Optimized Field Oriented Control Design by Multi Objective Optimization

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***Abstract*—Permanent Magnet Synchronous Motors are popular electrical machines in industry because they have high efficiency, low ratio of weight/power and smooth torque with no or less ripple. In addition to this, control of synchronous motor is a complex process. Vector control techniques are widely used for control of synchronous motors because they simplify the control of AC machines. In this study, Field Oriented Control technique is used as a speed controller of a Permanent Magnet Synchronous Motor. The controller must be good tuned for applications which need high performance, and classical methods are not enough or need more time to achieve the requested performance criteria. Optimization algorithms are good options for tuning process of controllers. They guarantee finding one of the best solutions and need less time for solving the problem. Therefore, in this study, Tree-Seed Algorithm is used for tuning process of the controller parameters and the results show that Tree-Seed Algorithm is good tool for controller tuning process. The controller is also tuned by Particle Swarm Algorithm to make a comparison. The results show that optimized system by Tree-Seed Algorithm has good performance for the applications which need changing speed and load torque. It has also better performance than the system which is optimized by Particle Swarm Optimization algorithm.**

Keywords—Permanent magnet synchronous motor; field oriented control; speed controller; tree-seed algorithm; optimization

I. Introduction

Permanent magnet synchronous motors (PMSM) are widely used in industry. Some of the application areas are robotics, aviation and aerospace, renewable energy, motion control etc. They have high efficiency, low ratio of weight/power and smooth torque with no or less ripple. Especially high efficiency makes it a good choice for applications which has limited energy. PMSMs maximize the performance in the applications which need variable speed [1].

PMSM has some motor loses like cooper loss, mechanical loss and iron loss. These loses are must be minimized for high efficiency and there are many studies which are focused on optimized motor design [2], [3]. However, efficiency is not only related to optimal design. The control strategies for speed or position control of a PMSM also must be optimal. There are different control strategies like i_d=0 control, maximum torque per ampere (MTPA) control, maximum speed per ampere or voltage (MSPA, MSPV) control, unity power factor (UPF) and loss model control (LMC). The advantage of i_d=0 control strategy is linear relationship between the electromagnetic torque and q axis current [4]. It is generally used for surface mounted PMSMs and prevents the magnets from damage. MSVP control has an effect on the iron loss by minimizing the terminal voltages of the windings [5]. The advantage of MTPA control is the minimum cooper loss because of the reduced armature current [6], [7]. LMC control decreases the iron and cooper losses and it can be said that it is an optimal technique for PMSMs [8], [9]. UPF control does not have any effect on the efficiency [10].

The control strategies mentioned above are frequently used with vector control methods. Field Oriented Control (FOC) is the most known vector control technique [11], [12]. In FOC, Stator phases are transformed in to d and q axes by Clark and Park's transformations. Then i_d and i_q currents are controlled independently. Transformations used in FOC need rotor position. An encoder can be connected to the motor or sensorless techniques can be used. Another vector control technique is Direct Torque Control [13]. The torque and stator flux are controlled directly using a switching table which is independent from the current controllers. Voltage Vector Control, Passivity Based Control and Nonlinear Torque Control are some other vector control techniques.

All PMSM control strategies use one or more controller like PID, Fuzzy, Backstepping, etc. All of them have some parameters, which affect the controller performance, and must be well tuned. Therefore, the optimization algorithms are an important tool for achieving a good controller performance by adjusting the controller parameters. There are many types of optimization algorithms in literature and algorithms which use stochastic approach are much popular. Genetic Algorithm is one of the popular ones which used for controller optimization [14]. Particle swarm algorithm [15], Grey Wolf Optimizer [16] and Krill Herd algorithm [17] are some other alternatives for controller optimization of PMSMs.

In this study, a PMSM is modelled and a speed controller is designed using FOC technique. There are three PI controllers in the used technique and they must be well tuned for an acceptable performance. Tree-seed algorithm, which is a novel and nature inspired optimization technique, is used for tuning of the controller parameters. A robust FOC controller is obtained using TSA. It has a good performance in the applications which cover changing of speed and load torque. Particle Swarm Algorithm, which is widely used in controller optimization studies, is also used for comparing with the TSA optimized system.

II. PMSM and Field Oriented Control

Permanent Magnet Synchronous Motor (PMSM) is electrical machine which produces rotational movement by the rotor. Its stator has windings and its rotor has permanent magnets which provide the field excitation. The permanent magnets provide a constant magnetic field in the air gap. There are two types of PMSM as surface mounted and interior permanent magnet (IPM). IPMs are the most used type of PMSMs. PMSMs need electronic commutation for controlling the currents in the windings because of its structure. The structure of a PMSM is given in Fig. 1. Its windings are placed on the stator and the commutation is made by an external circuit. The commutation circuit is a three phase switching invertor. PMSMs should be commutated with a three phase sinusoidal current, which has a 120° phase shift between the phases, for producing a smooth torque. A circuit diagram of three phase invertor circuit is given in Fig. 2. Transistors are driven by PWM signals or space vector modulation (SVM) to produce required three phase currents.

The currents which produce the flux and torque are orthogonal in DC motors. Thus, controlling the flux and current independently is possible. However, the rotor and stator fields are not orthogonal in AC machines. Only, the stator current can be controlled, but it is possible to control an AC motor like a DC motor. Field Oriented Control (FOC), one of the vector control techniques, is a technique that can be used to control the torque and flux independently in AC motors. It also transforms the complex AC model into a simple linear model. FOC has some other advantages like fast dynamic response and high efficiency.

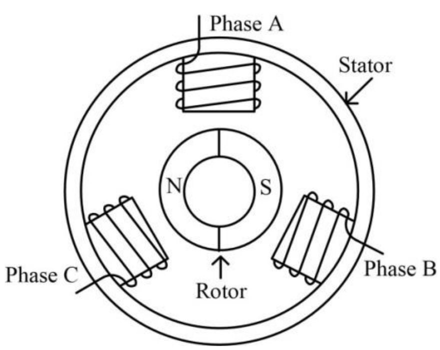

Fig. 1. Basic Structure of PMSM.

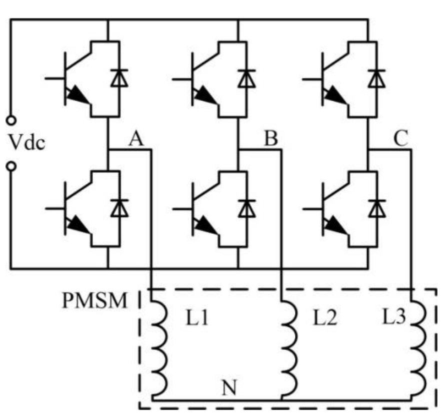

Fig. 2. Three Phase Invertor Circuit for PMSM.

Three reference frames given in Fig. 3 are used in FOC. First one is the stator reference (a,b,c) frame which has three vectors with 120° difference between each of them. Second one is the orthogonal reference frame (α, β) which has 90° between two axes and one of the axes is aligned with the "a" axis. The last one is the rotor reference frame (d, q) which has 90° between two axes. One of the axes placed along the N and S poles or aligned with the flux vector. If stator reference system is used, the amplitudes of the windings will change with time. So the calculations in the stator reference frame get complex with the three time varying vector. d and q reference system which is obtained from a, b, c reference system is used to overcome this problem.

Clark and Park's transformation, which are given in (1) and (2) [18], [19] are used for transformations between three and two phase reference systems. θ is the angle between d and α. After the transformation from stator reference frame into rotor reference frame, torque and flux can be controlled independently by any controller. The output of the controller is the voltage for each axis. The output voltages must be transformed back to the stator reference frame and then it can be applied to the motor. Invers park transformation is also given in (3).

$$\left.\begin{aligned} I_\alpha &= I_a \\ I_\beta &= \tfrac{1}{\sqrt{3}} I_a + \tfrac{2}{\sqrt{3}} I_b \\ 0 &= I_a + I_b + I_c \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} I_d &= I_\alpha \cos(\theta) + I_\beta \sin(\theta) \\ I_d &= I_\alpha \cos(\theta) + I_\beta \sin(\theta) \end{aligned}\right\} \quad (2)$$

$$\left.\begin{aligned} V_\alpha &= V_d \cos(\theta) - V_q \sin(\theta) \\ V_\beta &= V_d \sin(\theta) + V_q \cos(\theta) \end{aligned}\right\} \quad (3)$$

A general block diagram of FOC is given in Fig. 4. Firstly, the phase currents of the motor are measured. They are transformed to α and β by Clarke transformation. Then, α and β are transformed into d and q coordinate system by Park transformation. Stator current and flux can be controlled by any controllers. The outputs of the controllers are voltages of d and q axes. Voltages are transformed back from d and q coordinate system into α and β coordinate system. Finally, phase voltages are produced using the voltages in α and β coordinate by space vector modulation technique.

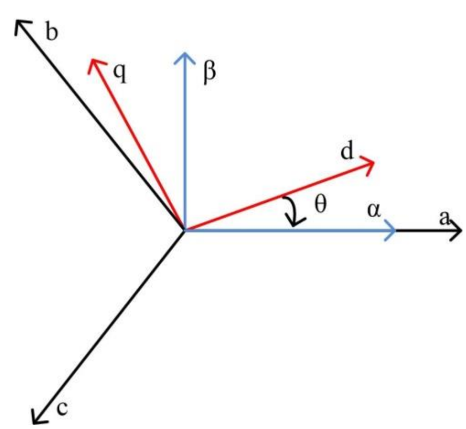

Fig. 3. Two and Three Phase Reference Systems.

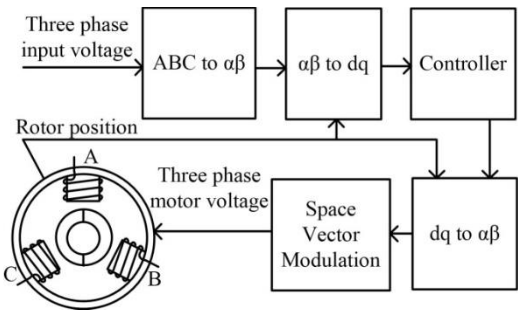

Fig. 4. General Block Diagram of FOC.

Modelling a PMSM in the rotor reference frame (d/q) is also possible. Equivalent circuit in d and q reference frame is given in Fig. 5 and Fig. 6. [20]. R_s is the stator resistance, L is the stator inductance, ω_r is the mechanical rotor speed, λ is the magnetic flux of the rotor, V_d is the direct input voltage and V_q is the quadrature input voltage. Subscripts d and q refer to the d and q axes.

The mathematical model of PMSM in the d-q coordinates is given in (4) - (7) [20]–[22]. I_d and I_q are respectively direct current and quadrature current, T_L is the load torque, T_e is the electromagnetic torque, p is the number of the pole pairs, B is the friction coefficient, J is the moment of inertia of the rotor, ω_r is the mechanical speed in rad/s, ω_m is the electrical speed, λ_d and λ_q are is the total flux of stator and λ_r is the flux created by the rotor.

$$\frac{di_d}{dt} = \frac{V_d}{L_d} - \frac{R_s I_d}{L_d} + \frac{L_q \omega_r i_q}{L_d} \quad (4)$$

$$\frac{di_q}{dt} = \frac{V_q}{L_q} - \frac{R_s I_q}{L_q} + \frac{L_d \omega_r i_d}{L_q} - \frac{\lambda_r \omega_r}{L_q} \quad (5)$$

$$\frac{d\omega_m}{dt} = \frac{1}{J}(T_e - B\omega_m - T_L) \quad (6)$$

$$\omega_r = p\omega_m \quad (7)$$

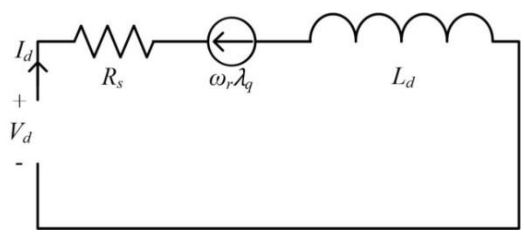

Fig. 5. Dynamic Model of PMSM in D axis.

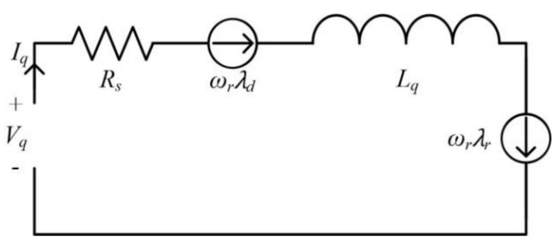

Fig. 6. Dynamic Model of PMSM in Q axis.

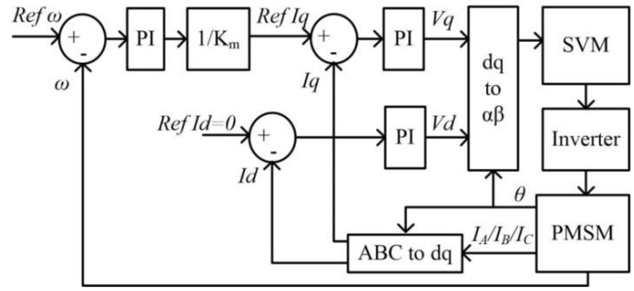

Fig. 7. Speed Control of PMSM by FOC.

Structure of FOC for speed control is given in Fig. 7 [19]. Difference of the reference speed (Ref ω) and motor speed is input for the speed controller. The output of the speed controller is reference torque and the torque is K_m*I_d. K_m is the torque constant of the motor. Reference I_q is obtained by dividing the reference torque, which is the output of the speed controller, by K_m and it is compared with the actual I_q current. The error is the input for the PI controller which determines the V_q voltage level for obtaining the required torque. Third controller is used for determining the V_d voltage level using the reference I_d and actual I_d currents. The reference I_d current equals to zero. The determined V_d and V_q voltages are transformed into d/q reference frame and it is used to produce three phase motor voltages by space vector modulation and inverter circuit. Measurements of I_d, I_q, rotor position and rotor speed are also made continuously for controllers' feedbacks. θ is the rotor position.

III. Tree-Seed Optimization Algorithm

Tree-seed optimization algorithm is a novel, population based, heuristic algorithm which has been improved for continuous optimization problems [23]. In nature, new trees are generated by the seed of the young or old trees. When a seed fall to the ground, it starts to grow up and becomes a tree which can produce new seeds after a while. Every tree produces random number of seeds and they fall to random positions on the ground. Therefore, the new trees are positioned randomly around the tree which produces the seeds. Of course, some of the seeds or trees can't survive, and die in the nature. Trees can spread over large areas by using this mechanism.

TSA algorithm was inspired from the spreading mechanism of trees. The algorithm is population based and the population number must be determined at the beginning of the algorithm. Positions of trees and seeds are the possible solutions of the optimization problem. Each tree generates random number of seeds. The number of the generated seeds is between the minimum and maximum bounds. Minimum number of the seeds is 10% of the population size and maximum number of the seeds is 25% of the population size. Ratios of maximum and minimum seeds number are determined for high performance in [23]. The objective function is evaluated on each iteration. If the position of a seed is better than the position of which tree generates the seed, then, the seed substitutes for the tree.

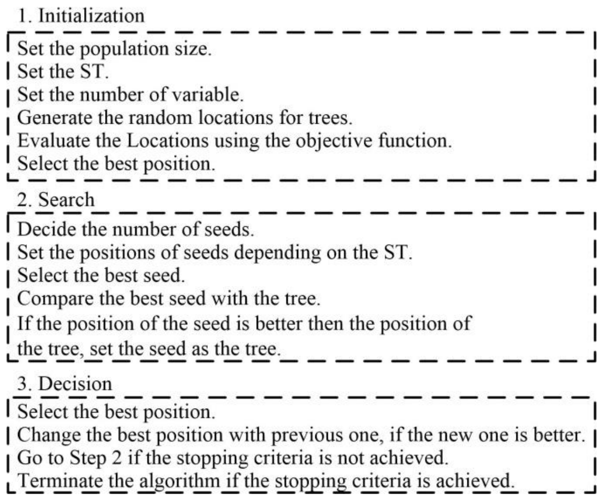

Fig. 8. Basic Structure of Tree-Seed Algorithm.

Seed generation process is the most important part of TSA. The positions of new generated seeds are dependent on a parameter named as search tendency and it is in the range of 0 and 1. A higher value of search tendency means a powerful local search and fast convergence. A lower value of search tendency means a powerful global search and slow convergence [23].

Basic structure of the TSA is given in Fig. 8. Firstly the initialization parameters like population size and ST are set. Search process starts after the first step. New seeds are generated and all positions are evaluated. If the stopping criteria are achieved, the algorithm is terminated and results are reported. If the stopping criteria are not achieved, the search step is repeated. Detailed information about TSA can be found in [23].

IV. Experimental Study

In this study, a PMSM is modelled; a speed controller is designed using FOC technique and PI controllers. All controllers are optimized for high performance by TSA. The controllers are also compared with a reference system which is optimized by PSO which is a popular and widely used optimization algorithm in controller optimization studies. Simulation of the motor model, controllers and optimization processes are made by MATLAB program.

The motor model is obtained using the PMSM equations which are given in (4) – (7). The motor parameters, which are used in simulations, are R_s=3.658 Ω, L_d=L_q=0.1496 *H*, *p*=2, *B*=0.00405; *J*=0.004 $kg.m^2$; *λ*=0.7 *Wb*. The used control schema is also given in Fig. 7. Three PI controllers are used for control of speed, i_d and i_q currents. An objective function which is given in (8) is used for the optimization process. This is a multi-objective optimization process because six parameters of three controllers are optimized simultaneously. The first three terms is the integral of absolute errors, ST is the settling time and OS is the overshoot value of the speed. The coefficients of the objective function are determined by trial-and-error method. The coefficients are a=5, b=50 and c=60.

$$f = \int_0^t |e_{wr}|\, dt + \int_0^t |i_q|\, dt + a\int_0^t |i_d|\, dt + bST + cOS \qquad (8)$$

The number of function evaluation for TSA and PSO is set as 3000. The ranges of the controllers' coefficients are set as 0-100. The best results are given below and compared for speed, i_q and i_d currents. ST measurements are made with 2% tolerance. Speed graphs of the motor are given in Fig. 9. As it is seen, TSA-optimized FOC has a good performance. Its settling time is 0.344s and the settling time of PSO-optimized FOC is 0.527s. The overshoot of TSA-optimized FOC is 3.873%, and the overshoot of PSO-optimized FOC is 4.710%. PSO-optimized system has 53.198% more settling time and 21.611% more overshoot than TSA-optimized system. The i_d and i_q current graphs are given in Fig. 10 and Fig. 11. Integral of the i_q currents are equal, they round about $2.4.10^3$. Integral of i_d currents are 43.97 for TSA-optimized system and 57.12 for PSO optimized system. Reference of i_d current is 0 in FOC technique which is used in this study and PSO-optimized system has 29.91% more total current value than TSA optimized one.

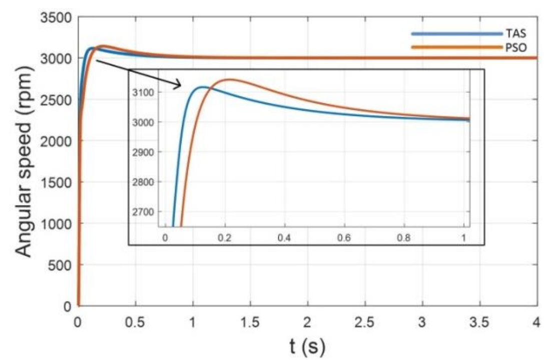

Fig. 9. Speed Graphs for TSA and PSO Optimized System.

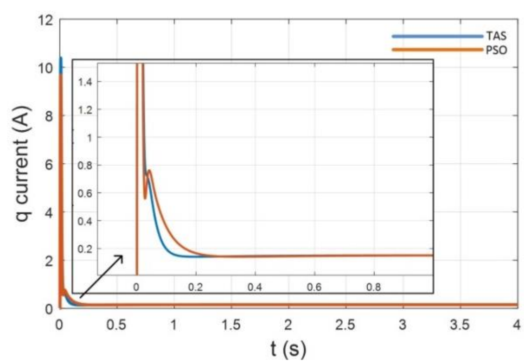

Fig. 10. IQ Currents for TSA and PSO Optimized System

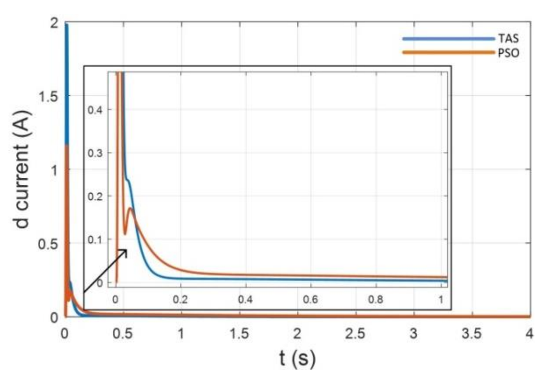

Fig. 11. ID Currents for TSA and PSO Optimized System.

The system is also analysed under the state of speed change and load torque change. Reference speed is set as 3500 in the third second and load torque is set as 6Nm in the sixth second. When the seeped reference and load torque are increased, TSA-optimized system has more overshoot but less settling time than PSO-optimized one, as seen in Fig. 12.

The graphs of i_q and i_d currents are also given in Fig. 13 and Fig. 14. Integral of i_q current of each optimized system is about the same as $2.82.10^4$. Integral of i_d currents are $1.028.10^3$ for the TSA-optimized system and $1.333.10^3$ for the PSO-optimized system. As it is seen, TSA-optimize system has less integral of i_d current value than PSO optimized system.

Three phase currents of the motor are given for the state of the speed and load torque change in Fig. 15 and Fig. 16. The sudden current change resulting from the speed reference change can be seen at the third second in Fig. 15. In a similar manner, the current change resulting from the load torque change can be seen starting from the sixth second in Fig. 16.

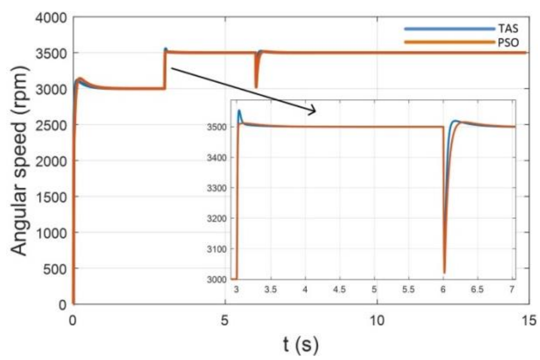

Fig. 12. Changes of the Speed Reference and Load Torque.

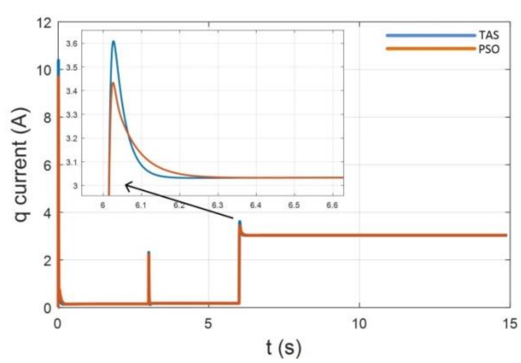

Fig. 13. IQ Currents While References Change.

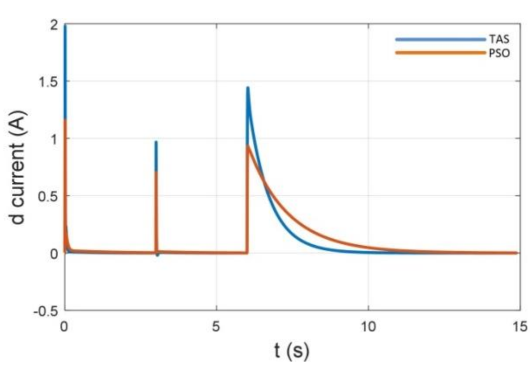

Fig. 14. ID Currents While References Change.

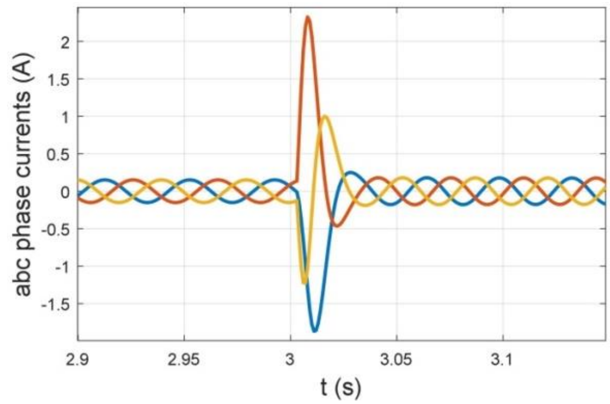

Fig. 15. Three Phase Currents While Speed Reference Changes.

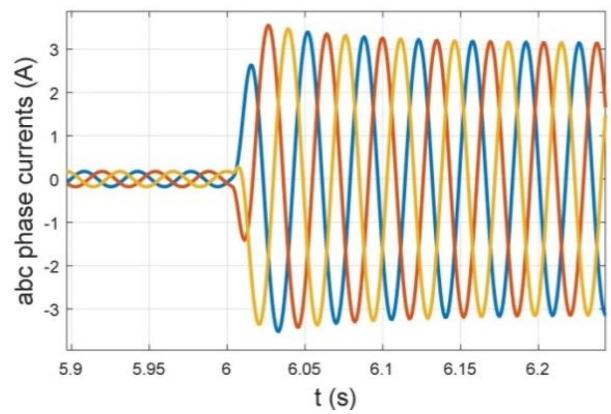

Fig. 16. Three Phase Currents While Load Torque Changes.

V. Conclusion

In this study, a PMSM is modelled and a speed controller is designed using FOC technique. The controller tuning process for high performance is modelled as a multi objective optimization problem and solved by TSA. It is also optimized by PSO for comparison. All study is made by simulations using MATLAB program.

The controller which is optimized by TSA has good speed control performance. Its settling time is 0.344s, and PSO optimized system has 53.198% more settling time then TSA-optimized system. The overshoot of TSA-optimized FOC is 3.873% and the overshoot of PSO-optimized FOC is 4.710%. PSO-optimized system has 21.611% more overshoot than TSA-optimized system.

When considered i_d current, it should be ideally 0, because the reference of i_d is 0 in the used FOC technique. Integral of the i_d currents are calculated for a comparison. They are 43.97 for TSA-optimized system and 57.12 for PSO optimized system. PSO-optimized system has 29.91% more total i_d current value than TSA optimized one.

The results show that TSA-optimized speed controller is better than PSO-optimized one. Although, the results may not be enough to decide which controller is better, they show that TSA is a good alternative for controller optimization processes of PMSM. A comparison study of TSA with other popular optimization algorithms is among the future plans of the author.

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