Designing the Transformer for Line Powering of Transmission Line Inspection Robots
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Abstract—This work aims to develop a transformer prototype, used in a power supply system that will be implemented at the RIOL robot [1]. This robot will be able to perform the inspection on high voltage overhead lines. The transformer operating principle is based on a efficient harvesting of the magnetic energy that is created, by the current floating in transmission lines.

The maximum power dissipated at a load of 10 ohm is aimed. This power will be used to move and perform all the inspection actions made by the robot.

Simulations and laboratory tests are presented and discussed.

Keywords —Power supply system, Current, Transformer, Induction, Magnetic field, Saturation.

I. INTRODUCTION

The necessity to ensure that electrical energy reaches the whole population, within the best conditions, became imperative in current times.

Provide electrical energy with the highest quality, is the main producing and distribution companies goal.

Nowadays traditional inspection methods, such as the use of helicopters, UAV’s to carry inspection cameras or placement of workers walking over the lines (visually inspecting them), are outdated due to conditions and costs associated with them. This paper is associated with the development of a new modern method for high voltage power lines inspection. A robot that can easily travel along the transmission line, without known constrains of these robots, like limited operating time, due to batteries technology, along with the advantage of keeping the line operating while the inspection is being performed, is the next step on this technology. To aim this goal, an autonomous power supply that can provide needed power to the robot and simultaneously, charge his own battery, is the key factor for the project.

The RIOL robot has an articulated body with three legs used for cable grasping, the middle leg will contain a transformer while the other ones are responsible for the robot movement along the line, they are equipped with tracking wheels. The robot will be mainly made of PVC and light metal alloys, since structural weight is one of the constrain this project has. The power transformer will be made of laminated silicon steal, its dimensions would need to fit the project.

This robot will be able to walk over the line and it will also be possible with this model, to overcome every obstacle in his way, such as aviation markers, and support towers with every kind of insulation, due to his articulated body. All the mechanic involved on the overcome is simple, each of his three arms can grab the cable tightly, grab the cable loosely, allowing the arm to slide along, and disengage from the line. To overcome an obstacle, the robot disengages each of the arms in sequence, such that there are always at least two arms grabbing the cable, this way the stability is ensured. A computer model is shown in Figure 1.

Figure 1- RIOL prototype model [2].

Since the arm containing the transformer must be disengaged as well, the robot will be supplied by a rechargeable battery, until the transformer is again clamped to the power line. This way, a LiPo battery pack provides the needed power so all system may operate. After the transformer is again connected to the line, the battery pack should be recharged.

The transformer created in this work aims to use magnetic energy around the transmission line. That line will be the primary turn of the transformer, and considering a voltage drop on that segment, it is tried to get maximum power at the secondary side of the transformer.

Since current on transmissions lines is normally limited to 1000 Ampere, this should be the maximum current considered on the transformer. For currents above this value the transformer should be disengaged from the line to assure safety of all the equipment.

A AC/DC converter must also be included on the project, since the robot will operate with continuous values, so a dynamic rectifier should be properly sized for the transformer [3]. The rectifier must be controlled in such a way that the transformer sees him as a slow variation resistor placed in the secondary side. Which means that, the power supply circuit seen from the transformer side can be resumed as a resistance

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at each instant. The test will then be made with a ten ohm resistance

The transformer will work on the same physical principles as current probes. Since maximum power is the main target, we should be aware of saturation condition on the core, an air gap use must be avoided, due to magnetic reluctance increase.

Section II of this paper describes all sizing steps for the transformer. Section III shows all computer simulation results from the transformer sized, this includes FEMM and MATLAB/Simulink software tests. Section IV presents the laboratory prototype tests, along with some explains for achieved results. Section V shows the sizing and testing conclusions.

II. TRANSFORMER CONFIGURATION

All the transformer concept is based on a number of windings coupled by a magnetic flux. For this work we have a special condition, the primary circuit has only one coil, that will be the power transmission line, made of aluminum and iron mainly. Secondary number of turns will then be calculated according to the power needs for the robot’s circuit.

Transformer core should be clamped to the primary winding according with Figure 2, as the secondary coil will be around the core.

![Clapped transformer prototype model.](image)

Figure 2 - Clapped transformer prototype model.

Relative magnetic permeability of the core material is \( \mu_r = 2000 \). This kind of silicon steel has a operation limit of 1.5 Tesla until it reaches the saturation point, according to Figure 3 curve.

The gap between the two ‘C’ core parts should be made, in such a way, that could be neglected. Normally with the help of high precision machines.

![Silicon steal magnetic curve.](image)

Figure 3 - Silicon steal magnetic curve.

Starting with the relationship between magneto motive force within two points \( x_1 \) and \( x_2 \) and magnetic field, shown in equation 1, it is obtained equation 2 for a uniform magnetic field, where \( l \) is the length between \( x_1 \) and \( x_2 \).

\[
\begin{align*}
f_{mm} &= \int_{x_1}^{x_2} H \, dl \\
&= HI
\end{align*}
\]

(1)

(2)

Having the same procedure for electric field we reach equation 3, which relates electromotive force (emf) with electrical field density (E), and section length (l).

\[
f_{em} = EI
\]

(3)

Then it is of major interest to define the magnetic flux that goes through a certain area, which is related with the magnetic flux density (B). Knowing that the core is uniform in all his section, therefore is defined magnetic flux as shown in (4). Where ‘A’ is the core section that is considered to be uniform.

\[
\phi = \iint_A B \, ds = B \times A
\]

(4)

Applying Faraday’s law to the primary winding will be the next step. Assuming that voltage drop has a sinusoidal waveform given by (5), or equivalently (6), where current will be a sinusoidal wave as well, and \( N \) is the winding turns number of the primary circuit [5].

\[
v(t) = V_{max} \cos(\omega t)
\]

\[
v(t) = R_i(t) + N \frac{d\phi(t)}{dt}
\]

(5)

(6)

Assuming simplifications presented in equations (7) and (8).

\[
R_i(t) = 0
\]

\[
\phi(0) = 0
\]

(7)

(8)

A result for generic voltage drop is presented in equation 9.

\[
v(t) = N \frac{d\phi(t)}{dt}
\]

(9)

Solving this expression in order to the inducted magnetic flux, we get equation 10.

\[
\phi(t) = \int_0^t \frac{v(t)}{N} \, dt \Rightarrow \phi(t) = \frac{V_{max} \sin(\omega t)}{\omega N}
\]

(10)

Considering (4), for the maximum flux through the iron core, we reach (11).
\[ \phi_{\text{max}} = B_{\text{max}} A_c \]  

Merging equations 10 and 11 it is presented the general transformer sizing equation (12).

\[ NB_{\text{max}} A_k = \frac{V_{\text{max}}}{\omega} \]  

Next step on this process is the secondary turns number calculation. According to the transformer equivalent circuit, in Figure 4, the following equations are achieved.

\[ i_p^2 = i_{\text{mag}}^2 + i_s^2 = i_{\text{mag}}^2 + \left( \frac{n_2}{n_1} i_s \right)^2 \]  

\[ i_{\text{mag}} = \frac{V_p}{\omega L_{\text{mag}}} \]  

Crossing them with the ideal transformer formulas,

\[ I_s = \frac{N_1}{N_2} I_s \]  

\[ V_s = N_2 \frac{d\phi}{dt} = \frac{N_2}{N_1} V_p \]  

Due to laboratory conditions, a primary current of 300 amperes and a magnetic path length \( l \) of 18 centimeters is chosen. Applying this values along with the ideal transformer equations (15) and (16), a secondary coil number, \( n_2 \), of 30 turns was calculated (17).

\[ n_2 = \frac{n_1}{i_s} \sqrt{\frac{k_f l_f B_{\text{max}}}{2\pi\mu_\rho\mu_n}} \]  

\[ A_k = \frac{V_i k_f}{k_f B_{\text{max}} n_1} \]  

\[ P_0 = k_f A_{\text{max}} n_1 f \sqrt{\frac{k_f l_f B_{\text{max}}}{2\pi\mu_\rho\mu_n}} \]  

From the obtained power equation, it’s clear that increasing magnetic flux density \( B_{\text{max}} \) cross-sectional area \( A_k \), or decreasing the magnetic mean path, will increase the power on a secondary placed load.

Next step is the measurement of the transformer core. Applying the transformer sizing equation (21), where \( k_f \) with a 4.44 value, is a form factor related with the almost perfect voltage and current sinusoidal waveform [6].

\[ A_k = \frac{V_p \times 10^4}{k_f \times B_{\text{max}} n_2 f} \]  

Therefore a core section \( A_k \) equals to 80 cm² is obtained. Using a metal plate with one centimeter side to build the transformer core, it is calculated a transformer with 80 centimeters length. For a shorter transformer see appendix A.

Last step on transformer sizing is the weight. Since the clapped transformer will be used up in transmission lines we must, due to movement issues, aim the less weight possible. A maximum weight of 10 kilograms is the core’s limit value. Knowing that silicon steel relative density \( \rho \) is 6910 kg/m³. A weight of 9.95 kilograms is reached according to equation (22).

\[ \text{Weight} = \text{Volume} \times \rho \]  

With this calculation transformer sizing is completed. Before building the transformer, some simulations will be performed in order to predict the prototype laboratory results.

### III. SIMULATIONS

Sized transformer simulations were made with two different kinds of software. Transformer magnetic circuit has been modeled with FEMM “Finite Element Method Magnetics”, while electrical circuit of the transformer has been modeled with MATLAB/Simulink.

#### A. Magnetic Circuit Simulation

With magnetic circuit simulations it is pretended to see the magnetic flux lines behavior inside the core, and if these lines come outside it. It’s also intended to know the magnetic field density \( B \) around the core, so we can identify sized core saturation points.

On this simulations, core geometry had to be changed due to the formats available to perform the prototype, so a “UI” core model was chosen. Air gap is represented but it was neglected, again its aimed a perfect contact between both core parts.
A datasheet of the primary material, aluminum 1100 is presented in Table 1.

Table 1 - Chemistry data of aluminum 1100.

<table>
<thead>
<tr>
<th>Material</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>99.6 min</td>
</tr>
<tr>
<td>Copper</td>
<td>0.05 max</td>
</tr>
<tr>
<td>Iron</td>
<td>0.35 max</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.03 max</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.03 max</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.28 max</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.03 max</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.05 max</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.05 max</td>
</tr>
</tbody>
</table>

Explaining Figure 5 model, primary circuit is represented by the central circle, with a 2.6 centimeters diameter surrounded by air, and made of aluminum 1100 [7]. The 30 turns secondary coil is represented by a rectangle on the left side, this means that the secondary is coiled around the left arm of the 'U' core part, chosen material is a 14 AWG cooper. The UI core is made of M-36 silicon steal.

Therefore three tests were performed. Open-circuit on the secondary side of the transformer, short-circuit on the same side, and a normal working simulation with a load that represents the robot, this way we can retrieve core losses at normal working conditions.

1. **Open Circuit Test**

   On this test the secondary 30 turns coil of the transformer is left open, which means that no current will flow on the secondary side of the equivalent circuit, all primary current will flow through the magnetization branch. This fact will lead to a maximum magnetization of the core, as it can be seen with Figure 6.

   It is concluded, from this test that the transformer will saturate for a primary side current of 300 Ampere and an open-circuit on the secondary side. The behavior of the transformer is similar to a normal current transformer that shouldn’t be operated with the secondary coil left open, which could bring security risks to the operating process.

   Since the robot will never work without a connection to the transformer this isn’t a major problem, even so, this situation could be easily resolved by two different ways. First, adding more iron to the core, increasing his size and weight. A second way is the creation of an air gap within the core. This solution would bring a high power loss on the secondary side of the transformer, which prevents its application.

   Analyzing Figure 6, we can also conclude that the 'UI' core is not the best choice for this kind of projects, looking to the inside and outside corners of the core, it is easy to see that the external corners are not being fully utilized, otherwise inside corners have a higher number of magnetic flux lines near, this fact shows that some iron of the external corners should be located on the inside ones. Ideal core configuration would be a torus, as shown in Figure 2.

2. **Short-circuit Test**

   With short-circuit conditions, voltage on the secondary is null. Ideal transformer secondary current should be proportional to the transmission line current, reflecting the transformation ratio (16). After analyzing Figure 7 it is visible an almost null magnetic density all over the core. This fact comes along with equation 1, since both currents are on opposite directions, the magnetic flux tends to be null.

   Despite a low value, it's obvious that the magnetic field density B isn’t null, this happens due to an asymmetric circuit.

   Figure 7 - Behavior of the magnetic field lines, short-circuit condition.
3. Load Test

With the load test it is pretended to simulate the transformer operating in normal function conditions. If the sizing is correct the magnetic core shouldn’t saturate, since secondary current is related with the needed power. Results are presented in Figure 8.

![Magnetic field behavior on the core, secondary loaded.](image)

Analyzing the obtained result, it is once again proven, that the choosing geometry isn’t the best for the core. Even so only a small area of the core is saturated which proves that sizing is correct.

4. Transformer Losses for Normal Operation

For the third test, a load of 10 ohm was simulated on the secondary side of the sized transformer. This load will lead to a current on the secondary side that will induce a magnetic flux on the magnetic core.

Two kinds of losses are defined: First, core losses, also called magnetic branch losses, which contains hysteretic losses, Eddy current losses and proximity effect losses [8]. All calculated with,

\[ W_{core} = \int i \, d\lambda = \frac{H_i L_i}{N} (A N dR_i) = A i \frac{1}{N} H_i dR_i \quad (23) \]

Losses on the magnetic branch will be 12,341 W.

Second kind of losses are the cooper ones, these are defined by the voltage drop on primary and secondary sides of the core, mainly due to a small resistance that the primary and secondary conduction cables have. Calculations are made following equation 24.

\[ W_{cooper} = \sum_{i=1}^{n} R_i i^2 \quad (24) \]

For cooper losses a value of 9,074 W was achieved.

Adding both losses we will reach a total loss value of 21,415 W, which leads to a 96,7% transformer yield.

B. Electrical Circuit Simulation

With the electrical circuit simulation it is pretended to get a prediction on waveform results, of the laboratory tests. Using MATLAB with his model simulator Simulink, a saturable transformer is defined, with the silicon steal magnetization curve values similar to the ones used with FEMM.

Three simulations will be presented, open and short-circuit tests and with a 10 ohm load placed at the secondary side of the sized transformer.

1. Open Circuit Simulation

Here the secondary circuit will be kept unloaded, measuring voltage at their terminals, the circuit is presented at Figure 9.

![Open circuit Simulink model.](image)

Secondary open circuit voltage is presented at Figure 10.

This test was made with a primary current of 75 Ampere, to match the laboratory conditions and avoid damaging the core. Effect of saturation are mostly visible with this test. Core saturation effects will be as higher as the primary current will be.

A small transitory is also watched at the beginning while core magnetization isn’t yet completed.

![Secondary open circuit voltage.](image)
2. Short-circuit Simulation

Short-circuit simulation is made by connecting both secondary terminals directly, this way a voltage drop of ideally zero is achieved and a measurement of the short-circuit current will be made. This current will be the highest one on the secondary side of the transformer, excluding raises on the primary one. Circuit for this simulation is presented at Figure 12.

Results on this test are presented in Figure 11. It’s clear that the current will be high on the secondary side, near 13 Ampere are estimated.

3. Secondary Loaded Test

With this simulation, an estimation of power supplied to a load is intended, with this value we will be able to see the effective efficiency of the transformer, and conclude if the prototype will be a viable element for the project.

Once again a 10 ohm load is placed according to Figure 13, current and voltage drop are measured at the load, and a unitary power factor is considered.

A yield of 97.29% is obtained. Combining this value with the output power, an estimation of 21.07 Watt for power losses is calculated. This value comes in line with the one obtained with FEMM test, which gives reliability to the chosen simulation methods.

IV. LABORATORY TESTS

For practical tests a transformer with the dimensioned characteristics was built. It is presented in Figure 17. It’s visible the 30 turns around one side of the core. Both ‘UI’ stacking was alternately made. With this solution it is tried to always provide a way to the flux, without an air gap crossing, avoiding this way dispersion that would come if a normal stacking was implemented.
Besides the three tests made on the simulation stage, the results of a fourth test, with a simple rectifier bridge is presented. For the first three tests channel 1 (yellow) presented on simulation indicate the primary voltage drop. Channel 2 (blue) is the primary current. Channel 3 (purple) secondary voltage drop. And channel 4 (green) is the secondary current.

With this test a secondary current, that in normal conditions will be equal to the primary times the transformer ratio, can be seen. With this test we are forcing all current that comes from the primary side, to flow through the secondary. Neglecting this way the magnetization branch.

With the results presented on Figure 19, it’s possible to see that the theory formulas have application, with the values almost perfectly matching them. Channel 2 has a scale of 200 Ampere per division, and channel 4 has 5 Ampere per division.

1. **Open circuit laboratorial test**

Open circuit test was made with the same conditions mentioned before. Current on the primary side was slowly raised, so a high saturation of the core was avoided. Figure 18 shows the oscilloscope results for this test.

A primary current of 75 ampere, far from maximum value we can achieve, already leads to a huge deformation of the waveform, these are clearly core saturation effects.

2. **Short-circuit laboratorial test**

With a pure resistive load, almost 10 ohm, placed on the secondary circuit, it was possible to take a characteristic curve for voltage and current. With this test, a working transformer simulation with all the robot mechanics coupled, is pretended. Figure 20 shows this practical test results.

As in section III, multiplying peak current from channel 4 (5 Ampere per division) and voltage drop in channel 3 (20 Volt per division), and then divide the result by two, it can be reached a power of 280 W.
Differences between simulation and practical tests, are justified by the non-ideal prototype model, as well as some imperfections related with handmade core and coil turning.

4. Rectifier bridge and capacitor on the secondary

By placing a rectifier diode bridge and a capacitor, a continuous value for voltage drop and current, on the secondary side, are pretended. While the rectifier bridge, also known as Graetz bridge, (due to the diodes conduction properties) makes the conversion, the capacitor is used to reduce the ripple those waveforms will have, this way a rectified current and voltage drop will be presented at load terminals.

Results for this test are presented with Figure 21, these show a really low power deliver to the load comparing to the previous one. A power of 220 W is clearly low. With it, is also possible to retrieve what happens to the primary voltage drop, due to the secondary load. Channel one waveform shows this influence.

![Figure 21 - Prototype test with a rectifier bridge and filter](image)

V. CONCLUSIONS

A transformer to be included in a power supply system that can be used in a transmission line inspection robot (RIOL) was designed, tested, and built along this work. It is indeed proved, by showing test results, that the magnetic field located around power supply cables, can induct, with the right core sizing, a magnetic flux so strong that will be enough, with an appropriate turns ratio, to supply a robot, turning this one in a self-sustainable vehicle.

A high efficiency of this transformer is obtained, also all the assumptions, such as size and weight are within reasonable limits. All transformer parameters must be calculated starting with a fictitious load that represents all the robot mechanics.

Results may although be improved by using the right core geometry, and coiling all secondary turns around it. Other aspects were tested on the full work. Where is shown that, with a higher current on the primary side, an improved power is obtained by the secondary. Nevertheless, this operation requires an adjustment to transformer’s size so it is possible to avoid saturation on the magnetic core.

REFERENCES


APPENDIX A - UU TRANSFORMER

Since transformer length is one of the project main constrains, and 80 centimeters is clearly a high value for the core, a new solution was tested.

An UU core with 21 centimeters was created. This is a test to split the long iron core in three different blocks, that would be located in each arm of the robot. Other changes including tracking mechanics would have to change as well.

Since the geometry of the core and the iron material aren’t the same as the ones used in the main project, some differences on values will come, so comparisons shouldn’t be linear.

Figure A.1 shows the prototype created with three coils on the primary and thirty on the secondary side.

![Figure A.1 - Prototype with three coils](image)

Laboratory results are presented in Figure A.2, where channels 1 and 2 are respectively primary voltage and current, channels 3 and 4 are secondary coil voltage and current.
Channel 1 scale is set at 2V per division, almost 4 volt peak. Channel 2 is set for a 500 ampere per division, which means that inside the core there is a 700A current divided by three turns. Analyzing both secondary voltage and current we get a value of 30 volts and 20 ampere, which gives a mean power of 300W. All these values were achieved with a secondary load of 1.5 ohm. For higher secondary load values, sized magnetic core will enter in a saturation zone, invalidating transformer’s correct operation. Since robot load won’t have such linear characteristics as the one used for this tests, a special rectifier with some power electronic solutions will be required for this approach right application.