# Speed Control of 6-Phase PMSM using Fuzzy Controllers

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***Abstract*— the article introduces a method for controlling the speed of a six-phase permanent magnet synchronous motor (PMSM) drive with the help of fuzzy logic controllers (FLCs). By utilizing the vector control technique, the fuzzy logic controller achieves a high level of dynamic performance. The FLC is implemented in the current and speed controllers of the six-phase PMSM drive. To evaluate its effectiveness under different operating conditions, the FLC with PMSM drives is designed and simulated using MATLAB. The FLC proves to be more robust and capable of overcoming the nonlinearity issues associated with the six-phase PMSM. The simulation outcomes confirm the efficiency of the suggested control technique for the PMSM drive system.**

**Keywords— PMSM, Fuzzy Logic Controllers, VSI, Speed Cotrol, six-phase.**

## 1. INTRODUCTION

Multiphase variable speed drives play a crucial role in the realm of industrial automation for the advancement of motion control systems. The multiphase drive system offers numerous advantages over other drive systems, including superior performance, a greater range of variable speeds, seamless agility, and enhanced efficiency. The noteworthy technical rationale behind the preference for six-phase PMSM (Permanent Magnet Synchronous Motor) in comparison to three-phase drives is attracting researchers and industries towards its adoption.

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1) The utilization of multiphase systems (consisting of more than three phases) offers enhanced dependability and efficiency numbers of variable speed .
2) The stator current for each phase decreased..
3) The superior dynamic performance is achieved due to the high ratio of torque to inertia.
4) The combination of increased power density and enhanced degree of freedom is notable.
5) Drives that exhibit high efficiency and fault tolerance are essential in modern systems.

The multiphase drive is commonly used in specialized applications that require high reliability and variable speed control, such as locomotive traction, aerospace, ship propulsion, and very large power applications, including traction in hybrid electric vehicles and electric vehicles. By using current limited devices, the multiphase drive helps overcome the challenges associated with high-power applications.

In a system consisting of n phases, torque pulsations arise due to supply time-harmonics of the order 2n±1, leading to a torque ripple harmonic that is 2n times greater than the supply frequency. Increasing the number of phases appears to be the most effective solution to this problem. Additionally, the absence of rotor winding eliminates the need for slip rings and brushes, reducing maintenance costs. The PMSM drive is preferred due to their simpler control compared to field-oriented control of induction motor drive. These drives have a high torque inertia ratio, resulting in rapid dynamic response.

The multilevel voltage source inverters possess a distinctive configuration that enables them to attain elevated voltage and power levels without necessitating transformers. The vector control system of a 6-phase PMSM fault-tolerant motor proficiently regulates motor speed and torque in both normal and open-circuit scenarios, resulting in enhanced operational efficiency. The winding design incorporates high reactance to restrict short-circuit current, while the magnets employed consist of samarium cobalt rare earth permanent magnet materials, which exhibit resistance to temperature-induced effects on their performance[5].

The PWM current controllers are utilized to regulate the currents of the six-phase PMSM motor in order to maintain the desired values consistently within the system. Accurate results are achieved by incorporating current feedback into the PWM current controllers. The firing of power electronic devices enhances current control. In this research paper, the control strategy is discussed using MATLAB/Simulink computer simulation software. The application of expert systems and fuzzy logic control techniques in the Six-phase PMSM drive is employed for motion control of the system. These tools enable the system to possess intelligent, learning, and self-organizing capabilities for decision-making. Fuzzy control offers significant advantages in controlling complex, time-varying, and nonlinear systems, without requiring the mathematical model of the controlled object. Additionally, it facilitates easy design.

## 2. DYNAMIC MODELING OF SIX-PHASE PMSM

The modeling of the six-phase PMSM, fuzzy logic controller, three-phase VSI, and PWM controller are all incorporated in the mathematical modeling of the six-phase PMSM drive. These assumptions play a crucial role in the overall process.

1. Saturation is neglected in the PMSM.
2. Losses are negligible in system (Eddy currents & hysteresis losses).
3. The windings capacitances are neglected.
4. The induced EMF in the stator is sinusoidal.

The six-phase PMSM is designed with two identical and balanced stator windings connected in a star configuration. These windings can be adjusted to have a phase shift of $0^0$, $30^0$, or $60^0$. A 0-degree phase shift is equivalent to a three-phase system, while a $60^0$ phase shift results in a symmetrical arrangement that can be simplified to a three-phase system due to the co linearity of the two phases from different stars. Conversely, a $30^0$ phase shift leads to an unsymmetrical arrangement that cannot be further simplified. The configuration with a $30^0$ phase shift is considered the most favorable in terms of torque pulsation and voltage harmonic distortion. As a result, the preference is given to the arrangement with a $30^0$ phase shift between star connections, as discussed in this paper [6].

The mathematical representation below illustrates the voltage equation and flux linkage equation for the six-phase PMSM drive. The fundamental equation is represented as follows:

$$[V_s] = [R_s][I_s] + d/dt\,(Ø_s) \qquad (1)$$

In the study, a six-phase PMSM consisting of two three phase windings namely abc and xyz,

$$V_{abc} = R_s\, i_{abc} + d/dt\,(Ø_{abc}) \qquad (2)$$

$$Ø_{abc} = L_{11} i_{abc} + L_{12} i_{xyz} + Ø_{mabc} \qquad (3)$$

$$V_{xyz} = R_s i_{xyz} + d/dt(Ø_{xyz}) \qquad (4)$$

$$Ø_{xyz} = L_{22} i_{xyz} + L_{21} i_{abc} + Ø_{mxyz} \qquad (5)$$

The resistance of the stator is denoted by Rs, which is a vector $[R_s\ R_s\ R_s]^T$. The voltage vector of winding abc is represented by Vabc, which is $[V_{abc}]^T$. The current vector of the stator abc is denoted by iabc, which is $[i_{abc}]^T$. Similarly, the voltage vector of winding xyz is $V_{xyz}$, which is $[V_{xyz}]^T$. The current vector of the stator xyz is $i_{xyz}$, represented as $[i_{xyz}]^T$. The flux linkage of the winding abc is $Ø_{abc}$, given by $[Ø_{abc}]^T$. The flux linkage of the winding xyz is $Ø_{xyz}$, represented as $[Ø_{xyz}]^T$. The inductance of the winding abc is denoted by $L_{11}$, while the inductance of the winding xyz is $L_{22}$. The mutual inductance between winding abc and xyz is denoted by $L_{12}$ and $L_{21}$ respectively. The mutual inductance of abc winding is $Ø_{mabc}$, and the mutual inductance of xyz winding is $Ø_{mxyz}$.

$$T_{qd1} = \frac{2}{3}\begin{bmatrix} \cos\theta r & \cos(\theta r - 120^{\circ}) & \cos(\theta r + 120^{\circ} \\ \sin\theta r & \sin(\theta r - 120^{\circ}) & \sin(\theta r + 120^{\circ} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (6)$$

$$T_{qd2} = \frac{2}{3}\begin{bmatrix} \cos(\theta r - 30^{\circ}) & \cos(\theta r - 150^{\circ}) & \cos(\theta r + 90^{\circ}) \\ \sin(\theta r - 30^{\circ}) & \sin(\theta r - 150^{\circ}) & \sin(\theta r + 90^{\circ}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (7)$$

$T_{qd1}$ and $T_{qd2}$ represent the transformation matrix for the abc and xyz windings respectively. The angle of the rotor flux is denoted as Ø. However, the machine model of a six-phase PMSM can be illustrated in the synchronous rotating reference frame as mentioned in [6].

$$V_{q1} = R_s i_{q1} + L_{q11} \frac{d}{dt} i_{q1} + \omega_e (L_{d11} i_{d1} + \varnothing_m) \qquad (8)$$

$$V_{d1} = R_s i_{d1} + L_{d11} \frac{d}{dt} i_{d1} - \omega_e L_{q11} i_{d1} \qquad (9)$$

$$V_{q2} = R_s i_{q2} + L_{q22} \frac{d}{dt} i_{q2} + \omega_e (L_{d22} i_{d2} + \varnothing_m) \qquad (10)$$

$$V_{d1} = R_s i_{d2} + L_{d22} \frac{d}{dt} i_{d2} - \omega_e L_{q22} i_{d2} \qquad (11)$$

$$\omega_e = \frac{P}{2} \omega_r \qquad (12)$$

Where $V_{q1}$ and $V_{d1}$ are the voltage of abc winding for d-q axis; $V_{q2}$ and $V_{d1}$ are the voltage of xyz winding for d-q axis; $i_{d1}$ and $i_{q1}$ are the current of abc winding for d-q axis; $i_{d2}$ and $i_{q2}$ are the current of xyz winding for d-q axis; $L_{d11}$ and $L_{q11}$ are the inductance of abc winding for d-q axis; $L_{d22}$ and $L_{q22}$ the inductance of xyz winding for d-q axis; $\omega_r$ and $\omega_e$ are rotor and electrical angular velocities; $\varnothing_m$ is the permanent magnet flux linkage ;P is the number of pole pair for the six-phase PMSM. In PMSM for the identical set of winding assume that($L_{d11}=L_{d22}=L_d$) and($L_{q11}=L_{q22}= L_q$). The electromagnetic torque in six-phase PMSM is represented by $T_e$ as follows :

$$T_e=(2/3)(p/2)[\varnothing_m(i_{q1}+i_{q2})+(L_d-L_q)(i_{d1}i_{q1}+i_{d2}i_{q2})] \qquad (13)$$

Furthermore, the six-phase PMSM's mechanical torque equation is provided as follows:

$$T_e = T_L + J d/dt\, \omega_r + B\, \omega_r \qquad (14)$$

Where B=damping coefficient, J =inertia, $T_L$ =load torque of the six-phase PMSM drive system[6], and the block diagram is shown in Fig.1.

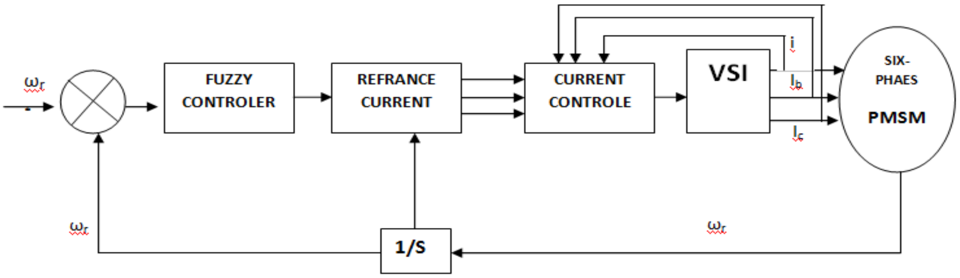

Fig.1 Block Digram Of Fuzzy Controled Six-Phase PMSM Drive.

TABLE I. MANCHINE PERAMETER

| S. NO. | Parameter | Rating |
|---|---|---|
| 1. | Rated power | 2Kw |
| 2. | Nominal voltage | 400 |
| 3. | No. of pole | 4 |
| 4. | Rated speed | 36.5rad/sec. |
| 5. | Stator resistance | 0.64ohm |
| 6. | Flux linkage in PM($Ø_{pm}$) | 2.08wb |
| 7. | Rated current | 11A |
| 8. | Rated torque | 6.4N |
| 9. | $L_d$ ,$L_q$ | 24.0mH,31.4mH |

## 3. FUZZY LOGIC CONTROLLERS

Fuzzy logic controller (FLC) is an intelligent control method that utilizes logical reasoning. It provides an algorithm, based on expert knowledge, for automatic control systems in electric drives control. The FLC operates on "crisp rules," which consist of 49 standard rules for speed control of six-phase PMSM. Figure 2 illustrates the block diagram of the FLC control system. The FLC has two input variables: speed error (E) and change in speed error (CE), and one output variable: current Iq (U).

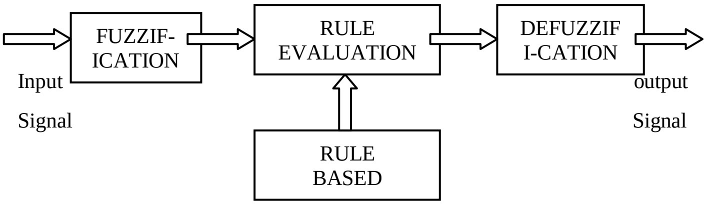

Fig.2: Internal structure of FLC.

In this paper fuzzy rule based matrix for the 'case design' divided into seven sets as followings;

A: Negative Large 0: Approximately Zero

B: Positive Small C: Negative Medium

D: Positive Large E: Negative Small

F: Positive medium

The mamdani-type fuzzy inference provided below solves the value of input and output constants, membership functions, and fuzzy sets. Additionally, the table demonstrates the 'case design' for the six-phase PMSM drive.

TABLE II. FUZZY RULE MATRIX FOR SIX-PHASE PMSM

| E ⇨ | | Speed Error,(E) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CE ⇩ | | A | C | E | 0 | B | F | D |
| Change in speed | A | A | A | A | A | C | E | 0 |
| | C | A | A | A | C | E | 0 | B |
| | E | A | A | C | E | 0 | B | F |
| | 0 | A | C | E | 0 | B | F | D |
| | B | C | E | 0 | B | F | D | D |
| | F | E | 0 | B | F | D | D | D |
| | D | 0 | B | F | D | D | D | D |

The defuzzification process in the system converts the output variable of the inference engine into a crisp value UFUZZY. Several defuzzification algorithms have been suggested in different papers. The centric defuzzification algorithm is employed, where the crisp value is determined as the center of gravity of the membership function [4].

## 4. RESULTS

The model presented in this paper is simulated by sing MATLAB/Simulink package. The outcomes of the simulation for the six-phase system with a fuzzy controller are presented below.

AT NO LOAD CONDITION:

The system is tested under no load condition and set the reference speed at 360rpm. Corresponding response of motor speed is shown in Fig. 3. The response of electromagnetic torque is depicted in Fig. 4, the torque is settled at ‘0’ once speed reaches its reference value. Respective phase currents are also shown in Fig. 5.

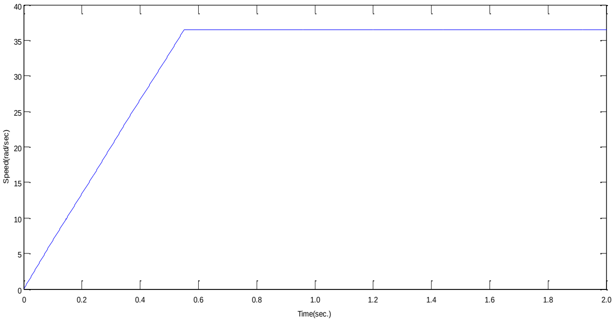

Fig.3: Speed response at no. load.

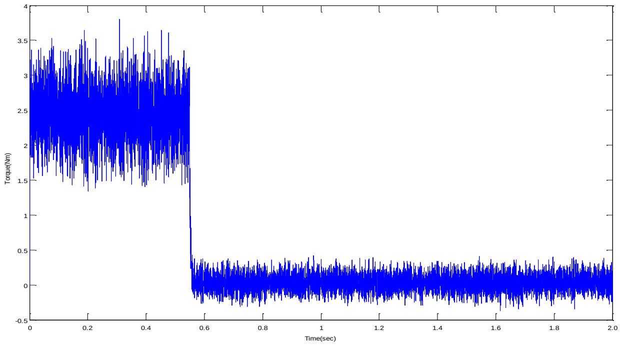

Fig.4: Torque response at no. load.

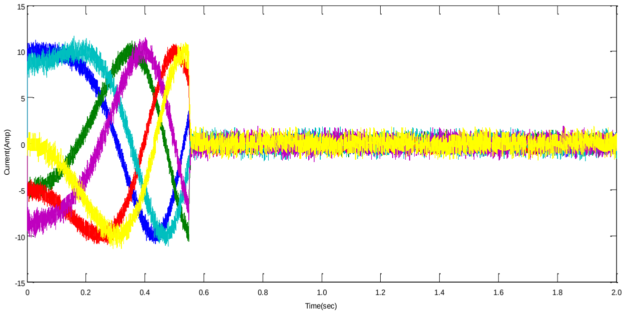

Fig. 5: Current response at no. load.

## AT LOAD CONDITION

Under the above conditions, considered the sudden load change at t=16 sec. Respective speed, torque and currents are shown in Fig. 6, Fig. 7 and Fig. 8 respectively. It is observed that there is no much change in speed when suddenly applied the load. This is achieved by proposed control method of fuzzy.

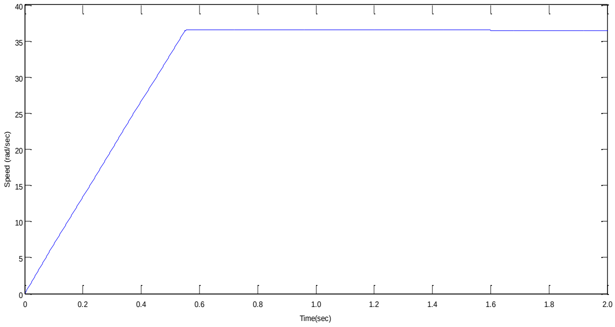

Fig.6 Speed response at load condition.

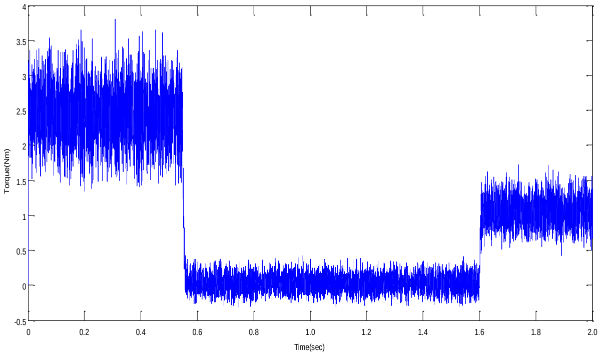

Fig.7: Torque response at load condition.

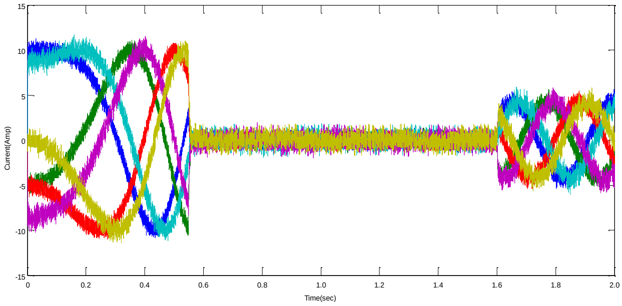

Fig.8: Current response at load condition.

AT CHANGE IN REFRANCE SPEED

Now the system is tested under change in speed. The reference speed is changes as per the response depicted in Fig. 9. Under this condition, the responses of the electromagnetic torque and currents are shown in Fig. 10 and Fig. 11 respectively.

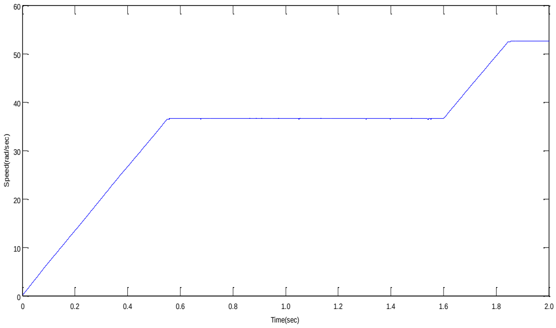

Fig.9: Speed response at reference speed change.

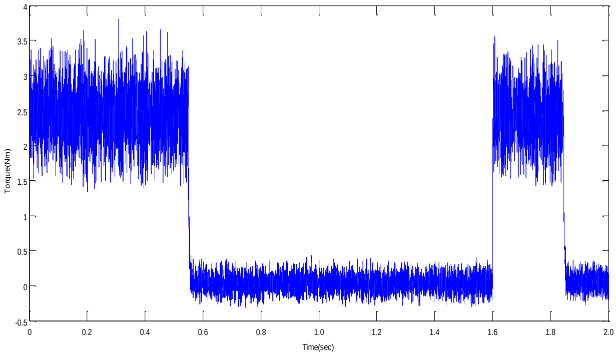

Fig.10 Torque response at reference speed change.

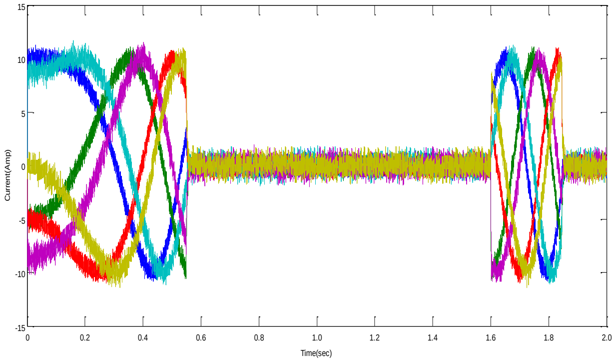

Fig.11: Current response at reference speed change.

## 5. CONCLUSIONS

The primary objective of this study is to examine and enhance the efficiency of a six-phase PMSM drive under various speed, torque, and current conditions. By utilizing a Fuzzy Logic Controller, the system becomes more resilient, eliminating speed overshoot and minimizing fluctuations in torque and current. The integration of supplementary control techniques within the MATLAB/Simulink environment has significantly reduced the time required for designing the Fuzzy Controller.

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