Transmission Line Inspection Robots: Design of the Power Supply System

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Abstract—This work aims to develop a power supply system to use with the RIOL robot, [1], useful for inspecting high voltage overhead power lines. The power supply operating principle is based on the harvesting of the magnetic energy around the power supply lines by clamping a transformer around the line.

A switching power rectifier, controlled to emulate a resistor, is then connected to the transformer secondary to obtain the robot needed voltages (55V ± 1%) and power (800W).

Simulation results are presented and discussed.

Index Terms—Power supply system, Transformer, Current power transformer, PWM rectifier, resistor emulating rectifier, AC/DC converter.

I. INTRODUCTION

This paper describes an energy harvesting system to use with the RIOL robot for inspection of high voltage overhead power lines. Full autonomy is a key factor when assessing the economical advantages in the use of this type of robots. As opposed to traditional inspection strategies, a fully autonomous robot can easily travel long distances, avoiding the recharging/refueling breaks required by common approaches, e.g., using helicopters or UAVs to carry the inspection sensors. Current state of the art battery technology limits the autonomy of robots to a couple of hours. Thus, an autonomous power supply that can power the robot and charge onboard batteries is a key component.

The RIOL robot is a 5-dof articulated multibody with three claws used for the cable’s grasping. The structure is made mainly of PVC (body) and light metal alloys (link couplings). The robot is able to overcome support towers and most of the obstacles arising in power lines, e.g., the aviation markers.

Two types of locomotion gaits are used. In the absence of obstacles the motion is generated by two traction wheels located in the grasping claws. Under this gait the robot essentially becomes a suspended cart when moving along obstacle free catenaries between support towers. In this case the claw mounted clamp-on transformer surrounds the line and the power supply system operates normally, feeding the two traction motors and associated systems.

The second gait is suitable to overcome obstacles. It is inspired by the concertina (contract-anchor-extend) motion of some invertebrates. Each of the three claws can (i) grab the cable tightly, (ii) grab the cable loosely, allowing the claw to slide along, and (iii) disengage from the line. To overcome an obstacle the robot disengages each of the claws in sequence such that there are always two claws grabbing the cable, thus ensuring static stability. Under this gait, the clamp transformer opens so that the claws can disengage from the line.

The robot is equipped with a LiPo battery pack that provides energy while overcoming an obstacle and crossing a support tower. In addition, when moving along a catenary, and in the absence of obstacles, the system can also recharge the battery pack.

A new power supply system is proposed on this paper. It is based on the magnetic energy around the power transmission lines [3]. To use the magnetic energy, a transformer (functioning mechanically alike a current probe) is clamped around the power line [4]. The project considers that the robot operates on power cables carrying currents from nearly 100A to roughly 1000A. If the transmission current drops below a certain limit the robot can be put to hibernation while still hanging from the line.

A switching rectifier is connected on the transformer secondary winding and feeds the robot while charging the battery. When obstacles appear on the line, the clamp-on transformer opens, and the battery backup system is temporarily used until transformer is opened and the robot overtakes the obstacle.

To design the clamp-on transformer and the switching rectifier, it must be considered that current of a high voltage line can vary by a tenfold factor (100A to 1000A). Therefore, saturation effects and magnetization current of the clamp-on transformer might not be negligible. Well known unity power factor rectifiers cannot be used in this case, because if the clamp-on transformer was ideal, it would operate as a current transformer and not as a voltage source (as usually required by these rectifiers). Furthermore, a current mode controlled unity power factor rectifier is not suited for this application due to possible iron saturation arising from the DC bias of the AC current introduced by the fast dynamic action of the DC voltage controller, as revealed in preliminary approaches.

Therefore, this paper proposes a new power supply solution in which the current-probe like transformer supplies a power switching rectifier that is controlled in such a way that the clamp-on transformer sees the switching rectifier as a slow varying (time dependent) resistor placed in the transformer secondary. This means that the Thévenin equivalent of the robot power supply system, seen from the transformer, can be resumed as a resistance at each instant.

Section II of the paper describes the proposed solution. Section III gives the main design rules and section IV presents the simulation results.

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II. POWER SUPPLY CONFIGURATION

Figure 1 shows the design of the proposed power supply system. The maximum power absorbed by the robot (800W) is much lower than the high voltage line transmitted power. With this in mind, the current in the high voltage line can be assumed to be a current source \( i_p \). The clamp-on transformer feeds a power MOSFET full-bridge inverter controlled to operate as a rectifier. The DC load includes the robot’s load, the DC filters and the battery charger.

The MOSFET bridge is operated as a pulse width modulation (PWM) converter and controlled to rectify the AC current of the transformer secondary winding. The PWM is devised to obtain a \( V_{PWM} \) voltage proportional to the secondary current \( i_s \) so that the power converter and load are seen as a resistance.

Since the primary current depends on the high voltage line transmitted powers, this resistance must vary (slowly) in order to provide the robot needed power, despite the tenfold line current variation.

A. Converter PWM Generation and Control Full-Bridge Inverter PWM Generator

To emulate a slow time varying resistor \( R(t) \) the transformer should see a secondary winding voltage \( v_s \):

\[
v_s = R(t)i_s
\]

Being

\[
i_s = \frac{N_1}{N_2}i_p
\]

where \( N_1/N_2 \) is the clamp-on transformer winding ratio (Section III-A).

Considering the input low pass 3rd order filter as nearly ideal, the secondary voltage \( v_s \) is obtained as the low frequency content of the PWM output of the full-bridge inverter. Therefore, the PWM is devised to obtain a \( V_{PWM} \) average voltage, \( V_{PWM} \), within a switching period \( T_{PWM} \), proportional to the secondary current \( i_s \).

\[
V_{PWM} = \frac{1}{T_{PWM}} \int_0^{T_{PWM}} v_{PWM} \, dt \approx v_s = R(t)i_s \tag{3}
\]

The instantaneous value of the output voltage \( v_{PWM} \) of the MOSFET full-bridge can be obtained using switching variables \( \gamma_1 \) and \( \gamma_2 \) defined as:

\[
\begin{align*}
\gamma_1 &= \begin{cases} 
1 & \text{if } Q_1 \text{ on and } Q_2 \text{ off} \\
0 & \text{if } Q_1 \text{ off and } Q_2 \text{ on}
\end{cases} \\
\gamma_2 &= \begin{cases} 
1 & \text{if } Q_3 \text{ on and } Q_4 \text{ off} \\
0 & \text{if } Q_3 \text{ off and } Q_4 \text{ on}
\end{cases}
\end{align*}
\]

Then, \( v_{PWM} \) is:

\[
v_{PWM} = V_{DC} (\gamma_1 - \gamma_2) = \begin{cases} 
V_{DC} & \text{if } \gamma_1 = 1 \land \gamma_2 = 0 \\
0 & \text{if } \gamma_1 = \gamma_2 \\
-V_{DC} & \text{if } \gamma_1 = 0 \land \gamma_2 = 1
\end{cases}
\tag{6}
\]

As said, \( v_{PWM} \) must be modulated so that its mean value, in each switching period \( T_{PWM} \), equals the desired \( v_s \) voltage, considered constant at each switching period, since \( T_{PWM} \) is much smaller than the line period (20ms). Therefore, it can be written:

\[
\frac{1}{T_{PWM}} \int_0^{T_{PWM}} (v_s - v_{PWM}) \, dt = 0 \tag{7}
\]

From sliding mode control theory [6], [7] this is a sliding surface. Considering the error

\[
e_v = \int_0^{T_{PWM}} (v_s - v_{PWM}) \, dt = 0 \tag{8}
\]

The semiconductors switching law can be obtained using the sliding mode stability condition [6], [7]:

\[
e_v \frac{d e_v}{dt} < 0 \tag{9}
\]

Considering the time derivative of the sliding surface (7), and a sufficiently small quantity \( \varepsilon \), then can be obtained (10)

This switching law gives the full-bridge PWM modulator (Fig. 2), where the gain before the integrator is \( 1/T_{PWM} \)
and helps to define the switching frequency in addition to the \( \varepsilon \) value. The switching law (8) is implemented using two hysteretic comparators with different hysteresis widths \( \varepsilon \) and \( \varepsilon/2 \), that directly give the switching variables \( \gamma_1 \) and \( \gamma_2 \). The switching signals for the lower semiconductors are obtained using two inverter gates.

![Diagram of a Full-Bridge inverter generator](image)

**Fig. 2.** Full-Bridge inverter generator

### B. Control of the DC Output Voltage

The dynamics of the DC output voltage \( v_{DC} \) can be written, assuming all the DC loads represented by an equivalent resistor \( R_o \) (\( I_o = V_{DC}/R_o \)):

\[
C_o \frac{d v_{DC}}{dt} = (\gamma_1 - \gamma_2) I_s - \frac{v_{DC}}{R_o}
\]

This equation means that, in steady-state, the average value of the term \( \gamma_1 - \gamma_2 \) is the DC gain \( G \), of the full bridge rectifier, given by:

\[
G = \frac{V_{DC}}{I_s R_o} = \frac{I_o}{I_s}
\]

Considering that the full-bridge rectifier is almost conservative and the rectifier input power factor is almost unity, the input power \( F V_s I_s \) nearly equals \( F \) is close to unity) the output power \( V_{DC} I_o \). Then, the DC gain is:

\[
G = \frac{I_o}{I_s} = \frac{F V_s}{V_{DC}}
\]

The DC output voltage dynamics (11) can be rewritten for average values:

\[
C_o \frac{d V_{DC}}{dt} = G I_s - \frac{V_{DC}}{R_o}
\]

Considering (1), the term \( G I_s \) is

\[
G I_s = I_s \frac{F V_s}{V_{DC}} = V_s \frac{F I_s}{V_{DC}} = R(t) \frac{F I_s^2}{V_{DC}}
\]

Then, the \( V_{DC} \) control block diagram can be represented in fig. 3, where the action of the \( \upsilon_s \) controller (10) is assumed to have a delay \( T_d = T_{PWM}/2 \), whose transfer function has been approximated by a first order polynomial (since \( T_d \) is very small). A simple proportional integral (PI) controller was chosen (pole in the origin and a zero at \(-1/T_z\)), to guarantee zero steady state error, even considering parameter variation and disturbances.

Linearizing around the DC operating point the \( V_{DC} \) control linear block diagram is represented in Fig. 4.

Canceling the load pole \((-1/C R_o)\) with the PI zero, the obtained system has a \( 2^{nd} \) order dynamics whose damping factor \( \xi \) can be used to determine the \( T_p \) value. Therefore, the PI parameters are:

\[
T_z = C R_o
\]

\[
T_p = 4\xi^2 H T_d F I_s^2 / V_o
\]

The control parameters are load dependent. To ensure stability it is usefull to consider \( \xi = \sqrt{2}/2 \).

Making \( H = F = 1 \), \( T_d = 1/(2 T_{PWM}) = 10^{-4} \), the PI gains are \( k_p = T_z/T_p = 0.15 \) and \( k_i = 1/T_p = 7.9 \).

### III. SPECIFICATIONS AND SIZING OF FILTERS

#### A. Clamp-On Current Transformer

A 1 kW Clamp-On Type Transformer (COT) is used to allow the transformer iron and secondary winding \( N_2 \) turns to surround the high voltage power line. The transformer with one turn primary \( (N_1 = 1) \) winding has two jaws that open when obstacles appear on the power line. The nominal COT power considered, for this problem, is the robot power consumption (increased in 25% for safety margin) plus the power required to charge the batteries.

From the needed power and AC line current range, the transformer ratio was determined to be \( N_2/N_1 = 4 \). Losses components and leakage fluxes were estimated for a transformer efficiency of 98\%, Tab. I, Fig. 5).

<table>
<thead>
<tr>
<th>TABLE I TRANSFORMER CHARACTERISTICS</th>
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<td>Resistance Inductance</td>
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#### B. DC OUTPUT CAPACITOR

The RIOL robot needs 55V DC, and consumes 7A to 15A (including power needed to recharge the batteries). In steady state, the voltage applied on the robot should have an error less than 2.5\%. This error is due to the voltage ripple in the DC capacitor \( C \).
The full bridge rectifier input current $i_R$ has a fundamental component at 50Hz and high frequency components that arise from the semiconductors switching action. Neglecting the switching components, since they must be small compared to the fundamental component [8], the instantaneous power injected in the rectifier $Fv_s(t)i_s(t)$ equals its instantaneous output power $V_{DC}i_{DC}$:

$$2FV_s I_s \sin^2(\omega t) = V_{DC}i_{DC} \Rightarrow$$

$$\Rightarrow FV_s I_s (1-\cos(2\omega t)) = V_{DC}i_{DC} \quad (17)$$

Then

$$i_{DC} = \frac{FV_s I_s}{V_{DC}} (1-\cos(2\omega t)) \quad (18)$$

The capacitor voltage ripple $v_c$ can be obtained integrating the AC component of the $i_{DC}$ current:

$$v_c = \frac{1}{C} \int_0^t -\frac{FV_s I_s}{V_{DC}} \cos(2\omega t)dt = -\frac{FV_s I_s}{2C\omega V_{DC}} \sin(2\omega t) \quad (19)$$

The peak to peak voltage ripple must be less than $\Delta V_{DC} = 0.025V_D$. The $C_o$ value is:

$$C_o = \frac{FV_s I_s}{\omega \Delta V_{DC}} = \frac{I_o}{\omega \Delta V_{DC}} \quad (20)$$

This gives $C_o$ around 35 mF considering $I_o$ nearly 15 A.

**C. AC INPUT LOW PASS 3rd ORDER FILTER**

The input low pass 3rd order filter (fig. 6) is designed assuming a Chebyshev approach with passband ripple equal to 0.5 dB and cut-off frequency of 600 Hz. Assuming a Thévenin equivalent network $R_T$ seen from the transformer ($R_T \approx V_{DC} I_0/I_s^2$), the 3rd order transfer function is:

$$\frac{v_p}{v_{PWM}} = \frac{R_T}{L_1 I_1 L_2 I_2 C_3} s^3 + \frac{R_T}{L_1 I_1} s^2 + \frac{L_1 I_1 + L_2 I_2}{L_1 I_1 L_2 I_2 C_3} s + \frac{R_T}{L_1 I_1 L_2 I_2 C_3} \quad (21)$$

Equating the denominator coefficients with the Chebyshev polynomial $s^3 + 4723s^2 + 2.181 \times 10^7 s + 3.835 \times 10^{10}$, the values for $L_1$, $L_2$, and $C_3$ are obtained ($R_T \approx 1\Omega$):

$L_1 = \frac{R_T}{4723} = 0.21 \text{ mH}; \quad L_2 = \frac{2.181 \times 10^7 R_T}{3.835 \times 10^{10}} - L_1 = 0.36 \text{ mH};$

$$C_3 = \frac{R_T}{3.835 \times 10^{10} I_1 I_2} = 0.35 \text{ mF}$$
IV. SIMULATIONS

The power supply system has been modeled and simulated with MATLAB/Simulink. The simulation values were obtained for a power transmission line with currents ranging from 100A to 1000A.

Simulation results shown that DC output voltages of $55V \pm 1\%$ with DC currents near 15A, are obtained at primary currents of 100A. The start up transient shows that the DC voltage stays close to its set-point ($55V$) in spite of strong AC current variations. The results suggests a good load regulation with step changes, the sensitivity to disturbances (current steps from 200 A to 400 A not likely to occur), being small enough (nearly 1 V at 55 V, better than 2%).

Transformer secondary sinusoidal voltage, full bridge PWM voltage and secondary current (fig. 8) are shown at 150 A AC line current.

Fig. 9 shows the voltage at the transformer primary at primary currents of 200A to 400A. The voltage amplitude is small meaning that the power supply system will not disturb the normal operation of the AC transmission power line.

Efficiency was predicted to vary between 97% at 100 A line currents, to 60% at 1000A line current.

V. CONCLUSIONS

An autonomous power supply for the RIOL robot was designed and tested by Matlab simulation. The power supply harvests magnetic energy from overhead power lines, using a clamp-on transformer around the line.

The transformer supplies a 3rd order Chebyshev low-pass filter which interfaces a full bridge MOSFET based rectifier, and sliding mode controlled to emulate a resistor. The value of this time dependent virtual resistor is then controlled using a PI to deliver the desired output voltage ($55V \pm 2.5\%$) and power (max 800W). The controller laws and parameters, together with transformer and filter design were addressed.

Simulation results show that the DC voltage is well regulated (disturbances are lower than 2%) in all the AC line current range from 100A to 1000A. The AC voltages injected in the transformer primary are low enough for the AC line. Predicted efficiency is lower than desired at high AC currents (60% at 1000A), but it is good at the normal operating AC currents (90% at 500A), and very good for low AC currents (97%).
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