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# Improving PMSM Control Based on Optimizing the Output Membership Function of Fuzzy PI Controller with Weighted Modified Jaya Algorithm

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***Abstract*—Electric vehicle manufacturers prefer permanent magnet synchronous motors for their drive systems because of their high efficiency and power density. PI controllers are ineffective in variable speed drives because they are only linearized to operate within a specific range. One of the solutions applied is to use fuzzy PI controllers instead of PI controllers. When using fuzzy controllers, the designer must be able to adjust the controller parameters to ensure the required control efficiency. There are many ways to improve the control quality of a fuzzy PI controller, such as changing the fuzzification and defuzzification coefficients, the fuzzy rules, the type of membership function, and the shape of the output membership function. In this paper, the method of changing the shape of the output membership function of the speed controller based on the fuzzy PI controller is used to improve the speed control quality of the PMSM motor. The Jaya algorithm and its variants have proven effective in recent publications. In this paper, the Jaya algorithm is supplemented with hybrid weights when targeting the best and worst values in the proposed population to determine the optimal shape of the output membership function implemented by the proposed weighted modified Jaya optimization algorithm. Experimental results on the physical model show the effectiveness of improving the quality of motor speed control when applying the proposed optimization algorithm compared with the basic fuzzy controller based on error assessment criteria such as integral time absolute error (ITAE), integral square error (ISE), and integral absolute error (IAE).***

***Keywords*—*Permanent Magnet Synchronous Motor; Fuzzy PI Controller; Output Membership Function; Weighted Modified Jaya Optimization Algorithm; Integral Time Absolute Error.***

## I. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) have outstanding advantages compared to other electric motors because they possess high efficiency characteristics, high power density, a durable mechanical structure, and no equipment maintenance costs. Therefore, PMSM motors are mainly used in electric vehicles and systems that require high control quality, flexibility, and the ability to continuously change load torque and speed, such as in electric cars, electric buses, and urban railways [1]-[4]. As the cost of manufacturing permanent magnets decreases and the quality of permanent magnets constantly improves, PMSM motors are becoming increasingly popular and widely used in electric drives.

Vector control methods, commonly known as conventional methods, are applied in PMSM speed controllers to improve the speed control performance and power factor of inverters. The primary traditional control methods include field-oriented control (FOC) [5]-[10] and direct torque control (DTC) [11]-[16]. The conventional FOC control method consists of two internal current control loops and one external speed control loop. Converting the three-phase voltages and currents (abc) into DC voltages and currents according to the rotor rotation coordinate system (dq0) allows PI linear controllers to perform control conveniently. Separating the two components, d and q axes, and controlling them independently gives the controller the flexibility to control the rotor speed when responding to changes in load torque and external reference speed. In addition, one of the main reasons traditional controllers are so popular is that the algorithm implementation is quite simple, does not take up much space, and does not require complex calculations.

The primary function of linear PI controllers is to quickly determine the control parameters at the input of the controlled object through the linear control law of the object. The control parameters of this controller are calculated according to the parameters of the mathematical model of the controlled object. Therefore, the main disadvantage of these controllers is that when the controlled object changes its parameters over time, the adjustment efficiency of the controller will decrease. The larger the change in the object's parameters, the lower the efficiency of the controller [17]-[22]. In other words, when the working conditions and parameters of the object are wide, the quality of the PI controller will be significantly reduced.

To address the problem of reduced control efficiency of conventional PI controller-based vector controllers, two control solutions have been proposed: (i) replacing linear PI controllers with more efficient controllers [23]-[28] or (ii) using new control methods to replace conventional vector controllers [29]-[34]. Many recent publications have been made on both of these research directions, and each direction has proven effective in improving control quality by reducing speed errors, speed jitter, and electromagnetic torque ripple.

The improved method allows for adjusting the coefficients of the conventional PI controller based on the recognition of changes in the working conditions of the system. The fuzzy control method proposes to replace the PI controller with a fuzzy controller [35]-[37]. This proposal allows for flexible adjustment of the electromagnetic torque through controlling the q-axis current. The controller's efficiency is flexibly adjusted when operating in a static state, when there is a slight change in the working conditions. However, when there is a relatively significant change in the transmission system, the controller is also significantly limited by the output limit of this controller. In the fuzzy PI control method, the control coefficients of the PI controller (Ki and Kp) are flexibly changed according to the change in speed error and the variation of this speed error [38]-[40]. The new control law allows the motor speed to be quickly adjusted to the reference speed when the speed error increases, and it can minimize electromagnetic torque fluctuations when the motor operates in a static state. This method does not directly adjust the electromagnetic torque of the motor but only indirectly controls it by changing the controller parameters. Therefore, the effective range of the PI Fuzzy controller is wider than that of the pure fuzzy controller. However, more expert adjustments are needed to bring about higher efficiency because the influence of the control object parameters on the control efficiency is significant [41], [42].

Another proposed intelligent control method is to use an ANN controller instead of a PI-based speed controller [43], [44]. There are many studies on this issue, and its effectiveness has been proven through recent scientific publications. The advantage of ANN algorithms in control is that they are highly adaptable to the uncertainty and high nonlinearity of the controlled object. However, calculating parameters through nonlinear functions inside the ANN controller and training the ANN network to perform PMSM speed control effectively also requires a lot of resources and expert experience. Therefore, the proposed ANN controllers are often applied in high-quality, high-power, and high-cost controllers [45], [46].

Another popular PMSM speed control method recently proposed to replace the FOC method is the sliding mode controller (SMC) [47]-[49]. SMC allows for improving the transient response quality of the drive to changes in load torque and sudden changes in the reference speed. However, using a sign function instead of the speed error value, the chattering phenomenon becomes an inherent weakness of this control method. Therefore, many improvements of the SMC method appear to preserve the advantages of this control method in the dynamic response of the PMSM drive system [50], [51]. A hybrid control method between FLC and SMC is proposed in [52], [53]. A hybrid control method between ANN and SMC is proposed in [54], [55]. However, applying hybrid methods will complicate the calculation and control than a single control method.

The model predictive controller (MPC) control method [56], [57] is applied to improve the quality of PMSM speed control. Incorporating model prediction into the control helps to improve the controller's adaptability to changes in model parameters and the operating point of the drive system. However, the requirement of model prediction also requires complex calculations to estimate parameters without going through the model, and the impact of measurement noise is also an issue that needs to be addressed.

To ensure the high efficiency of the PMSM drive system in variable speed and torque applications, the paper proposes to apply the Fuzzy PI controller instead of the traditional PI controller. The coefficients Kp and Ki of the fuzzy PI controller are adjusted based on the speed error and speed error variation. This makes the fuzzy PI controller more efficient than the traditional PI controller. At the same time, the output membership functions are also adjusted in shape and output value by using the fuzzy PI controller. The improvement allows further improvement of the controller's compatibility with the PMSM motor in rotor speed control.

Determining the shape and value of the output MF is a complex and challenging task because the relationship between them and the speed control quality is a highly nonlinear process. In this paper, the weighted modified Jaya optimization algorithm (WMJOA) is used to determine the output MF with the most suitable shape and value to minimize the error between the reference speed and the actual speed of the PMSM motor during operation. WMJOA helps to increase the ability to reach the global optimal solution as it allows for calibrating the hybrid coefficient with the best and worst results.

Jaya algorithm has proven its effectiveness through algorithm evaluation research [58], [59] and algorithm application [60]-[65] in optimization problems published in recent times. The published results show the effectiveness of the algorithm in finding optimal results and the ability to escape local minima of the algorithm when compared with optimization algorithms such as particle swarm optimization (PSO) [66], [67], genetic algorithm (GA) [68], [69], differential evolution (DE) [70], [71]. According to the results proposed in the publications, the Jaya algorithm is effective for multi-extremal and complex problems with many interacting objects. Therefore, to optimize the shape of the output MF with 7 MFs with nine interrelated parameters, the paper proposes to apply the Jaya algorithm with hybrid weight adjustment. This helps to improve the convergence ability of the optimal solution search process.

The effectiveness of the proposed control method in controlling the speed of the PMSM motor is demonstrated through experimental results on the physical model. The obtained speed control results show the effectiveness of optimizing the output MF of the PI fuzzy controller compared to using a conventional fuzzy controller. The evaluation is performed based on quality evaluation indexes based on speed errors, such as integral time absolute error (ITAE), integral absolute error (IAE), and Integral Square Error (ISE) [72], [73]. The results obtained from the indices have demonstrated the effectiveness of the proposed control method.

The research contribution is to use the weighted modified Jaya optimization algorithm to determine the shape and value of the output MFs in the speed fuzzy PI controller of the PMSM drive system. The study shows that the proposed solution improves the PMSM speed control performance compared to the conventional fuzzy PI controller under the same reference speed and load torque. In addition, the weighted modified Jaya optimization algorithm allows faster convergence than the popular optimization methods PSO and DE.

The rest of the paper is divided as follows: Part 2 presents the PMSM mathematical model and PMSM speed control method based on the Fuzzy controller. Part 3 introduces the optimization of the output membership function parameters of the Fuzzy PI controller based on the improved Jaya optimization algorithm. Part 4 presents the simulation results, optimization calculation, and control experiments based on the results obtained by the physical model. The final part is the conclusion.

## II. Ease of Use

### *A. Mathematical Model of PMSM*

The relationship between voltage, current, and speed of the PMSM is shown by (1) and (2) corresponding to voltage values in terms of $d$ and $q$ components in the $dq0$ coordinate system [74]. $L_d$ and $L_q$ represent the d-axis and q-axis inductance, respectively; $\lambda_{pm}$ denotes the flux linkage value; $\omega_e$ is the electrical speed of the stator flux.

$$v_d = R_s.i_d + L_d\frac{di_d}{dt} - \omega_e L_q i_q \tag{1}$$

$$v_q = R_s.i_q + L_q\frac{di_q}{dt} + \omega_e L_d i_d + \omega_e\lambda_{pm} \tag{2}$$

The electromagnetic torque generated by the force interaction between the stator flux and the permanent magnet flux in the rotor is calculated according to (3) where $P$ is the number of stator pole pairs.

$$T_e = \frac{3}{2}.P\left(\lambda_{pm}i_q + \left(L_d - L_q\right).i_q i_d\right) \tag{3}$$

The speed variation of the PMSM motor rotor is determined based on Newton's 2nd law and is shown as in (4). In this case, J is the moment of inertia of the PMSM drive system; TL is the PMSM shaft moment, and F is the Hybrid viscous/friction coefficient of the PMSM system.

$$\frac{d}{dt}\omega_m = \frac{1}{J}(T_e - T_L - F\omega_m) \tag{4}$$

### *B. Fuzzy PMSM Speed Control is based on a Fuzzy PI Controller*

Based on the mathematical model of PMSM, the speed control principle of PMSM based on a Fuzzy PI controller is proposed as shown in Fig. 1. A Fuzzy PI controller replaces the traditional PI controller in the proposed speed control principle.

Many fuzzy PI controller structures have been proposed to suit the characteristics of different controlled objects. Thuyen *et al.* [75] implies a typical fuzzy PI structure. In this paper, to fine-tune the PI controller control coefficients according to the change in the operating conditions of the PMSM, the structure chosen is the fuzzy ΔPI structure, as shown in Fig. 2. In the basic fuzzy PI controller, the input and output membership functions have the conventional form in Fig. 3. The input and output values are adjusted based on the gain generators before entering and after leaving the fuzzy set. The fuzzy rules used to determine the output values Δki and Δkp are specified in the fuzzy rule tables Table I and Table II, respectively.

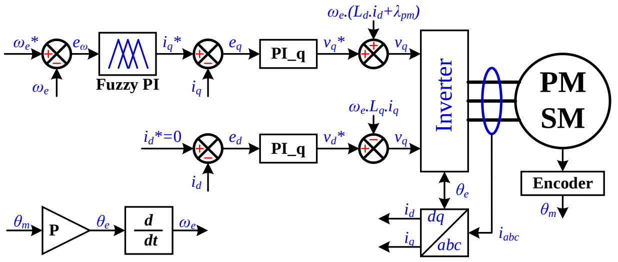


Fig. 1. PMSM speed control principle based on a Fuzzy PI controller

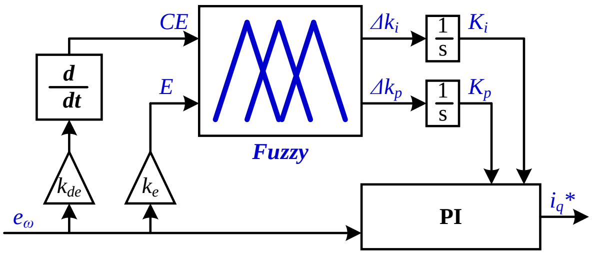


Fig. 2. Structure of Fuzzy PI controller

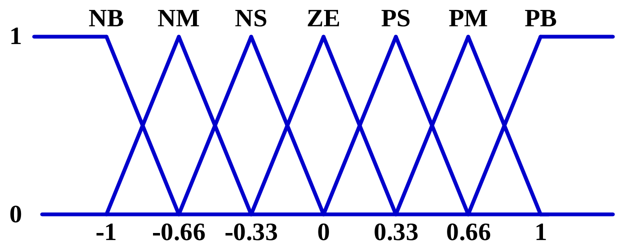


Fig. 3. Input and output of a typical membership function

In a typical PI Fuzzy controller, the input gains (de, dce) and output gains are adjusted by trial and error or optimization. With appropriate gain coefficients, the speed control performance is significantly improved. However, the membership function is fixed and evenly spaced, which reduces the controller's flexibility.

TABLE I. Fuzzy Logic Rules of KI

| DE | E | | | | | | |
|---|---|---|---|---|---|---|---|
| | NB | NM | NS | Z | PS | PM | PB |
| NB | NB | NB | NM | NM | NS | ZO | ZO |
| NM | NB | NM | NM | NS | NS | ZO | ZO |
| NS | NM | NM | NM | NM | ZO | PS | PS |
| ZO | NM | NM | PS | PS | PM | PM | PM |
| PS | NS | NS | ZO | PS | PS | PM | PM |
| PM | NS | ZO | PS | PM | PM | PM | PB |
| PB | ZO | ZO | PM | PM | PM | PB | PB |

Adjusting the output membership function of the Fuzzy PI controller according to different control objects will increase its flexibility in operation and its adaptability to changes in control objects or working conditions. Many other studies have been published recently on optimizing membership functions to increase control quality for many different control objects [76]-[79].

TABLE II. FUZZY LOGIC RULES OF KP

| DE | E | | | | | | |
|---|---|---|---|---|---|---|---|
| | NB | NM | NS | ZO | PS | PM | PB |
| NB | PB | PB | PM | PM | PS | ZO | ZO |
| NM | PB | PM | PM | PM | PS | ZO | ZO |
| NS | PM | PM | PM | PS | ZO | NS | NS |
| ZO | PM | PM | PS | ZO | NS | NM | NM |
| PS | PM | PS | ZO | NS | NS | NM | NB |
| PM | ZO | ZO | NS | NS | NM | NM | NB |
| PB | ZO | ZO | NS | NM | NM | NB | NB |

## III. OPTIMIZATION OF MF BASED ON WMJOA

### A. Fitness Function of MF

This paper proposes a fuzzy set with seven input MFs and seven output MFs to ensure computational capability and control quality. Using this number of fuzzy rules improves the control quality of the traditional fuzzy PI set. From there, the comparison of control efficiency between the traditional fuzzy PI set and the fuzzy PI set with optimized MF parameters is shown more objectively.

The output membership function structure is shown in Fig. 4 with $x_i(\mathrm{i}=1:9)$ in the range [0; 1]. Adjusting the $x_i$ will allow changing the output MF structure, thereby changing the fuzzy PI unit's output value and the PMSM speed control quality accordingly. The goal of the MJOA algorithm is to find a set of $x_i(\mathrm{i}=1:9)$ so that the ITAE value is minimized. The ITAE is obtained during the execution of the PMSM speed control according to (5), where $e(t)$ is the speed error between the reference speed and the motor's actual speed at time t [80].

$$ITAE=\int_0^\infty t|e(t)|dt \quad (5)$$

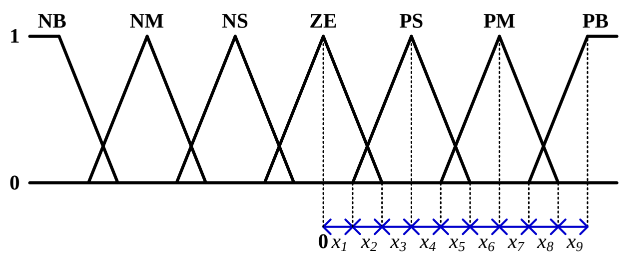


Fig. 4. The principle of determining MF according to the value of elements in each individual

### B. MJOA Algorithm in Optimizing the Output Membership Function of the Fuzzy PI Controller

The JOA algorithm is an optimization algorithm proposed by Venkata Rao. Several studies have improved the original algorithm to accelerate the convergence time of the Jaya optimization algorithm and have improved the efficiency of the Jaya algorithm in various optimization problems [81]-[83]. In this paper, an improvement of the JOA algorithm is the weighted modified Jaya optimization algorithm (WMJOA), with the establishment of additional hybridization coefficients in the hybridization process of the JOA algorithm.

Under the same torque and reference speed simulation conditions, each MF structure will receive different deviations between the actual speed on the rotor and the desired speed. People often rely on the characteristics of this error to compare the quality between controllers and different control parameters. Some criteria for evaluating control efficiency through errors include ISE, ITAE, and IAE. The evaluation criteria may differ in the calculation method and the nature of the calculation. Still, no conflict has been found in the evaluation results between the requirements in the same evaluation. Therefore, in this paper, the ITAE criterion is used to evaluate the efficiency of the output MF structures with each other. The evaluation principle is that the MF structure that gives a lower ITAE means that the structure is better.

Thus, the task of the WMJOA algorithm in this proposed control algorithm is to determine the set of $x_i$($i$=1:9) with the lowest ITAE value obtained. The WMJOA-based output MF parameter optimization algorithm flowchart is proposed and implemented to accomplish this task, as shown in Fig. 5.

- Step 1: Initialization step. Determine all the main parameters in an MJOA implementation program, including: the number of elements in an individual $n$ ($n$=9 when it is necessary to determine 9 $x_i$ values of the output MF); the number of individuals in the population N (choose N=30); and determine the maximum allowed number of iterations G=100 (to avoid infinite loops); The upper bound of the elements in the individual is the matrix LB=[0,0,0,0,0,0,0,0,0,0] and the lower bound of the elements in the individual is the matrix LB=[1,1,1,1,1,1,1,1,1,1]. Each element of the initial population is randomly generated. The random generation of the jth component of the ith individual is performed as in (6) where $rand(1,1)$ is a randomly generated number with a value in the range [0;1] and $g$ represents the iteration step of the population. In the initial random population, g=0.

$$X_{i,j,g}=LB_j+rand(1,1)*\left(HB_j-LB_j\right) \quad (6)$$

- Step 2: Calculate the objective function for each individual in the created population. The i-th individual is the i-th row matrix in the population as shown in (7). The values in will form the structure of the output MF when applied to Fig. 4. The Fuzzy PI speed controller will be newly created based on the parameters provided by the individual. After the simulation process with the newly created Fuzzy PI controller, the ITAE value is recorded after the simulation process, and is called F(Xi). This is the objective function value of the corresponding individual.

$$X_i=[X_{i,1};X_{i,2};X_{i,3};X_{i,4};X_{i,5};X_{i,6};X_{i,7};X_{i,8};X_{i,9}] \quad (7)$$

- Step 3: Identify the best (Xbest) and worst (Xworst) individuals among the recorded individuals.

- Step 4: Create a population (Y) with the same number of individuals as the current population X. The principle of constructing the i-th individual of population Y is shown in (8).

$$Y_{i,j,g} = X_{i,j,g} + C_1.r_1.(X_{best,j} - |X_{i,j,g}|) \\ -C_2.r_2.(X_{worst,j} - |X_{i,j,g}|) \quad (8)$$

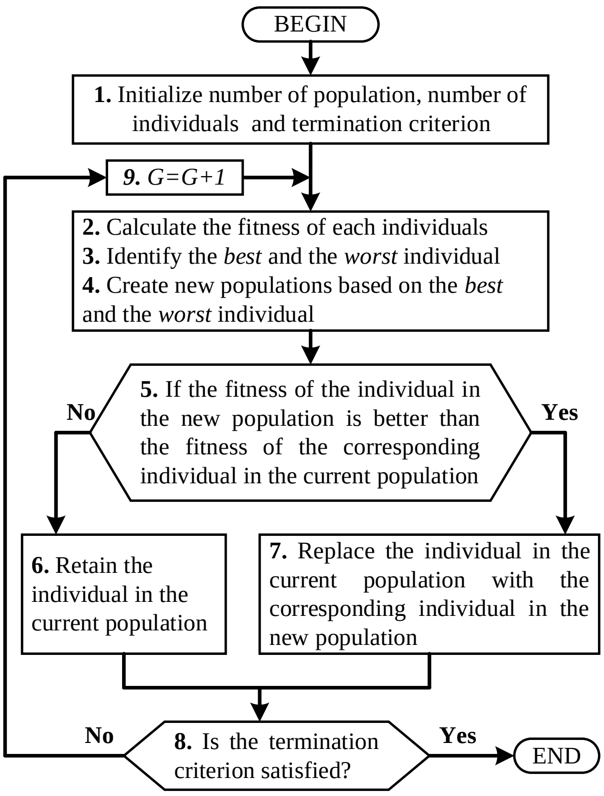


Fig. 5. MJOA optimization algorithm in ML optimization of Fuzzy PI

- Step 5-6-7: Individual selection. Individual Yi in population Y is calculated with the objective function, and the result is called F(Yi). The i-th individual in the next population X (Xi, g+1) is determined based on retaining the individual with the better (smaller) objective function between the two individuals Xi and Yi. This principle is expressed as a selection function in (9). The calculation is performed for all N individuals in population X.

$$X_{i,g+1} = \begin{cases} Y_{i,g} & if F(Y_{i,g}) < F(X_{i,g}) \\ X_{i,g} & \text{otherwise} \end{cases} \quad (9)$$

- Step 8: Check the program termination condition. The program will stop if one of the two conditions is satisfied: (i) the desired objective function value is achieved, or (ii) the maximum number of iterations has been reached. If neither of these conditions is satisfied, the program will repeat step 2 for the next iteration (the g+1 iteration). If the condition is satisfied, the individual to be found is the Xbest individual of the program.

## IV. PMSM Speed Control Results

The WMJOA method proposed in the paper has proven effective through simulation on the MATLAB software and experimental processes on the existing physical model. The results obtained will be analyzed and evaluated in the following sections.

### A. PMSM Speed Control System Simulation

To evaluate the impact of the output MF in the Fuzzy PI controller on the quality of PMSM speed control, a simulation model of the PMSM speed control system is built on the MATLAB/Simulink software. The PMSM motor parameters are presented in detail in Table III. The simulation model is shown in Fig. 6(a). The simulation model is built based on the operating principle of the PMSM drive system with the Fuzzy PI controller shown in Fig. 1.

The simulation model consists of three main blocks: the PMSM block with parameters shown in Table III. The Control block with a Fuzzy PI controller in the speed control loop is built as shown in Fig. 6(b). The inverter block is responsible for converting the impulse value of the semiconductor switches into the voltage value applied to the terminals of the PMSM motor coils. The PMSM block is a simulation block of the PMSM motor with inputs being the voltages applied to the stator coils, the previous PMSM motor speed, and the load torque that the motor serves. The output of the motor is the calculated motor speed value.

TABLE III. PMSM PARAMETERS

| Parameters | Value | Unit |
|---|---|---|
| Rate power | 750 | W |
| Rated speed | 3000 | RPM |
| Rated torque | 2.4 | N.m |
| Number of pole pairs | 4 | --- |
| Stator resistance | 1.86 | Ω |
| Stator inductance | 2.8 | mH |
| Flux linkage | 0.109 | Wb |
| Inertia Factor | $1.39{\times}10^{-4}$ | $Kg.m^2$ |

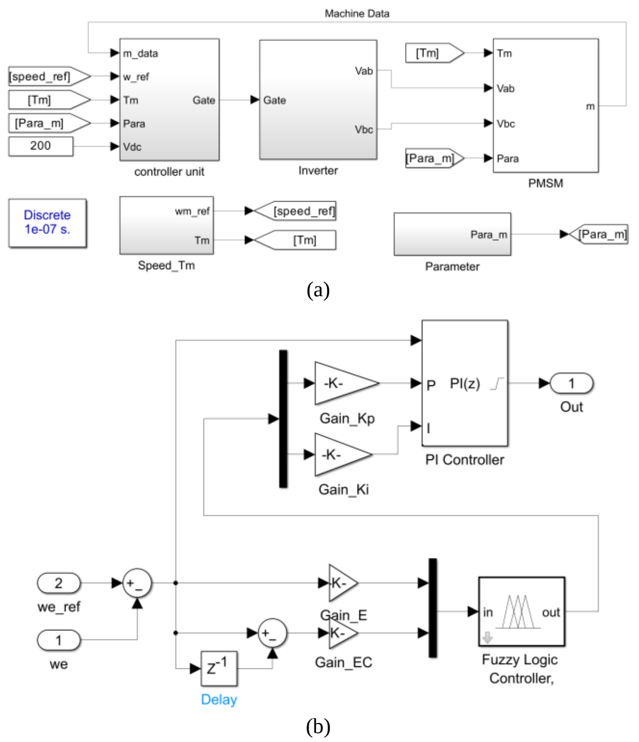


Fig. 6. Simulation model of PMSM speed control system based on Fuzzy PI controller

### B. *Calculate the Objective Function for Each Given Individual*

A MATLAB program is created to implement the proposed WMJOA program application in searching for the optimal output MF parameter of the speed fuzzy PI controller. The flowchart of the optimization program is shown in Fig. 7. This flowchart explains the principle of determining the fitness value of each individual in the optimization program. This program follows the steps as follows:

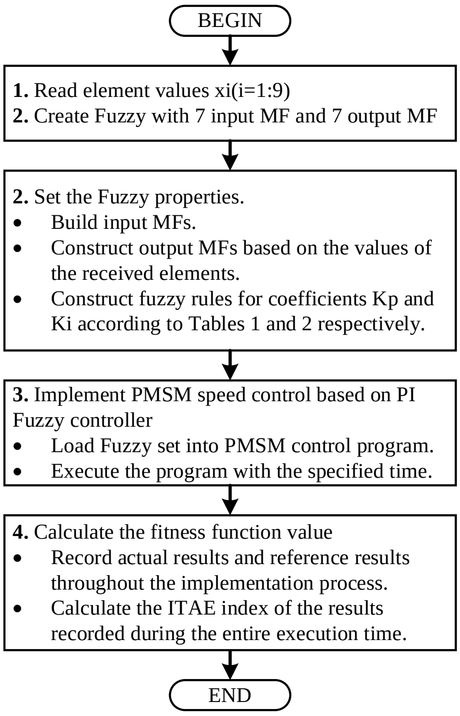


Fig. 7. Flowchart for calculating the objective function for each identified individual

- Step 1: The program will read the values of the elements in the individual. This input data creates the output MFs determined for each corresponding individual. Next, the program will create a Fuzzy set consisting of 7 input MFs and seven output MFs as required. With the program's current version, a Fuzzy set must be made each time a simulation is performed.
- Step 2: Set up the Fuzzy set. First, the Fuzzy generates seven new input MFs as shown in Fig. 3. The input MFs are kept constant for all executions. Second, based on the values of the elements in the individual recorded in Step 1, 7 output MFs are constructed based on the description as shown in Fig. 4. The Third, the output of the Fuzzy set includes two values, ΔKp and Δki. The fuzzy rule of ΔKi is shown in Table I, and the fuzzy rule of ΔKp is shown in Table II. The last step, through the results, a Fuzzy set is built by the program on MATLAB. The created Fuzzy set will be embedded in the corresponding simulation or experimental program.
- Step 3: Implement PMSM speed control based on a PI Fuzzy controller. During the implementation, before simulation and experiment, the Fuzzy initialization program built in step 2 is entered into the control program. If experimenting, the program is embedded into the TMS320F28379D controller. A variable is created and entered into the simulation program if the simulation is performed. Then, the program will perform a simulation for a predetermined time.
- Step 4: Calculate the fitness function value. After the speed control process is performed, the Fuzzy PI controller is set to the value of the corresponding individual. The measured speed results of the PMSM during the control period are stored. Based on the deviation between the reference speed set for the controller and the measured speed at the corresponding time, the ITAE value is calculated according to (5). The ITAE result is the objective function value of the individual used from the beginning of the program.

### C. *Simulation Results of Estimated Output MF Parameters*

The WMJOA algorithm is executed many times, with the program parameters set according to Table IV. The optimal MF result of the fuzzy PI controller is recorded and shown as in Fig. 8. Based on the optimal result, it can be seen that the algorithm has converged at the place with the lowest possible ITAE value. This shows the algorithm is not stuck in a local extremum like other optimization methods.

Using the results after one execution of the optimal output MF parameter for the experiment, the output MF property results of the PI fuzzy controller are shown as in Fig. 9.

TABLE IV. PROGRAM SPECIFICATIONS OF IMPROVED JAVA ALGORITHM

| Parameters | Value |
|---|---|
| Number of individuals in a population | 50 |
| Maximum number of iterations | 100 |
| Worst-case cross-match coefficient $C_1$ | 0.3 |
| Best value crossbreeding coefficient $C_2$ | 0.7 |

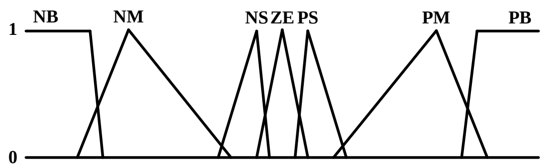


Fig. 8. Properties of output MF

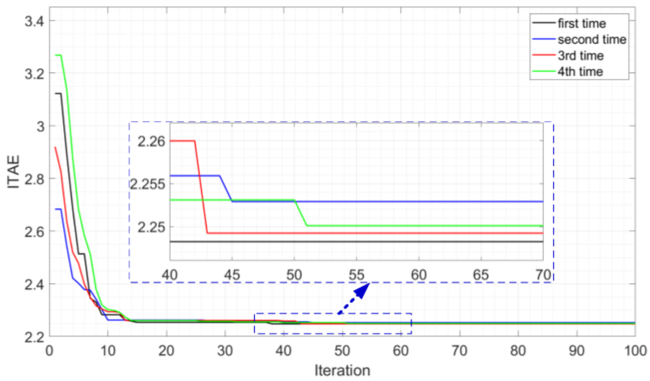


Fig. 9. The objective function results in MF optimization based on WMJOA

To compare the efficiency of the proposed optimization algorithm with other optimization algorithms in terms of convergence speed, the DE and PSO algorithms are implemented to optimize the shape and value of the output MFs. The parameters of the PSO and DE optimization programs are shown in Table V and Table VI, respectively.

TABLE V. DIFFERENTIAL EVOLUTION PARAMETERS

| Parameters | Value |
|---|---|
| Number of individuals | 50 |
| Number of Generations | 100 |
| Weighting factor F | 0.3 |
| Crossover constant CR | 0.7 |

TABLE VI. PARTICLE SWARM OPTIMIZATION PARAMETERS

| Parameters | Value |
|---|---|
| Number of individuals | 50 |
| Maximum number of iterations | 100 |
| Cognitive Acceleration Constant C1 | 0.3 |
| Social Acceleration Constants $C_2$ | 0.7 |

The optimization program is executed many times, and the best results of the program are shown in Fig. 10. It is found that all three optimization methods can approach the optimal point with a large enough number of iterations. The PSO optimization method has the best location reference feature of the population, so the objective function value decreases slowly at the extremes, where the value change is less than at other points. When exceeding the local extreme, the value decreases rapidly when approaching other extreme points. This shows that local minima affect the PSO optimization method's efficiency.

For the DE optimization algorithm, the impact of local values is significantly reduced. The best objective function of the elements in each iteration is gradually reduced until reaching the global maximum. However, the method needs more iterations to reach the global optimum due to the lack of high variability.

For the proposed weighted modified Jaya optimization algorithm, the advantage is that it passes the local extremum faster than the PSO method because, in addition to referring to the best individual, this method also pushes the individuals away from the worst point. Therefore, the program can move towards the extremum better. On the other hand, because the individual is pushed away from the worst point, the minimum values after each iteration have decreased faster than PSO. Therefore, the program needs fewer iterations to move towards the global optimum. This shows that the proposed method applies to calculating complex and highly nonlinear multivariate functions. This has also been concluded in the study [59].

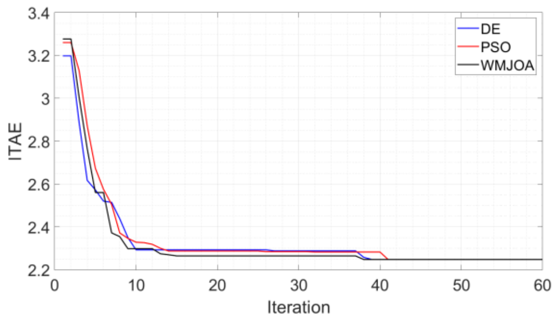


Fig. 10. The objective function of different optimization algorithms over iterations

## D. Experimental model of PMSM speed control

The working principle of the experimental model of PMSM speed control using TMS320F28379D is shown in Fig. 11. TMS320F28379D is used to record the current value flowing into the stator coils and the rotor position output from the encoder. Based on the pre-set reference speed, the speed control loop based on the Fuzzy PI controller will determine the magnitude of the q-axis current that needs to be supplied to the PMSM motor. The current control loop will be based on the desired current injected into the motors to determine the voltages in the d and q axes that need to be applied to the stator coils, respectively. Finally, through the SVPWM, the impulse for the semiconductor switches in the inverter will be determined. By changing the motor's reference speed and recording the motor's actual speed, the motor speed control efficiency is defined under the condition of changing the reference speed.

To evaluate the response of the algorithm in case of load torque changes, a simulator is also used to have the ability to change the load torque. The working principle of the simulated load model is shown in Fig. 12. A PMSG generator is connected coaxially to the PMSM motor, as shown in Fig. 13. The ends of the generator windings are connected to power resistors. By changing this load resistor, the current flowing in the stator windings of the PMSG generator also changes inversely with the change in resistance value. As a result, the electromagnetic torque of the generator also changes accordingly. Thus, with the coaxial connection and acting as a generator load, the load torque of the PMSM motor shaft also changes accordingly. During the simulation, the switches K1 and K2 are opened at predetermined times, which causes the load torque of the motor to change abruptly. The effect of the change in load torque is that the motor speed increases (when the load torque decreases) or decreases (when the load torque increases). Based on the ability to return to the reference speed when the load torque changes, the speed transient time and speed overshoot can be used to evaluate the speed control quality of the proposed speed controller.

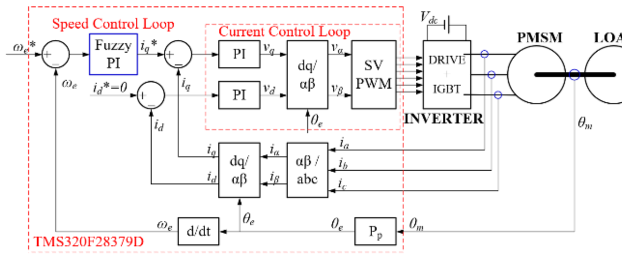


Fig. 11. Operating principle of the experimental model of PMSM speed control

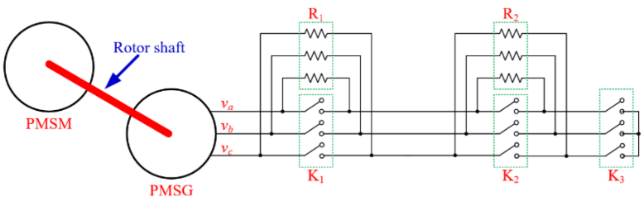


Fig. 12. PMSM load model

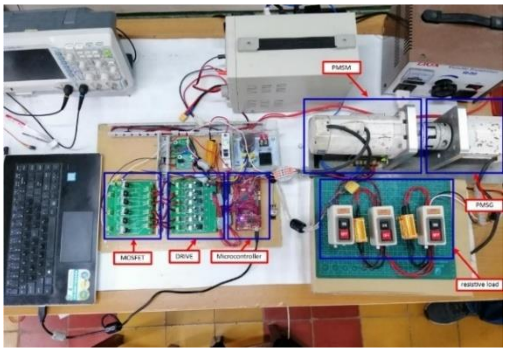

Fig. 13. PMSM motor drive model

### E. *Experimental Results of PMSM Speed Control*

The speed control results of the PMSM motor using two Fuzzy PI controllers and fuzzy PI with optimized output membership function parameters based on weighted modified Jaya optimization algorithm are shown in Fig. 14. The motor speed results based on the fuzzy PI controller with output membership function are denoted as "optimal fuzzy PI", and the motor speed when using a non-optimal fuzzy PI controller is "conventional fuzzy PI". In general, it can be seen that the different controllers are capable of stabilizing at the reference speed after the transient time caused by changes in the reference speed or load torque.

As the reference speed increases at time t=30 s, the motor speed is also controlled to increase, as shown in Fig. 15(a). It can be seen that the parameter-optimized Fuzzy PI controller has lower speed overshoot and shorter time to approach the reference speed.

On the contrary, when the reference speed decreases at time t=130 s, the motor speed is also controlled to decrease, as shown in Fig. 15(b). It can be seen that the Fuzzy PI controller with the optimized output membership function has a lower speed decrease and a shorter time to reach the reference speed. This shows that the proposed controller can respond faster to the reference speed change in variable speed drive applications.

To evaluate the speed stability of the controllers when the load changes suddenly, the load resistance switches of the PMSG generator are activated with the principle: the load torque increases when the switches are shorted in parallel with the resistors in Fig. 12. The speed response of the motor when the load increases is shown in Fig. 15(c) at time t= 50 s. At this time, the motor speed will be reduced due to the imbalance between the load torque and the electromagnetic torque of the motor. However, after a while, the motor speed recovers to the reference speed when the controllers set up the mechanism to increase the current into the coils. Each method has a different response. Based on the results, it can be seen that the optimal Fuzzy PI controller helps the PMSM speed progress faster than the conventional Fuzzy PI controller. Similar control performance is also recorded when the load torque is reduced at time t=99 s in Fig. 15(d). Thus, during sudden load torque change due to operating conditions, the PMSM motor speed is kept stable after a short transient time. This shows the control ability of the fuzzy PI controller. In addition, the recorded speed control results show that the PMSM speed control quality of the proposed Fuzzy PI controller with optimized output MF has better transient time and post-transition stability.

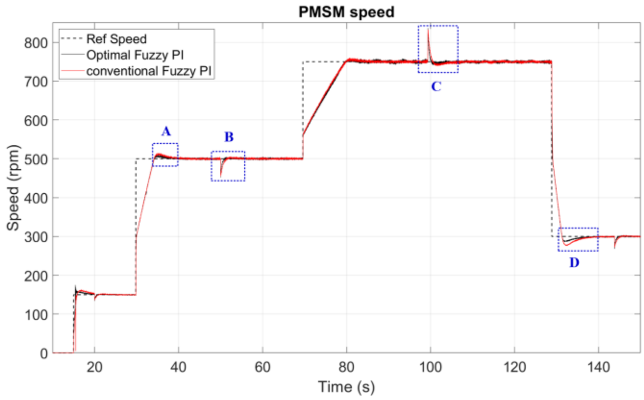


Fig. 14. PMSM speed with change in reference speed and load torque

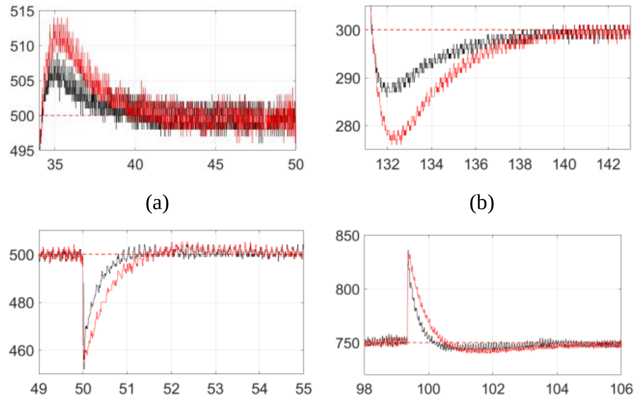

Fig. 15. Zoom out of PMSM speed response with changes in reference speed and load torque

To compare the performance of PMSM speed control based on two speed controllers, the quality evaluation results based on the actual and desired speed errors are presented as in Table VII. The smaller the index, the lower the deviation of the reference speed from the actual speed. Based on the collected data, it can be seen that when compared with the non-optimal fuzzy PI controller, the proposed optimal controller has significantly improved the control quality, with an enhancement of 3.38%, 6% and 7.23% at the evaluation indexes ITAE, IAE, and ISE, respectively. Thus, it can be seen that overall, the quality of the controller proposed in the paper gives better results than leaving the output MF in its basic form.

TABLE VII. SPEED CONTROL QUALITY IN PMSM MOTOR SPEED CONTROL EXPERIMENT

| Method | ITAE | IAE | ISE |
|---|---|---|---|
| Conventional Fuzzy PI | 1416.39 | 12.66 | 988.26 |
| Optimal Fuzzy PI | 1368.47 | 11.90 | 916.83 |
| Percentage (%) | 3.38 | 6 | 7.23 |

## V. CONCLUSIONS

This paper proposes a PMSM speed control method using a new advanced Fuzzy PI control method by applying a Fuzzy PI controller combined with tuning the output MF parameters based on the weighted modified Jaya optimization algorithm.

Both simulation and experiment demonstrate the speed control results on a physical model. Based on the experimental and simulation results, it can be seen that the control method combining the fuzzy PI controller with the output MF optimization algorithm has brought better efficiency without the need for additional hardware. The efficiency of the new controller compared to the original one has increased by 3.38%, 6% and 7.23% respectively in the ITAE, IAE, and ISE evaluation indexes. However, in addition to the initial results, more research is needed to evaluate the efficiency of the MF optimization method of the Fuzzy PI controller. The first problem is that the paper only stops at optimizing the "trimf" function without considering other distributions, such as the Gaussian distribution, so more research is needed to optimize different types of MFs or to coordinate between MFs to improve the optimization efficiency. This is a potential new research direction, with higher requirements in terms of the structure of the objective function and hardware requirements with strong computing capabilities.

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