A Feasibility Study on Autonomous 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 sag of the conductors (e.g., due to temperature variations, aging, or icing of conductors as a result of extreme weather conditions) may increase safety margins and limit the operability of these power lines. Furthermore, heavy loads due to icing or vibrations excited by wind streams increase the risk of line breakage. With online condition monitoring of power lines, critical states can be detected early, and appropriate countermeasures can be applied. In this paper, we investigate possibilities for monitoring devices that are directly mounted onto a conductor. The feasibility of powering the device from the electric field, protection of electronic circuitry from strong electric fields, and data transmission by means of a wireless link is demonstrated, as well as its operability during the presence of strong magnetic fields due to high currents and transient signals due to partial and spark discharge events.**

***Index Terms*—Data transmission, energy harvesting, online condition monitoring, overhead power lines.**

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 the icing of a power line [1], [2], as it constitutes additional weight and may further increase the sag. In 1998, 150 transmission towers collapsed in a Canadian power system due to ice accumulation [3]. Furthermore, laminar wind streams may excite vibrations of the conductor, which may induce mechanical damages to the cable near the mounting brackets of the transmission tower [4]. Based on the knowledge of the eigenfrequency of the conductor, adequately mounted damping objects may minimize the vibrations and may therefore provide a longer lifetime for the conductor.

Fig. 1 sketches the basic idea of a condition-monitoring system incorporating several sensors to determine relevant parameters such as the wire temperature, the distance to the ground, and the degree of icing. The sensor system is directly attached to the conductor, and measurement data are wirelessly transmitted to a control station. The power for sensors, signal processing, and data transmission is obtained from the electric field, the magnetic field [5], solar energy (e.g., [6]), or wind energy. In [7], the ground wire is used for power transmission. In this paper, which is an extension of [8], we focus on energy harvesting from the electric field, as it offers advantages compared with other methods. A short comparison of the different methods is provided in Table I.

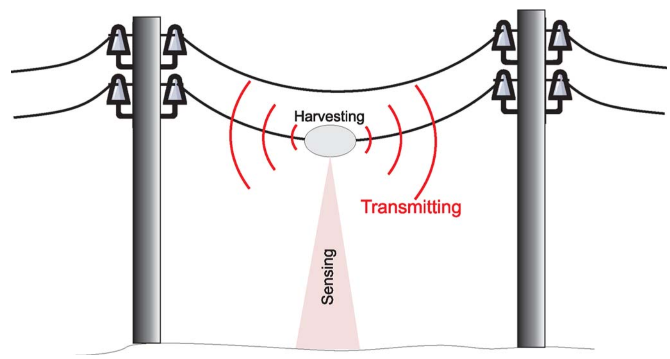

Fig. 1. Principle of the proposed monitoring system for overhead power lines. Sensors are used to determine relevant parameters such as the wire temperature, the distance to the ground, and the degree of icing. The data are wirelessly transmitted to a relay station or a mobile provider. The power for 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. Fig. 2 shows the principle setup of the harvester and a finite-element model of the energy harvester. The harvester prototype comprises a tube with a diameter of 30 cm and a length of 55 cm, which is about the size of aviation markers mounted on power lines. It is mandatory to eliminate sharp edges to avoid partial discharge. Consequently, donut-shaped objects are placed at the ends of the tube to remove sharp edges [cf. Figs. 2(b) and 8]. The displacement current depends on the capacitance C_{CMG} [equivalent circuit in Fig. 2(a)] of the tube to the environment and the voltage applied to the tube

$$\underline{I} = \frac{\underline{U}}{\underline{X}_c} = \underline{U} j\omega C_{\mathrm{CMG}}. \quad (1)$$

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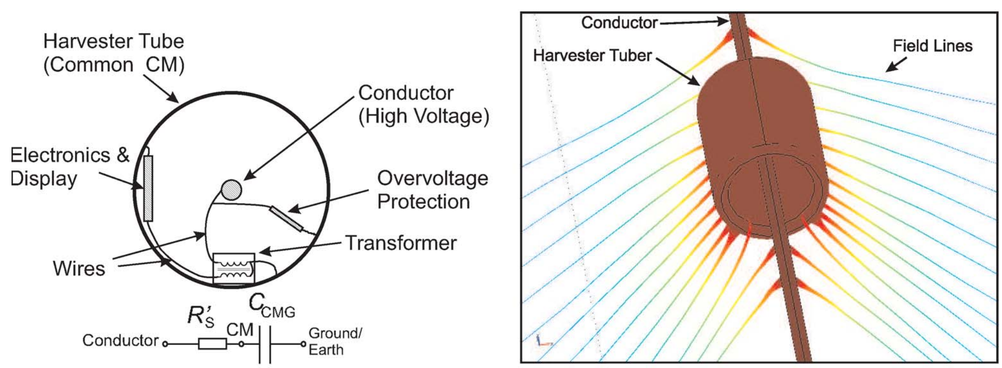
TABLE I

COMPARISON OF DIFFERENT ENERGY HARVESTING PRINCIPLES USED FOR CONDITION MONITORING OF OVERHEAD POWER LINES

Method	Advantages	Disadvantages
Magnetic Field	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 is 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 is turned off	Power not always available, moving parts, maintenance costs, can hardly be mounted on a conductor



(a) (b)

Fig. 2. Harvesting system. (a) Cross-sectional view and simplified equivalent electric circuit. The harvesting tube is mounted on a conductor of an overhead power line using polyvinyl chloride fixtures. For the electric and electronic components, the tube is on common potential (CM). The primary coil of a high-voltage transformer is connected between the tube and the conductor, and the secondary side is connected to the electronic circuit. All electronic and electric components are located close to the tube. (b) Three-dimensional finite-element model of the energy harvester tube. The electric field is illustrated by means of selected field lines. Their thicknesses correspond to the electric field strength, and their colors correspond to the electric potential. The electric potential sharply decreases in the vicinity of the wire. For larger distances, the disturbance of the field due to the tube is negligible. According to the simulation, a capacitance with respect to the environment of about 19 pF can be expected for a conductor at a height of approximately 10 m.

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

$$\underline{I}_s = \frac{N_1}{N_2}\frac{\underline{U}}{\underline{X}_c} = u\underline{U}j\omega C_{\mathrm{CMG}} \tag{2}$$

where $N_1 = 24\,000$ and $N_2 = 236$ are the numbers of turns in the primary and secondary coils; we used an effective ratio $u = (N_1/N_2) \approx 100$ for our prototype. An EI-66/37,7 durethane coil form and grain-oriented silicon steel M111-35 [9] as core material (EI-66 core, 66 mm$\times$55 mm$\times$35 mm, [10]) were used. The transformer was manufactured by Rusa GmbH, Vienna.

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

According to finite-element simulations [cf. Fig. 2(b)], the capacitance C_{CMG} obtained between the harvester tube (CM) and the ground amounts to about 19 pF for a distance of 10 m. As the voltage on the equivalent resistor R'_{s} is regulated to $U_{R'_{\mathrm{s}}} = 1000$ V, the voltage on the capacitance C_{CMG} is almost equal to the nominal voltage. With (1) and a nominal voltage of, e.g., $U = 100$ kV (between the conductor and the earth), a displacement current of 597 μA is obtained. With a voltage of $U_{R'_S} = 1000$ V between the tube of the harvester and the conductor (R'_S as the simplified equivalent of energy consumers between the tube and the conductor), an active power of about $P \approx 0.6$ W on R'_S should be obtainable.

III. PROTOTYPE AND EXPERIMENTAL SETUP

Fig. 3 shows the principle schema 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 V on the secondary side (provided that the primary voltage is sufficiently high). As the equivalent circuit of the topology

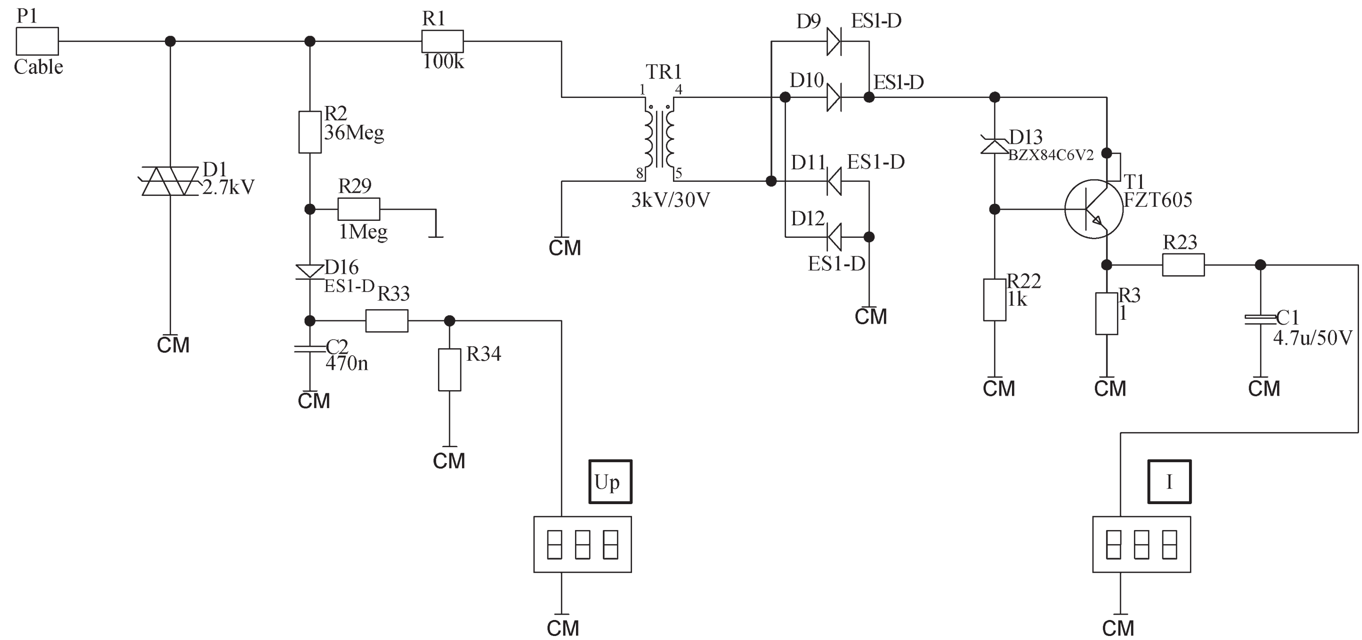


Fig. 3. Schema of the energy harvester circuitry. It consists of a voltage transformer (TR1) connected between the conductor (cable) and the outer tube (common, CM) followed by a rectifier (D9–D12) and a shunt regulator comprising Zener diode D13 and power transistor T1. Resistor R1 is used to reduce fast transient voltages on the primary coil of the transformer, e.g., due to partial-discharge events. D1 represents an overvoltage protection comprising several suppressor diodes, which are connected in series, yielding a clamping voltage of about 2.7 kV. The current is measured as the voltage drop on resistor $R3 = 1\ \Omega$, averaged using the low-pass filter comprising R23 and C1. To be able to observe the increase in voltage and current starting from the low levels, the instruments are powered by means of batteries rather than the harvested power.

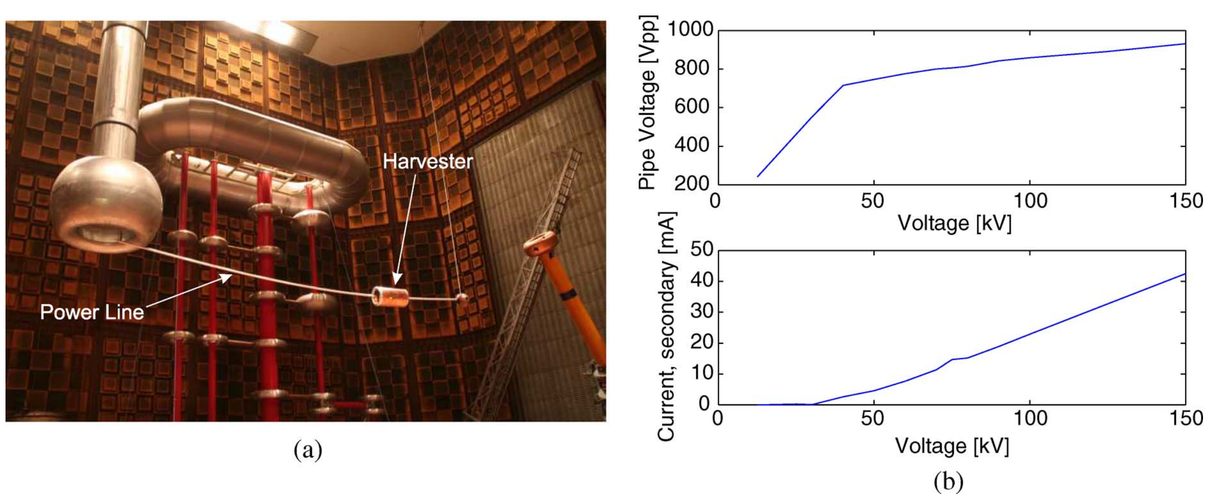


Fig. 4. (a) Measurement setup in the power hall. (b) Runs of primary voltage and secondary current (out of 9 V) for different nominal voltages on the power line for the test setup shown in Fig. 4(a).

can be seen as a high-impedance current source (very small coupling capacitance between the outer diameter of the tube and the ground), a low magnetizing current for 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 and 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 Fig. 4(a). The distance to the ground was approximately 4.5 m. This is somewhat lower than in an actual application. However, the coupling capacitance to the ground decreases only slowly with the height, as could be seen in Fig. 5.

Fig. 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

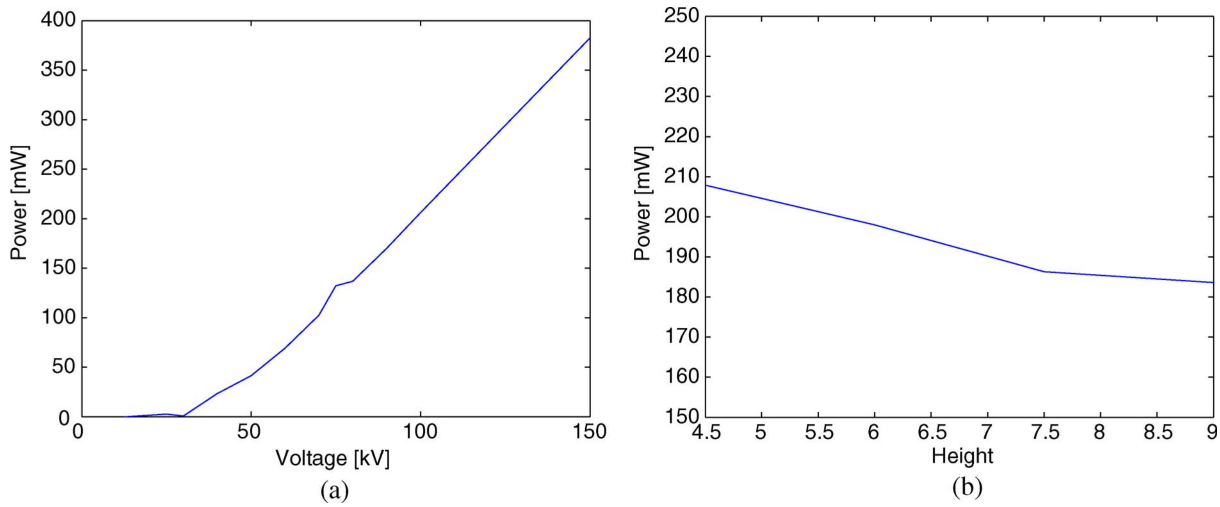


Fig. 5. (a) Dependency of the available power on the nominal voltage. (b) Influence of the distance between the ground and the conductor (nominal voltage 100 kV) on the available power. The first measurement was taken at about 4.5 m and the last at about 9 m between the ground and the conductor [cf. Fig. 4(a)].

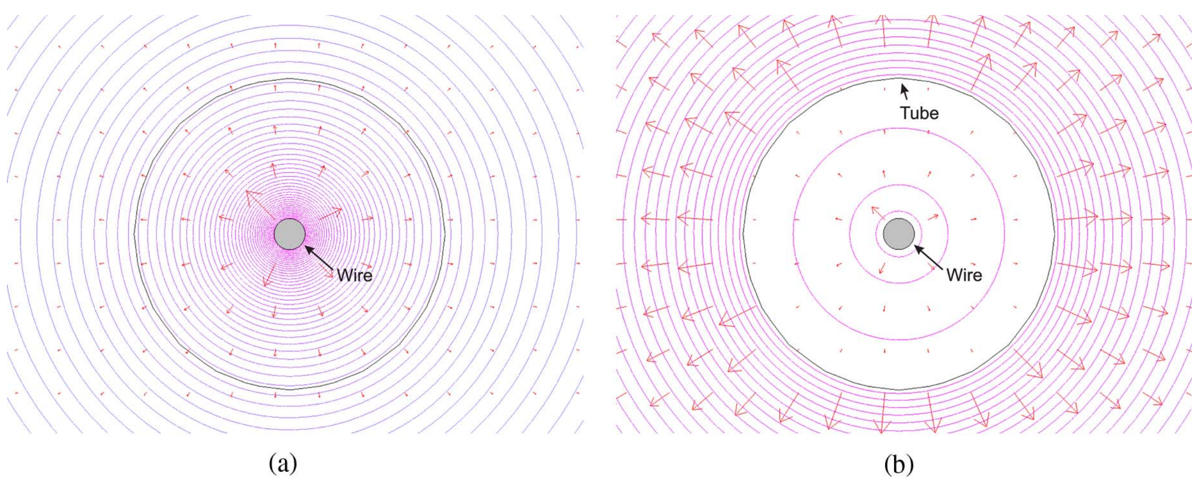


Fig. 6. (a) Electric field in the vicinity of a high-voltage conductor. The density of equipotential lines (in steps of 1000 V) is high, which corresponds to a high field strength (also indicated by arrows). The potential difference between points separated by millimeters can exceed hundreds of volts; 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.

electronic devices is displayed in Fig. 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 increasing [cf. (1)]. At a nominal voltage of 150 kV, a power level of about 370 mW is obtained, which is sufficient for many measurement principles. The power could be further increased either by increasing the capacitance (larger diameter or length of the harvester) or by increasing the voltage on the tube with respect to the conductor without the need for geometric adaptation. Here, a larger transformation ratio u would be required; the power could be increased with the ratio u by at least a factor of three with our current transformer (limited by the voltage rating of the transformer) and even more with a special high-voltage transformer.

The influence of the distance between the ground and the conductor is shown in Fig. 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 m to approximately 9 m reduces the available power by only 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 Fig. 6(a). Therefore, appropriate protection mechanisms have to be applied. The tube that is required by the energy harvester can at the same time be used for field strength reduction. As the voltage between the tube and the conductor is limited by a shunt regulator (cf. 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 Fig. 6(b). Inside the tube, the field strength is low, particularly close to the tube. Here, electronic devices can be operated.

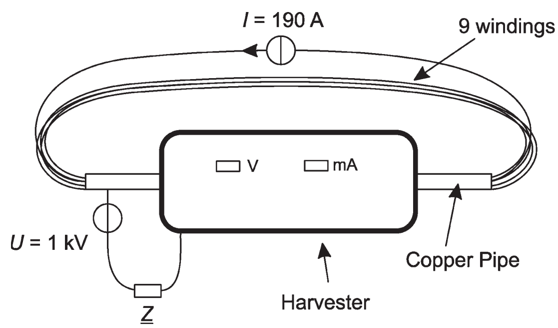


Fig. 7. Setup for the high-current test. A current source with $I = 190$ A and nine windings are used, representing an effective current of about 1710 A. The harvester was powered by means of a stray transformer at 1 kV.

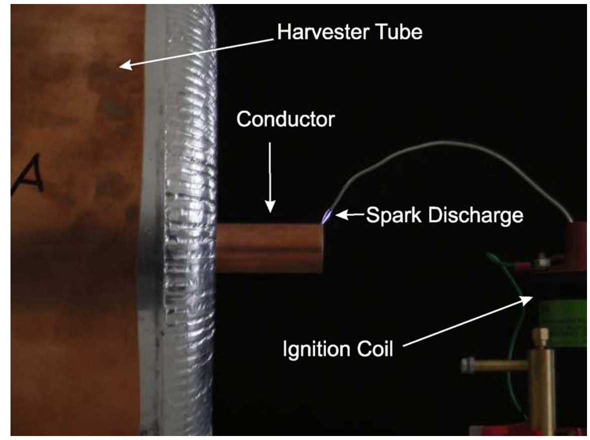


Fig. 8. Laboratory setup for testing the robustness with respect to electrostatic discharge and transient voltages. A tip is placed in the vicinity of the conductor and connected to a high-voltage source; a spark discharge occurs. Corresponding signal runs are depicted in Fig. 9(a).

A. High Currents

High currents may be present in the power line and may affect the power efficiency of the harvester. For the laboratory model of a high current on a power line, a power transformer capable of providing approximately 190 A was used. The setup is sketched in Fig. 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 high currents, a small interference in 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 affected even with several kiloamperes of 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 significant displacement currents [11], [12]. Furthermore, overvoltages 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 overvoltage protection comprising several suppressor diodes, which are connected in series, yielding a clamping voltage of about 2.7 kV (cf. Fig. 3). In the prototype, the voltage between the tube and the wire is measured through a voltage divider. To avoid high transient currents through capacitive coupling over the resistor and to achieve a withstand voltage, which is in accordance with the overvoltage 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 (the total resistance amounts to 100 kΩ) to the transformer. Compared with the impedance of the outer capacitor, this resistor is negligible with respect to energy harvesting yet very useful for the suppression of transient voltage signals.

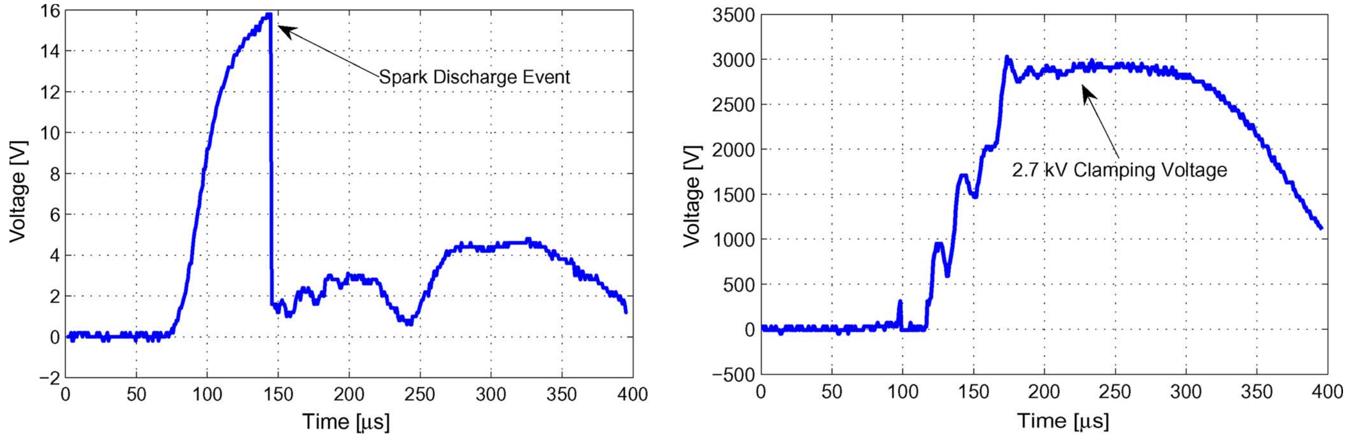
Partial discharge and overvoltage are emulated in the laboratory using a spark discharge to the wire from an ignition coil. A photograph is shown in Fig. 8.

The voltage signal on the exciting wire is shown in Fig. 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. Fig. 9(b) shows the potential difference between the tube and the wire during a spark discharge. The voltage is limited to about 2.7 kV by the clamping circuitry. 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 reach slopes of many kilovolts per microsecond.

V. Communication to a Control Station

The proposed online condition-monitoring system should autonomously collect data. The relevant information will be transmitted to a control center, thus providing a comprehensive view of the state of the supervised power line. As the system will be directly mounted on the conductor, approaches for establishing a communication link between the monitoring system and the control station have to be investigated and experimentally validated.

One approach may be the use of the conductor itself for wire-bound communication. Although this method was used in the past (e.g., for remote control of actuator elements within the power grid), it is now more or less obsolete due to the high density and availability of the mobile network infrastructure. Consequently, the necessary infrastructure for communication via the conductors of a power line (e.g., transformer stations



(a) (b)

Fig. 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 overvoltage protection. The potential difference between the tube and the wire is clamped to about 2.7 kV.

have to provide appropriate communication bridges) is no longer provided throughout the whole power grid.

Consequently, a wireless communication link between the monitoring system and a host is the preferred choice, as there are power-aware components readily available. With appropriate antenna structures, the radiation pattern could be optimized to maximize the available signal strengths at the receiver. However, these antenna structures may be exposed to strong electric and magnetic fields in the vicinity of the power line. Therefore, adequate measures against potential high-energy electromagnetic compatibility (EMC) disturbers have to be applied and investigated with respect to their efficiency.

In this paper, we concentrate on communication within the globally standardized frequency band of 433 MHz (a free industrial scientific medical radio band for Region 1, covering Europe, Africa, the Middle East, and further parts of Asia, according to the International Telecommunications Union). The experiments were conducted with commercially available battery-powered transmitter modules with built-in antenna structures and amplitude modulation (eumig TR-502SV). As stated in the previous section, the harvester setup offers sufficient protection for electrical components inside the tube against EMC disturbers. Therefore, the transmitter modules are fixed inside the tube near the existing electronic circuitry. In field experiments, the prospective shielding effect of the tube on the achievable range of operation and the radiation pattern of the transmitter were investigated. The EMC behavior of the harvester system with a wireless communication unit is analyzed in further experiments in a high-voltage measurement hall.

Due to the small wavelengths associated with the selected frequency band, the geometry of the harvester tube may induce directivity and shielding effects. However, for versatile applicability of the monitoring system, communication should be possible, regardless of the orientation of the harvester relative to a receiver. The experiments for 433 MHz showed that the maximum received signal strength is observed when the receiver is located at a direction that is rotated by 45° with respect to the longitudinal extension of the harvester tube. In contrast, in the transverse direction, the minimum signal strength could be observed.

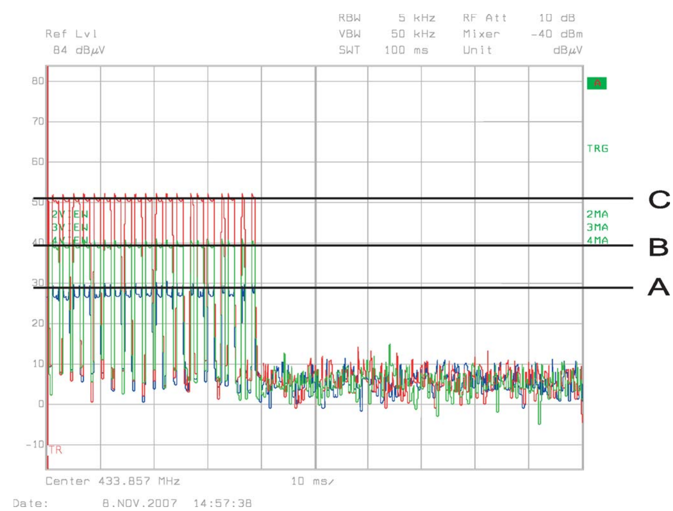


Fig. 10. Signal strengths at a distance of 100 m on a field received from a harvester with a 6-m copper conductor. (A) Reference measurement with the standalone transmitter module. (B) Spectrum obtained in the transverse orientation. (C) Spectrum obtained at a rotation of 45° with respect to its longitudinal orientation. The increase in SNR is due to an enlarged effective antenna size caused by the harvester tube and the conductor wire.

Fig. 10 summarizes the obtainable SNRs for different orientations of the harvester tube compared with a reference measurement of a standalone transmitter (cf. the blue-marked spectrum). The transmitter is optimally adjusted to provide the maximum signal strength at the receiver location. Spectrum "B" is obtained in the transverse orientation with respect to the harvester tube. The highest SNR is at the receiver at 45° with respect to the longitudinal extension of the harvester tube (spectrum "C" in Fig. 10). Although the received signal strength in the transverse orientation is about 10 dB lower than the maximum achievable SNR, it is still about 10 dB higher than the signal strengths available in the reference setup without the harvester (spectrum "A"). Therefore, the harvester tube does not decrease the radiated power but increases the radiated power due to an enlarged antenna size. Note that the antenna of the transmitter module was not electrically connected to the harvester tube during this experiment.

VI. Experimental Results in a High-Voltage Measurement Hall

The results of the presented experiments promote the feasibility of using wireless transmitters within the harvester tube to establish a communication link with a control station. It was shown that no additional antenna structures are necessary and that the harvester tube even enhances the radiation characteristics. Therefore, based on the outcomes in the previous section, the protection and, hence, operability of communication modules within the harvester tube is ensured. However, the impacts of strong EMC disturbers have to be investigated.

As shown in Fig. 4(a), the setup comprising the harvester tube equipped with a 433-MHz transmitter and the protection circuitry was tested in a high-voltage measurement hall. High-voltage capacitors [see the left side in Fig. 4(a)] are used to induce enduring spark discharges, thus generating EMC disturbances higher than those typically expected in actual applications.

In the following, the conducted EMC stress tests and observed impacts on the functionality of the harvester system with respect to the provided amount of energy and quality of the communication link are described.

A. Partial-Discharge Effects

To resemble partial-discharge effects close to the harvester tube, three welding wires with lengths of approximately 10 cm were mounted on the high-voltage conductor in varying distances to the harvester tube. Due to the high field strength around the sharp edges of the welding wires, corona effects could be observed. The maximum voltage was 250 kV. Throughout the experiment, no negative impacts of the partial-discharge effects on the functionality of the harvester tube or on the communication channel are observed.

B. Discharge Effects Due to Icicles

In cold regions, it is expected that icicles may form directly at the harvester tube. Again, such icicles exhibit sharp edges and corona effects, and thus, corona effects may occur directly on the harvester tube. For the experiments, welding wires of 40 cm in length were used, and this time, they are mounted onto the harvester tube. As in the previous experiment, where the welding wires were attached to the conductor, strong corona effects were observed but did not show any negative impact on the functionality of the harvester tube or the wireless link.

C. Enduring Spark Discharges

Enduring sparks usually occur during switching operations in the power grid. To resemble such sparks, two high-voltage capacitor plates were placed at close distance, leading to enduring spark discharges. These sparks lead to strong EMC disturbances that are in excess of what we expect in the actual application. Whereas the energy harvesting is hardly affected by these sparks, the noise floor is drastically raised. Thus, the available SNR at the receiver is reduced (cf. Fig. 11). However, for the chosen data rate, the SNR is sufficient for demodulation, and the transmission range would not be significantly reduced. This is because both signal and noise will decrease with the distance of the receiver until the noise of the spark discharge vanishes in the background noise.

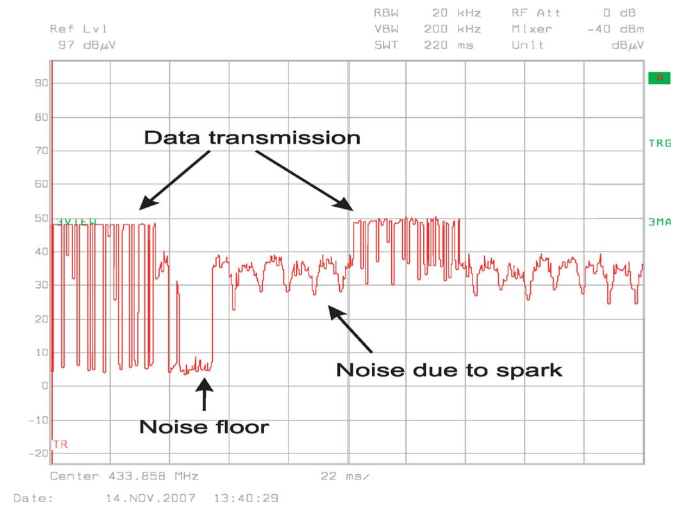


Fig. 11. Spectrum of a communication burst in the presence of disturbances induced by enduring spark discharges. The basic functionality of the harvester system is provided. The noise floor is drastically raised, thus lowering the SNR at the receiver.

D. Giant Spark Discharges

Fast transients and high-voltage variations may occur during lightnings. Such effects were investigated using a 1-MVA enduring spark discharge between the conductor and spark clamps at the isolator, at a nominal voltage of 300 kV. The circuitry of the harvester system is not affected, and the current provided by the harvester remains at about 170 mA. For the short duration of the event, the communication channel may be disturbed. However, short interruptions are usually acceptable.

VII. Conclusion

This paper has presented theoretical and experimental results on power harvesting from the electric field and the operation of electronic devices in the vicinity of the conductors of a high-voltage overhead power line. It has been 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. Robustness with respect to partial discharges and giant spark discharges, which may occur due to lightning strikes, has been demonstrated.

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