Design, Optimization, and Control of a Linear Tubular Machine Integrated with Levitation and Guidance for Maglev Applications

Hamid Reza Esfahanian¹, Saeed Hasanzadeh*² (corresponding Author), Mojtaba Heydari³, Josep M. Guerrero⁴

1-Departmenet of Electrical and Computer Engineering, Qom university of Technology, Qom, Iran (e-mail: Esfahanian.h@qut.ac.ir, phone: +98-9354442829).
²-Departmenet of Electrical and Computer Engineering, Qom university of Technology, Qom, Iran (e-mail: hasanzadeh@qut.ac.ir, phone: +98-9127123710).
³- Department of Electrical and Computer Engineering, Qom university of Technology, Qom, Iran (e-mail: heydari@qut.ac.ir, phone: +98-9126513556).
⁴-Department of Energy Technology, Aalborg University, Aalborg, Denmark (e-mail: joz@energy.aau.dk, phone: +45-99409726).

Abstract— Nowadays, with the increase of population, demand for efficient public transportation systems has increased. Magnetic levitation (maglev) trains are one of the best choices for the future. There are three separated systems in a classical magnetic train to achieve desirable performance. Hence, several control systems and sensors are essential for train operation. Accordingly, the classical maglev trains include complex structures, and they are so expensive. This paper presents the design, optimization, and control of a combined magnetic train structure with the integrated performance of suspension and guidance and a complementary propulsion system. These combined topologies provide a simple design, more convenient movement, and reduce construction and operation costs.

Index Terms—Magnetic levitation (maglev) trains; Linear induction motor (LIM); Finite element method (FEM); Optimization; Integrated Controller

I. INTRODUCTION

Nowadays, with the increase of population, demand for new public transportation systems has increased. These systems must be rapid and secure. Among the available options, the magnetic levitation (maglev) train is one of the best choices that has many advantages over the classical trains: 1) the fastest ground transportation system; 2) lower power consumption; 3) less noise and vibration; 4) more safety and more convenient; 5) better performance of acceleration and deceleration and also, better movement on a slope; 6) reduction in maintenance costs; 7) elimination of gear, coupling, axles, and bearings; 8) less impressionability to weather conditions; 9) environmentally friendly. So far, much research has been done on these trains' technologies, such as modeling and analyzing linear electric machines, superconducting magnets, and permanent magnets [1-3]. Three forces are required to achieve the desired performance in a maglev train: 1) levitation force that lifts the train; 2) guidance force that prevents train derailing; 3) propulsion force generated by a linear motor to move the train. There are three separate systems in the conventional maglev trains to generate these three forces [1, 4-6]. Thus, many sensors and control systems are necessary for the operation of the train that causes classical maglev trains complex and expensive. Furthermore, control of the levitation force is a severe challenge for engineers. In addition, it is one of the most challenging operations to apply in classical maglev trains [4, 7]. Some combined topologies are developed to eliminate these challenges that provide more convenient movement, simpler structure, and cheaper operation [4, 8-10]. Among suspension technologies used in maglev trains, the suspension system is inherently unstable in electromagnetic suspension (EMS) technology due to the nonlinear dynamic model. Therefore, the control of levitation force is necessary for this technology [1,11]. Even though, so far, different control techniques have been used to control the levitation force of the maglev trains. In most articles related to the suspension of magnetic trains, only the presentation and analysis of a control technique and improvement of the control process are considered. Indeed, usual suspension structures are used for mathematical modeling and control, while the design and geometry of the suspension structure
are not considered. Another problem of classical magnetic trains, which use separated systems for suspension and guidance, is the electromagnetic coupling effect of the levitation and guidance systems (of these two separated systems) which leads to the control disturbance of both systems and the complexity of the control process [11-13].

This paper presents a new magnetic train topology with integrated suspension and guidance and a complementary propulsion system. The proposed hybrid structure utilizes two separate force generation systems: A system for simultaneously achieving suspension and guidance performance and another system for propulsive force generation. In addition, the propulsion system serves as a complement for the suspension and guidance performance and supports the first system. In addition, the propulsion system has a complementary role and supports the first system for suspension and guidance performance. Next, we will introduce each of these designed systems and then provide a suitable controller for the integrated suspension and guidance system. And after that, we will evaluate this controller.

II. THE COMBINED TOPOLOGY OF THE MAGNETIC TRAIN

The combined structure of the magnetic train is shown in Fig. 1. The electromagnets are embedded at 45 degrees angle to the horizontal surface on the arms in two sides of the wagon for suspension and guidance performance. The propulsion force of the train is supplied through several linear tubular induction motors located below the train in the center of the rail or path (energization on the vehicle onboard). It should be noted that these linear motors have a common secondary.

A. Integrated suspension and guidance system

In classical magnetic trains, given that the suspension electromagnets are at zero degrees angle to the horizontal surface, the gap distance and its changes, as well as the balance between the magnetic force of the electromagnets and the weight of the train, are measured perpendicular to the horizontal surface. The suspension operation leads to maintaining the vertical gap distance at the optimum level and preventing any vertical displacement due to disturbances that affect on suspension system in Vertical alignment. Similarly, guidance operation in classical magnetic trains prevents any lateral deviations (deviations to the right or left) under the influence of lateral disturbances. So, in general, it can be concluded that the suspension system and the guidance system in a classical magnetic train prevent train movement in vertical and horizontal directions.

In the proposed hybrid structure with the new geometry of position of suspension electromagnets relative to the classical maglev structures, the electromagnetic attraction forces created by them, in addition to the suspension performance, will also act as guidance forces. In this way, we no longer need a separate magnetic system to generate guidance force, and this will simplify and cheapen the maglev structure and reduce the need for control systems and sensors.

Fig. 2 shows the vector diagram of forces in the proposed suspension system. According to the 45degree angle of electromagnets to the horizontal surface, by parsing the weight force into two components along the magnetic forces produced by two electromagnets and in opposite directions, to achieve balance, the magnetic force of each electromagnet must be equal to the weight component force in its direction. Any disturbances of force along with the vertical and horizontal directions (irrespective of their direction), just like the weight force, can be separated into two components along with two electromagnet forces. Therefore, despite disturbances, the control system changes two electromagnet forces to balance the forces in the direction of each electromagnet and maintains both air gaps in their desired amount. So, what is described as the integrated performance of suspension and guidance in the proposed system, achieves by controlling the air gap. In other words, any horizontal and vertical displacement will change the desired amount of air gap.

In addition to the suspension and guidance simultaneously with maintaining the air gap in the integrated suspension and guidance system, another issue that should be considered as an advantage of the proposed structure over the suspension system of classical magnetic trains is the reduction impact of air gap from vertical deviations and lateral deviations. According to Fig. 3. If Z1 is considered as ideal air gap in the suspension system of a classic magnetic train, as well as in the integrated suspension and guidance system, if vertical deviations X affect both systems, the new air gap in the suspension system of the classical magnetic train (Z'2) and the air gap in the integrated suspension and guidance system (Z2) are obtained by (1) and (2), respectively.

\[ Z'2 = Z1 \pm X \]
\[ Z2 = Z1 \pm 0.7X \]

By comparing two relations, a 30% reduction of air gap changes by the influence of vertical deviations is determined in the proposed system relative to the suspension system of classical magnetic trains. Similarly, concerning the integrated suspension and guidance performance, there will be a 30% reduction of air gap changes by the influence of lateral deviations relative to the classical magnetic train guidance system.

Fig. 4 shows the problem of (Electromagnetic Coupling Effect) magnetic interference of the suspension system and the guidance system in the classical magnetic trains. However, it will be resolved in the proposed hybrid structure due to the integrated suspension and guidance by one system.
B. Complementary propulsion system

As said at the beginning of this section, linear air-cored tubular induction motors are used to generate propulsion force in the proposed structure in this paper. This type of linear induction motor, like a rotary induction motor, consists of two main parts: 1) the primary or the drive coils that are installed underneath of the wagons; 2) the secondary that consists of an aluminum slit sleeve that surrounds the drive coils and locates on the rail. The tubular linear induction motor operates similarly to classical three-phase induction motors. A traveling magnetic wave is created by the three-phase excitation in the drive coils that induce currents in the sleeve. Both drive coils and sleeve currents generate the resultant magnetic flux. The flux density can be decomposed into two components, one in the longitudinal direction and the other in the radial direction. Interaction between the radial component of the flux density and the sleeve current generates the propulsion force.

In contrast, the flux density component in the longitudinal direction interacts with the sleeve current to produce the radial forces [4, 14]. The theory of the production of these forces is presented in [14]. Linear induction launchers (LLL) are another application of linear air-cored tubular induction motors that, studying them gives a better view of these types of motors [15]. Since the drive coils are supported only by electromagnetic force rather than Physical connection with secondary, the center (axis) of the drive coils may not coincide with that of the sleeve for many reasons, such as vibration, disturbances, gravity, or other causes. When the drive coils are placed in the secondary center, the radial forces around them are balanced. However, if the central axes of the drive coils and sleeve do not coincide, the radial forces around the drive coils are not balanced, and there exists a transverse force due to the asymmetry. This force is called the restoring force, and it is the fundamental tool for the analysis of the dynamic motion of the coil drives in the transverse (radial) direction [16]. A 3D FEM analysis presented in [4] shows that the restoring force acting on the moving part is satisfactory to levitate and guide the moving part and deal with the low-damping problem, which is one of the most important dynamic stability problems that occur in the maglev systems.

In the maglev system, as mentioned earlier, the opening of the sleeve causes the radial forces to be unbalanced and generates the restoring force that rebalances the radial forces. It can be seen from Fig. 5(a) that the x components of the radial forces at points A and B, also at points C and D (The x-axis and y-axis are considered as the symmetrical axes), are the same in magnitude but opposite in direction. There is the same balance between the y components of the radial forces at points A and C, also at points B and D. This balance of the drive coils is achieved by the restoring force that eliminates the effect of the opening angle of the sleeve. Any change from the balanced position of the drive coils, which is shown in Fig .5(a), leads the radial forces to be unbalanced. Fig .5(b) shows the movement of the drive coils in the direction of the y-axis. This will cause the y components of the radial forces at points A and C, also points B and D, to be unequal [16], but due to the restoring force that exists between two noncoaxial circular coils, the moving part is placed in the center again [15]. In order to calculate the equivalent force between sleeve and drive coils, instead of integrating the force on the differential element over the entire loop of the drive coils, it is better to distinguish the two force elements in each half of the drive coils circle. As a result, these two forces are in the direction opposite to each other, and the difference between them is defined as the restoring force:

$$ F_s = F_1 - F_2 $$

Where $F_1$ and $F_2$ are the force elements in the left and right half loop of the drive coils, respectively, and $F_s$ is the restoring force. $F_1$ and $F_2$ forces are obtained by integrating the force on the differential element over the drive coils' left and right half loop, respectively [15]. The two forces, $F_1$ and $F_2$, are equal in a balanced condition, and the restoring force will be zero [16].

Due to the performance of the motor and the nature of the restoring force, the complementary role of the motor for the integrated suspension and guidance system is determined. As stated, the performance of the integrated suspension and guidance system in the proposed structure is such that, while maintaining the desired air gap, it avoids any horizontal and vertical deviations of the wagon. According to Fig. 1, the designed structure is like, in the desired air gap of the integrated suspension and guidance system, the motor is in the balance condition (central axes of the drive coils and sleeve are coincide). Therefore, any horizontal and vertical deviation of the wagon, which causes the change of the air gap and also unbalancing the motor, will be simultaneously eliminated by both systems. The benefit of using this type of motor in the proposed structure is that the suspension performance and guidance produced by the motor, in contrast to the integrated suspension and guidance system, is achieved without the need for a control system. In other words, the inherent self-levitating and self-guiding properties is provided only by the restoring force between two main parts of the motor [4].

After expressing the performance of the propulsion system and its inherent guidance and suspension, extracting and analyzing the components of the motor force and improving them is an introduction to designing the controller of the integrated suspension and guidance system at the end of this paper. Because any disturbance in the performance of the motor disturbs the control process of the air gap, in other words, if the proposed structure is in balance condition, there should not be any force of the motor on the suspension and guidance electromagnets. In the following, by performing a 3D modeling of finite element method in Maxwell software, the components of the motor force are extracted, and the process of improving its performance will be presented.

III. 3D Modeling And Optimization of Propulsion System Using Finite Element Method

3D modeling of the motor is presented considering the design conditions and the basic design criteria given in [4, 17] and its dimensions. According to Fig. 6, the motor modeling is done in a way that the opening angle of the sleeve is placed between the x
and y axes. In other words, the x-axis and y-axis and the motor cross-section are symmetrical to the vertical axis. Since the moving part is placed in the center and due to the symmetry of two axes, x, and y, the magnitude of the radial forces in the x-axis must be equal to the magnitude of the radial force in the y-axis. The 3D modeling of the motor in Maxwell software is shown in Fig. 7.

The analysis starts to access the forces acting on the moving part in the x, y, and z axes. Fig 8 shows the forces. Though the motor dimension was obtained by using design conditions and basic design criteria in [4,17], as shown in Fig. 8, the radial forces have minor differences; so, eliminating or reducing the difference between them leads to a more desirable performance. This paper uses an alternative method to achieve optimal performance by utilizing 3-D finite element method (FEM) analysis. Therefore, using a parametric simulation, only the radius of the sleeve is changed with the specified steps (0.5mm) around the nominal value (32 mm). The increase in the secondary radius causes the reduction of the force components. In the following, their RMS (Root Mean Square) values in the steady-state are utilized to compare waveforms. As shown in Fig. 9, to determine the effect of changing the radius of the sleeve on force components, the RMS values of each force must be obtained as a function of radius. As shown in Fig. 9, the RMS values of the forces decrease with increasing the air gap or increasing the radius of the sleeve. Therefore, a range that contains a value less than the initial radius of the sleeve will be desirable by performing another parametric simulation with a minor step (0.05mm) in the range of 30 mm to 32 mm for sleeve radius. According to the results shown in fig. 10 and Table 1, for a radius of 30.7 mm, the radial forces have the least difference.

As the results shown in Fig. 11, by replacing the optimal radius obtained from parametric simulations (30.7mm) with the initial value, the difference between radial forces is reduced by 96%; In addition, the amplitude of the force components is increased, which is highly desirable.

IV. CONTROL OF INTEGRATED SUSPENSION AND GUIDANCE SYSTEM

A. Modeling of suspension and guidance electromagnets

In order to design a control system, the mathematical modeling of the integrated suspension and guidance system will consist of three categories of relationships: 1) the relationships of the magnetic circuit of the electromagnets; 2) the electrical circuit relationships of the electromagnets, 3) the dynamic relations associated to the applying the magnetic force of the electromagnets to the Integrated Suspension and Guidance system. Therefore, if the electromagnets are placed on two arms in front of each other (fig. 1) are considered as a unit of suspension and guidance, two systems of (4) and (5) describe the relations of each electromagnet in a unit of suspension and guidance.

\[
F_{mf1} = \frac{\mu_0 AN^2}{4} \left( \frac{I_1}{Z_1} \right)^2
\]

\[
V_1 = rI_1 + \frac{N^2 \mu_0 A}{2Z_1} I_1 - I_1 \frac{N^2 \mu_0 A}{2Z_1} \ddot{Z}_1
\]

\[
F_{mf1} - \frac{\sqrt{2}}{2} mg = m\ddot{Z}_1
\]

\[
F_{mf2} = \frac{\mu_0 AN^2}{4} \left( \frac{I_2}{Z_2} \right)^2
\]

\[
V_2 = rI_2 + \frac{N^2 \mu_0 A}{2Z_2} I_2 - I_2 \frac{N^2 \mu_0 A}{2Z_2} \ddot{Z}_2
\]

\[
F_{mf2} - \frac{\sqrt{2}}{2} mg = m\ddot{Z}_2
\]

In each of the two systems of (4) and (5), the first Formula is related to the electromagnetic circuit of the electromagnet, the second is associated with the electrical circuit of the electromagnet, and the third describes the dynamic of the electromagnet in the unit of suspension and guidance. The parameters used in two systems of (4) and (5) are given in Table 2.
Since the purpose of controlling the integrated suspension and guidance system is to achieve the desired air gap by controlling the voltage applied to the electromagnets, the nonlinearity of the system dynamics is evident. In fact, the magnetic force of the electromagnets is proportional to the inverse square of the air gap \( F_m \sim \frac{1}{Z^2} \).

**B. State-space mode of the Integrated Suspension and Guidance system**

due to the relations expressed in the system of (4) and (5), the air gap, the first derivative of the air gap, and the current are determined as the state variables describing the behavior of a unit of suspension and guidance, and so, the state vector of the system will be in accordance with (6).

\[
X = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 \end{bmatrix}^T
\]

By replacing the state vector variables in two systems of (4) and (5), the representation of the nonlinear state space of a suspension and guidance unit is obtained in (7), where \( \rho = \mu_0 AN^2 \).

\[
\dot{x} = f(x,u)
= \begin{bmatrix} \dot{x}_1 & \dot{x}_2 & \dot{x}_3 & \dot{x}_4 & \dot{x}_5 & \dot{x}_6 \end{bmatrix}^T
= \begin{bmatrix} f_1 & f_2 & f_3 & f_4 & f_5 & f_6 \end{bmatrix}^T
\]

\[
\begin{bmatrix}
f_1 \\
f_2 \\
f_3 \\
f_4 \\
f_5 \\
f_6 \\
\end{bmatrix}
= \begin{bmatrix}
x_2 \\
\frac{\rho}{4m} \left( \frac{x_5}{x_1} \right)^2 + \frac{\sqrt{2}}{2} g \\
x_4 \\
\frac{\rho}{4m} \left( \frac{x_6}{x_3} \right)^2 + \frac{\sqrt{2}}{2} g \\
\frac{-2r}{\rho} x_1 x_3 + \frac{x_2 x_5}{x_1} + \frac{2x_1 u_1}{\rho} \\
\frac{-2r}{\rho} x_3 x_6 + \frac{x_2 x_5}{x_3} + \frac{2x_1 u_2}{\rho} \\
\end{bmatrix}
\]

**C. Designing the Optimized controller for the integrated suspension and guidance system**

despite the nonlinear model of the proposed approach and also advantages and widespread use of linear control systems in controlling the nonlinear systems, in this section, after linearization, the nonlinear model of integrated suspension and guidance unit, an optimal linear control technique called Linear Quadratic Regulator (LQR) will be used for control [17]. Since the system has no equilibrium point, after specifying a specific point as an operation point or nominal point of the system \((x_r, u_r)\), by applying the change of variables according to (8) and (9), a new system with an origin equilibrium point is obtained. Therefore, it is possible to design an LQR controller for a new system after linearizing it around the origin.

\[
\begin{align*}
\bar{x} &= x - x_r \\
\bar{u} &= u - u_r
\end{align*}
\]  

Regarding the change of the variables expressed in 8 and 9, if the variables or inputs in the new system move to the origin\((\bar{x} = 0, \bar{u} = 0)\), the states in the initial system will move to the specified operation point\((x = x_r, u = u_r)\).
In order to determine the operating point or nominal point, by setting the first and third variables of the state vector (air gaps) and assuming no changes in the operation point, other states, as well as the corresponding inputs with the nominal point, are obtained by using (6) and accordance with (9) and (10).
\[
x_r = \begin{bmatrix} x_{1r} & 0 & x_{3r} & 0 & \sqrt{\frac{2\sqrt{2mg}}{\rho}x_{1r}} & \sqrt{\frac{2\sqrt{2mg}}{\rho}x_{3r}} \end{bmatrix}^T \tag{10}
\]
\[
u_r = \begin{bmatrix} u_{1r} & u_{2r} \end{bmatrix}^T = \begin{bmatrix} rx_{5r} & rx_{6r} \end{bmatrix}^T \tag{11}
\]

After determination, the nominal point, by applying the change of the variables in (8) and (9) to the nonlinear state space of the system in (7) and the linearization of the new system around the origin, the state matrix of the linear system is obtained by (12).

\[
\begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 \\
1386.9 & 0 & 0 & 0 & -1.3284 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 1386.9 & 0 & 0 & -1.3284 \\
0 & 1044.1 & 0 & 0 & -7.8595 & 0 \\
0 & 0 & 0 & 1044.1 & 0 & -7.8595
\end{bmatrix} \tag{12}
\]

Regarding the matrix of (12) due to the zero value of the mutual entries of the first and third, second and fourth, and fifth and sixth, the states of each two electromagnets in a unit of suspension and guidance are independent of other. Therefore, by transforming the state vector into a triple vector, accordant with (13), the design of the control system can be done for an electromagnet.

\[
x = \begin{bmatrix} Z_1 & \dot{Z}_1 & I_1 \end{bmatrix}^T \tag{13}
\]

The optimal control of LQR is expressed for a linear system with 14. In fact, in this control technique, which is a subset of the family of state feedback controllers, inputs to the system are constructed according to a combination of state variables [18].

\[
u = -kx \tag{14}
\]

The feedback gain matrix in 14 (K) is calculated to minimize the cost function of (15). By minimizing the cost function, which means minimizing specific errors in the control process, the poles of the closed-loop system are located in places called optimal locations of the poles [18].

\[
J = \int_0^\infty \left( x^T Q x + u^T R u + 2 x^T N u \right) dt \tag{15}
\]

The matrices N, R, Q in (14) are the controlling (Weighted Parameters) parameters of the state’s error, the importance of the inputs, and the importance of multiplication of state’s error in the control inputs, respectively and sets by the designer. The calculation of the feedback gain matrix K is from (16) [18].

\[
K = R^{-1} \left( B^T P + N^T \right) \tag{16}
\]

In which P is obtained from the solution of the continuous Roquette algebraic (17) [18].

\[
A^T P + PA - \left( BP + N \right) R^{-1} \left( B^T P + N^T \right) + Q = 0 \tag{17}
\]

To design an optimal LQR controller for an electromagnet in a unit of suspension and guidance, according to the three entries of the state vector expressed in 13, the weighted matrix Q will be a 3x3 matrix, which is initially considered as a unit diagonal matrix. In addition, given that the system has one input (the voltage applied to the electromagnet’s coil), the value of the weighted matrix R is Equal to one. Assuming that the state’s error and input of the system are not interacting with each other, the matrix N is considered zero. After determining the weighted matrices and designing the optimal LQR controller, the optimal feedback gain matrix is obtained following (18).

\[
K = \begin{bmatrix} -8713.3 & -136.21 & 5.9314 \end{bmatrix} \tag{18}
\]

As shown in Fig. 12, by applying the designed linear controller to the nonlinear system of an electromagnet, the result of controlling the air gap in the presence of disturbances and changing the nominal point is obtained by Fig. 13.
Given that the weighted matrices are designed by the designer to achieving optimal function in the control response, in the following, the entries of the matrix Q will be changed so that the better control response is achieved. It was found that with(by) changing (increasing) in the entries of the matrix Q, the third entry of matrix, that is corresponding with the electromagnet current error, has a significant effect on the control response, while the impact of the change in the entries corresponding with the first and second state’s error on the Frequency response form can be ignored. The amount of the current justifies this compared with the air gap at the nominal point (l ≃ 100µm). Another point that needs to be considered to finding a better control response is the practical limitations of the control signal. Fig. 14 shows the control signal in the case that Q is a unit diagonal matrix. According to Fig. 15, the control signal is associated with a mutation at the time of change in the operation point (T = 0.5 s and T = 5 s). In practice, the amount of these mutations cannot be considered more than four times the values initial since it is impossible to construct them by operators. Therefore, considering the effect of the weighted matrix Q entries on the control response in this system and considering a triple allowable range of control signal mutation compared to the initial values, the first and second entries of Q are assumed constant. The third entry is increased until the control signal does not exceed the specified range. After several simulations, it was determined that by replacing the number 33 with the third entry value of the matrix Q, the control signal’s mutation stays in the specified range, the speed of the control response increases (reduction of the rise time), and its overshoot decreases. The position of the control signal mutation in the range of three times the initial value and the improvement of the control response by changing entries of the matrix Q are shown in Figs. 15 and 16, respectively.

V. CONCLUSION

This paper first introduced a magnetic train topology with integrated suspension and guidance and a complementary propulsion system. Subsequently, using a 3D modeling of finite element method, the components of propulsion system force are extracted, analyzed, and optimized. After optimizing the propulsion system’s performance and reducing its impact on the integrated suspension and guidance system, the nonlinear state space of a unit of integrated suspension and guidance system was obtained with mathematical modeling. Then, by determining the operation point, changing the variables, and linearizing the system model, the optimal LQR controller design process for the linear system was performed and the optimal controller performance was obtained. Finally, to achieve a more favorable control response, considering the limitation of the control signal and applying a change in the weighted matrix Q in the cost function, the speed of the control response was increased, and the reduction of overshoot was obtained. This hybrid topology simplifies and cheapens the structure of maglev and reduces the need for control systems and sensors. Furthermore, the electromagnetic coupling effect will be resolved in this structure due to the integrated performance of suspension and guidance by one system.

REFERENCES

List of Captions:
* Figure Captions:
  Fig. 1. The combined structure of the magnetic train
  Fig. 2. Vector diagram of forces in integrated suspension and guidance system
  Fig. 3. Comparison of air gap deviation in the proposed suspension system with the classic suspension system
  Fig. 4. Electromagnetic coupling effect of the suspension system and the guidance system in the classical magnetic train
  Fig. 5. a) Motor cross-section in balanced position b) The movement of the drive coils in the direction of the y axis
  Fig. 6. The cross-section of the simulation model
  Fig. 7. 3D simulation Modeling of the motor in Maxwell Software
  Fig. 8. Forces acting on the moving part of the motor
  Fig. 9. Changes in force components with the change of secondary radius
  Fig. 10. Changes in force components with the change of secondary radius
  Fig. 11. Comparison between force components before and after optimization
  Fig. 12. Controlling the nonlinear system of an electromagnet
  Fig. 13. Controlling the air gap in the presence of disturbances and with changing the nominal point
  Fig. 14. Control signal in the case that Q be a unit diagonal matrix
  Fig. 15. Position of the control signal mutation in the range of three times the initial value
  Fig. 16. Improvement of the control response by changing entries of the matrix Q

*Table Captions:
  TABLE I. Results of parametric simulation
  TABLE II. Parameters used in two systems of relations (4) and (5)
Fig. 2. Vector diagram of forces in integrated suspension and guidance system

Fig. 3. Comparison of air gap deviation in the proposed suspension system with the classic suspension system

Fig. 4. Electromagnetic coupling effect of the suspension system and the guidance system in the classical magnetic train
Fig. 5. a) Motor cross-section in balanced position   b) The movement of the drive coils in the direction of the y axis

Fig. 6. The cross-section of the simulation model

Fig. 7. 3D simulation Modeling of the motor in Maxwell Software

Fig. 8. Forces acting on the moving part of the motor
Fig. 9. Changes in force components with the change of secondary radius

Fig. 10. Changes in force components with the change of secondary radius

Fig. 11. Comparison between force components before and after optimization

Fig. 12. Controlling the nonlinear system of an electromagnet
Fig. 13. Controlling the air gap in the presence of disturbances and with changing the nominal point.

Fig. 14. Control signal in the case that $Q$ be a unit diagonal matrix.

Fig. 15. Position of the control signal mutation in the range of three times the initial value.

Fig. 16. Improvement of the control response by changing entries of the matrix $Q$. 
**TABLE I**
RESULTS OF PARAMETRIC SIMULATION

<table>
<thead>
<tr>
<th>Sleeve radius [mm]</th>
<th>RMS(coil force.Force_x) [N]</th>
<th>RMS(coil force.Force_y) [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.5</td>
<td>101.7484164</td>
<td>142.986268</td>
</tr>
<tr>
<td>30.55</td>
<td>135.1463087</td>
<td>185.3646056</td>
</tr>
<tr>
<td>30.6</td>
<td>184.3090923</td>
<td>156.802813</td>
</tr>
<tr>
<td>30.65</td>
<td>245.7121226</td>
<td>201.8437067</td>
</tr>
<tr>
<td><strong>30.7</strong></td>
<td><strong>140.1078119</strong></td>
<td><strong>141.6969531</strong></td>
</tr>
<tr>
<td>30.75</td>
<td>125.0982781</td>
<td>134.4862308</td>
</tr>
<tr>
<td>30.8</td>
<td>80.74267072</td>
<td>64.42590301</td>
</tr>
<tr>
<td>30.85</td>
<td>111.9342799</td>
<td>89.26949629</td>
</tr>
<tr>
<td>30.9</td>
<td>91.34702088</td>
<td>89.19752575</td>
</tr>
<tr>
<td>30.95</td>
<td>161.5155959</td>
<td>54.2226583</td>
</tr>
<tr>
<td>31</td>
<td>185.3727095</td>
<td>163.3875246</td>
</tr>
<tr>
<td>31.05</td>
<td>170.0994439</td>
<td>140.5974931</td>
</tr>
<tr>
<td>31.1</td>
<td>87.77955837</td>
<td>95.10431383</td>
</tr>
<tr>
<td>31.15</td>
<td>71.90093814</td>
<td>64.02198813</td>
</tr>
<tr>
<td>31.2</td>
<td>66.29826361</td>
<td>92.67014693</td>
</tr>
<tr>
<td>31.25</td>
<td>100.4469585</td>
<td>130.5362383</td>
</tr>
<tr>
<td>31.3</td>
<td>98.05764367</td>
<td>150.9641208</td>
</tr>
<tr>
<td>31.35</td>
<td>83.63232552</td>
<td>94.43662876</td>
</tr>
<tr>
<td>31.4</td>
<td>143.7374532</td>
<td>110.4886499</td>
</tr>
<tr>
<td>31.45</td>
<td>173.4268767</td>
<td>113.6014034</td>
</tr>
<tr>
<td>31.5</td>
<td>153.3003984</td>
<td>136.4016887</td>
</tr>
<tr>
<td>31.6</td>
<td>133.6854658</td>
<td>149.8384951</td>
</tr>
<tr>
<td>31.65</td>
<td>127.3928041</td>
<td>156.3621002</td>
</tr>
<tr>
<td>31.7</td>
<td>134.446692</td>
<td>194.8343938</td>
</tr>
<tr>
<td>31.75</td>
<td>104.1294056</td>
<td>123.6723358</td>
</tr>
<tr>
<td>31.8</td>
<td>102.69293</td>
<td>79.8195047</td>
</tr>
<tr>
<td>31.85</td>
<td>92.93456248</td>
<td>87.53540343</td>
</tr>
<tr>
<td>31.9</td>
<td>91.7297089</td>
<td>76.18283235</td>
</tr>
<tr>
<td>31.95</td>
<td>100.58268</td>
<td>125.2544449</td>
</tr>
<tr>
<td>32</td>
<td>61.7409704</td>
<td>85.86895861</td>
</tr>
</tbody>
</table>

**TABLE II**
PARAMETERS USED IN TWO SYSTEMS OF RELATIONS (4) AND (5)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Measurement unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I_1 ) and (I_2)</td>
<td>Dc currents of electromagnets</td>
<td>A= ampere</td>
</tr>
<tr>
<td>(r)</td>
<td>Coil's resistance of electromagnets</td>
<td>(\Omega = \text{ohm})</td>
</tr>
<tr>
<td>(Z_1 ) and (Z_2)</td>
<td>Air gaps of electromagnets</td>
<td>m = metre</td>
</tr>
<tr>
<td>(m)</td>
<td>The mass applied to the suspension unit</td>
<td>Kg = kilogram</td>
</tr>
<tr>
<td>(g)</td>
<td>gravitational acceleration</td>
<td>(m/s^2 = \text{meter/second}^2)</td>
</tr>
<tr>
<td>(F_{mf_1} ) and (F_{mf_2})</td>
<td>Magnetic force of electromagnets</td>
<td>(1 \text{G } \rightarrow 10^3/(4\pi) \text{A/m})</td>
</tr>
<tr>
<td>(\mu_0)</td>
<td>vacuum permeability</td>
<td>H/m=henry/metre</td>
</tr>
<tr>
<td>(A)</td>
<td>Cross section of electromagnets</td>
<td>(m^2 = \text{metre}^2)</td>
</tr>
<tr>
<td>(N)</td>
<td>Number of turns of electromagnet’s coil</td>
<td>–</td>
</tr>
<tr>
<td>(v_1 ) and (v_2)</td>
<td>Electromagnet’s voltage</td>
<td>V=volt</td>
</tr>
</tbody>
</table>
Biography:

Hamid Reza Esfahanian received the B.Sc. degree from K. N. Toosi University of Technology, Tehran, Iran, and the M.Sc. degree from Qom University of Technology, Qom, in 2013 and 2017, respectively, both in electrical engineering. His research interests include design, modeling, and control of power electronics converters and their applications electrical traction systems.

Saeed Hasanzadeh received the B.S. degree from Shahroud University of Technology, Shahroud, Iran, in 2003, and the M.Sc. and Ph.D. degrees from University of Tehran, Tehran, Iran, in 2006 and 2012, respectively, all in electrical engineering. He joined the faculty of Electrical and Computer Engineering, Qom University of Technology as an Assistant Professor in 2013. His research interests include Power Electronics, Inductive Power Transfer Systems, Electrical Machines and Drives, Electric Vehicles, Magnetic Levitation Systems.

Mojtaba Heydari received the undergraduate and graduate degrees from Kashan University, Isfahan, Iran, Iran University of Science and Technology, Tehran, Iran, and Tarbiat Modares University, Tehran, all in electrical engineering. From 2012 to 2013, he was a Research Scholar with the Power Electronics Laboratory, University of California at Irvine, Irvine, CA, USA. Since 2014, he has been with the Faculty of Electrical and Computer Engineering, Qom University of Technology, Qom, Iran. His current research interests include power electronics, renewable energy systems, and motor drives.

Josep M. Guerrero received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalonia, Barcelona, Spain, in 1997, 2000, and 2003, respectively. Since 2011, he has been a Full Professor with the Department of Energy Technology, Aalborg University, Aalborg, Denmark, where he is responsible for the Microgrid Research Program. His research interests include different microgrid aspects, including power electronics, distributed energy storage systems, hierarchical and cooperative control, energy management systems, smart metering, and the Internet of Things for ac/dc microgrid clusters, and islanded minigrids.