A FUZZY-BASED SPEED CONTROLLER FOR DUAL PMSM DRIVES FED BY A SINGLE INVERTER

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Abstract – **A Fuzzy-based speed controller is proposed for the parallel operation of dual PMSM motors which are fed by a single inverter. For this operation, a controller is proposed that estimates an error value from the motor speed and reference speed which is then fed to a fuzzy logic controller (FLC), the rotor position and the value of Fc are calculated thus giving the gate pulse signals which in turn are fed to the single inverter. Here the Master/Slave technique is performed to ensure smooth operation of the system. The practicality of the system has been verified in MATLAB by simulation.**

***Index terms* - Fuzzy Logic Control, Master/Slave control, Permanent Magnet Synchronous Machine.**

1. INTRODUCTION

Permanent Magnet Synchronous Machines (PMSM) are used at large in industrial applications owing to their advantages. Hence these motors are connected in parallel and used in electric traction, conveyor belts, hoist and crane operation. Usually, the parallel operation is done by individually connecting each motor to a different supply, by doing this not only increases the input sources but also the switching devices required for the inverters overall increase the cost [1]-[3]. The objective of this paper is to implement a single inverter as a source to multiple motors connected in parallel, this reduces the overall cost and number of switching devices. By using a single inverter for multiple motors, a lot of parameters have to be tuned for smooth operation. If there are no load changes in the system the motors will run without losing synchronism as the motors should run at the same speed despite disturbances, but if there is a slight load change then the motors may lose synchronism thus changing the rotor position and making the system inefficient. Though the speed of the motors is the same the rotor position might be different for the motors after the disturbances. So, to mitigate the issue the master/slave method is proposed, as the name indicates the motor with a higher load is assigned as the master motor and the other motor is assigned as the slave motor. In this method of control if the torque angle of a motor dealing with a higher load is controlled to be less than 90 degrees, then the torque angle of a motor dealing with a lower load will naturally be achieved to be smaller than 90 degrees, which means if the motor handling the higher load requires a larger torque angle to overcome the increased resistance, while the motor with the lower load naturally has a smaller torque angle since it encounters less resistance. This method has the advantage of assigning multiple motors in parallel by making a single motor as the master motor [10].

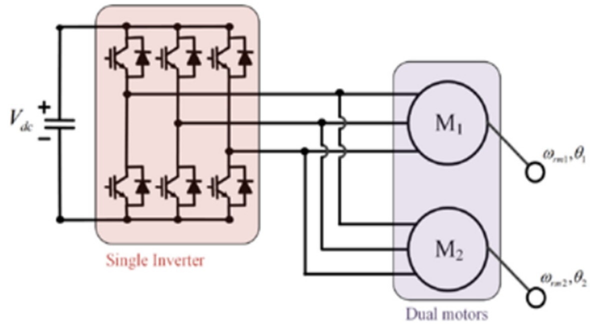


Figure 1. Dual PMSM connected to Single Inverter.

After knowing the importance of the rotor position in dual motor setup and sorting the issue there is still a control scheme to be proposed that controls the system during load changes. Fuzzy logic control (FLC) is such a scheme which ensures the system mitigates the above-mentioned issue.

The objective of this paper is to implement an FLC to a single inverter dual PMSM setup and observe the speed changes and how the motors behave during load changes, and the feasibility of the proposed controller is verified through simulation and experimental results.

2. MASTER/SLAVE CONTROL SCHEME

This section describes the proposed solution to overcome the rotor position changes. Usually, within the master-slave control setup, the output speed or position of the master serves as the reference speed or position for all the slaves. This approach makes sure that any disruptions in load affecting the master will be mirrored and linked by the slaves. However, disturbances occurring in any individual slave will not transmit feedback to the master or other slaves. Fig. 2 provides a simplified representation of a traditional dual-motor master-slave synchronization technique, focusing on closed-loop speed regulation. Alternatives utilizing closed-loop position control are also feasible. Over the years, this synchronization approach has demonstrated its effectiveness in various applications like industrial applications and robotics for coordinated motion [4].

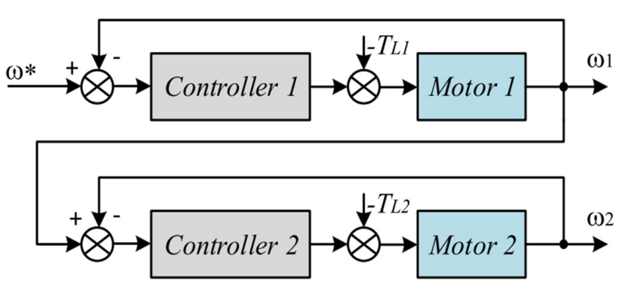


Figure 2. Master - Slave Configuration of motors.

3. FUZZY LOGIC SPEED CONTROLLER

The fuzzy controller operates without the necessity of a mathematical system. It relies on linguistic rules structured as 'if-then' statements to handle nonlinearities of arbitrary complexity. This controller comprises several stages to generate desired outputs corresponding to given inputs [11]. The inference mechanism utilizes fuzzy logic to transform input into output, [12] leveraging components such as if-then rules, membership functions [11-12], and logical operations from earlier stages.

The proposed system incorporates a Mamdani fuzzy logic controller with two inputs: the system error and the change in error. Trigonometric membership functions are employed due to their high accuracy in representing system dynamics. A reference speed ranging from 1000 to 1500 rpm and back to 1000 rpm is provided as input to the system. The closed-loop control procedure commences with comparing the motor speed to the reference speed, resulting in two input signals that are subsequently inputted into the fuzzy logic controller.

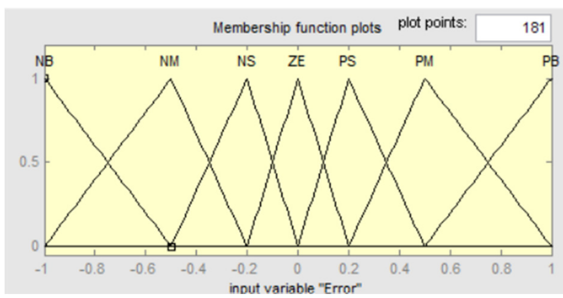


Figure 3. Fuzzy control logic Input 1.

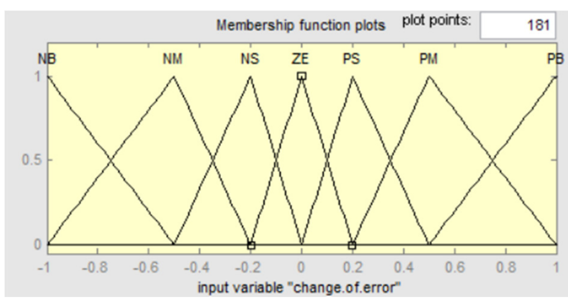


Figure 4. Fuzzy control logic Input 2.

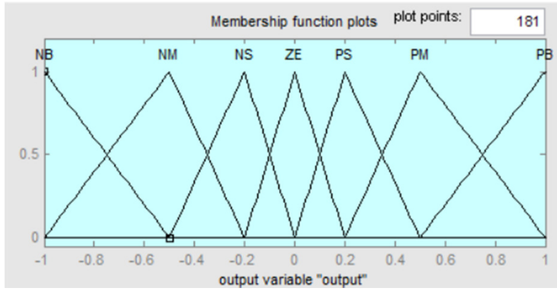


Figure 5. Fuzzy control logic Output.

Utilizing an If-and-then logic structure, the controller defines two input types: error and change in error. The output is generated based on these inputs, i.e., error (input-1) and change in error (input-2) when fed into the FLC.

To initiate the development of the Fuzzy Logic Controller (FLC) based system, the primary step involves acquiring the motor speed data from the master motor. Subsequently, a gain value (denoted as 'k') of 9.549 is incorporated, effectively amplifying the motor output speed. Following this, the signal is directed to the subtractor module, wherein it undergoes a subtraction process with the reference signal assigned to the system. This operation generates a resultant signal, which undergoes further refinement through tuning procedures in the FLC block. Eventually, the refined signal yields a conclusive output comprising six gate pulses, which are fed to the inverter unit. This process alters the system parameters thereby influencing the overall system dynamics.

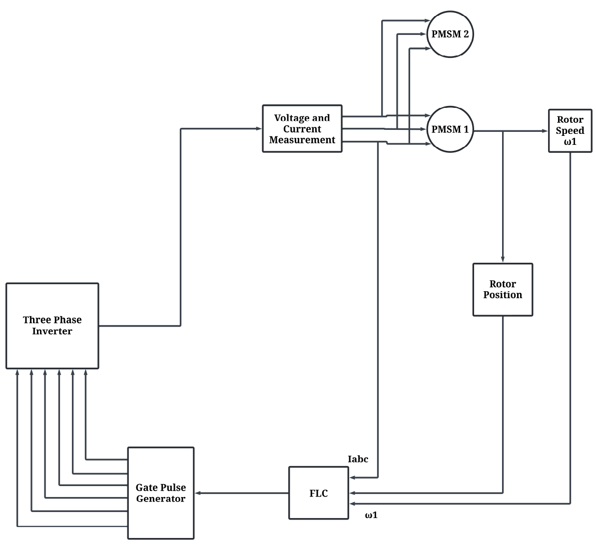


Figure 6. Fuzzy based Speed controller for dual PMSM drive fed by a single Inverter

In the Fuzzy logic speed controller for the Single Inverter Dual PMSM, the simulation framework is divided into three principal components: the Three-phase inverter block, the Fuzzy logic controller block, and the Gate pulse generator block. Within the Three-phase inverter block, the presence of the DC source is present alongside the gate-controlled switches. These switches are modulated by the signal generated from the Gate Pulse Generator block, which, in turn, receives input from the Fuzzy Logic Controller (FLC) block.

The list of parameters utilized in the system is mentioned in Table 1 below.

TABLE 1. System Parameters.

Parameter	**Value**
Rated Voltage (V)	102.8
Rated Torque (Nm)	2.15
Rated Speed (rpm)	1000
Number Of Poles (P)	8
Flux Linkage (Wb)	0.1194
Moment Of Inertia ($Kg.m^2$)	1.092e-4
Stator Inductance (H)	6.71e-3
Stator Resistance (Ω)	0.993

An additional gain parameter is added to the speed of the motor which is k = 9.549.

In the closed-loop configuration, once the input signals undergo comparison within the fuzzy system, the resultant signal from the fuzzy logic controller is fed to a series of comparators. These comparators process the signal, which is generated when subjected to comparison with the logical NOT operator leading to the generation of a total of six gate signals. These gate signals are fed to the inverter, these gate signals regulate the operation of the inverter. By effectively translating the output from the fuzzy logic controller into actionable gate signals, the system achieves great control over motor operations, facilitating seamless adjustments in response to dynamic environmental conditions.

4. SIMULATION RESULTS

A MATLAB simulation was carried out to confirm the effectiveness of the proposed system. In Figure 8(a), a reference speed is introduced into the system, mimicking a scenario where the motor's speed fluctuates in response to changes in the load it is subjected to. The motor responds by adjusting its speed accordingly, albeit with a slight delay. To delve deeper into the motor's speed behaviour, the results are presented in two separate figures: Figures 8(a) and 8(b), as well as Figures 9(a) and 9(b). This segmentation allows for a more detailed examination of the motor's speed dynamics.

The focus of this study revolves around the investigation of speed as the primary parameter of interest. Specifically, our analysis centres on Master Motor's capability to accurately reproduce a predefined reference speed, alongside Slave Motor's capacity to synchronize its speed adjustments with those of Master Motor. This examination is particularly suitable due to the application of a Master/Slave control scheme, wherein Motor 1 acts as the master, dictating speed changes, while Motor 2 functions as the slave, mirroring these adjustments. To see the effectiveness of the speed controller the same system is implemented with the PID controller. Consequently, the research dives into the comparative study of the output speed produced when the controller used in the system is PID instead of FLC and the regard is explained below.

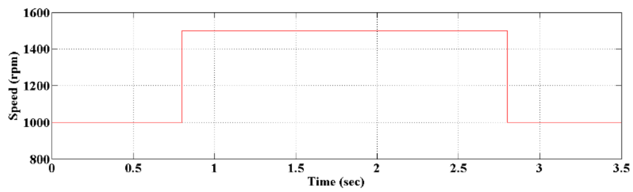
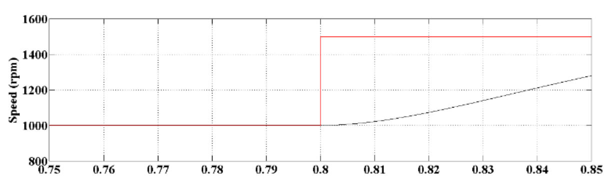


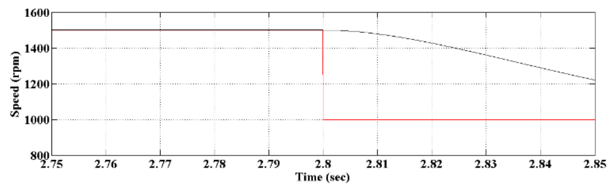
Figure 7. Reference Speed fed to the Mater motor.

The above diagram illustrates a change in reference speed, which initially stands at 1000 rpm and then steps up to 1500 rpm at 0.8 seconds. Subsequently, it steps back down to 1000 rpm from 1500 rpm at 2.8 seconds.

Figures 8(a) and 8(b) below are the output speed characteristics, the figures are zoomed in for a better look. The time taken by the PID controller to adapt to the change is 0.1 sec.



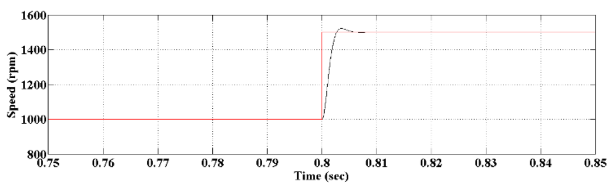
(a)



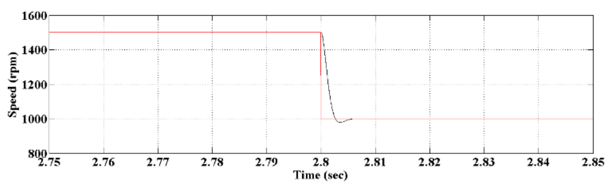
(b)

Figure 8. Output speed of the Master motor when PID controller is implemented.

Figures 9(a) and 9(b) below show the output speed of the master motor when FLC is implemented.



(a)

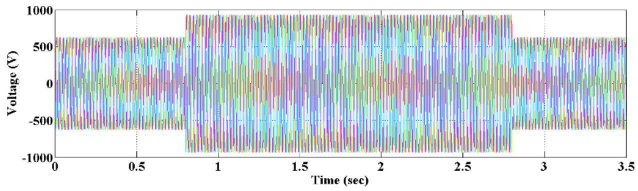


(b)

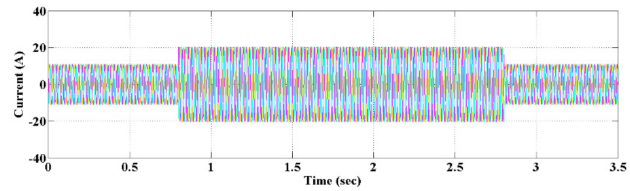
Figure 9. Speed of motor when FLC controller is implemented

The FLC (Fuzzy Logic Controller) demonstrates remarkable adaptability, showcasing a time delay of merely 0.003 seconds in adjusting to changes. Comparative analysis between the FLC speed controller and the PID (Proportional-Integral-Derivative) speed controller underscores the superior performance of the FLC controller. Results indicate a notable difference of 0.097 seconds in response time, with the FLC speed controller exhibiting a significantly quicker and less delayed response. This difference although seemingly negligible, is pivotal in enhancing the system's efficiency, particularly in adjusting to variations in motor speed.

Furthermore, the appropriate results of the system when the FLC speed controller implemented is are shown below.



(a)



(b)

Figure 10. (a)Voltage (b)Current waveforms of Master motor.

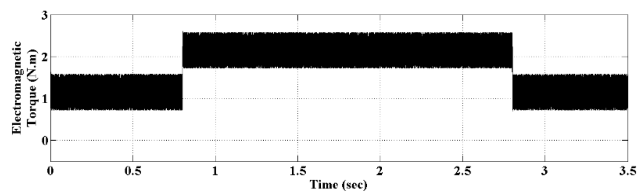


Figure 11. Torque of Master Motor.

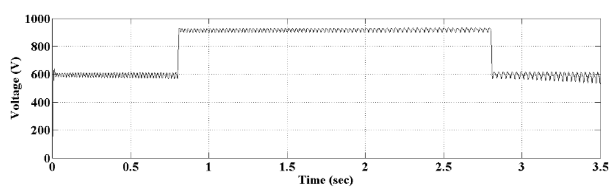


Figure 12. Direct axis voltage.

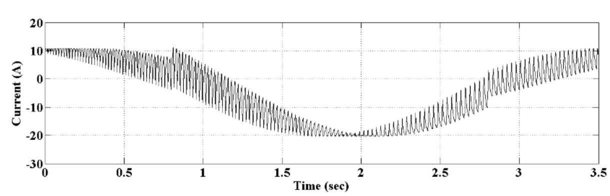


Figure 13. Direct axis current of Motor.

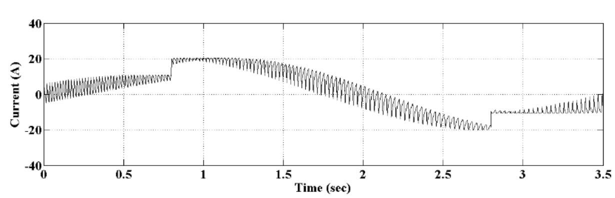


Figure 14. Quadrature axis current of Motor.

The torque for Master Motor is shown in Figure 11 which rises to 2.55 Nm from 1.56 Nm when the speed changes to 1500rpm from 1000rpm and comes back to 1.56 Nm and remains till the end. The Total Harmonic Distortion of the Current for PID controller and FLC controller is shown in Figures 15 and 16 respectively.

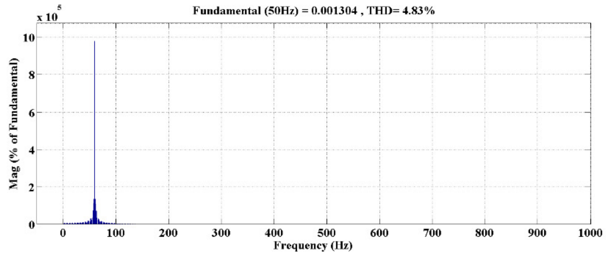


Figure 15. THD of Current with the implementation of PID.

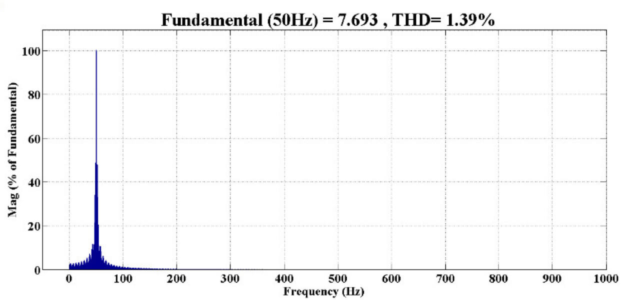


Figure 16. THD of Current with the implementation of FLC.

After comparing the THD of current with FLC and with PID which are 1.39% for FLC and 4.83% with PID controller, the THD of FLC exhibits a remarkably clean and stable waveform, indicating minimal distortion and high quality of power supply. Conversely, when compared with the current THD of PID which exhibits a higher THD value of 1.39%, suggestive of relatively greater harmonic content and potential fluctuations. This disparity in THD values underscores the importance of carefully monitoring and optimizing the current profile to mitigate potential issues such as power losses and interference with sensitive equipment.

The acceptable Total Harmonic Distortion (THD) of current in a drive system, as per IEEE standards, typically falls within the range of 5% to 8%. This range ensures that the current waveform remains relatively clean, minimizing harmonic distortion and potential adverse effects on the electrical system and connected equipment.

Discussed below are Table 2 and Table 3 provide an analysis of the system's performance in the time domain. This analysis dives into how the system behaves over time, offering insights about the speed dynamics and response characteristics.

Table 2. Time domain analysis of the Motor Speed with FLC.

PARAMETERS	**VALUE**		
For Speed	From 0-1000 rpm	From 1000-1500 rpm	From 1500-1000 rpm
Overshoot	4.8%	1.3%	2%
Rise Time	0.003 sec	0.004 sec	0.003 sec
Settling Time	0.06 sec	0.06 sec	0.05 sec

Table 3. Time domain analysis of the Motor Speed with PID.

PARAMETERS	**VALUE**		
For Speed	From 0-1000 rpm	From 1000-1500 rpm	From 1500-1000 rpm
Overshoot	4.9%	1.67%	3.8%
Rise Time	0.1 sec	0.1 sec	0.1 sec
Settling Time	0.25 sec	0.15 sec	0.25 sec

From the above Table 2 and Table 3 the comparative time domain analysis is made. From the comparative analysis, one thing is clear that the FLC is more efficient than PID in every aspect.

The findings presented in Figures 8, 9, 15 and 16 illustrate a notable difference between the performance of the system employing Fuzzy Logic Control (FLC) and that utilizing Proportional-Integral-Derivative (PID) control. Despite the motor's ability to replicate the reference speed in both cases, it is evident that the system equipped with FLC exhibits superior performance and outpaces its PID-controlled counterpart [14]. However, it is noteworthy that while the motor achieves the desired speed, the time required for this process is significantly longer when employing PID control. A comprehensive analysis of the system's efficiency, particularly through a time domain examination, further displays the distinct advantages offered by FLC in optimizing system performance and response time. The THD analysis was also made for the system with PID controller and the result is shown below in figure 15 and 16.

5. CONCLUSION

In the paper, the utilization of a single inverter dual PMSM motor controlled by a fuzzy logic controller has demonstrated significant advantages in enhancing system performance. Through the experimental investigation presented in this paper, it has been established that the implementation of this control strategy effectively manages the speed transitions of the motor. The findings of this study underscore the potential of fuzzy logic control in mitigating torque ripples and time delay thereby enhancing the overall stability of PMSM motor drive, by effectively regulating the speed transitions.

Furthermore, a comparative study is made between the PID and FLC controller which showcases the upper hand of the proposed controller.

Moreover, the results validate the feasibility and effectiveness of employing a single inverter dual PMSM motor configuration, which offers advantages in terms of simplicity, cost-effectiveness, and space efficiency. This configuration, combined with the fuzzy logic controller, presents a viable solution for optimizing motor drive systems, particularly in applications where precise speed control, minimal torque fluctuations, and high efficiency are required.

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