Kỷ yếu Hội nghị KHCN Quốc gia lần thứ XII về Nghiên cứu cơ bản và ứng dụng Công nghệ thông tin (FAIR); Huế, ngày 07-08/6/2019
DOI: 10.15625/vap.2019.0002

ADVANCED INTELLIGENT IDENTIFICATION OF PMSM PARAMETER USING MODIFIED JAYA OPTIMIZATION ALGORITHM

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ABSTRACT*. This paper proposes a new method for intelligent identification of PMSM machine parameter based on Modified Jaya optimization algorithm (MJA). The fact is that the performance of PMSM motor drive system using the vector control depends on the PI regulator. Those regulator parameters will be tuned based on appreciate PMSM motor parameter. Consequently as to improve the PMSM operation performance parameters of regulator need to be adjusted suitable to the PMSM parameters. The intelligent identification of PMSM machine parameter results, using modified MJA optimization algorithm, prove the outperforming performance in comparison with the modified differential evolution (MDE) and the particle swarm optimization (PSO) optimization methods.*

Keywords*: Intelligent Identification, Permanent Magnet Synchronous Machine (PMSM), Parameter Identification, Modified Jaya (MJA) Optimization Algorithm, Modified Differential Evolution (MDE) Algorithm, Particle Swarm Optimization (PSO).*

I. INTRODUCTION

Permanent Magnet Synchronous Machine (PMSM) has been increasingly applied in numerous drive applications since it possesses lots of benefits, for example simple structure, good reliability and high power/weight ratio. Nowadays it has been applied in numerous industrial drive fields including CNC machine, train drive systems, electric vehicle (EV) among others. As to efficiently control the PMSM machine, field-oriented control (FOC) and direct torque control (DTC) methods can be regarded as two well-established control approaches used in VSI-PMSM [1]. Those approaches can adjust rotor speed automatically by using PI controller as presented in Figure 1. The fact is that the parameters of the PI controller greatly affect the control quality of the PMSM drive systems. The determination of these parameters depends mainly on the accuracy of PMSM parameters Therefore accurate identification of PMSM parameters plays the key work in improving the quality control of PMSM drive systems based on vector control methods. Currently, there have been several research studies recently published related to the identification of PMSM parameters. Generally, there are two main principles of PMSM parameter identification, namely online identification and offline identification.

In offline identification, a proposed mathematical model for the PMSM motor as well as is required. Then the determination of the PMSM parameters is made by finding the mathematical model parameters such that the total squared error between the calculated currents from the PMSM model and measured currents on the PMSM machine are minimal. Parameter identification based on LSA [1], Windowed Least Square Algorithm (WLSA) [2] and Multi-Innovation Least Squares (MILS) [3] are main researches belong offline methods.

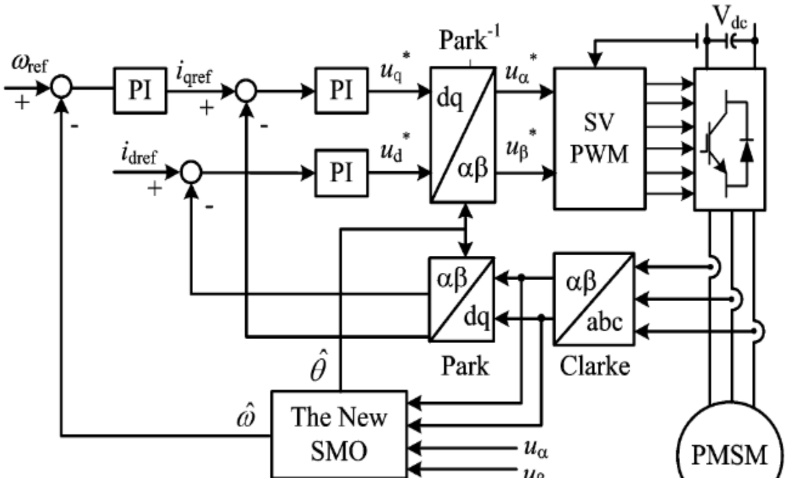

Fig.1. Schematic of PMSM drive systems based on FOC control

In offline identification, the mathematical model parameters are considered as the actual motor parameter. Depending on the parameters to look for that will have the corresponding mathematical model. The advantage of this method is that many different algorithms can used it to determine the motor parameters and have a simple hardware structure with current and voltage sensors. Model parameters are received by using specified computer software. However, those methods spent more time for execution and they can’t perform at the same time with machine operation. In this paper the proposed mathematical model for the PMSM motor is as well as given in Fig.2

Online identification method is published in numerous recent studies [4-7]. There are some methods were proposed using particle swarm optimization PSO [4], dead-time compensation [5], extended Kalman filter [6], Immune Clonal Selection Differential Evolution (ICS-DE) algorithm [7] and so on. Online methods have been developing in recent years because their main advantage relates to the fact that they are implemented in parallel with the operation of machine. Then it helps to improve the efficiency of drive system. However, those methods need the powerful microcontroller which can executive big data include control and identification data. As a result it will increase PMSM drive system cost due to upgrade for controller.

Recently an advanced optimization algorithm called Jaya, first proposed by Venkata Rao [8] obtains outperformed features such as simple to implement, not need any specified control coefficients. The Jaya optimization approach has been proved to be able of effectively resolving not only constrained but also unconstrained optimized-orientation tasks, and its potentiality has demonstrated that this method proves more efficient than recently well-known optimization approaches, such as genetic algorithm (GA), particle swarm optimization (PSO), differential evolution (DE) [8]. The Jaya algorithm has now been increasingly used and improved for versatile problems in numerous domains such as mechanical engineering [9][10][11], artificial neural network training [12], structural optimization [13].

Based on such analysis abovementioned related to promisingly potential capability of the Jaya optimization method, this paper proposes a new approach for PMSM parametric identification based on modified Jaya optimization algorithm (MJA).

In the paper, a PMSM drive system model built on the MATLAB / Simulink software as a model for recognition and computation in the MATLAB environment. In addition, as to prove the effectiveness of proposed Jaya algorithm against other computational algorithms, this paper also performs simulations of PSO-based and modified DE-based PMSM parametric identification, respectively, for comparison purpose.

The rest of this study is structured as follows. Section 2 introduces the implementation of PMSM model. Section 3 presents the proposed Modified Jaya Algorithm (MJA) innovatively applied for PMSM parametric identification. Section 4 presents and analyses the simulation PMSM parametric identification results using the proposed Modified Jaya Algorithm (MJA) and comparatively demonstrates the superiority of proposed Jaya method with modified MDE and PSO optimization approaches. Finally Section 5 includes the conclusions.

II. IMPLEMENTATION OF PMSM MODEL

A. Mathematical Model of PMSM

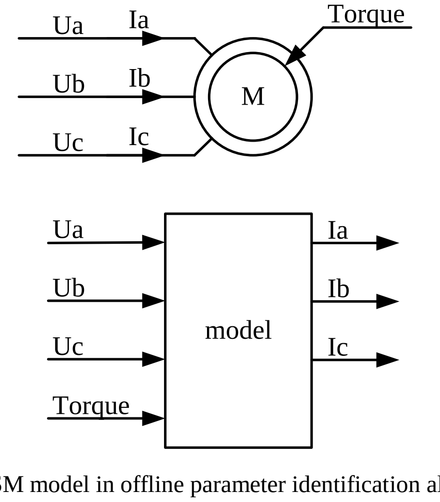

Fig.2. PMSM model in offline parameter identification algorithms

The machine model is based on the transfer of voltage supply to the stator windings, the load torque into the current of windings, the rotor speed. Three-phase inverter supply three-phase voltage values to winding terminals, based on Clark transformation (1), voltage of α-axis and β-axis of αβ0-coordinate was received by (2) and (3) respectively.

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$$\begin{bmatrix} F_\alpha(t) \\ F_\beta(t) \\ F_0(t) \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} F_a(t) \\ F_b(t) \\ F_c(t) \end{bmatrix} \tag{1}$$

$$u_\alpha = \frac{1}{3}(2u_a - u_b - u_c) = \frac{1}{3}\left[(2u_a - 2u_b) + (u_b - u_c)\right] = \frac{1}{3}(u_{ab} + u_{bc}) \tag{2}$$

$$u_\beta = \frac{\sqrt{3}}{3}(u_b - u_c) = \frac{\sqrt{3}}{3}u_{bc} \tag{3}$$

The voltage equations represented in d-q axis parameters (udq0) in the rotor reference frame using Park's transformation are given by (4).

$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & -\cos(\omega t) & 0 \\ \cos(\omega t) & \sin(\omega t) & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} \tag{4}$$

Apply (2) and (3) into (4) and expand this matrix, the equations of voltage in the rotor reference frame are present as (5) and (6).

$$u_q = u_\alpha.\cos(\theta) + u_\beta.\sin(\theta) = \frac{1}{3}(u_{ab} + u_{bc}).\cos(\theta) + \frac{\sqrt{3}}{3}u_{bc}.\sin(\theta) \tag{5}$$

$$u_d = u_\alpha.\sin(\theta) - u_\beta.\cos(\theta) = \frac{1}{3}(u_{ab} + u_{bc}).\sin(\theta) - \frac{\sqrt{3}}{3}u_{bc}.\cos(\theta) \tag{6}$$

According to [14], in dq axis frame, currents of d-axis and q-axis were present by (7) and (8) respectively.

$$\frac{d}{dt}i_q = \frac{1}{L_q}u_q - \frac{R}{L_q}i_q - \frac{L_q}{L_q}p\omega_m i_d - \frac{\lambda p\omega_m}{L_q} \tag{7}$$

$$\frac{d}{dt}i_d = \frac{1}{L_d}u_d - \frac{R}{L_d}i_d + \frac{L_q}{L_d}p\omega_m i_q \tag{8}$$

where:

L_d, L_q : q and d axis inductances.
R : Resistance of the stator windings
i_d, i_q : q and d axis currents
v_d, v_q : q and d axis voltages.
ω_m : Angular velocity of the rotor.
λ : Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases.

Electric torque generated in the machine:

$$T_e = 1.5p\left[\lambda i_q + (L_d - L_q)i_d i_q\right] \tag{9}$$

Electromagnetic torque equations is shown in (10)

$$T_e = T_m + B\omega_m + J\frac{d\omega_m}{dt} \tag{10}$$

Rewrite (10) can get rotor speed as present in (11)

$$\frac{d}{dt}\omega_r = \frac{1}{J}\ T_e - F\omega_m - T_m \tag{11}$$

When:

J : Combined inertia of rotor and load.
F : Combined viscous friction of rotor and load.
θ : Rotor angular position.
T_m : Shaft mechanical torque.
ω_m : Angular velocity of the rotor (mechanical speed)

Currents in rotor dq-axis frame, which are calculated as present in (7) and (8), are transformed to stator coordinate by invert Park transformation as mention in (12)

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \sin\ \omega t & \cos\ \omega t & 1 \\ \sin\ \omega t - 2\pi/3 & \cos\ \omega t - 2\pi/3 & 1 \\ \sin\ \omega t + 2\pi/3 & \cos\ \omega t + 2\pi/3 & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \tag{12}$$

Based on (1)-(12), the voltage supply to the PMSM is converted into current in the stator windings and the motor speed corresponds to the specified load torque. The calculated value used in the next iteration. Thus, by repeating the iteration for equations (1)-(12), with array of voltage values and load torque, we obtain a series of current values at the specified PMSM motor parameters shown in (13)

$$\left[\ i_a\ ,\ i_b\ ,\ i_c\ \right] = f\ \ v_{ab}\ ,\ v_{bc}\ , R, L_d, L_q, \lambda, T_m \tag{13}$$

where:

$v_{ab}\ ,\ v_{bc}$: The voltage input array.

$i_a\ ,\ i_b\ ,\ i_c$: The current output array.

B. Simulation Model of PMSM

A simulation model is comprehensively built based on (1)-(12) which is demonstrated in Fig.3

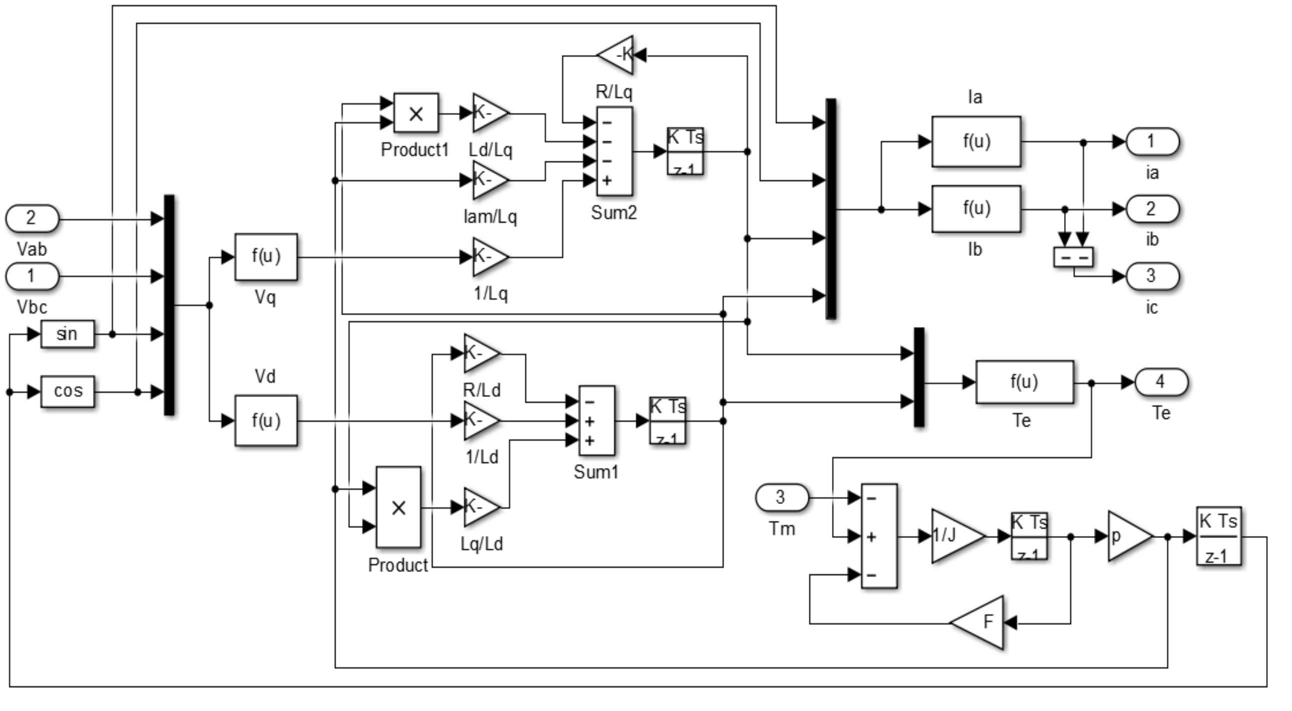

Fig.3. Simulation model of PMSM machine

III. PROPOSED MODIFIED JAYA ALGORITHM (MJA)

A. Classical Jaya Algorithm

The Jaya method, firstly introduced by Venkata Rao (2016), belongs to global seeking-based swarm algorithm. This method improves the notion that it persistently focuses in reaching the best solution and in avoiding local optimum-solutions. Furthermore, it proves very simple to install since it needs only popular control coefficients, such as population and number of iterations. The comprehensive contents of this method can be concisely described in four following stages.

At the first stage of the Jaya method, it randomly generates the initial swarm containing NP particles in the searching area. Every particle in NP considered a candidate vector composing of n variables $X_j = x_1, x_2, ..., x_n$ and is implemented as follows:

$$x_{j,i} = x_{j,i}^{l} + rand\ 0,1 \times\ x_{j,i}^{u} - x_{j,i}^{l} \tag{14}$$

Where $i = 1, 2, ..., NP$; $j = 1, 2, ..., n$; x_j^l, x_j^u represent the min and max bounds of variable x_j, respectively; rand[0, 1] is evenly dispersed between 0 and 1; and NP denotes the swarm size.

The second stage, a vector $x_{i,G}'$ is generated as shown in (15) below.

$$x_{j,i,G}' = x_{j,i,G} + r_1.\ x_{j,best,G} - \left|x_{j,i,G}\right| - r_2.\ x_{j,worst,G} - \left|x_{j,i,G}\right| \tag{15}$$

With $x_{j,i,G}$ represents the value of the jth variable for the ith candidate solution during the Gth iteration. $x_{j,\text{best},G}$ and $x_{j,\text{worst},G}$ represent the j^{th} variable values attaining the best and the worst temporary candidate solution, respectively; r_1 and r_2 denote the randomized coefficients in the boundary [0, 1]; the component $+r_1.\ x_{j,best,G} - \left|x_{j,i,G}\right|$ determines the trend of the solution towards the best solution; and the last component $-r_2.\ x_{j,worst,G} - \left|x_{j,i,G}\right|$ determines the trend of the eventual solution in avoiding from the worst result. The norm of the temporary solution $\left|x_{j,i,G}\right|$ plays the role to improve the exploitation capability of the method.

In the third stage, an operation is executed with respect to the term value $x_{j,i,G}'$ as to reflect back to the area available in case its values overtake the preset min and max limits. This operator can be expressed as

$$x_{j,i,G}' = \begin{cases} x_j^l + \left|x_j^l - x_{j,i,G}'\right| & if\ x_j^l > x_{j,i,G}' \\ x_j^u - \left|x_j^u - x_{j,i,G}'\right| & if\ x_j^u < x_{j,i,G}' \\ x_{j,i,G}' & \text{otherwise} \end{cases} \tag{16}$$

Eventually in the fourth stage, using the fitness function value, the vector $X_{i,G}'$ is updated with its target value $X_{i,G}$. In case the $X_{i,G}'$ vector obtains a better functional value, it is to survive to the next iteration. On the contrary, the target value $X_{i,G}$ will be maintained as present in (17).

$$X_{i,G+1} = \begin{cases} X_{i,G}' & if\ F\ X_{i,G}' < F\ X_{i,G} \\ X_{i,G} & \text{otherwise} \end{cases} \tag{17}$$

where F is the cost function that is required to be minimized.

B. Modified Jaya Algorithm (MJA)

Jaya is an algorithm that has not any calibration parameters. This shows a great advantage since it needs not any process of algorithm parameter adjustment. However, it is not possible to adjust the parameters with respect to the characteristics of each objective function. As a result the algorithm sometimes does not converge. To overcome the problem, this paper proposes a modified Jaya algorithm (MJA) with newly adding parameters. This makes the MJA algorithm more flexible in programming and the ability to quickly converge to global solution.

The proposed modified Jaya algorithm MJA is similar to the conventional Jaya algorithm except using (18) instead of (15). The constant C_1, C_2 are the innovatively added parameters. Depending on the specified optimal problems, these parameters C_1, C_2 will be chosen appropriately.

$$x'_{j,i,G} = x_{j,i,G} + C_1.r_1.\left(x_{j,best,G} - \left|x_{j,i,G}\right|\right) - C_2.r_2.\left(x_{j,worst,G} - \left|x_{j,i,G}\right|\right) \quad (18)$$

C. The Objective Function of PMSM Parameter Identification

Each PMSM machine contains the actual parameter set $\left[\dot{R}, \dot{L}_d, \dot{L}_q, \dot{\lambda}, \dot{T}_m\right]$. When supply voltage source (v_{ab}, v_{bc}) at stator winding terminals, measured stator current $\left[\dot{i}_a, \dot{i}_b, \dot{i}_c\right]$ will be received when it simulates this PMSM model. In case there is assumed parameter set $\left[\hat{R}, \hat{L}_d, \hat{L}_q, \hat{\lambda}, \hat{T}_m\right]$, simulated stator currents $\left[\left[\hat{i}_a\right], \left[\hat{i}_b\right], \left[\hat{i}_c\right]\right]$ will be calculated by using (19) as follows,

$$\left[\left[\hat{i}_a\right], \left[\hat{i}_b\right], \left[\hat{i}_c\right]\right] = f\left((v_{ab}, v_{bc}), \hat{R}, \hat{L}_d, \hat{L}_q, \hat{\lambda}, \hat{T}_m\right) \quad (19)$$

Parameter identification mean that the task is finding the minimum least square of error between the measured stator currents and the simulated stator currents as demonstrate in (20), it is called the fitness function or objective function.

$$F\left((V_{ab}, V_{bc}), \hat{R}, \hat{L}_d, \hat{L}_q, \hat{\lambda}, \hat{T}_m\right) = \left(\hat{i}_a - \dot{i}_a\right)^2 + \left(\hat{i}_b - \dot{i}_b\right)^2 + \left(\hat{i}_c - \dot{i}_c\right)^2 \quad (20)$$

IV. SIMULATION RESULTS

SIMULINK model built for testing performance of proposed approach as shown in Fig.4. Computer configuration is included i5 8250U CPU, 1.6GHz, 4GB RAM. Results of PMSM parameter identification based on proposed Modified Jaya algorithm (MJA) performed several times and compared with Modified DE and PSO approaches in order to highlight the efficiency of proposed MJA method. The PMSM parameters are used in simulation are listed in Table 1:

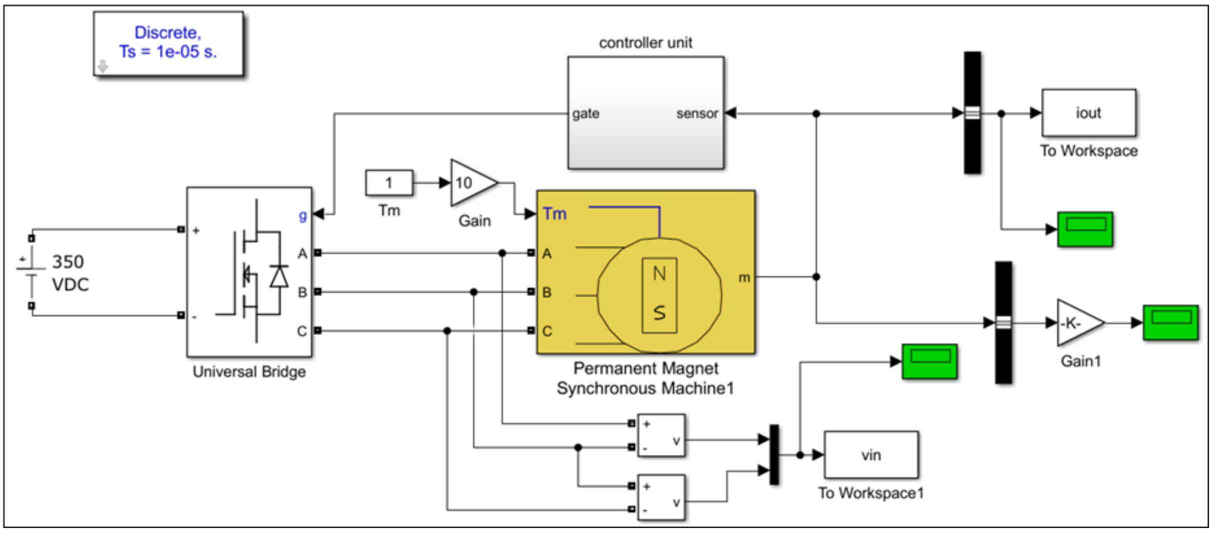

Fig.4. Model of PMSM drive systems

Table 1. PMSM parameters in the simulation

Parameter	Kí hiệu	Giá trị	Đơn vị
Winding resistance of stator	R	0.7	Ohm
D-axis inductance	Ld	0.835	mH
Q-axis inductance	Lq	0.835	mH
PM flux linkage	λ	0.105	V.s
Combined inertia	J	0.0008	kg.m^2
Combined viscous friction	F	0.001	N.m.s
Number of pole pairs	p	4	
Load torque	Tm	10	N.m

A. Result of PMSM Parameter Identification Based on Modified Jaya Algorithm

In order to validate the performance and quick convergence speed of proposed identification algorithm, simulation performed for 10 times and these values fully presented in Table 2. As it can see in the table, with modified Jaya algorithm, the difference values collected show that estimated values are quite approximately with actual parameter. Moreover the convergence rates of proposed Modified Jaya algorithms shown in Fig.5. As present in this Figure, proposed MJA-based PMSM identification approach attains the best convergence speed and smoothness.

B. Comparison of Proposed Modified Jaya Algorithm, MDE and PSO in PMSM Parameter Identification

In order to comparatively demonstrate the efficiency obtained by the Modified Jaya Algorithm in comparison with PMSM parameter identification based on the PSO and MDE algorithms [15]. The simulation parameters are comprehensively investigated so that there is the exact similarity. These selected parameters are presented in the Table 3 below. After implement those algorithms, the results shown in Table 4 for PSO algorithm and in Table 5 for modified differential evolution algorithm.

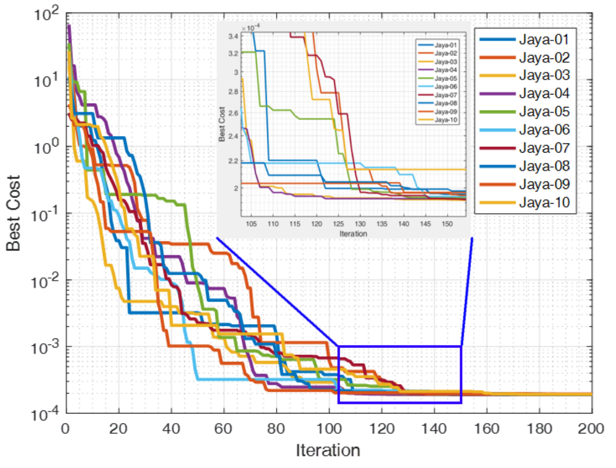

Fig.5. Optimization process of the objective function based on Modified Jaya Algorithm

Table 2. PMSM parameters determined based on Modified Jaya Algorithm

Modified Jaya Algorithm					
	Ld	Lq	R	λ	Tm
Run 1	0.835	0.8359	0.6987	0.1055	10.057
Run 2	0.835	0.8359	0.6987	0.1055	10.056
Run 3	0.835	0.8359	0.6987	0.1055	10.056
Run 4	0.835	0.8359	0.6987	0.1055	10.056
Run 5	0.835	0.8359	0.6987	0.1055	10.056
Run 6	0.835	0.8359	0.6987	0.1055	10.056
Run 7	0.835	0.8359	0.6987	0.1055	10.056
Run 8	0.835	0.8359	0.6987	0.1055	10.056
Run 9	0.835	0.8359	0.6987	0.1055	10.056
Run 10	0.835	0.8359	0.6987	0.1055	10.056
Average	**0.835**	**0.8359**	**0.6987**	**0.1055**	**10.056**

Table 3. Parameter values of algorithms for parameter identification

Parameters	Jaya Algorithm	MDE	PSO
Number of Population	50	50	50
Number of generation	200	200	200
Crossover rate	-	0.3	-
Scaling factor	-	0.9	-
C1;C2	1;0.4	-	1;1.5

Table 4. PMSM parameters determined based on PSO Algorithm

PSO					
	Ld	Lq	R	λ	Tm
Run 1	0.8374	0.8333	0.6986	0.1055	10.059
Run 2	0.8354	0.836	0.6987	0.1055	10.057
Run 3	0.8356	0.8456	0.6984	0.1056	10.065
Run 4	0.8339	0.845	0.6985	0.1055	10.061
Run 5	0.836	0.8339	0.6987	0.1055	10.057
Run 6	0.8339	0.8379	0.6987	0.1055	10.056
Run 7	0.8355	0.8465	0.6984	0.1056	10.065
Run 8	0.8355	0.8199	0.6991	0.1054	10.045
Run 9	0.8351	0.8373	0.6986	0.1055	10.058
Run 10	0.8361	0.8371	0.6986	0.1055	10.06
Average	**0.8354**	**0.8372**	**0.6986**	**0.1055**	**10.058**

Table 5. PMSM parameters determined based on MDE Algorithm

MDE					
	Ld	Lq	R	λ	Tm
Run 1	0.8351	0.8361	0.6986	0.1055	10.058
Run 2	0.835	0.8359	0.6987	0.1055	10.055
Run 3	0.835	0.8359	0.6987	0.1055	10.056
Run 4	0.835	0.8359	0.6986	0.1055	10.057
Run 5	0.835	0.8359	0.6987	0.1055	10.057
Run 6	0.835	0.836	0.6987	0.1055	10.055
Run 7	0.835	0.8359	0.6987	0.1055	10.056
Run 8	0.835	0.8358	0.6987	0.1055	10.056
Run 9	0.835	0.836	0.6987	0.1055	10.055
Run 10	0.835	0.8359	0.6987	0.1055	10.056
Average	**0.835**	**0.8359**	**0.6987**	**0.1055**	**10.056**

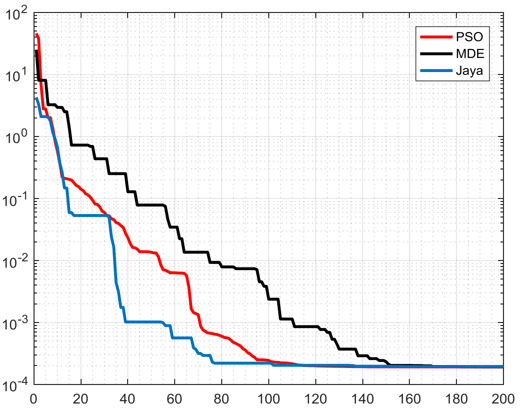

Fig. 6. Comparative optimization process of the fitness function of proposed MJA, MDE and PSO

Based on optimization process of proposed Modified Jaya Algorithm, modified differential evolution MDE algorithm and PSO algorithms presented in Fig.6, it is evident to check that the convergence rate of proposed Modified Jaya Algorithm seems quite better than others, with the smaller fitness function values. The proposed MJA method requires only 75 iterations to attain the optimum fitness value in comparison with 110 iterations in case PSO and 155 iterations in case MDE algorithm. It means that the proposed Modified Jaya approach obtains the best performance in PMSM parameter identification problem.

V. CONCLUSIONS

This paper proposes a new approach for PMSM parameter identification based on novel modified Jaya algorithm (MJA). Via the simulation results of PMSM parameter identification, proposed MJA method demonstrates that this approach is quite suitable for PMSM parameter identification and strongly improves the accuracy of estimated parameter. Furthermore in order to enhance proposed algorithm performance, in the next research, the author will try to adjust crossover rate and mutant factor as to obtain more accurate identification results.

VI. ACKNOWLEDGEMENT

This research is funded by Ho Chi Minh City University of Technology - VNU-HCM under grant number TNCS-ĐĐT-2017-05.

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NHẬN DẠNG THÔNG MINH NÂNG CAO THÔNG SỐ MÁY ĐIỆN PMSM SỬ DỤNG THUẬT TOÁN TỐI ƯU JAYA CẢI TIẾN

Phạm Quốc Khánh, Hồ Phạm Huy Anh

TÓM TẮT. *Bài báo đề xuất một phương pháp mới trong nhận dạng thông minh thông số máy điện PMSM dựa trên thuật toán tối ưu Jaya cải tiến (MJA). Hiệu suất của các hệ thống truyền động dùng động cơ PMSM phụ thuộc chủ yếu vào các bộ điều khiển PI. Các thông số của bộ điều khiển này được hiệu chỉnh dựa trên thông số cụ thể của các thông số có trên động cơ PMSM. Kết quả các thông số máy điện của PMSM dựa trên thuật toán nhận dạng thông minh, dựa trên thuật toán Jaya sẽ được dùng trong cải thiện hiệu quả hoạt động của tín hiệu ra khi so sánh với các thuật toán khác như thuật toán tiến hóa vi sai cải tiến hay thuật toán tối tối ưu hóa bầy dàn.*

Từ khóa: *nhận dạng thông minh; Máy điện đồng bộ nam châm vĩnh cửu; Nhận dạng thông số; Yaja cải tiến; Thuật toán tối ưu; thuật toán tiến hóa vi sai cải tiến; thuật toán tối tối ưu hóa bầy dàn.*