ANALYSIS OF PSO TECHNIQUE TO TUNE UPDATING FACTORS OF PD-BASED FUZZY LOGIC CONTROLLERS

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ABSTRACT

A fuzzy logic technique - based controller has been considered to be an efficient control strategy in dealing with systems characterized by nonlinearities and uncertainties. To design such a fuzzy logic controller, there are several issues which should be taken into account. They are the determination of rule base, the selection of membership functions and the tuning of input and/or output updating factors. With a defined fuzzy logic-based controller, e.g. PD-type, the last one can strongly affect control performances of the system applying such a fuzzy logic regulator. This study presents a feasible method using particle swarm optimization (PSO) technique to solve this problem. The PSO technique has not only a simple and fast implementation but also a good optimization efficiency. The paper also analyzes a typical simulation example of the speed control strategy for a DC motor applying the proposed control method in order to demonstrate the feasibility and efficiency of the proposed method.

Keywords: *PD-based FLC; PI regulator; PSO; tuning; updating factors.*

TÓM TẮT

Bộ điều khiển logic mờ được xem là một giải pháp điều khiển hiệu quả cho các hệ thống điều khiển có các yếu tố phi tuyến và bất định. Khi thiết kế một bộ điều khiển logic mờ ta thấy tồn tại một số vấn đề cần được quan tâm. Đó là sự xác định luật mờ, lựa chọn các hàm thuộc và chỉnh định các hệ số cập nhật vào/ra. Với một cấu trúc bộ điều khiển mờ nhất định, chẳng hạn bộ điều khiển mờ kiểu PD, yếu tố thứ ba có thể ảnh hưởng mạnh mẽ đến các chỉ tiêu chất lượng điều khiển cho hệ thống. Nghiên cứu đề xuất một giải pháp khả thi áp dụng giải thuật tối ưu hóa bầy đàn (PSO) để giải quyết vấn đề này. Kỹ thuật PSO không chỉ có cơ chế thực hiện đơn giản và nhanh chóng mà còn có hiệu quả tối ưu tốt. Bài báo cũng phân tích một ví dụ mô phỏng điển hình cho bài toán điều khiển tốc độ của động cơ một chiều ứng dụng chiến lược điều khiển đã đề xuất để chứng minh tính khả thi và hiệu quả của nó.

Từ khóa: *FLC kiểu PD; bộ điều chỉnh PI; PSO; chỉnh định; các hệ số cập nhật.*

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1. INTRODUCTION

It can be said that fuzzy controllers should be a class of knowledge based controllers using artificial intelligence techniques with origins in fuzzy logic [1-4]. Fuzzy logic is a special structure of numerous - valued logic which is derived from fuzzy set theory. As opposed to "crisp logic", in which binary sets have two - valued logic, the variables in fuzzy logic can have a true value that ranges in degree between "0" and "1". Fuzzy logic controllers (FLCs), which have been used efficiently in many nonlinear control systems, can be applied to solve a control problem thanks to the following reasons:

(i) FL is a thinking process of users combined in a control strategy, thus it is not essential to understand clearly and fully parameters of the control system,

(ii) FLCs could use efficiently the incomplete information to make a good control decision, which only depends upon the knowledge of experts, and

(iii) When applying FL rules, it is well known to set up successfully a Human Machine Interface (HMI), which can be highly useful for the interaction characteristic of a modern control scheme.

In reality, the most dominant usefulness of the FLCs is that the control parameters are able to modify fast enough to respond effectively to the dynamic variations of the system. The reason is that none of parameters may be needed to estimate according to the working principle of the fuzzy logic architecture. Consequently, using the fuzzy logic - based controllers, the above performances could be significantly enhanced so as to obtain the desired control characteristics.

Every FL model contains three processes as follows:

(i) The suitable membership functions (MFs) are established to change a set of crisp values into fuzzy logic domain,

(ii) A fuzzy logic rule base needs to be decided to process and evaluate control rules,

(iii) A defuzzification process is executed to convert a set of fuzzy logic values into the corresponding crisp set that could be employed to make the control signal for the system.

If a control system is being applied a standard fuzzy logic architecture, there is an issue needs to be considered.

It is the determination of the scaling factors for the inputs and outputs of the fuzzy logic model. In fact, these factors can affect strongly the control performances of the system, so that it is necessary to establish an efficient method to determine them.

Beside "try and error" methods with poor control performances, optimization algorithms - based methods are much preferred. Even though they are timely methods, they can obtain much better control performances, especially for a number of complicated control issues when compared to previous methods or conventional regulators, such as PI, PD or PID. In this study, particle swarm optimization (PSO) with a simple working mechanism and high efficiency [5-7] will be chosen to deal with the determination of the optimal scaling factors of a typical PD-type fuzzy logic controller. Also, the control strategy will be specifically presented in this paper. Then, a DC motor with speed control problem is selected as a typical example to verify the feasible control performances of the proposed control scheme. Finally, a comparative simulation process between the PSO - based PD-type fuzzy logic controller and a conventional PI regulator will also be executed using MATLAB/Simulink package to testify the feasibility and superiority of the control strategy proposed in this study.

2. PD-BASED FUZZY LOGIC CONTROLLER

Among fuzzy logic - based architectures, the PD - type fuzzy logic controller has been widely used in control strategies since it can obtain good control performances. The basic type of a PD - type fuzzy logic strategy applied to a control plant is presented in Fig. 1.

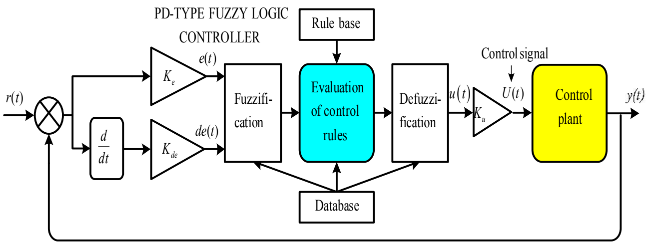

Fig. 1. The PD-type fuzzy logic controller architecture for a control plant

The output of the given controller $u(t)$ is related to the control signal of the control plant by the proportional factor K_{ui}. In most cases, each fuzzy logic controller is an input/output static nonlinear mapping, therefore the principle of such a fuzzy logic architecture could be indicated as follows [4]:

$$U(t) = K_P^{FL} e(t) + K_D^{FL} \frac{de(t)}{dt} \tag{1}$$

Where K_P^{FL} and K_D^{FL} are respectively two factors, which are very much similar to the proportional and derivative coefficients, i.e. K_P and K_D, of a conventional PD regulator. It can be said that these two factors strongly affect on the control quality of a control system applying such a PD controller. The following characteristics should be taken into account [8]:

- K_p accounts for present values of the error. For example, if the error $e(t)$ is large and positive, the control output will also be large and positive.
- K_D accounts for possible future developments of the error based on its current rate of change.

Increasing the proportional gain K_P has the effect of proportionally increasing the control signal for the same level of error. The fact that the controller will "push" harder for a given level of error tends to cause the closed-loop system to react more quickly, but also to overshoot more. Another effect of increasing K_P is that it tends to reduce, but not eliminate, the steady-state error.

The addition of a derivative term to the controller K_D adds the ability of the controller to "anticipate" error. With simple proportional control, if K_P is fixed, the only way that the control will increase is if the error increases. With derivative control, the control signal can become large if the error begins sloping upward, even while the magnitude of the error is still relatively small. This anticipation tends to add damping to the system, thereby decreasing overshoot.

Similarly to such a conventional PD regulator, the two factors, i.e. K_P^{FL} and K_D^{FL}, have a big influence on a control system, making a need of their determination. These factors can be calculated from three scaling factors of the fuzzy logic architecture [4]. In this perspective, it can be said that the type of such fuzzy logic – based control methodology is dependent on the PD principle (PD - type fuzzy logic controller).

In this study, to design such a PD-type FL controller, Gaussian MFs are employed for all of its two inputs and one output. Seven logic levels, including NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big), are employed for each Gaussian MF of inputs and output of the proposed PD – type FL controller. Table 1 gives a description of a rule matrix employed for the proposed PD - type FL controllers adopting the Mamdani method. There are absolutely 49 rules used for such control strategy. Every rule is able to be shown as: "IF the first input e(t) is e and the second input e(t) is de THEN the output u(t) is u". For example, the first rule means: "IF e(t) is NB and de(t) is NB THEN the output u(t) is PB". In the opinion of the composition rule theory of the FL model, every given rule could be employed to perform a meaningful control action corresponding to a specific condition of the variables. Such a composition rule, used for the FL inference to generate the output control signal, needs to be chosen properly enough to obtain the desired control quality. For this research, the MAX-MIN composition is selected because it is the most common and efficient composition for the FL inference. Based on such a rule, the output MF is computed by employing a MIN mechanism. On the other hand, a MAX mechanism will be adopted to calculate the output of the proposed fuzzy logic model.

Table 1. Rule matrix for the proposed PD-type FL controller [4]

e(t)	de(t)						
	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	ZE
NM	PB	PM	PM	PM	PS	ZE	NS
NS	PB	PM	PS	PS	ZE	NS	NM
ZE	PM	PM	PS	ZE	NS	NM	NM
PS	PM	PS	ZE	NS	NS	NM	NB
PM	PS	ZE	NS	NM	NM	NM	NB
PB	ZE	NS	NM	NM	NB	NB	NB

3. PRINCIPLE OF PSO ALGORITHM

As a biological - inspired optimization technique, the PSO has been applied successfully in a number of control strategies [5-7]. This mechanism is based on the social behaviour of a population, e.g., a flock of birds. The metaphorical idea of the PSO method is explained briefly as follows. It is assumed that there are initially *m* particles swarms and each of them includes *n* individuals. At the k*th* iteration, the position and velocity of the ith swarm can be determined by two vectors, i.e., $\overrightarrow{P_i^0} = \left(x_{i,1}^0, x_{i,2}^0, \ldots x_{i,n}^0\right)$ and $\overrightarrow{V_i^0} = \left(v_{i,1}^0, v_{i,2}^0, \ldots v_{i,n}^0\right)$. All individuals of a swarm must be controlled to move towards the local optimal position $\overrightarrow{P_{i,best}}$, which is evaluated by a fitness or objective function. In addition, at each iteration, this best local position must be compared with the global optimal position $\overrightarrow{G_{best}}$, which would be obtained from their previous neighbours. Then, the new optimal vectors of global and local positions will be determined and saved for the next step. The PSO algorithm is continued by updating the two vectors of position and velocity of the present swarm as:

$$\vec{V}_i^{k+1} = \omega \vec{V}_i^{k} + c_1 \xi_1 \left(\vec{P}_{i,best}^{k} - \vec{P}_i^{k}\right) + c_2 \xi_2 \left(\vec{G}_{best}^{k} - \vec{P}_i^{k}\right) \quad (2)$$

$$\vec{P}_i^{k+1} = \vec{P}_i^{k} + \vec{V}_i^{k+1} \quad (3)$$

where c_1 and c_2 are learning factors, ξ_1 and ξ_2 denote the random positive numbers in [0, 1], and ω is an inertia weight coefficient. When updating the above two vectors, they should satisfy the constraint of the search problem. For instance, the following constraint should be satisfied:

$$x_{L,j} \le x_{i,j}^{k+1} \le x_{U,j} \quad (4)$$

where $x_{L,j}, x_{i,j}^{k+1}$ and x_{Uj} denote the *j*th elements of the lower bound, position and upper bound vectors, respectively. It is noted that the stop criteria, which are typically defined as the maximum values of iterations or the desired values of the fitness functions, should be checked at any iteration of the PSO mechanism. The optimization process will be terminated if one of the criteria is met.

In order to apply the PSO algorithm to a control system, especially a system applying the PD-type fuzzy logic controller, it is necessary to establish an efficient mechanism. As shown in Fig. 3, the PSO mechanism is being employed to tune three scaling factors of a PD-type fuzzy logic controller. They are called three updating factors: alpha, beta and gamma (see Fig. 3). These factors, as discussed earlier, strongly affect the performances of a control system, so that they must be determined as exactly as possible. The PSO with a simple and strong operation mechanism is able to execute it successfully. To verify the feasibility of the proposed control approach illustrated in Fig. 3, the next section will present a typical example of a speed control system for a DC motor.

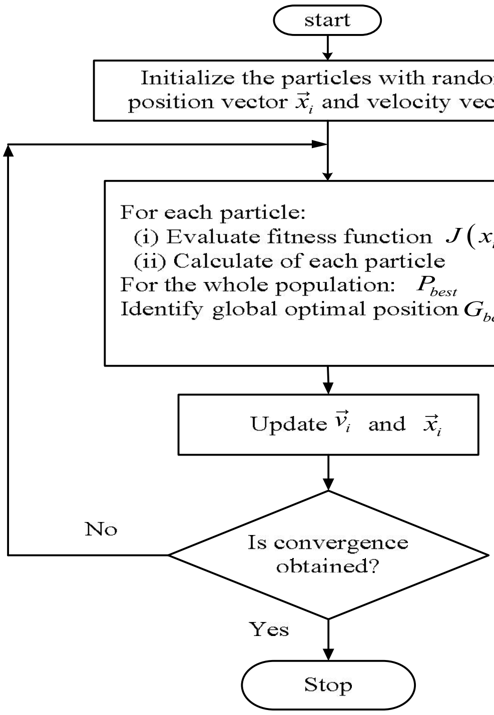

Fig. 2. The flow chart for the PSO algorithm

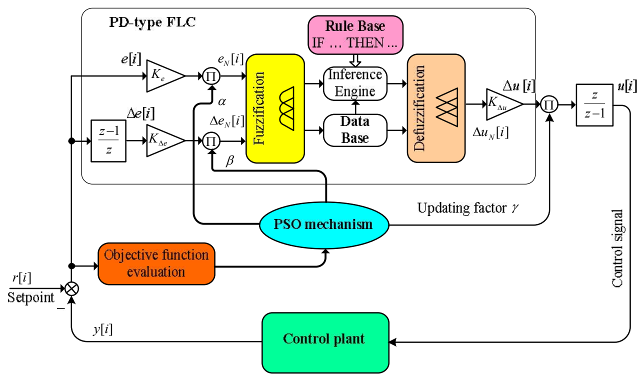

Fig. 3. Applying the PSO mechanism to tune scaling factors of a PD-type fuzzy logic controller in a control system

4. APPLICATIONS OF THE PROPOSED CONTROL METHODOLOGY

In this section, a typical application of the proposed control method is presented. A speed control system for a DC motor is considered to be a typical example to express the efficiency of the proposed control strategy. In general, a mathematical model of a DC motor can be described by the following equations [4,9]:

$$u = R_a i + L_a \frac{di}{dt} + e \quad (5)$$

$$e = K_e \omega \quad (6)$$

$$M - M_C - D\omega = J\frac{d\omega}{dt} \quad (7)$$

$$M = K_t . i \quad (8)$$

Where R_a and L_a are armature resistance and armature inductance of the DC motor. The others symbols can be found in [9].

From the above equations, a simulation model of the DC motor is built in Simulink environment as follows:

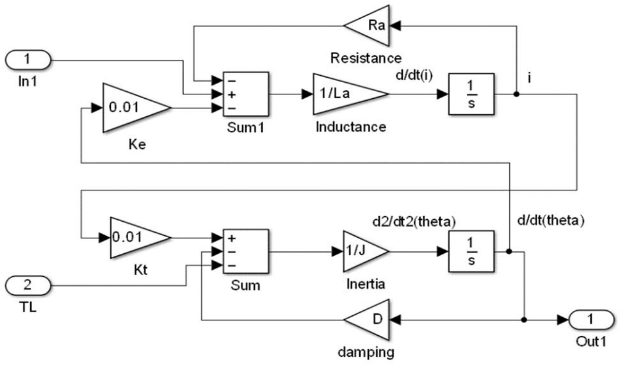

Fig. 4. A typical DC motor model built in Simulink

The above DC model is used to be the control plant as given in Fig. 4 to testify the efficiency of the proposed control strategy.

5. SIMULATION RESULTS AND DISCUSSIONS

In this section, the proposed PSO - based PD-type fuzzy logic control scheme will be applied in dealing with control speed of a DC motor as presented in the above section. The PSO is executed to optimize three updating factors of the PD - type fuzzy logic controller including two inputs (alpha and beta) and one output (gamma). The necessary parameters used in this study for both the DC motor as well as the PSO mechanism are given in Appendices of this paper. The objective function for the PSO algorithm employed in this section is as follows:

$$J = \int_0^{\tau} |e(t)|\, tdt = \int_0^{\tau} |n(t) - n^*|\, tdt \quad (9)$$

where $n(t)$ is the actual speed in *rpm* of the motor, n^* is the desired speed and τ is the simulation time.

The convergence of the PSO is given in Fig. 5 for the objective function and presented in Fig. 6 for three updating factors. To demonstrate the efficiency of the control strategy, Figs. 7-9 illustrate comparative simulation results for a conventional PI regulator and the proposed PSO-based PD-type fuzzy logic controller in both cases: without and with load torque. In fact, the conventional PI-based speed controller has been applied to a DC motor with acceptable control performances. However, when a DC motor system requires increasingly high control quality, such a PI-based speed controller might not be suitable anymore. It means that the speed control system applying the PI regulator for a DC motor needs to be replaced with a better controller. Through simulation results presented in this sections, it is clear to evaluate control quality of the proposed controller compared to that of the PI regulator.

As shown in Fig. 7, when the DC motor is in no-load mode, and the reference speed is being changed from the beginning to tenth second, the actual speeds for both PI and FL controllers are tracking this desired speed. However, the proposed fuzzy logic based speed controller is obtained much better result than the counterpart using the PI regulator. The actual revolution speed of the DC motor applying the proposed PD-type FL controller tracks well the reference speed. There are no overshoots or undershoots for the PD-type FL controller, and the steady-state times are smaller than those of the PI speed regulator. It verifies the efficiency and feasibility of the control strategy proposed in this study.

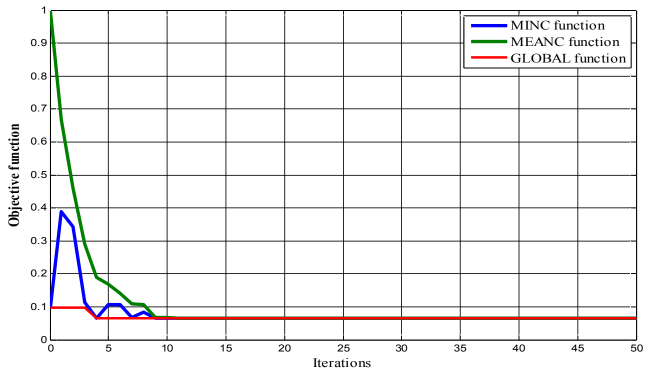

Fig. 5. The convergence of the PSO algorithm

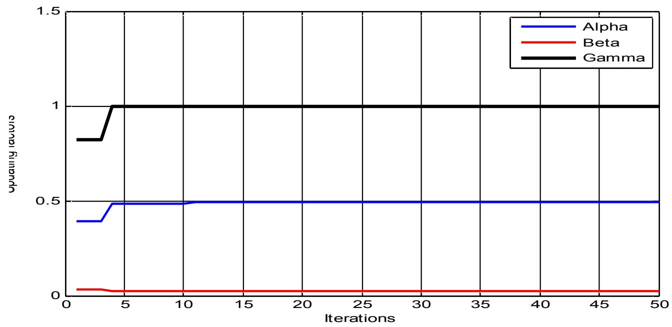

Fig. 6. Updating factors derived from the PSO algorithm

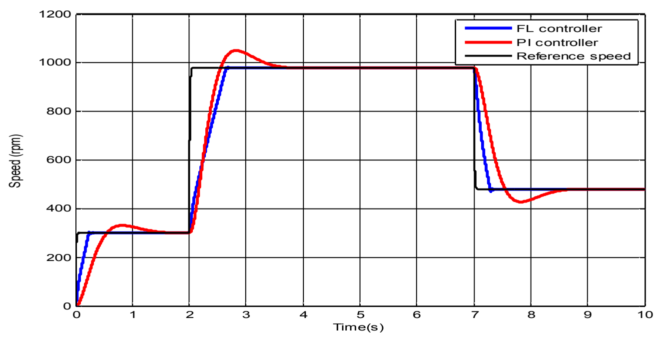

Fig. 7. A comparative simulation result for PI and PSO-based PD-type FL controllers (no load mode)

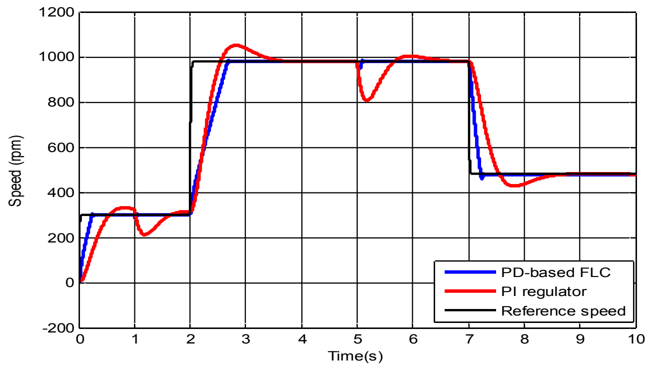

Fig. 8. A comparative simulation result for PI and PSO-based PD-type FL controllers (with load at 1st and 5th seconds)

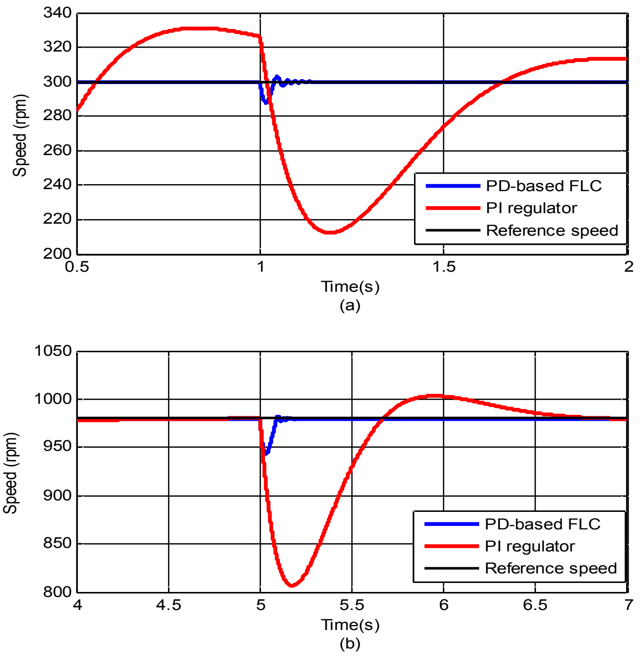

Fig. 9. Extractions from Fig. 8

In the second case, when a load torque is applied to the DC machine, it is assumed to be changed at the first and the fifth seconds (see Fig. 8). It should be found clearly from Fig. 8 and Fig. 9 the proposed PD-type FL controller is able to obtain the desired results and outperforms the conventional PI regulator. There are highly small overshoots and/or undershoots resulting from the proposed FL controller and the settling times are also quite short. Therefore, the proposed PSO-based FL controller is a good control solution to the speed regulation of a DC machine for both cases: with and without load. This type of FL controller significantly outperforms the conventional PI regulator.

6. CONCLUSIONS

In this study, a PD-type fuzzy logic control strategy applying the PSO algorithm has been presented. The PSO mechanism is employed to optimize three scaling factors of a standard PD-type fuzzy logic model (two for the inputs and one for the output), which affect strongly the control performances of the system. To demonstrate the feasibility of the proposed control strategy, a speed control example for a DC motor is chosen as a typical case study. The better simulation results obtained in both operation cases of the DC motor, when compared to those of the conventional PI regulator, have verified the feasibility and superiority of the proposed control strategy. In addition to this typical example, the proposed control strategy can be applied for a number of control problems, especially for uncertain and nonlinear ones. This suggests research directions in the future to develop the present study.

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APPENDICES

Motor parameters [9]:

Armature resistance: R_a = 1Ω; Armature inductance: L_a = 0.5H; Inertia: J = 0.01; Damping factor: B = 0.1.

PSO parameters:

Size of the swarm: N = 6; Dimension of the problem: n = 3; Maximum number of iterations: N_{max} = 50.

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