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Designing Transformers for the Power Supply of a Transmission Line Inspection Robot

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SUMMARY

This work describes the design and the prototype essays of power transformers to be part of a power supply system that grabs energy from power line cables to supply line inspection robots. The power levels obtained are compatible with the robot power needed when using a carefully designed energy management system. Two variants of the designed transformer, based on UI or UU laminations, denoted respectively TUI and TUU, are presented in the paper along with a discussion on limitations and possible improvements.

The basic design principle to harvest the magnetic energy requires a magnetic core surrounding the power cable which acts as a single turn primary winding of a transformer. The secondary is coiled around the core. The typical range of line currents to be considered for the operation of the transformer lies between 100 and 1000A, with the transformer itself having almost no influence in this current. The line current variation must be accounted for in the power converter stage that interfaces the transformer from the robot, by making the transformer supplying a slowly varying resistive load [2,3].

The power cable cylindrical structure leads naturally to a toroidal shape for the transformer core. With a primary winding section around 500 mm2 (the typical section area of a high voltage power line) the toroid inner window must accommodate the power cable and the secondary winding, while allowing some margin for isolation. The prototypes developed use off-the-shelf UI and UU cores instead.

The resulting transformers show very interesting measured power outputs of 600W (TUI) and 290W (TUU), respectively at 300A and 350A line currents. Such power levels clearly indicate that this type of power supply is indeed a valid option that can still be improved by selecting adequate toroidal cores and tuning the design parameters.

KEYWORDS

Power Line Inspection Robot. Energy Harvesting. Current Transformer.

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INTRODUCTION

This work follows previous research on the full power supply system for a line inspection robot which focused on the power electronics converter [2,3] required to transfer the energy in the transformer secondary to the robot. In this paper the focus is (i) the transformer design and (ii) experimenting with real transformer prototypes.

Typical robots for line inspection use hybrid wheeled-legged locomotion (see examples in [4]) that allows a transformer to slide along the line, capturing energy from the magnetic field associated to the current flowing in the power cable. When transposing the support towers the transformer core must be opened and removed from the line, the robot power being supplied by batteries. This type of power supply enables full autonomy for inspection robots yielding clear economical advantages as opposed to traditional inspection strategies.

The prototypes described in this paper target a power of 300W to 700 W at intermediate line currents near 300A. As a reference, the power required by the RIOL prototype, [1] (see Figure 1), is estimated to be between 500W and 800W, depending on the energy management options.

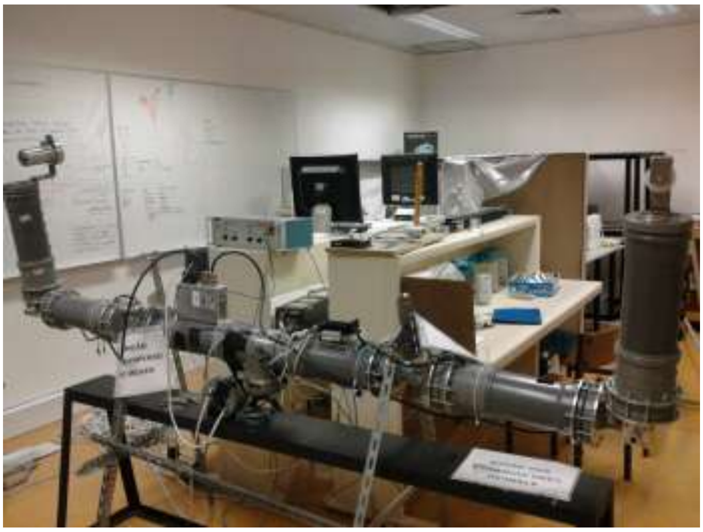


Figure 1: The RIOL robot prototype for line inspection

The power transformer design for this type of application is subject to harsh constraints, namely on the weight, and require a careful design, distinct from usual non-moving voltage driven transformers.

TRANSFORMER DESIGN

Using Faraday law, the relation between the voltage V_k at the kth winding having n_k turns, given the voltage waveform factor k_f and frequency f_s, transformer core section area A_{Fe} and maximum magnetic flux density $B_{\max}$ (assuming linearity and neglecting resistive and leakage voltage drops) is given by,

$$V_k=k_f\, n_k\, B_{\max}\, f_s\, A_{Fe} \qquad (1)$$

The primary winding is the power line cable carrying the line current i_p, being n_1 =1. Thus, the transformer is current driven (current transformer) and particular attention must be given to the transformer magnetizing current, which must be minimized to maximize power transfer. This implies maximizing the magnetizing inductance L_{mag} value. Neglecting air gaps, stray and fringing fluxes, the magnetizing inductance depends on the square of the primary number of turns n_1 and on the magnetic core permeability μ and mean magnetic length M_{gl}, through the magnetic reluctance $R_M=M_{gl}/(\mu\, A_{Fe})$ of the core:

$$L_{mag} = \frac{n_1^2}{R_M} = \mu\, n_1^2\, \frac{A_{Fe}}{M_{gl}} \tag{2}$$

The magnetizing inductance is proportional to the magnetic core permeability μ, primary winding turns n_1 squared, and to the ratio between A_{Fe} and the core mean magnetic length M_{gl}.
Since n_1=1, the transformer must be built using a magnetic material with very high μ and the transformer shape and dimensions must maximize the ratio A_{Fe}/M_{gl}. This means reducing the core cross-section mean path around the power cable to reduce M_{gl}, while increasing the total transformer iron (and windings) length, since A_{Fe} is given by the required winding voltages (1) and power.
Referring to the transformer equivalent model (see Figure 2), neglecting stray flux, considering currents i_{mag} and i'_s 90º out of phase ($I_p^2 = I_{mag}^2 + I'^2_s$) and using (1), written for the secondary voltage $V_s=k_f n_2 B_{max} f_s A_{Fe}$, the maximum secondary output apparent power $S_o=V_sI_s$ can be obtained as $S_o=k_f n_2 B_{max} f_s A_{Fe} I_s$, or:

$$S_o = k_f B_{\max} f_s A_{Fe} \sqrt{\left(n_1 I_p\right)^2 - \left(\frac{k_f M_{gl} B_{\max}}{2\pi\,\mu}\right)^2} \tag{3}$$

Since f_s is either 50Hz or 60Hz and k_f=4.44 for sinewave operation, if M_{gl} is minimized and μ is maximized in (3) so that the magnetizing current is negligible regarding I_p, the maximum output power S_o is roughly proportional to B_{max}, to A_{Fe} and to the primary current I_p.

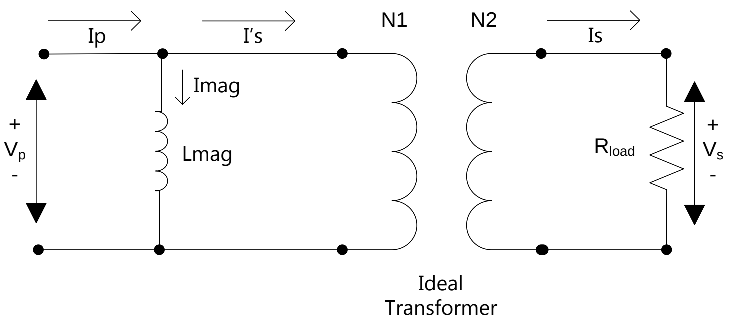


Figure 2: Transformer equivalent model.

The secondary number of turns n_2 can be calculated from (1), given the needed secondary voltage, or calculated from (4), given the equivalent R_{load} value:

$$n_2 = n_1 \frac{I'_s}{I_s} = \sqrt{\frac{R_{load}\sqrt{\left(n_1 I_p\right)^2 - \left(\frac{k_f M_{gl} B_{\max}}{2\pi\,\mu}\right)^2}}{k_f B_{\max} A_{Fe} f_s}} = \sqrt{R_{load}\sqrt{\left(\frac{n_1 I_p}{B_{\max} A_{Fe} k_f f_s}\right)^2 - \left(\frac{M_{gl}}{2\pi\,\mu A_{Fe} f_s}\right)^2}} \tag{4}$$

To start the design, the required output apparent power (S_o=700VA) together with the line current (I_p=300A) and the attainable M_{gl} (M_{gl}=0.18m) and available core material characteristics are estimated (B_{max}=1.5T, μ=4.4π×10^{-4}Hm^{-1}). In particular, the value M_{gl} must take into account the diameter of the power line cable, the diameter of the secondary winding wires, the needed isolation layer thickness and the available laminations width.
From (3), the A_{Fe} value can be calculated as A_{Fe}=0.008m^2, and from (4) the secondary turns are n_2≈30 using R_{load}=9Ω. The secondary number of turns n_2 could also be estimated from (1) written for the secondary winding, and specifying the necessary output voltage V_s to supply the robot.
Assuming UI laminations with 10^{-2} m width, this gives a 0.8m long transformer that will present great difficulties to be maneuvered by the robot arm. Wider UI laminations would result in a short

transformer, but would increase the M_{gl} value, thus not maximizing the ratio A_{Fe}/M_{gl} and increasing the transformer weight. Therefore, improvements on the transformer core μ and B_{max} values are necessary, or a distributed solution with several transformers can be sought using shorter tape wound toroidal or UU cores.

TRANSFORMER TESTS

A first prototype transformer was built using FeSi M-36 standard UI laminations (denoted TUI transformer), stacked to form a hollow core with rectangular section with 6 cm external and 4cm internal width (see Figure 3a). To minimize air gaps, stray and fringing fluxes (minimizing the magnetic reluctance), the laminations are interleaved to always provide a continuous path to the magnetic flux.
A smaller prototype was designed for 310VA at I_p=350A, and assembled using available tape wound UU cores (TUU transformer), as shown in Figure 3b, were the power line cable was replaced by a copper bus bar due to the available space shape.

a) TUI transformer, 80cm long

b) TUU transformer

Figure 3 : Prototype transformers.

The main characteristics of the two transformers, driving currents, output powers and weights are summarized in Table 1.

Table 1 : TUI and TUU transformer characteristics, output powers and weight.

Parameter / Transformer	B_{max} (T)	μ (Hm^{-1})	M_{gl} (m)	I_P (A)	Required S_O (VA)	A_{Fe} (m^2)	n_2	Measured P_O (W)	Estimated S_O Ip=1000A	Weight (kg)
TUI	1.5	$4.4\pi\times10^{-4}$	0.18	300	700	80×10^{-4}	30	600	2500	11.5
TUU	1.5	$6\pi\times10^{-4}$	0.2	350	310	28×10^{-4}	30	290	900	5.4

The measured output power shows an error near 15% for the TUI transformer, while the same error in the TUU transformer is near 7%. These results point to the possible source for these errors being air gaps, stray and fringing fluxes, which are usually lower in tape wound transformers like the TUU.
For inspection robots such as RIOL, the transformer has to be installed at the end of one of the articulated arms the robot uses to overcome obstacles on the lines and support towers. The TUI transformer estimated weight is around 11.5 Kg which is a harsh constraining specification for these arms, requiring large actuation torques. In the case of the RIOL robot, a distributed solution can be foreseen using 3 TUU like smaller transformers (3×5,4kg), one in each robot arm to reach nearly 900W at I_p=350A.
Table 1 also shows that estimated output apparent powers for the full power line current of I_p=1000A can rise to 2.5kVA for the TUI and to 900VA for the TUU. These estimated values are well in excess

of those required by the robot for most power line currents (Figure 4). The transformer output power must be specified knowing the daily and weakly power line current profiles.

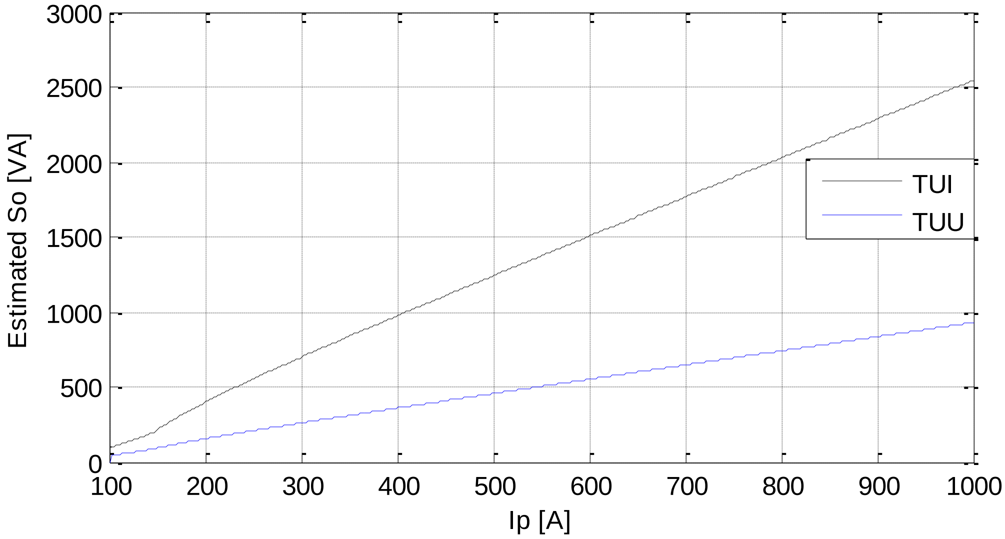
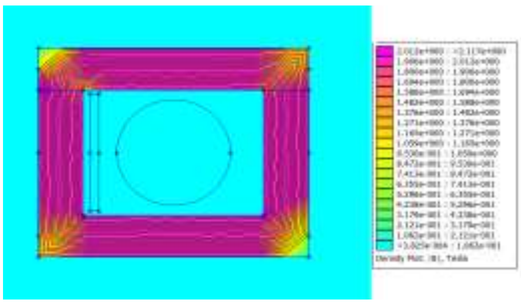
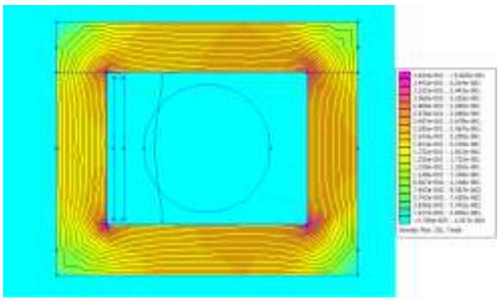


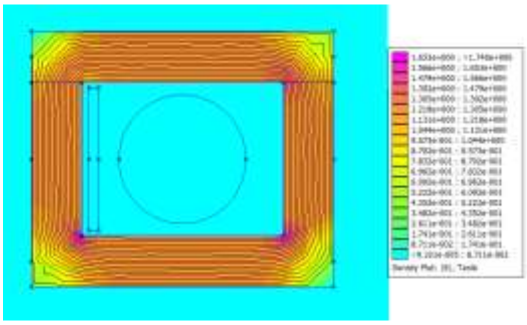
Figure 4 : Estimated apparent output power versus power line currents for the TUI and the TUU transformers.



a) No-load condition



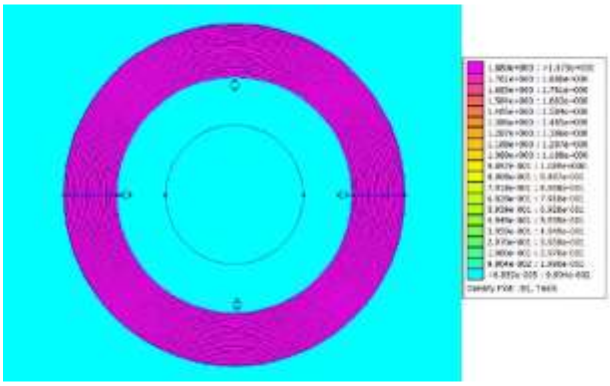
b) Short-circuit condition

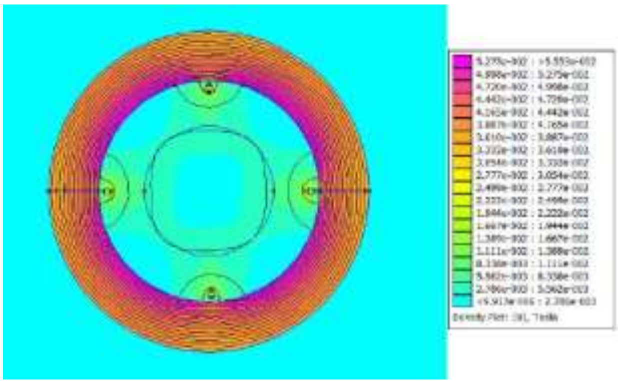


c) 10 Ω load test

Figure 5 : Simulations using the TUI transformer

No-load, short-circuit and nominal load simulation of the magnetic lines distribution (using FEMM software) are shown respectively in Figure 5a,b,c for the TUI transformer.
The distribution of the magnetic lines indicates that the rectangular section for the core is not the best option (the choice was made from the availability of materials as toroid cores were not readily available). Figure 5c shows a light saturation in the inner corners, under a 10Ω resistive load. Similar tests for a toroidal shaped transformer are illustrated in Figure 6 where the more uniform distribution of the magnetic flux is clearly visible.

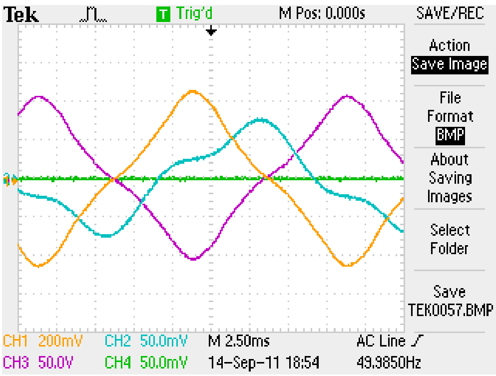




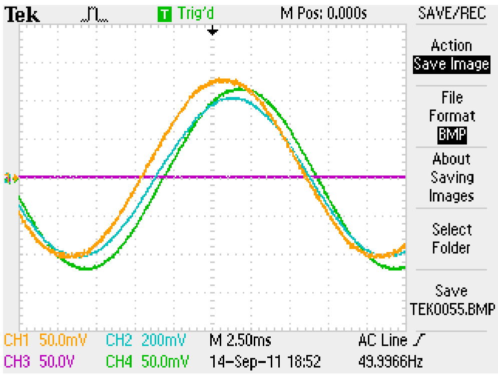
a) No-load condition b) Short-circuit condition

Figure 6: Simulations using a toroidal transformer

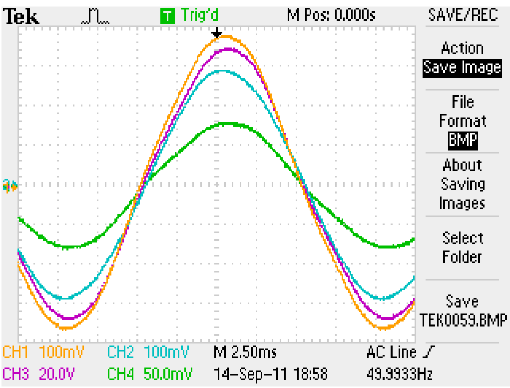
Test results of the real prototypes are shown in Figure 7a-e. The images were taken directly from the measuring oscilloscope (the yellow, blue, purple, and green curves represent, respectively, the primary voltage, primary current, secondary voltage, and secondary current). Under no load and primary current of 75A, TUU core saturation effects are clearly visible in Figure 7a.



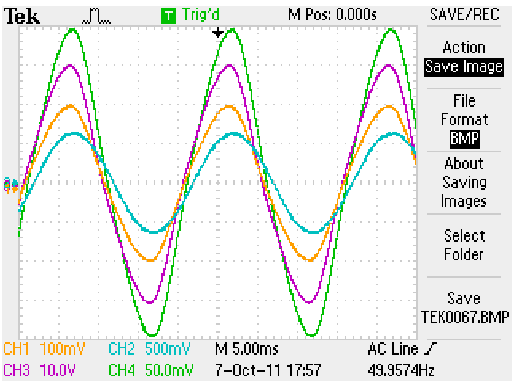
a) TUU core: no-load condition



b) TUU core: short-circuit test



c) 10 Ω load test (TUI core)



d) 1.5 Ω load test (TUU core)

Figure 7 : Results obtained with the real prototypes

Figure 7c shows the voltage and current waveforms for the TUI transformer shown in Figure 3a. In Figure 7d, the TUU transformer output power is near 300W. This transformer easily saturates for high value resistive loads, but suggests the interesting possibility of having multiple, smaller, power supply units onboard the robot. In a sense, this is also likely to increase the flexibility in energy management.

Obtaining a continuous voltage able to supply the robot systems requires adding a rectifier bridge and a capacitor to filter the output. Figure 8 shows the results obtained for the TUU prototype. The low power factor of the rectifying stage yields only an output power near 220 W. An active rectifier with near unity power factor is mandatory as described in [2,3].

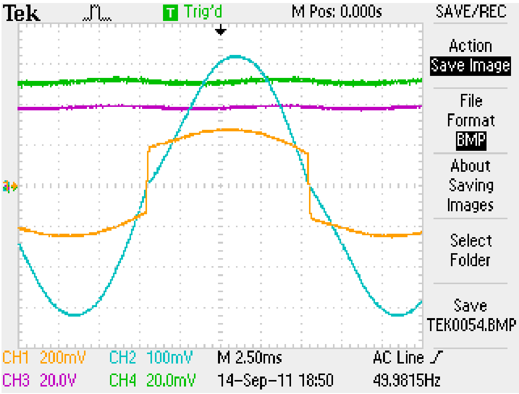


Figure 8: Testing with a rectifier bridge and filter

CONCLUSIONS

The results obtained demonstrate the viability of building a power supply based on the capture of the magnetic energy directly from the power lines. The weight of the prototype transformers described in the paper, though relatively high, seems compatible with most of the robots described in the literature.

The power levels obtained are very interesting not only for robotics applications, with moving devices, but also for static devices that can be placed on the power lines.

Future work includes assembling a toroidal transformer, optimizing the materials and shape, and the prototyping of the mechanical structure required for the transformer to grab and detach from the line and installation onboard the RIOL robot, and the implementation of the active rectifier with controllable power factor.

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