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Energy Harvesting for Online Condition Monitoring of High Voltage Overhead Power Lines

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Abstract *– For electric power transmission, high voltage overhead power lines play an important role as the costs for power transmission are comparatively low. However, the environmental conditions in many geographical regions can change over a wide range. Due to the high voltages, adequate distances between the conductors and objects in the environment have to be ensured for safety reasons. However, sag of the conductors (e.g. due to temperature variations or aging, icing of conductors as a result of extreme weather conditions) may increase safety margins and limit the operability of these power lines. Heavy loads due to icing or vibrations excited by winds increase the risk of line breakage. With online condition monitoring of power lines, critical states or states with increased wear for the conductor may be detected early and appropriate counter measures can be applied. In this paper we investigate possibilities for monitoring devices that are directly mounted onto a conductor. It is demonstrated that such a device can be powered from the electric field around the conductor and that electronic equipment can be protected from the strong electric and magnetic fields as well as transient signals due to partial discharge events.*

Keywords: Online Condition Monitoring, Overhead Power Lines, Environmental Sensors

I. INTRODUCTION

Several critical parameters may affect the operability and availability of power lines. Due to temperature and aging effects, the sag of the conductor changes and may extend to a critical state i.e. the minimum distance to objects in the environment may not be guaranteed with adequate safety margins. Another important aspect is icing of the power line ([1], [2]), as it constitutes additional weight and may further increase the sag. Laminar wind streams may excite vibrations of the conductor, which may induce mechanical damages to the cable nearby the mounting brackets of the transmission tower [3]. Based on the knowledge of the eigenfrequency of the conductor, adequately mounted damping objects may minimize vibrations and may therefore provide longer life time of the conductor.

Figure 1 sketches the basic idea of a condition monitoring system incorporating several sensors to determine relevant parameters such as wire temperature, distance to ground and degree of icing. The sensor system is directly attached to the conductor, measurement data is wirelessly transmitted to a control station. The power for sensors, signal processing and data transmission is obtained either from the electric field, the magnetic field, solar energy or wind energy. In this paper we focus on the energy harvesting from the electric field. A short comparison of the different methods is provided in Table I.

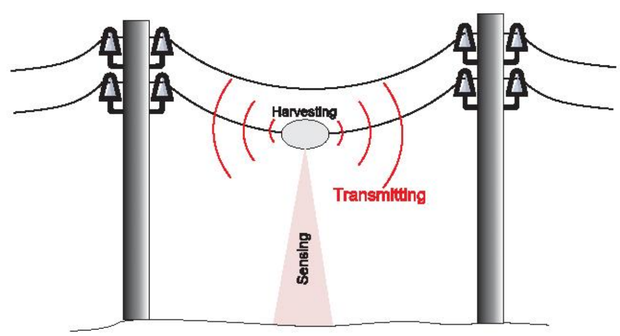

Figure 1. Principle of a monitoring system for overhead power lines: Sensors are used to determine relevant parameters such as wire temperature, distance to ground and icing. The data is wirelessly transmitted to a relay station. The power for sensors, signal processing and data transmission is obtained from the electric field.

II. THEORETIC CONSIDERATIONS AND SIMULATIONS

The energy that can be obtained from the electric field is estimated using Finite Element Analysis (FEA). The harvester prototype comprises a tube with a diameter of

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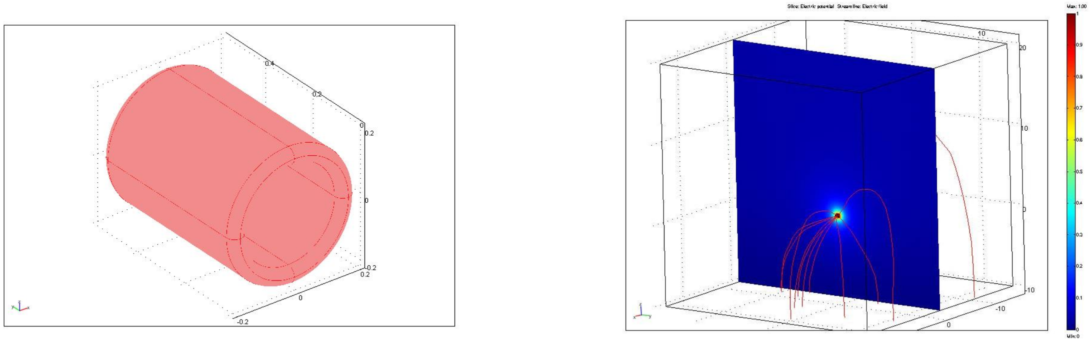


(a) 3D FEA model of the energy harvester tube (b) Electric field distribution around the sensor area

Figure 2. 3D FEA model of the energy harvester tube. A diameter of 30 cm is chosen, which is in line with the maximum dimensions of objects mountable on power supply lines. The electric potential sharply decreases in the vicinity of the wire. The capacitance is found to be 19 pF for a conductor in approximately 10 meters height.

TABLE I. Comparison of different energy harvesting principles used for condition monitoring of overhead power lines.

Method	Advantages	Disadvantages
Magnetic Field	Rather small, easy to attach to power line	Requires sufficient electric current in the conductor
Electric Field	Easy to attach to power line, robust, operates as soon as power line is turned on, no current in the conductor is required	Larger than a magnetic harvester
Solar Energy	Can work even when power line turned off	Power not always availabe (nights, cloudy days, occlusion with snow etc.), can be destroyed by hail, requires high capacity energy storage
Wind Energy	Can work even when power line turned off	Power not always available, moving parts, maintenance costs, can hardly be mounted on a conductor

30 cm and a length of 55 cm, which is in the size of aviation markers mounted on power lines. The displacement current depends on the capacitance of the tube to the environment and the voltage applied to the tube:

$$\underline{I} = \frac{\underline{U}}{\underline{X}_c} = \underline{U} j\omega C \quad (1)$$

As the current is rather small, we propose to use a transformer to obtain a higher current,

$$\underline{I}_s = \frac{N_1}{N_2}\frac{\underline{U}}{\underline{X}_c} = u\underline{U} j\omega C \quad (2)$$

where N_1 and N_2 are the number of turns in the primary and secondary coil, the ratio $u = \frac{N_1}{N_2} = 100$ for our prototype.

The voltage on the tube can be chosen over a wide range and is clamped by the electronic circuitry. It is limited by the maximum rating voltage of the transformer (in our case 2.7 kV).

Figure 2(a) shows a FEA model of the energy harvester. It comprises a tube with a diameter of 30 cm. An increase of the diameter would also increase the capacitance to the environment (proportional to the surface of the object) and thus the displacement current. However, the diameter is limited as the objects on the conductor should not be too large and heavy. It is mandatory to eliminate sharp edges in order to avoid partial discharge. Consequently, tubes with diameters of 5 cm are applied at each end of the tube.

The capacitance obtained from simulations (compare Figure 2(b)) with a conductor situated in a height of 10 m amounts to about 19 pF. Consequently, a displacement current of about 500 μA can be expected. With a voltage of 1000 V between the outer pipe of the harvester and the conductor, a power of about 0.5 Watt would be obtained.

III. PROTOTYPE AND EXPERIMENTAL SETUP

Figure 3 shows the principle schematic of the energy harvester. A high voltage transformer is connected between the conductor and the outer tube. A shunt regulator maintains a voltage of 9 Volts on the secondary side (provided, the primary voltage is sufficiently high). As the equivalent circuit of the topology can be seen as a high

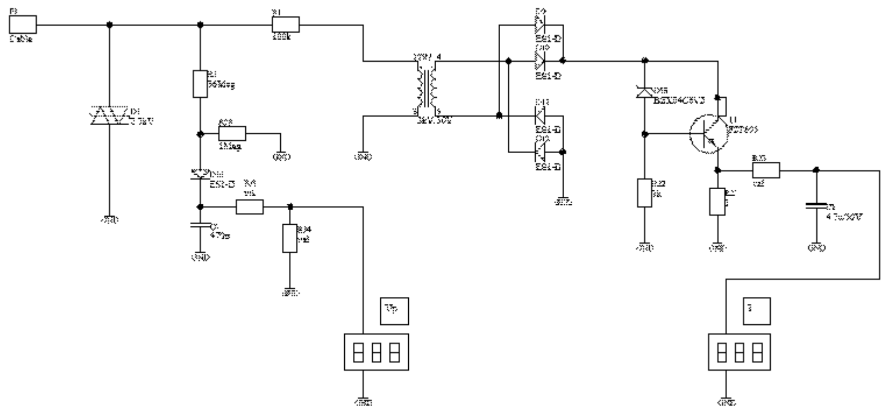


Figure 3. Schematic of the energy harvester circuitry. It consist of a voltage transformer connected between the conductor and the outer tube followed by a shunt regulator. System ground symbolizes the outer tube.

impedance current source (very small coupling capacitance between the outer diameter of the tube to ground), low magnetizing current of the transformer is mandatory for maximum power efficiency. Therefore, the characteristic of the transformer itself is chosen similar to the properties of a voltage transformer (high inductance, good coupling) instead of a power transformer to achieve maximum main inductance. Experiments validated, that with reasonable dimensions of the transformer (although with high main inductance), an adequate coupling coefficient between primary and secondary windings is achievable. Hence, the required voltage regulation of the primary side (maximum of 3 kV at the primary side of the transformer) could be achieved by clamping on the secondary side.

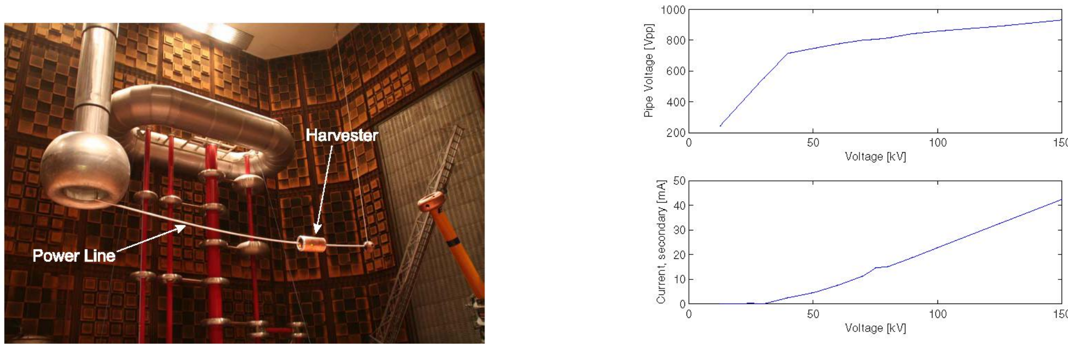
The system was tested in a high voltage measurement hall. The setup is shown in Figure 4(a). The distance to ground was approximately 4.5 meters. This is somewhat lower than in an actual application. However, the coupling capacitance to ground decreases only slowly with the height as could be seen in Figure 5.

Figure 4(b) shows the runs of the voltage on the tube and the current available for powering electronic devices for different nominal voltages applied to the power line in the high voltage measurement hall. A certain minimum level of voltage is required such that the potential of the tube attains approximately 1000 V with respect to the conductor. Then, a further increase is limited by the shunt regulator, as the impedance between the tube and the wire is reduced and the available current on the secondary side is increased. The available power for electronic devices is displayed in Figure 5(a). Starting at about 30 kV the power is constantly increasing with the voltage as the displacement current between the tube and the environment is also increased (compare Equation 2). At a nominal voltage of 150 kV a power level of about 370 mW was obtained, which is sufficient for many measurement principles. The power could be further increased by either increasing the capacitance (larger diameter or length of the harvester) or by an increase of the voltage on the tube with respect to the conductor without the need for geometric adaption. Here, a larger transformation ratio u would be required, the power could be increase with the ratio u at least by a factor of three with our current transformer and even more with a special high voltage transformer.

The influence of the distance between ground and the conductor is shown in Figure 5(b). As expected, the power decreases with an increase of the distance, but the decrease is rather slow due to the nonlinear change of the capacitance. An increase of the distance from about 4.5 meters to approximately 9 meters reduces the available power only by about 10%.

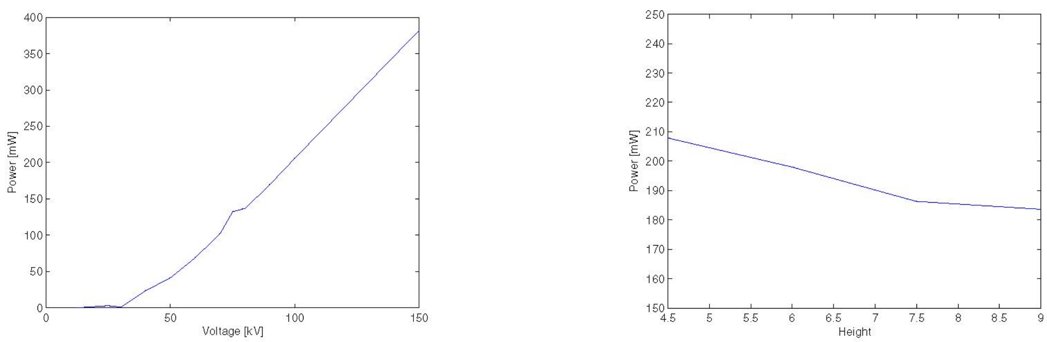
IV. OPERABILITY OF ELECTRONIC DEVICES

For the operation of electronic devices it is necessary that the electric field strength does not exceed certain limits. In particular, the enormous field strength in the vicinity of a high voltage conductor could easily destroy electronic equipment. This is illustrated in Figure 6(a). Therefore, appropriate protection mechanisms have to be applied. The tube that is required by the energy harvester can also be used for field strength reduction. As the voltage between the tube and the conductor is limited by a



(a) Measurement setup in the power hall (b) Current and voltage

Figure 4. (a) Measurement setup in the power hall. Runs of primary voltage and secondary current (out of 9 V) for different nominal voltages on the power line for the test setup shown in Figure 4(a).



(a) Available power (b) Influence of height on the power

Figure 5. (a) Dependency of the available power on the nominal voltage. (b) Influence of the distance between ground and the conductor (nominal voltage 100 kV) on the available power. Please note that the x-ticks are not meters but measurements. The first measurement was taken at about 4.5 meters, the last at about 9 meters between ground and the condcutor (compare Figure 4(a)

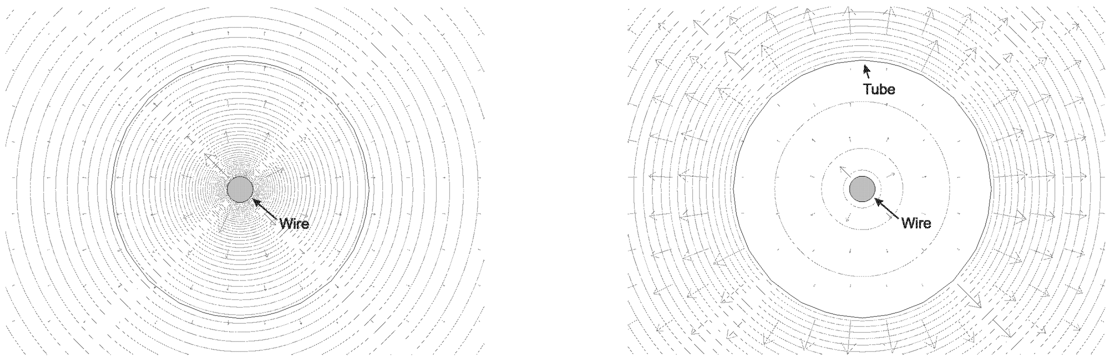
shunt regulator (compare section III), the field strength inside the tube is also strongly reduced. This is demonstrated by a closer look at the Finite Element simulation shown in Figure 6(b): Inside the tube, the field strength is low, in particular close to the tube. Here, electronic devices can be operated.

A. *High Currents*

High currents may be present in the power line and may affect the power efficiency of the harvester. For the simulation of the high current, a power transformer capable to provide approximately 190 A was used. The setup is sketched in Figure 7. Nine windings were placed in a copper tube (forming the wire) such that the resulting effective current amounted to about 1700 A. The harvester was powered by a high voltage stray transformer, the potential difference between the wire and the tube was approximately 1 kV as in the experiments in the high voltage laboratory. It could be demonstrated that the influence of high currents is rather small. Due to the strong magnetic field associated with the current, a small interference of the magnetic fields in the transformer occurs such that the current provided by the energy harvester can be slightly increased or decreased depending on the phase of the current. However, the impact is minor and the operation of the electronic devices powered by the harvester would not be effected even with several kilo amperes load on the conductor.

B. *Discharge and Transient Voltages*

Partial discharge due to uneven surfaces of the power wire may lead to large variations of the potential and sig-



(a) Electric field around the conductor

(b) Influence of height on the power

Figure 6. (a) Electric field in the vicinity of a high voltage conductor: The density of equipotential lines (in steps of 1000 V) is high, which corresponds to a high field strength (also indicated by arrows). The potential difference between points separated by millimeters can exceed hundreds of volts, therefore this environment is hostile for electronic devices. (b) Effect of the harvester tube (radius of 15 cm) for a field reduction in the vicinity of the conductor. The density of equipotential lines is drastically reduced and the field strength (indicated by arrows) is acceptable for electronic devices.

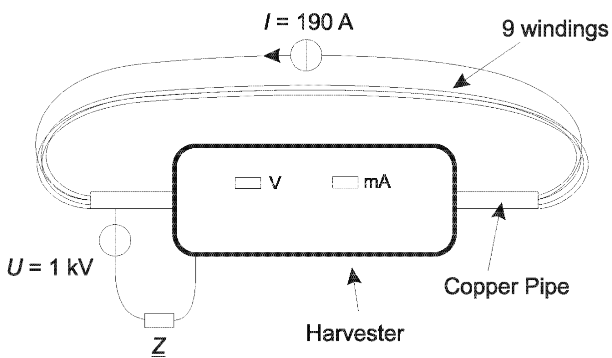


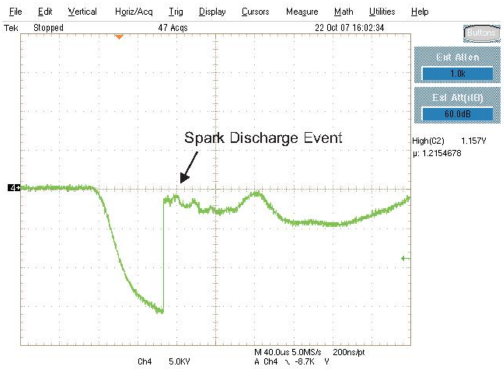
Figure 7. Setup for high current test: A current source with I=190 A and 9 windings are used, representing an effective current of about 1710 A. The harvester was powered by means of a stray transformer at 1 kV.

nificant displacement currents ([4], [5]). Furthermore, over voltages may occur due to direct or indirect lightning strokes. Therefore, appropriate measures for the protection of the circuitry are required. To evaluate the sensitivity of the circuitry, spark discharge is used.

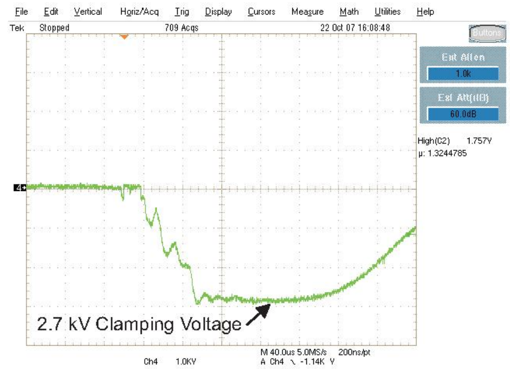
For the protection of the circuitry the voltage is clamped by an over voltage protection comprising several suppressor diodes which are connected in series, yielding a clamping voltage of about 2.7 kV (compare Figure 3). In the prototype, the voltage between the tube and the wire is measured through a voltage divider. In order to avoid high transient currents through capacitive coupling over the resistor and to achieve a withstand voltage which is in accordance to the over voltage protection device (clamping diodes), the divider is built by a series connection of several varistors. The same applies to the transformer: Several resistors are connected in series (total resistance amounts to 100 kΩ) to the transformer. Compared to the impedance of the outer capacitor, this resistor is negligible with respect to energy harvesting but yet very useful to suppress transient voltage signals.

Partial discharge and over voltage are simulated using a spark discharge to the wire from an ignition coil. A photography is shown in Figure 8.

The voltage signal on the exciting wire is shown in Figure 9(a). Due to the vicinity of the discharge location and the tube, the impedance is rather low and high transient signals between the wire and the tube can occur. In the field, the capacitance between the tube and the environment will be low and thus the impedance will be significantly higher. Consequently, it is assumed that the test is significant also for outdoor applications because both the voltage for the discharge and the impedance will be higher such that the effective disturbance remains similar. Figure 9(b) shows the potential difference between the tube and the wire during a spark discharge, which is limited to about 3 kV. Thus, the electronic circuitry is effectively protected. As the impedance of the pipe to the environment is rather high, the currents that need to be suppressed by the suppressor components remain low even when the transient voltages reaches slopes of many kV/μs.



(a) Voltage of a spark discharge



(b) Effect of the over voltage protection

Figure 9. (a) Voltage signal on the exciting coil for the spark discharge experiments. The peak voltage attains about 20 kV (negative polarity). (b) Effect of the over voltage protection: The potential difference between the tube and the wire is clamped to about 3 kV.

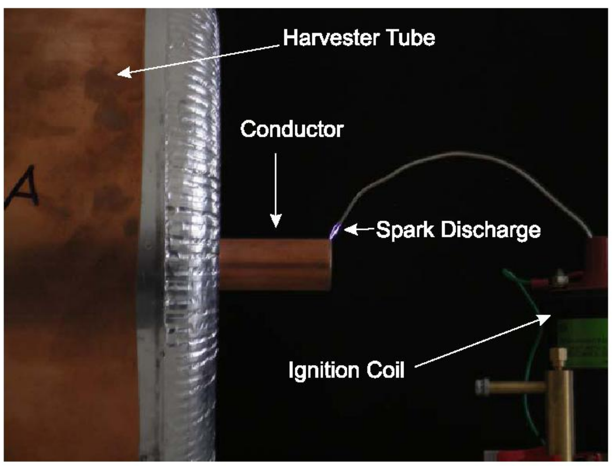


Figure 8. Laboratory setup for testing robustness with respect to electrostatic discharge and transient voltages. A tip is placed in the vicinity of the conductor and connected to a high voltage source; a spark discharge occurs. Corresponding signal runs are depicted in Figure 9(a).

V. CONCLUSION

This paper presents theoretical and experimental results on power harvesting from the electric field and operation of electronic devices in the vicinity of the conductors of a high voltage overhead power lines. It could be demonstrated that energy harvesting from the electric field provides sufficient energy to power sensor devices and means for wireless communication. Simulations based on Finite Element Models show good accordance with the experimental results obtained in a high voltage measurement hall.

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