Abstract—This paper investigates characteristics of ironless permanent magnet linear synchronous motor (PMLSM) based on Halbach array used for medium-speed (200km/h) maglev train. Long primary ironless coil is laid in the middle of track and the Halbach permanent magnet array is attached to the bottom of each bogie as a source of traction. U-shape electromagnets at the both sides of the train for levitation. Two dimensional analytical model of single-sided ironless PMLSM based on Halbach array is established, using linear overlay method, the no-load air gap magnetic field is calculated firstly, winding current density distribution is obtained for calculating the characteristics of thrust and normal force against power angle, including force characteristics with equal and unequal pole pitch, the influence of steel sleeper, etc. Besides, the mathematical model for this type motor is built by 3D finite element method, the traction characteristics of medium-speed PMLSM under maximum speed 200km/h are calculated. The characteristics of this type motor are satisfactory owing to there is no detent force in the motor and thrust force reach maximum meanwhile normal force can be eliminated. Calculation method is verified by comparing finite element results, experimental result on a 200kW type motor further validates the accuracy of calculation and some important conclusions are obtained.

Index Terms—Force characteristics, Halbach array, medium-speed Maglev, Single-sided ironless PMLSM.

I. INTRODUCTION

NOWADAYS, maglev train has successful commercial operation in the world [1–12]. It is represented by Shanghai high-speed (430km/h) maglev train and Nagoya low-speed (100km/h) HSST. Shanghai maglev train adopts normal conducting magnetic levitation technology of Germany, which adopts long primary linear synchronous motor (LSM) as traction power, the maglev vehicles are suspended by the attractive force between the electromagnets and primary core (EMS), this type maglev train is more suitable for high speed operation due to long primary LSM and additional guidance electromagnets. Other high-speed maglev train, such as the Japanese MLX utilizes superconducting electro-dynamic (EDS) technology for levitation [7, 8]. The EDS is stable without closed-loop air gap control. However, the system is speed depended, and the vehicle requires wheel below a certain speed. Short primary linear induction motor (LIM) is used in low-speed maglev train, it is favorable for low speed operation due to the limited guiding force generated by the difference of reluctance of the U-shape levitation magnet. Besides, the thrust performance of short primary LIM is seriously affected by longitudinal and transverse end-effects, however, this structure of low-speed maglev train is simpler and the construction cost is lower [4–6].

With the rapid development of rail transit, medium speed operation about 150-250km/h is increasingly in demand of inter-city rail transit. By comparing several maglev train technologies above, this paper investigates a novel single-sided ironless permanent magnet linear synchronous motor (PMLSM) based on Halbach array used for medium-speed maglev. The structure of this medium speed maglev train is shown in Fig.1, long primary ironless coil is laid along the track and the Halbach permanent magnet array is attached to the bottom of each bogie as a source of traction. Permanent magnet Halbach array is used for establish strong and approximately sinusoidal magnetic field, it has advantages of low thrust fluctuation, high power factor and efficiency. The normal attraction force can be decreased by ironless primary armature. Furthermore, this novel medium-speed maglev train adopt U-shaped electromagnet levitation make sure the advantages of simple structure and low cost, the propulsion and levitation systems are independent of each other.

Fig. 1. Structure of medium speed maglev train.

Compared with single-sided ironless PMLSM, many researchers focus on double-sided ironless PMLSM [13–19], it
has advantages of low thrust fluctuation, high positioning precise, high dynamic performance, etc. The structure as fig.2 shows, it includes long stationary secondary and short motive primary usually, there is no normal force between primary and secondary because of ironless coil. Authors of [15–17] use this topology motor for electromagnetic launch, the model of air gap magnetic field is established by magnetic charge method and image method for global optimization of PMLSM thrust. Researches mainly focus on analytical and finite element method or combined two methods. Literature [18] base on magnetic vector potential equation and boundary conditions, flux density distribution induced by the permanent magnet array is analysed analytically, thrust characteristics are obtained analytically and compared with the finite element simulation results. Paper [13, 19] deals with the electromagnetic design of double-sided ironless PMLSM for various geometrical configurations of primary and secondary parts by means of Finite Element method in 2D and 3D, the results are in very good coincidence.

![Structure of short primary double-sided ironless PMLSM.](image)

The main drawback to short primary double-sided double-sided ironless PMLSM is mover cannot travel too far owing to the moving supply cable. Therefore, this paper studies single-sided ironless PMLSM that applied in high power electric traction system. Its long primary fixed on track relative to short secondary moving with load, permanent magnet Halbach array is used for establish strong and approximately sinusoidal magnetic field. In view of this type motor, literature [20] deduces the field of a single permanent magnet with arbitrary magnetization angle based on surface current, and then Denavit-Hartenberg transform technique is used to calculate permanent magnet Halbach array, the ideally characteristics of this structure PMLSM are obtained. A novel Halbach PM ironless linear motor with trapezoid windings which produce single-sided and perfectly sinusoidal magnetic field is proposed by [21, 22]. Unfortunately, the trapezoid windings motor is less power efficient and not appropriate to be used in power-sensitive applications.

Several research works have been done on the design and analysis of Halbach PMSM [23–33]. The theoretical analysis method and 2D/3D finite element method (FEM) of the Halbach PMLSM are introduced in [23–28]. Literature [29] different optimization design approaches of the ironless PMLSM are proposed to reduce the thrust ripple, increase the thrust density and so on [24, 26]. Authors of [30] design each core less-typed LSM model with a distributed winding and a concentrated winding for 600km/h VHST, electromagnetic characteristics of Coreless-typed LSM with a distributed winding and a concentrated winding are compared. However, this system is a hybrid system combining only the merits of the conventional wheel-rail system and the linear propulsion system.

This paper mainly investigates the characteristics of thrust and normal force against power angle on single-sided ironless PMLSM based on Halbach array, two dimensional analytical model of single-sided ironless PMLSM is established, the electromagnetic field equation is deduced to calculate flux density with no current fed, the characteristics of thrust and normal force against power angle are obtained by using linear overlay method. It is found that the amplitudes of thrust and normal force with power angle are the same, but angles are staggered by 90 degrees. Furthermore, characteristics with steel sleeper and end effect of Halbach array are analyzed, the accuracy of the calculation is verified by finite element calculate and experiment. Besides, the mathematical model of this type motor is built by 3D finite element method, including flux linkage of Halbach array, inductance of ironless coil, etc. thus the traction characteristics of medium-speed maglev under maximum speed 200km/h are calculated and analyzed, the feasibility and applicability that single-sided long primary ironless PMLSM based on Halbach array for medium-speed maglev train are verified.

II. Theory Foundation of Single Sided IPMLSM

The analysis model of single-side ironless PMLSM is built as Fig.3 shows. every four square magnets to form a magnetic pole and mutual 45-degrees difference in each magnetization direction of magnet to make sure the nearly sinusoidal magnetic field of air gap. Some assumptions are in analysis model, ① coordinate in x and y direction are infinity, ② the Halbach magnet array has no magnetic flux leakage on its back, ③ the magnetic permeability of magnet is the same as that of air, ④ the permanent magnet demagnetization curve is a straight line. Since ferromagnetic materials have not been used in the motor, the core saturation and corresponding nonlinear factors can be ignored. The motor can be considered as an idealized model with two analytic areas.

![Analysis model of single-sided ironless PMLSM based on Halbach array.](image)
The whole solution area is divided into the magnetic pole region I and the air gap region II, the Halbach permanent magnet array is equivalent to magnetized intensity \( M \) and it is decomposed in \( x \) and \( y \) directions as Fig.3 shows. Due to the cross section of each magnet is square, the period and amplitude of \( M \) are the same with that of \( M_y \), according to the Fourier decomposition, \( M_x \) and \( M_y \) are

\[
M_x(x) = \sum_{n=1}^\infty M_{x_n} \cos\left(\frac{n\pi}{\tau_x} x\right) \quad (n = 1, 2, 3 \ldots)
\]

\[
M_y(x) = \sum_{n=1}^\infty M_{y_n} \sin\left(\frac{n\pi}{\tau_y} x\right) \quad (n = 1, 2, 3 \ldots)
\]

where \( \tau_x \) is the pole pitch, \( n \) is harmonic number, magnetized intensity \( M \) of Halbach PM array on the \( x \)-axis and \( y \)-axis can be acquired by expressions (3) and (4).

\[
M_{x_n} = \frac{B_x}{\mu_0 n\pi} \left[ \sin\left(\frac{n\pi}{8}\right) + \sin\left(\frac{3n\pi}{8}\right) + \sin\left(\frac{5n\pi}{8}\right) + \sin\left(\frac{7n\pi}{8}\right) \right]
\]

\[
M_{y_n} = \frac{B_y}{\mu_0 n\pi} \left[ \cos\left(\frac{n\pi}{8}\right) + \cos\left(\frac{3n\pi}{8}\right) - \cos\left(\frac{5n\pi}{8}\right) - \cos\left(\frac{7n\pi}{8}\right) \right]
\]

Magnetic vector potential in magnetic pole region I satisfy the poisson equation (5) and Magnetic vector potential in air gap region II satisfy the laplace equation (6)

\[
\frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} = -\frac{\mu_0}{\tau_x} \frac{\partial M_x(x)}{\partial x} - \frac{\partial M_y(x)}{\partial y}
\]

\[
\frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} = 0
\]

The general solutions of the two equations are (7) and (8), respectively.

\[
A_x(x, y) = \sum_{n=1}^\infty \left( C_{x_n} \sin\left(\frac{n\pi}{\tau_x} y\right) + D_{x_n} \cos\left(\frac{n\pi}{\tau_x} y\right) + \frac{\tau_x \mu_0 M_{x_n}}{n\pi} \right) \cos\left(\frac{n\pi}{\tau_x} x\right)
\]

\[
A_y(x, y) = \sum_{n=1}^\infty \left( A_{y_n} \sin\left(\frac{n\pi}{\tau_y} y\right) + B_{y_n} \cos\left(\frac{n\pi}{\tau_y} y\right) \right) \sin\left(\frac{n\pi}{\tau_y} x\right)
\]

Undetermined coefficients can be calculated according to the boundary conditions (9), (10), (11), (12)

\[
H_x(x, y) = H_{x_0}(x, y) \quad |y=0
\]

\[
B_{x_0}(x, y) = B_{x_0}(x, y) \quad |y=0
\]

\[
A_x(x, y) = 0 \quad |y=a
\]

\[
A_y(x, y) = 0 \quad |y=-a
\]

Where, the tangential and normal components of flux density are (13) and (14), respectively.

\[
B_x = -\frac{\partial A_x}{\partial y}
\]

\[
B_y = -\frac{\partial A_y}{\partial x}
\]

Bring the (7) and (8) into the formula (13) and (14), flux density in region I and region II can be acquired by

\[
B_{x_0}(x, y) = \sum_{n=1}^\infty \mu_0 M_{x_n} \left( ch\left(\frac{n\pi}{\tau_x} h_x - 1\right) \left( sh\left(\frac{n\pi}{\tau_y} y + ch\left(\frac{n\pi}{\tau_y} y \right) \sin\left(\frac{n\pi}{\tau_y} y\right) \right) \sin\left(\frac{n\pi}{\tau_x} x\right)ight)
\]

\[
B_{y_0}(x, y) = \sum_{n=1}^\infty \left( sh\left(\frac{n\pi}{\tau_y} h_y + ch\left(\frac{n\pi}{\tau_y} h_y \right) \right) \cos\left(\frac{n\pi}{\tau_x} x\right)ight)
\]

From the expression (15) (16), it can be seen that the amplitudes of fundamental component \( B_{x_0} \) and \( B_{y_0} \) are the same, angles are staggered by 90 degrees. The distribution function of face coil current density of is

\[
J(x) = \begin{cases} \sqrt{2}N_i \sin(\theta), & -\frac{3d_x}{2} < x < -\frac{3d_x}{2} - b_x \\ \sqrt{2}N_i \sin(\theta + 120^{\circ}), & -\frac{d_x}{2} < x \leq -\frac{d_x}{2} + b_x \\ \sqrt{2}N_i \sin(\theta - 120^{\circ}), & \frac{d_x}{2} < x \leq \frac{d_x}{2} + b_x \end{cases}
\]

where, \( N \) is the number conductors of each slot, \( J \) is effective value per phase current, \( b_x \) is groove width, \( d_x \) is tooth width, \( h_x \) is groove high, respectively. \( \theta \) is initial angle of A phase current, it also represents the power angle of angle.

Using above expressions, the thrust and normal force against different power angle of motor can be calculated by

\[
F_x = 2P_L \int \frac{dx}{dx} \int_{-d_x}^{d_x} B_{x_0}(x, y) \cdot J(x) \cdot dx \cdot dy
\]

\[
F_y = 2P_L \int \frac{dy}{dy} \int_{-d_x}^{d_x} B_{y_0}(x, y) \cdot J(x) \cdot dx \cdot dy
\]

III. FORCE CHARACTERISTICS ANALYSIS

Table I lists main parameters of motor, Halbach magnet array is 500mm. The mechanical gap clearance is 11mm, and the pole pitch of the secondary is 196mm. Epoxy is used to replace iron core of primary, that eliminates cogging force and reduce normal attractive force between primary and secondary.
A. The magnetic field and influence of end effect

Based on theoretical analysis of single-side ironless PMLSM, it can be found that the field distribution of the ironless Halbach PMLSM is linear and symmetrical. In order to verify the analytical model, FEM results are used here for comparison. Fig. 5 shows results of open circuit flux density $B_{1/2}$ waveforms calculated by analytical solutions and FEM.

As can be seen from Fig. 4, the flux distribution is close to sinusoidal and the peak flux density waveform is 0.52 T, which is less than that of conventional motor due to the large air-gap. The results of analytical solutions and FEM match well in most area of the motor. However, the flux density with the FEM at both ends of Halbach array is about 0.42 T, which is smaller than that of analytical solutions. The reason is that end effect also exists in the proposed PMLSM. In the analytical model, the Halbach magnet is assumed as infinite long in $x$ direction. Actually, the Halbach magnet array in $x$ direction is discontinuous, which will induce leakage flux at the both end of the motor. The simulated flux leakage distribution is shown in Fig. 5. The influence of end effect on thrust performance will be weakened with the increases of number of magnet poles.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phase</td>
<td>$m$</td>
<td>3</td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>$p$</td>
<td>7</td>
</tr>
<tr>
<td>Pole pitch of secondary</td>
<td>$t_s$</td>
<td>196 mm</td>
</tr>
<tr>
<td>Mechanical clearance</td>
<td>$g$</td>
<td>15 mm</td>
</tr>
<tr>
<td>Slots of every phase pole</td>
<td>$q_1$</td>
<td>3</td>
</tr>
<tr>
<td>Width of Halbach array</td>
<td>$d$</td>
<td>500 mm</td>
</tr>
</tbody>
</table>

**Table I. Parameters of Motor**

Fig. 4. Flux density in the airgap calculated by analysis and FEM.

Fig. 5. Flux density distribution of Halbach PM array.

B. Force characteristics with different primary pole pitch

Normally, the pole pitches of secondary $t_s$ and primary $t_p$ are the same. However, unlike that in rotary motor, the primary and secondary pole pitch of the PMLSM cannot always be hold as equal due to the installation errors of the long primary armature windings and multiple levitation bogies.

The thrust and normal force-angle characteristics with equal and unequal pole pitch are calculated and compared with both analytical solutions and FEM method. In the calculation, a constant $dc$ current of $I_s=1200$ A is applied for the primary armature windings. By moving the Halbach PM for two pole pitch in several steps, the force-angle curves of the motor are obtained.

The force-angle curves with equal pole pitch are given in Fig. 6. It can be found that the thrust is zero and the normal force is attractive when the power angle is 0°. The thrust reaches maximum when the power angle is 90°. The normal force waveform is 90° ahead of that of thrust. The amplitudes of thrust and normal force are equal and about 6065 N calculated by FEM. The analytical maximum thrust and normal force is 6390 N, which is about 5.09% larger than that of FEM since the influence of end effect has not taken into consideration.

For unequal pole pitch characteristics comparisons, the primary pole pitch is set as 195.6 mm, while the secondary is still hold as 196 mm. The force-angle characteristics are given in Fig. 7. It can be found that when the power angle is 0°, thrust and normal force calculated by FEM are -256 N and -5905 N respectively. When the power angle is 90°, the maximum thrust is 5905 N, which decreases about 2.64% compared with that of equal pole pitch. In the meantime, the normal force is attractive when the power angle is 90°. The force-power angle characteristics can also be calculated with the condition that the primary pole pitch is larger than that of secondary. It can be predicted that the thrust will also be decreased and the normal force will be repulsion when the pole power angle is 90°.

C. Force characteristics analysis with steel sleeper

Usually, the sleepers of the track are made of concrete. However, in some special route like the turnout section, steel sleeper will be utilized for reducing the mass of the track. Thus, the flux distribution as well as the force performance of the motor will be influenced.
Fig. 8 (a) and (b) shows the flux and flux density distribution when the steel sleeper is placed under the horizontal and vertical magnetization position of the Halbach magnet. Compared with that in Fig. 5, some of the flux lines close through the sleeper, and then the attraction force will be produced between Halbach magnet array and sleeper. It can be seen that the leakage flux with the sleeper under horizontal magnetization position is more than that under vertical magnetization position. Fig. 9 shows the corresponding force-angle characteristics with different sleeper placed positions. Compared with that in Fig. 8, it can be found that there is no change in output thrust while the attraction normal force increases from 0 to -6031 N at 90° power angle with sleeper under vertical magnetization position. With the sleeper under horizontal magnetization position, the normal force will be increased 0 to -7981 N.

In actual operation, the angle between the sleeper and the Halbach PM will be changed periodically with the moving of vehicle. Fig. 10 shows the simulated normal force in one sleeper interval when motor operated at 90° power angle. According to the above analysis and calculation results, it is known that the normal attraction force reaches maximum when sleeper under horizontal magnetization position, correspondingly, it reaches minimum when sleeper under vertical magnetization position. So the normal force changes with a period half of pole pitch. From the analysis above, it can be seen that additional attraction normal force will be induced due to the steel sleeper, which will bring disturbance to the levitation system.

IV. TRACTION CHARACTERISTICS CALCULATION

Due to magnetic field in ironless PMLSM has 3D open boundary problem, the 3D finite element model of ironless coils is built in Fig.11 in order to calculate accuracy inductance. Owing to the permeability of the permanent magnet is the same as that of the air, Halbach Array can be replaced by the air in finite element model when calculating inductance. One phase winding feed by 1A DC current, the flux linkage of this winding is self-inductance and flux linkages of other windings are mutual inductance of motor. Thus $L_d$ and $L_q$ can be calculated in 3D finite element model. Besides, flux linkage of Halbach PM array is obtained by

$$\psi = \frac{r e_0}{\sqrt{3}}$$

where $e_0$ is the amplitude of line back EMF.

Taking speed of train into account, one segment primary is set 500 meters, other electromagnetic parameters of medium speed maglev train are lists in Table II. The permanent magnetic permeability is the same as it of air and ironless primary and there is no saliency effect in ironless motor, magnetic resistance in secondary covered area and uncovered area are the same, therefore, inductance per kilometer is the same with it in secondary covered area. Besides, $L_d$ of motor are also equal to $L_Q$.

![Fig. 11. Primary ironless coils finite element model (2P=14).](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>flux linkage of Halbach PM array</td>
<td>$\phi_r$</td>
<td>0.14wb</td>
</tr>
<tr>
<td>resistance</td>
<td>$r/km$</td>
<td>0.41</td>
</tr>
<tr>
<td>inductance in d-axis</td>
<td>$L_d/km$</td>
<td>4.16$\mu$H</td>
</tr>
<tr>
<td>inductance in q-axis</td>
<td>$L_q/km$</td>
<td>4.16$\mu$H</td>
</tr>
<tr>
<td>leakage inductance per phase</td>
<td>$L_1/km$</td>
<td>1.13$\mu$H</td>
</tr>
<tr>
<td>length of one segment primary</td>
<td>$l$</td>
<td>500 m</td>
</tr>
</tbody>
</table>
The mathematical model is obtained by (23), this model considering the feeder cable in secondary uncovered area. What needs to be specified is that \( L_d \) and \( L_q \) are the whole power supply cable inductance. \( F_Z \) is train resistance, it including air resistance, current collector resistance and reluctance force.

\[
\begin{align*}
\psi_d &= L_d i_d + \psi_f \\
\psi_q &= L_q i_q + \psi_f \\
u_d &= r i_d + p \psi_d - \frac{\pi}{\tau} v \\
u_q &= r i_q + p \psi_q + \frac{\pi}{\tau} v \\
F_c &= \frac{3\pi}{2\tau} [\psi_d i_d + (L_d - L_q) i_d i_q] \\
\frac{dv}{dt} &= (F_c - F_f) / m
\end{align*}
\]  

(23)

Based on the mathematical model of motor, the traction performance of medium speed maglev train can be calculated, there are five motors fixed in each carriage and it is 22 tons per carriage. From Fig.12 to Fig.14, it is seen that motor has constant thrust in the case of constant input current at the acceleration of train, staring acceleration of train reaches 1.2m/s\(^2\) and the maximum speed reaches 200km/h. The traction of motor adopts \( \text{id}=0 \) control strategy, there is no weak magnetic control region, therefore the normal force impact on traction can be ignored. Fig.15 shows the capacity of converter, the max capacity is 7.5MVA when the train reaches 200km/h, and meanwhile, the efficiency of motor is 0.83, as Fig.16 shows, it is proportional to the speed of train. During the deceleration of the train, -90\(^\circ\) power angle control strategy is used to produce braking force, which is the same as thrust value at the same current. By calculating traction performance of single-sided PMLSM, the feasibility and superiority of this type motor are verified used in medium speed maglev train.

---

V. EXPERIMENT

Experimental platform consisted of a 300KVA converter, long primary single sided ironless PMLSM, and pressure testing equipment. Magnet Halbach array of secondary fixed to stainless steel base, long ironless primary is laid along track. Fig.17 is picture of 200KW type motor.
In order to verify the designed characteristic of the proposed ironless Halbach PMLSM, the blocked-secondary thrust force test has been firstly carried out. In the experiment, the secondary Halbach array is fixed to the base through a force sensor. The thrust of the motor is measured while the magnitude and the electrical angle of primary current are adjusted by the converter.

Fig. 18 shows the comparison of test and calculation thrust with the primary current of 1200 A. The thrust characteristic with different power angle is nearly sinusoidal. The maximum test and FEM calculated thrust at $I_s=1200$ A are 5806 N and 6065 N respectively when power angle is 90°, and the error is about 4.27%. The errors in the other power angles are within 5%, which can prove the accuracy of the analytical results in the previous sections.

![Fig. 18. Comparison of test and calculation results.](image)

**VI. CONCLUSION**

This paper mainly investigates the characteristics of single-sided long primary ironless PMLSM based on Halbach array used for medium-speed maglev train. The analytical model of this type motor is built, flux density and force formulas are deduced for calculating force-angle characteristics. Some important conclusions can be summarized as follows,

1. The amplitudes of thrust and normal force are equal, angles are staggered by 90 degrees when $\tau_s=\tau_p$. Thrust reaches maximum corresponding normal force is zero when the power angle is 90° with $\tau_s=\tau_p$.

2. The amplitudes of thrust and normal force are reduced with $\tau_s \neq \tau_p$.

3. Normal force is attractive when the power angle is 90° with $\tau_s > \tau_p$, comparing normal force is repulsion when the power angle is 90° with $\tau_s < \tau_p$.

The mathematical model of motor is built by using 3D FEM, traction performance under maximum speed 200km/h is calculated and analyzed. Calculation method is verified by finite element and experimental results.

**REFERENCES**


Zhihua Zhang was born in Henan, China, in 1984. He received the B.S. degree in institute of electrical engineering of Henan Polytechnic University, Henan, China, in 2007 and the Ph.D. degree in power electronics and power drives from the Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China, in 2014. He joined the Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China, in 2014, where he is currently an Assistant Researcher. His research interests include design and control of linear motors and AC drives.

Yaohua Li was born in Henan, China, in 1966. He received the Ph.D. degree in 1994 from Tsinghua University, Beijing, China. From 1995 to 2007, he was a Postdoctoral Research Fellow in the Institute of Electrical Machine, Technical University of Berlin, Berlin, Germany. He joined the Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China, in 1997, where he is currently a Professor and Vice Director of the Institute of Electrical Engineering, Chinese Academy of Sciences. His research interests include analysis and control of electrical machines, and power electronics technology.

Liming Shi (M’12) was born in Henan, China, in 1964. He received the Ph.D. degree in 1998 from Kyushu University, Fukuoka, Japan. From 1998 to 2000, he was a Postdoctoral Research Fellow in the Japan Society for the Promotion of Science, Japan. From 2000 to 2002, he was Chief researcher in Yaskawa Electric Co., Ltd., Kitakyushu, Japan. He joined the Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China, in 2002, where he is currently a Professor. His current research interests include analysis and control of electrical machines, contactless power supply.

Zhihua Zhang was born in Henan, China, in 1983. He received the B.S. degree in electrical engineering from Beijing Jiaotong University, Beijing, China, in 2000 and the Ph.D. degree in power electronics and power drives from the Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China, in 2009. He joined the Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China, in 2009, where he is currently an Associated Professor. His research interests include analysis and control of linear motors and AC drives.

Yaohua Li was born in Henan, China, in 1966. He received the Ph.D. degree in 1994 from Tsinghua University, Beijing, China. From 1995 to 2007, he was a Postdoctoral Research Fellow in the Institute of Electrical Machine, Technical University of Berlin, Berlin, Germany. He joined the Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China, in 1997, where he is currently a Professor and Vice Director of the Institute of Electrical Engineering, Chinese Academy of Sciences. His research interests include analysis and control of electrical machines, and power electronics technology.