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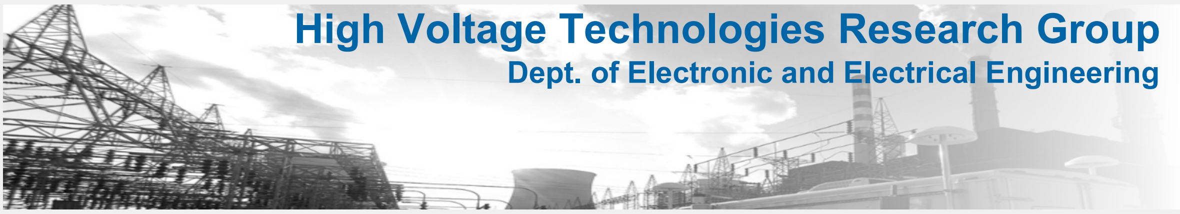

High Voltage Technologies Research Group

Dept. of Electronic and Electrical Engineering

Energy Harvesting from Electric and Magnetic Fields in Substations for Powering Autonomous Sensors

Minan Zhu, Nina Roscoe and Martin Judd*

Motivation

Monitoring the electricity transmission infrastructure more closely will bring efficiency, financial and operational benefits to the grid operator. Power consumption of new generation sensors is decreasing, but they still need a source of power to operate. Barriers that prevent the large scale uptake of sensor networks include:

- The cost cable installation is many times the sensor cost - not justified for the majority of assets.
- Using batteries limits deployment to those areas which are accessible when the system is energised. Replacing batteries also imposes a costly maintenance requirement.

Proposed Solution and Necessary Work

Harvesting energy from the electric and magnetic fields within substations could ensure that sensors are self-sufficient and **maintenance-free** over their lifetime.

Research is progressing on two fronts:

- Investigate the typical field strengths within substations, especially at prospective sensing locations.
- Develop generic devices that are able to harness, store and deliver energy from these ambient fields.

Field Survey Example

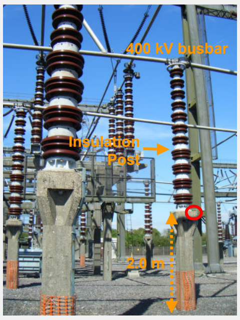

Figure 1: Low level busbar in an outdoor 400 kV substation

Table 1: Field strength reading at the red circle spot in Fig. 1

Electric Field	57 kV/m
Magnetic Field	6.5 ~ 20 µT (over a 2 hour period)
Possible Application	Insulator surface pollution monitor

- Field surveys so far have been carried out in the 'safe area' of the substation.
- Electric field readings are generally stable because the voltage level is carefully regulated.
- Magnetic field readings can vary in a wide range because the load current changes with demand. This aspect has been taken into consideration.

Harvesting Energy from Magnetic Fields

Inductive coils are used to harness energy from magnetic fields. Two different types of inductive harvesters have been developed, as shown in Fig. 2.

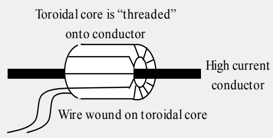

Figure 2(a): Threaded inductive harvester

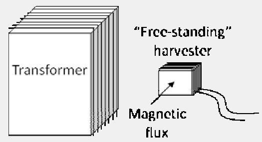

Figure 2(b): Free-standing inductive harvester

Optimal design for the threaded inductive harvester

- Both inner outer radii of the core should be made as small as possible.
- Height of the core should be 10 times the difference between outer and inner radii. This dimension is found to give the maximum output power output for per unit volume.
- Multiple coils can be connected together to obtain higher power, as shown in Fig. 3.
- Further improvement in power output is possible if the best core material (M449 and M451) could be formed in the optimal shape.

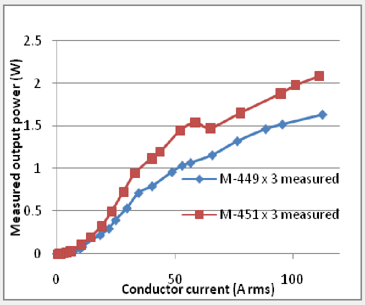

Figure 3: Measured output power three stacked M449 cores and three stacked M451 cores (both cores supplied by Magnetec).

Free-standing inductive harvester

- It is beneficial to use a core with the largest practical length to diameter ratio (L/D).
- For the same geometry, no additional improvement can be achieved by using ferrite cores compared to cast iron at practical L/D.
- If the coil inductance is compensated with a matching capacitance, increasing the number of turns can improve the power output. However, eventually distributed effects become dominant, as shown in Fig. 4.
- Free-standing harvester can be deployed at locations where a threaded inductive harvester would be neither feasible nor practical.

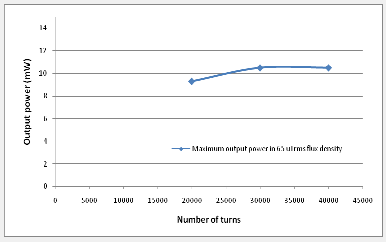

Figure 4: Variation in harvesting coil output power as a function of the number of turns. Measured in a 65 µT flux density with a cast iron core 50 cm long and 5 cm in diameter. The uniform magnetic field is generated by a Maxwell coil test apparatus.

Harvesting Energy from Electric Fields

Capacitive electrodes are used to harvest energy from electric fields. A hemisphere was found to be the optimal shape for the harvesting electrode. A demonstrator is shown in Fig. 5.

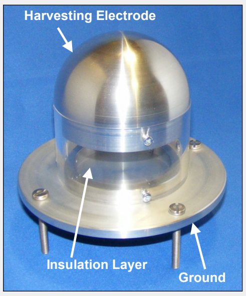

Figure 5: Capacitive harvesting demonstrator

Technical challenge

The voltage generated across the capacitive electrodes appears in series with an extremely high impedance due to the low (50 Hz) operating frequency. This effect greatly reduces the amount of energy that can be transferred to the load.

Mitigating method

A non-linear conversion technique, synchronising switching harvesting on inductor, is employed to mitigate the loading effect. An energy buffer, such as a capacitor, is placed between the conversion circuit and the load. The energy buffer regulation circuit allows the harvested energy to accumulate on the capacitor before the load, such as a wireless sensor, is energised.

The principle of the non-linear capacitive harvesting device and associated simulation result are shown in Figs. 6 and 7.

Table 2: A typical experimental result

Field Strength	60 kV/m
Energy Output	55 mJ
Duration to accumulate the energy	16 min 17sec
Discharging time	≈ 14 sec @ 2 mA

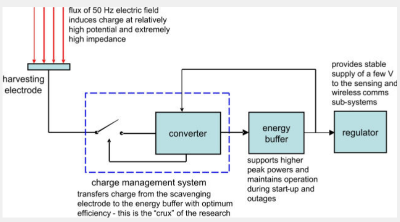

Figure 6: Block diagram of the capacitive harvesting device employing non-linear conversion technique

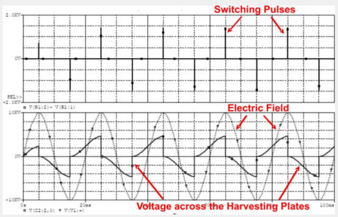

Figure 7: Output of the non-linear conversion circuit – switching occurs at the peaks and troughs of the ambient electric field

Energy Buffer Concept

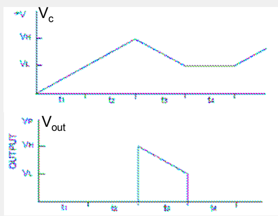

Figure 8: Voltage waveforms of the energy buffer

- $V_c < V_H \rightarrow V_{out} = 0$, the buffer is charging.
- $V_c = V_H \rightarrow V_{out} = V_H$, the buffer starts to discharge.
- V_c drops from V_H to $V_L \rightarrow V_{out} = V_c$, the buffer is discharging.
- $V_c = V_L \rightarrow V_{out} = 0$, the buffer starts to charge again.

Future Work

- Integrate the harvesting devices with the wireless sensors currently used by National Grid and evaluate their performance.
- Exploit the fields inside restricted access areas of the substation, such as in close proximity to an HV disconnector arm, as shown in Fig. 9.

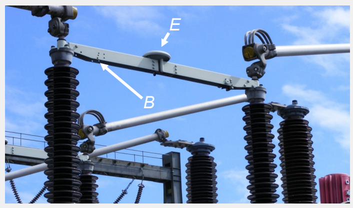

Figure 9: High voltage (132 kV) disconnector

Table 3: Power consumption profile of a prospective temperature sensor

Activity of the Sensor	Current Consumption	Event Frequency
Quiescent Monitoring Phase	100 µA	at all times
Data Transmission	300 mA for 20ms	every 15 min

*Contact: Dr Martin Judd Email: m.judd@eee.strath.ac.uk Tel. +44 (0) 141 548 2171