Investigation of Forces and Secondary Losses in Linear Induction Motor with the Solid and Laminated Back Iron Secondary for Metro

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Abstract—In this paper, two main kinds of the secondary, i.e. the solid and laminated back iron secondary, are applied in linear metro, as well as electromagnetic forces and secondary losses of the single-sided linear induction motor (SLIM) with different secondary are calculated by the finite-element method (FEM). Firstly, in solving region, the fundamental equations of the magnetic field with eddy currents in the secondary are deduced, and specific boundary conditions for each parts of SLIMs are given. Equations of the secondary loss and efficiency are presented. Secondly, 120-kW SLIMs with two types of the secondary for metro are calculated by 3-D FEM respectively. The efficiency and secondary loss are analyzed for different secondary back iron. The optimal number of the back iron is then obtained. Thirdly, considering the influence of the end and edge effect, the air-gap flux density with different secondaries is calculated. Then, the thrust and vertical force are analyzed. Therefore, the efficiency, thrust and vertical force, which are obtained from different secondaries, are experimentally validated by measurement on the test rig of the SLIM.

Index Terms—Laminated back iron secondary, linear induction motor, end effects, solid back iron secondary, three dimensional finite-element method, thrust, edge effects, vertical force

I. INTRODUCTION

The thrust of the single-sided linear induction motor (SLIM) can be directly obtained for the linear metro and maglev[1-3]. In the linear metro, non-adhesion drive of the SLIM makes the car travel on grades as steep as around 8% and 60-m turning radius rails while the limitation is only around 3.5% and 200-m for rotary motor railcars. Thin rectangular body of the SLIM can reduce the cross-section area and construction cost of tunnels. Hence, a SLIM for linear metro contributes to the future reduction of construction cost and improvement of the railcars performance.

Control algorithms [4-9], parameter estimation schemes [10-12], as well as performance analysis and design [13-21], are three main research fields of the SLIM. In the research field of the performance analysis and design, the secondary is an important design factor for the cost of reaction plates and performances of the SLIM for metro. Due to the easy manufacture and low cost, two main kinds of the secondary, i.e. the solid and laminated back iron secondary, are applied in the metro. Nevertheless, influences of the construction and laminated back iron secondary on the secondary losses and forces of SLIMs have not yet been studied.

Some constructions of the secondary have been investigated by FEM in a few papers. In [22], an effective 3-D analysis model for considering the transverse edge effect is proposed. However, the effective 3-D analysis model is only 1/2 pole model and the end effect is neglected. In [23], some types of the secondary construction have been considered, and the simplified field calculation is given through 3-D numerical analysis. However, only the flat and full-cap secondary, which belong to the solid back iron, are investigated. In [24], the 3-D FEM model of the SLIM is developed, and the secondary is a solid back iron. In [25-26], characteristics of the SLIM according to secondary conductor structures are investigated. However, the types of the secondary also belong to the solid back iron secondary, so the laminated back iron secondary and losses of the secondary are yet to be investigated. In [27], the wound secondary of the SLIM and edge effects are investigated, and this type secondary is seldom used in metro. Hybrid finite-element-boundary element is analyzed [28] and a 2-D FEM model [29] is used to calculate the effect of contact resistance between the side-bar and the secondary conductors, while the transverse edge effect is neglected. In [30], a quasi-1-D analytical method is proposed to analyze a double-sided linear motor for transportation, and the longitudinal and transversal edge effects are considered.
In this paper, based on the numerical analysis method of the SLIM, 3-D numerical models of the SLIM considering the solid and laminated back iron secondary for metro are developed, as well as variations of electromagnetic forces and secondary losses are calculated when different secondaries are applied. Experiments are carried out by a test rig of the SLIM to validate the analysis of the force and efficiency, and results are compared when two types of the secondary are applied.

II. STRUCTURE OF THE SLIM FOR METRO

The linear metro system is shown in Fig.1. The SLIM is hanged under the bogie, as well as the secondary is installed in the center of rails and along the whole track. The primary, which is supplied by an inverter to change the voltage and frequency, consists of iron cores and coppery coils. The secondary side is a combination of a magnetically conductive part, such as an iron plate, and an electrically conductive part, such as an aluminum or copper plate. The solid and laminated back iron secondary are usually applied in engineering practice for the simple structure and low cost. In Fig.1, the entry and exit end causes end effects along the direction of travel.

Another type of the secondary, i.e. the laminated back iron secondary, is also applied and shown in Fig.3. Comparing to the solid secondary, two changes are as follows: 1) The equivalent conductivity of the laminated back iron decreases with the increase of the lamination number owing to the change of the air-gap transversal effect. 2) The equivalent air-gap flux decreases with the increase of the lamination number, because the back iron magnetic reluctance decrease which is caused by the increase of the field penetration depth.

III. METHODS OF NUMERICAL ANALYSIS

The following assumptions are proposed:

1) Nonlinear magnetic characteristic is considered in the back iron of the secondary and the primary core, as well as B-H curves are set up.

2) Eddy currents exist in both the aluminum plate and secondary back iron. The conductivity of the secondary back iron is constant.

In the solving region, fundamental equations of the magnetic field with eddy currents of the secondary taken into account can be written as follows

$$
\begin{align}
\frac{\partial}{\partial x} \left( \frac{1}{\mu_x} \frac{\partial A_{x}}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{1}{\mu_y} \frac{\partial A_{y}}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{1}{\mu_z} \frac{\partial A_{z}}{\partial z} \right) &= -J_{\mu_x,i} - J_{\mu_y,i} \\
\frac{\partial}{\partial x} \left( \frac{1}{\mu_x} \frac{\partial A_{x}}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{1}{\mu_y} \frac{\partial A_{y}}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{1}{\mu_z} \frac{\partial A_{z}}{\partial z} \right) &= -J_{\mu_y,j} - J_{\mu_z,j} \\
\sigma_i \left[ \frac{\partial A_{x}}{\partial t} + v \times (\nabla \times A_{x}) \right] &= J_{x,i} \\
\sigma_i \left[ \frac{\partial A_{y}}{\partial t} + v \times (\nabla \times A_{y}) \right] &= J_{y,j} \\
\sigma_i \left[ \frac{\partial A_{z}}{\partial t} + v \times (\nabla \times A_{z}) \right] &= J_{z,i}
\end{align}
$$

where $v$, $A$, $\mu$, $J_p$, $J_e$ are the velocity, the vector magnetic potential, the permeability, the conductivity, the current density of the primary and eddy current in secondary, respectively. Subscripts $x$, $y$, $z$, $i$, denote $x$-, $y$-, $z$- components and the region number in Fig.2, respectively.

In each region, we get
Region 1: \( J_{p,i} = 0 \), \( J_{x,i} = 0 \), \( \sigma_i = 0 \), \( \mu_i = \mu_{\text{core}} \)
Region 2: \( J_{x,i} = 0 \), \( \sigma_i = \sigma_{\text{Cu}} \), \( \mu_i = \mu_0 \)
Region 3: \( J_{p,i} = 0 \), \( J_{x,i} = 0 \), \( \mu_i = \mu_0 \)
Region 4: \( J_{p,i} = 0 \), \( \mu_i = \mu_{\text{Al}} \), \( \sigma_i = \sigma_{\text{Fe}} \)
Region 5: \( J_{p,i} = 0 \), \( \mu_i = \mu_{\text{Iron}} \), \( \sigma_i = \sigma_{\text{Fe}} \)

where \( \mu_{\text{core}}, \mu_{\text{Al}}, \mu_{\text{Iron}} \) and \( \mu_0 \) are the permeability of the primary core, iron plate and vacuum, respectively. \( \sigma_{\text{Al}}, \sigma_{\text{Fe}} \) and \( \sigma_{\text{Cu}} \) are the conductivity of the aluminum, iron plate and coil.

The Neumann boundary condition is used for boundaries between different materials. FEM solution boundary is as follows

\[
A = 0, B = 0
\]  

Eq. (1)-(3) can be solved by Newton-Raphson method, and \( x\)-, \( y\)-, \( z\)-components of the flux density can be obtained from \( B = \nabla \times A \). Then, the thrust and vertical force can be obtained by the virtual displacement method as follows

\[
\begin{align*}
F_i = & \frac{\partial W_m}{\partial x} = \frac{\partial}{\partial x} \left[ \sum_{j=1}^{m} \frac{1}{2 \mu_j} \left( B_{xj}^2 + B_{yj}^2 + B_{zj}^2 \right) V_j \right] \\
F_i = & \frac{\partial W_m}{\partial z} = \frac{\partial}{\partial z} \left[ \sum_{j=1}^{m} \frac{1}{2 \mu_j} \left( B_{xj}^2 + B_{yj}^2 + B_{zj}^2 \right) V_j \right]
\end{align*}
\]

where \( W_m \) is the magnetic co-energy of the SLIM. \( B_{xj}, B_{yj} \) and \( B_{zj} \) are the \( x\)-, \( y\)- and \( z\)-components of the flux density in element \( j \), respectively. \( m \) is the total number of the meshed elements in the solving region of the SLIM, i.e. region 1, 2, 3, 4 and 5, as well as \( \mu_j \) is the permeability in the element \( j \).

Including the additional running resistance caused by the vertical force, the motion equation of the SLIM are as follows

\[
M \frac{d^2 x}{dt^2} + k_1 \frac{dx}{dt} + k_2 \left( Mg - F_x \right) = F_s
\]

where \( M \) is the load weight, \( k_1 \) and \( k_2 \) are coefficients of the viscosity and friction, respectively. The relative movement is taken into account in the FEM by using the time-stepping analysis and Lagrange multiplier method.

While the velocity is determined by Eq. (5), the efficiency can be calculated from the output power and total losses of the SLIM as

\[
\eta = \frac{P_e \cdot V}{F_s \cdot V + P_L}
\]

Due to the self-cooling, the total loss of the SLIM \( P_L \) includes the AC loss of the windings \( P_{Ac} \), primary iron-core loss \( P_{Fe1} \), eddy current loss of the secondary aluminum plate \( P_{Eddy1} \), secondary iron loss \( P_{Fe2} \), mechanical loss \( P_{Fe2} \) and stray loss \( P_g \).

Secondary losses, which include the eddy current losses in the secondary aluminum plate and the iron loss in the secondary back iron, are the main difference when the solid and laminated back iron secondary are applied with the same primary. Hence, only the secondary loss \( P_{Sc} \) is calculated in this paper as follows

\[
P_{se} = P_{Eddy1} + P_{Fe2}
\]

\[
P_{Eddy1} = \sum_{j=1}^{n_{4}} \left[ k_{ca} \cdot f^2 \cdot B_{mj}^2 \cdot V_j \right]
\]

\[
P_{Fe2} = P_{Fe1} + P_{Eddy2} + P_{ex}
\]

\[
P_{Fe2} = \frac{n_{5}}{k_{ex}} \left[ \left( k_{cf} \cdot f^2 \cdot B_{mij}^2 \right) + \left( k_{cf} \cdot f^2 \cdot B_{mij}^2 \right) \right] \cdot V_j
\]

where, \( P_{Eddy1} \) and \( P_{Eddy2} \) are eddy current losses of the secondary aluminum and back iron plate. \( n_4 \) and \( n_5 \) are the number of the meshed elements in region 4 and 5. \( k_{ex} \) is Steinmetz parameters [31] which can be extracted experimentally under the sinusoidal test signal at different frequencies and flux densities. \( k_{ca} \) and \( k_{cf} \), which are the coefficient of eddy current losses in the aluminum and iron plate, are calculated by

\[
k_{ca} = \pi^2 \tau^2 \sigma_{\text{Al}} / 6, \quad k_{cf} = \pi^2 \tau^2 \sigma_{\text{Fe}} / 6
\]

where \( \tau \) is the pole pitch. \( k_e \) is the coefficient of the excess losses in the secondary iron plate and it can be obtained by

\[
k_{e} = 8.67 \cdot \sqrt{\sigma_{Fe} GV_{o}^{\frac{s}{m}}}
\]

where \( G \) is a dimensionless coefficient and \( V_{o} \) is a parameter characterizing the statistical distribution of the local coercive fields. \( S \) is the surface area of the secondary iron plate.

The maximum flux density \( B_{mij} \) of the element \( j \) can be calculated by

\[
B_{mij} = \sqrt[2]{\frac{B_{xij}^2 + B_{yij}^2 + B_{zij}^2}{3}}
\]

IV. FEM ANALYSIS RESULTS

A. 3-D FEM model and parameters of the SLIM

The 3-D FEM model of the SLIM is performed using ANSYS 15.0 as well as parameters of the primary and secondary are listed in Table I and II.

<table>
<thead>
<tr>
<th>Table I</th>
<th>PARAMETERS OF PRIMARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>Value</td>
</tr>
<tr>
<td>( I_p )</td>
<td>160 A</td>
</tr>
<tr>
<td>( f )</td>
<td>35 Hz</td>
</tr>
<tr>
<td>( \rho )</td>
<td>8</td>
</tr>
<tr>
<td>( r )</td>
<td>28 cm</td>
</tr>
<tr>
<td>( m )</td>
<td>3</td>
</tr>
<tr>
<td>( \beta )</td>
<td>7/9</td>
</tr>
<tr>
<td>( e_1 )</td>
<td>13 cm</td>
</tr>
<tr>
<td>( L )</td>
<td>248 cm</td>
</tr>
<tr>
<td>( U_p )</td>
<td>1100 V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table II</th>
<th>MAIN PARAMETERS OF SECONDARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>Value</td>
</tr>
<tr>
<td>( d_1 )</td>
<td>0.7 cm</td>
</tr>
<tr>
<td>( d_2 )</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>( W_1 )</td>
<td>48 cm</td>
</tr>
<tr>
<td>( e_2 )</td>
<td>9 cm</td>
</tr>
<tr>
<td>( W_2 )</td>
<td>2.66</td>
</tr>
<tr>
<td>( n )</td>
<td>18</td>
</tr>
</tbody>
</table>
Conductivities of the coil, secondary aluminum and iron plate are $5.9 \times 10^7$ S/m, $3.4 \times 10^7$ S/m and $1.03 \times 10^7$ S/m, respectively. The permeability of the secondary back iron and primary core is nonlinear, as well as $B$-$H$ curves are shown in Fig. 4 (a) and (b). $k_{ca}$ and $k_{cf}$ are 11.8 and 2.07 W/(m$^3\cdot$Hz$^2\cdot$T$^2$). $k_b$ and $k_c$ are 103.4 W/(m$^3\cdot$Hz$\cdot$T$^2$) and 0.25 W/(m$^3\cdot$Hz$^{1.5}\cdot$T$^{1.5}$). In addition, lap windings and two layers are used in the model.

In Fig. 5, the balloon boundary is applied to the solving region and denoted by band I. Other boundaries, i.e. primary core, coils, secondary back iron and aluminum plate, are all set by Neumann boundary condition. In addition, band II and III shown in Fig. 5 are used to defy the operating region and the running part of the SLIM, respectively. The solid and lamination secondary are denoted by i and ii, as well as discretization data and CPU time are listed in Table III.

### Table III

<table>
<thead>
<tr>
<th>Analyzed model</th>
<th>i</th>
<th>ii</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element number of primary core</td>
<td>189148</td>
<td>189765</td>
</tr>
<tr>
<td>Element number of windings</td>
<td>189679</td>
<td>18324</td>
</tr>
<tr>
<td>Element number of iron plate</td>
<td>317323</td>
<td>401365</td>
</tr>
<tr>
<td>Element number of aluminum plate</td>
<td>103046</td>
<td>114351</td>
</tr>
<tr>
<td>Number of passes</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>CPU time</td>
<td>5:06:20</td>
<td>5:40:45</td>
</tr>
</tbody>
</table>

Computer used: Intel® Core i7 CPU 3.60GHz, RAM 16.0GB

### B. Losses of the Secondary and Efficiencies of the SLIM

Per unit values of losses are proposed to eliminate the influence caused by different secondary, i.e. $p_s=P_s/W_s$ (W/kg), and $W_s$ is weight of the secondary which couples with the primary.

The solid and 18-lamination back iron secondary are applied, and losses of the secondary in the time-domain are shown in Fig. 6 (a) when $I_p=160$ A, $f=5, 15, 25, 35$ Hz and $s=0.2$. About 300-400 ms, curves of the secondary loss are stable, and the second harmonic, which can be seen in the partial enlarge, is

![Fig.4. B-H curves: (a) B-H curves of the secondary back iron (b) B-H curves of the primary core](image)

![Fig.5. Boundaries of the SLIM](image)

![Fig.6. Losses of secondary: (a) Losses of secondary in the time-domain with solid and 18-lamination back iron secondary (b) Losses of secondary with different lamination numbers and frequencies](image)
presented. The second harmonic is mainly caused by the square of the eddy current which is a sinusoidal function with double frequency of the primary current.

In order to investigate the relation of secondary losses and the number of the lamination, relation curves of the losses and slip, shown in Fig.6 (b), is obtained from 19 steady values of the transient solution when the number of the lamination is 2, 3, 4… 20, respectively. With the number of the back iron lamination increase, the equivalent conductivity of the secondary iron back decreases and the path of the eddy current increases, therefore, the eddy current loss decreases. It can be seen clearly form Fig.6 (b) that the decrease of losses tends to be slowed down when the lamination number is 18. Hence, 18 is the optimal lamination number if the construction costs of the secondary are neglected.

SLIMs for metro usually works in the slip range from 0.05 to 0.25, and Fig.7 shows the FEM simulation results of the efficiency with different lamination numbers as a function of the slip when \( I_P = 160 \) A. Due to the decrease of the hysteresis and eddy current losses in the secondary, the efficiency increases with the increase of the lamination number.

C. Eddy Current Densities in the Secondary

Eddy current densities in the secondary are given in Table IV, and the solid and lamination secondary are denoted by i and ii, respectively.

<table>
<thead>
<tr>
<th>Type</th>
<th>5 Hz</th>
<th>15 Hz</th>
<th>25 Hz</th>
<th>35 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>8.24</td>
<td>8.80</td>
<td>8.88</td>
<td>8.93</td>
</tr>
<tr>
<td>ii</td>
<td>6.46</td>
<td>7.03</td>
<td>7.33</td>
<td>7.52</td>
</tr>
</tbody>
</table>

Due to the application of the lamination back iron and the increase of the transverse edge effect, the equivalent conductivity of the lamination secondary decreases. On the other hand, the equivalent field penetration depth in the lamination back iron is higher than one in the solid back iron. Hence, eddy current destinies of the solid back iron secondary are higher than those of the 18-lamination back iron secondary.

D. Air-gap Flux Densities

Maximum values of the air-gap flux density \( (B_m) \) in the transverse and longitudinal direction, when \( I_p = 160 \) A, \( f = 5, 15, 25 \) Hz, are presented in Table IV.

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Type} & 5 \text{ Hz} & 15 \text{ Hz} & 25 \text{ Hz} \\
\hline
\text{i} & 8.24 & 8.80 & 8.88 \\
\text{ii} & 6.46 & 7.03 & 7.33 \\
\hline
\end{array}
\]

Unite: \( \times 10^6 \) A/m²

Fig.8. Air-gap flux densities with different secondaries: (a) Transverse air-gap flux density (b) Longitudinal air-gap flux density
25, 35 Hz and \( s=0.2 \), are calculated and shown in Fig.8. In Fig.8 (a), \( B_m \) in the transverse direction is U type owing to edge effects which cause the demagnetizing reaction. Hence, the transverse edge effects lead to the reduction of the thrust and power factor. The edge effect of SLIMs with the laminated secondary is weaker than that with the solid secondary, so SLIMs with the laminated secondary produces larger thrust than those with the solid secondary done.

In the FEM model, the entry and exit end are considered. When the primary moves, longitudinal end effects occur and can be calculated. In Fig.8 (b), poles of the SLIM become more and more weaker from the exit end to entry end. This phenomenon causes much less thrust produced in the entry end. Hence, the total thrust of SLIMs decrease as well as the notable reduction in efficiency and power factor are caused. In addition, due to the longitudinal end effect, the vertical force has a nonuniform distribution in the longitudinal direction and the dolphin couple occurred.

The equivalent conductivity of the laminated back iron is smaller than that of the solid back iron, and the eddy current in the laminated back iron is lower. Hence, in partial enlarged drawing of Fig.8 (b), higher air-gap flux density can be obtained in the SLIM with the laminated secondary.

V. EXPERIMENTAL VALIDATION

In order to verify the numerically predicted result, a test rig for the SLIM is built and shown in the Fig.9 (a). In Fig.9 (b), several pressure and tension sensors are installed on the bogie to measure forces, and major specifications of pressure and tension sensors are shown in Table V. In Fig.9 (c) and (d), the solid and laminated back iron secondary are shown, and the number of lamination is optimized to be 18.

<table>
<thead>
<tr>
<th>Main Parameters of Pressure and Tension Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>Fz1, Fz2</td>
</tr>
<tr>
<td>Fy1, Fy2</td>
</tr>
<tr>
<td>Fx1, Fx2</td>
</tr>
</tbody>
</table>

By using the numerical analysis method described in Section III, the force performance of the SLIM with solid and laminated back iron secondary has been evaluated by the 3-D numerical
model. Thrust and vertical force variations in time are calculated and shown in Fig.10-11, when \( I_p = 160 \) A, \( f = 5, 15, 25, 35 \) Hz and \( s = 0.2 \). Experiments are carried out in two sets and the SLIM is driven by the vector control inverter. The primaries are the same, as well as the solid and optimal back iron secondary are used in two sets respectively.

Thrust and vertical forces per kg of the SLIM are proposed, i.e. \( f_x = F_x / W_m \) and \( f_z = F_z / W_m \) (N/kg), and \( W_m \) is weight of the SLIM. The specific thrust in the time-domain is shown in Fig.10 when the solid and 18-lamination back iron secondary are used, respectively. In Fig.10 (a), the curve of specific thrust is stable after 400 ms, and second harmonic is presented because the product of the eddy current and flux density is a sinusoidal function with double frequency. FEM analysis and experiment results of the specific thrust are presented in Fig.10 (b). In the low-velocity region, the train needs high thrust to be accelerated, and the specific thrust will decrease with the increase of the velocity when SLIM works in the region of the constant power.

In Fig.11, eddy currents in the secondary with 18-lamination back iron are less than those in secondary with the solid back iron, and repulsive components of specific vertical forces in the secondary with 18-lamination back iron are lower than those in the secondary with solid back iron. Hence, the specific vertical force of the SLIM with the lamination back iron secondary is higher than that of the SLIM with solid ones. In Fig.11 (b), due to low eddy currents in the low-velocity region, the specific vertical force is high and it means that the train has high running resistances when it is slow. The specific vertical force decreases with the increase of the velocity when the SLIM works in the region of the constant power.

FEM analysis and experiment results of the efficiency are presented in Fig.12. Due to the constant thrust, the efficiency is low in the low-velocity region and maximum values are obtained when the SLIM works in the region of the constant power. About 4% improvement of the efficiency is obtained if the solid secondary is replaced by the 18-lamination secondary.

**VI. CONCLUSION**

Two types of secondary are investigated and 3-D FEM is used to analyze the influence of the solid and laminated back iron secondary on forces and secondary losses of the SLIM for metro. In order to do this work, not only 3-D FEM model but also numerical analysis methods are proposed. Then, the air-gap flux density, eddy currents in the secondary, secondary losses, thrust, vertical force and efficiency are predicted and validated by the measurement on a SLIM prototype. It can be concluded as following to aid secondary designs:

1) About 10% and 4% improvement of the thrust and efficiency is obtained respectively for the SLIM in this paper if the solid secondary is replaced by the 18-lamination secondary. Hence, the lamination secondary is a way to improve performances of the SLIM.

2) About 20% increase of the vertical force is obtained if the solid secondary is replaced by the 18-lamination secondary. So much more running resistances and pressures of rails caused by the vertical force must be considered if the lamination back iron secondary is applied.
REFERENCES


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