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Integration of Sparrow Search Optimization with Terminal Synergetic Control for Permanent Magnet Linear Synchronous Motors

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***Abstract*—This paper proposes a theoretical framework of the procedure to design an optimal robust terminal synergetic control (TSC) for the permanent magnet linear synchronous motors (PMLSMs). The general component and the mathematical equations of the PMLSM are first introduced. Based on the established model of the PMLSM, the control law of the TSC is developed. The tuning process of the TSC gains is enhanced by employing sparrow search optimization (SSO) based on the Integral Time of Absolute Errors (ITAE). The effectiveness of the proposed control algorithm has been verified by numerical simulations using MATLAB software for a step input. Additionally, the results have been compared with the classical synergetic control (CSC). The comparison shows that the TSC exhibits a good performance in normal operation and in a robustness test involving system parameters' changes as compared to the CSC.**

***Keywords*—Robust Control; Permanent Magnet Linear Synchronous Motor; Terminal Synergetic Control; Metaheuristic Algorithms; Sparrow Search Optimization; Parameter Uncertainty.**

I. INTRODUCTION

Linear motion is not less importance than rotary motion in the fields of industry, automation, and many health or military applications. Conventionally, many techniques and mechanisms are applied in order to change the motion from rotary to linear, such as gearboxes, chains, and screw connections, or by using pneumatic and hydraulic actuators. However, due to the limitations and drawback represented by energy loss, corrosion, vibrations, the need for frequent maintenance, lack of cleanliness, and the difficulty of sealing the leak points of hydraulics and compressed air. In order to overcome these impedimenta, permanent magnet linear synchronous motors (PMLSM) are used which have the ability to produce linear motion from electrical power without any conversion mechanism [1]-[3].

PMLSM is steadily being used in many modern systems and contemporary industries such as electromagnetic launch (EML) systems [4], rope less elevator [5], semiconductor manufacture [6], precision machine tools [7], laser cutting machine [8], CNC systems [9], nano-manufacturing [10], 3D printers [11], transportation maglev train [12]-[13], high-speed injection molding [14]. PMLSM has technical characteristics that make it suitable for the mentioned applications, thanks to its simple design, high positioning accuracy, fast dynamic responses, high thrust density, wide thrust range, high acceleration and high energy saving [15]-[19].

Interest of researchers and engineers in the PMLSM increases as the amount of vital applications increases and vastness to ensure the best performance and most accurate implementation of the tasks assigned to it. An overview of a collection of studies and researches that have made significant contributions to the further understanding and development of PMLSM are presented as follows:

Dongxu Yang et al. [20] adopted an iterative learning control approach to activate the sliding mode controller using the feedforward compensation strategy to ensure the reduction of the ripple in the PMLSM thrust. He first analyzed the ripple of the PMLSM thrust using the 2-D finite element method. The results confirmed the validity of the approach used to significantly reduce the ripple in the motor thrust. Zhonggang Yin et al. [21] solved the problems of load disturbance and time varying uncertainty in PMLSM by designing a backstepping controller based on an extended state observer, due to the features of this controller design, high speed response and strong neutralization of unwanted load disturbances is achieved. Xiaowen Zhang et al. [22] proposed a fuzzy adaptive kalman filter to suppress the force ripple effect in PMLSM. According to the fuzzy control theory, this method takes the axis current error and the error rate as the input of fuzzy control, and takes the parameter in the measurement noise covariance matrix as the output of fuzzy control, which reduces the burden of parameter adjustment and improves the disturbance rejection performance. Rui Yang et al. [23] paid attention to the processing of thrust ripple and used second-order sliding mode observer with super-twisting algorithm, and the results of the paper confirmed the efficiency of this proposed controller. Ben Hur Bandeira et al. [24] addressed the problem of the counter-force effect at the ends by using the multi-loop resonant controller method for the current in the direct-axis direction of the first loop with a proportional-integral (PI) controller and the current in the quadrature-axis direction of the second loop with a modified PI plus a multiple resonant (PI-RES) controller, thus ensuring the best performance. Xinyi Su et al. [25]

successfully applied a neural network (NN)-based adaptive sliding mode controller to determine the unknown parameter values and nonlinearities of the PMLSM motor, and thus address the effect of friction and undulation on the thrust force.

II. Mathematical Modeling

The increasing scope of industrial applications for permanent magnet linear synchronous motors (PMLSM) reflects the urgent needs to further develop a robust, accurate and fast control techniques and controller in order to meet the basic requirements of these required industrial applications. Electromechanical systems are considered as complex and difficult systems in nature. As a result, they require an accurate mathematical modeling to simulate the system and allows to improve their performance, studying and analyzing their behavior, in order to control them in a manner that is compatible with the application for which they were used [26]-[27].

Based on the general theory of electrical and mechanical engineering, in addition to the assumptions were taken, the mathematical model of the PMLSM is obtained [28]. The best method is to derive PMLSM mathematical model is to change the rotary coordinates of the position and speed to the linear. It is well known that all the mathematical models of the electromechanical systems consist of two parts: the first is electrical part (voltage equations) and the second is mechanical part (torque equation) [29]. In terms of electrical part, the notations of this part are listed below:

θ_e is the electrical angle.

r_a, r_b and r_c are the stator winding resistances and they are equal ($i.e. r_a = r_b = r_c\ r$).

i_a, i_b and i_c are the stator current.

Φ_a, Φ_b and Φ_c are the stator flux linkage.

L_d, L_q The inductances on d-q axis.

Ω_e is an electrical speed (rad/sec).

Φ_q, Φ_d are flux linkages of the stators on d-q axis.

i_d, i_q are the stator currents on d-q axis.

E_d, E_q are the stator voltages on d-q axis.

Φ_r is the permanent magnet flux.

Ω_e is the electrical speed.

This part is consisted of two basic components according to Ohm's Law and Faraday's Law, as follows [30]:

$$[E]_{abc} = [R]_s[i]_{abc} + \frac{d}{dt}[\Phi]_{abc} \tag{1}$$

where

$$\Phi = Li, [R]_s = \begin{bmatrix} r_a & 0 & 0 \\ 0 & r_b & 0 \\ 0 & 0 & r_c \end{bmatrix}, [i]_{abc} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, [\Phi]_{abc} = \begin{bmatrix} \Phi_a \\ \Phi_b \\ \Phi_c \end{bmatrix}$$

In order to simplify the mathematical model of a PMSM, it is very useful to write it in the direct-quadrature synchronous coordinates by [P⁄C] Park-Clark transformation matrix (Based on the principle of FOC) [31].

$$[P/C] = \frac{2}{3}\begin{bmatrix} \cos\theta_e & \cos\left(\theta_e - \frac{2\pi}{3}\right) & \cos\left(\theta_e + \frac{2\pi}{3}\right) \\ -\sin\theta_e & -\sin\left(\theta_e - \frac{2\pi}{3}\right) & -\sin\left(\theta_e + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{2}$$

In accordance to the following approach, the d-q axis voltage equations of the rotary PMSM is given by:

$$\begin{bmatrix} E_d \\ E_q \\ E_0 \end{bmatrix} = [P/C]\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \tag{3}$$

$$\left.\begin{aligned} E_d &= ri_d - \Omega_e\Phi_q + \frac{d\Phi_d}{dt} \\ E_q &= ri_q + \Omega_e\Phi_d + \frac{d\Phi_q}{dt} \end{aligned}\right\} \tag{4}$$

Where

$\Phi_q = L_q i_q$, $\quad \Phi_d = L_d i_d + \Phi_r$

Substituting values of Φ_q and Φ_d into Eq. (4) gives:

$$\left.\begin{aligned} E_d &= ri_d - \Omega_e L_q i_q + \frac{d}{dt}(L_d i_d + \Phi_r) \\ E_q &= ri_q + \Omega_e(L_d i_d + \Phi_r) + \frac{d}{dt}(L_q i_q) \end{aligned}\right\} \tag{5}$$

Regarding the mechanical part, the torque balance equation is given by [28]:

$$\begin{gathered} J\frac{d}{dt}(\Omega_r) = T_e - T_l - B\Omega_r \\ \frac{d}{dt}(\Omega_r) = \frac{-B\Omega_r}{J} + \frac{1}{J}(T_e - T_l) \end{gathered} \tag{6}$$

Where, T_e is the electromagnetic torque produced by the motor, T_l is the load torque, J is the moment of inertia of system, B is the damping coefficient, Ω_r is angular speed. T_e is an electromagnetic torque of the PMSM has to be expressed corresponding to d-q axes flux linkages, rotor flux linkage, and d-q-axis inductances as stated in is given as [30]:

$$\begin{gathered} T_e = \frac{3}{2}p\left(\Phi_d i_q - \Phi_q i_d\right) \\ T_e = \frac{3}{2}\left(\Phi_r i_q + \left(L_d - L_q\right)i_d i_q\right) \end{gathered} \tag{7}$$

Since $L_d = L_q$, Eq. (7) becomes:

$$T_e = \frac{3}{2}p\Phi_r i_q \tag{8}$$

where p is defines the pole pairs. In order to get the complete mathematical model of the PMLSM, it has to establish the equivalent equation of θ_e and Ω_e based on the linear coordinate by x and v respectively [28]:

$$\theta_e = P\frac{\pi}{\tau_p}x \tag{9}$$

$$\Omega_e = \frac{d\theta_e}{dt} = P\frac{\pi}{\tau_p}\frac{dx}{dt} = P\frac{\pi}{\tau_p}\dot{x} = P\frac{\pi}{\tau_p}v \tag{10}$$

Therefore, F_e the electromagnetic force of PMLSM can be expressed as:

$$F_e = \frac{3}{2}\frac{\pi}{\tau_p}\Phi_r i_q \tag{11}$$

Eq. (11) can be formulated as:

$$F_e = \kappa_e i_q \tag{12}$$

where $\kappa_e = \frac{3}{2}\frac{\pi}{\tau_p}\Phi_r$.

The final step the mathematical model of PMLSM can be made by integrating the electrical and mechanical dynamics as follows.

$$\frac{di_d}{dt} = -\frac{r}{L_d}i_d + \frac{L_q\pi}{L_d}vi_q + \frac{1}{L_d}E_d \tag{13}$$

$$\frac{di_q}{dt} = -\frac{L_d\pi}{\tau L_q}vi_d - \frac{r}{L_q}i_q - \frac{\Phi_r\pi}{\tau L_q}v + \frac{1}{L_q}E_q \tag{14}$$

$$\frac{dx}{dt} = v \tag{15}$$

$$\frac{dv}{dt} = \frac{1}{M}(F_e - F_l - Bv) \tag{16}$$

where F_l load torque, M is the mass of system, B is the damping coefficient, v is the linear traveling mechanical velocity of the motor mover part, x is the linear displacement of the motor mover part (actual position) [32].

According to Crescent et al., Syuan-Yi et al. and Fayez, [33]-[35], the main purpose of the controller design to the PMLSM is to create maximum thrust that minimum energy consumption, and this is achieved by forcing the current to maintain a zero value, so the thrust becomes the absolute value defined in Eq. (9) above. In this article, the variable required to be controlled is the distance (x), so the system can be represented by the following two equations with specifying the state variables $[x_1\ x_2] = [x\ v]$ and i_q as the control input u:

$$\frac{dx}{dt} = \dot{x}_1 = x_2 \tag{17}$$

$$\frac{dv}{dt} = \dot{x}_2 = \frac{1}{M}(\kappa_e u - F_l - Bx_2) \tag{18}$$

Eq. (18) can be formulated as:

$$\dot{x}_2 = f(x) + b - F_l \tag{19}$$

where $f(x) = -\frac{B}{M}x_2$ and $b = \frac{\kappa_e}{M}$

III. Controller Design

System's performance can be improved by using feedback controller. This improvement has been demonstrated for wide range of systems [36]-[47]. In this paper, the objective of the controller is to make the PMLSM follows a desired step input. For this purpose, the classical synergetic control (CSC) and terminal synergetic control (TSC) techniques are introduced in this section. Synergetic control is a simple, robust, nonlinear control algorithm has been implemented for numerous systems such as driven-pendulum system [48], ball and beam system [49], magnetic bearing systems [50] and twin-tanks system [51]. The design procedure for both CSC and TSC for the PMLSM system is given in the following subsections:

A. *Classical Synergetic Control*

In the first step, the tracking error e_t is defined as follows:

$$e_t = x_r - x_1 \tag{20}$$

where x_r is the input reference.

In CSC approach, the marco-variable σ is given by:

$$\sigma = \dot{e}_t + \lambda_1 e_t \tag{21}$$

where λ_1 is a positive scalar tuning coefficient.

Differentiating σ with respect to time obtains:

$$\dot{\sigma} = \ddot{e}_t + \lambda_1\dot{e}_t \tag{22}$$

Differentiating e_t with respect to time obtains:

$$\dot{e}_t = \dot{x}_r - \dot{x}_1 = \dot{x}_r - x_2 \tag{23}$$

Differentiating $\dot{e}_t$ with respect to time obtains:

$$\ddot{e}_t = \ddot{x}_r - \dot{x}_2 \tag{24}$$

The following trajectory equation is used to determine the motion of the controlled system:

$$\dot{\sigma} + \lambda_2\sigma = 0 \tag{25}$$

where λ_1 is a positive scalar tuning coefficient.

Substitute Eq. (22), (24) and (19) in Eq. (25) gives:

$$\ddot{x}_r - f(x) - bu + \lambda_2\dot{e}_t + \lambda_2\sigma = 0 \tag{26}$$

Rearrange Eq. (26) to determine u yield:

$$u_{SC} = \frac{1}{b}(\ddot{x}_r - f(x) + \lambda_1\dot{e}_t + \lambda_2\sigma) \tag{27}$$

B. *Terminal Synergetic Control*

The procedure to design TSC is given as follows:

The marco-variable σ is defined as follows:

$$\sigma = \lambda_1 {e_t}^q + \dot{e}_t \tag{28}$$

where the power q is a positive less than one.

Then, differentiating σ with respect to time obtains:

$$\dot{\sigma} = \lambda_1 q({e_t}^{1-q})\dot{e}_t + \ddot{e}_t \tag{29}$$

Determine the state trajectory of σ as:

$$\dot{\sigma} + \lambda_2\sigma = 0 \tag{30}$$

Substitute $\dot{\sigma}$ gives:

$$\ddot{e}_t + \lambda_1 q({e_t}^{1-q})\dot{e}_t + \lambda_2\sigma = 0 \tag{31}$$

Substitute $\ddot{e}_t$:

$$\ddot{x}_r - f_x - bu + \lambda_1 q({e_t}^{1-q})\dot{e}_t + \lambda_2\sigma = 0 \tag{32}$$

Rearrange Eq. (32) to determine u yield:

$$u_{TSC} = \frac{1}{b}(\ddot{x}_r - f_x + \lambda_1 q({e_t}^{1-q})\dot{e_t} + \lambda_2 \sigma) \quad (33)$$

IV. SPARROW SEARCH OPTIMIZATION

Swarm optimization techniques are superior to other optimization techniques in that they are fast and simple in implementing convergence as well as not being limited in distinguishing the objective function, self-organized, and in addition to their strength in global search [52]-[57]. Hence, researchers are interested in adopting these algorithms to solve a large number of optimization problems in practical applications [58]-[63].

From deep observing and analyzing the social living behaviors of sparrows, Xue and Shen in 2020 was inspired to introduce the sparrow search optimization (SSO) method [64]. Compared to other types of birds, sparrows have a good memory and an extreme intelligence. Sparrows always select one of two various strategies to find food and to avoid birds of prey and other predators. Another species of sparrow parasitizes producers and steals food they have already collected from them, while producers continue to actively search for other areas for food sources and avoid the scroungers [65]. Algorithm 1 presents the algorithm's pseudo code. The following is an explanation of the algorithm: Inside the specified problem's search space, a random initialization of $\mathrm{N_{pop}}$ sparrows is performed. Next, each sparrow's objective function is evaluated according to its position. In order to, determine whether each sparrow if it is a producer or a scrounger, the evaluation of the objective function must be executed for all sparrows, each according to its own location. Producers sparrow are constantly seeking out for new regions of food sources, while scroungers follow them directly so as to share them the same regions and food sources.

The position of the producers (N_{pd}) is updated in two directions. In the first direction, they move in a broad range searching for food. However, once there is a detection of a predator, all sparrows move quickly to other safe areas. These two mechanisms of movement can be modeled mathematical as follows [48]:

$$s_i(itr+1) = \begin{cases} s_i(itr)e^{\left(\frac{-itr}{k_1 T_{max}}\right)}, & if\ r_s < p_s \\ s_i(itr) + k_2, & if\ r_s \geq p_s \end{cases} \quad (34)$$

where s_i, itr, T_{max} and i are the sparrow position, iteration index, the iteration maximum number and population index. A random value is taken for the coefficient k_1 ($k_1 \in [0,1]$). The user randomly selects the coefficient p_s which represents safety threshold within a range of ($p_s \in [0.5,1]$). The coefficient r_s within a range of ($r_s \in [0,1]$) is also selected randomly. The coefficient k_2 is any arbitrary value that obeys normal distribution. According in the Eq. (34) if the condition $\mathrm{r_s} < \mathrm{p_s}$ is satisfied, may considerd that there is no scarein the surrounding area where the sparrows can fly searching for food. While, if $r_s \geq p_s$, that indicate there are predators and the sparrows should moves rapidly to a safe area [66].

The position update of the remaining scroungers may achieve as follows [48].

$$s_i(itr+1) = \begin{cases} k_2 e^{\left(\frac{s_w(itr) - s_i(itr)}{itr^2}\right)}, & if\ itr > \frac{N_{pop}}{2} \\ s_p(itr) + |s_i(itr) - s_p(itr)|A^+, & otherwise \end{cases} \quad (35)$$

Where $s_w(itr)$ represents the worst sparrow position, $s_p(itr)$ represents the best producer position. A^+ is randomly assigned either 1 or -1. In Eq. (35), the scroungers follow the location of the best sparrows. Nevertheless, when $itr > \frac{N_{pop}}{2}$, sparrows moves towards the sparrows with the worse objective function for survival [67].

Algorithm1. SSO pseudo code.

1. **Input**
   - Objective function, Population size ($\mathrm{N_{pop}}$), Number of producers ($\mathrm{N_{pd}}$), Number of sparrows who perceive the danger ($\mathrm{N_{sd}}$), Number of iteration ($\mathrm{T_{max}}$), parameter $\mathrm{p_s}$
2. **Initialization**
   - Initialize population $\mathrm{N_{pop}}$
   - Evaluate objective functions
   - Rank objective functions and find $\mathrm{s_p}$ and $\mathrm{p_w}$
3. **Loop:**
   - **while** ($\mathrm{itr} < \mathrm{T_{max}}$)
     - Update r_s
     - **For** $\mathrm{i} = 1{:}\,\mathrm{N_{pd}}$
       - ✓ Update the location of the sparrow using Eq. (34)
     - **End for**
     - **For** $\mathrm{i} = \mathrm{N_{pd}} + 1{:}\,\mathrm{N_{pop}}$
       - ✓ Update the location of the sparrow using Eq. (35)
     - **End for**
     - **For** $\mathrm{i} = 1{:}\,\mathrm{N_{sd}}$
       - ✓ Update the location of the sparrow using Eq. (36)
     - **End for**
     - Rank objective functions and update $\mathrm{s_p}$ and $\mathrm{p_w}$
     - $\mathrm{itr} = \mathrm{itr} + 1$
   - **End while**
4. **Print the Optimal Solution**

Lastly, suppose that the percentage of the population that detects a danger (N_{sd}) is in the range of 10% to 20%. In that status, the sparrows will as fast they could move to a safe region to explore a better one. Accordingly, the location of the sparrows, which are sober up the danger, is updated as follows [68]:

$$s_i(itr+1) = \begin{cases} s_g + k_4|s_i(itr) - s_g(itr)|, & if\ f_{s_i(itr)} > f_{s_g} \\ s_i(itr) + k_5\left(\frac{|s_i(itr) - s_w(itr)|}{\left(f_{s_i}(itr) - f_{s_w}(itr)\right) + k_6}\right), & if\ f_{s_i}(itr) = f_{s_g}(itr) \end{cases} \quad (36)$$

where the global optimal value position is s_g , the global optimal value is f_{s_g}, the current sparrow objective function is $f_{s_i}(itr)$ and the worst objective function is $f_{s_w}(itr)$.

k_4 and k_5 can be chosen randomly, considering that k_4 follows the normal distribution and k_5 is in the range ($k_5 \in$[-1,1]). In order to avoid division by zero, choose k_6 any small number. However in the case of $f_{s_i}(itr) > f_{s_g}$, the sparrows will fly directly to the best location. Whilst, in the case of if $f_{s_i}(itr) = f_{s_g}$, sparrow fly closer and closer to each other's.

V. SIMULATION EVALUATION

In this section, computer simulations based on MATLAB are performed to evaluate the proposed TSC and

CSC that are applied to tracking control of PMLSM system. To conduct the computer simulations, the PMLSM system that is described by Eq. (1)-(3) and the value of its main physical components that are listed in Table I [28] are used in the simulation to represent the dynamics of the system. The performance of the controlled systems is simulated for 6 seconds with a zero initial position and velocity. A step input with amplitude of a 0.6m is used to assess the performance of the TSC and CSC that are applied to PMLSM system.

TABLE I. PARAMETERS OF PMLSM SYSTEM

Parameter	Value
Mass (M)	96 K_g
Pole pitch (τ_p)	39 mm
Viscous Friction Coefficient (B)	0.1 Ns/m
Permanent magnet flux linkage (λ_{pm})	0.2324 Wb
Number of pole pair (P)	3

To optimize the performance proposed controllers, the SSO is employed to tune the design parameters of the CSC and TSC controllers. To see the impact of the terminal attractor technique, the tuning parameters (c_1 and c_2) of the CSC is firstly optimized. Then, the same value obtained for the CSC is used in the TSC. Furthermore, the additional adjustable parameter q is then optimized. The objective function of the SSO to tune the performance of the two controllers is based on the Integral Time of Absolute Errors (ITAE) as given in Eq. (37) [69].

$$ITAE = \int_{t=0}^{t=t_{sim}} t|e(t)|dt \tag{37}$$

where t_{sim} refers the total simulation time.

The population size (N) of the CO is 20 and the number of Iterations (T_{max}) is 30. Table II lists the design parameters values for TSC and CSC based on the SSO.

TABLE II. OPTIMAL SETTING OF TSC AND CSC

Parameters	Controller	
	CSC	TSC
c_1	12	12
c_2	47	47
q	-	0.9

The PMLSM's position response with TSC and CSC methods is depicted in Fig. 1. To determine the effectiveness of the proposed TSC approach, a numerical value of the ITAE is given in Table III. The visualized result in Fig. 1 with the help of the numerical result in Table III reveals that TSC and CSC follow the desired step input successfully. However, the TSC improves the overall performance of the system by reducing the value of the ITAE (1.22) in comparison with the CSC (1.44). This result show that the ITAE with TSC is reduced by 15.2% in compared with CSC.

TABLE III. ITAE IN NORMAL OPERATION

Controller	ITAE
TSC	1.22
CSC	1.44

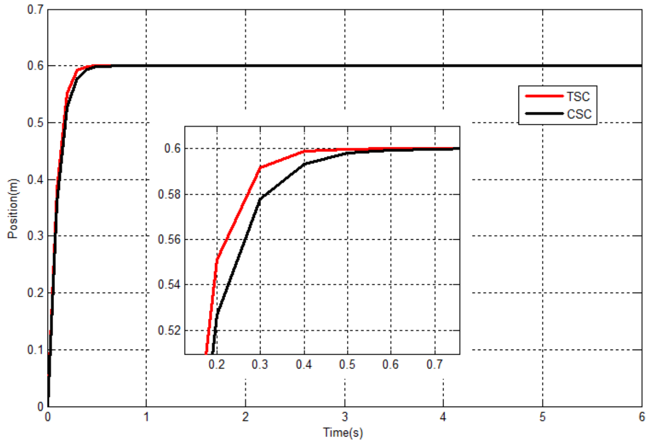

Fig. 1. PMLSM's position response for step input

To illustrate the resilience of the designed control laws in the face of mass variation, other simulation is conducted under 20% change in mass of the load. Fig. 2 shows the tracking performance of the position. The position for both controller tracks the given reference in the presence of mass variation thus proving the insensitive feature of the TSC and CSC to load variation.

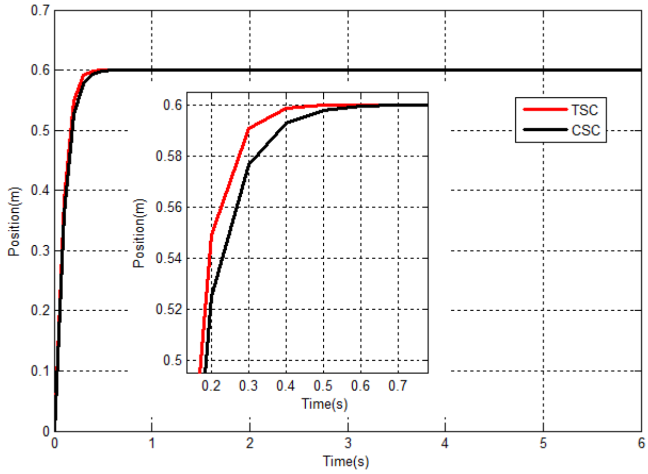

Fig. 2. PMLSM's displacement response for step input with 20% change in mass

The numerical value of the ITAE under mass variation is reported in Table IV. Based on Table IV, it can be said that the TSC slightly more robust that CSC by keeping the value of the ITAE of TSC at 1.22 in comparison with CSC where the value of the ITAE is increased from 1.44 to 1.45.

TABLE IV. ITAE WITH 20% CHANGE IN MASS

Controller	ITAE
TSC	1.22
CSC	1.45

The aforementioned results of the two scenarios reveal that the additional terminal factor that has been added to CSC increased the capability of the controller in terms of performance and robustness. This improvement could be further cross-validated on other systems in the future.

VI. Conclusion

A new robust control scheme for permanent magnet linear synchronous motors (PMLSMs) based on terminal synergetic control (TSC) is developed in this paper. According to its mechanical and electrical characteristic, the mathematical model of the PMLSM system is driven. The tuning process of the controller was carried out using sparrow search optimization (SSO). It was proven based on the numerical simulation using MATLAB that the TSC to be more effective in controlling PMLSMs and more robust compared to the classical synergetic control (CSC). The outcomes show that the TSC reduces the ITAE by 15.2% compared to with CSC. Moreover, with 20% change in the mass, the TSC presents more robust performance than CSC by keeping the value of the ITAE constant in comparison with CSC where the value of the ITAE is increased.

This work can be extended into different directions for future work. For example, the performance of the TCS can be examined under real-world implementation. Besides, a comparative study with other advanced control techniques can also be another potential area of future work.

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