Development of a contactless voltmeter based on capacitive coupling

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Abstract. The aim of this study was to develop a voltmeter using the capacitive coupling technique for voltage measurements. The proposed voltmeter design offers a simple and cost-effective alternative to traditional voltage measurement methods. By using capacitive coupling, the need for direct electrical contact between the measuring circuit and the voltage source is eliminated, allowing for non-invasive voltage measurements. The development process involved the design and construction of a capacitive coupling circuit, which enabled the transfer of the voltage signal to a measurement circuit. The measurement circuit included signal conditioning components and an analog-to-digital converter for accurate voltage readings. The system has been calibrated and tested using a known voltage source to ensure reliable and accurate measurements. The experimental results show that the voltmeter obtained satisfactory performance for the usual voltage of 127 V AC and a maximum distance of 0.2 m from the point of interest, maintaining a low level of interference from external electrical noises. The proposed voltmeter design has potential for several applications, especially in scenarios where direct electrical contact with the voltage source is undesirable or impractical. It offers a reliable and efficient solution for voltage measurements, being suitable for both industrial and research purposes.

1. Introduction

The use of voltmeters by the electrical industry and the service sector is extremely relevant. The purpose is to measure the difference in electrical potential between two points to ensure the correct functioning of the equipment and the safety of users and operators.

In general, for these measurements to be made, the voltmeter needs to be placed in contact with the energized points between which the potential difference is desired, which characterizes an intrusive method of quantifying the value of said quantity and which can sometimes become extremely complicated, expensive and dangerous.

A conventional analog voltmeter consists of a galvanometer (electric current meter) associated in series with a high resistance (typically 10 MΩ) and two probes that are inserted in parallel with the circuit. The electric current circulating through the instrument causes the moving coil of the galvanometer to deflect the pointer on a graduated scale, indicating the measured voltage value [1].

In a common industrial scenario, different voltage levels are used in different equipment. Typically, one has the voltage levels of 127 V, 220 V, 380 V, 440 V and 760 V, all in alternating current (AC). Although these values are considered as low voltage [2], the risk of opening an electric arc is very large, especially from 380 V. This implies a complicated operation of data collection with low safety, reflecting negatively on production and exposing operators to the possibility of accidents.

Measuring electrical voltage in a non-invasive way is possible and can minimize such problems. Using capacitive coupling techniques it is possible to measure the voltage levels of an alternating voltage electrical network without the need to strip or even touch the conductors [3].

The Regulatory Standard 10 – NR10 is a Brazilian regulation that establishes the guidelines and minimum requirements of safety and health at work in electrical installations [2]. The electrical hazards mentioned in this standard refer to hazards associated with the use of and exposure to electricity, among which are: electric shock, electric arc, fires, and explosions. The zones where risks related to electricity may occur are defined by this standard as risk zone, controlled zone and free zone, having their radii delimited directly by the voltage value involved.

The risk zone is defined as the "surroundings of an energized part, not segregated, accessible even accidentally, whose approximation is allowed only to authorized professionals with the adoption of appropriate techniques and instruments at work" [2]. This work took into account voltage values ranging from 50 V AC to 1000 V AC, which delimits the radius of the risk zone at 0.2 m from the point of interest [2]. Thus, the measurements performed with the contactless voltmeter ranged from 20 cm down to 1 cm between the probe and the energized part.

The contactless voltmeter herein described has two main functions: (i) detecting that a part of interest is energized by alternating current with 60 Hz; and (ii) identifying the voltage level among the possible values commonly used in residential and industrial installations. It is worth noting that a system with three 127 V phases would have 220 V between any two phases, and that a wrong installation could yield 220 V in a point that should have 127 V, so it is important to identify the voltage level among the discrete possible values. In this work we used only 127 V AC as input, due to power availability at the laboratory, so the main goal is to identify the presence of such a voltage level at the point of interest.

This work is divided into five sections, including this introduction. In the next section fundamental concepts are presented, such as the principle of measuring the voltmeter by approximation based on capacitive coupling, as well as the nature of capacitance and the concept of capacitive coupling, highlighting its application in the transfer of signals and energy between circuits. It also addresses considerations about the nonlinear frequency response of capacitive coupling and the importance of selecting suitable capacitors and designing circuits carefully to minimize distortions.

Section 3 presents the details of the capacitive voltmeter design. The concept of measurement is described, which involves the formation of a capacitor between the energized point of interest and the voltmeter. Information is provided on the components used, such as the aluminum flat plate and the high-value resistor, which make up the voltmeter. Also presented is the electronic circuit, including an instrumentation amplifier and an active tuned filter, which amplify the input signal and reduce unwanted interference.

Next, section 4 presents the results obtained with the voltmeter by capacitive approximation in different situations. The variations in the dimensions of the test plates and how this affects the range of measurement values are mentioned, in addition to the plots that demonstrate the consistency of the results and the possible applications of the voltmeter, as well as possible errors associated with the measurements.

Finally, the conclusions highlight the relevance and effectiveness of the voltmeter by capacitive coupling-based approach as a non-invasive solution to detect and measure electrical voltage. The main benefits of this device are summarized, such as simplifying the maneuvers required for data collection, ensuring the safety of operators and reducing costs. Possible areas for future improvements and developments related to the capacitive voltmeter are also identified.

2. Background

The contactless voltmeter presented in this work is based on capacitive coupling, exploiting the electrical characteristic called capacitance [4]. Capacitance, in general terms, is the measure of the ability to store electrical charge of an object or system. It is defined as the ratio of the stored electric charge (q) to the applied electric potential difference (voltage) (V), i.e.,

$$C = \frac{q}{V} \tag{1}$$

The unit of measurement of capacitance in the International System of Units (SI) is the farad (F) [5]. The most common example of a device that exhibits capacitance is the capacitor, which is composed of two conductive plates separated by an insulating material, called a dielectric [6,7]. When an electric potential difference is applied to the capacitor, electric charge accumulates on each of the plates, generating an electric field between them. The magnitude of the capacitance of the capacitor depends on the area (A) and separation of the plates (d), as well as the insulating material [6,7], characterized by its dielectric constant ε_0, as expressed by

$$C = \varepsilon_0 \frac{A}{d}\,. \tag{2}$$

Capacitive coupling is a mode of electrical connection in which the transfer of signal or energy between two circuits occurs through a capacitive structure [4]. It is widely applied in electronic circuits to transfer signals from one point to another without the need for a physical connection between them [6]. In capacitive coupling, one of the capacitor plates is placed at the output of one circuit and the other plate at the input of another circuit. Thus, when a signal is applied to the output of the first circuit, it charges the capacitor, which then transfers that charge to the input of the receiving circuit. In this way, the signal is transmitted without the need for a cable or any other type of connector between the two circuits.

It is worth mentioning that capacitive coupling can introduce distortions in the signal due to its nonlinear frequency response, which can affect the quality of the transmitted signal. For this reason, it is important to select a suitable capacitive structure for the application and to design the circuit carefully to minimize these distortions.

Another restriction refers to the need for the signal to be transmitted to be variant in time, because the electric current is proportional to the derivative of the voltage applied to the capacitor [6][7], with the capacitance being is the constant of proportionality, that is,

$$I = C\frac{dV}{dt}\,. \tag{3}$$

3. Capacitive voltmeter design

3.1. Measurement concept

In order to effectively measure an electric potential difference by capacitive coupling, a capacitor must be formed by the energized point of interest and the voltmeter sensor. Thus, the probe (sensor) of the voltmeter is basically made up of a flat square plate of aluminum. This board is connected in series with a high-value R_p resistor, typically 100 kΩ with 1 % tolerance, which will complete the sensing part of the voltmeter, as shown in figure 1. In this way, the resistor acts as a shunt and provides a voltage measurement point that allows to estimate, indirectly, the input voltage.

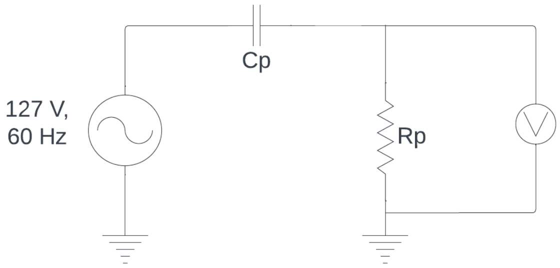

Figure 1. Basic Measurement Circuit

In figure 1, the sinusoidal source represents a V_0 power phase of alternating voltage with $f = 60$ Hz, in the example with 127 V of root mean square (RMS) value. In this work, the energized point of interest was represented also by a flat square aluminium plate, as shown in figure 2 for the case with 5 cm dimension.

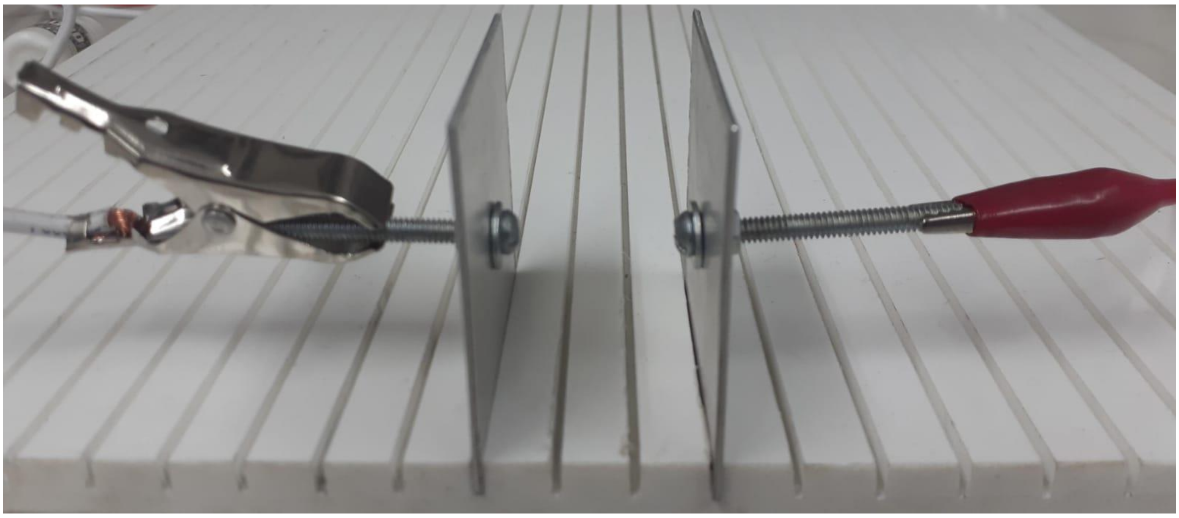

Figure 2. Flat square 5 cm cx 5 cm aluminum plates that represent, respectively, the energized point of interest (left plate) and the contactless voltmeter probe (right plate).

The capacitor C_p in figure 1 jointly represents the energized point (left plate) and the probe of the contactless voltmeter (right plate).

The value of voltage V_p on the resistor, measured by the voltmeter V, is given by

$$V_p = \frac{R_p}{R_p + X_C} \cdot V_o \quad . \tag{4}$$

where X_c is the capacitive reactance, given by

$$X_C = \frac{1}{2\pi f C}. \tag{5}$$

The value of capacitance C was measured with the aid of a capacimeter, being in the range from 26.29 pF to 22.29 pF for the typical operating distances ranging from 0.01 m to 0.20 m. This results in typical capacitive reactance values in the range of 100 MΩ to 119 MΩ, subsequently generates currents on the order of microamperes. Therefore, when using a resistor, R_p, of 100 kΩ, potential differences within the range of hundreds of millivolts are obtained, allowing for adequate measurement.

3.2. Electronic circuit

Figure 3 shows the schematic diagram of the complete electronic circuit of the contactless capacitive voltmeter.

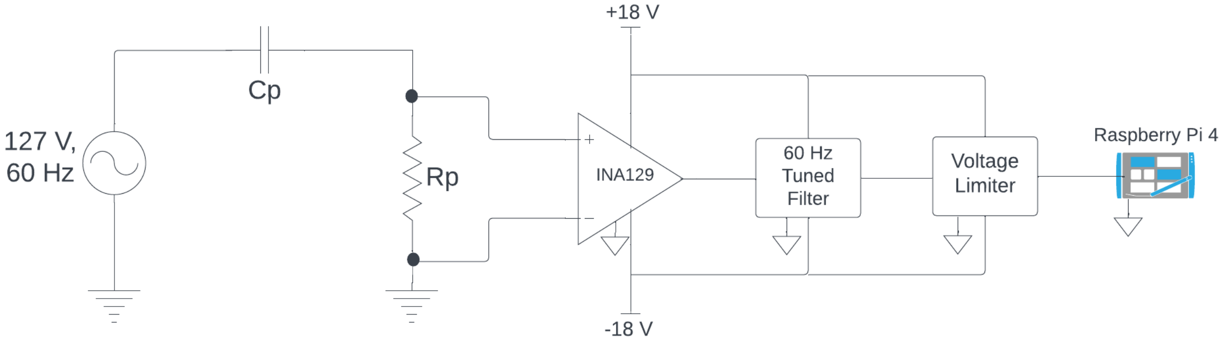

Figure 3.- Complete Measuring Circuit

The first stage is based on an instrumentation amplifier suitable for low amplitude differential signals, model INA129 from Texas Instruments, with voltage gain of 5 V/V and operating in the frequency range of 0.1 Hz to 10 kHz [8].

The signal obtained, despite a good amplitude for measurement, suffers from interference from other frequency bands of the external environment that directly affects data collection. As the usual alternating voltages have known frequencies, this problem was solved with the application of a bandpass resistive-capacitive filter. This filter allows a specific range of frequencies to pass through the circuit, in this case ranging from 55 Hz to 65 Hz while frequencies outside that range, including eventual harmonis, are blocked [9]. This filter also applies a gain of 4 V/V, yielding a total gain of 20 V/V. Thus, the input signal, which typically ranges from 354 mV to 401 mV, is amplified to values ranging from 0.5 V to 1.5 V depending on the distance between the sensing board and the point of interest.

To avoid overlaps and interference, all the electronics of the voltmeter are powered by independent source with values from -18 V direct current (DC) to +18 V DC and a distinct ground in relation to the neutral conductor of the AC network. Thus, at the output of the frequency filter, the signal will always be less than +18 V DC.

The last block of the circuit is a voltage attenuator based on an operational amplifier inverter topology, with an attenuation of 3.6 V/V, ensuring that the Raspberry-Pi 4 never receives input signals greater than 5 V, thus avoiding damaging its analog/digital (A/D) converter.

Finally, the signal is measured by a Raspberry Pi microcontroller, to which an ADS1115 [10] A/D converter has been connected, with 15 bits of resolution and 860 Hz of acquisition frequency, which is responsible by the acquisition of 0.25 s voltage windows and for the calculation of the RMS value of this sinusoidal signal, which is related to the input voltage to be measured.

4. Results

The voltmeter showed similar behaviour in four different situations: with test plates of 0.30 m by 0.30 m; 0.20 m by 0.20 m; 0.10 m by 0.10 m; and 0.05 m by 0.05 m. As a result, one obtains a range of values that is, according to equation 4, proportional to the voltage value at the point of interest. The consistency of the results can be seen in the figures 4 to 7.

Also, in order to verify the stability of the voltage input, figure 8 shows the RMS values of the input voltage measured by a commercial voltmeter (Fluke, model 87V) simultaneously with the measurements performed by the contactless voltmeter herein presented. The series of values have an average value of 129.00 V and a standard deviation of 0.48 V (0.37 %), thus characterizing an excellent stability during the tests.

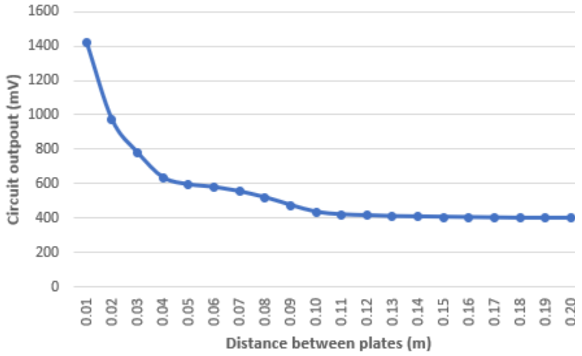

Figure 4. Plates 0.3 m x 0.3 m.

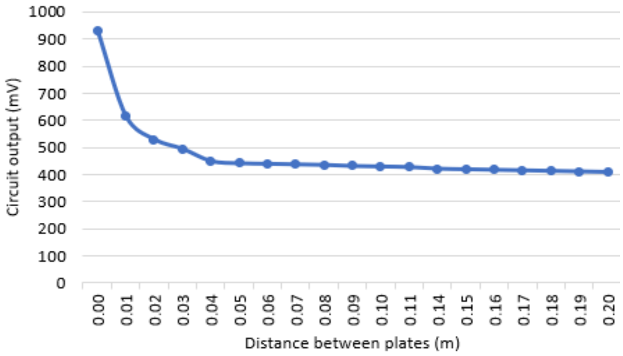

Figure 5. Plates 0.2 m x 0.2 m

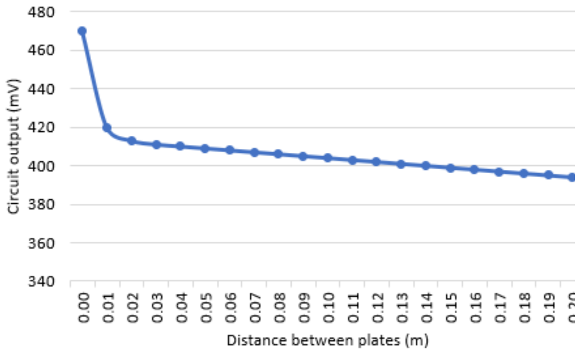

Figure 6. Plates 0.1 m x 0.1 m

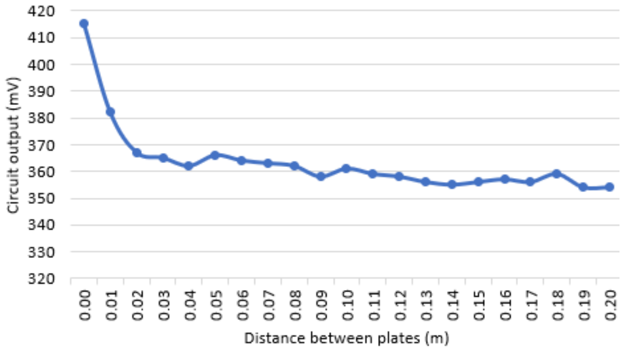

Figure 7. Plates 0.05 m x 0.05 m

As can be seen in the graphs, within the radius of the risk zone established by NR-10, the voltmeter has a stable behaviour with all probes tested, rapidly increasing once within the risk zone (< 0.2 m), and thus allowing a fast and reliable detection of an energized point that could pose a risk to the operator.

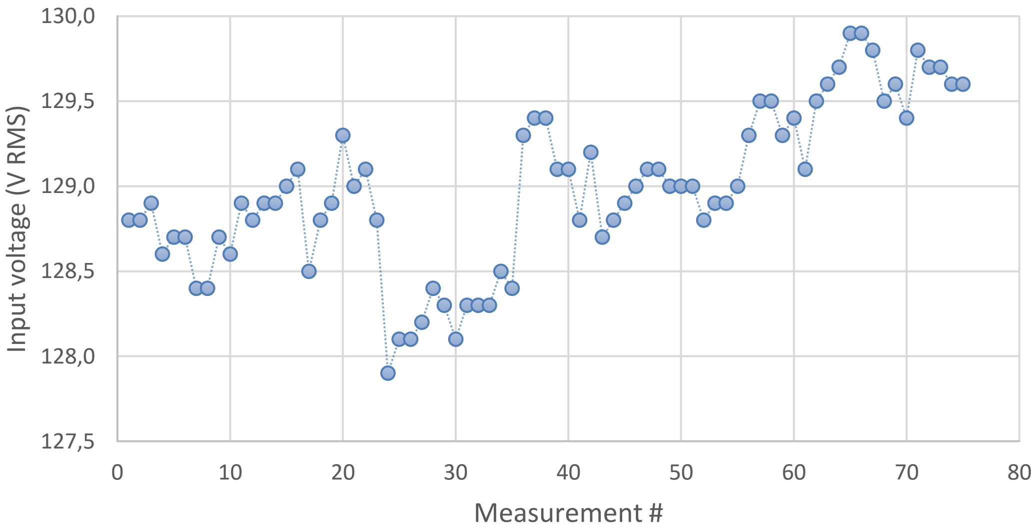

Figure 8. Input voltages measured by a conventional voltmeter simultaneously with each measurement performed by the contactless voltmeter.

5. Conclusions

The contactless voltmeter, which first prototype was herein presented, offers a viable and safe solution for the measurement of alternating electrical voltage at industrial frequencies. The device eliminates the need for direct contact with the voltage source, which is especially relevant in high-risk situations or in hard-to-reach locations. The voltmeter is composed of a capacitive coupling circuit and a measuring circuit with adequate amplification and filtering. The test results show a satisfactory performance for usual voltage of 127 V AC and maximum measuring distance of 0.2 m, with low interference from external electrical noises. This non-invasive approach can simplify data collection operations, ensure operator safety, and reduce costs. The project has potential for various industrial and research applications, opening possibilities for future improvements and developments, however tests are needed for other levels of alternating voltages of usual values and frequencies, as well as increasing the distance between the test plate and the point of interest.

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