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ANALYSIS AND DESIGN OF A NONLINEAR TORQUE CONTROLLER FOR PMSM DRIVE SYSTEM - A LYAPUNOV TECHNIQUE APPROACH

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Abstract- Permanent Magnet Synchronous Motor (PMSM) drives become very popular in many industrial applications. The aim of this paper is design of effective and simple torque control by Lyapunov method for PMSM. The designed system includes specifications such as fast transient response, good stable response and acceptable accuracy. Overall stability is shown by using Lyapunov method. Lyapunov functions increases stability by getting of effective error penalty term. More attention in this paper focuses on this fact that by using control variables and building high-grade systems, we can bring system output to intended purpose step by step by Lyapunov functions in present of external loads and disturbances. In this paper, by choosing two Lyapunov functions and compare them, we show that choice of function is effective in method of disturbances damping and torque fluctuations control.

Keywords: Permanent Magnet Synchronous Motor, Lyapunov Function, Torque Control, Stability.

I. INTRODUCTION

Today permanent magnet synchronous machines are used as a serious challenger for DC or induction machine in applications of servo drive with high capability. The comparison of induction motors and Permanent Magnet Synchronous Motor (PMSM) that has not field winding shows a PMSM have better performance. PMSM compared to induction motors have advantages such as, power production with low cost and improvement of magnetic characteristics that is in inherent of each motor.

Because of advantages of these motors, they are used in servomechanisms that require fast and accurate torque response [1-2]. These motors have simpler structure, less weight and size and have higher efficiency due to reduction of losses [3, 4]. Generally we can talk about PMSM in two categories, adjustable speed drive system and position control system. Adjustable speed drive system has two control loops include current loop and speed loop. Most researchers have focused on this control system. The dynamic model of this motor because of the combination of motor speed and electrical quantities such as current of dq-axes is nonlinear.

PMSM motor drive system usually is controlled by the PI controller which has a simple structure. PI controller can not improve simultaneously transient stability and load disturbances [5-6]. Many papers can be found on application, control and simulation of the PMSM [7-8]. In [9] with comparison of back stepping, nonlinear sliding mode and the PI controller for speed control of PMSM fed by a three levels PWM voltage source inverter is presented. An accurate model includes all motor losses for an effective torque estimation based on voltage and current measurements presented in [10].

A generalized predictive control associated with a sliding mode control based on reference model control is proposed for PMSM system in [11] to the direct stator current and to the motor electromagnetic torque. Direct torque control with a PI controller for torque control an interior PMSM is used in [12], which the relationship between the gains of the PI controller and the torque response is derived based on the transfer function of the torque control loop. A direct torque control strategy using duty cycle optimization for matrix converter voltage vectors based PMSM drive system is proposed in [13], which is characterized by low torque ripples.

High-performance motors usually require fast and accurate answers that will improve quickly against any disturbances. Dynamic behavior of AC motor is introduced by using the vector control theory that moves motor variables to the dq-axes, one in direction of speed control and another in direction of torque control. The Lyapunov controllers are used widely in recent years [14, 15]. In addition, mainly is used in systems that have a triangular or series structure. A nonlinear adaptive state feedback controller for a PMSM is design in [16], which Lyapunov based analysis approach is used to determine stability and performance results.

An effective torque control for PMSM is presented in [17], which the Lyapunov functions used contain a term penalizing incremental energy of control error, torque and stator flux, enhancing stability. Applying the Lyapunov control method can meet control aims such as favorable and accurate torque. To achieve this purpose it is necessary to put the rotor flux value equal to a fixed nominal value. At the same time optimized magnetic circuit, has maximum efficiency [18].

Its mathematical model uses an alternating current AC, which includes several nonlinear ordinary differential equations with high degree. Therefore, fully controlled AC motor is a multi-input nonlinear system with phase's voltage inputs and the outputs are position or torque in the motor shaft. The new advances in modern control methods suggest that electrical motors controller is designed directly by nonlinear methods. Therefore, linear method of feedback requires complete and correct parameters and some of nonlinear benefits often are eliminated [19].

This method can eliminate a lot of property such as non-variable situations or sensitivity and dynamic response speed. The Lyapunov theory would be a tool for linearized of linear controller for long time. Therefore, by using the theory that is applied for nonlinear control has problem to find Lyapunov function in considered system. The considered system is stable if this function is found. An experience designer should do finding the function.

The aim of this paper is design of control rules for PMSM motors for achieving to good torque control in steady state and transient state. In addition, comparison two Lyapunov functions for PMSM motor control and demonstrate improvement of motor performance by using the new function. For applying Lyapunov functions we should be achieve term of route error integral penalty. In part II we will describe the PMSM motor model in state space. In part III nonlinear controlled torque and stability of this controller will be extracted. In part IV simulation results will be expressed. For validation the proposed controller and the overall results are expressed in part V.

II. PMSM MODEL

The usual way to control permanent magnet synchronous machine is conversion of voltage and current equations to synchronous form dq-axes. By using the theory of synchronous reference system, voltage, current, and inductance of each phase of PMSM are transferred to the two axes dq-axes. Dynamic equivalent circuit for PMSM motor is show in Figure 1. According to the theory of synchronous reference system, PMSM model in two axes dq is described as follows [20]:

$$\frac{d}{dt}\lambda_q = U_q - R_s i_q - \omega_s \lambda_d \tag{1}$$

$$\frac{d}{dt}\lambda_d = U_d - R_s i_d - \omega_s \lambda_q \tag{2}$$

$$\lambda_d = L_d i_d + \lambda_m \tag{3}$$

$$\lambda_q = L_q i_q \tag{4}$$

In PMSM simulation based on MATLAB, we will use closed loop control system that simulation model is based on $i_d = 0$. Electrical torque is as follows:

$$T_e = \frac{3}{2}\frac{p}{2}[(L_d - L_q) i_d \, i_q + \lambda_m i_q] \tag{5}$$

$$T_e = \frac{3}{2}\frac{p}{2}[\lambda_d i_q - \lambda_q i_d] \tag{6}$$

In addition, motor dynamic equation is as follows:

$$T_e = T_L + B_m \omega_m + J_m \frac{d}{dt}\omega_m \tag{7}$$

PMSM state equations to be defined as follows [21]:

$$\frac{d}{dt} i_d = -\frac{R_s}{L_d} i_d + \frac{L_q}{L_d} i_q \omega_s + \frac{1}{L_d} U_d \tag{8}$$

$$\frac{d}{dt} i_q = -\frac{R_s}{L_q} i_q - \frac{L_d}{L_q} i_d \omega_s + \frac{\lambda_m}{L_q}\omega_s + \frac{1}{L_q} U_q \tag{9}$$

$$\frac{d}{dt}\omega_m = \frac{3}{2}\frac{P}{2}\frac{\lambda_m}{J_m} i_q + \frac{3}{2}\frac{P}{2 J_m}(L_q - L_d) i_d i_q \tag{10}$$

$$-\frac{B_m}{J_m}\omega_m - \frac{1}{J_m} T_L \tag{11}$$

$$\frac{d}{dt}\theta_m = \omega_m \tag{12}$$

Figure. 1. Dynamic equivalent circuit for PMSM motor

III. NONLINEAR CONTROL DESIGN

According to model of torque that is as $T_e = (3/2)PKi_q$ can be said that i_q and T_e relationship is linear. In this paper to setting the speed, at first the initially rotor field current component i_d is kept constant then the speed is set by using current i_q. Therefore, reference current i_d should be considered zero. The proposed control system is designed to getting objective function, which is the most effective of torque. Input voltage ensures convergence of (i_q, i_d) to (i_q*, i_d*). When $i_d^* = 0$, the observed electromagnetic torque is directly proportional to current i_q*.

At first, we define the function of first Lyapunov as follow according to [22]:

$$U = \frac{1}{2}K_1\theta_d^2 + \frac{1}{2}e_d^2 + \frac{1}{2}K_2\theta_q^2 + \frac{1}{2}e_q^2 \tag{103}$$

The derivative of this Lyapunov function is defined as follow:

$$\begin{aligned}\dot{U} &= e_d (K_1\theta_d - \frac{U_d}{L_d} + \frac{R_s}{L_d} i_d - \omega\frac{L_q}{L_d} i_q + \\ &+ e_q (K_2\theta_q - \frac{U_q}{L_q} + \frac{R_s}{L_q} i_q + \omega\frac{\varphi_m}{L_q}\end{aligned} \tag{114}$$

For public simultaneously stability in current loop, the produced control voltages d-q are as follow:

$$U_d = K_d L_d e_d + K_1 L_d \theta_d + R_s i_d - \omega L_q i_q \tag{125}$$

$$U_q = K_q L_q e_q + K_2 L_q \theta_q + R_s i_q + \omega L_d i_d + \omega\varphi_m \tag{136}$$

where, K_d and K_q are positive constant. By placing Equations (15) and (16) in Equation (14), derivative of Lyapunov function is as follow:

$$\dot{U} = -K_d e_d^2 - K_q e_q^2 \le 0 \tag{147}$$

By selecting the appropriate regulatory variables, the second Lyapunov function is designed in three stages as follow:

Step 1- the speed error is defined as follow:

$$e_\omega = \omega_m^* - \omega_m \tag{158}$$

For Convergence of Lyapunov function, this stage is defined as follow:

$$U_1 = \frac{1}{2}K_m e_\omega^2 + \frac{1}{2}K_n \theta_\omega^2 \quad (169)$$

$$\theta_\omega = \int_0^t e_\omega(\tau)\,d\tau \quad (20)$$

That is integral of speed effective error.

$$T_e = \frac{3}{2}\frac{P}{2}[(L_d - L_q)\,i_d + \varphi_m]i_q \quad (171)$$

$$K = \frac{3}{2}\frac{P}{2}[(L_d - L_q)\,i_d + \varphi_m] \quad (182)$$

$$\dot{U} = \frac{K_m}{J_m}e_\omega[-T_e + T_L + B_m\omega_m + K_n e_\omega \theta_\omega] \quad (193)$$

$$\frac{K_5}{K_m} = K_i \quad (204)$$

$$\frac{K_n}{K_m} = K_j \quad (215)$$

where, K_i and K_j have positive value and for stabilizing, the following equation is used:

$$i_q^* = \frac{K_i\,J_m}{K}e_\omega + \frac{K_j}{K}\theta_\omega + \frac{1}{K}T_L \quad (226)$$

$$\dot{U}_1 = -K_5\,e_\omega^2 \le 0 \quad (237)$$

Step 2- For objective current of d-axis, the effective error is defined as follow:

$$e_d = i_d^* - i_d \quad (248)$$

$$\frac{de_d}{dt} = -\frac{U_d}{L_d} + \frac{R_s}{L_d}i_d - \omega\frac{L_q}{L_d}i_q \quad (259)$$

That Lyapunov function is as follow:

$$U_2 = \frac{1}{2}e_d^2 + \frac{1}{2}K_1\theta_d^2 \quad (30)$$

where K_1 is positive value.

$$\theta_d = \int_0^t e_d(\tau)\,d\tau \quad (261)$$

That is integral of d-axis current effective error.

$$\dot{U}_2 = e_d[K_1\theta_d - \frac{U_d}{L_d} + \frac{R_s}{L_d}i_d - \omega\frac{L_q}{L_d}i_q] \quad (272)$$

For public simultaneously stability in current loop, the produced control voltage d-axis is as follows:

$$U_d = K_d L_d e_d + K_1 L_d \theta_d + R_s i_d - \omega L_q i_q \quad (283)$$

By placing Equation (33) in Equation (32) derivative of Lyapunov function is as follow:

$$\dot{U}_2 = -K_d e_d^2 \le 0 \quad (294)$$

Step 3- For objective current of q-axis, the effective error is defined as follow:

$$e_q = i_q^* - i_q \quad (305)$$

$$\frac{de_q}{dt} = -\frac{U_q}{L_q} + \frac{R_s}{L_q}i_q + \omega\frac{L_d}{L_q}i_d + \omega\frac{\varphi_m}{L_q} \quad (316)$$

In other words, to ensure convergence of effective errors, the objective function in the q-axis is defined as follow:

$$U_3 = \frac{1}{2}e_q^2 + \frac{1}{2}K_2\theta_q^2 \quad (327)$$

where, K_2 is positive value.

$$\theta_q = \int_0^t e_q(\tau)\,d\tau \quad (338)$$

That is integral of q-axis current effective error.

$$\dot{U}_3 = e_q[K_2\theta_q - \frac{U_q}{L_q} + \frac{R_s}{L_d}i_q + \omega\frac{L_d}{L_q}i_d + \omega\frac{\varphi_m}{L_q}] \quad (349)$$

For stability, we define the voltage V_a as follows:

$$U_q = K_q L_q e_q + K_2 L_q \theta_q + R_s i_q + \omega L_d i_d + \omega\varphi_m \quad (40)$$

By placing Equation (35) in Equation (34) derivative of Lyapunov function is as follow:

$$\dot{U}_3 = -K_q e_q^2 \le 0 \quad (351)$$

So by combination roles of these integrals with Lyapunov functions, we are sure that the effective error convergence to zero is Imminent in the presence of disturbances and system unknown models. So total Lyapunov function is as follow:

$$\begin{aligned} U_q &= U_1 + U_2 + U_3 = \\ &= \frac{1}{2}K_m e_\omega^2 + \frac{1}{2}K_n\theta_\omega^2 + \frac{1}{2}K_1\theta_d^2 + \\ &+ \frac{1}{2}e_d^2 + \frac{1}{2}K_2\theta_q^2 + \frac{1}{2}e_q^2 \end{aligned} \quad (362)$$

The derivative of total Lyapunov function is as follow:

$$\dot{U} = -K_s e_\omega^2 - K_d e_d^2 - K_q e_q^2 \le 0 \quad (373)$$

where, all K values are calculated with use of genetic algorithm. Genetic algorithm will progress step by step by performing following stages:

Stage 1- Algorithm starts with a population consisting of N individuals which each one have a chromosome length L.

Stage 2- Calculation of fitness for each individual.

Stage 3- Selection two individuals based on higher fitness (parent selection).

Stage 4- Apply of crossover and children's birth from parents.

Stage 5- Apply of mutation with probability P for each bit

Stage 6- Putting borne children into one set as a new generation.

Stage 7- Changing initial population follow with entrance of new generation.

Stage 8- Going to Stage 2.

At the beginning of genetic algorithm, we create an initial population consist of N random possible answers. Then, the evaluation function calculates fitness value of each answer. A selection function will select two parents based on that, each answer which has higher fitness has more selection chance. In the next step, crossover and mutation operators are applied on selected chromosomes.

After this stage will remove a number of bad solutions with low fitness and will give their place to newborn children and new generation. After fixation new generation, the algorithm is return to the evaluation stage again. The result of fitness function convergence is shown in Figure 2. The method of genetic algorithm calculation is show in Figure 3. Simulation of Lyapunov control block is shown in Figures 4 to 6.

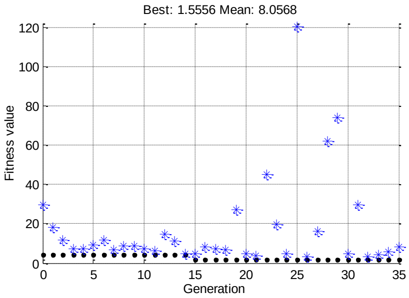


Figure 2. Objective function situation

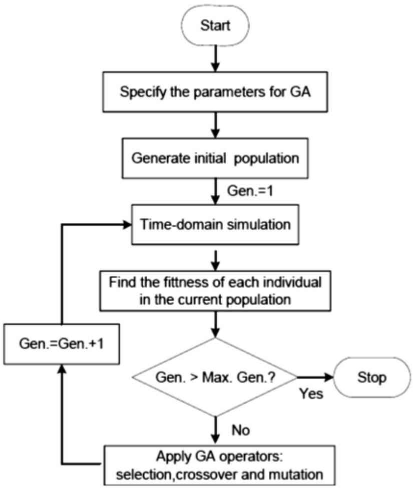


Figure 3. Method of genetic algorithm calculation

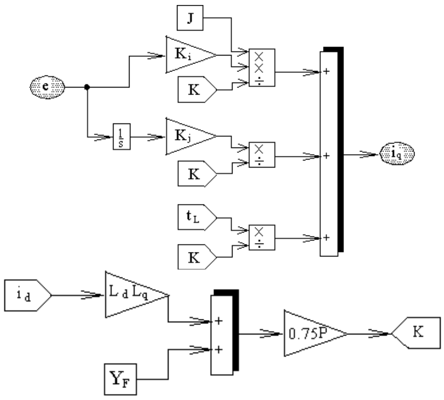


Figure 4. Controller block diagram for *iq*

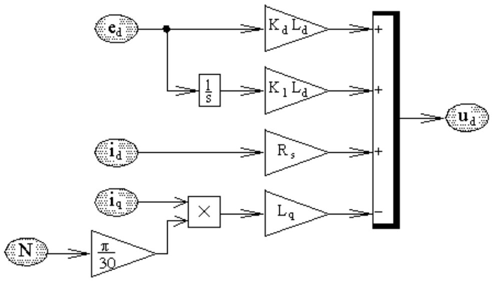


Figure 5. Controller block diagram for u_d

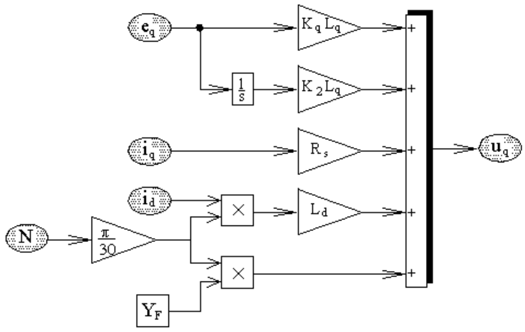


Figure 6. Controller block diagram for u_q

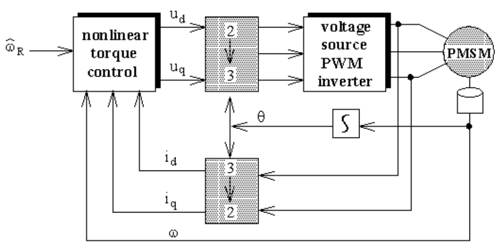


Figure 7. Overall system block diagram related to PMSM motor torque control

IV. SIMULATION RESULTS

To demonstrate correction of mathematical analysis and also to performance investigation of the proposed nonlinear control scheme, simulation is shown in Figure 7 for PMSM motor control system. The speed and current loop are designed and simulated separately with Lyapunov control. Results of simulation for both Lyapunov function are shown below. The block diagram of the system for nonlinear control based Lyapunov approach in MATLAB/Simulink is show in Figure 8. In Figure 9 the proposed controller simulation results for the first Lyapunov function is shown in nominal state for PMSM. The electromagnetic torque and the stator current are shown in Figures 9(b) and 9(c), respectively.

In addition, simulation results for the second function Lyapunov is given in Figure 10 in nominal state. The electromagnetic torque and the stator current are shown in Figures 10(b) and 10(c), respectively. According to the results of both figures, it is specified that electromagnetic torque in second Lyapunov function have less oscillations (approximately half) respect to the electromagnetic torque in first function. Thus, we see that in proposed controller, it can be near to the desired torque with acceptable speed and accuracy.

Figures 10 and 11 show a two-way control performance by Lyapunov method. The shown torque is given from 1 N.m to -1 N.m. Figure 10 is for first Lyapunov function and Figure 11 is for the second Lyapunov function. These figures indicate the speed and accuracy of controller in nominal parameters. Again, the second function as well as is better than the first function in control of both torque oscillations and disturbance arising from direction change of torque.

In the next simulation is studied influence of servo drive parameters under deviation parameters. Deviation parameters in control will be described in the following regulatory values dq-axis stator induction in +30%, rotor leakage flux in +30%, mechanical inertia in +400%. Results are shown in Figures 12 and 13.

We can see that wrong performance in parameters does not effect on the controller stability. In these figures, we see that the motor torque will converge quickly to the main amount and will compensate effect of disturbance load. From expressed results, it is partly identified that above method has good and high performance at effective torque in regulation and it has impressive role in increasing the stability and elimination of current effective error.

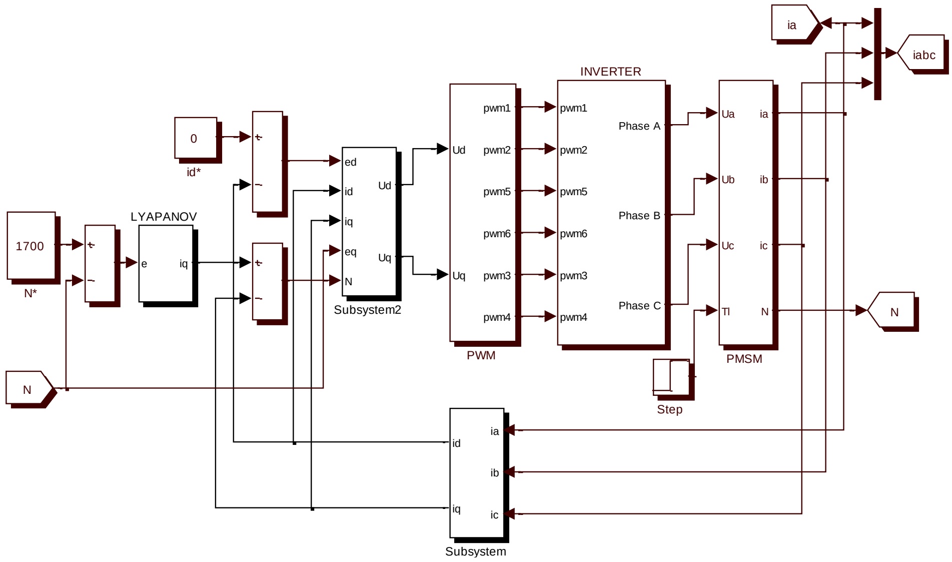
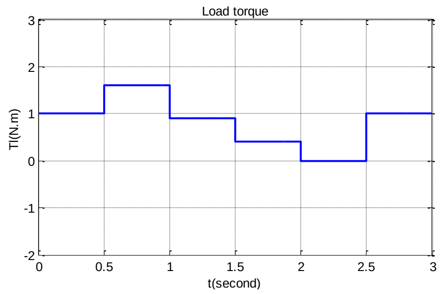
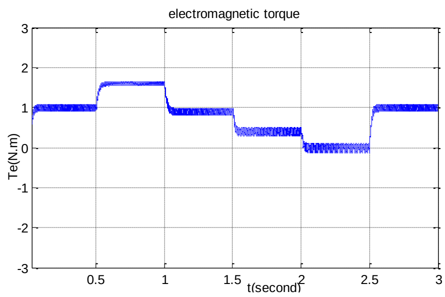


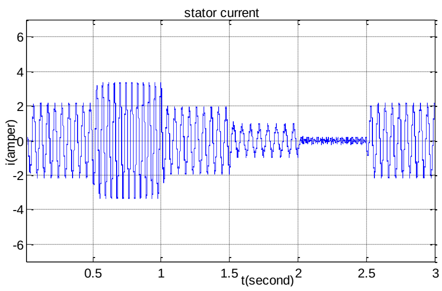
Figure 8. Block diagram of the system for nonlinear control based Lyapunov approach



(a)

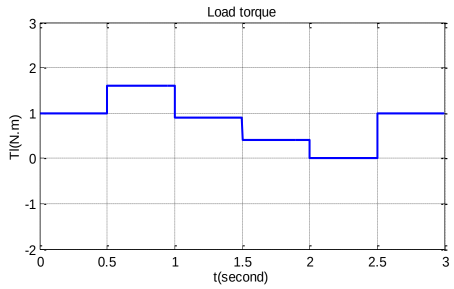


(b)

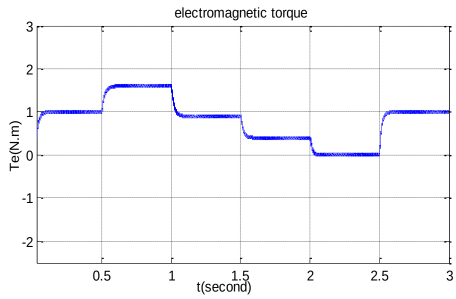


(c)

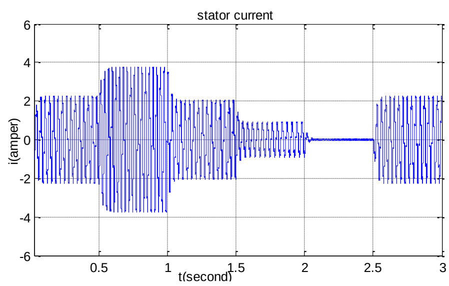
Figure 9. Controller performance in nominal state of PMSM motor in different load for the first Lyapunov function, (a) Load torque, (b) Electromagnetic torque, (c) Stator current of one phase



(a)

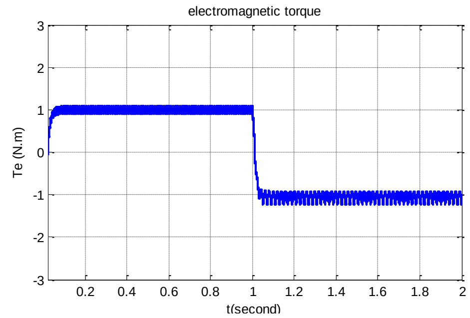


(b)

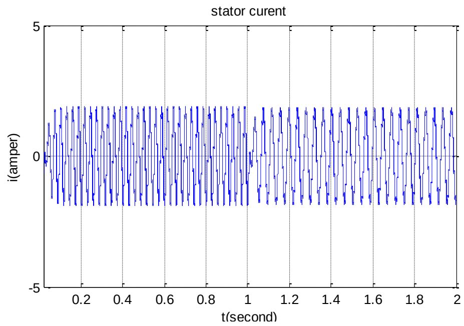


(c)

Figure 10. Controller performance in nominal state of PMSM motor in different load for the second Lyapunov function, (a) Load torque, (b) Electromagnetic torque, (c) Stator current of one phase

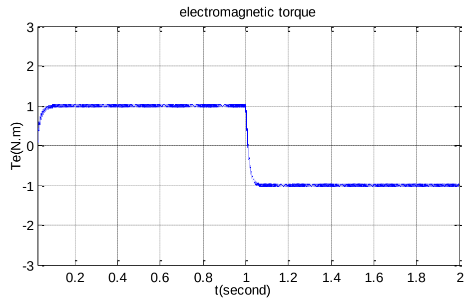


(a)

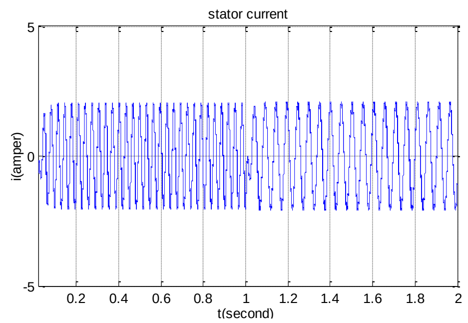


(b)

Figure 11. Two-way performance control of PMSM motor drive system in nominal state for the first Lyapunov function, (a) Electromagnetic torque, (b) Stator current of one phase



(a)



(b)

Figure 12. Two-way performance control of PMSM motor drive system in nominal state for the second Lyapunov function, (a) Electromagnetic torque, (b) Stator current of one phase

This controller also show influence of incorrect or change in load parameters, including load disturbances and the inertia. In addition, the second Lyapunov function has shown acceptable performance in control of load disturbances and power oscillations in three cases. As a result, this function is properly selected for our controller.

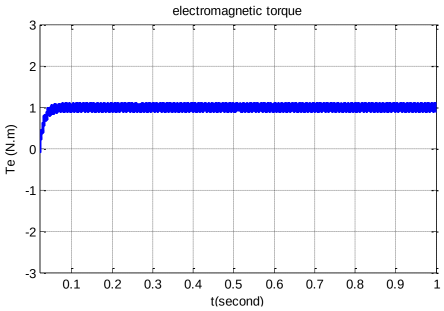


Figure 13. Electromagnetic torque for the proposed controller of the first Lyapunov function under load with deviation parameters in $L_d = L_q = +30\%$, $J_m = +400\%$

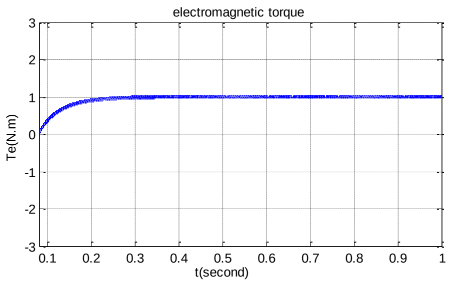


Figure 14. Electromagnetic torque for the proposed controller of the second Lyapunov function under load with deviation parameters in $L_d = L_q = +30\%$, $J_m = +400\%$

V. CONCLUSIONS

In this paper, a simple and effective torque control system is designed and proposed for PMSM. The results show the proposed control system has good performance. The simulation result indicates one accurate and fast response without overshoot for the deviant parameters and actual parameters and load disturbances. The Lyapunov functions increase stability by getting of effective error penalty term. Simulation results indicate that to achieving one fast and accurate torque, the PMSM motor torque control method by using the Lyapunov theory in transient state and stability, is better than in comparison with the situation we have not used the Lyapunov method. Also for achieving to this objective, it requires an accurate and true Lyapunov function.

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