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Simulation Study of a Six-Step Discontinuous Current Mode Inverter Fed Permanent Magnet Synchronous Motor: An Interactive Modeling Approach

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Abstract : A six-step discontinuous current mode inverter interfaced with a Permanent Magnet Synchronous Motor drive was modelled using MATLAB/Simulink in this work. Ins this work the dq-axis Voltage-Current and Torque relations are model in terms of machine parameters. It makes use of MATLAB/Simulink's gate drive capabilities and a six-step 120-degree mode inverter. The model makes it simple to modify the gate drive inverter and machine characteristics. Changes in power supply information, phase angle advance, and PMSM parameters like, machine stator resistance, machine inductance, number of poles of the machine, constants of rotor magnets, moment of inertia, and lastly the damping constant of the machine. Testing for a phase angle advance of 30° and 45° using a six-step discontinuous current mode inverter supplied PMSM drive under no-load circumstances is part of the simulation study.

***IndexTerms* – Permanent Magnet Synchronous Machine, Electric Drive System, Three phase Inverter.**

I. INTRODUCTION

The advent of electric propulsion systems and renewable energy integration has led to an increased demand for efficient motor drive systems. Among these, the Permanent Magnet Synchronous Motor (PMSM) stands out for its high efficiency, power density, and precise control characteristics. To effectively drive PMSMs, various inverter topologies have been explored, with the six-step discontinuous current mode inverter emerging as a viable solution due to its simplicity and cost-effectiveness. This paper focuses on the simulation study of a Six-Step Discontinuous Current Mode Inverter fed Permanent Magnet Synchronous Motor [1], employing an interactive modeling approach within the MATLAB/Simulink environment. The interactive modeling aspect enables users to dynamically explore and analyze the behavior of the motor-inverter system under different operating conditions, providing valuable insights for research, education, and practical applications in power electronics and drives laboratories.

The motivation behind this paper stems from the growing importance of electric propulsion systems in various industries, including automotive, aerospace, and renewable energy sectors. PMSMs [2], being key components in such systems, require efficient and reliable drive solutions to meet the demands of modern applications. The Six-Step Discontinuous Current Mode Inverter presents a promising option for driving PMSMs, offering simplicity, robustness, and cost-effectiveness compared to more complex modulation schemes. Understanding the dynamic behavior and performance characteristics of the Six-Step Discontinuous Current Mode Inverter fed PMSM is crucial for optimizing system design, control strategies, and energy efficiency [3].

The primary objective of this project is to develop a comprehensive MATLAB/Simulink model for the Six-Step Discontinuous Current Mode Inverter fed Permanent Magnet Synchronous Motor. This model will accurately capture the dynamic behavior of the motor-inverter system and allow for interactive exploration of key performance metrics such as speed control, torque production, and efficiency.

II. PERMANENT MAGNET SYNCHRONOUS MACHINE MODELING

PMSMs, or permanent magnet synchronous motors, are extensively utilized in a wide range of industrial applications because of their exceptional power density, efficiency, and accurate control characteristics [4]. The modeling of PMSMs involves understanding the electromagnetic principles governing their operation and developing mathematical representations that accurately capture their dynamic behavior. The fundamental equations governing PMSM operation include the electromagnetic equations that describe the relationship between magnetic fields, currents, voltages, and torque production [5] – [7]. Park's Transformation: To simplify analysis and control, the three-phase time-domain equations are often transformed into a two-coordinate reference frame known as the dq-axis (direct and quadrature) reference frame, which rotates synchronously with the rotor flux. This transformation decouples the equations, making them easier to analyze and control. Dynamic Equations: The dynamic equations for PMSMs typically include equations describing the electromagnetic torque, rotor dynamics, electrical dynamics, and mechanical dynamics. These equations capture the interactions between electrical, magnetic, and mechanical variables in the motor. Back Electromotive Force (EMF) and Torque Equations: The back EMF generated in the motor windings opposes the applied voltage and affects the motor's speed-torque characteristics. Torque equations relate the electromagnetic torque produced by the motor to the currents flowing through its windings and the rotor position. PMSM models can be implemented in simulation environments such as MATLAB/Simulink using differential equations or state-space representations. High-fidelity models may include nonlinear effects and saturation characteristics for more accurate simulations. Sensorless control techniques, such as observer-based methods, can be incorporated into PMSM models to estimate rotor position and speed without the need for physical sensors, enhancing cost-effectiveness and reliability.

The stator flux-linkage equations are:

$$v_{qs} = R_s i_{qs} + s\lambda_{qs} + \omega_{re}\lambda_{ds} \tag{1}$$

$$v_{ds} = R_s i_{ds} + s\lambda_{ds} - \omega_{re}\lambda_{qs} \tag{2}$$

where : V_{ds} , V_{qs} are the *dq* axis stator voltages, ω_{re} : is the angular speed of the rotor in electrical radians/second. The representation of *q* and *d* axes stator flux linkages rotor reference frames are:

$$\lambda_{qs} = L_q . i_{qs} \tag{3}$$

$$\lambda_{ds} = L_d . i_{ds} + \lambda_m \tag{4}$$

Where: λ_m : is the amplitude of the stator flux linkages established by the permanent magnet,. By substituting the equations (3) and (4) in equations (1) and (2) equation (5) is as:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \end{bmatrix} = \begin{bmatrix} R_s + sL_q & -\omega_{re} L_d \\ -\omega_{re} L_q & R_s + sL_d \end{bmatrix} * \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \begin{bmatrix} \omega_{re}\lambda_m \\ 0 \end{bmatrix} \tag{5}$$

in equation (5), Rs, L_d, L_q : represents resistance, inductance of the stator in dq axis respectively. The expression for electromagnetic torque is represented by equation no (6) as shown below:

$$T_{em} = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)(\lambda_{ds} . i_{qs} - \lambda_{qs} . i_{ds}) \tag{6}$$

Where P is the number of poles. Using equation (3) and (4) in equation (6) equation (7) follows:

$$T_{em} = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left(\lambda_{ds}.i_{qs} + \left(L_d - L_q\right)i_{qs}.i_{ds}\right) \tag{7}$$

The equations related to the rotor electromagnetic torque, of the machine speed are co-related as:

$$T_{em} = J\left(\frac{\partial \omega_{rm}}{\partial t}\right) + D\omega_{rm} + T_{mech} \tag{8}$$

Where: ω_{rm} - rotor speed in mechanical radians per second, J - rotor inertia, D - is damping constant and T_{mech} - mechanical load torque. The three phase currents ate represented by considering the currents as inputs as below equations:

$$\left.\begin{aligned} i_{as} &= i_s \sin\left(\theta_{re} + \delta\right) \\ i_{bs} &= i_s \sin\left(\theta_{re} + \delta - \frac{2\Pi}{3}\right) \\ i_{cs} &= i_s \sin\left(\theta_{re} + \delta + \frac{2\Pi}{3}\right) \end{aligned}\right\} \tag{9}$$

Where: θ_{re} - product of electrical rotor speed and time, δ - angle between the rotor field and stator current phasor. The rotor field is traveling at a speed of ω_r rad/sec. The q and d axes stator voltages in the rotor reference frame: for a balanced three phase operation are represented by:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_{re} & \cos\left(\theta_{re} - \frac{2\Pi}{3}\right) & \cos\left(\theta_{re} + \frac{2\Pi}{3}\right) \\ \sin\theta_{re} & \sin\left(\theta_{re} - \frac{2\Pi}{3}\right) & \sin\left(\theta_{re} + \frac{2\Pi}{3}\right) \end{bmatrix} * \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \tag{10}$$

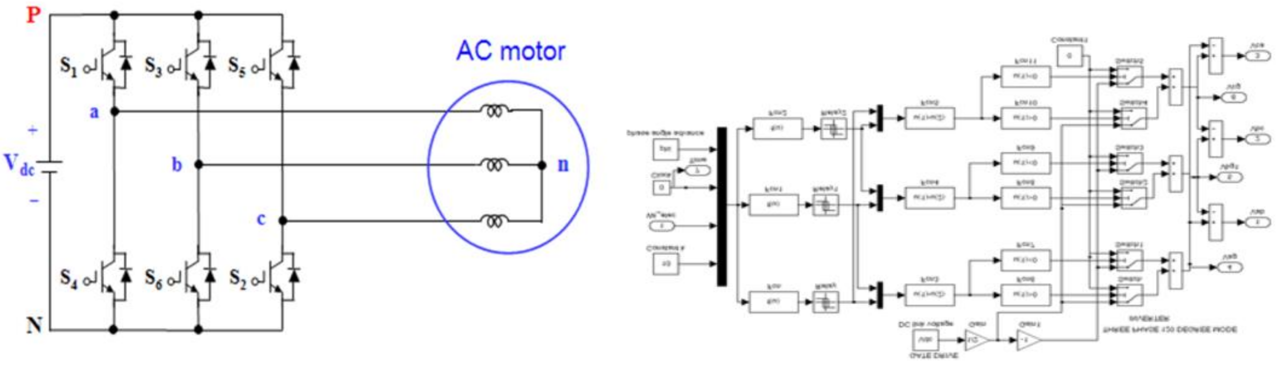
Where: θ_{re} - angular position of the rotor in electrical radians. The following equations represents the stator currents in the three phases a, b and c system:

$$\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta_{re} & \sin\theta_{re} \\ \cos\left(\theta_{re} - \frac{2\Pi}{3}\right) & \sin\left(\theta_{re} - \frac{2\Pi}{3}\right) \\ \cos\left(\theta_{re} + \frac{2\Pi}{3}\right) & \sin\left(\theta_{re} + \frac{2\Pi}{3}\right) \end{bmatrix} * \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} \tag{11}$$

Where: θ_{re} - the angular position of the rotor in electrical radians.

III. SIX STEP THREE PHASE CURRENT SOURCE INVERTER

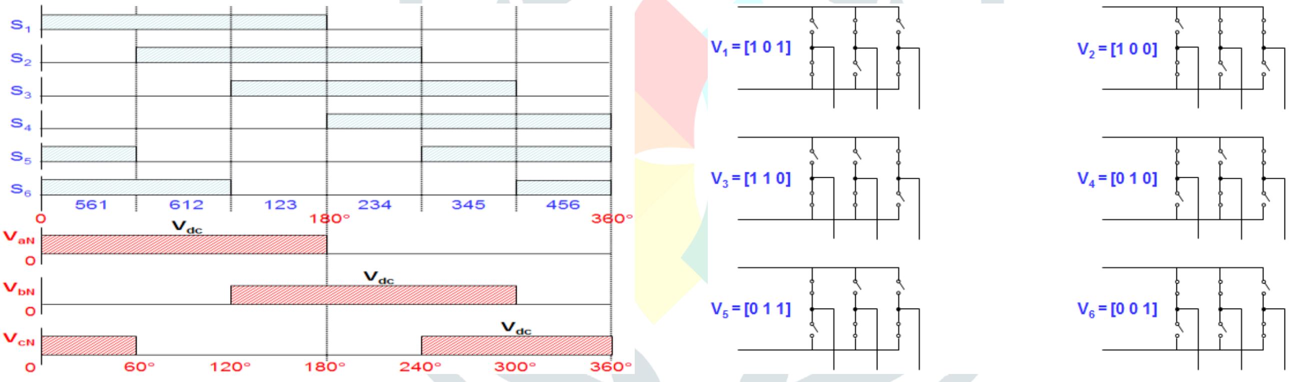
A Six-Step Three-Phase Current Source Inverter (CSI) is a type of power electronic converter used to control the speed and torque of three-phase AC motors as shown in Fig. 1. Unlike voltage source inverters (VSIs), which maintain a constant voltage output, CSIs maintain a constant current output. Here's an overview of the operation and key features of a Six-Step Three-Phase Current Source Inverter: Operation: Controlled Current Output**:** The main distinguishing feature of a CSI is its ability to regulate the output current, making it suitable for applications where precise current control is required. Six-Step Commutation**:** The CSI operates by switching the current through each phase in discrete steps, resulting in six distinct current states per electrical cycle. This six-step commutation scheme simplifies the control algorithm and reduces switching losses. Diode Rectifier Input**:** CSIs are often fed by a diode rectifier, which converts AC input power from the grid into DC power. The DC link capacitor smooths the rectified DC voltage before it enters the CSI. Key Features: The six-step commutation scheme simplifies the control algorithm compared to more complex modulation techniques used in voltage source inverters. CSIs are known for their high reliability due to the robustness of GCTs and the absence of shoot-through conditions, which can occur in VSI configurations. Regenerative Braking: CSIs can facilitate regenerative braking, allowing the motor to act as a generator and return energy to the power supply during deceleration. Unlike VSIs, which can vary the output voltage, CSIs have limited voltage control capabilities. The output voltage is determined by the load impedance and the available DC link voltage. CSIs are commonly used in applications where precise current control is required, such as in electric traction systems, wind turbine generators, and high-performance industrial drives [8] – [10].



(a) (b)

Fig. 1 (a) Three-phase current source inverter, (b) Six Step 120 Degree Mode Gate Drive and Inverter.

A 180° cycle is conducted by each IGBT in the 180-degree mode CSI. Similar to a 180° mode inverter, a 120° mode inverter needs six steps to complete one cycle of the output ac voltage, each lasting 60°. where the three-phase load is considered to be star linked and the IGBTs are S_1 through S_6. The IGBTs are numbered according to the order in which the voltages at the inverter's output terminals a, b, and c are obtained. A 180° cycle is conducted by each IGBT in the 180-degree mode CSI. Similar to a 180° mode inverter, a 120° mode inverter needs six steps to complete one cycle of the output ac voltage, each step lasting 60°. where the three-phase load is considered to be star linked, and S_1 through S_6 are the IGBTs.



(a) (b)

Fig. 2. (a) Waveforms of gating signals, switching sequence, line to negative voltages for six-step current source inverter. (b) Six inverter voltage vectors for six-step current source inverter

The IGBTs S_1, S_4, S_3, S_6, S_5, and S_2 are turned on at 180-degree intervals, as can be seen in the image. This indicates that S1 conducts for one whole cycle. IGBTs in the upper group, specifically S_1, S_3, and S_5, conduct 120° intervals. It suggests that S_3 and S_5 must fire at 120° and 240° respectively if S_1 is shot at 0°. This also applies to the lowest class of IGBTs. Consequently, as seen in Fig. 2. Only three IGBTs—one from each of the upper and lower groups, or two from each of the groups—are conducting (a) and (b).

IV. SIMULINK STUDIES

Simulation studies involve the use of computer software to model, analyze, and predict the behavior of complex systems or processes. These studies are widely used in various fields including engineering, science, economics, and social sciences. The simulation outputs for the V_{LN} and RMS V_{LN} of the PMSM for a switching advance of $\frac{\Pi}{6}$ are plotted as:

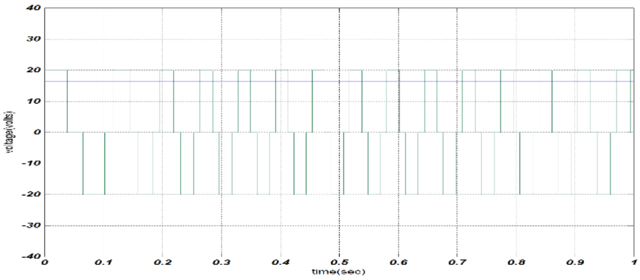


Fig. 3. – V $_{LN}$ and RMS V $_{LN}$ vs TIME

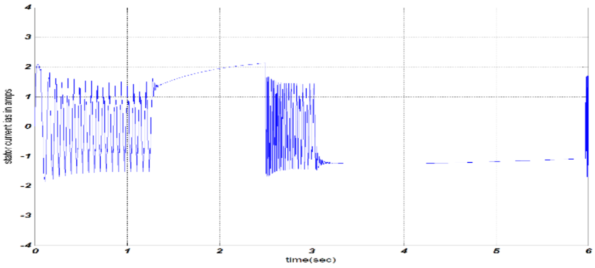
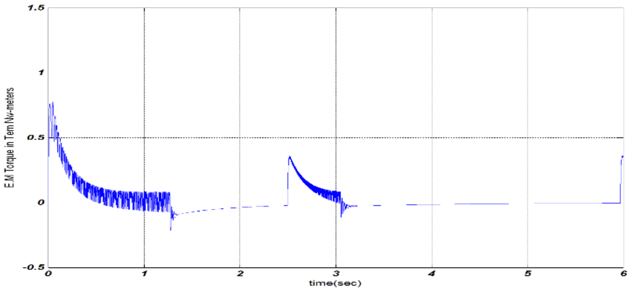


Fig. 4. - Stator Current I$_{as}$ vs Time



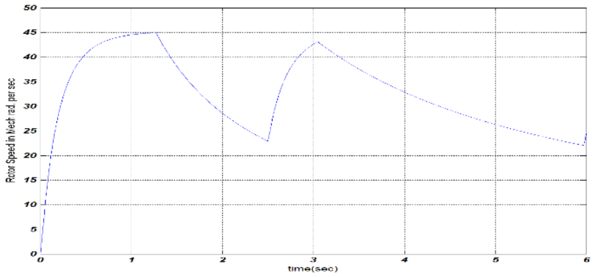


Fig. 5. Rotor Speed vs Time

Fig. 6- E. M. Torque vs Rotor Speed

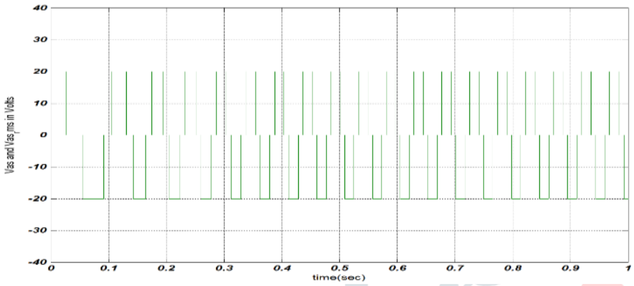


Fig. 7. – V $_{LN}$ and RMS V $_{LN}$ vs TIME

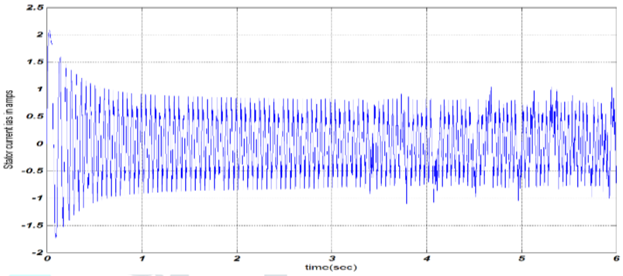
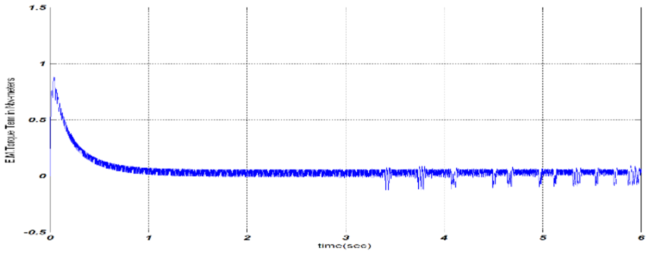


Fig. 8.- Stator Current I$_{as}$ vs Time



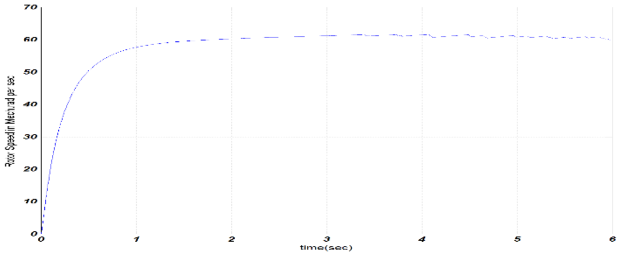


Fig. 9. E.M. Torque vs Time

Fig. 10. Rotor Speed vs Time

In Fig. 3, In Fig. 4, In Fig. 5 simulation results shows the outputs for the Line to neutral voltage, Line Current, Rotor Speed Rotor Speed, respectively for the PMSM for a switching advance of Π /6 are plotted. And similarly In Fig. 6, In Fig. 7, In Fig. 8, In Fig. 9, In Fig. 10 shown the Torque, V$_{LN}$, Stator Current, E. M. Torque, Rotor Speed and E. M. Rotor Speed respectively for the PMSM for a switching advance of Π /6 are plotted.From these results it is observed that the speed of the drive system is effectively maintained constant with the modelled Six-Step Discontinuous Current Mode Inverter Fed Permanent Magnet Synchronous Motor drive system.

V. CONCLIUSONS

With the use of an interactive modeling technique to feed a Six-Step Discontinuous Current Mode Inverter fed Permanent Magnet Synchronous Motor (PMSM), power electronics and motor drives have evolved dramatically. The creation of an interactive MATLAB/Simulink model for a permanent magnet synchronous motor drive interfaced with a six-step discontinuous current mode inverter is presented in this work. In terms of machine characteristics, this model has a gate drive capability, a six-step 120-degree mode inverter, and the dq-axis Voltage-Current and Torque relations. The simulation investigation is carried out for phase angle advances of 30° and 45° with a six-step discontinuous current mode inverter provided PMSM drive and no load. The simulation trials show how effective the built Six-Step Discontinuous Current Mode Inverter fed Permanent Magnet Synchronous Motor driving system is.**References**

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