A NOVEL PSO-BASED PI-TYPE FUZZY LOGIC SPEED CONTROL APPROACH FOR SWITCHED RELUCTANCE MOTORS

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Abstract:

This work concentrates on the design of a novel speed control strategy for a 10/8-type switched reluctance motor (SRM) applying particle swarm optimization (PSO) algorithm and fuzzy logic technique. Due to the simple operation mechanism and high effectiveness, the PSO technique is successful to optimize some crucial parameters of a PI-type Fuzzy Logic (FL) speed controller, i.e. membership functions and an output scaling factor. This method will also be employed to determine the most effective switching angles of an asymmetrical DC-DC converter which is used to feed power to the SRM. Therefore, a total of twelve variables in accordance with a swarm of particles is successfully optimized through five integrated steps proposed in this paper. The convergence of this optimization process provides optimal parameters for designing the PI-type FL speed controller and the determination of two switching angles. Subsequently, numerical simulation processes using various load conditions will also be executed to validate the effectiveness and superiority of the proposed control strategy compared with those of the conventional PI regulator. It is found from the simulation results the control scheme devised is an optimal solution for designing the intelligent speed controller of a 10/8-type SRM drive system in practice.

Key words:

10/8-type switched reluctance motor, PI-type fuzzy logic controller, particle swarm optimization, optimal tuning, membership functions, gain-updating factor, switching angles.

Tóm tắt:

Bài báo này đề xuất một chiến lược điều khiển tốc độ mới cho các hệ truyền động sử dụng động cơ từ trở thay đổi loại 10/8 sử dụng thuật toán tối ưu hóa bầy đàn (PSO) và lý thuyết điều khiển mờ. Thuật toán tối ưu hóa PSO với ưu điểm nổi bật như cơ chế làm việc đơn giản và hiệu quả cao sẽ được áp dụng để tối ưu hóa một số tham số quan trọng của bộ điều khiển tốc độ mờ kiểu PI như các hàm thuộc và hệ số chỉnh định đầu ra. Thuật toán này cũng được sử dụng để xác định các góc chuyển mạch tối ưu cho một bộ biến đổi áp DC/DC không đối xứng cấp nguồn cho động cơ từ trở thay đổi loại 10/8 nói trên. Giải thuật tối ưu hóa PSO sử dụng trong nghiên cứu này sẽ bao gồm 12 biến, và quá trình tối ưu hóa được thực hiện thông qua 5 bước được đề xuất chi tiết trong bài báo. Sự hội tụ của thuật toán tối ưu PSO đã đưa ra các tham số tối ưu hiệu quả cho thiết kế bộ điều khiển mờ kiểu PI cũng như xác định được các góc chuyển mạch van hợp lý nhất. Quá trình mô phỏng sử dụng nhiều điều kiện khác nhau của phụ tải được thực hiện để minh chứng cho sự hiệu quả và đặc tính vượt trội của giải pháp điều khiển đã đề xuất so với phương pháp điều khiển kinh

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điển sử dụng bộ điều chỉnh PI truyền thống. Các kết quả mô phỏng khẳng định giải pháp điều khiển mới đưa ra trong nghiên cứu này là một phương pháp tối ưu hiệu quả trong việc thiết kế bộ điều khiển tốc độ thông minh cho các hệ truyền động sử dụng động cơ từ trở thay đổi loại 10/8 trong thực tế.

Từ khóa:

động cơ từ trở thay đổi loại 10/8, bộ điều khiển logic mờ loại PI, giải thuật tối ưu hóa bầy đàn, chỉnh định tối ưu, các hàm thuộc, hệ số chỉnh định cập nhật, các góc chuyển mạch.

1. INTRODUCTION

Switched reluctance motors (SRMs) with many attractive features, i.e. high torque to weight ratio, simple construction and rigged structure have gained much attention to researchers as well as engineers. The novel categories of the SRMs have been continuously investigating in order to enrich their SRM family [1-4]. Despite the fast widespread application, the SRM drive systems have still been studied to deal with their inherent disadvantages, such as the nonlinearity, the torque ripple and the difficult control of electronic power converters which feeds energy to the machines [5-7]. It is found that the efficient control strategies need to be further investigated to obtain the desired control performances, such as the stability, efficiency and the optimal dynamic responses of the phase current, electromagnetic torque as well as the angular speed. In general, control strategies, which mainly focus on designing speed and current controllers, have applied both the conventional and modern regulators. The conventional controllers (i.e., PI, PD and PID regulators) have been initially considered due to their simplicity of the design and operation [2]. However, the poor control characteristics obtained, such as the high overshoot and undershoot as well as the long rise and settling time, have restricted the widespread use of such controllers. This would be highly meaningful in the drive systems requiring strictly good control quality, e.g., the traction drives of EVs. Hence, these regulators should be replaced with the improved controllers using the modern techniques, e.g., Fuzzy Logic (FL), in order to obtain the better control properties. Based on the FL technique, the PI-type FL controllers (FLCs) have been adopted widely and efficiently in many control systems [8-10], especially in the SRM drives.

When applying such a PI-type FLC for a speed and/or a current controller, the determination of membership functions (MFs) and the output scaling factor, which affect significantly the control performances of the drive system, plays an important role to obtain the desired quality and efficiency. Many reports have been conducted this issue [8-10]. However, the SRM drive system, which is supplied by an electronic power converter (e.g., an asymmetrical DC-DC inverter), is usually subjected to the switching states of the semiconductor devices. This leads to the difficulty of the control strategies to obtain entirely the desirable characteristics. Basically, an optimal control strategy applying the FLC has to make sure that not only the parameters of such FLCs but also the switching angles of the inverter should be optimized successfully.

In this paper, the PSO algorithm will be used to carry out the above problem in order to design an optimal control scheme for a new category of the SRM family, namely, a 10/8-type SRM drive system. The SRM is mathematically modeled first to design the corresponding control drive system. Thereafter, the PSO algorithm, which is one of the most efficiently biological-inspired optimization techniques [11], will be applied to optimize twelve parameters (nine variables for the MFs, one argument for the gain-updating factor and two variables for the switching angles). This optimization mechanism will be conducted online through a simulation process using MATLAB/Simulink environment. In order to evaluate the effectiveness of the proposed control strategy in comparison with that of the conventional PI regulator, various cases of loads are taken to the SRM drive system. Numerical simulation results obtained will be used to demonstrate the feasibility and superiority of the control scheme devised in this work.

2. DESIGN OF A 10/8-TYPE SRM MODEL

It can be said that a *m*/*n* – type SRM has a *m*-pole stator and a *n*-pole rotor. Naturally, *m* is an even number, meaning that half of *m* phases will be powered for a *m*/*n* – type SRM. The SRM investigated in this study is a 10/8 – type SRM, corresponding to 5 phases will be powered for this SRM. Theoretically, a DC/DC or an AC/DC voltage converter can be used as a power converter for the SRM. For instance, an asymmetrical DC/DC power converter with two switching angles, turn-on and turn-off angles, can be applied for a SRM drive system. In this case, determination of these two angles is one of the most important problems affecting the control quality of the system. This problem will also be solved successfully in the present study.

The SRMs have a lot of nonlinearities such as flux linkage, inductance and torque, making the design of a mathematical model for a SRM highly challenging. When neglecting the mutual inductance between the phases of a SRM, it is possible to establish a simple single-phase equivalent circuit for the SRM including a resistor R_k, a variable inductance $L_k(i, \theta)$ and an induced *emf* (electromotive force) $e_k(t)$ in series [1,2]. Thus, to establish a mathematical model for a 10/8-type SRM, the *k*-th instantaneous phase voltage can be calculated as follows [2]:

$$V_k(t) = R_k i_k(t) + L_k(i_k, \theta)\frac{di_k}{dt} + e_k(t) \qquad (1)$$

where $L_k(i_k, \theta)$ denotes the *k*-th phase bulk inductance and $e_k(t)$ is the induced *emf* given below [2]:

$$e_k(t) = i_k(t).\frac{\partial L_k(i_k, \theta)}{\partial \theta}.\omega \qquad (2)$$

The mechanical equation describing the

motion of an SRM can be written as follows:

$$J.\frac{d\omega}{dt} = T - T_L - f.\omega \quad (3)$$

where J, f, T_L and T are the total inertia, the friction coefficient, the load torque and the total output torque, respectively. The total output torque is calculated as

$$T = \sum_{k=1}^{5} T_k(i_k,\theta) \quad (4)$$

where $T_k(i_k,\theta)$ denotes the k-th phase torque, which is computed depending upon the derivative of the co-energy $W_{CE}(i_k,\theta)$ at a fixed value of the phase current as follows:

$$T_k(i_k,\theta) = \left.\frac{\partial W_{CE}(i_k,\theta)}{\partial\theta}\right|_{i_k=\text{constant}} . \quad (5)$$

The co-energy $W_{CE}(i_k,\theta)$ defined theoretically relying upon the magnetization curve $\Psi_k(i_k,\theta)$ as shown in Fig. 1 can be computed below:

$$W_{CE}(i_k,\theta) = \left.\int_0^{i_k} \Psi_k(i_k,\theta)di_k\right|_{\theta=\text{constant}} . \quad (6)$$

It is noted that the flux linkage is a nonlinear function with respect to the rotor position θ and the phase current i_k. Depending on specific values of the angle θ, it is possible to obtain a family of magnetization curves as shown in Fig. 2 for a 10/8 – type SRM, which will be used for simulation in this work. The instantaneous phase torque can be comprehensively calculated as:

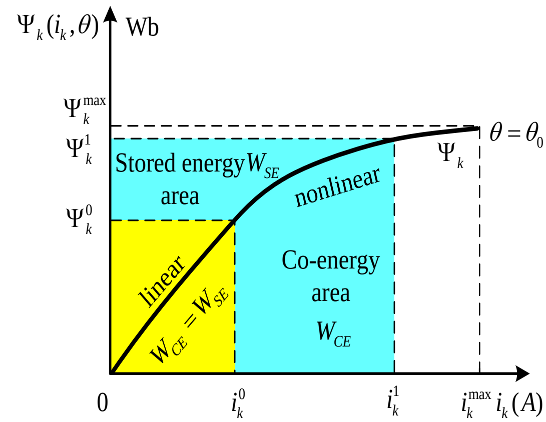

Fig. 1. The definition of stored energy and co-energy based on the magnetization curve

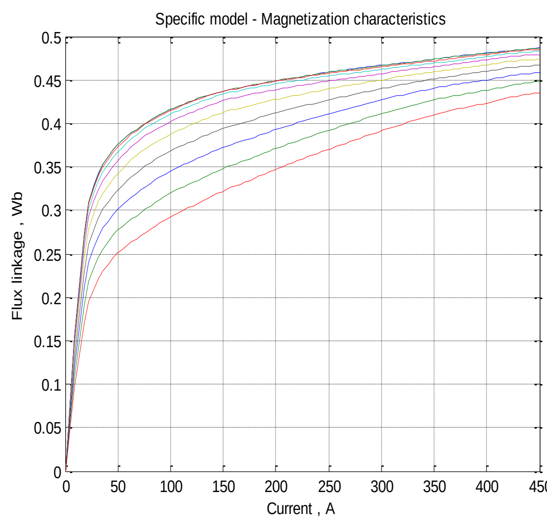

Fig. 2. Illustration of magnetization characteristics for a 10/8-type SRM with parameters given in Appendix

$$T_k = \begin{cases} \frac{1}{2} i_k^2 \frac{dL_k}{d\theta}, & \text{unsaturated area} \\ \int_{i_k^0}^{i_k^1} \frac{\partial L_k(i_k,\theta)}{\partial\theta} i_k di_k, & \text{saturated area} \end{cases} \quad (7)$$

The above mathematical model of a 10/8-type SRM is employed for the design of a novel speed control approach presented below.

3. NOVEL PI-TYPE FLC BASED ON THE PSO ALGORITHM FOR A 10/8-TYPE SRM

3.1. Algorithm of the PSO

PSO is one of the most efficient optimization methods which can be applied for various problems, including control problems. The idea of PSO algorithm is inspired from a habit of an organism swarm (e.g., a group of birds) called "search for food". It is assumed that there exists a particular area (search space), in which such swarm is trying to look for the food. In this context, the birds of such a swarm can fly at random speed as well as trajectory, which should be considered as the stochastic distributions, such as the uniform distribution. Although these birds may not know exactly the food area, it is able to determine their positions by using mathematical computations in a coordinate system (e.g., the Cartesian coordinate system). Thus, at each time, an elite individual, which is moving towards the nearest position of the food area, can be easily identified. Naturally, the other birds then should follow such an individual to finish searching for food as quickly as possible. The detailed execution process of the PSO algorithm can be found in [11].

The PSO, when applied for designing a speed control approach, needs an objective function (or cost function) to evaluate the terminal condition of the optimization process. Choosing this function should depend on a specific goal of the control problems. For instance, this work uses the following objective function for the PSO-based control approach:

$$f_{Obj} = \int_0^{\tau} t.\left|\omega_{ref} - \omega(t)\right|dt = \int_0^{\tau} t.|\,e(t)\,|\,dt \quad (8)$$

where ω_{ref}, $\omega(t)$, $e(t)$ and τ denote the reference angular speed, the real angular speed, the speed error and simulation time, respectively. Obviously, one of the most important aims is to minimize the value of the objective function to ensure the high quality of control performances, i.e. the shorter speed transient, lower overshoot and smaller settling time.

```
Create the initial swarms (population)
        Given swarm size: n
        Given particle size: m
        Given iterations: N
        Given lower, upper bounds:  Lb→, Ub→
        Given objective function: f_Obj

Iteration implementation
      (while the stopping criterion is satisfied)
 For k =1 to N
    For i =1 to m
        Calculate the objective function f_Obj
        Determine local/global optimal positions
        Update the velocity and position vectors
    i = i+1
 k = k+1
```

Fig. 3. Pseudo-code of the PSO algorithm

Basically, the pseudo-code of the PSO algorithm can be written as shown in Fig. 3. In the iteration implementation of the PSO algorithm, the stopping criterion should always be tested to ensure the convergence of the optimization process. Normally, the stopping criterion would be the acceptable value of the objective function given in the optimization issue. Accordingly, the PSO algorithm will be terminated when either the criterion or the maximum value of iterations is met. In the context of this study, the PSO algorithm, which is applied to design the robust PI-type FL speed controller of the 10/8-type SRM drive, will be introduced specifically in the following section

3.2. Design of the robust improved PI-type FLC applying the PSO algorithm

The basic PI-based FLC has some drawbacks, such as the fixed MFs and the undefined output scaling factor [9-10]. It is the fact that the determination of MF shapes and the output scaling factor strongly affect the control performances of a drive system, leading to the essential need to design the tuning methods, which are employed to realize such determination. In this study, the PSO mechanism will be applied to deal with this problem as follows.

3.2.1. Tuning membership functions based on the PSO method

The standard-triangular MFs used for the PI-type FLC need to be modified to adapt to the control issue of an SRM drive system. To carry out this, these MFs must be parameterized first. According to the Mamdani model, such MFs can be symmetrically parameterized as shown in Fig. 4. Here, three variables are employed to parameterize symmetrically for each of inputs and output. For example, three parameters, namely, m_e, n_e and p_e are used for the input $e_N[k]$. Similarly, two groups of variables, including (m_{de}, n_{de}, p_{de}) and (m_o, n_o, p_o), are employed for the other input $\Delta e_N[k]$ and the output $\Delta u_N[k]$, respectively. Our objective is to determine the values of these variables to achieve the better control properties of the SRM drive. In fact, there are totally nine parameters need to be optimized to design the adaptive PI-type FLC. This should be solved together with the tuning of the output gain factor by applying the PSO algorithm.

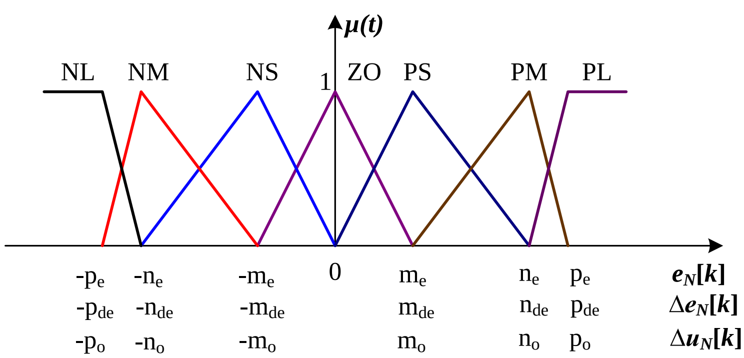

Fig. 4. Parameterized process of membership functions using for the PSO algorithm

3.2.2. Tuning the gain-updating factor applying the PSO mechanism

The output gain factor of a FLC $G_{\Delta u}$ plays an important role in seeking an optimal solution of many control problems [9-10]. Basically, this gain factor can be modified as:

$$G_{\Delta u}^{\gamma} = \gamma . G_{\Delta u} \quad (9)$$

where $G_{\Delta u}$, $G_{\Delta u}^{\gamma}$ and γ are the previous outputs factor, the new counterpart and the gain-updating factor, respectively. Our objective is to regulate the gain-updating factor γ in order to optimize the final scaling coefficient $G_{\Delta u}^{\gamma}$. In this work, we first set $G_{\Delta u}$ which is equal to 0.05 as the initial value. Thereafter, the PSO algorithm will be used to determine the value of γ. Finally, this updating factor will be multiplied by $G_{\Delta u}$ to generate the modified factor $G_{\Delta u}^{\gamma}$. By combining with the tuning process of the MFs as mentioned earlier, the PSO algorithm is run following five steps as:

Step 1: Initialization

The initial parameters for the PSO algorithm should be set, including particle size *m*, number of swarms *n*, number of iterations *N* and constraints $\left(\overrightarrow{Lb},\overrightarrow{Ub}\right)$.

Step 2: Determination of the objective function

In this work, the objective (fitness) function is determined as expressed in (8). This fitness function needs to be minimized according to the objective of the PSO algorithm.

Step 3: Design of the FL reasoning

The FL model is built here using Mamdani architecture with symmetric - triangular MFs which are parameterized as shown in Fig. 4. In addition, the basic 49 rules base for a classical PI-based FLC (as illustrated in [8]) will also be applied to the proposed FL model.

Step 4: Design of the SRM system

A 10/8 type SRM, which has been modeled in Section 2, can be used here applying the proposed PI-based FL speed controller. In addition, switching angles are able to be determined by either the experience or applying the PSO technique.

Step 5: Run PSO algorithm and get the optimal results

The PSO algorithm will be run according to steps as introduced earlier. Finally, results obtained shows the optimal parameters of MFs and gain-updating factor γ.

3.3. Determination of switching angles applying PSO method

This work applies the PSO algorithm to determine not only the parameters of a PI-type FLC but also the switching angles, i.e. turn-on angle α (θ_{on}) and turn-off angle β (θ_{off}). It is the fact that such two switching angles impact significantly on the electromagnetic torque generation of the SRMs [1,2]. Therefore, control performances of the SRM drive system will also be affected, leading to the need of their optimization.

In the context of this study, α and β can also be optimized by using the PSO method. To perform it, two arguments need to be added to the variable space of the PSO algorithm. Hence, the total of variables used in such PSO method is twelve (nine for MFs, one for gain updating factor γ and two for α and β). Using the trial and error method, the lower and upper bounds of the turn-on angle α and the turn-off angle β can be determined respectively as: $10° \le \alpha \le 22°$ and $39° \le \beta \le 45°$. The optimization process will be carried out through five steps as mentioned above. Accordingly, the optimal control strategy proposed in this study will be represented finally in Fig. 5. The effectiveness and feasibility of the proposed control strategy will be discussed in the following section.

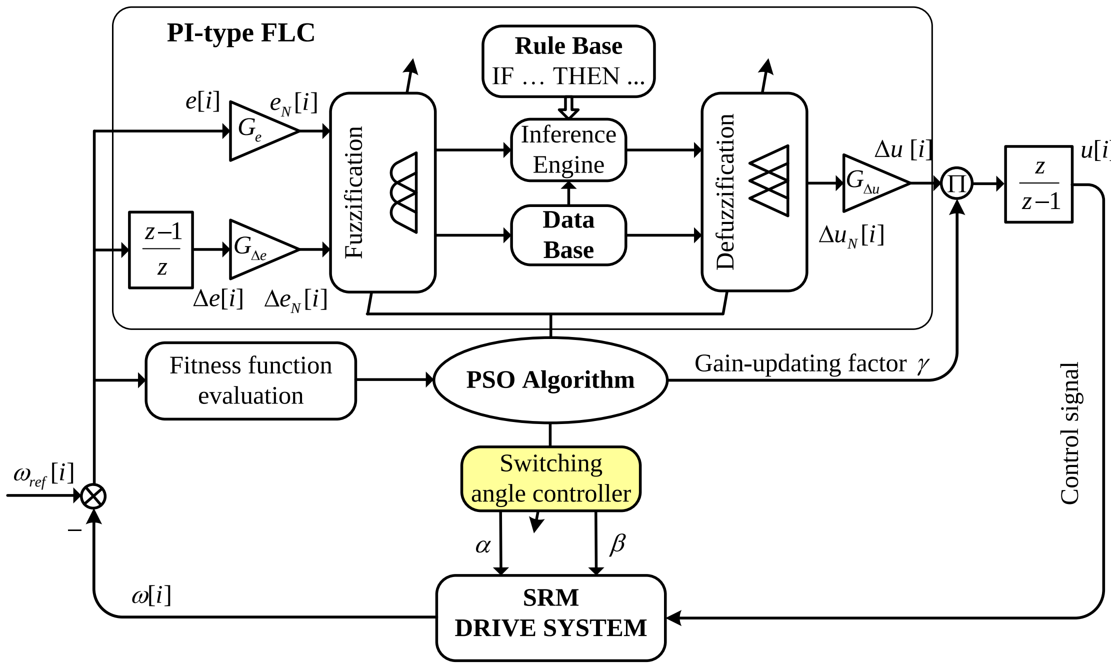

Fig. 5. The proposed control strategy of the 10/8-type SRM drive

4. NUMERICAL SIMULATION RESULTS

In order to justify the effectiveness and the feasibility of the proposed control strategy, a simulation configuration for the 10/8-type SRM drive is designed in Matlab/Simulink environment corresponding to the system shown in Fig. 5. Here, the PSO algorithm is implemented through a *m*-file written in Matlab/Script environment. In this study, the PSO algorithm will be applied to optimize totally twelve variables as mentioned in the previous section. It is known that not only the speed FL controller with the corresponding MFs and output scaling factor but also two switching angles are tuned to obtain the optimal parameters for the SRM drive system. Thus, the variable space in accordance with a particle swarm is given below:

$$\vec{P} = (m_e, n_e, p_e, m_{de}, n_{de}, p_{de}, m_o, n_o, p_o, \gamma, \alpha, \beta). \tag{10}$$

The PSO technique is initialized with parameters indicated in Appendix of this paper. To implement the PSO algorithm, in the simulation process, a high reference speed 3000*rpm* will be set on the input of the SRM drive system. Also, a PI regulator is employed as the current controller of this drive system. Using the objective function given in (8) as the cost to evaluate the optimization process of the PSO algorithm, the optimal results are obtained as shown in Fig. 6-8. In Fig. 6, the cost functions have been calculated and plotted through 100 iterations for the local, global and mean optimal variable vectors corresponding to a set of parameters as expressed in (10). It can be seen obviously that these functions are converging to the optimal value. The details of this convergence evolution are represented in Fig. 7(a) and 7(b) for the switching angles (α, β) and the gain-updating factor (γ), respectively. Moreover, based on the PSO method, the MFs of two inputs ($e_N[k]$, $\Delta e_N[k]$) and one output ($\Delta u_N[k]$) are tuned to obtain the optimal values as illustrated in Fig. 8(a), 8(b) and 8(c), respectively. As shown, the number of the MFs has been reduced due to their overlapping. Concretely, there are only three remaining MFs used for both the first input $e_N[k]$ and the output $\Delta u_N[k]$. Meanwhile, the second input $\Delta e_N[k]$ of the PI-FL speed controller only employs five instead of seven MFs as the basic control strategy [9-10]. Obviously, after the PSO method, the FL inference has been simplified significantly. This will dramatically speed up the simulation process of the control system in comparison with the basic FLC. The optimal parameters obtained is applied to design an effective control strategy for the 10/8-type drive system.

To evaluate the superiority of the optimal PI-type FL speed controller over the conventional PI regulator, 3 cases of load torques are applied to the SRM drive as:

(i) Case 1: there is no load $T_L = 0$ (see Fig. 9(a)).

(ii) Case 2: there is only a load torque (T_L = 100 N.m) which will be appeared at 1(s) (see Fig. 9(b)). In fact, this can be used for a process of the machining machinery applying the SRM drive system.

(iii) Case 3: there is a symmetrically repeated load torque (see Fig.s 10(a) and 10(b)). This can be employed practically to design the repeated machining machinery drive system with highly exact quality characteristics.

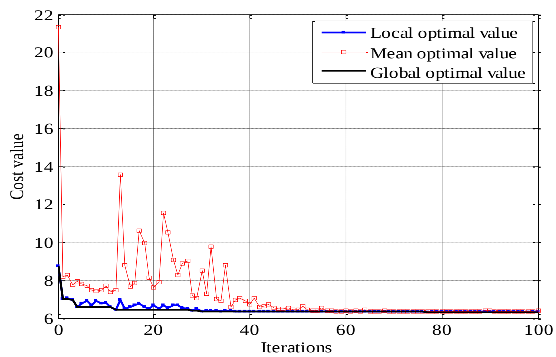

Fig. 6. Optimization process of the PSO algorithm

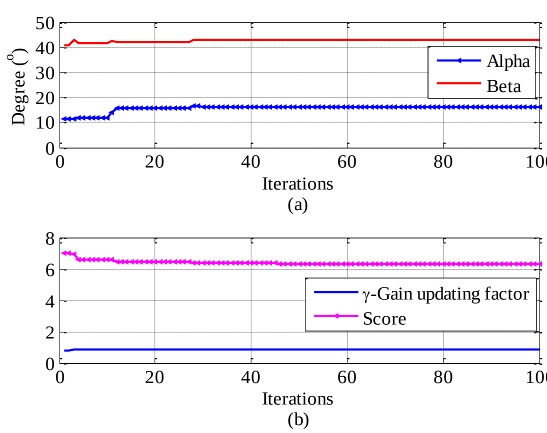

Fig. 7. Convergence of the PSO algorithm (a) Switching angles; (b) Gain-updating factor

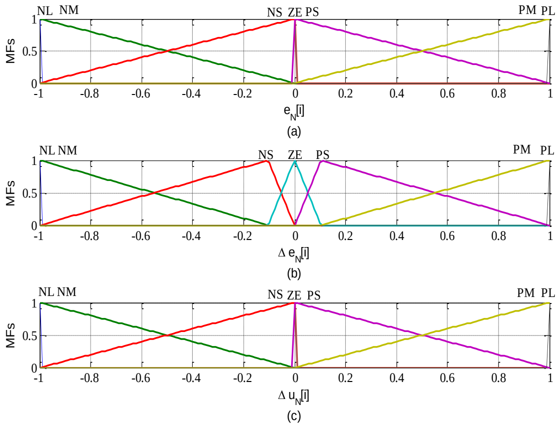

Fig. 8. Optimal membership functions of the PI-type FLC applying the PSO

Both of the SRM drive systems (applying PI-type FLC and conventional PI controller (PIC)) use the optimal switching angles taken from the PSO mechanism (α = 16.0116° and β = 42.7951°). It can be seen from Figs. 9 and 10 the proposed FLC has obtained much better results compared with the conventional PI regulator. The dynamic control performances of the angular speed response obtained by using the PI-type FLC, such as the overshoot, transient time and settling time, are much smaller for all of three load cases.

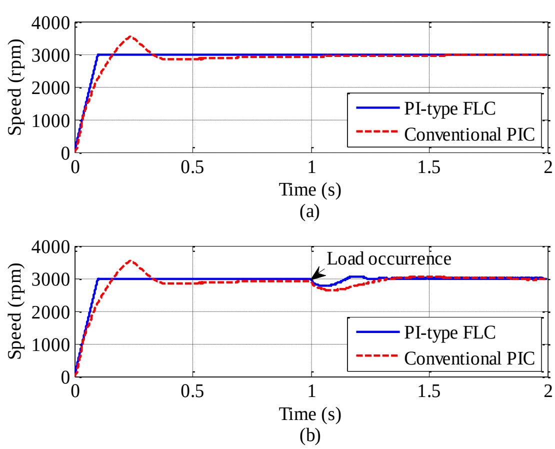

Fig. 9. The dynamic response of the angular speed. (a) Case 1: No load; (b) Case 2: Load occurs at 1(s)

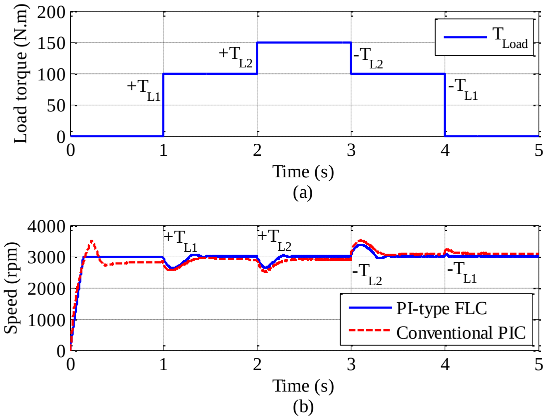

Fig. 10. Load torque and angular speed for the third simulation case (a) Symmetrically repeated load torque; (b) Dynamic response of the angular speed

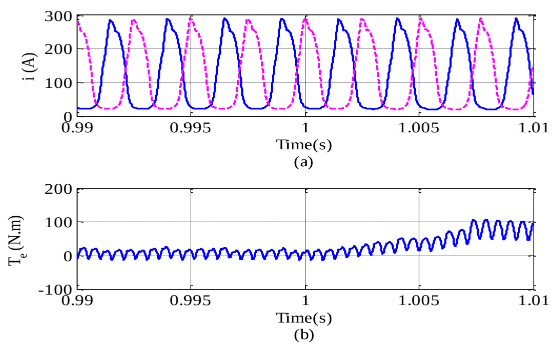

Fig. 11. Phase currents and electromagnetic torque around 1(s) in the third simulation case (a) Phase currents: i_A (blue-solid line) and i_C (magenta-dashed line); (b) Electromagnetic torque T_e

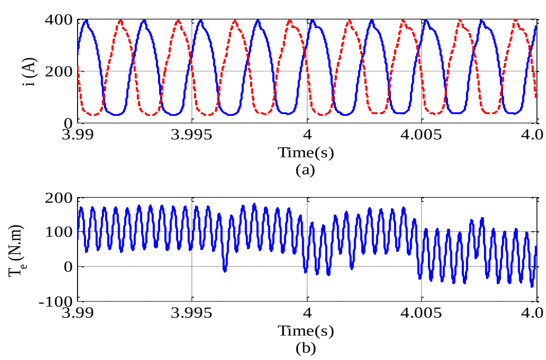

Fig. 12. Phase currents and electromagnetic torque around 4(s) in the third simulation case (a) Phase currents: i_B (blue-solid line) and i_E (red-dashed line); (b) Electromagnetic torque T_e

In addition, Fig. 11(a) and 11(b) illustrate the dynamic responses of current phases and electromagnetic torque around 1*s* corresponding to an increase of the load torque in the third simulation case. On the other hand, when load moment falls in the second time (at 4*s*), such two dynamic responses can be affected as shown in Fig. 12(a) and 12(b). It is found that the oscillations of the current phases are kept to be stable even though the electromagnetic torque is being affected by the change of the load. Indeed, this is very meaningful when designing the drive systems that require strictly high control characteristics, e.g., the electric traction drive systems of electric vehicles.

5. CONCLUSIONS AND DISCUSSIONS

The efficient application of the PSO algorithm has been investigated in this paper to design the optimal PI-type FL speed controller for a 10/8-type SRM drive system. All of the MFs as well as the gain-updating factor of this FLC are optimized successfully. In addition, the PSO method is applied to determine the optimal switching angles of the asymmetrical DC-DC converter, which has been used to feed the power energy to the SRM drive. Using five integrated steps of the PSO technique proposed in this study, the optimization process has been implemented in order to design a highly feasible and efficient control strategy for the 10/8-SRM drive system. Through the simulation results obtained with various cases of loads, the superiority of the proposed control scheme has been demonstrated compared with the traditional counterpart using the PI regulator. It is well known that the control process has been outperformed efficiently enough to apply to various drive systems in reality.

For future work, the investigation of different types of the SRM drive systems applying the optimal controllers, e.g., the PI-type FLC based on the PSO algorithm, should be considered. Moreover, a hybrid control strategy using the combination of fuzzy logic and neural network techniques based on means of the biological-inspired optimization will catch more attention to design an efficiently practical SRM system.

Appendix

10/8-type SRM parameters

$$R_k = 0.05\Omega, J = 0.05 kg.m^2, f = 0.02 N.m.s,$$
$$L_k^{\min} = 0.67 mH, L_k^{\max} = 23.6 mH, i_k^{\max} = 500 A$$

PSO parameters

$$n = 10, m = 12, N = 100;$$
$$\overrightarrow{Lb} = [0,0,0,0,0,0,0,0,0,0,10,39];$$
$$\overrightarrow{Ub} = \left[1,1,1,1,1,1,1,1,1,1,22,45\right]$$

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