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Simulation of PMSM Speed Control System with Vector Control Method based on Matlab

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Abstract
Permanent magnet synchronous motors (PMSM) are used in various motion control applications in industry and it maximizes the performance in variable speed application. There are many approaches regarding both the controller type used for PMSM and the hardware-software implementations. The aim of this study is modeling and simulation of a permanent magnet synchronous motor speed controller by effective use vector control method with space vector pulse width modulation. The modeling & simulation for speed control system of PMSM is developed using Matlab Simulink environment and various parameters for speed control are analyzed through simulations.

Keywords: PMSM, vector control, FOC, Matlab, modeling and simulation, SVPWM.

1. Introduction

The permanent magnet synchronous motor is increasingly playing an important role in advanced motor drives. A "permanent magnet synchronous motor" (PMSM) or "permanent-magnet motor" (PMM) is a synchronous motor that uses permanent magnets rather than windings in the rotor that create constant magnetic field. The PMSM can be thought of as a cross between an AC induction motor and a brushless DC motor (BLDC). They have rotor structures similar to BLDC motors which contain permanent magnets. However, their stator structure resembles that of its ACIM, where the windings are constructed in such a way as to produce a sinusoidal flux density in the airgap of the machine. As a result, they perform best when driven by sinusoidal waveforms. The use of magnets enables an efficient use of the radial space and replaces the rotor windings, therefore suppressing the rotor copper losses. There are two types of PMSM depending on the mounting of permanent magnets. One is surface mounted PMSM and another is interior permanent magnet. Interior permanent magnet (IPM) is the most widely used type in PMSM.

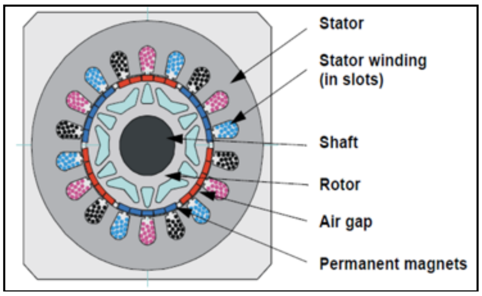


Fig 1: Permanent Magnet Synchronous Motor

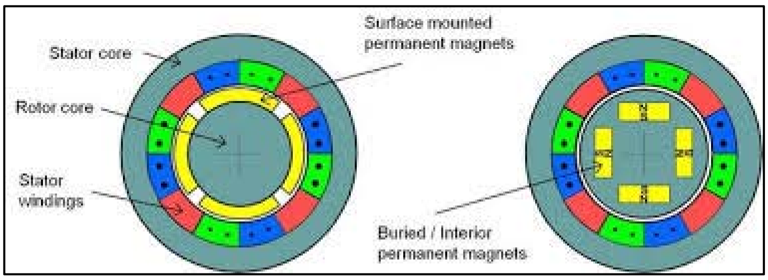


Fig 2: Types of PMSM

Because of their high performance cost ratio, these are mostly used in variable speed applications. PMSM has gained a wide acceptance in motion control applications due to its high performance, compact structure, high air-gap flux density, high power density, high torque to inertia ratio, and high efficiency. Recent research has reported that the PMSM is being increasingly used in high-performance applications, such as robots and industrial machines and motor drives. But these require speed controllers that provide not only accuracy and high performance, but also flexibility and efficiency in the design process and implementation. But in industrial applications, there are many uncertainties, such as system parameter uncertainty, external load disturbance, friction force, unmodeled uncertainty, which diminish the performance quality of the motor driving system. To cope with this problem, in recent years, many intelligent control techniques and other control methods have been developed and applied. Therefore the various control strategies and methodologies are available for speed control of PMSM.

Permanent magnet motor control is mainly consisting of the type of controller used and the implemented algorithm. There are many approaches regarding both the controller type used for drive system and hardware-software implementation. To enhance the control performance, in recent years, many control methods have been developed such as Linearization control, Adaptive control, Robust control, Sliding mode control, Finite time control, Fractional order control, Fuzzy control, Neural network control. These approaches improve the control performance of the motor from different aspects. Control of torque, rotation speed, position and low speed operation, with high-performance dynamic behavior, are often required in industrial applications but they are sensitive from the standpoint of the control strategies reliability. Vector control (also called Field-Oriented Control, FOC) is one of the methods used in variable frequency drives to control the torque and thus finally the speed of three-phase AC electric motors. Vector control provides better dynamic responses, more accurate machine torque regulation and often more silent operations.

2. Field Oriented Control principle for speed control of PMSM

In order to achieve better dynamic performance, an efficient control scheme needs to be applied to control the PM motor. With the mathematical processing, advanced control strategies can be implemented, which uses mathematical transformations in order to decouple the torque generation and the magnetization functions in the PM motors. These are called as field oriented control or vector control.

In DC motors, the flux and torque producing currents are orthogonal. So the magneto motive forces, developed by these currents are also held orthogonal and hence they can be controlled independently. AC machines do not have the same key features as the DC motor. On the synchronous machine, the rotor excitation is given by the permanent magnets mounted onto the shaft. On the synchronous motor, the only source of power and magnetic field is the stator phase voltage. Obviously, the flux and torque depend on each other. So in AC machines, the stator and rotor fields are not orthogonal to each other. The only source that can be controlled is the stator current. The FOC consists of controlling the stator currents represented by a vector. This control is based on projections that transform a three phase time and speed dependent system into a two coordinate (d and q coordinates) time invariant system.

The goal of field oriented control on the synchronous and asynchronous machine is to separately control the torque producing and magnetizing the flux components. The FOC allows you to decouple the torque and the magnetizing flux components of stator current. According to the electromagnetic laws, the torque produced in the synchronous machine is equal to the vector cross product of the two existing magnetic fields of stator and rotor. With decoupled control of the magnetization, the torque producing component of the stator flux can be considered as independent torque control. To decouple the torque and flux, it is necessary to engage several mathematical transforms. Clarke transformation converts balanced three-phase quantities into balanced two-phase quadrature quantities. Park transformation converts vectors in balanced two-phase orthogonal stationary system into orthogonal rotating reference frame. In brief, the three-phase voltages, currents, and fluxes of the AC-motors can be analyzed in terms of complex space vectors and if you know the right rotor flux position then, the d,q component becomes a constant. At this point, the control becomes easier where constant isd (flux component) and isq (torque component) current components controlled independently using PI controllers for respective component. The reference parameters and feedback parameters are input to PI controllers. PI controller consists of a proportional gain that produces an output proportional to the input, eliminating the error. Using PI control, the steady state error can be brought down to zero, and simultaneously, the transient response can be improved. Then Inverse Park and Inverse Clarke are used to obtain three phase quantities from two phase reference frame. Duty cycle or pulses are generated by using the space vector PWM generator & are applied to the inverter. Inverter drives permanent magnet synchronous motor to generate controlled rotor speed.

In addition to the decoupling, model of the motor is used for the computation of many quantities such as rotor flux angle and rotor speed. The angle or position is obtained by using encoder and used in transformations. This means that their effect is accounted for and the overall quality of control is better.

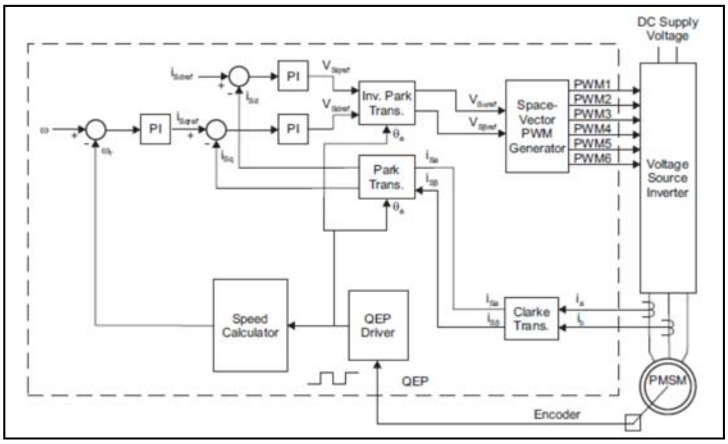


Fig 3: Block Diagram of field oriented control

A. Transformations Theory

The performance of three-phase AC machines is described by their voltage equations and inductances. A change of variables is often used to reduce the complexity of these differential equations. FOC technique involves three reference frames and needs transformations from one to the other. The Clarke and park transforms & their inverse transforms are used for it. Clarke and Park transformations are mainly used in vector control architectures related to permanent magnet synchronous machines (PMSM) and asynchronous machines. Using these transformations, many properties of electric machines can be studied without complexities in the voltage equations.

a. Clarke Transformation

Clarke transformation converts balanced three-phase quantities into balanced two-phase quantities (a-b-c→α-β). The three-phase quantities are translated from the three-phase reference frame to the two-axis orthogonal stationary reference frame as shown in Figure. The Clarke transformation is expressed by the following equations:

$I\alpha = 2/3(Ia) - 1/3(Ib - Ic)$

$I\beta = 2/\sqrt{3}(Ib - Ic)$

where, Ia, Ib, and Ic are three-phase quantities.

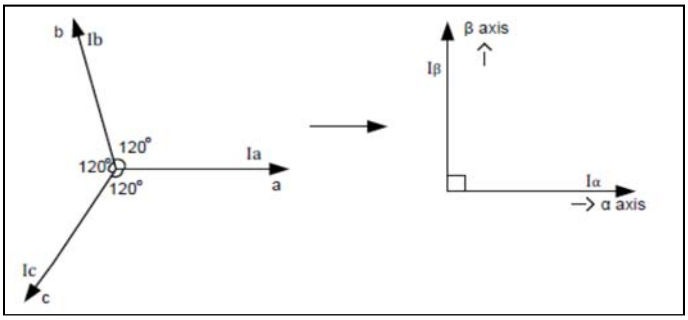


Fig 4: Clarke transformation

Iα and Iβ are stationary orthogonal reference frame quantities. When Iα is superposed with Ia and Ia + Ib + Ic is zero, Ia, Ib, and Ic can be transformed to Iα and Iβ as:

$I\alpha = Ia$

$I\beta = 1/\sqrt{3}(Ia + 2Ib)$

where, Ia + Ib + Ic = 0

b. Inverse Clarke Transformation

The transformation from a two-axis orthogonal stationary reference frame to a three-phase stationary reference frame is accomplished using inverse clarke transformation (α-β → a-b-c). as shown in Figure. The Inverse Clarke transformation is expressed by the following equations:

$Va = V\alpha$

$Vb = (-V\alpha + \sqrt{3} * V\beta)/2$

$Vc = (-V\alpha - \sqrt{3} * V\beta)/2$

where,Va, Vb, Vc are three-phase quantities. Vα, Vβ are stationary orthogonal reference frame quantities

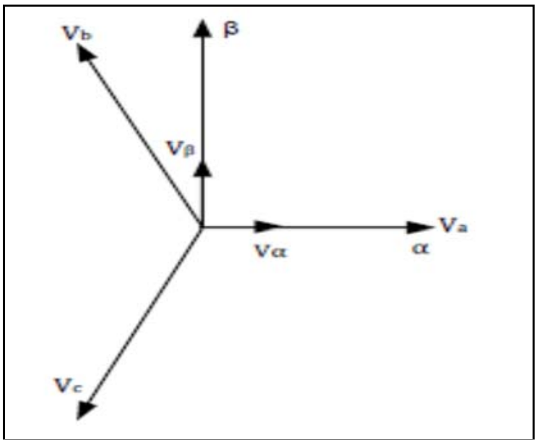


Fig 5: Inverse Clarke transformation

c. Park Transformation

The two-axis orthogonal stationary reference frame quantities are transformed into rotating reference frame quantities using Park transformation (α-β→d-q) as shown in Figure. The Park transformation is expressed by the following equations:

$Id = I\alpha * \cos(\theta) + I\beta * \sin(\theta)$

$Iq = I\beta * \cos(\theta) - I\alpha * \sin(\theta)$

where, Id, Iq are rotating reference frame quantities. Iα, Iβ are orthogonal stationary reference frame quantities. θ is the rotation angle

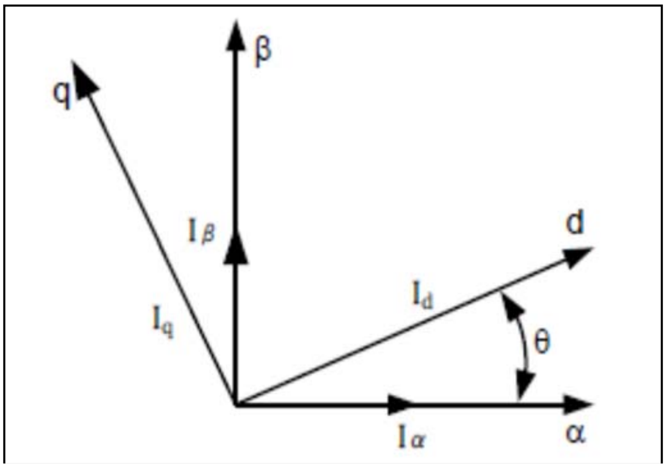


Fig 6: Park transformation

d. Inverse Park Transformation

The quantities in rotating reference frame are transformed to two-axis orthogonal stationary reference frame using Inverse Park transformation (d-q→α-β) as shown in Figure. The Inverse Park transformation is expressed by the following equations:

$V\alpha = Vd * \cos(\theta) - Vq * \sin(\theta)$

$V\beta = Vq * \cos(\theta) + Vd * \sin(\theta)$

where, Vα, Vβ are orthogonal stationary reference frame quantities. Vd, Vq are rotating reference frame quantities.

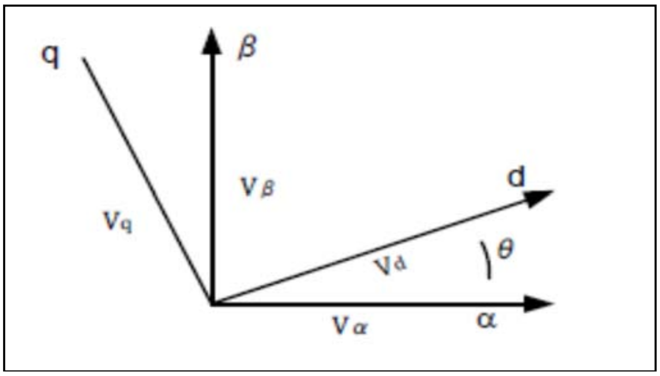


Fig 7: Inverse Park transformation

Basically, the three reference frames considered in this implementation are:

1. Three-phase reference frame, in which Ia, Ib, and Ic are co-planar three-phase quantities at an angle of 120 degrees to each other.
2. Orthogonal stationary reference frame, in which Iα (along α axis) and Iβ (along β axis) are perpendicular to each other, but in the same plane as the three-phase reference frame.

3. Orthogonal rotating reference frame, in which Id is at an angle θ (rotation angle) to the α axis and Iq is perpendicular to Id along the q axis.

The combined representation of the quantities in the entire reference frames is shown in Figure.

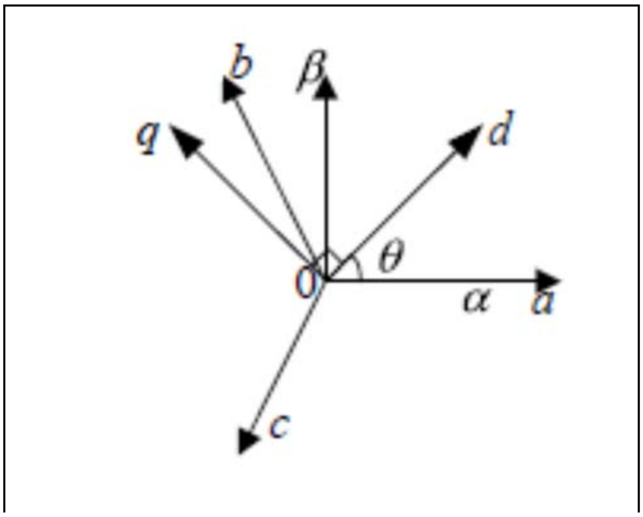


Fig 8: Combined Vector representation

B. Space Vector Modulation

The output of the Inverse Clarke transformation provides the duty cycles of the PWM channels that correspond to the three-phase voltages. For Sinusoidal excitation of the phase voltages, these duty cycle values can be used directly. There are many conventional ways of implementing the available space vector pulse width modulation (SVPWM) algorithms. The objective of SVPWM technique is to generate average output of inverter by approximating reference voltage.

The basic approach of SVPWM refers to selecting a special switching sequence of power transistors of three phase inverter. Voltage is divided into sectors i.e set of vectors which are created by various switching states and the average output is obtained in the small time period. The first step is to determine in which sector the voltage vector defined by Vsαref, Vsβref is found. The second step is to calculate and saturate the duration of the two sector boundary vectors application. The third step is to compute the three necessary duty cycles. The last step is to assign the right duty cycle (txon) to the right motor phase. It generates less harmonic distortions in output voltage or output current applied to phases of an AC motor and to provide more efficient use of supply voltage.

A simplified approach, which is equivalent to the conventional modulation strategy, can be used. In this approach, the instantaneous average of the minimum and maximum of all three-phase voltages is calculated as the Voltage offset. This instantaneous Voltage offset is then subtracted from each of the instantaneous three-phase voltages. This method is known as SVPWM MIN-MAX method. The Va, Vb, and Vc outputs of the Inverse Clarke transformation that correspond to the phase voltages A, B, and C respectively. The following equations are used for the SVPWM MIN-MAX method (sine with third harmonics injection).

$Voff = [(Va,b,Vc)+MAX(Va,Vb,Vc)]/2$

$Va' = Va - Voff$

$Vb' = Vb - Voff$

$Vc' = Vc - Voff$

where, Va′, Vb′ and Vc′ are the third harmonic injected phase voltages.

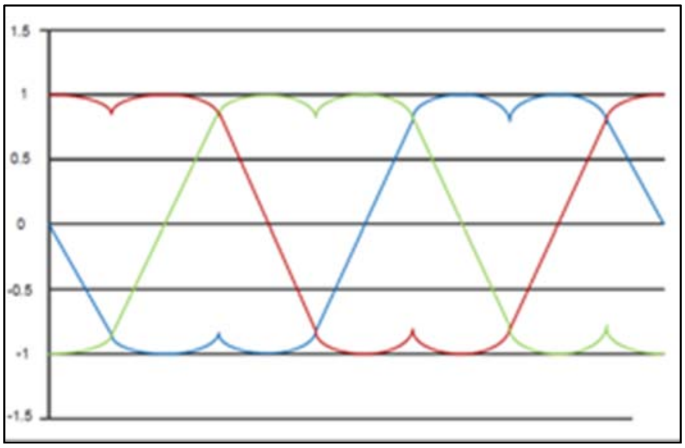


Fig 9: PWM Duty cycles for Space Vector Pulse Width Modulation

The main objectives of space vector pulse width modulation is to generate gate pulses that have wide linear modulation range, less switching loss, less total harmonic distortion in the spectrum of switching waveform, easy implementation and less computational calculations.

3. Simulation & Result

Simulation tools have the capabilities of performing dynamic simulations of motor drives in a visual environment so as to facilitate the development of new systems. Matlab Simulink has the advantages of being capable of complex dynamic system simulations, graphical environment and broad selection of tool boxes. The simulation environment of Simulink has a high flexibility and expandability which allows the possibility of development of a set of functions for a detailed analysis of the electrical drive. Its graphical interface allows selection of functional blocks, their placement on a worksheet, selection of their functional parameters interactively, and description of signal flow.

The simulation of PMSM drive is done in Matlab Simulink environment. The entire PMSM control system can be divided into several independent functional modules: PMSM module, inverter module and coordinate transformation module and SVPWM production module, PI controller and so on. By combining these modules simulation model of PMSM control system has been developed. The diagram shows the Matlab Simulink model for speed control system of PMSM.

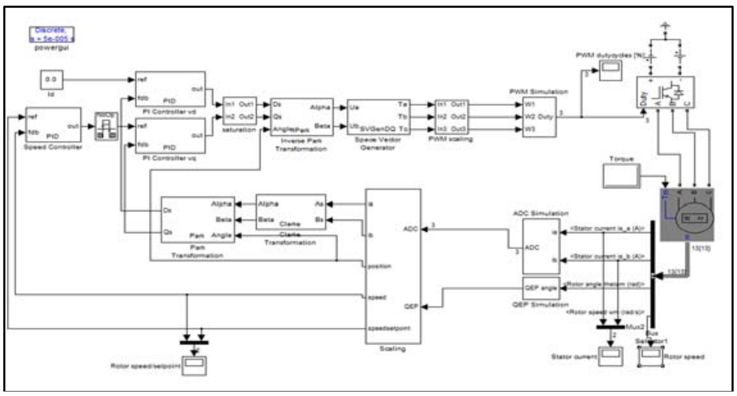


Fig 10: Matlab/Simulink Model for PMSM speed control system

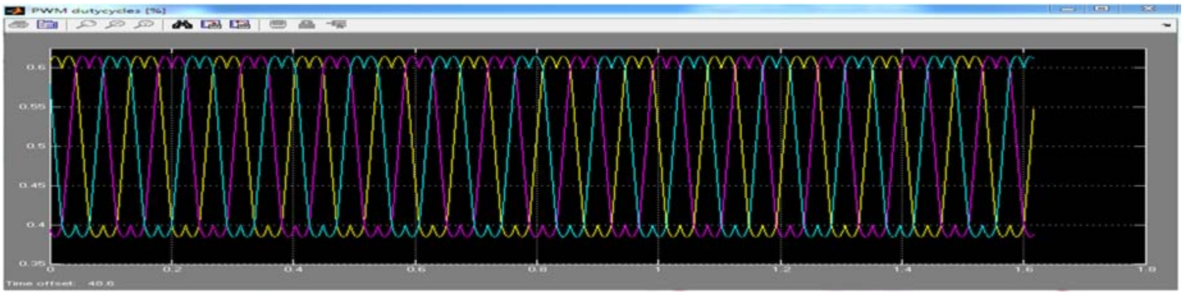
The simulation consists of several steps. The Space Vector Generation using Clark & Park transforms has been implemented. The inner current loop is present with two PI

controllers for d and q axis separately. The speed and angle measurement is done by using Encoder. Then outer speed loop is present with PI speed controller. The drive system consists of the motor model, average value inverter fed by a 200 V dc supply. The duty cycles are provided to inverter by the SVPWM block. The inverter drives the motor to generate controlled rotor speed. To check the model performance and field oriented control, conditions for different DC voltage values are simulated and the results are analyzed.
The motor control and input parameters are defined for the system given in Table 1. Based on these parameters, duty cycles, stator current and rotor speed are observed.

Table 1

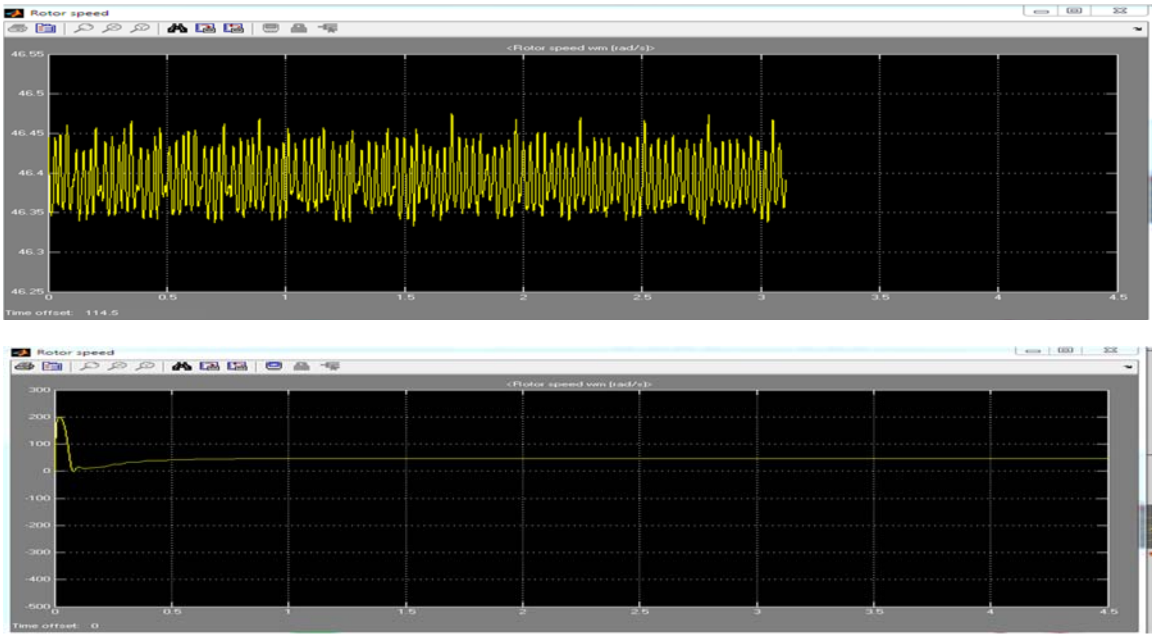
Pole pairs P	1
Stator Resistance Rs	1.6 Ω
Inductances Ld=Lq	0. 006365 H
Inertia J	0.0001854 kgm^2
DC voltage	200V
Encoder resolution	2000

Figures shows the final harmonic injected phase voltage waveforms corresponding to each phase, then stator currents and rotor speed.



(a) Voltage for three phases (PWM Duty cycles)

(b) Stator current



(c) Rotor speed

Fig 11: Simulation waveforms

From graph it is observed that duty Cycle varies from 0.4 to 0.6, stator current range is 30 to -30, rotor speed range is 46.35 to 46.55 rad/s which is almost constant. Duty cycle vary a bit based on the waveform as waveform varies for different level of voltage input. For Stator Current, graph shows the rotation rate of the stator's magnetic field (based on three phase input), which is expressed in revolutions in time scale. For rotor speed, graph shows the rotating magnetic field against the time scale. Simulations are carried out for different DC voltage values and analyzed.

5. Conclusion

The graphs show the simulations for 200V DC voltage. The Matlab Simulink model for PMSM drive and speed control system with field oriented control for different DC voltage values is simulated and the results are analyzed. Matlab Simulink library provides easy modeling of PMSM drives and the simulated results can be helpful in implementation of the drive. The transient and steady state values of current, speed and duty cycles are analyzed. From the graph and analysis is clear that the variation is not in Rotor Speed and Stator Current. It means system design is capable enough to maintain the constant speed within the variation of input. This means rotor speed is maintained within the tolerance range for the given input. Thus this technique has the advantage of less overshoot and quick response.

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