PMLSM position control based on continuous projection adaptive sliding mode controller

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ABSTRACT
In this paper, the design of projection-based Adaptive Sliding Mode Controller (ASMC) is presented for position control of Permanent Magnet Linear Synchronous Motor (PMLSM) with unknown mover mass. The PMLSM model was first established and a vector control based on field orientation is used to decouple the cross-coupling in motor model. ASMC has been adopted to deal with the unknown mover mass and to give robust operation against external load thrust. Based on the Lyapunov method, the stability of adaptive sliding mode-controlled PMLSM has been proven and the adaptive law has been developed. Additionally, a continuous projection operator is applied to adaptive law such as to enforce the estimated mover mass within a pre-specified bound. The performance of ASMC based on continuous projection operator is investigated via simulation results within MATLAB environment. Also, a comparison study in ASMC performance is made due to the inclusion continuous and discontinuous projection operators. The simulated results showed that ASMC based on continuous projection gives better performance than that based on discontinuous one.

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PMLSM; vector control; ASMC; continuous projection operator; discontinuous projection operator

1. Introduction
The fast development in industrial society attracted wide attention to development in linear drive systems. Conversion from rotary based drive systems to linear ones degrades the precision capabilities due to possible occurrence of mechanical interconnections and ratio reduction and backlashes (Zhu, Han, Wang, Zhu, & Guo, 2017). Permanent magnet linear motors (PMLSMs) represent one solution for the modern linear drive systems, which characterized by high thrust density, low losses, and small electrical time constant (rapid response) (Zhu, Wang, Xu, & Feng, 2012). They became the main part of many automation factories, which requires linear actuating processes. Permanent Magnet Linear Synchronous Motor (PMLSM) differs in structure than rotary Permanent Magnet Synchronous Motor (PMSM) in that the PMLSM contains a moving part named as mover, which mainly constructed from laminated iron sheets grooved uniformly. The three-phase winding of the stator are uniformly distributed in these grooves and the stationary part of the PMLSM contains the permanent magnets stacks along the moving path (Boldea, Pucci, & Xu, 2018). The interaction between the generated electromagnetic thrust, due to applying three-phase voltage, with that produced by permanent magnet leads to actuating the mover (Chen, Huang, Chen, & Lu, 2014; Zhu et al., 2017).

The working with PMLSM in industrial environments often encounters uncertain variation in mover mass during the operation cycle. As such, classical control theory with stationary gains fails to cope with the changes in system parameters and these conventional control strategies become less effective and lead to loss of robustness characteristics. However, in the literature of position control for PMLSM, the challenging problem due to the presence of uncertain and unknown mover mass has been avoided, which is mainly addressed in the present work.

Recently, the position control of PMLSM drive system attracted many researchers. In what follows the most recent and relevant works are briefly surveyed. Chen and Lu (2014) applied the adaptive backstepping with sliding mode controller for position control of PMLSM where the PID controller is used as a baseline controller combined with both adaptive backstepping with sliding mode controllers to improve the robustness of the controller, a non-modified adaptive law may be considered a counter robustness effect. Lin and Lin (2016) proposed the integral backstepping control with percentage uncertainty observer based on adaptive recurrent neural network.
uncertainty observer RNNUO. Jun, Li, and Chao (2017) proposed Energy Shaping Method based on Hamiltonian feedback dissipative control strategy. This control method is to make the input and output energy of the system reach a dynamic equilibrium state. Xiao and Pan (2017) employed the classical PID controller. Dynamic surface backstepping Sliding mode control (SMC) has been developed by Xiaoying, Limei, and Yibiao (2017); in this research, both backstepping and SMC design have been combined and a low pass filter is included for chattering suppression due to hard switching functions. In Yahiaoui, Kechich, & Bouserhane, (2017), the performance of SMC combined with adaptive disturbance estimator has been investigated. Predictive current control with adaptive internal model control has been presented by Yang, Wang, Zhang, and Li (2017). El-Sousy and Abuhasel (2018) presented adaptive nonlinear disturbance observer using a double-loop self-organizing recurrent wavelet neural network, where feedback linearization controller mixed with double-loop self-organizing recurrent wavelet neural network disturbance observer to enhance the stability and robustness of predictive current control system which is highly affected by the parameters mismatch. Ty et al. (2018) presented Laguerre Model-Based Model Predictive Control Law. Finally, Xi et al. (2018) proposed adaptive 2 DoF P-PI controller based on an improved just-in-time learning technique for ultra-low-velocity (Xi, Dong, Ding, Liu, & Ding, 2018).

This paper is highly motivated by the recent studies in precise position and speed control of recent contributions of robust adaptive control theory presented by (Humaidi and Hameed 2017–2018) (Humaidi, Hameed, & Hameed, 2017; Humaidi, Hameed, & Hameed, 2018; Humaidi, Badr, & Hameed, 2018; Humaidi & Hameed, 2017).

The main contributions of this paper are to propose an ASMC-based continuous projection operator to achieve the following objectives:

1. To robustly control the position of PLMSM using adaptive SMC,
2. To cope with unknown variation of parameters due to totally unknown mover mass using adaptive control,
3. To confine the estimated mover mass within a prescribed bound (projection operator).
4. Continuous projection operator is used instead of a discontinuous version of projection operator.

In addition to this section, the whole paper comes with: Section 2, the derivation of the dynamic model of the PMLSM and the vector control represented by field orientation, Section 3, the controller design based on Lyapunov stability analysis, Section 4 discusses the simulation results and finally Section 5 comes with the conclusions.

2. Dynamic model of PMLSM based on vector control

Dynamic model of PMLSM is developed based on the machine theory of rotary PMSM. The PMLSM dynamic model is a combination of two interconnected systems; the electrical system which devoted to the electrical equilibrium assessed by stator and rotor voltages according to Kirchhoff’s voltage law and the mechanical system equation which represent the force or thrust equilibrium gathered by means of Newton’s second law. To adapt the dynamic model of three-phase PMLSM with advanced control theory, the three-phase reference frame is transformed to two synchronously rotating reference frames using Clarke and Park transformations. The following assumptions are considered throughout the analysis of PMLSM mathematical model (Chen et al., 2014);

- Sinusoidal induced back induced electromagnetic motive force (e.m.f.)
- No losses have been assumed due to Eddy currents and magnetic hysteresis.
- No permanent magnet saturation.
- No consideration for excitation dynamics due to constant permanent magnet flux.

Based on these considerations, the dynamics of the PMLSM in the synchronously rotating reference frame is
described as (Chen et al., 2014; Zhu et al., 2017).

\[ v_d = r_s i_d + d \lambda_d / dt - \omega_e \lambda_q, \]  

(1)

\[ v_q = r_s i_q + d \lambda_q / dt + \omega_e \lambda_d, \]  

(2)

where \( \lambda_d = L_d i_d + \lambda_{pm} \lambda_q = L_q q, \) and also \( v_d, i_d, \lambda_d, L_d, \) \( r_s \) represent the direct axis voltage, current, flux linkage, inductance and stator resistance, respectively; \( v_q, i_q, \lambda_q, L_q \) represent the quadrature axis voltage, current, flux linkage and inductance, respectively; while \( \lambda_{pm} \) represents permanent magnet flux linkage and \( \omega_e \) represents the synchronous rotary angular equivalent velocity which is calculated as:

\[ \omega_e = (P_n \pi / \tau_p)v, \]  

(3)

where, \( v \) represents the mechanical linear speed of the motor mover, \( \tau_p \) is the pole pitch and \( P_n \) defines the pole pairs. The developed electromagnetic force is used to overcome the mover mass, load force and linear friction as indicated in the following equation:

\[ f_e = \dot{M} v / dt + B v + f_l, \]  

(4)

where \( \dot{M} \) represent the mover mass (which is assumed to be unknown), \( v \) is defined as the mechanical linear speed of the motor mover, \( f_e \) represent the electromagnetic-generated thrust, \( f_l \) represents the load thrust and \( B \) accounts for viscous friction coefficient.

Electromagnetic thrust and its relationship to other machine variables can be found by analysing the power equation where the electromagnetic thrust can be described as (Chen et al., 2014; Zhu et al., 2017):

\[ f_e = \frac{3P_n \pi}{2 \tau_p} (\lambda_{pm} + (L_d - L_q) q) q. \]  

(5)

Using Equations (1), (2) and (4) gives the following set of first order differential equations:

\[ dx / dt = v, \]

\[ dv / dt = (f_e - B v - f_l) / \dot{M}, \]

\[ di_d / dt = (-r_s i_d + (L_q P_n \pi / \tau_p) v q + v_d) / L_d, \]  

(6)

\[ di_q / dt = (-r_s i_q - (L_d P_n \pi / \tau_p) v id - (\lambda_{pm} P_n \pi / \tau_p) v + v_q) / L_q. \]

where \( x \) represents the linear position of the mover. It is obvious that the model described by Equation (8) is coupled and nonlinear equation. The model of PMLSM can be customized to work like a DC-Motor using filed orientation control.

Field orientation is simply done by making \( i_d^* = 0, \) hence the commanded thrust force \( f_e^* \) becomes (Zhu et al., 2012):

\[ f_e^* = (3 \lambda_{pm} P_n \pi / 2 \tau_p) i_q^* q. \]  

(7)

Therefore, the mechanical part of Equation (6) can be reduced to

\[ \dot{x} = v, \]

\[ \dot{M} v = (3 \lambda_{pm} P_n \pi / 2 \tau_p) i_q^* - B v - f_l. \]  

(8)

where the differential operator \( d / dt \) is replaced by a dot on the variable. Setting the state variables \( \{x_1, x_2\} = [x, v], \)
Equation (8) can be written in terms of state variable \( x_1 \) and \( x_2 \) as follows:
\[
\dot{x}_1 = x_2,
\]
\[
\ddot{M}x_2 = Bx_1 + bi_q^* - f_i, \tag{9}
\]
where \( b = (3\lambda_p\rho P_n\pi/2\tau_p) \).

The projection-based adaptive SMC with vector control principle (field orientation control) can be schematically described in Figure 1.

The figure shows that the ASMC generates the commanded quadrature current \( i_q^* \) described in synchronously rotation frame, in which the current \( i_q^* \) has a dc value. The commanded quadrature current is compared with actual quadrature current \( i_q \) to yield desired voltage in the synchronously rotating frame. A transformation from synchronously rotating frame to stationary frame is performed using \( dq \Rightarrow \alpha \beta \) transformation block with the help of instantaneous rotating angular position extracted from the mover position. The transformed voltages \( u_\alpha \) and \( u_\beta \) in stationary \( \alpha \beta \) frame, instantaneously varying quantities, are fed to PWM to generate the required signals to inverter such as to properly actuating the PMLSM. To produce the actual quadrature currents \( i_q \) and \( i_q^* \), the abc current quantities measured from three-phase lines, using any suitable measuring sensors, are converted to stationary \( \alpha \beta \) frame using \( abc \Rightarrow \alpha \beta \) transformation block. Then, these currents \( i_q \) and \( i_q^* \) are transformed to \( dq \) frame using \( \alpha \beta \Rightarrow dq \) transformation block. The converted quadrature currents \( i_q \) and \( i_d \) are characterized by having dc values since they are riding on synchronously rotating \( dq \) frame.

### 3. Adaptive SMC

#### 3.1. Controller design and stability analysis

Referring to the field-oriented dynamics described by Equation (9) and assuming the friction term is either equal to zero or lumped with load term, the following form can be obtained
\[
\dot{x}_1 = x_2,
\]
\[
\ddot{x}_2 = \dot{i}_q^* + N_i, \tag{10}
\]
where \( x_1 \in \mathbb{R} \) represents the position state variable, \( x_2 \in \mathbb{R} \) represents the speed state variable, \( i_q^* \in \mathbb{R} \) represents the control action, \( M = \ddot{M}/b \) is an unknown moment of inertia parameter with bound of variation \( M \leq M_{\text{max}} \), and \( N = (B/b)x_1 - f_i/b \) represents the uncertainty term, which is described by matched uncertainty and disturbance and has the upper bound \( N \leq N_{\text{max}} \).

In order to design a robust controller to the system of the Equation (10) taking into account, the effect of both unknown inertia and uncertainty term \( N \), the ASMC is adopted such that the actual position state variable \( x_1 \) tracks the desired trajectory \( x_d \). The position error is defined as:
\[
e = x_1 - x_d. \tag{11}
\]

The position error derivative is given by:
\[
\dot{e} = x_1 - \dot{x}_d = x_2 - \dot{x}_d. \tag{12}
\]

Generally, the selection of the sliding surface is based on the following equation (Utkin et al., 2009):
\[
s(e) = (d/dt + c)^{-1}e,
\]
where \( r \) is the system relative degree. For the system described in Equation (10), the relative degree is equal to \( r = 2 \). Therefore, the sliding surface can be written as:
\[
s = \dot{e} + ce. \tag{13}
\]
where \( c > 0 \) is a design constant.

Defining \( q = \dot{x}_d - ce \), Equation (13) can be rewritten as:
\[
s = x_2 - q. \tag{14}
\]

Taking the derivative of the above equation, one can have
\[
\dot{s} = \dot{x}_2 - \dot{q}. \tag{15}
\]

The control action \( i_q^* \) is selected to have three terms (Liu & Wang, 2012):
\[
i_q^* = i_{qa}^* + i_{qf}^* + i_{qr}^*, \tag{16}
\]
where \( i_{qa}^* \), \( i_{qf}^* \), and \( i_{qr}^* \) represent the adaptive part, the feedback part and robustness part of the controller, respectively. These parts can be expressed as follows (Liu & Wang, 2012):
\[
i_{qa}^* = \dot{M}q,
\]
\[
i_{qf}^* = -ks, \tag{17}
\]
\[
i_{qr}^* = -\lambda \cdot \text{sgn}(s).
\]
Combining Equations (16) and (17) to have:
\[
i_q^* = \dot{M}q - ks - \lambda \cdot \text{sgn}(s). \tag{18}
\]
where \( k > 0 \) and \( \lambda \) a constant to be determined later.

Selecting the following Lyapunov candidate function:
\[
V(\dot{M}, s) = \frac{1}{2} Ms^2 + \frac{1}{2\gamma} \Delta M^2 \tag{19}
\]
where \( \gamma > 0 \) represent the adaptive learning rate and \( \Delta M = \dot{M} - M \) represents adaptive gain estimation error.
The time derivative of Lyapunov function gives:
\[ \dot{V}(\hat{M}, s) = Ms\ddot{s} + \frac{1}{\gamma} \Delta \hat{M} \dot{M}. \]

or,
\[ \dot{V}(\hat{M}, s) = s(M\dot{x}_2 - Mq) + \frac{1}{\gamma} \Delta \hat{M} \dot{M}. \]

Using Equation (10), one can have
\[ \dot{V}(\hat{M}, s) = s(i_q^* + N - Mq) + \frac{1}{\gamma} \Delta \hat{M} \dot{M}, \]

Using simple linear algebra, Equation (26) can be written as
\[ \dot{V}(\hat{M}, s) \leq -ks^2 - \lambda|s| + sN_{\text{max}}. \]

By choosing \( \lambda > N_{\text{max}} > 0 \), the term \( -\lambda|s| \) will dominate the term \( +sN_{\text{max}} \). This leads to:
\[ \dot{V}(\hat{M}, s) \leq -ks^2 - \mu, \]

where \( \mu > 0 \) which guarantees the negative definiteness of \( V(\hat{M}, s) \).

3.2. Projection operator based adaptive law

The concept of projection operator was firstly proposed in adaptive control theory by Pomet and Praly (1992). This technique became widely used in different methodologies of adaptive control design. The key with technique is to restrict the solution of adaptive law within a prescribed bound such that the trajectory never leaves this bounded region at all.

Projection operator modification is combined with the adaptive law in order to make pre-specified bounded adaptive gain. It has been shown that the projection operator technique, which may have different schemes, can be used to improve the robustness of the adaptive law against the effect of uncertainty and disturbance (Lavretsky & Wise, 2013). Hence, it is an efficient tool for robustness purposes.

If the parameter vector \( -\gamma qs \) belongs to a convex set, \( \Omega_0 = \{ \hat{M} \in \mathbb{R}^n f(\hat{M}) \leq 0 \} \) and there is another convex set, \( \Omega_1 = \{ \hat{M} \in \mathbb{R}^n f(\hat{M}) \leq 1 \} \), then it becomes obvious that \( \Omega_0 \subseteq \Omega_1 \) as indicated in Figure 2. It is clear from the figure that \( \text{Proj}(\hat{M}, -\gamma qs) \) does not change the vector \( -\gamma qs \) if \( \hat{M} \) belongs to the convex set \( \Omega_0 \).

Inside the annulus set \( 0 \leq f(\hat{M}) \leq 1 \), the Projection operator algorithm subtracts the vector, which is normal to the boundary \( f(\hat{M}) = M_{\text{max}} \), from the vector represented by \( -\gamma qs \). This results in a smooth transformation from the original vector field \( -\gamma qs \) for \( \hat{M}^* \), where \( f(\hat{M}) = 0 \), to the tangent of the boundary vector for \( M_{\text{max}} \), at which \( f(\hat{M}) = 1 \) (Lavretsky & Wise, 2013).

The scheme of Projection operator algorithm adaptive law suggested in Liu and Wang (2012) is a discontinuous version of Projection operator, which can be defined as:
\[ \dot{\hat{M}} = \text{Proj}(\hat{M}, -\gamma qs), \]

where
\[ \text{Proj}(\hat{M}, -\gamma qs) = \begin{cases} 0 & \text{if } \hat{M} = M_{\text{max}} \text{ and } -\gamma qs > 0 \\ 0 & \text{if } \hat{M} = M_{\text{min}} \text{ and } -\gamma qs < 0 \\ -\gamma qs & \text{otherwise} \end{cases} \]

The discontinuity nature of the projection operator described by Equation (34) may acts adversely in case of using the projection operator modification for smooth and bounded adaptive gain. In the present work, the continuous projection operator is replaced instead of discontinuous projection operator to cope the loss of Lipchitz continuity in the discontinuity points which may cause a
lack in existence and uniqueness of the adaptive law solutions. Also, the lower and upper bounds for the unknown mass is a pre-requisite for the discontinuous projection operator, while the continuous requires only the upper bound.

As such, the continuous version of the projection has been suggested to replace the discontinuous projection operator algorithm. For this, the adaptive law can be defined as

\[
\dot{\hat{M}} = \text{Proj}(\hat{M}, -\gamma \dot{q} s, f(\hat{M})), \tag{35}
\]

where

\[
\text{Proj}(\hat{M}, -\gamma \dot{q} s, f(\hat{M})) = \begin{cases} 
-\gamma \dot{q} s + \nabla f^T \nabla f \nabla f f(\hat{M}), & \text{if } f(\hat{M}) > 0 \land (-\gamma \dot{q} s)^T \nabla f > 0, \\
-\gamma \dot{q} s & \text{elsewhere}
\end{cases}, \tag{36}
\]

where a convex function \( f(\hat{M}) \) is necessary for Projection Operator algorithm, \( \nabla f \) represents the Gradient vector of convex function \( f(\hat{M}) \), and \( \nabla f^2 = \nabla f^T \nabla f \) is the weighted Euclidean squared norm of \( \nabla f \). Also, the fact \( \text{Proj}(\hat{M}, -\gamma \dot{q} s, f(\hat{M}))) + \gamma \dot{q} s \) is considered as a bargain because it contributes to make the Lyapunov candidate time derivative negative definite (Lavretsky & Wise, 2013).

### Table 1. PMLSM parameters (Zhu et al., 2012).

| Parameter                        | Value and units |
|----------------------------------|-----------------|
| Number of pole pair \( P_n \)    | 3               |
| Pole pitch \( r_p \)             | 39 mm           |
| Stator resistance \( r_s \)      | 1 Ω             |
| Direct axis inductance \( L_d \) | 13.91 mH        |
| Quadrature axis inductance \( L_q \) | 13.91 mH  |
| Mover mass \( \bar{M} \)         | 96 kg           |
| Viscosity friction coefficient \( B \) | 0.1 Ns/m       |
|Permanent magnet flux linkage \( \lambda_{pm} \) | 0.22324 Wb |
| Maximum linear displacement of mover \( x_{max} \) | 1.5 m          |

### Table 2. Performance report of position response based on adaptive law with continuous and discontinuous projection operators.

| Time (s) | 3       | 9.55    | 15.75   | 22.1    |
|----------|---------|---------|---------|---------|
| Position response error \( e(m) \) | Adaptive law with Continuous proj. | -0.033 | -0.0015 | -0.0223 |
|          | Adaptive law with Discontinuous proj. | -0.0351 | -0.0014 | -0.024  |

4. Simulated results

The PMLSM model is simulated using MATLAB/SIMULINK. The running parameters of PMLSM are listed in Table 1. The simulation is excited by sinusoidal desired position trajectory. The maximum excursion of sinusoidal desired trajectory is ±0.6 m with initial condition of +0.2 m and 0.5 rad/s frequency. The design parameters \( c = 3 \), \( k = 100 \), \( \gamma = 300 \) and \( \lambda = 230 \) are selected based on the try-and-error procedure to give a suitable dynamic performance. Three configurations of SMC adaptive law schemes have been considered. The first scenario of simulation is based on adaptive law without projection operator, the second scenario is based on adaptive law with continuous projection, while the third scenario is concerned to the adaptive law based on discontinuous projection operator.

The position response of the controlled motor is simulated in Figure 3. The figure shows that the position response based on adaptive law with continuous projection gives better transient characteristics than that based on discontinuous projection or that without the presence of projection. Also, the dynamic performance of three adaptive schemes is investigated under disturbance application. The load is composed of step load of height 200 N, which has been exerted at time 7 s, added to it a sinusoidal disturbance of amplitude of 50 N with

![Figure 3. Sinusoidal position response of mover.](image-url)
the frequency of 5 rad/s along the whole run of simulation. Again, the dynamic performance based on adaptive law with continuous projection outperforms that based on discontinuous projection or based on projection-free adaptive law. Table 2 evaluates the minimum instantaneous error at different times described by zoomed plots within Figure 3. One can see that the error due to continuous projection is less than that resulting from discontinuous one.

Figure 4 shows the ASMC-based velocity response of PMLSM. It is clear that a faster response is obtained with an adaptive law based on continuous projection.

**Figure 4.** The velocity response of mover.

**Figure 5.** The response developed electromagnetic thrust.

**Figure 6.** The estimated mass value of mover mass (adaptive gain).
operator. The response of developed electromotive thrust is illustrated in Figure 5. One can see that the developed electromotive thrust effort with adaptive law based on continuous projection operator is less than that seen in other adaptive schemes.

One main solution of projection-based adaptive law is to confine the estimated mover mass (adaptive gain) with limited bound; otherwise, the gain may grow without bound and lead to instability problems. Although the drift in estimated mover mass is not sensible for the considered run time, this drift can be considerable for a long time of simulation. However, both continuous and discontinuous based adaptive scheme could successfully prevent the adaptive gain to go out a pre-described bound. Figure 6 shows the evolution of adaptive gain based on continuous and discontinuous projection operator. Again instantaneous evaluation of estimated adaptive gain at samples of time instants, represented by a zoomed snapshot of the figure, is presented in Table 3. In the minimum sense, the table declares that continuous projection performs better than discontinuous one.

Table 3. Adaptive gain observations.

| Time (s) | 0.05 | 12 | 17.5 | 30 |
|----------|------|----|------|----|
| Adaptive gain $\hat{M}$ (Continuous proj.) | -124.5 | 3.5 | 2.5 | 33 |
| Adaptive gain $\hat{M}$ (Discontinuous proj.) | -127.5 | 4.6 | 4 | 36 |

Table 4. Control action observations.

| Time (s) | 0.543 | 21.95 |
|----------|-------|-------|
| Control action $i^*_{q}$ (Continuous proj.) | 2.73 | 2.92 |
| Control action $i^*_{q}$ (Discontinuous proj.) | 2.75 | 2.93 |

Table 5. Numerical improvement comparison of projection schemes.

| Variable | Continuous proj. | Discontinuous proj. | Improvement% |
|----------|------------------|---------------------|--------------|
| Control action $i^*_{q}$ (A) | 4.7351 | 4.7987 | 1.3254 |
| Adaptive gain $\hat{M}$ | $1.4416 \times 10^3$ | $1.4658 \times 10^3$ | 1.651 |
| Position response error $e(m)$ | $2.7387 \times 10^{-4}$ | $2.7946 \times 10^{-4}$ | 2.0003 |

Figure 7. Sliding surface response.

Figure 8. Control action response.
The sliding surface response, shown in Figure 7, indicates that the sliding mode controller could conduct the sliding surface to zero equilibrium point, at which the error and error velocity is identically zero. Figure 8 shows the control action response, where less control action can be given by the continuous projection-based adaptive law. Table 4 evaluates the instantaneous value of commanded quadrature current at two samples of time. Table 4 tells that the current driven by adaptive law based on continuous projection is less than that developed by discontinuous one.

Table 5 summarizes the improvement comparison given by the two schemes of projection techniques. The evaluation has been based on variance calculation and

Figure 9. Stator currents and voltages response (continuous projection operator).

Figure 10. Three-phase Stator currents and voltages response (discontinuous projection operator).

Figure 11. Response of generated electromagnetic thrust with applied load.
one can see that a slight improvement has been gained using continuous projection.

Figures 9 and 10 show the responses of stator currents and voltages resulting from adaptive laws based on continuous and discontinuous projection operators, respectively. The effect of the loaded thrust on the current response can be examined, where a less effect on current with the presence of continuous projection-based adaptive law. The response of developed electromagnetic thrust due to the application of load thrust is shown in Figure 11. It is obvious that the generated thrust has responded to compensate the load effect. The phase portrait of error versus the error derivative for three schemes of adaptive laws based on projection (continuous and discontinuous) and without projection is depicted in Figure 12. The figure indicates that the convergence rate of trajectory is faster in case of ASMC based on continuous projection than that based on others. However, it is clear from the figure that how the disturbance prevents the solution trajectory to settles at equilibrium point and remains within cycling trajectories nearby the equilibrium point.

5. Conclusion

In the present work, adaptive SMC has been designed for position control of PMLSM to cope with the total unknown and uncertain mover mass. The continuous projection-based adaptive law is considered to confine the adaptive gain within defined bound. The performance of adaptive law based on continuous projection operator is compared to discontinuous projection operator from the previous study. The effectiveness of ASMC based on modified adaptive laws has been investigated based on computer simulation within MATLAB environment.

The simulation results show that the ASMC could successfully lead the sliding surface to zero equilibrium point under unknown and uncertain mass mover. Moreover, for sinusoidal desired trajectory, the adaptive law based on continuous projection operator could give better transient characteristics, faster rate of convergence, less control action and less estimated mover mass than that given by the adaptive law based on discontinuous projection operator.

Disclosure statement

No potential conflict of interest was reported by the authors.

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