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PARAMETER ESTIMATION OF PERMANENT MAGNET SYNCHRONOUS MACHINES USING PARTICLE SWARM OPTIMIZATION ALGORITHM

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In this article, the particle swarm optimization toll (PSOT) is proceeded for solving the online parameters estimation of PMSM. The estimation procedure depends on the real measurement of motor current and speed. The competitive algorithms are assessed in terms of the closeness between estimated and actual parameters' which is considered the main target to be optimized in this work. Experimental verifications are carried out in Ecole Centrale de Nantes laboratories. The calculated results signify the effectiveness and reliability of the suggested tool. According to the results obtained, PSO has the capability and stability to calculate optimal values of PMSM parameters and then can calculate the performance of PMSM. The suggested PSO optimization tool leads to the highest closeness between estimated and experimental-based parameters. In addition, the POT is the outperformance optimization algorithm that gives the best values between the estimated and actual parameters.

1. INTRODUCTION

Permanent magnet synchronous machines (PMSM) are used in manufacturing because of the many features Compared with most other machines [1,2]. These machines are highly efficient and compact, and their control methods are well-advanced and robust. However, the disadvantage of this type of motor is the need for accurate knowledge of the position of the rotor to achieve a more efficient operation [3].

Modeling, simulation, and control of PMSM using FOC, two-level PWM rectifier, seven-level VSI cascade, vector control [4–6], current predictive control based on MRAS parameter identification [7,8], current control methods for dual three-phase PMSM considering machine parameter asymmetry [9,10], reduction of voltage surges by using optimal control [11], considering current harmonics and vibration [12], Takagi-Sugeno fuzzy logic control [13], a simple current-constrained controller [14], by using phase-shift PWM on dual ac winding to reduce motor vibration [15], verification and development of control technique for PMSM used to drive brake booster [16].

The PMSM takes advantage of high application efficiencies in industrial equipment, electric vehicles, domestic appliances, aerospace, and aircraft [1,17].

The PSO algorithm is one of the optimization algorithms. It is used in several applications like transformer parameter estimation [18], design and optimal operation of synchronous motor [19,20], multi-phase induction motor parameter estimation [21], of flux-weakening adaptive strategy using parameter optimization for PMSM drives [22].

The parameter estimation of PMSM is presented in [23–25] using windowed least square algorithm [26] super-twisting tool with online parameter estimation depending on sliding-mode observer for sensorless speed control, chaotic whale algorithm using for parameters estimation [27–29], whale optimization algorithm [30], a hybrid thermal model using for high-speed operation [31], multi-innovation least squares [32], on line parameters identification [33–36], off line parameter estimation [37], impact errors of parameter estimation on feed-forward control of current [38]. The electrical and mechanical parameters of PMSM using PSO is presented in [39], estimation of VSI-Fed PMSM parameters using a dynamic PSO and learning strategies [40].

This article proposes the PSO to estimate the optimal parameters for the PMSM model using laboratory tests [41]. In addition, PMSM parameters will be estimated using the online current and speed measurements. A closed loop of control drive using a PI controller in the speed regions has been proposed to work in flux weakening regions and fixed load torque. The results recorded from the simulation are four-speed regions, one zero speed and a second region for speed acceleration and third region for rated speed, and a fourth region for speed deceleration. The main features of this manuscript are mentioned as follows:

- This article suggested PSOT for online parameters estimation of PMSM,
- Parameter estimation of PMSM is achieved by carrying out physical experiments and speed control with the DSpace controller.
- The estimation work aims to investigate the good values of current and speed calculating by using dynamic modeling of PMSM.
- Experimental work is done on dynamic models of PMSM to investigate the online parameters estimated.

2. D-Q MODEL OF PMSM

Figure 1 shows the d-q dynamic model of PMSM. The PMSM sinusoidal three-phase voltages can be written as [4]:

$$v_{as} = V_m \sin(\omega t), \tag{1}$$

$$v_{bs} = V_m \sin\left(\omega t - \frac{2\pi}{3}\right), \tag{2}$$

$$v_{cs} = V_m \sin\left(\omega t - \frac{4\pi}{3}\right). \tag{3}$$

The stationary reference frame expresses about *dq*-axis reference frame [34]. Therefore, the voltage components in the d-q axes can be reformulated as:

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$$V_{qs}=\frac{3}{2}\left[\sum_{k=1}^{3} v_k \cos\left(\theta-\frac{(k-1)\pi}{2}\right)\right], \quad (4)$$

$$V_{ds}=\frac{3}{2}\left[\sum_{k=1}^{3} v_k \sin\left(\theta-\frac{(k-1)\pi}{2}\right)\right], \quad (5)$$

where: k is the phase number, V_m is the maximum amplitude voltage.

Figure 1 gives the equivalent circuit of the PMSM in the rotor reference frame $\omega_r\psi_{qs}$.

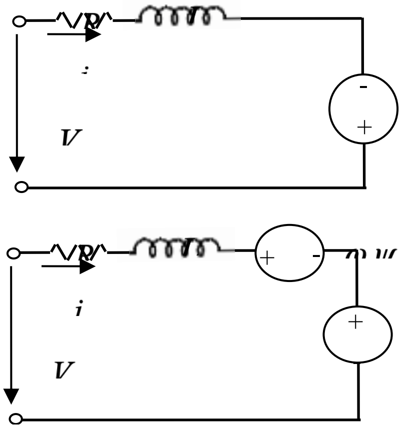

Fig. 1 – Direct and quadrature- axis equivalent circuits of PMSM.

From q-axis equivalent circuit in Fig. 1, the current i_{qs} and flux ψ_{qs} components is written as [5,42,43]:

$$\psi_{qs}=\frac{1}{s}\left[V_{qs}-R_a i_{qs}-\omega_r\psi_{ds}\right], \quad (6)$$

$$i_{qs}=\frac{1}{L_{qs}}\left[\psi_{qs}\right], \quad (7)$$

where: R_a stator resistance, L_{qs} is the stator quadrature inductance.

From the d-axis equivalent circuit in Fig. 1, the current and flux components of PMSM are written as:

$$\psi_{ds}=\frac{1}{s}\left[V_{ds}-R_a i_{ds}+\omega_r\psi_{qs}\right], \quad (8)$$

$$i_{ds}=\frac{1}{L_{ds}}\left[\psi_{ds}-\psi_m\right], \quad (9)$$

L_{ds} is the stator direct inductance. The motor torque T_e and speed n_r components are expressed as follows:

$$T_e=\frac{3}{2}\frac{p}{2}\left[\psi_{ds}i_{qs}-\psi_{qs}i_{ds}\right], \quad (10)$$

$$\omega_r=\frac{p}{2}\frac{1}{s}\left[\frac{1}{J}\left(T_e-T_L-B\frac{2}{p}\omega_r\right)\right], \quad (11)$$

$$n_r=\frac{2}{p}\frac{60}{2\pi}\omega_r, \quad (12)$$

where: p is the motor poles, J motor moment of inertia, B is the viscous friction coefficient, ω_r is the angular speed.

3. **PROPOSED PSO ALGORITHM**

The PSO algorithm is designed to enumerate random values and seek to update them by particle updating. In PSO, the proposed particles move through the desired space following the optimum particles before updating [18,20].

In PSO, several random results in the desired area towards the desired value by applying several trials based on significant data about the desired area, that is, participation by all swarms. The particle's position is modified by the particle's current position and moved to a new location. Each particle motion can be represented as a two-dimensional motion that indicates the value found through personal and group numbers. PSO algorithm relies on the particle's basic data from personal and group knowledge related to the particle's current position. The PSO update equation value is written as [6]:

$$\begin{gathered}\Delta v_{k+1}=v_k.\Delta v_k+c_1r_1(x_k^{best}-x_k)+c_2r_2(x_k^{gbest}-x_k),\\ x_{k+1}=x_k+\Delta v_{k+1}.\end{gathered} \quad (13)$$

The velocity updated of control variables at iteration number k is written as:

$$v_k=v_k^{\max}-(v_k^{\max}-v_k^{\min})\times k/Iter^{\max}, \quad (14)$$

where c_1 and c_2 are the learning coefficients expressing the weight of the best personal and global solutions factor, and each value adjusts its place in the update eq. (15). The PSO updating formula is shown in eq. (13) as for the place and value of the transfer, it shall be notified of the minimum and maximum transfer values as follows:

$$\Delta x^{\min}\le\Delta x_k\le\Delta x^{\max}, \quad (15)$$

where $\Delta x^{\min},\Delta x^{\max}$ are defined as:

$$\begin{gathered}\Delta x^{\max}=k_m(x_k^{\max}+x_k^{\min}),\\ \Delta x^{\min}=k_m(x_k^{\max}-x_k^{\min}).\end{gathered} \quad (16)$$

The PSO parameters estimation steps of PMSM are:

1) *Entering:* the PMSM constraints, limits, and the coefficients of PSO toll (inertia – factors),
2) *Calculated:* run the dynamic model of the PMSM motor using the parameter limits and calculating the objective function (17) and choose the minimum value of the objective function.
3) *Determining:* the PMSM parameters stator resistance, direct inductance, and quadrature inductance.

Figure 2 explains the flowchart for PSO optimization algorithm steps for the PMSM.

4. **PARAMETER ESTIMATION OF PMSM**

The objective function of the online parameter estimation of PMSM aims to reduce the error value between the readings of the instruments and the estimated current and speed. The optimized parameters, R_a, L_d, and L_q are affecting eqs. (6)-(12) to obtain the PMSM performance.

The computed values are needed to converge with the actual reading of current and speed. To achieve the convergence of the problem, the collection of absolute values for error (CAE) between real reading and optimized values must be low as possible. The objective function error used to estimate the parameter of PMSM using PSO optimization algorithm is expressed as:

$$CAE=(I_{\alpha A}-I_{\alpha E})^2+(I_{\beta A}-I_{\beta E})^2+(n_A-n_E)^2. \quad (17)$$

The problem equation can be written as

$$DE=\min(CAB). \quad (18)$$

Use Clarke's Transformation to convert abc current to alpha and beta [44,45]:

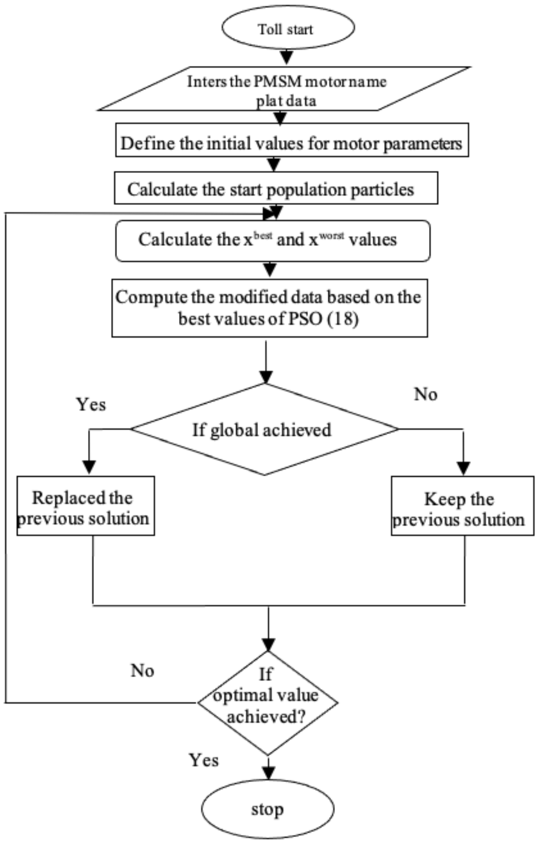

Fig. 2 – PSO Optimization toll Flowchart

The resulting transformation is

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} . \quad (19)$$

5. PMSM STRATEGY OF CONTROL

The speed and current closed loop using vector control strategy are specified by its good accuracy and simplicity of PMSM. The proposed PID controller has two main functions; the first is responsible for controlling the PMSM speed, and the second is for direct and quadrature current control. Figure 3 shows the schematic block diagram of the suggested vector closed-loop speed and current control for the PMSM.

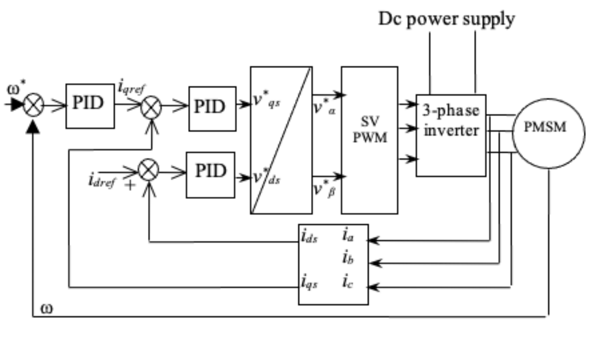

Fig. 3 – Schematic block diagram of control system.

6. APPLICATIONS

The optimal current achieves the validation of the PSO algorithm and speed estimation of PMSM referred to as the speed and current measurements. PMSM details are tested in Ecole Centrale de Nantes laboratories as studied cases.

Case study: 380 V, 50 Hz, 6-pole three-phase PMSM: the experimental work Photograph is located at Ecole Centrale de Nantes laboratories and is shown in Fig. 4. Table 1 represents the experimental parameters of PMSM.

Table 1

Actual data of three-phase PMSM

Variables	Value	Variables	Value
Voltage (V)	220	P	6
R_s (Ω)	0.45	J (kg.m^2)	0.00609
L_d (H)	0.0038	ψ_m (Wb. turns)	0.14
L (H)	0.0038		

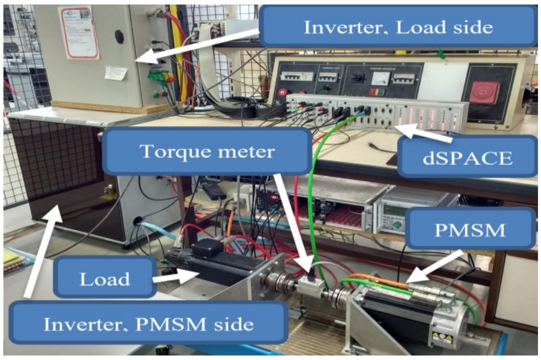

Fig. 4 – Experimental setup of system under study.

In this work, the actual data of three-phase PMSM have been obtained using the experimental tests. The PMSM parameters have been estimated using the actual measurements of motor current and speed by the proposed algorithms PSOT compared to the actual parameters.

The estimated values are used to compute the PMSM current, and speed at variable-load conditions. Table 2 shows the comparison between the optimal estimated parameters and the actual parameters in two cases.

Table 2

Optimal parameters Case1 and Case2

Algorithm	Case 1		Case 2	
	Actual	PSO(99)	Actual	PSO(200)
R_s (Ω)	0.45	0.4553	0. 675	0.6719
L_d (H)	0.0038	0.0038	0.0038	0.0038
L_q (H)	0.0038	0.0038	0.0038	0.0038
Average error (%)	0	2.07×10^{-4}	0	2.05×10^{-4}

To achieve the performance of the suggested PSO toll, the complete dq dynamic model of PMSM mentioned before is computed using MATLAB Simulink. The dynamic model simulation is run at different speeds and mechanical loading values. The parameters estimated for PMSM are plotted versus the number of iterations, as shown in Fig. 5–11. The PSO optimization toll runs with 200 iterations in the swarm and 60 populations.

Figure 5 shows the resistance of stator winding versus the number of iterations. The resistance values have two case studies, case 1 normal resistance, and case 2 increased resistance by 50 % from its rated value. Related to temperature increases, the resistance of stator winding is increased by 50% over the nominal value. The estimated value corresponds with the actual value only after 100 iterations.

The resistance of stator winding versus the number of iterations is plotted in Fig. 5, and Fig. 6 shows that the parameter estimation is near to actual values at iteration number 45. Further, when the resistance of a stator winding is assumed to be raised by 50 % from its rated value (due to the temperature increase of stator windings due to copper losses), the parameters computed from the optimization toll are close to the actual parameters after iterations number 25. The forecast of direct and quadrature inductances (L_d and L_q) is shown clearly in Fig. 6 and 7. The PSO algorithm in the dynamic process converges faster with less oscillation to give the best results.

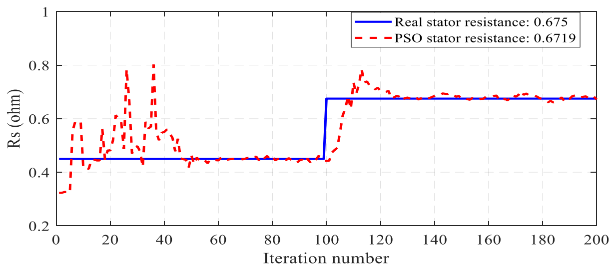

Fig. 5 – Stator resistance.

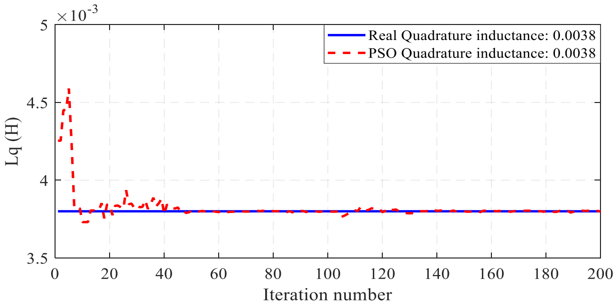

Fig. 6 – Quadrature inductance

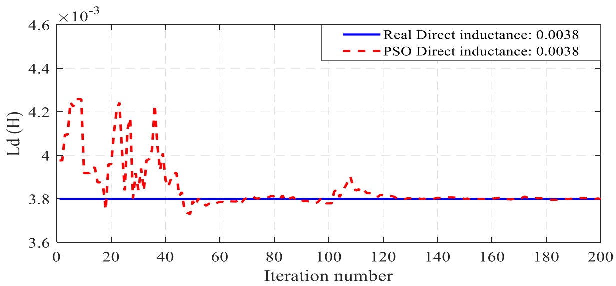

Fig. 7 –Direct inductance.

Figure 8 shows simulated values computed using estimated parameters of the motor current, speed, and torque versus time at the end iteration of case 1 (normal stator resistance value 0.45 Ω and iteration No. 99). From this figure, the parameters estimated of PMSM (current, speed and torque) the simulated parameters have a slight error and a significant affinity between the optimized and the actual values. Figure 9 shows three axes drawing of parameters stator resistance, direct inductance, and quadrature inductance at the end of case one (iteration No. 99), and the global best fitness value is 2.07×10^{-4}.

Figure 10 shows simulated values computed using estimated parameters of the motor current *Is*, motor speed *Nm* and load torque T_L versus time at the end iteration of Case 2 (normal stator resistance value 0.675 Ω and iteration No. 200).

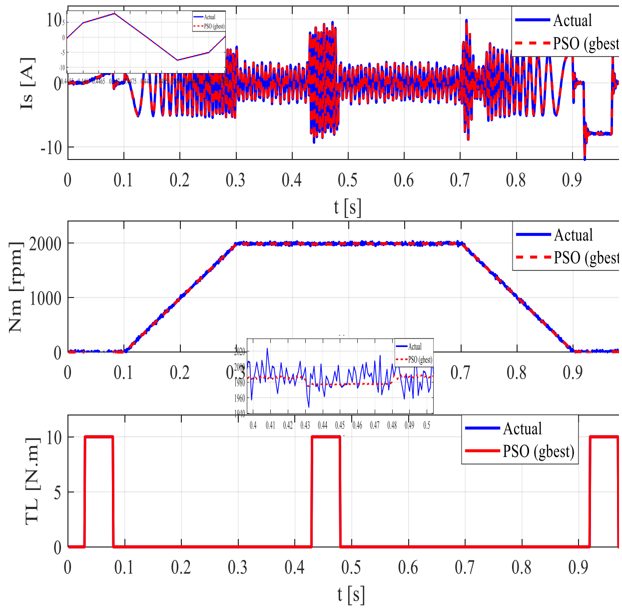

Fig. 8 – Current, speed and torque characteristics of case 1

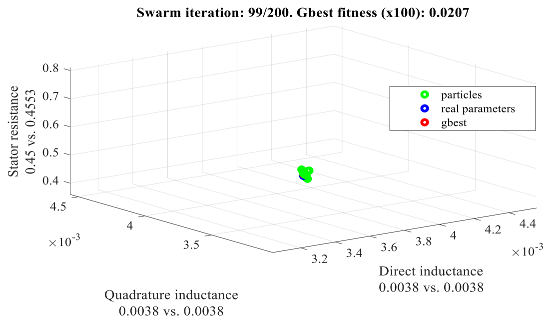

Fig. 9 – Global beast values at iteration 100 of case 1.

From this figure, the parameters estimated of PMSM (current, speed and torque) the simulated parameters have a slight error and a significant affinity between the optimized and the actual values. Figure 11 shows three axes drawing of parameters stator resistance, direct inductance, and quadrature inductance at the end of case 2 (iteration No. 200), and the global best fitness value is 2.05×10^{-4}.

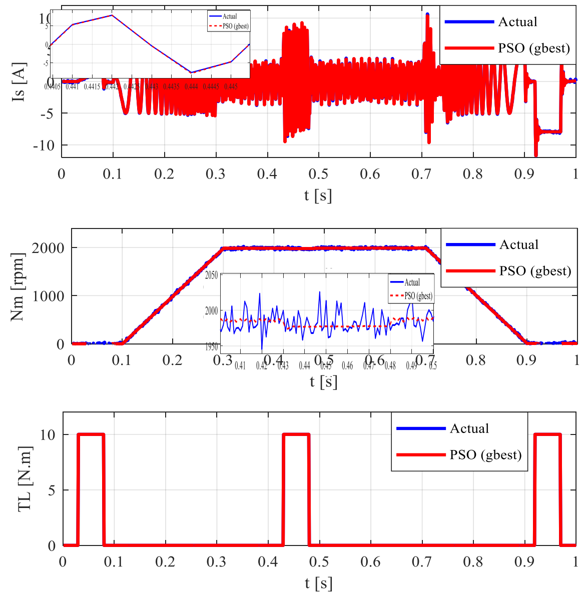

Fig. 10 – Current, speed and torque characteristics of Case 2.

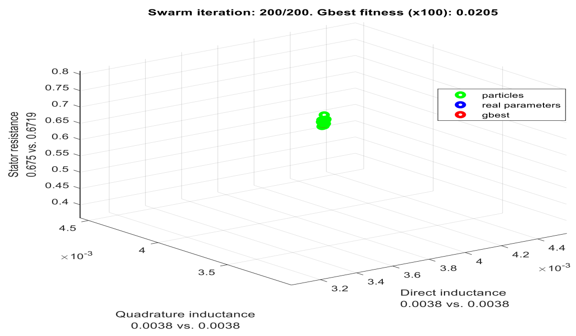

Fig. 11 – Global beast values at iteration 200 of case 2.

Figure 12 shows the experimental dynamic operation of speed, speed error, and torque for PMSM. This figure shows clearly that the PMSM speed is very close to the reference speed value and have small error values of less than 10 rpm in all operating range. Table 2 shows the comparative values between the estimated value using PSO algorism and actual parameters value.

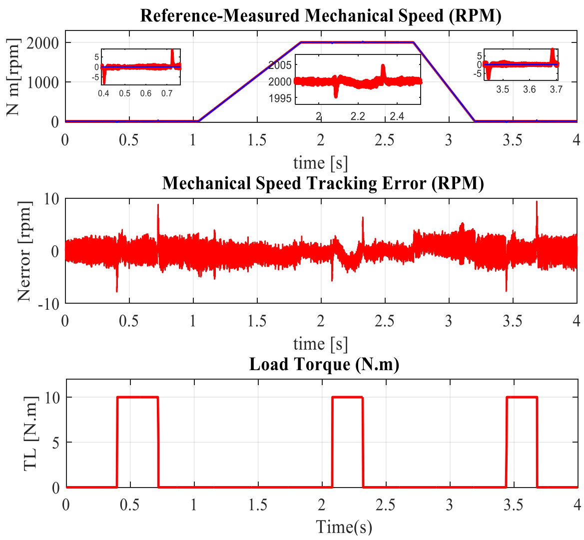

Fig. 12 – Experimental speed, speed error and load torque time characteristics

7. CONCLUSIONS

In this article, a PSOT optimization algorithm for online parameter estimation is proposed and compared with the real values for the exact model of PMSM. The estimated parameters of the PSO algorithms are used to estimate the operational performance of PMSM at different values of speeds and different values of mechanical loading. The results obtained using the estimation of the parameters by the PSO tool were compared with those obtained using the real parameters of the equivalent circuit. The high convergence between the results obtained from the model proposed by PSOT for estimating parameters with the results obtained from the actual model indicates the efficiency of the proposed model for estimating parameters for PMSM under online operation. PSOT is given smooth, stable, and fast convergence. According to the values that were calculated with the proposed algorithms, it was found that the PSOT has a great ability to calculate the optimal parameters under operation for PMSM. It is proved that the parameter estimation gives the best approximation, as it was found that the average error rate for the first case at iteration number 99 was 2.07×10^{-4}, while it was found that the average error for the second case at the 200th iteration is 2.05×10^{-4}. In the end, it can be concluded that the use of PSOT gives the best results in simplicity, efficiency, and stability, and this is based on the results obtained that in the first case, the program began to stabilize at the actual values at the 45th iteration, while in the second case the stability was faster at the 25th iteration after resistance change.

CONFLICT OF INTEREST

The authors have no conflicts of interest, and this article has not been sent for publication anywhere.

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