Application of Vector Control Technology for PMSM Used in Electric Vehicles

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Abstract: Based on the equation of small pure electric vehicle (PEV) and the mathematic model of permanent magnet synchronous motor (P M S M), synchronous motor (PMSM), the dynamic model is presented for small PEV driven by PMSM. With space vector pulse width modulation (SVPWM) algorithm, a velocity and current double closed-loop simulation model of PMSM control system is build in Matlab7.6/Simulink environment. Simulation results show that: the system has the advantages of fast response, high precision, strong anti-interference ability, and this novel method offers a new thought way for designing and debugging driving system of PEV.

Keywords: PEV, PMSM, SVPWM, Vector control, Simulation.

1. INTRODUCTION

Electric vehicles with the advantage of no pollution, low noise, zero emission, high energy conversion efficiency, have become the trend of the automotive industry. As the main executive body, electric vehicle driving system has profound theoretical significance and practical value for the study of driving motor and its control system [1]. The PMSM with its simple structure, small size, light weight, small inertia, high power density, is very suitable for the limited space of electric vehicles; In addition, its high efficiency, high power factor, torque to inertia, strong overload capacity, high output torque especially at low speed, which means that the PMSM is also very suitable for the needs of starting and acceleration [2]. Therefore, a variety of factors have determined that the PMSM has become one of the important choices for driving system of electric vehicles.

Currently there are many control strategies and algorithms for PMSM. Vector control is characterized by high accuracy, fast dynamic response, and wide speed range, but its control performance is easily influenced by the variation of motor parameters [3-5]; The performance of direct torque control is not affected by parameters, and it has high reliability, but more difficult to control [6, 7]; Single neuron PID control optimize the starting performance of the motor, but its control effect largely depends on the learning rate of neurons [8].

The operating environment and requirements of electric vehicles vary greatly, so different control strategies are adopted at different stages. In this paper, a composite control scheme is designed by employing the space vector pulse width modulation (SVPWM) technology and PI control

algorithm, a velocity and current double closed-loop simulation model of PMSM control system is build in Matlab7.6/Simulink environment, the dynamic performance of control system is being test under different speed when the electric vehicle traveling in the direct gear. Simulation results show that the system has good dynamic, steady-state performance and robustness. This novel method provides a theoretical basis and project reference for the design and implementation of the actual control system.

2. SYSTEM DESIGN

Vector control methods of PMSM mainly include: $i_d = 0$ control, the maximum torque/current control, field weakening control, the maximum output power control and etc, these several control methods can meet the requirements of different operating characteristics.

A velocity and current double closed-loop control strategy is employed in this system, considering the characteristics of strong coupling, time-varying and nonlinear, the SVPWM algorithm is used in the inner loop; In order to enhance the robustness and anti-interference ability, PI speed controller is used in the outer loop. Schematic diagram of control system is shown in Fig. (**1**). The system consists of coordinate transformation, SVPWM, three-phase inverter, speed and position signal modules and PI controller.

3. MATHEMATICAL MODEL ANALYSIS

3.1. Mathematical Model of PMSM in the *dq* Coordinate System

For the speed PMSM, the damper windings on the rotor does not exist, therefore the mathematical model of PMSM in *dq* coordinate system is expressed as follows [9]:
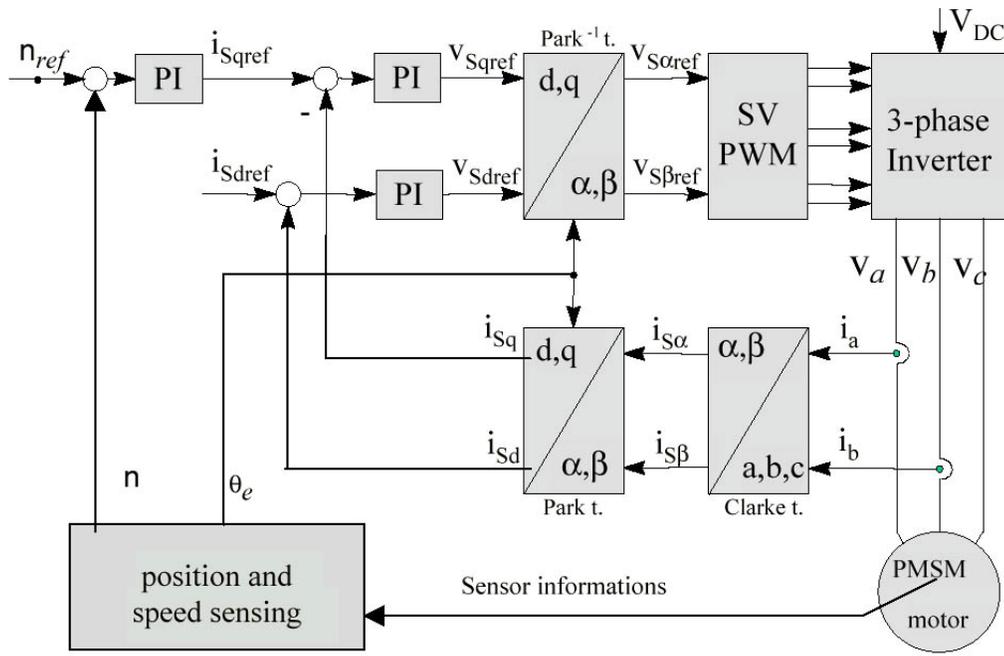
Fig. (1). Structure diagram of vector control for PMSM.

Voltage equations:

$$\begin{cases} u_d = \dfrac{d\psi_d}{dt} - \omega\psi_q + R_1 i_d \\ u_q = \dfrac{d\psi_q}{dt} + \omega\psi_d + R_1 i_q \end{cases} \quad (1)$$

Stator flux equations:

$$\begin{cases} \psi_d = L_d i_d + L_{md} i_f \\ \psi_q = L_q i_q \end{cases} \quad (2)$$

Electromagnetic torque equation:

$$T_{em} = p[L_{md} i_f i_q + (L_d - L_q) \cdot i_d i_q] \quad (3)$$

Mechanical motion equation:

$$\frac{J}{p}\frac{d\omega}{dt} = T_{em} - T_L \quad (4)$$

In the above formula, u_d and u_q are components of stator voltage on dq axis; i_d and i_q are components of the stator current on dq axis; ψ_d and ψ_q are components of the stator flux on dq axis; L_d, L_q are inductances of the stator winding on dq axis; R_1 is stator resistance; L_{md} is mutual inductance between the stator and the rotor on d axis; i_f is equivalent excitation current of permanent magnet; T_{em} is electromagnetic torque of the motor; T_L is load torque; J is

moment of inertia; p is number of rotor pole pairs; ω is the electric angular speed of the rotor.

3.2. Mathematical Model of the PEV and its Driving System

Battery is the energy device; PMSM is the driving device; PEV runs through the transmission system. Therefore, before creating a mathematical model of PEV system, the mathematical model of an automotive transmission module should be analyzed [10].

The running equation of electric vehicles :

$$\frac{T_{tq} i_g i_0 \eta_T}{r} = G(f_0 + k u_a)\cos\alpha + \frac{C_D A u_a^2}{21.15} + G\sin\alpha + \delta m \frac{du_a}{dt} \quad (5)$$

The speed and motor output speed equation:

$$u_a = 0.377\frac{nr}{i_0 i_g} \quad (6)$$

In the above formula, T_{tq} is torque acting on the drive wheels; i_0 is final drive transmission ratio; i_g is transmission gear ratio; η_T is the mechanical efficiency of transmission system; r is wheel radius; G is vehicle weight; f_0 is coefficient that does not vary with speed; k is velocity coefficient; u_a is vehicle speed; n is motor speed; α is slope angle; C_D is air resistance coefficient; A is windward area; m is vehicle weight; δ is rotating mass conversion coefficient.
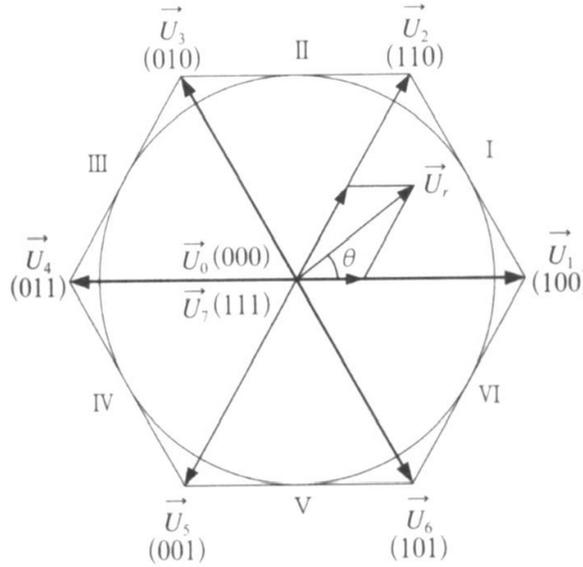
Fig. (2). Basic space voltage vector.

4. THE VECTOR CONTROL PRINCIPLE OF PMSM

4.1. Coordinate Transformation of PMSM

In the control process of PMSM, the actual current in armature winding is three-phase alternating current i_A, i_B, i_C, therefore, certain transformation should be done to get current components on d axis and q axis. First is the transform from three-phase stationary coordinate to two-phase stationary coordinate, namely Clark transform:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \tag{7}$$

Then the transform from two-phase stationary coordinate to the synchronous rotating coordinate, namely Park transform:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{8}$$

4.2. The Simulink Implementation of SVPWM Module

The SVPWM technology's main idea is as follows: take the ideal flux path as a benchmark, when PMSM is powered by three-phase sine wave voltage, approach the benchmark flux circle with the actual flux produced by inverter's 8 switch mode, and the motor could obtain a constant amplitude circular magnetic field (sine magnetic field), so as to achieve high performance. With the SVPWM technology, we select two adjacent effective vectors and the vector zero from these eight, and form the space voltage vector U_r that needed according to their respective response time, the principle is shown in Fig. (2).

According to SVPWM principle, the real-time calculation procedure of SVPWM signal is as follows:

1. The sector judgment

According to the relationship between U_α and U_β, the judgment is as follows:

a. When $U_\beta > 0$, makes *A*=1, else *A*=0;

b. When $\sqrt{3}U_\alpha - U_\beta > 0$, makes *B*=1, else *B*=0;

c. When $-\sqrt{3}U_\alpha - U_\beta > 0$, makes *C*=1, else *C*=0.

The sector: *N*=*A*+2*B*+4*C*; U_α and U_β are components on α axis and β axis of synthetic vector U_{ref}.

2. The calculation of *X*, *Y*, *Z* and T_1, T_2

T_1 means the main vector's operating time in current working sector, T_2 means vice-vector's operating time, the operating time T_1 and T_2 can be calculated as follows.

$$\begin{cases} X = \dfrac{2U_\alpha}{\sqrt{2}U_{dc}} t_z \\[2mm] Y = \dfrac{(\sqrt{3}U_\alpha + U_\beta)}{\sqrt{2}U_{dc}} t_z \\[2mm] Z = \dfrac{(\sqrt{3}U_\alpha - U_\beta)}{\sqrt{2}U_{dc}} t_z \end{cases} \tag{9}$$

When $T_1 + T_2 - t_z > 0$, and t_z is switching period, calculate the new value of T_1 and T_2, make $T_1 = T_1 t_z / (T_1 + T_2)$,

Table 1. Assignments of T_1, T_2 **.**

I	II	III	IV	V	VI
Z	Y	-Z	-X	X	-Y
Y	-X	X	Z	-Y	-Z

Table 2. Assignments of $T_{cm1}, T_{cm2}, T_{cm3}$ **.**

I	II	III	IV	V	VI
T_b	T_a	T_a	T_c	T_c	T_b
T_a	T_c	T_b	T_b	T_a	T_c
T_c	T_b	T_c	T_a	T_b	T_a
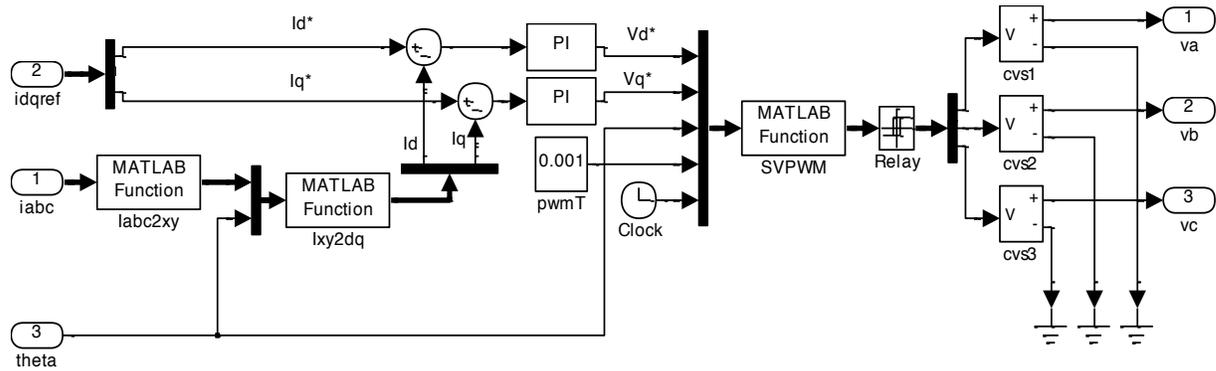
Fig. (3). Simulation block of SVPWM.

$T_2 = T_2 t_z / (T_1 + T_2)$. For different sectors, the assignments of T_1 and T_2 can be derived from Table **1**.

3. The determination of vector switching points $T_{cm1}, T_{cm2}, T_{cm3}$

$$\begin{cases} T_a = 0.25(T - T_1 - T_2) \\ T_b = T_a + 0.5T_1 \\ T_c = T_b + 0.5T_2 \end{cases} \qquad (10)$$

For different sectors, the assignments of $T_{cm1}, T_{cm2}, T_{cm3}$ can be derived from Table **2**.

Compare the isosceles triangular wave with $T_{cm1}, T_{cm2}, T_{cm3}$ (isosceles triangular wave is produced by integrating the pulse generator), we can get the symmetric SVPWM waveform.

SVPWM simulation module is written by M file functions in Matlab, build the core part of vector control

algorithm, as shown in Fig. (**3**), including the decoupling of feedback current, PI regulator of current loop and SVPWM generation module.

5. SIMULATION AND RESULTS ANALYSIS

Based on the input-output relationship between each module, a velocity and current double closed-loop simulation model of PMSM control system is build in Matlab7.6/Simulink environment, as is shown in Fig. (**4**). The PMSM control system mainly includes: PMSM body module, three-phase voltage inverter module, coordinates transformation module and SVPWM module.

The sample motor parameters: Rated power: $P = 1.1kw$; $U = 220v$; $R_s = 2.875\Omega$; $p = 4$; $L_d = L_q = 0.0085H$; $J = 0.0008kgm^2$; $\psi_f = 0.175Wb$.

The PMSM starts with no load, the simulation output are shown in Figs. (**5-7**). The given simulation speed is rated speed $3000r / m$, load $1N \cdot m$, the time unit is ms. Simulation
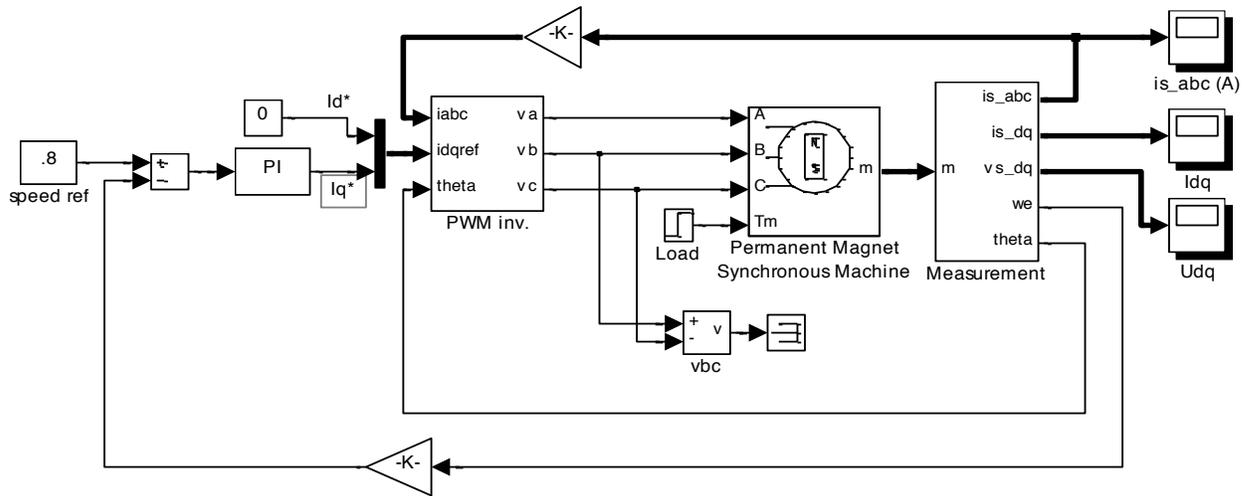
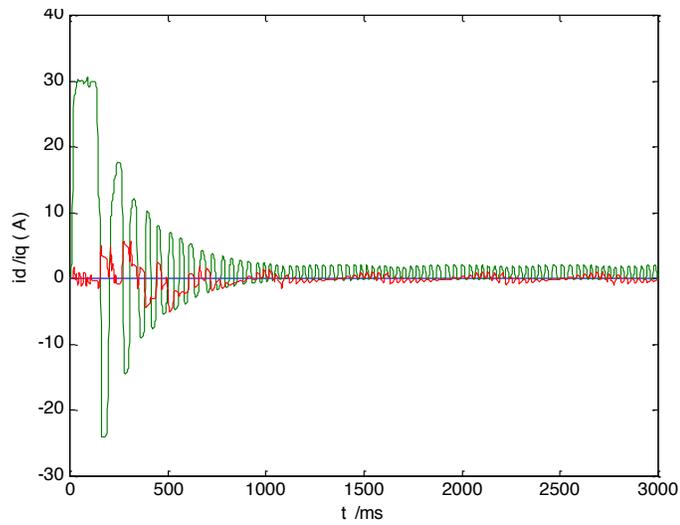**Fig. (4).** Simulation model of the driving system.

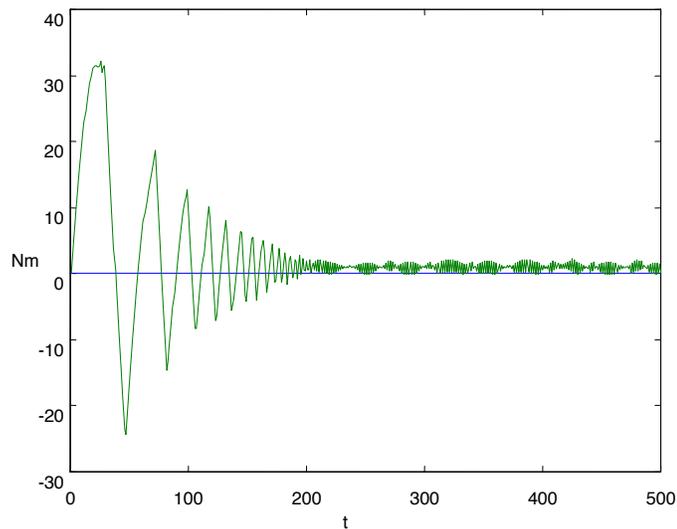**Fig. (5).** Current waveform on *dq* axis.
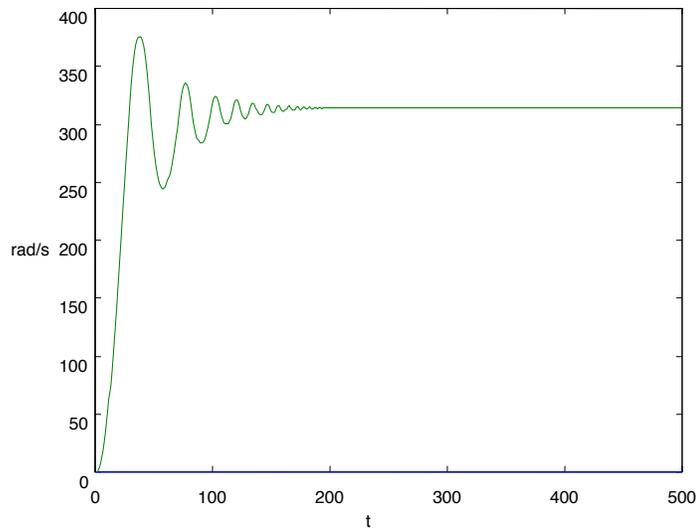

Fig. (6). Output torque waveform.

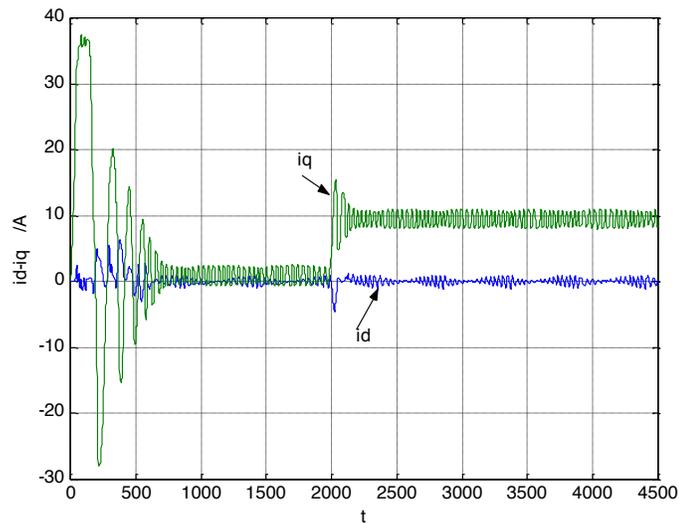**Fig. (7).** Velocity waveform.

Fig. (8). Current on *dq* axis under variable load.

results show that: with this control method, we can achieve better control performance. The current, output torque and velocity reach stable values within 0.2 seconds, the start speed of PMSM is fast, and we can accurately track the given speed.

Figs. (**8-10**) show response to load mutation, the initial load is 1N.m, and at 0.02 seconds, the load suddenly rises to 10N.m. The system response shows that: with double ring structure, we can quickly track the changes of torque, as is shown in Fig. (**9**); In case of load, speed can track the given value after a short volatility, which is shown in Fig. (**10**). Fig. (**8**) shows that, currents on *dq* axis both are straight flow with slight fluctuation, the output torque is proportional to i_q, the complete decoupling is realized. These results are

consistent with the pre-analysis for the control system, the expected control effect achieved, and the control method is proved feasible.

CONCLUSION

According to the needs of small PEV, based on the mathematical analysis of PMSM and PEV, a velocity and current double closed-loop control system is designed by employing the SVPWM technologies and PI algorithm. The results show that: the system has fast response speed, good robustness and stronger anti-interfere ability, which could meet the city traffic demand of PEV. This novel method offers a new thought way for designing and debugging driving system of small PEV.
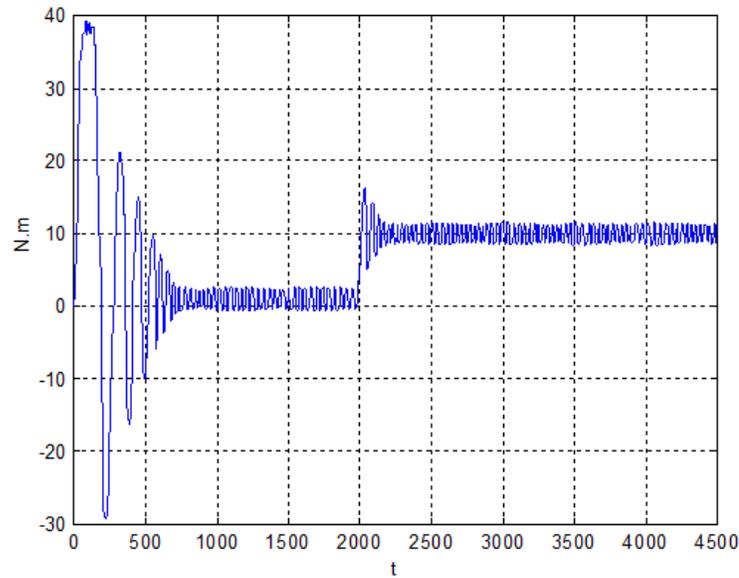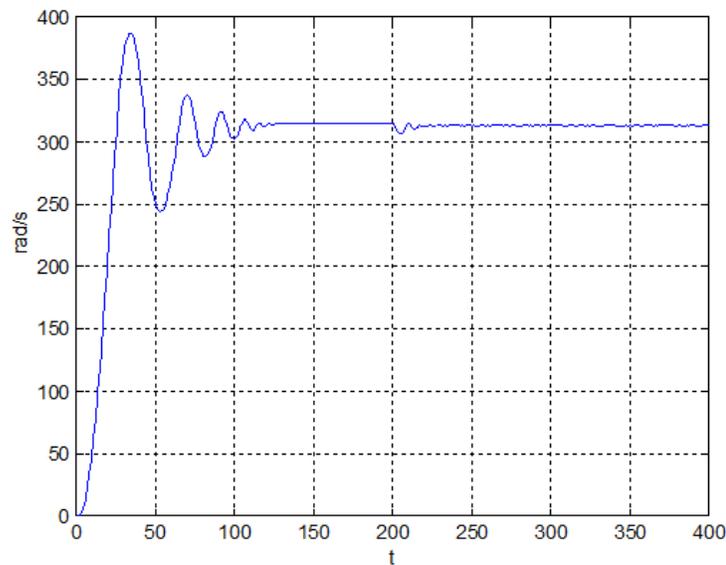
Fig. (9). Output torque under variable load.

Fig. (10). Velocity under variable load.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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