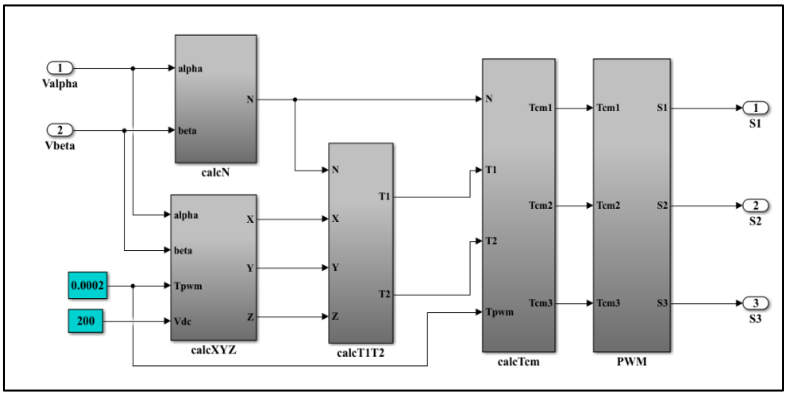

Figure 5. ign steps of SVPWM.

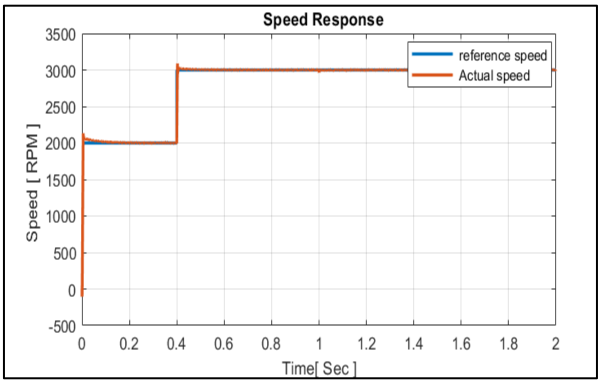

Figure 6. Speed response with reference to PMSM.

5 Space Vector Technique of Pulse Width Modulation

In this work, the vector control system incorporating the strategy of SVPWM for voltage inverting the supply from DC to AC is verified. A fundamental requirement with respect to the vector control system to the PMSM drive is SVPWM, which mainly a rotating vector that depends on a similar sinusoidal three-phase variable voltage. Using some examples of reference values, the motor torque and speed are regulated to check the vector control system drive for PMSM, and the findings indicate that the motor variables are almost tracking their reference. The torque and speed are displayed in **Figure 6** and **Figure 7** respectively. The measured motor speed of 3000-rpm constant speed, which is when any disturbance is shed the controller responds to the reference speed variables (step Ref). Speed and torque responses at full load torque (1.27 N.m) as illustrated below:

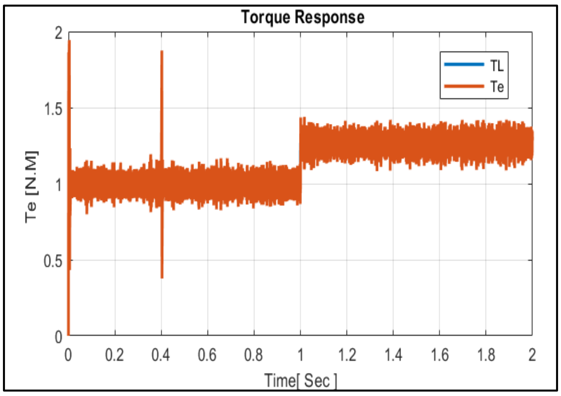

Figure 7. Electromagnetic torque with torque load..

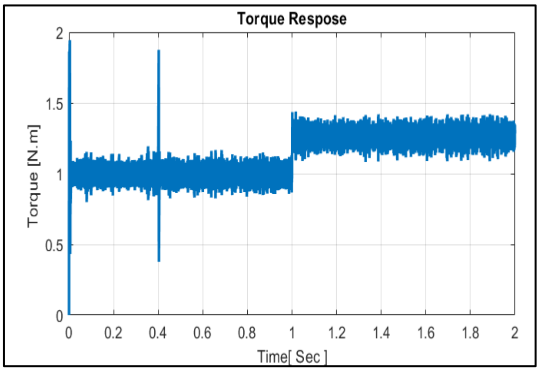

Figure 8. Three-phase stator current with PI controller.

The sinusoidal current flowing through a three-phase stator is seen in **Figure.8**. This value is updated during the velocity adjustment. The value of the rated phase current is used to verify the stator current's response (2.7A RMS) in table 4. That is when the load at its maximum value of the load torque TL is (1.27 N.m), at shown in **Figure.9**. The current value is (2.7 A RMS) at full load, and the torque response graph with the PI controller in the PMSM is show.

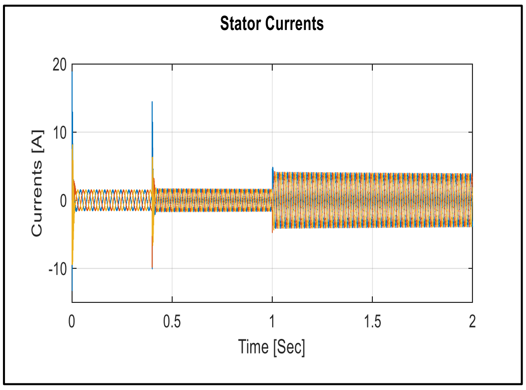

Figure 9. Torque response of the PMSM with PI controller.

A proportional-integral (PI) controller must be used to remove steady-state error [26]. This error is a result of a comparison between both the measured and reference motor speeds. This error must be equal to zero to produce tracking results as shown in **Figure. 10**. The settings of a traditional proportional-integral (PI) speed controller are controlled by manually adjusted to maintain the reference speed tracking [27]. Error resulting from a difference between the actual and desired speeds of the output. A proportional Kp parameter is utilized to reduce the time required for the rise time, and the integral parameters Ki are employed to reduce settling time and overshoot [28].

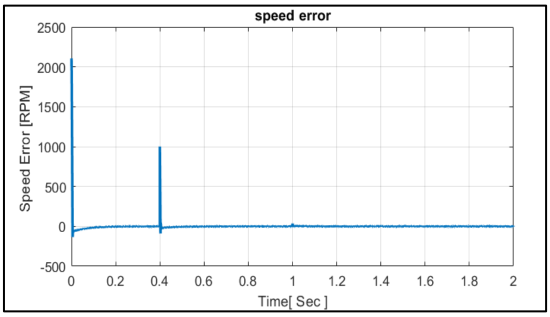

Figure 10. Error between reference speed and actual speed.

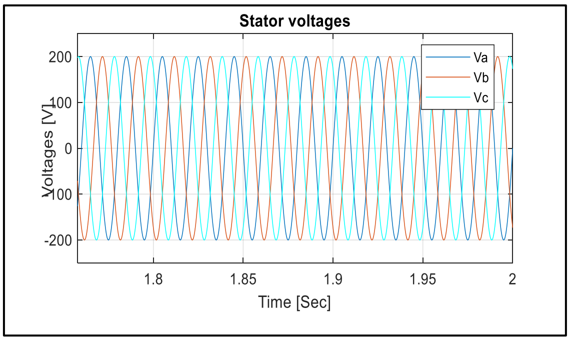

Figure 11. The stator voltages waveform.

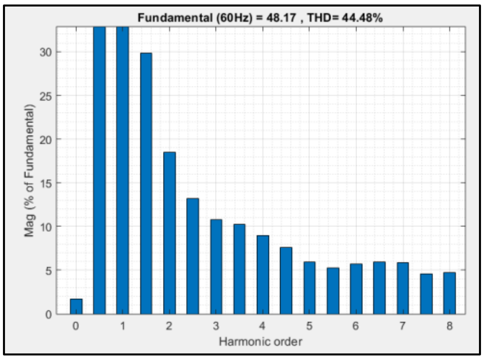

Figure 12. The total harmonics distortion for different starting time (0.6s and 1s).

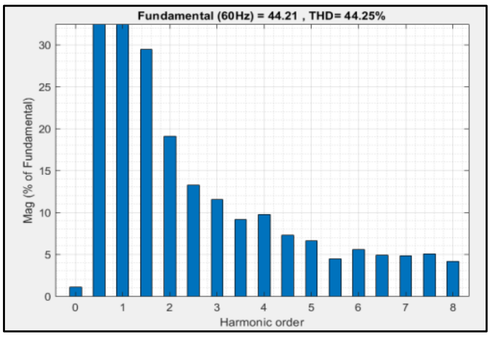

Figure 13. Percentage of Magnitude versus teh harmonic order.

Table 3. Nominal Parameters of the PMSM.

Variable	Value
Rated current	2.7 A_{rms}
Rated voltage	200 V_{rms}
Speed rated	3000 rpm
Torque rated	1.27 N.m
Number of pairs of poles the	4
Resistance to Stator winding (Rs)	2.7Ω
Stator inductance (L=Ld=Lq) (SPMSM)	8.5mH
Constant Torque	0.301 N.m/A
Linkage of flux	0.0615 Wb
Moment of Inertia	31.69e^{-6} kg.m^{2}
Viscous friction B	52.79e^{-6} N.m.s/rad
Static Nominal friction	0.289

6 Conclusion

Vector control schemes using the SVPWM method in the MATLAB/SIMULINK framework has been simulated and tested. For vector transformation, PMSM was decoupled into torque and excitation elements can be performed. In order to convert the three-step sinusoidal frame to reference frames and vice versa, Clark and park transformation are utilized with its inverses. The PMSM, however, has a robust nonlinear characteristic, which results in a discrepancy between the parameters built and the actual parameters. The simulation model of the PMSM vector control system, which is based on closed-loop flux and current in PMSM vector control systems, proposes and designs the simulation model of the PMSM vector control system using the SVPWM method in this work, which effectively simulates the complete system.

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