Research of slip’s problem in multi-stage synchronous induction coil launcher

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Abstract. In order to clarify the conception and the connotation of slip distance in the firing control model for multi-stage synchronous induction coil launcher (MSSICL), the conceptions and the connotations about slip’s problem (which includes slip speed, slip ratio and slip distance) are defined in the paper through the reference to the conception of rotation slip speed and rotation slip ratio in rotation induction machine (RIM). The slip speed, the slip ratio and the slip distance for the second stage in three-stage synchronous induction coil launcher (TSSICL) with given structure are calculated based on the simulative results of dynamically accelerative characteristic under the conditions of different initial working voltages and proper firing energized locations. The influences of the slip speed and the slip ratio on the working characteristics of MSSICL are discussed. These have important theoretical instruction significance for the determination of slip distance in the solved process of the firing control’s problem in MSSICL.

1. Introduction

Linear magnetic travelling wave (LMTW), which moves in the axial direction of MSSICL, is produced when pulsed currents are fed into the driving coils at given time sequence in its working process [1-5]. The speed of LMTW is not usually the same as the speed of the armature’s movement. From the aspects of increasing the skin depth of inductive current in the armature and lessening the local heat of the armature, the armature should be in an approximate constant magnetic field in the whole accelerative process [1]. This is helpful to enhance the launch efficiency of MSSICL. But a series of slip’s problems arise, such as slip speed, slip ratio and slip distance because of the speed difference between LMTW and the armature [6-8].

Energized condition of MSSICL, \( Z_c - Z_a \leq Z_{slp} + L_{rise} \), is mentioned in [7, 8]. \( Z_c \) is the centre location of the driving coil, \( Z_a \) is the armature tail’s location, \( Z_{slp} \) is the slip distance, \( L_{rise} \) is the rise length of the driving current. It is difficult to understand the concept of slip distance. In addition, the other concepts about slip’s problem are also obscure, and their influences on the working characteristic of MSSICL are rarely mentioned in public references. Therefore the research on slip’s problem is very significance to solve the firing control problem of MSSICL.

Slip speed, slip ratio and slip distance are investigated through the reference of the concepts of rotation slip speed and rotation slip ratio. Firstly the concepts about slip’s problem are defined. Mathematical expressions of depicting slip speed, slip ratio and slip distance are given. Then slip
speed, slip ratio and slip distance for the second stage in TSSICL with given structure are calculated based on the simulative results of dynamically acceleration characteristic. Finally the influences of slip speed and slip ratio on the working characteristic of MSSIICL are discussed.

2. Conceptions of slip speed, slip ratio and slip distance

From the angle of electric machine, the slip speed and the slip ratio in MSSIICL are respectively similar with the rotation slip speed and the rotation slip ratio in RIM. Therefore the slip speed and the slip ratio in MSSIICL can be defined through the reference of the rotation slip and the rotation slip ratio in RIM. Magnetic travelling wave in RIM is rotation travelling wave [9], and that in MSSIICL is LMTW. The concept of LMTW’s speed must be determined in the course of defining the slip speed and the slip ratio. LMTW’s speed is explained through figure 1. MSSIICL in figure 1 is made up of n stages driving coils. The axial lengths of all driving coils are the same, and the axial distance between the adjacent driving coil’s centers is \( l_{cc} \).

![Figure 1. Structure scheme of MSSIICL.](image)

The rotation magnetic field in RIM is usually depicted through the rotation of the air peak magnetic field synthesized by three-phase or multi-phase windings, and it is usually foundational magnetic field. The air peak of rotation magnetic field lies on the axial line of phrase winding that peak phase current is flowing [9]. According to the depicting method of rotation magnetic field, LMTW in MSSIICL should also be depicted through the movement of the air peak magnetic field.

Supposed that the peak times of Stage \( m-1 \), Stage \( m \) and Stage \( m+1 \) are \( t_{m-1} \), \( t_{m} \) and \( t_{m+1} \) respectively. LMTW moves from Stage \( m-1 \) to Stage \( m \) at the period of \( t_{m-1}-t_{m} \), and that moves from Stage \( m \) to Stage \( m+1 \) at the period of \( t_{m+1}-t_{m} \). So the average speed of LMTW at the periods of \( t_{m+1}-t_{m} \) and the average speed of LMTW at the periods of \( t_{m}-t_{m-1} \) are respectively expressed as

\[
v_{(m-1),m} = \frac{l_{cc}}{(t_{m} - t_{m-1})} \quad ,
\]

\[
v_{m,(m+1)} = \frac{l_{cc}}{(t_{m+1} - t_{m})} \quad .
\]

As far as Stage \( m \) is concerned, it is not proper to depict the LMTW’s speed \( v_m \) by (1) or (2) because \( v_m \) may be not equal to \( v_{(m-1),m} \) or \( v_{m,(m+1)} \). Under the condition of linear uniform acceleration, the LMTW’s speed of Stage \( m \) can be approximately expressed as

\[
v_m = 2l_{cc} / (t_{m+1} - t_{m-1}) \quad .
\]

Supposed that the armature speeds at the peak times of the driving currents of Stage \( m-1 \), Stage \( m \) and Stage \( m+1 \) are \( v_{am-1} \), \( v_{am} \) and \( v_{am+1} \) respectively, the slip speed and the slip ratio for Stage \( m \) can be respectively expressed as

\[
\Delta v_m = v_m - v_{am} \quad ,
\]

\[
s_m = (v_m - v_{am}) / v_m \quad .
\]

LMTW’s speed quickens with the increase of stage number according to (3). Slip speed changes with the LMTW’s speed and the armature’s speed, so does the slip ratio. The slip speed and the slip ratio are both positive when the LMTW’s speed is larger than the armature’s speed at the peak time according to (4) and (5). The slip speed and the slip ratio are both zero when the LMTW’s speed
equals to the armature’s speed at the peak time. The slip speed and the slip ratio are both negative when the LMTW’s speed is lower than the armature’s speed at the peak time.

Slip distance can be calculated by means of slip speed or slip ratio under the condition of linear slip speed or constant slip speed. Slip distance for Stage \( m \) can be expressed as

\[
Z_{\text{slip}-m} = \Delta v_m \cdot t_m
\]  

(6)

\[
Z_{\text{slip}-m} = s_m \cdot Z_a
\]  

(7)

3. Calculation of slip speed, slip ratio for TSSICL

The main parameters of TSSICL with given structure are listed in table 1. \( l_c=80 \) mm. Let the tail of Stage 1 lies on the location of \( Z=0 \). The center locations of Stage 1, Stage 2 and Stage 3 can be respectively expressed \( Z_{cm1}=30 \) mm, \( Z_{cm2}=110 \) mm and \( Z_{cm3}=190 \) mm. The capacitor’s capacitances in three-stage driving circuit are 1200\( \mu \)F. Let the initial working voltage \( U_{c1}=U_{c2}=U_{c3}=5 \) kV, 6 kV, 7 kV, 8 kV, 9 kV and 10 kV. Here relative calculations are made based on the dynamically simulative results under the condition of proper energized location.

| Table 1. Main parameters of TSSICL. |
|-----------------------------------|
| **Driving coil’s parameters of Stage 1** |
| Axial length/mm | Inner radius/mm | Radial thickness/mm | Turn number | DC resistance/mΩ |
| 60 | 43.5 | 20 | 110 | 64 |
| **Driving coil’s parameters of Stage 2** |
| Axial length/mm | Inner radius/mm | Radial thickness/mm | Turn number | DC resistance/mΩ |
| 60 | 43.5 | 16 | 88 | 49 |
| **Driving coil’s parameters of Stage 3** |
| Axial length/mm | Inner radius/mm | Radial thickness/mm | Turn number | DC resistance/mΩ |
| 60 | 43.5 | 12 | 66 | 35 |
| **Armature’s parameters** |
| Axial length/mm | Inner radius/mm | Radial thickness/mm | Material | Mass/kg |
| 120 | 31 | 10 | Al | 1.36 |

Proper energized locations \( Z_{ae} \) of each stage for the different initial working voltages are listed in table 2.

| Table 2 Proper firing energized locations. |
|--------------------------------------------|
| Initial working voltage/kV | Firing energized location/mm | \( Z_{ae1} \) | \( Z_{ae2} \) | \( Z_{ae3} \) |
| \( U_{c1}=U_{c2}=U_{c3}=5 \) | 15 | 42 | 107 |
| \( U_{c1}=U_{c2}=U_{c3}=6 \) | 15 | 33 | 95 |
| \( U_{c1}=U_{c2}=U_{c3}=7 \) | 12 | 27 | 88 |
| \( U_{c1}=U_{c2}=U_{c3}=8 \) | 9 | 20 | 80 |
| \( U_{c1}=U_{c2}=U_{c3}=9 \) | 6 | 16 | 74 |
| \( U_{c1}=U_{c2}=U_{c3}=10 \) | 6 | 15 | 69 |

Peak times of the driving current are listed in table 3.

| Table 3 Peak times of each driving current. |
|---------------------------------------------|
| Initial working voltage /kV | Peak times of driving current/ms | \( t_1 \) | \( t_2 \) | \( t_3 \) |
| \( U_{c1}=U_{c2}=U_{c3}=5 \) | 1.06 | 2.26 | 2.98 |
| \( U_{c1}=U_{c2}=U_{c3}=6 \) | 1.00 | 1.90 | 2.48 |
| \( U_{c1}=U_{c2}=U_{c3}=7 \) | 0.98 | 1.74 | 2.26 |
| \( U_{c1}=U_{c2}=U_{c3}=8 \) | 0.94 | 1.60 | 2.08 |
| \( U_{c1}=U_{c2}=U_{c3}=9 \) | 0.94 | 1.56 | 2.00 |
| \( U_{c1}=U_{c2}=U_{c3}=10 \) | 0.86 | 1.46 | 1.86 |
The LMTW’s speed of Stage 2 can be calculated according to (3) and peak times listed in table 3. The LMTW’s speed $v_2 \approx 83.33 \text{ m/s}$, $108.11 \text{ m/s}$, $125.00 \text{ m/s}$, $140.35 \text{ m/s}$, $150.94 \text{ m/s}$, $160 \text{ m/s}$ when the initial working voltages $U_{c1} = U_{c2} = U_{c3} = 5 \text{ kV}$, $6 \text{ kV}$, $7 \text{ kV}$, $8 \text{ kV}$, $9 \text{ kV}$, $10 \text{ kV}$.

The armature’s speeds at the peak times of each stage driving current under the conditions of different initial working voltages and its proper energized location are listed in table 4.

| Initial working voltage /kV | Armature’s speeds / (m/s) |
|-----------------------------|---------------------------|
| $U_{c1}=U_{c2}=U_{c3}=5$   | 28.44 81.05 117.08       |
| $U_{c1}=U_{c2}=U_{c3}=6$   | 36.53 96.53 141.93       |
| $U_{c1}=U_{c2}=U_{c3}=7$   | 43.55 115.31 167.15     |
| $U_{c1}=U_{c2}=U_{c3}=8$   | 46.11 128.67 189.02     |
| $U_{c1}=U_{c2}=U_{c3}=9$   | 48.25 145.35 212.13     |
| $U_{c1}=U_{c2}=U_{c3}=10$  | 47.85 161.71 234.13     |

Slip speeds and slip ratios for Stage 2 can be calculated according to (4) and (5). Slip speeds and slip ratios for Stage 2 are shown in table 5.

| Initial working voltage /kV | Slip speed $\Delta v_2 / (\text{m/s})$ | Slip ratio $s_2$ |
|-----------------------------|----------------------------------------|------------------|
| 5                           | 2.28                                   | 0.027            |
| 6                           | 10.15                                  | 0.094            |
| 7                           | 9.69                                   | 0.078            |
| 8                           | 11.68                                  | 0.083            |
| 9                           | 5.59                                   | 0.037            |
| 10                          | -1.71                                  | -0.011           |

Slip distances of Stage 2 can be obtained according to (6), slip speeds listed in table 5 and peak times listed in table 3. Slip distances of Stage 2 $Z_{\text{slip}2} \approx 5.15 \text{ mm}$, $19.28 \text{ mm}$, $16.86 \text{ mm}$, $18.68 \text{ mm}$, $8.72 \text{ mm}$, $-2.50 \text{ mm}$.

4. Discussion of slip’s problem
From table 5, we can know that the slip speed and the slip ratio of Stage 2 can be positive or negative. The slip speeds and the slip ratios of Stage 2 when $U_{c1}=U_{c2}=U_{c3}=5 \text{ kV}$, $6 \text{ kV}$, $7 \text{ kV}$, $8 \text{ kV}$, $9 \text{ kV}$ are positive. The slip speed and the slip ratio of Stage 2 when $U_{c1}=U_{c2}=U_{c3}=10 \text{ kV}$ are negative.

Linear slip speed is employed and the slip speed $\Delta v = 3 \text{ m/s}$ in the representative example of SLINSHOT [6]. The representative value of $s = -0.01$ for MSSICL with the axial length of 10 m and the armature with the axial length of 10 cm. The slip distance of MSSICL’s tail is zero, and that of MSSICL’s head is 10 cm. As far as the MSSICL in [7] with the axial length of 60 m and the armature with the axial length of 40 cm is concerned, linear slip speed is also employed and $s = 4.17e^{-3}$. The slip distance of the last stage is about 25 cm. The sum of the slip distance of the last stage and the rise length of the last stage’s driving current 15 cm just equals to the axial length of the armature. The relationship has become the method of determining the armature’s length.

The absolute values of $s_2$ listed in table 5 are evidently larger than that employed by Sandia National Laboratory. The smaller the absolute value of $s$, the more possible the armature’s tail reaches the coil’s center at the driving current’s peak time.

Figure 2 gives the axial electromagnetic force of the armature in TSSICL under the conditions of proper energized locations and different initial working voltages.
Figure 2. Curves of axial electromagnetic force on the armature vs. time.

From figure 2, we can see that there is not the electromagnetic braking force on the armature except for the area of the armature’s tail breaking away from the head of Stage 3. This means that the electromagnetic accelerative force still exerts on the armature under the condition of the negative slip speed and the negative slip ratio. Therefore the influences of slip ratio on the axial force of the armature in MSSICL are completely similar to the influences of rotation slip ratio on the rotator’s torque in RIM. Rotation slip ratio  \( s = (n_s - n) / n_s \). Here \( n_s \) is the rotation speed of magnetic field and \( n \) is the rotator’s speed. RIM is in the state of motor, the state of generator and the state of electromagnetic brake respectively when \( 0 < s < 1 \), \( s > 1 \) and \( s > 1 \) [9]. The armature’s acceleration is both obtained when the absolute values of \( s \) are small and whether \( s \) is positive or negative in MSSICL. The peak location of LMTW will transcend the armature’s head and the brake force will be produced when slip ratio is positive and it is over large. This is similar to the condition of \( s > 1 \) in RIM. The location of the armature’s tail will transcend the peak location of LMTW when slip ratio is negative and its absolute value is over large. This is helpless to the armature’s acceleration.

The structure difference between MSSICL and RIM is the main reason that results in the above characteristic difference. The rotator has the rotation symmetry and the infinite continuity about the stator windings in RIM. But the armature’s axial length is constant or finite. The armature’s location relative with all stage driving coil continuously changes and it has not the axial symmetry in the working process of MSSICL.

5. Conclusions
Taking a TSSICL system as an example, the slip’s problem in MSICL is analyzed. The conclusions are summarized as follow:

1. The slip speed and the slip ratio are not fix values in MSSICL. They can be positive or negative. When the absolute value of slip ratio is small, the armature can be accelerated whether slip ratio is positive or negative.
2. When slip ratio is positive and it is over large, the peak location of linear magnetic travelling will transcend the armature’s head and the brake force will be produced.
3. When slip ratio is negative and its absolute value is over large, the location of the armature’s tail will transcend the peak location of linear magnetic travelling wave. This is helpless to the armature’s acceleration.

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