Inductive energy harvesting from variable frequency and amplitude aircraft power lines

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Abstract. This paper presents a non-contact method of harvesting energy from an aircraft power line that has an AC current of variable amplitude and a frequency range of 360-800 Hz. The current and frequency characteristics of the aircraft power line are dependent on the rotation speed of the electrical generators and will therefore change during a flight. The harvester consists of an inductive coil with a ferrite core, which is interfaced to a rectifier, step-down regulator and supercapacitor. A prototype system was constructed to demonstrate reliable output voltage regulation across a supercapacitor that will supply a peak power of 100 mW under duty cycled load conditions. The system could fully charge a 40 mF supercapacitor to 3.3 V in 78 s from a power line current of 1.5 A_{rms} at 650 Hz.

1. Introduction

Energy harvesting for aircraft-based applications has gained considerable interest as a means of realising a localised power source, thus reducing the weight and complexity of aircraft wiring looms. Kinetic harvesters have had little impact in this environment, however, partly because of reliability issues and also the difficulty of operating with the low vibration levels typical of modern aircraft. Contrastingly, thermoelectric generators used with phase-change materials have been demonstrated for powering sensors outside the heated cabin environment [1].

The research presented here focuses on another non-kinetic energy harvester for aircraft applications, coupling the magnetic field from a variable amplitude and frequency aircraft power supply line into an inductive coil. In this case, the metal frame of the aircraft forms the ground return path. The target application is a wireless sensor node that typically requires tens of mW and the harvesting system should be easily retrofitted onto an aircraft power line cable.

2. Inductive energy harvester design and characterisation

Figure 1(a) shows a schematic of the split-ring cores, inductive coil and power line cable, and figure 1(b) shows an equivalent circuit model of the inductive energy harvester [2]. It consists of a current source I to represent the power line current, N is the number of turns of the inductive coil, the winding and leakage inductances are L_w and L_{leak} respectively, a winding resistance R_w and the losses in the ferrite core are modelled by a resistor R_i. A tuning capacitor C_t is chosen to resonate with L_w at a specific frequency. Finally, a load resistor R_L completes the circuit. All the reactive and resistive components have been referred to the secondary side. For the frequencies of interest, 360-800 Hz, the loss in the core is negligible and hence R_i is only present in figure 1(b) for completeness.

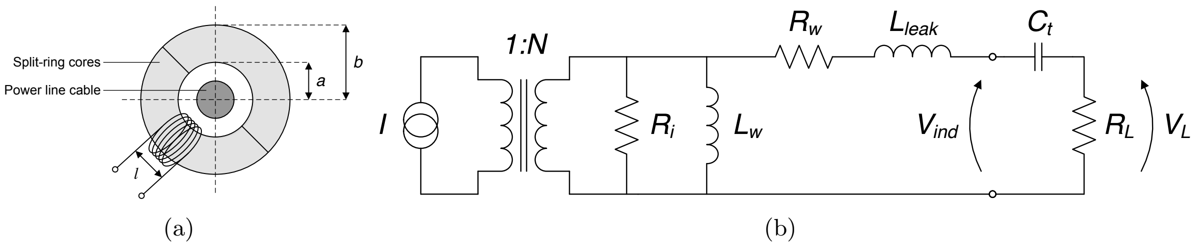


Figure 1. (a) Schematic of the inductive coil energy harvester and (b) equivalent circuit of the power line cable and inductive coil connected to a tuning capacitor and load.

2.1. Number of coil turns, N

The induced open-circuit voltage of the coil may be deduced by use of Ampere's Law. In (1), f and I are the power line frequency and current respectively, μ_r is the relative permeability of the ferrite core and a, b and l represent the inner and outer core radii and the coil length respectively, as shown in figure 1(a).

$$V_{ind} = 2\pi f N I \mu_0 \mu_r \ln\left(\frac{b}{a}\right) l \tag{1}$$

There is freedom when designing the coil to change the number of turns N and the coil wire diameter, which determines the coil resistance. Intuitively, it seems desirable to maximise N because the induced voltage across the coil is proportional to N. However, in a practical application there is a volume constraint on the total device size and for a given volume, increasing the number of turns increases the coil resistance since thinner wire is necessary to accomodate the additional turns. Consequently, the design strategy is to select N such that the induced coil voltage is above the minimum input voltage of the power electronics circuit and the winding resistance is comparable to the expected input impedance of a switch-mode interface circuit.

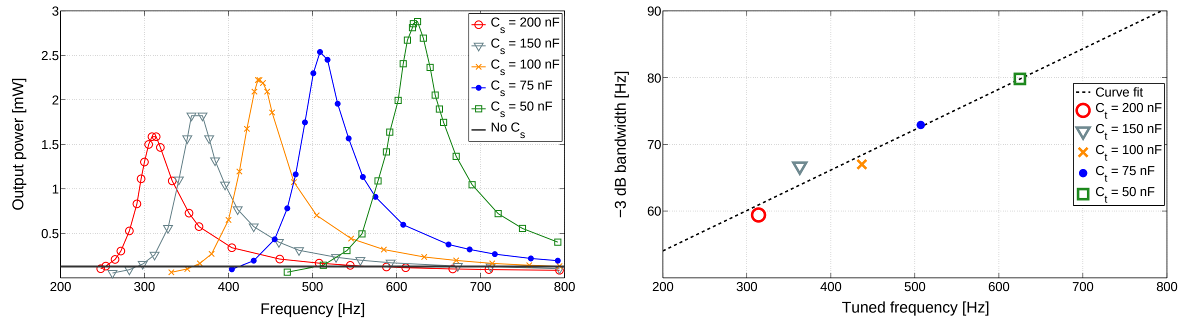
2.2. Tuning capacitor, C_t

The combination of coil inductance and tuning capacitor determines the resonant peak of the harvesting system according to (2) [3]:

$$f_{res} = \frac{1}{2\pi\sqrt{L_w C_t}} \tag{2}$$

In an aircraft application, C_t should be chosen such that resonance occurs at the dominant frequency of the flight cycle during the cruising phase. If, however, a dominant frequency does not exist, it will usually be better to have resonance occur in the lower frequency range. This is because the output power increases with frequency and hence, more power is harvested at the higher frequencies compared to the lower frequencies.

Figure 2(a) plots the power provided to a resistive load that is matched to the coil resistance for various values of C_t and also with no tuning capacitor. Figure 2(b) shows the variation in bandwidth for different tuned frequencies. The measurements in figure 2 were taken from a prototype harvester with 1100 turns hand wound onto a split ferrite core. The characteristics of the coil are summarised in table 1.



(a) (b)

Figure 2. Measurements of (a) output power dissipated into a matched load resistor against power line frequency and (b) -3dB bandwidth for different tuned frequencies, from a power line current of 0.9 A_{rms}.

Table 1. Measured inductive coil and ferrite core characteristics for $N = 1100$.

Parameter	Coil			Ferrite core (Würth Elektronik: 7427021)			
	Inductance	Resistance	Wire diameter	Inner diameter	Outer diameter	Length	μ_r
Value	1.4 H @ 500 Hz	100.9 Ω	100 μm	8.2 mm	16.3 mm	20 mm	≈600

3. Power management electronics

A block diagram of the interface electronics topology is shown in figure 3. A signal generator and an audio amplifier were used to simulate the aircraft power line current for test purposes.

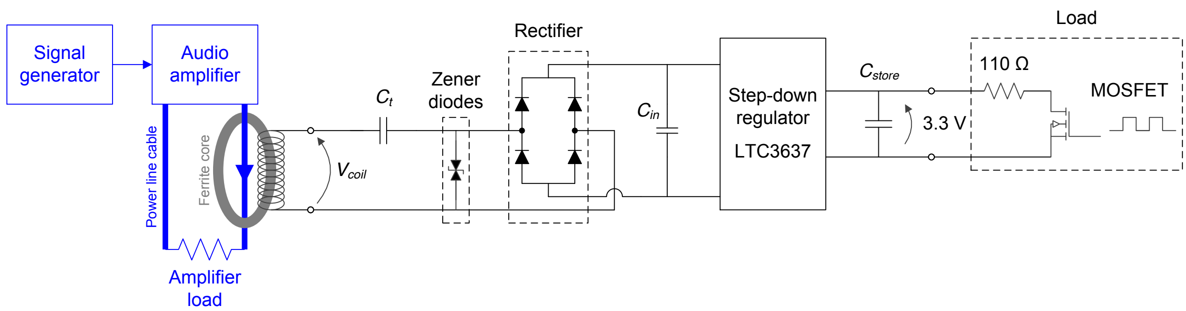


Figure 3. Power processing stages for the power line energy harvesting system.

A bidirectional Zener diode is used to protect the power processing electronics from excessive induced voltages due to surges in the power line. The induced coil voltage needs to be rectified. The simplest implementation is a full-wave bridge rectifier using four BAT46W Schottky diodes with N chosen to provide a sufficiently high voltage to overcome the diode voltage drops. Supercapacitors were chosen for energy storage because of their larger number of charge and discharge cycles before degradation and higher specific power rating compared to batteries.

The LTC3637 step-down regulator has an input voltage range of 4-76 V and it will be used to regulate the voltage across the supercapacitors at 3.3 V. Since the LTC3637 requires a minimum input voltage of 4 V, the number of coil turns N should be sufficiently large to exceed this threshold. Therefore, a 1100 turn coil was chosen because this could be reliably hand wound using 100 μm enamelled wire, given the size of the split-ring ferrite core.

3.1. Supercapacitor charging time

The choice of supercapacitors depends on the duty cycle and power consumption of the sensor node. Higher value capacitors will require a longer charging time compared to lower values ones but they can store more energy. So, there is a trade-off between the energy requirement of the load and the permissible charging time.

The system was constructed as shown in figure 3, using a 40 mF Cellergy CLG04P04L17 supercapacitor as the storage element. This was fully discharged prior to each measurement. The energy harvesting capability was tested for various power line currents and the process of charging the supercapacitor, without a tuning capacitor, is shown in figure 4(a). Figure 4(b) summarises the the charging times for $C_t = 100\ nF$. The induced voltage peaks at the tuned frequency of 421 Hz, resulting in a shorter charging time for a given current.

The charging time can be shortened by looping a slackened length of power line cable multiple times around one half core, as shown in figure 4(c), and subsequently aligning it with the second half core using a clamp. The thinner enamelled wire on the left half core is the inductive coil. Figure 4(d) shows the effect of doubling or tripling the loops of power line cable.

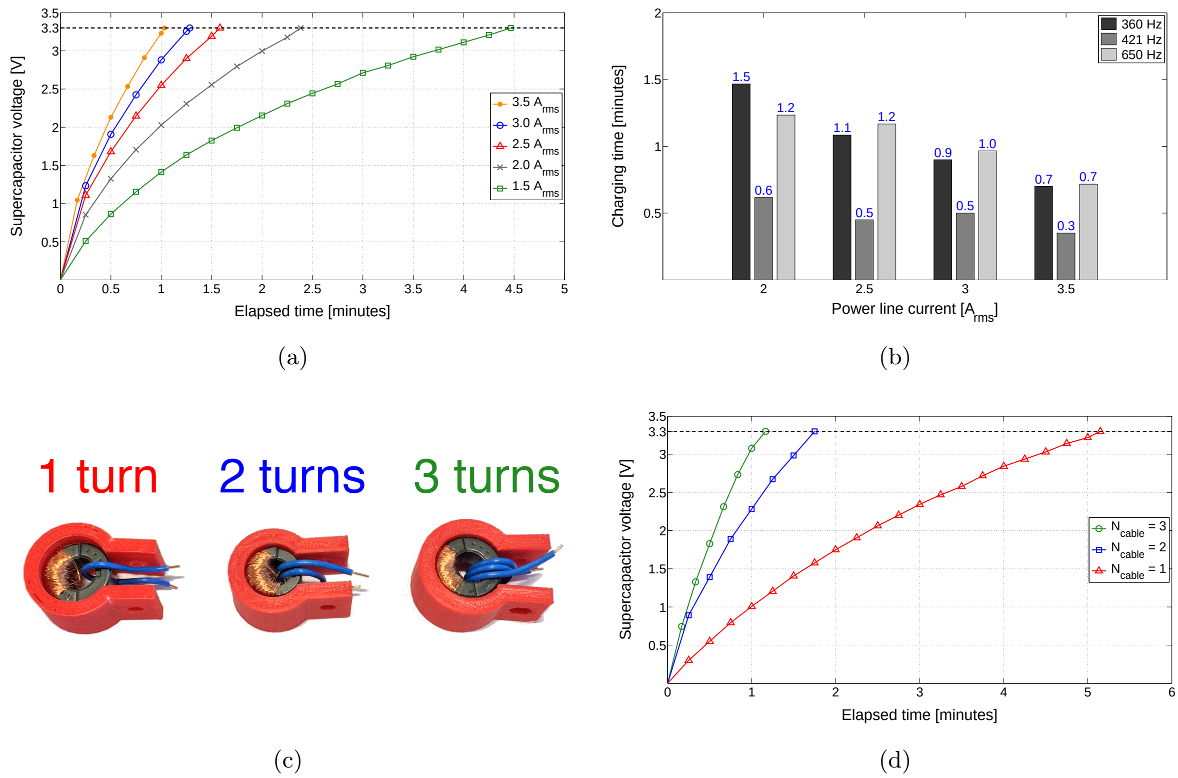


Figure 4. (a) Measured charging times of a 40 mF supercapacitor at 650 Hz and a single turn of power line cable carrying 1.5 A_{rms} without C_t, (b) charging time variations for $C_t = 100\ nF$ with a single turn power line cable, (c) photograph showing multiple turns of a power line cable, and (d) charging times of a 40 mF supercapacitor using multiple turns of a cable carrying 1.5 A_{rms}.

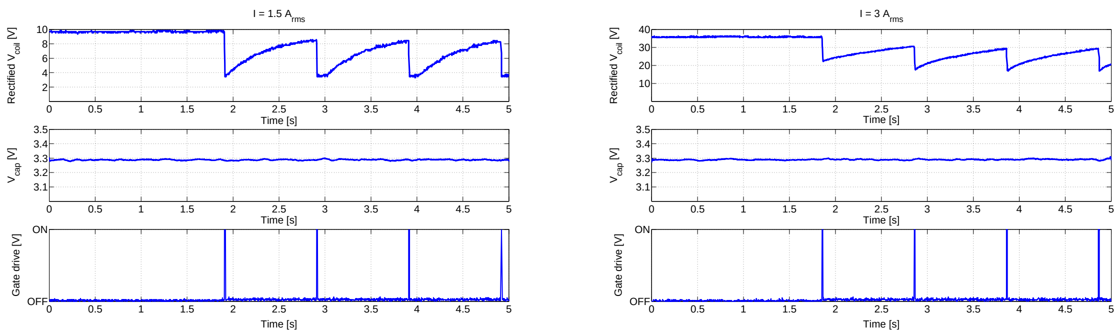
The prototype could fully charge a 40 mF supercapacitor to 3.3 V in 78 s with a power line current of 1.5 A_{rms} and three turns of the power line cable, *i.e.* delivering 0.22 J to the supercapacitors in 78 s.

4. System characterisation

A typical application for this system would be a wireless sensor node, requiring about 100 mW at a 1% duty cycle [1]. To emulate such a load, a 110 Ω resistor in series with a MOSFET switch was connected in parallel with the supercapacitor. When the MOSFET is turned on by the appropriate gate drive, the resistor draws ≈100 mW from the system.

Initially, the load is disconnected and the supercapacitor was charged using the inductive coil. During the charging phase, the LTC3637 input voltage is held at the under-voltage lockout threshold, which ranges between 3.5-3.65 V. In this mode, all the harvested energy is used to charge the supercapacitor. Once the supercapacitor is charged to 3.3 V, the LTC3637 input voltage will change according to the induced coil voltage.

Figure 5 shows measurements of the rectified coil voltage and supercapacitor voltage for power line currents of 1.5 A_{rms} and 3 A_{rms} at 650 Hz. In this example, the 40 mF supercapacitor can sufficiently supply 100 mW once per second, for four consecutive gate drive pulses. Whenever the 110 Ω was connected, the supercapacitor voltage remains at 3.3 V whilst the rectified coil voltage decreases because the harvested energy is being used to recharge the supercapacitor. Once the supercapacitor is fully charged, the rectified coil voltage will rise accordingly. In the 3 A_{rms} case, the rectified coil voltage never decreases to the lockout threshold because the supercapacitor is being recharged at a faster rate. This agrees with the charging times observed in figure 4.



(a) (b)

Figure 5. Experimental measurements using a continuous power line current of (a) 1.5 A_{rms} and (b) 3 A_{rms}, with a switched load to draw 30 mA once per second at 1% duty cycle.

5. Conclusions

A prototype power line energy harvesting system has been developed for aircraft applications. A tuning capacitor can be used to resonate out the coil inductance at specific frequencies. The system successfully charged a 40 mF supercapacitor to 3.3 V and supplied 100 mW to a duty cycled load. The weight and volume of the prototype are 80 g and 103 cm^3 respectively and this equates to an energy density of 2.7 mJ/g or 2.1 mJ/cm^3. The energy density of the system can be increased because the prototype was designed for laboratory tests.

References

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