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Measurement and analysis of equivalent impedance for three-stage synchronous Induction coil launcher

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Abstract. Equivalent impedances (EQIM) of three-stage synchronous induction coil launcher (SICL) under the different conditions, such as the EQIM before three-stage driving coils are assembled, the EQIM with armature and without armature after three-stage driving coils are assembled, are measured by means of digital electric bridge of UC2856A. Measurement results under the different conditions are compared and analyzed. The change laws of equivalent inductance (EQIN) and equivalent resistance (EQRE) of each stage versus the armature’s location are provided when the armature moves along the axial line of the three-stage SICL. Measurement results are in accordance with the theoretical analysis results of EQIN and EQRE of each stage. These have important significances for the prediction of each stage driving current’s wave and the determination of the initial value of each stage driving current’s change ratio at energized time in the solution process of the firing control model.

1. Introduction

Synchronous induction coil launcher (SICL) is one kind of coil launchers. Linear magnetic travelling wave is produced when pulsed driving currents are fed into the driving coils at approximately synchronous time sequence with the armature’s location in the working process of SICL [1-6]. Eddy is induced in the armature, and the armature is accelerated because of the interaction of the eddy and the magnetic field. Equivalent impedance (EQIM) of each stage constantly changes because of the armature’s eddy effect and the armature’s location change in the accelerative process of multi-stage SICL [7]. The change of EQIM affects not only the frequency of the driving current but also the peak of the driving current. Exact calculations of electrical parameters for each stage are the basis of the accelerative performance simulation of multi-stage SICL. The calculation results of electric parameters need to be validated through the method of experiment measurement. The change ratio of each stage’s driving current at the energized time need to be determined in the solved process of firing control model of multi-stage SICL. The change ratio of each stage’s driving current at the energized time can be obtained by means of the initial working voltage and equivalent inductance (EQIN) of each stage. Therefore the measurement of equivalent impedance has important significance to predict the driving current’s wave and to determine the initial value of the driving current change’s ratio.

Taken three-stage SICL for example, the EQIM before the driving coils are assembled and the EQIM with the armature and without the armature after the driving coils are assembled are measured. The EQIM measured under the above different conditions are compared and their connotations are
analyzed. The change laws of EQIN and equivalent resistance (EQRE) of each stage versus the armature’s location are provided.

2. Structure model of three-stage SICL
Structure model of three-stage SICL is shown in figure 1. The axial length of three-stage driving coils is 60 mm. The inner diameter of three-stage driving coils is 88 mm. The radial thicknesses of three-stage driving coils are 22 mm, 20 mm, 15 mm respectively. The turn numbers of three-stage driving coils are 90, 80 and 60 respectively. The axial length of the armature is 120 mm. The outer diameter of the armature is 82 mm. The radial thickness of the armature is 10 mm. The armature can be accelerated in the direction of Z axis. The materials of the armature and the driving coil are aluminum and copper respectively.

3. Analysis of influencing factors for EQIM’s measurement
The EQIM of each stage driving coil is the impedance when it is seen from its two ends to the driving coil. The EQIM before assembled is the self-impedance. The EQIM after assembled may be influenced by the other stage. In addition, the EQIM of each stage driving coil under the condition of the armature loaded is influenced by the armature eddy’s effect, the armature location and the factor of inter-stage magnetic couple.

The EQIM of each stage driving coil can be expressed as

\[ Z_c = R_c + j\omega L_c \]  

where, \( R_c \) denotes EQRE, \( L_c \) denotes EQIN, \( \omega \) denotes angle frequency.

According to (1), we can know that real part of EQIM is EQRE and imaginary part of EQIM is the product of EQIN and the angle frequency. Therefore the measurement of EQIM can be realized through the measurements of EQRE and EQIN. The influences of the armature eddy’s effect on EQIM need to be considered under the condition of the armature loaded. Measurement frequency must be determined in the measurement process of EQIM because the eddy’s effect is closely related with the measurement frequency. The armature’s location also needs to be given because the measurement result is directly influenced by the armature’s location.

4. Measurement and analysis of EQIM
4.1. EQIM before driving coils assembled
EQIM of three-stage driving coils before assembled are measured by means of digital electric bridge of UC2856A at the measurement frequency \( f = 50 \text{ Hz}, 60 \text{ Hz}, 100 \text{ Hz}, 120 \text{ Hz}, 200 \text{ Hz}, 400 \text{ Hz}, 500 \text{ Hz}, 1000 \text{ Hz} \). The measurement results are shown in table 1.
Table 1. Measurement results of EQIM before assembled.

| Frequency f/Hz | Driving coil 1 | Driving coil 2 | Driving coil 3 |
|---------------|----------------|----------------|----------------|
|               | Lc1/μH | Rc1/mΩ | Lc2/μH | Rc2/mΩ | Lc3/μH | Rc3/mΩ |
| 50            | 836.976 | 61.69 | 664.194 | 54.63 | 347.568 | 39.80 |
| 60            | 836.719 | 62.34 | 664.075 | 54.76 | 347.526 | 39.38 |
| 100           | 836.295 | 63.10 | 661.974 | 54.99 | 347.225 | 40.15 |
| 120           | 835.816 | 64.30 | 661.807 | 55.86 | 347.057 | 40.54 |
| 200           | 835.243 | 70.96 | 661.463 | 60.79 | 346.921 | 42.01 |
| 400           | 833.129 | 99.72 | 659.863 | 82.21 | 346.451 | 50.72 |
| 500           | 831.591 | 120.34 | 658.711 | 97.53 | 346.011 | 57.89 |
| 1000          | 821.876 | 268.71 | 651.648 | 209.51 | 343.247 | 107.20 |

From table 1, we can see that EQRE of each stage driving coil takes on an increase trend and that EQIN of each stage driving coil takes on a decrease trend with the enhancing of measurement frequency.

4.2. EQIM without armature after driving coils assembled

Three-stage driving coils are installed on the launch tube, and their wounded directions are the same. Three-stage driving coils and the launch tube lie in the reinforcing tube. The material of the launch tube and the reinforcing tube are both the compound of epoxy resin and glass fiber. The axial distance of adjacent driving coil’s fringes is 20 mm.

Detailed measurement conditions are the same as the foregoing measurement conditions except measurement frequency. Here measurement frequency \( f = 400 \) Hz. The ends of the other stage driving coils keep open when EQIM measurement of one stage is made. Measurement scene is shown in figure 2.

![Figure 2. Measurement scene of EQIM after assembled.](image)

EQIN and EQRE of Driving coil 1 are respectively 808.226 μH and 103 mΩ. EQIN and EQRE of Driving coil 2 are respectively 648.106 μH and 87.49 mΩ. EQIN and EQRE of Driving coil 3 are respectively 342.277 μH and 51.46 mΩ. EQIN of each stage driving coil after assembled is smaller than that before assembled and EQRE of each stage driving coil after assembled is larger than that before assembled through the comparison those data with the corresponding data of \( f = 400 \) Hz in table 1. The reason of resulting in the difference is mainly the influences of adjacent driving coils.

4.3. EQIM with armature after driving coils assembled

Measurement frequency \( f = 400 \) Hz. The ends of the other stage driving coils keep open when EQIM measurement of one stage is made. The axial measurement step of the armature is 2 mm considering
the distinct influences of the armature’s location on the EQIM. Here the armature’s location is its tail’s location, and its initial location is O point in figure 1.

The measurement results of EQIN and EQRE are shown in figure 3.

![Figure 3](image)

**Figure 3.** Measurement results of EQIM.

Figure 3 (a) indicates the change laws of the equivalent inductances of three-stage driving coils versus the armature’s location, and figure 3 (b) indicates the change laws of the equivalent resistances of three-stage driving coils versus the armature’s location.

EQIN of driving coil with the armature is distinctly smaller than that of driving coil without the armature and EQRE of driving coil with the armature is distinctly larger than that of driving coil without the armature. From figure 3, we can know that EQIN of Driving coil 1 gradually becomes large and that EQRE of Driving coil 1 gradually becomes small when the armature moves along the Z axis from O point. The EQIM of Driving coil 1 when the armature lies in the location of Z=100 approximately equals to the EQIM of Driving coil 1 without the armature after assembled. The change law of the EQIN of Driving coil 2 is firstly decreases, then approximately keeps constant, subsequently increases to the EQIN of Driving coil 2 without the armature when the armature transcends Driving coil 2. The change law of the EQRE of Driving coil 2 is firstly increases, then approximately keeps constant, subsequently decreases to the EQRE of Driving coil 2 without the armature when the armature transcends Driving coil 2. The EQIN of Driving coil 3 gradually decreases and the EQRE of Driving coil 3 gradually increases when the armature runs through Driving coil 3. The EQIN of Driving coil 3 gradually increases to the EQIN of Driving coil 3 without the armature after assembled in the process of the armature breaking away from Driving coil 3. The EQRE of Driving coil 3 gradually decreases to the EQRE of Driving coil 3 without the armature after assembled in the process of the armature breaking away from Driving coil 3.

The main reason of resulting in EQIM’s change is that magnetic couple interaction between the armature and the driving coil is closely related with the armature’s location. Magnetic couple interaction becomes strong when the armature lies in the driving coil. Magnetic couple interaction becomes weak when the armature does not lie in the driving coil. Strong magnetic couple interaction makes EQIN of driving coil small and EQRE of driving coil large. Weak magnetic couple interaction makes EQIN of driving coil large and EQRE of driving coil small.
In order to analyze the influences of inter-stage magnetic couple interaction on the EQIM of each stage driving coil, EQIM with the armature on some locations is measured when the other stage driving coils are in short circuit. The measurement results of EQIM of Driving coil 2 are the following: the EQIN are 347.092 μH, 346.613 μH, 346.517 μH and the EQRE are 217.35 mΩ, 216.01 mΩ, 215.81 mΩ when the armature locations Zae=30, 40, 50. The measurement results of EQIM of Driving coil 3 are the following: the EQIN are 174.297 μH, 174.59 μH, 129.63 μH and the EQRE are 130.79 mΩ, 129.63 mΩ, 129.28 mΩ when the armature locations Zae=110, 120, 130. EQIN and EQRE under the other two-stage driving coils in short circuit state are little smaller than those under the other two-stage driving coils in open circuit state through the comparison of the above measurement results and the measurement results on the corresponding locations shown in figure 3. These mean that the inter-stage magnetic couple-function in the three-stage SICL has little influences on the EQIM of each stage driving coil.

4.4. Analysis of main reasons of measurement error
Above all, the error of measurement instrument can bring measurement error. Then, the contact states and the space locations of the measurement joints of driving coils and the measurement clamps are the main reason resulting in measurement error. The contact states between the measurement joints of driving coils and the measurement clamps influence the measurement results of EQRE. The space locations of the measurement joints of driving coils and the measurement clamps maybe bring about the uncertainty of EQIN.

5. Conclusions
EQIM of the driving coil before assembled is different from that after assembled. The EQIN of each stage driving coil after assembled is smaller than that of each stage driving coil before assembled, while the EQRE of each stage driving coil after assembled is larger than that of each stage driving coil before assembled. The armature eddy’s effect has distinctly influences on the EQIM of each stage driving coil. EQRE becomes large and EQIN becomes small when frequency becomes large. The armature location has also distinctly influences on the EQIM of each stage driving coil. EQIN and EQRE of each stage driving coil fluctuate in large range. EQIN becomes small and EQRE becomes large when the armature lies in the driving coil.

Acknowledgments
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