Design and Analysis of Non-Invasive Capacitive Coupling Voltage Sensor

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Abstract: This paper present a study on an alternative way of measuring voltage waveform without contacting to conductive part. By employing the proposed voltage electrode based on parasitic capacitance, an non-invasive voltage measurement system was realized. The system provide consistent voltage waveform that can be used to calculate power parameters. Currently, an auto calibration process development in underway to improve system performance and measurement accuracy.

Keywords: non-invasive, voltage sensor, voltage measurement, auto calibration

1. Introduction

Electric energy is very important nowadays in the daily life of every human being. In the recent years, the demand for electricity has been increased despite energy resources are limited, and tend to run out in the future. Therefore, understanding the behavior of consuming electricity and determine the cause of wasteful use will help conserve the limited resource. These reasons increase the necessity of electricity use awareness. Thus, we contribute to this issue by adding a more convenient way for acquiring the information of electricity consumption by using non-invasive measurement fashion. In this work, we proposed a development of capacitive voltage sensor for non-intrusive energy meter. We exploited a technique to calibrate voltage without intruding the cable. The voltage waveform is measured by using noninvasive voltage sensor, which exploited capacitive coupling technique.

This paper is organized as follows: section 2 presents the design technique, section 3 shows the experiment and results, and section 4 ongoing development the paper.

2. Design of non-intrusive voltage sensor

The knowledge of the voltage waveform is essential for calculating active power (W) and apparent power (VA) and power parameters such as power factor (PF). This requires precise voltage measurement in order to obtain correct voltage information. Conventional voltage measurement techniques in an AC power line require electrical connection to the conductive wire inside the power cord. In contrast to conventional methods, we propose a contactless voltage probe consist of a small and thin copper film placed around the insulating sheath of the cable by using capacitive coupling between the internal conductive element of the wire and the external body as shown in Fig. 1.

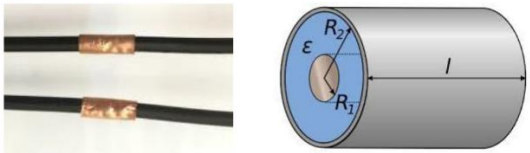

Fig. 1. Capacitive coupling sensor

We can obtain a cylindrical capacitor situated between the inner side of the copper plate of radius R2 and the surface of the conductive wire of the cable for radius R1. The insulating of the cable, with permittivity ε, separates these radii. We can calculate the capacitance between the two conductors of such structure given by the formula:

$$C_{sensor} = \frac{2\pi\varepsilon l}{\ln\frac{R_2}{R_1}} \quad (1)$$

The problem statement consists of equations, which permits to calculate two unknown variables: C_{sensor} and V_{in}. These two equations are given by the transfer functions of two identical filters we chose to realize the analog processing front end. The filter is illustrated in Fig. 2.

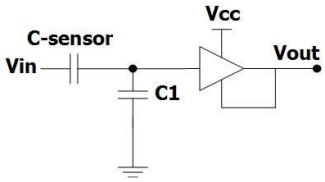

Fig. 2. The filter used to implement the mathematical

The filter simply is a voltage divider for AC signal made of two capacitors: the capacitor C_{sensor} and a precision capacitance C_1. The output relationship of this filter is:

$$V_{out} = \frac{C_{sensor}}{C_{sensor}+C_1} V_{in} \quad (2)$$

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Where C_{sensor} is capacitive coupling and C_1 is precision capacitor. In addition, an analog front-end converting signal from both filters (voltage divider) through an input of ADC by using differential amplifier as shown in Fig. 4.

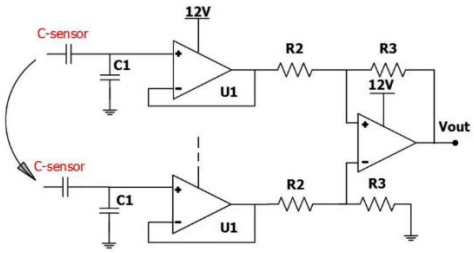

Fig. 3. The Analog front-end circuit

Once the value of C_{sensor} is known, the calculation of V_{in} can be performed by using eq.3. To appropriately measures AC voltage from a power line, C_{sensor} and C_1 should be chosen to result in a ratio that defines V_{out} in the range of operating voltage of the analog front-end circuit. Fig. 3. The Analog front-end circuit.

$$V_{in} = \left(1+\frac{C_1}{C_{sensor}}\right) V_{outCC} \qquad (3)$$

3. Result

3.1 Experimental setup

A pair of copper sheets of dimension (l=1.25cm-length) wrapped around both side of Line and Neutral standard TI 11-2531 cables. However, as stated earlier, C_{sensor} of the filters are still unknown and need to be identified. In this work, as for preliminary study, we used direct measurement of the capacitance value of C_{sensor} by using LCR HITESTER HIOKI 3531 with the set-up illustrated in Fig. 5. With this measurement, the capacitance value C_{sensor} is identified as 13pF for both sensors. This also defines the value of C_1, which was chosen as 470pF by regarding the value of the two capacitors. Differential Amplifier ratio is 0.02

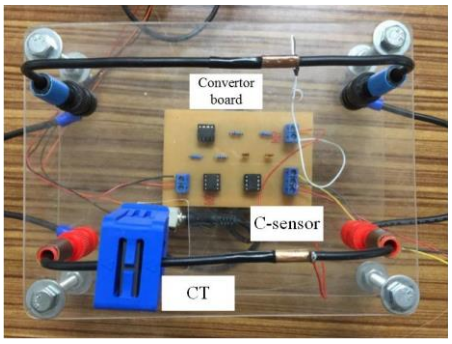

Fig 4. Experiment setup

3.2 Experiment results

Figure 5 illustrate measured V_{out} from the experimental set-up. The results shown that V_{out} = 864mV_{p-p}, by using backward calculation, we can calculate the value of V_{outCC} = 8.64V_p (voltage follower). At the same voltage, we got the value of capacitor sensor 13pF. Finally, we can calculate V_{in} approximately 226.987Vrms.

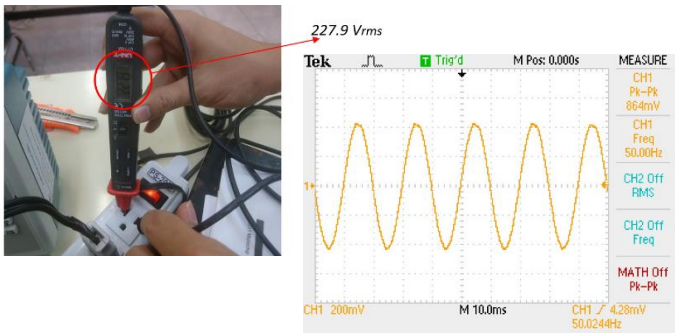

Fig 5. Result of voltage while testing compare with the reality

4. Ongoing development

Since the accuracy of the measured voltage strongly depends on the actual capacitance of the parasitic capacitor at electrodes. However, the capacitance may vary from several factors such as type of insulator material, installation practice. More importantly, in operation, temperature and humidity cause significant drift in capacitance value. For this reason, a calibration process will be required to perform frequently. To tackle this issue, we propose an auto calibration process by employing an additional electrode connected to a high frequency reference signal generator. By this topology, as shown in Fig.6, the signal generator is simply coupled by two cascade C_{sensor} capacitors. A high-pass filter is connected at the output of the electrode buffer to provide measured reference signal without power line interference. The voltage at the filter output is attenuated by the value of the C_{sensor}. This relation will be used to calculate actual C_{sensor} value at operation time.

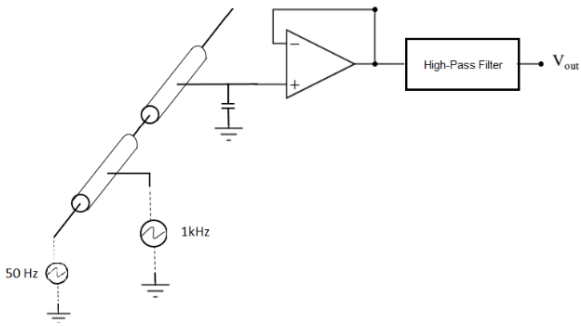

Fig 6. Proposed auto-calibration topology

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