Non-intrusive voltage measurement of ac power lines for smart grid system based on electric field energy harvesting

S. Kang, S. Yang and H. Kim✉

A new non-intrusive ac voltage measurement technique based on stray electric filed energy harvesting is presented whereby the voltage of ac power lines can be measured without removing insulation and therefore without direct contact with conductors of the power lines. The energy of electric field around the power lines is picked up and stored in a capacitor by a wire wound around insulated 3-wire household power lines or by a conductor plate placed in the vicinity of overhead high-voltage power lines. Autonomous switches are used to monitor the stored electric field energy in a storage capacitor and to generate pulse train. Experimental results show that the repetition rate of the output pulse is a linear function of the line voltage. Since the voltage of insulated 3-wire household power line can be measured without removing insulation and the voltage of high-voltage power transmission line can be measured without any contact to the conductor of the power line, the proposed technique can be widely applied to smart grid system.

Introduction: In modern smart grid system, for the reliable and cost effective supply of electric power, simple and easy-to-install voltage measurement is essential [1]. Since most of the voltage measurements require direct contact with conductor of the power line, when the line voltage is measured in an existing distribution system, insulations of the power line should be removed and, in some cases, power should be shut down for safety. In this paper, a novel non-intrusive ac voltage measurement technique that can measure voltage of the insulated multi-wire power line without removing insulation is presented. When voltage is applied to power lines and the lines carry current, according to the Poynting vector, electric power is delivered to the load through the space, which implies that, at any point in the space, there is time-varying field energy. Even in the case of open circuit, since there are parasitic capacitances between lines and earth ground, ac current still flows. In 60 Hz power system, according to quasi-static approximation, the intensity of the stray electric field around the power line is determined by the line voltage only. Therefore, it is possible to estimate the line voltage using harvested electric field energy. In this paper, we present two experimental results, one is for insulated 3-wire household power line and the other is for overhead high-voltage power line.

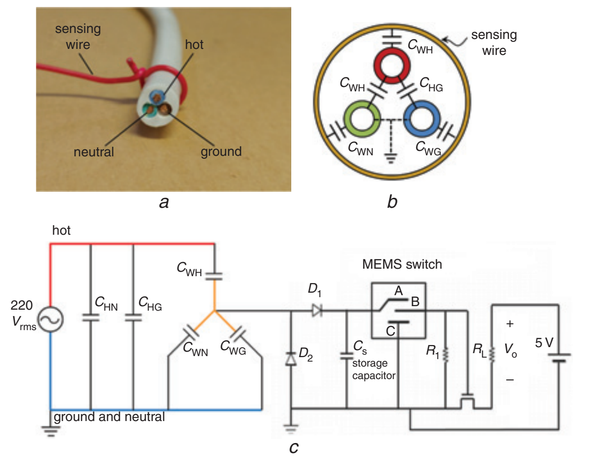

Fig. 1 *Picture of sensing wire and equivalent circuits*

a Picture of sensing wire wounded on insulated 3-wire power line for electric field energy harvesting
b Diagram showing parasitic capacitances
c Equivalent circuit of measurement system

Voltage measurement of insulated power line: The first experiment demonstrates that the stray electric field energy harvesting can be applied to measure the voltage of the insulated power line without removing the insulation or without direct contact with the dangerous hot wire. In Fig. 1*a*, just one turn of sensing wire is wound around an insulated single-phase 3-wire 220 V household power line to harvest the stray electric field energy. Fig. 1*b* shows the parasitic capacitances between sensing wire and conductors in the insulated power line and Fig. 1*c* shows the equivalent circuit of voltage measurement system, where the schematic diagram of micro-electromechanical system (MEMS) switch is used [2]. The radio frequency (RF) MEMS switch is adopted as an autonomous switch since it has hysteretic characteristics, near zero leakage current and ultra low-power consumption [2, 3]. The circuit works as follows: The MEMS switch is normally off, and gate voltage of the field effect transistor (FET) is zero volts, which makes the output voltage across R_L be zero. When the voltage is applied to the power line, the stray electric field energy is accumulated in the storage capacitor C_s and the capacitor voltage increases since it does not have discharge path. When the voltage increases to the on-voltage (21 V) of the MEMS switch, movable electrode A moves down to connect with B. This results in voltage on the gate, which turns on the FET and thereby the output voltage is the voltage (5 V) of the external power supply for a while. However, C_s discharges through the R_1, and when the capacitor voltage decreases to off-voltage (19.8 V) of the MEMS switch, then the electrode A moves up to be disconnected from B, which isolates the storage capacitor and resumes charging sequence. Gate voltage discharges quickly through R_1, and this turns off the FET to have zero volt output. Then the whole cycle repeats periodically to generate voltage pulse train across R_L.

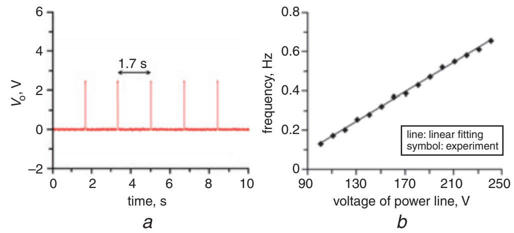

Fig. 2 *Experimental results*

a Output voltage pulse train across R_L
b Frequency of pulse train vs. line voltage

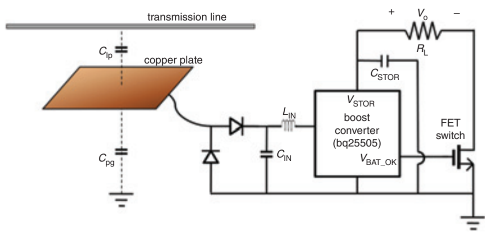

Fig. 3 *Schematics of copper plate type energy harvester and power management circuit*

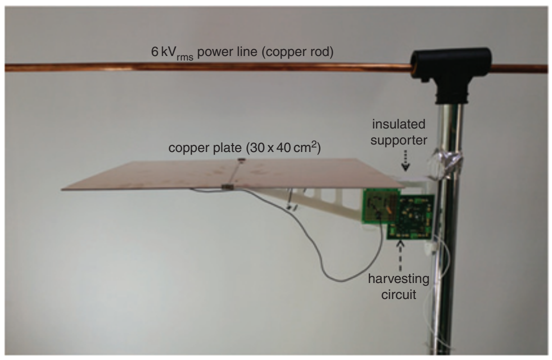

Fig. 4 *Photo of experimental setup*

Fig. 2*a* shows the output pulse train with a period of 1.7 s when 47 nF of storage capacitor is used and the line voltage is 220 V_{rms}. It is found that, with one turn of wire around the power line, 1.15 µJ is harvested in one period and 680 nW is harvested in average. Circuit analysis shows that the charging current is limited by the impedance of C_{WH} which is the capacitance between sensing wire and hot line. Based on measured value in our previous work [2], C_{WH} is in the order of fF in this case and the impedance is a few G Ω at 60 Hz. Therefore the charging current is in the order of nA. Since this small charging current is proportional to the line voltage and the voltage change in the storage capacitor is only 1.2 V in one period, it is expected that the charging period is inversely proportional to the line voltage. Fig. 2*b* shows that the repetition rate of the output pulse is a linear function of the line voltage in wide voltage range as expected, which implies that we can estimate the ac voltage in every a few seconds by measuring the period of the output pulse train without removing insulation.

Two points should be noted for this experiment where extremely low power (~nW) is harvested. The first is that since the charging current with one turn of sensing wire is of the same order as leakage current of general purpose diodes, ultra low leakage diode such as PAD1 should be used, and otherwise, it is difficult to charge the storage capacitance to high enough voltage to turn on the MEMS switch [4]. The second is that, since the harvested power is of the order of nW, MEMS switch should be used as an autonomous switch since its leakage current is almost zero, has hysteretic characteristics and therefore it does not require any other power supply, reference voltage and pulse forming circuit for operation. However, unfortunately, the MEMS switch used in this experiment is not available anymore [5]. If reliable low price MEMS switch of low operation voltage is developed, it will make advances in the areas of sensor and energy harvesting.

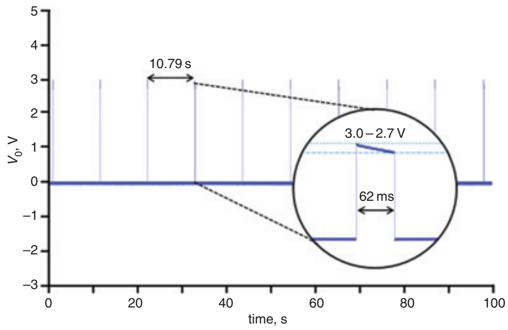

Fig. 5 *Output voltage wave form across load resistance (10 kΩ) when distance between harvesting plane and power line (6 kV) is 15 cm*

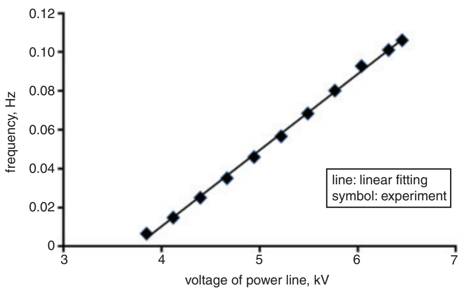

Fig. 6 *Frequency of pulse train against line voltage*

Voltage measurement of high-voltage power transmission line: The second experiment demonstrates that voltage of a high-voltage overhead transmission line can be also measured using the proposed method without direct contact to the dangerous high-voltage conductor. When the voltage of the power line is of the order of kV, the charging current or harvested power becomes high enough to operate low-power consumption electronic devices. Therefore, in the second experiment, a cost effective intelligent integrated boost converter chip (TI's bq25505) designed for energy harvesting is adopted to build multifunctional power management circuit without external power supply.

In Fig. 3, when a copper plate is placed between power line and earth ground, two series-connected capacitors (C_{lp}: between line and plate, C_{pg}: plate and ground) compose a capacitive divider. The electric field energy is initially stored in 4.7 µF C_{IN} and C_{STOR} is charged to the boosted voltage by the boost converter chip with the help of boost inductor L_{IN}. Output load resister R_L and FET are connected to C_{STOR}, then the schematic circuit diagram becomes as shown in Fig. 3. To replicate the real situation where the harvesting plate is to be attached to the power transmission tower, 30×40 cm^2 copper plate is fixed to the grounded metallic pole as shown in Fig. 4 in lab experiment. For the safety, 3–6 kV$_{rms}$ is applied to a copper rod of 10 mm diameter as a power line, and the height of the copper rod is set to 1.5 m.

The circuit works as follows: During energy harvesting stage, the chip keeps V_{BAT_OK} be low, therefore FET turns off and output voltage across R_L is zero. When the voltage of C_{STOR} increases to V_{ON} (3 V), the V_{BAT_OK} toggles to high, then FET turns on, and C_{STOR} discharges through the load resistor R_L, consequently output voltage across R_L appears. When the voltage of C_{STOR} decreases to V_{OFF} (2.7 V) due to discharge, the V_{BAT_OK} toggles to low, then FET turns off. Voltage across R_L returns to zero and energy accumulation in C_{STOR} resumes. V_{ON} and V_{OFF} are set using external resistors (not shown). Fig. 5 shows the output voltage wave form across 10 kΩ load resistor when the line voltage is 6 kV$_{rms}$. During the energy harvesting stage, since the load resistor is isolated from the chip, charging time of C_{STOR} is inversely proportional to the line voltage only and experimental results are shown in Fig. 6. As in the first demonstration, pulse repetition rate is a linear function of the line voltage, which means the voltage of dangerous high-voltage power line can be measured without any contact to the conductor.

Conclusion: For the first time as far as we know, without removing the insulation of single-phase 3-wire 220 V$_{rms}$ household power line, the line voltage is measured based on stray electric field energy harvesting. The line voltage of high-voltage overhead power transmission line is also measured without direct contact with conductor of the power line using presented technique. Experimental results show that the frequency of output pulse train is a linear function of line voltage. It is believed that the presented non-intrusive ac voltage measurement technique can be widely applied to Smart Grid system. In addition, we believe that the presented technique opens new application area of MEMS switch and intelligent energy harvesting chip as an ultra low-power autonomous switch and harvesting of extremely low electric field energy.

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One or more of the Figures in this Letter are available in colour online.

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