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Modeling and State Feedback Controller Design of Tubular Linear Permanent Magnet Synchronous Motor

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ABSTRACT

In this paper a state feedback controller for tubular linear permanent magnet synchronous motor (TLPMSM) containing two gas springs, is presented. The proposed TLPMSM controller is used to control reciprocating motions of TLPMSM. The analytical plant model of TLPMSM is a multi-input multi-output (MIMO) system which is decoupled to some sub single-input single-output (SISO) systems, then, the sub SISO systems are converted to sub-state space models. Indeed, the TLPMSM state space model is decoupled to some sub-state spaces, and then, the gains of state feedback are calculated by linear quadratic regulation (LQR) method for each sub-state space separately. The controller decreases the distortions of the waveforms. The simulation results indicate the validity of the controller.

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1. INTRODUCTION

Tubular linear permanent magnet synchronous motors are used in industrial application such as the linear compressors, elevators, pumps, electromagnetic valve actuators, vibrators, and the industrial robots [1-3]. This kind of linear motors has some advantages such as good dynamic respond, accurate position, and reliability [4]. The TLPMSM reciprocating motion is used in drilling applications inoil industry efficiently. TLPMSM has two gas springs that acts like a linear hammer, particularly suitable for drilling the hard rocks. This kind of motor can transmit electrical power from an electric source to drill without using any mechanical intermediate. Existence of two gas springs in both sides of the piston increases the efficiency significantly and decreases the drilling time [18]. Several control techniques are used for controlling the TLPMSM reciprocating motion. To control the position, speed, acceleration, and force of linear permanent magnet synchronous machine, modeling, dynamic analysis, and parameter estimation have been studied in [4-7]. Prescribed closed-loop speed control method offered an accurate realization in [8]-[9]. The sensor-less control method for a miniature application has been validated in [3]. An advanced scheme, based on neuralnetwork, has been proposed in [10] to compensate for sudden variations of the load. The TLPMSM which is used in this work has been introduced in [11] and [12]. Analysis of the force performance of this machine has been carried out in [11].

Displaying system, using its transfer function, defines the input-output behavior of the system inthe time domain.The state space equations, not only has the input-output data but also prepares comprehensive information of inner system structure to control engineers. Displaying transfer function in the frequency domain is used in classical designs and SISO compensators and its efficiency is limited in analyzing and designing MIMO systems. Displaying system in space state universalize analyzing and designing of SISO systems to MIMO systems [21].

In this paper, TLPMSM modeling and state feedback controller have been considered to have good dynamic responses. A state space that increasingly exploited in diverse fields in order to modeling and analyzing systems, is a mathematical model originated form some first-order differential equations describing a physical system. A state space includes a set of state variables, input variables, and output variables. The variables are defined in vector form. Moreover, if the considered system is a linear and time-invariant system, the equations can be expressed in matrix form. State feedback can arbitrarily assign the closed loop system poles at any position but has no effect on the system zeroes [19]-[20].

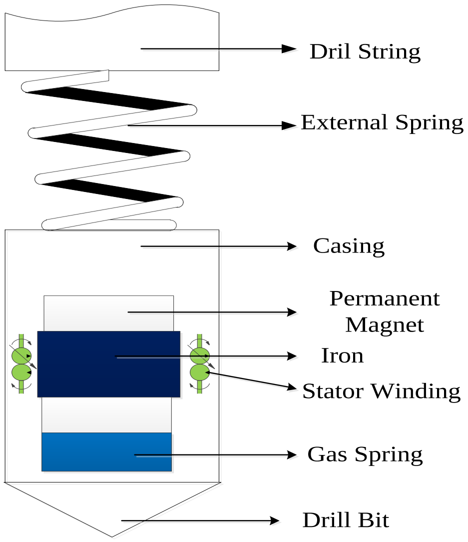


Figure 1. TLPMSM

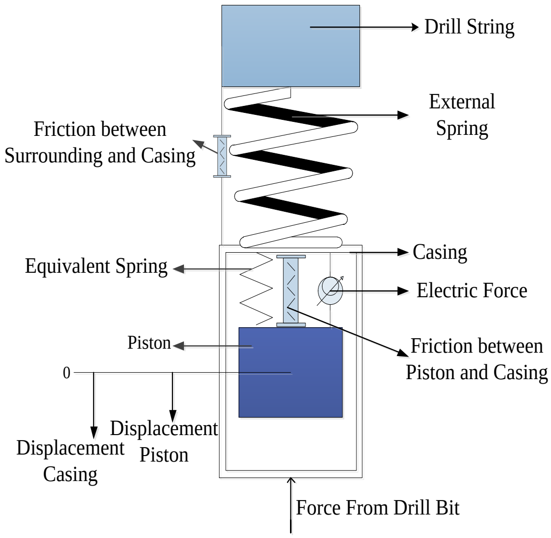


Figure 2. Equivalent model of TLPMSM

The rest of paper is organized as: Overview of the TLPMSM model and the equivalent circuit are given in section II. In section III, the TLPMSM mathematical model is presented. Section IV presents the theory and design of state feedback controller. The simulation results for the controlled system with state feedback controller in full load mode are presented in section V. Finally, section VI presents summary and conclusions.

2. MATHEMATICAL MODELING OF TLPMSM

The TLPMM prototype is shown in Figure 1. The explained TLPMSM is included a case with the stator winding, piston with permanent magnets, and two gas springs on both sides of the case [13].Figure.3 shows the equivalent circuit of TLPMSM stator winding. To facilitate simulations, the equivalent form of spring and dampers is used for modeling gas springs and friction between the case and piston. The whole system hits the rock with a constant speed. Each collision makes some cracks between rocks and makes some more space between drill beat and rock, causes better performance for next hitting. Themiddle point of the piston isdefinedas an origin for the case. The piston and the positive case displacement direction are shown in Figure 2. According to the mentioned equivalent circuit, piston oscillates between gas springs [13].

Gas springs are assumed as linear elements, while the stroke length of piston is small enough compared with the length of gas springs, therefore, the characteristic function of gas springs is obtained as follows:

$$f_{gas}(y) = k_{es}.y \tag{1}$$

where f_{gas} is the gas spring force,k_{es} is the equivalent stiffness coefficient formatting and y is the spring displacment.

The electromagnetic force, friction force between case and piston, and the spring force are the three main forces that are subjected to the piston as illustrated in Figure 4. The following equation in vertical direction can be expressed using Newton's second law:

$$m_p.\ddot{y}(t) = f_{netp}(t) = f_e(t) - b_p.\dot{y}(t) - k_{es}(t).y(t) \quad (2)$$

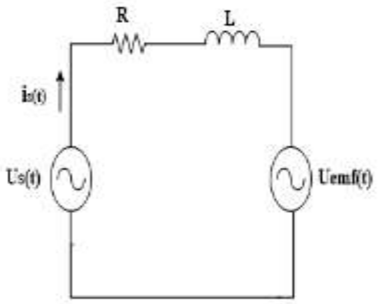


Figure 3. Equivalent electric circuit of stator winding

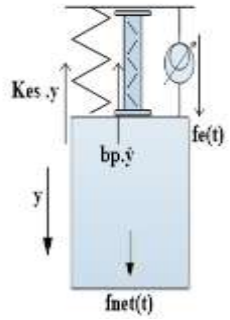


Figure 4. Force analysis for piston

where m_p is mass of piston, b_p is friction coefficient between piston and casing, k_{es} is stiffness coefficient of equivalent spring, $\dot{y}(t) = \dot{y}_p(t) - \dot{y}_c(t)$ is piston velocity respective to the case,$y(t) = y_p(t) - y_c(t)$is piston displacement respective to thecase, $y_p(t)$is the piston displacement and $y_c(t)$ is the case displacement.
The subjected forces to case are shown in Figure 5. According to Figure 5, case is subjected to four forces:
i. Counter force by the piston-gas spring-damper subsystem
ii. Friction force between the case and neighboring
iii. External spring force
iv. Force from rock subjected to case because of impact.
Equation in vertical direction is obtained as (3):

$$m_c.\ddot{y}_c(t) = f_{netc}(t) = -f_{netp}(t) - k_{ext}.y_c(t) - b_c.\dot{y}_c(t) - d.f_c \quad (3)$$

wher em_c is the mass of casing,b_c is the friction coefficient between casing and surroundings,k_{ext} is stiffness coefficient of external spring, $k_{ext}.y_c(t)$ is the external spring force,$b_c.\dot{y}_c(t)$ is the friction force between the case and neighboring, $d.f_c$is acounter force by rocks because of impact which is assumed as follows:

$$d = \begin{cases} 1 & during\ collision \\ 0 & no\ collision \end{cases} \quad (4)$$

Using the Lorentz force equation, the electromagneticforce is obtained as:

$$f_e(t) = B.l.i_s(t) \quad (5)$$

where $i_s(t)$ is stator winding current, B is flux density around stator winding.
Voltage equation for the circuitshown in Figure 3 is acquired from Kirchhoff's voltage law (KVL):

$$u_s(t) = R.i_s(t) + L\frac{di_s(t)}{dt} + u_{emf}(t) \quad (6)$$

where $u_s(t)$ is stator's winding input voltage, R is resistance of coil, and L is inductance of coil, $u_{emf}(t)$isback EMF of stator winding. Using Faraday's law, back EMF of stator winding, $u_{emf}(t)$ is obtained as:

$$u_{emf}(t) = B.l.\dot{y}(t) = B.\pi.D.N.\dot{y}(t) \quad (7)$$

where D is diameter of chamber, and N is number of turns of stator winding. State space variables are determined:

$x_1 = y_p(t)$, $x_2 = \dot{y}_p(t)$, $x_3 = y_c(t)$, $x_4 = \dot{y}_c(t)$, $x_5 = i_s(t)$.Using equations (1) to (7), the state space model is obtained as:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\\ \dot{x}_5\end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0\\ -\frac{k_{es}}{m_p} & -\frac{b_p}{m_p} & \frac{k_{es}}{m_p} & \frac{b_p}{m_p} & \frac{BND\pi}{m_p}\\ 0 & 0 & 0 & 1 & 0\\ \frac{k_{es}}{m_c} & \frac{b_p}{m_c} & -\frac{k_{ext}+k_{es}}{m_c} & -\frac{b_c+b_p}{m_c} & -\frac{BND\pi}{m_c}\\ 0 & -\frac{BND\pi}{L} & 0 & \frac{BND\pi}{L} & -\frac{R}{L}\end{bmatrix}\cdot\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\\ x_5\end{bmatrix} + \begin{bmatrix}0 & 0\\ 0 & 0\\ 0 & 0\\ 0 & -\frac{d}{m_c}\\ \frac{1}{L} & 0\end{bmatrix}\cdot\begin{bmatrix}u_s\\ f_c\end{bmatrix}$$

$$y = [0 \quad 0 \quad 0 \quad 0 \quad 1].\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\\ x_5\end{bmatrix} \tag{8}$$

3. STATE FEEDBACK CONTROLLER DESIGN

Undoubtedly, most control methods are based on the mathematical model of physical systems. In classic methods, transfer function in the frequency domain is used to design of control systems such as frequency response and Root-Locus method. These models are presented simple SISO physical and industrial systems properly, also approximate the input-output behavior of systems with acceptable accuracy [14].

Precision study of complicated industrial systems needs more integral models. For controlling these kinds of system with optimal function, progressive control system designs are required.. Description of state space of a system gives a complete view of internal system structure. State variables describe internal dynamics of the system. This model shows how state variables have mutual effect on each other, how input signals affect state variables, and how can compute the output response with various synthesizing of state variables. Models of SISO systems can be universalized to MIMO systems easily with this method [15]-[16]. The significant advantage of the modern control system analysis and design according to classical control systems is their usage in the MIMO and the time-invariant (TI) systems, however, the classical control system usage is only in SISO-LTI systems [17]. The other advantage of using the state space model is the convenience of close loop system function optimization. Therefore, optimal control systems can be designed in space state. The most utilization of state space concept in modern control are the pole assignment and the stabilization of systems that implemented with state feedback variables. In this paper, a closed-loop state feedback controller is designed for a TLPMSM. Generally, the state space system equation can be written as:

$$\begin{aligned}\dot{X}(t) &= AX(t) + BU(t)\\ Y(t) &= CX(t) + DU(t)\end{aligned} \tag{9}$$

where t is time variable, X(t) is state vector, U(t) denotes the controlling signal, Y(t) is output vector and A, B, C, D are constant matrixes. The values of TLPMSM prototype parameters areexpressed in Table 1. With these parameter values, the poles of system as shown in Figure 5.

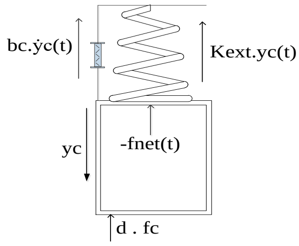


Figure 5. Force analysis for casing

Table 1. TLPMM prototype parameters

Parameter	Value	Unit
Flux density around stator winding (B)	0.42	T
Diameter of chamber (D)	0.0476	M
Number of turns of stator winding(N)	157	-
Period of collision (T)	0.005	S
Mass of piston (m_p)	1.68	Kg
Mass of casing (m_c)	5.14	Kg
Friction coefficient between piston and casing (b_p)	0.005	-
Friction coefficient between casing and surroundings (b_c)	0.001	-
Stiffness coefficient of equivalent spring (k_{es})	7.93 e4	N/M
Stiffness coefficient of external spring (k_{ext})	2.578 e4	N/M
Resistance of Coil (R)	1.20	Ω
Inductance of Coil (L)	0.00119	H

$$\begin{aligned} p_1 &= -92.26 \\ p_2 &= -3.18 + 213.77\, i \\ p_3 &= -3.18 - 213.77\, i \\ p_4 &= 0.04 + 60.85\, i \\ p_5 &= 0.04 - 60.85\, i \end{aligned} \tag{10}$$

The state space controlling signal is shown as:

$$u(t) = -kX(t) + R(t) \tag{11}$$

where matrix k is the state feedback gain and R(t) is the reference input signal. With this assignments, the equation (8) is converted as follows:

$$\dot{X}(t) = (A - Bk)X(t) + B.R(t) \tag{12}$$

The appropriate pole assignment can be obtained by setting matrix k to the proper value. The sate feedbackschematic model for this approach is shown in Figure 6.
This paper focuses on designing a closed-loop state feedback controller for stable output respond in the full-load mode for a TLPMSM. Therefore, the closed-loop controller design objective is considered to track a set of desired references. The transfer function can obtain from state space model as:

$$G = C.(SI - A)^{-1}.B + D \tag{13}$$

According to (9), this system has two inputs and one output, therefore, the transform function matrix is obtained as follows:

$$\begin{aligned} G &= [g_{11} \quad g_{22}] \\ g_{11} &= \frac{2.8e8s^4 + 1.3e13s^2 + 2e9s + 1.3e17}{2e9s^9 + 1.3e7s^7 + 6.5e11s^3 + 9.7e13s^2 + 6.8e15s + 1e18} \\ g_{22} &= \frac{-8.8e7s^3 - 2.8e12s}{2.5e6s^5 + 3.8e8s^4 + e11s^3 + 1.7e13s^2 + 1.2e15s + 1.8e17} \end{aligned} \tag{14}$$

For designing state feedback controller, these two separate transfer functions are converted to space states separately (each array of G matrix is converted to one state space) as shown in Figure 7. Indeed, the state space of TLPMSM is converted to two sub-state spaces (SS1 and SS2). Each sub-state space is a SISO system which can becontrolled by the gain of state feedback controller separately. Designing state space controller for SISO system is much easier than MIMO systems.

In the next step of controller designing, the optimal gain of state feedback is calculated for obtained state spaces including both of two separate state spaces using linear quadratic regulator (LQR) method in sense of optimal control. The LQR algorithm is a well-known procedure of finding the pertinent gain of state feedback controller [22]. Briefly, in LQR, for a continuous time system, the state feedback law $u(t) = -kX(t) + R(t)$ minimizes the quadratic cost function of:

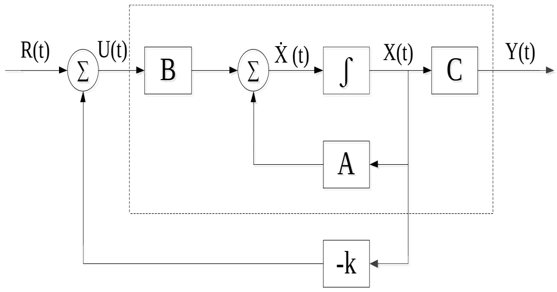


Figure 6. State feedback control model

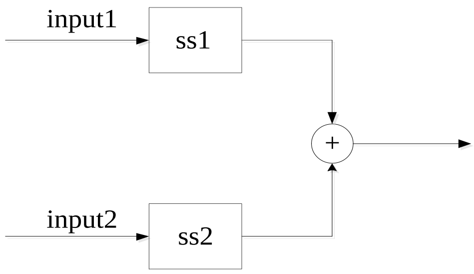


Figure 7. Separating state space model of TLPMSM to two state spaces

$$J(u) = \int_0^\infty (x^T Q x + u^T R u) dt \tag{15}$$

k is calculated as:

$$k = R^{-1} B^T p \tag{16}$$

where p is computed by associated Riccati equation as follow:

$$A^T p + pA - pBR^{-1}B^T p + Q = 0 \tag{17}$$

where R and Q are symmetric positive matrixes. State feedback gains can be achieved using LQR as follows:

$$\begin{aligned} k_1 &= [0.40 \quad 0.22 \quad 1.82 \quad 30.40 \quad 9.76] \\ k_2 &= [0.71 \quad 0.35 \quad 0.45 \quad 19.94 \quad 15.01] \end{aligned} \tag{18}$$

where k_1 is the state feedback gain for first state space and k_2 is the gain of second space state. With these gains, the poles replacement is done as:

$$\begin{aligned} p_1 &= -92.26 \\ p_2 &= -3.18 + 213.77\, i \\ p_3 &= -3.18 - 213.77\, i \\ p_4 &= -0.015 + 60.84\, i \\ p_5 &= -0.015 - 60.84\, i \end{aligned} \tag{19}$$

It is clear that the poles on the right side of real axis in (9) have been displaced to the left side of real axis which makes the system stable. This replacement makes enhancement in the system response.

4. SIMULATION RESULTS

In this section, the results of TLPMSM simulation and the designed state feedback controller are presented. The system is considered in the full-load condition. In simulations, beats are happened in TI mode. The transferred energy equation can be shown as follows:

$$m_c \dot{y}_{cb}(t) + 0.5 k_{ext} y_{cb}^2(t) = 0.5 m_c \dot{y}_{ca}^2(t) + 0.5 k_{ext} y_{ca}^2(t) + w_{col} \tag{20}$$

where the terms of $m_c \dot{y}_{cb}(t)$ is the kinetic energy in casing before the collision, and the terms of $0.5 k_{ext} y_{cb}^2(t)$ is the potential energy in external spring before the collision. The overall left-hand side of (20) is the system energy before collision. The term of $0.5 m_c \dot{y}_{ca}^2(t)$ is the kinetic energy in casing after the collision, $0.5 k_{ext} y_{ca}^2(t)$ is the potential energy in the external spring after the collision, w_{col} is the transferred energy to the rock during the collision, and the overall right side term of (20) is the system energy after the collision.

The effective energy incomes to rocks is only the kinetic energy. Potential energy remains in the system and has no direct effect to the rocks. The ideal beat happens when $y_{cb}(t) = 0$ in (20). In this case, the whole kinetic energy andthe potential energy are restored in the system. So the energy transfer equation is:

$$w_{col} = 0.5 m_c \dot{y}_{cb}^2(t) \tag{21}$$

Therefore, the most of energy transferring rate is based on the motion of the case. Base on collection (2) to (6), the case motion is a function of the input current. By utilizing state feedback controller, input current walks away from instability mode, makes the moment of case movement, according to most energytransfers to rocks at the hitting moment. So the system acts on full-load mode if each beat takes place in the mentioned point. The input voltage of TLPMSM is shown in Figure 8. The amplitude of input voltage is 12V and the frequency is even with the natural frequency of mass-spring-damper.

Input current in the moment of hitting to the rock, before and after using space feedback is illustrated in Figure 9. According to Figure 9, the current waveform in full-load mode by using state feedback controller is similar to current waveform in no-load mode that shows good functioning and good system dynamic response of the system via state feedback controller. It is also illustrated that the most of stored energy in the case is transferred to the rock, and the little bit of energy stored in the spring is stored for displacement of the case in this period. Back EMF before and after exerting state feedback controller is shown in Figure 10. Electromagnetic force before and after exerting space feedback is illustrated in Figure 11.

Indeed, this force is the driving piston force that is called electromagnetic force. By using proposed controller, this force is similar in both cases of full-load and no-load conditions, shows the proper behavior of system under space feedback controller.

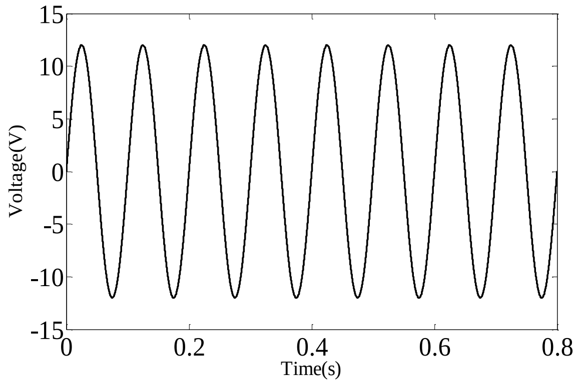
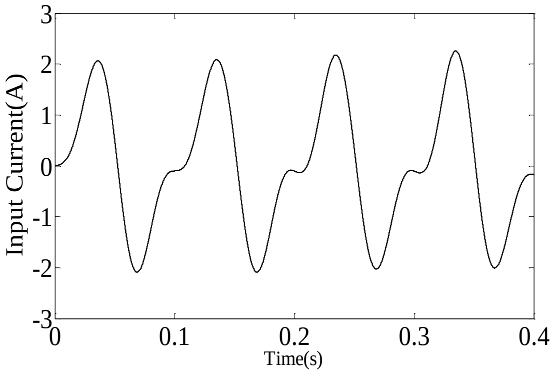
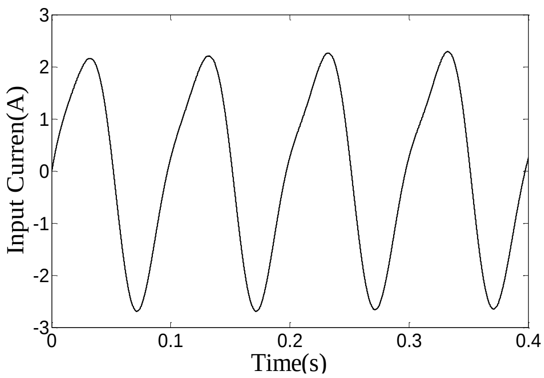


Figure 8. Input voltage

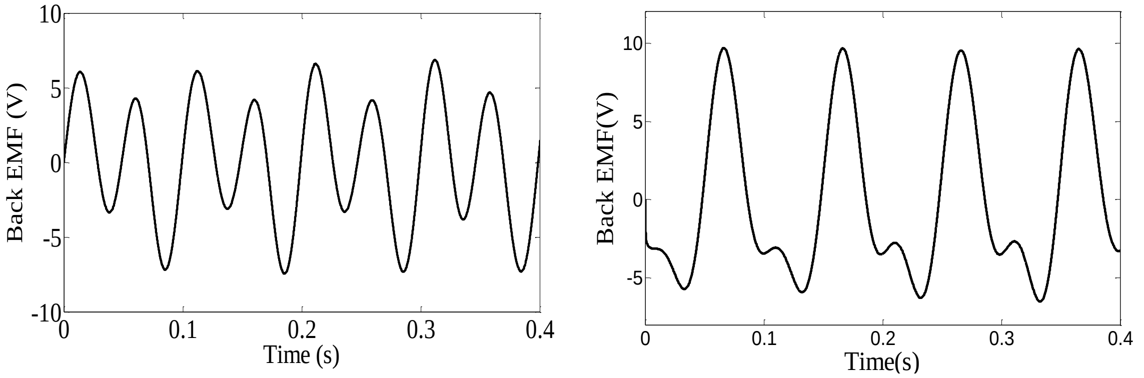


(a)



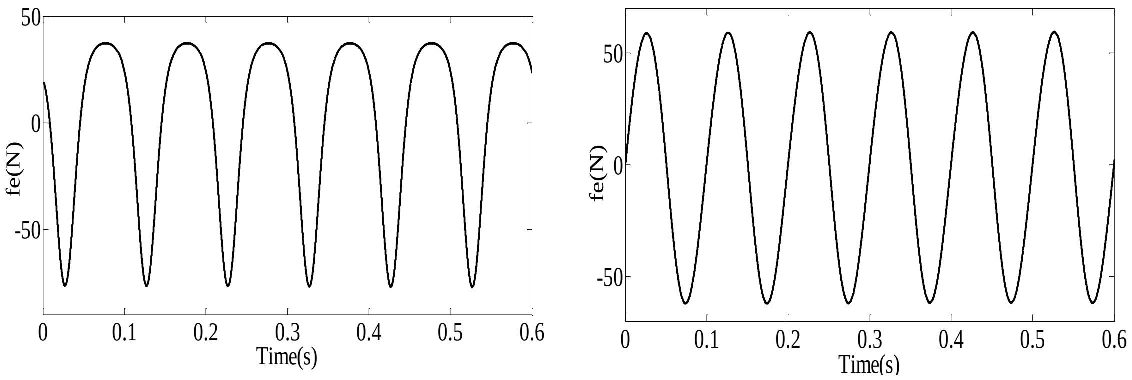
(b)

Figure 9. Input current: (a) before and (b) after exerting state feedback controller



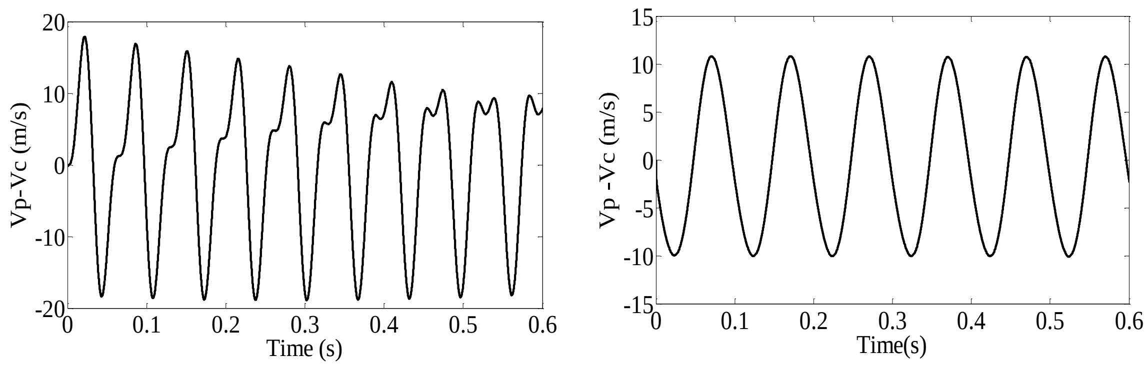
(a) (b)

Figure 10. Back EMF (a) before and (b) after exerting state feedback controller



(a) (b)

Figure 11. Electromagnetic force: (a) before and (b) after exerting state feedback controller



(a) (b)

Figure 12. Piston velocity respect to case velocity: (a) before and (b) after exerting state feedback controller

The piston velocity respect to the case velocity, with and without state feedback is shown in Figure 12. According to Figure 12(a), the system cannot keep its stability without using state feedback controller.Therefore, these velocities cannot coordinate together and the efficiency is descended drastically. The system keeps stability by using space feedback controller, and acts in ideal functioning point as shown in Figure 12(b).

5. CONCLUSION

In this paper, a new state feedback controller for TLPMSM is proposed. The concept of TLPMSM with two gas springs and state feedback control has been achieved in details. Functioning and dynamic responseare studied in full-load condition. The TLPMSM state space model is decoupled to some sub-state spaces. Indeed, the MIMO model of TLPMSM is decoupled to some sub-SISO systems, and then, these sub-SISO systems are converted to sub-state space models, and the gains of state feedback are calculated by LQR method for each sub-state space separately. Results are encouraging and confirm the effectiveness of proposed state feedback method. By using of this state space controller for explained TLPMSM, nearly the whole energy is transferred to the rock in the collision moment, and in this situation, high efficiency is achieved.

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