# Magnetic Circuit Modeling for the Railway Inductive Power Supply

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ABSTRACT: In transportation systems electricity is used to replace fossil combustible as the energy source, this change reduces the emissions of greenhouse effect gases. Contact systems are used to supply energy to the vehicle; however maintenance cost and electric shocks hazard are disadvantages in comparison with fossil fuels. To overcome these limitations contactless transfer systems were developed. Railway Inductive Power Supply , contactless system developed in Korea Railroad Research Institute is analyzed in this paper. The magnetic circuit is presented in this paper. To calculate the magnetic circuit the analytical method is used. To validate the model the results are compared with the prototype measures.

## 1 INTRODUCTION

Recently to protect and preserve the environment is of growing concern. Global warming caused by greenhouse effects sparked the interest in clean energies, especially the substitution of fossil combustibles for renewable sources.

Fossil combustibles are used as the main source of energy in majority of the fields of our society. The substitution of these combustible for renewable sources are in different steps of development, in different fields.

Electric and transportation system are in the two sides of this debate, in one side the electric system where the renewable sources are growing very fast and in the other the transportation that are basically dependent on fossil combustibles.

To change this scenario many researches are being made to create electric vehicles, fuel cells and bio fuels. Furthermore mass transportation systems are being seen as a more rational solution than individual transports.

In mass transportation systems renewable sources are already being used, electric trains, trolley bus, etc. Although electricity is used the search for more efficient systems guided the focus of this paper.

Railway systems have been using electricity since the end of XIX century. However the systems are based on contact systems which are divided in overhead contact systems and auxiliary electrified rail.

Overhead contact system consists in an energy wire the runs above the track and the supply for the train is provide by a pantograph, moving device that assure the contact with the wire. Auxiliary electrified rail or third rail is a system where a rail runs along the way and a contact shoe assures the contact and the supply.

Contact systems has security problems, the presence of bare conductors offers electric shock risks. The efficiency decreases every time that the collector losses the contact with the conductor causing sparkling and electric losses.

With the intention to overcome this limitation contactless power transfer systems have been developed. Contactless transfer systems transmit the energy using electromagnetic fields.

In railways contactless transfer systems can be utilize in high speed lines like Transrapid Maglev [1] and slow urban line, for example Trams [2].

In the same direction the Korea Railroad Research Institute, KRRI, constructed the Railway Inductive Power Supply, RIPS. The RIPS is based on a contactless transformer with a fixed coreless primary and moving E shape core in the secondary.

Due to the presence of a big air gap between the primary and the secondary the coupling between the coils is small and compensation circuits should be used to improve the efficiency.

The induction from the primary to the secondary depends on the current and voltage level and in the signal frequency. Moreover the RIPS uses a IGBT drive switching in 20 kHz and use this signal as the input for the contactless transformer. To connect the load a rectifier is used.

Figure 1 shows the scheme of the RIPS

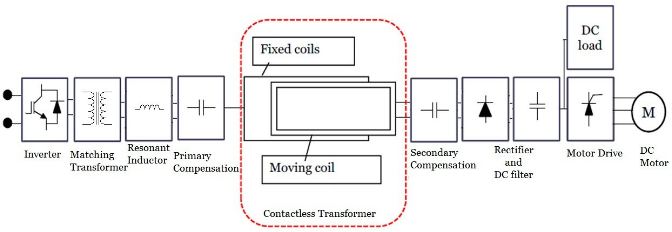


Figure 1. RIPS design

The electric analysis of the RIPS was already performed. However the magnetic circuit of the contactless transformer is not yet modeled. Being the essence of all the contactless power transfer system know the characteristics of the contactless transformer are essential.

This paper presents the magnetic circuit of the contactless transformer of the RIPS. To construct the model is used an analytical approach. The model is confronted with the measures of the prototype.

## 2 MODELING

The contactless transformer of the RIPS is formed by a primary fixed coil and a moving secondary. The secondary is formed by 8 pieces of E shape core. The coils in both sides is constructed using litz wires, ferrite is used as material for the secondary core.

Litz wires consist of multiple strands individually insulated twisted together, the construction design reduce the skin effect and the proximity effect. They are selected to construct the coils because the skin effect in high frequencies increases the resistance in the conductors, increasing the losses.

The ferrite is selected as the material to the core because ferrite materials have high electrical resistance. In high frequency induction of eddy currents are greater and losses can be very high, moreover with the utilization of ferrite the high resistance prevent the occurs of eddy current and thus the losses.

In the model the lizt wire will be considered as a round solid conductor, the ferrite permeability will be considered the mean value presented by the ferrite supplier.

The signal used in the RIPS is a square wave with the frequency of 20 kHz. To simplify the analysis only the peak value of input current will be considered.

The primary coil will be considered infinity in comparison of the secondary. No flux leakage will be considered in the secondary, so the flux flowing through the flux path will be constant.

The reluctance air gap will be modeled as an interaction between length of the air gap and the fringing flux and will be used an equation proposed by Krishnan (2010).

Figure 2 shows a 3D model of one of the segments of the contactless transformer

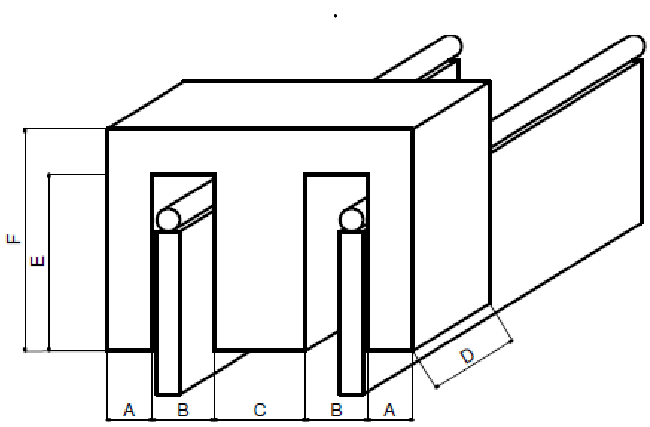


Figure 2. Contactless transformer segment 3D model.

From the 3D model the 2D model is extracted and the measures of the core are present in Table 1.

Table 1. Measures of the Contactless transformer.

| Branch | Measure (mm) |
|---|---|
| A | 17.50 |
| B | 24.00 |
| C | 35.50 |
| D | 35.00 |
| E | 69.00 |
| F | 85.50 |

By the assumption of no flux leakage, all the flux that goes to the air gap will link again in the core. It will be assume that the flux path is a semicircle with radius equal to the distance between the legs of the core.

The flux path and the magnetic circuit are presented in figure 3.

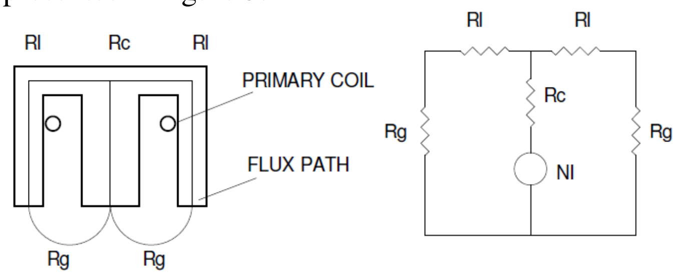


Figure 3. Flux path and magnetic circuit.

To calculate the reluctances the ferrite core pieces are considered as one and the width D is multiplied by 8 in the calculation of the cross sectional area..

The reluctances, $\mathfrak{R}_c$ and $\mathfrak{R}_l$, are calculated using the follow equation:

$$\mathfrak{R} = \frac{l_c}{\mu . A_e} \quad (1)$$

where $l_c$ = mean magnetic path, $\mu$ = permeability and $A_e$ = cross sectional area of the core.

Equation 1 is used to calculate the reluctance in the core, for the air gap is used the equation proposed by Krishnan (2010), as follows:

$$\mathfrak{R}_g = \frac{l_g}{\mu_0\left(A_e + 2(A + 8D)l_g + \pi l_g^2\right)} \quad (2)$$

where $l_g$ = length of the air gap, $\mu_0$ = permeability of the free space, $A_e$ = cross sectional area of the core leg, $A$ = length core leg and $D$ = width of the core leg.

The results of the calculation for the magnetic circuit are presented in the Table 2

Table 2. Reluctance circuit.

| Branch | $10^5$A.turn/Wb |
|---|---|
| $\mathfrak{R}_c$ | 0.031 |
| $\mathfrak{R}_l$ | 0.10 |
| $\mathfrak{R}_g$ | 8.64 |

After calculating each one of the reluctances is possible to calculate the total reluctance of the secondary core, $\mathfrak{R}_t$. The segment reluctance is calculated using the equation below:

$$\mathfrak{R}_t = \mathfrak{R}_c + \frac{\mathfrak{R}_g}{2} + \frac{\mathfrak{R}_l}{2} \quad (3)$$

With $\mathfrak{R}_t$ value, now is possible to calculate the flux and the inductance of the secondary using follow equations:

$$L = \frac{N^2}{\mathfrak{R}_t} \quad (4)$$

$$\phi = \frac{NI}{\mathfrak{R}_t} \quad (5)$$

where $N$ = number of turns $L$ = inductance and $\phi$ = flux.

Table 3 presents the results for the total reluctance, and coil inductance, the number of turns, $N$ in the secondary is equal to 13.

Table 3. Secondary parameters.

| Parameter | Value |
|---|---|
| $\mathfrak{R}_t$ | 4.40 $10^5$A.turn/Wb |
| L | 383,83 mH |
| I | 311 mA |

## 3 MEASUREMENTS

To validate the magnetic circuit the result will be compared with the results of measures in the RIPS contactless transformer.

The measures in the contactless transformer were performed in two moments, in the first moment the inductance of the coils were measured using a LCR Meter, in a second moment the contactless transformer is supply directly with the signal from the inverter excluding the resonance circuit, the measurement was performed with a current probe connected to Tektronix digital oscilloscope .

The measure of the inductance is performed in the frequency of 20 kHz, the operating frequency of the system. To measure the current of the secondary is used a resistance of 110 $\Omega$.

The measure of the inductance is show in figure 4 and the wave form of the input and output current is presented in figure 5.

Figure 4. Measurement of the inductance of the secondary coil.

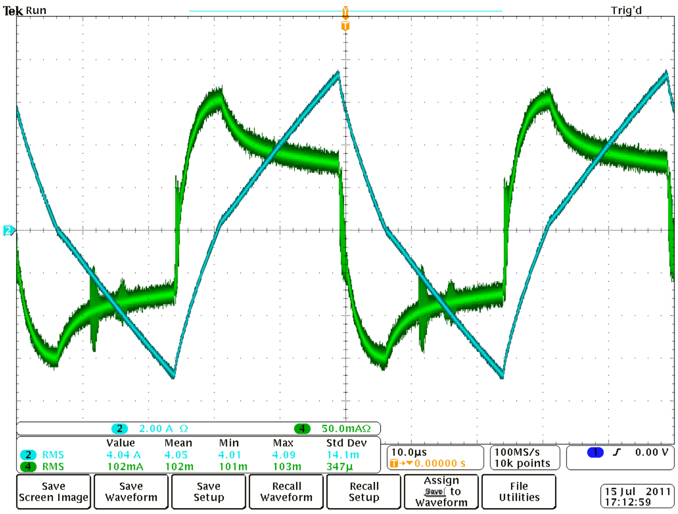


Figure 5. Input and output current of the RIPS's contactless transformer

The results of the measures are presented in Table 4.

Table 4. Contactless transformer measures.

| Parameter | Value |
|---|---|
| Inductance (L) | 268 mH |
| Current (I) | 102 mA |

## 4 DISCUSSION AND CONCLUSION

Comparing the results from Table 3 and Table 4 is possible to see that the model presents a bigger inductance and a bigger current.

The difference in the value of the inductance is related in the definitions of the modeling of the core. The core is formed with 8 ferrite pieces and between them are gaps that change the total value of the reluctance and further the inductance.

The difference in the current value is related to modeling of the electric circuit of the contactless transformer. The large air gap make that the turn ratio between the primary and the secondary is the ratio between the inductance of the secondary coil and the mutual inductance between the primary and secondary coils. Moreover only a percentage of the primary current is induced to the secondary

The magnetic circuit for the RIPS contactless transformer was presented, due to assumption of no flux leakage, simple model for the core and simplification of the reluctance of the air gap the results were not precise.

To the future a finite element method will be used to improve the results, the electric characteristics will be meshed with the finite element method to create a model that will enable the study of different shapes with the intention to improve the efficiency.

## 5 REFERENCES

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