An Accurate Nonintrusive Type AC Voltage Measurement System

Anwar Ulla Khan[1,*], Mashhood Hasan[1],
Mohammad Ehtisham Khan[2], Wahid Ali[2],
Waleed Alhazmi[3] and Waleed Zakri[3]

[1]*Department of Electrical Engineering Technology, CAIT, Jazan University, Jazan, Saudi Arabia*
[2]*Department of Chemical Engineering Technology, CAIT, Jazan University, Jazan, Saudi Arabia*
[3]*Department of Mechanical Engineering, Jazan University, Jazan, Saudi Arabia*
E-mail: anwarkhan@jazanu.edu.sa; anwar.ullak@gmail.com
[*]*Corresponding Author*

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Abstract

In this work, a completely non-intrusive type alternating current (a.c) voltage measurement system based on the novel capacitively coupled technique is proposed. In literature, most of the reported capacitive coupling technique require a direct contact of sensor to the ground potential of power system. Human operator, whose body is in contact with the ground must touch the capacitive sensor to provide the power system ground. The reliability of those types of approach is limited, as the human operator must be in direct contact to a conductive part of the sensor. Also, there is the effect of nature of impedance exist between the body of the human operator and the ground, which is not taken care by most of the existing methods. In this work, a

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new method regardless of the variations in the impedance exist between the measurement unit and the ground potential through the earth, is proposed. Simulation analysis has been conducted in detail to validate the proposed approach. A prototype measurement system has been developed and then tested for a line voltage (200 to 250 V), at 60 Hz. The capacitance output w.r.t applied voltage was linear and the worst-case non-linearity error was recorded as -0.42%. Sensitivity of the sensor is low, which is taken care by the high resolution (24-bit), high linearity ($\pm 0.01\%$), and highly accurate (± 10 fF) capacitance to digital convertor (AD7747).

Keywords: Capacitive sensor, non-intrusive voltage measurement, capacitance-to digital convertor, power system.

1 Introduction

In the modern electric power system, sometimes it is important to continuously monitor the line voltage in nonintrusive manner at different nodes. It aids to predict/ locate the fault and improve the performance of the power system. The development in the sector of power system utility, affordable as well as reliable nonintrusive sensors for the continuous monitoring of current/voltage are in great demands [1]. Application involves the condition monitoring of high-voltage transmission lines [2, 3], smart metering [4], electrical machines state monitoring [5], load monitoring of appliance at industries and smart home [6–9], etc. For non-invasive detection of d.c or a.c current, various methods are available, such as current transformer [11], Hall effect current sensor [10]. But for non-invasive a.c voltage measurement, limited schemes are available such as capacitive type sensors for transmission line voltage monitoring [12–14]. However, the reported methods are only appropriate at defined locations specially designed for measurement purpose and for high voltage measurement. Also, such types of schemes are inaccurate due to coupling capacitance (between the cable conductor and the sensor) variation. In [15], a nonintrusive a.c voltage has been measured by using another known a.c voltage, and to improve the linearity and accuracy (with the help of fast Fourier transform (FFT) and appropriate calibration schemes) additional work has been done in [16]. To fulfil the requirement of expensive ADC, complex computation and dedicated processor (for FFT), an inexpensive digitizer (work on dual slope technique) was presented in [17]. The measurement system proposed in [18] detect the root mean square value of line voltage at the fundamental frequency, but a significant error was noted due to the presence of harmonic in line voltage. This paper presents a simple measurement technique, with the help of that true-rms value of unknown a.c voltage can be measured accurately. The output is insensitive to the parasitic capacitances of the presented sensor. Also, the proposed scheme does not require any ground potential which is required in most of the reported capacitive coupling techniques [19]. The organization of the proposed work are as follows. Operating principle of measurement system are presented in Section 2. To prove the concept of proposed work, a simulation study has been explained in Section 3. Section 4 provides the details of fabricated sensor. Section 5 gives the details of an experimental setup, developed to test the fabricated sensor, and provide the important results.

2 Operating Principle of the Proposed Scheme

The working principle of the proposed nonintrusive type voltage detection system is based on the measurement of cylindrical capacitance between the two concentric ring-shaped electrodes by using a capacitance to digital convertor (CDC). Figure 1 shows a schematic diagram of the proposed non-intrusive type voltage detection scheme. The proposed system consists of a capacitive sensor and the suitable measurement circuit. The capacitive sensor consists of two concentric ring-shaped copper electrodes *A* (inner) and *B* (outer). The two electrodes are insulated from each other by a thin dielectric and were firmly fixed on the surface of insulated cable. A complete view of the capacitive sensor and insulated cable can be seen in Figure 1. In the proposed capacitive sensor arrangement, the two important capacitances C_A and C_B are formed. Capacitance C_A is formed between the electrode *A* and the cable conductor whereas capacitance C_B exists between electrode *A* and *B*. Most of the existing noncontact voltage sensors is based on the measurement of capacitance (C_A) between the electrode *A* and cable conductor [19]. In those cases, electrode *A* will act as primary electrode of the capacitance and for second electrode, a power system ground is required in order to measure the capacitance C_A. To provide the power system ground, body of the operator, must be in contact with the ground, which is less reliable method due to the unbalanced nature of the impedance between the operator and the ground. The proposed work is based on the measurement of capacitance (C_B) between the inner electrode *A* and outer electrode *B*, shown in Figure 1. This scheme does not require power system ground and will give reliable and accurate results.

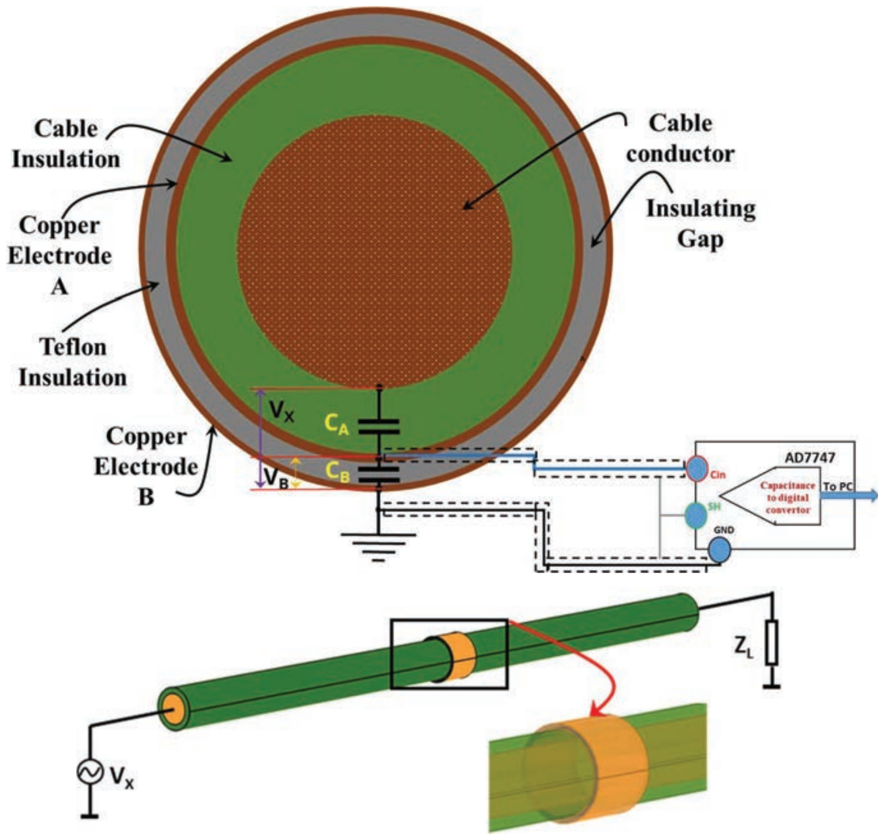


Figure 1 Schematic diagram of the proposed voltage measurement scheme.

To test the proposed system, consider a voltage $v_X(t) = \sqrt{2}V_X \sin \omega_X(t)$ is applied to an insulated cable, where V_X is the root mean square value of unknown voltage and ω_X is the known angular frequency (in rad/s). When the conductor (insulated cable) voltage V_X changes, electric field inside the cable insulation and at the surface of the insulation will change due to which capacitances C_A and C_B (see Figure 1) will also change [20].

Hence, by measuring C_B, one can measure the conductor voltage V_X by a nonintrusive manner.

The value of the capacitance C_B of the proposed capacitive sensor at various voltage levels was measured with the help of AD 7757 CDC procured by Analog devices [21]. This board was found suitable to accurately measure the capacitance C_B with a very high resolution.

3 Simulation Analysis

In order to analyse the working and to understand the functionality of the proposed measurement system, a simulation study has been conducted using the COMSOL Multiphysics software. The geometry of the system (conducting cable, concentric electrodes) has been simulated in accordance to the dimensions given in Section 4. Outer conducting electrode are connected to ground potential and a 3.2 V is given to inner electrode.

If the cable voltage is changed, electric field between the conductors will also change (see Figure 2), which results change in capacitance C_B. To see the effect of cable voltage on electric field distribution between the conductors, three different voltages (200 V, 225 V and 250 V) are given to the cable and a 3.2 V is connected to electrode *A* in COMSOL Multiphysics software. Simulated result in Figure 2 shows that, electric field distribution has been changed due to the change in cable voltage, results in change of capacitance C_B.

Hence, one can say that, there is relationship between cable voltage and capacitance C_B. To see the relationship between cable voltage and capacitance C_B, cable voltage was varied from 200 V to 250 V in the steps of 5 V (60-Hz pure sine wave) and noting down the value of capacitance C_B.

The results show a linear relationship between cable voltage and capacitance C_B as depicted in Figure 3.

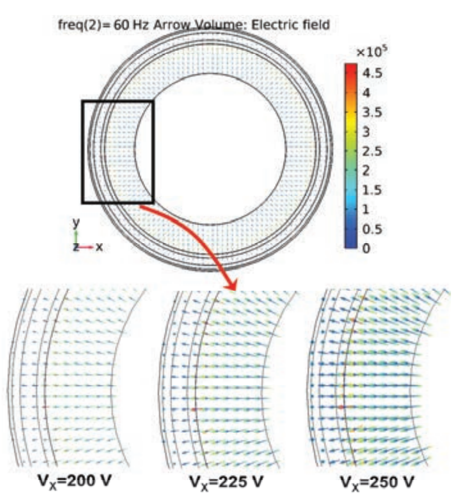


Figure 2 Effect of cable voltage on electric field distribution inside and at the surface of the cable insulation.

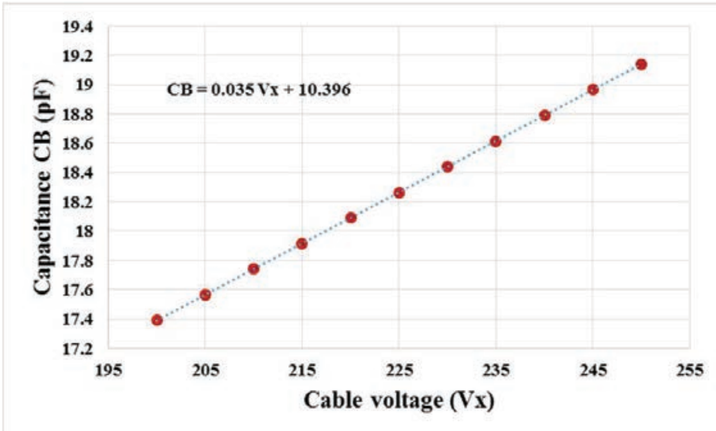


Figure 3 Measured value of the capacitance using the simulation w.r.t to applied voltage.

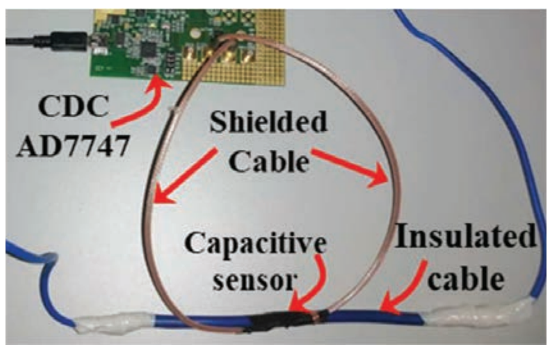


Figure 4 Fabricated sensor.

4 Fabrication of the Proposed Sensor

The proposed capacitive sensor for the nonintrusive a.c voltage measurement was realized by a copper tape (0.1 mm thick) which permits an easy and cheap fabrication of the complete sensor unit. One copper electrode (length = 3 mm, thickness = 100 μm, Outer diameter = 5.94 mm) were firmly fixed on a 11.88 mm diameter insulated cable of 0.6 mm thick insulation and 97.7 mm long as shown in Figure 4. An insulated Teflon tape of 100 μm thickness was then placed on the first electrode. Another outer copper electrode (100 μm thick) served the purpose of a ground electrode were firmly fixed on the Teflon insulation. The schematic diagram of the sensor is given in Figure 1, and Figure 4 shows the photograph of the sensor.

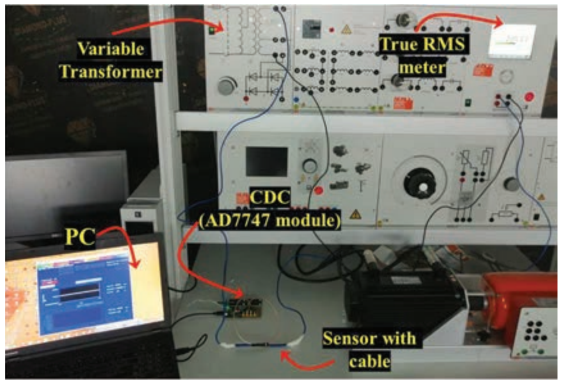


Figure 5 The photograph of the implemented experimental setup.

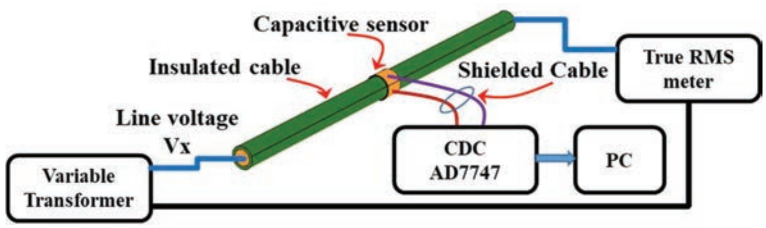


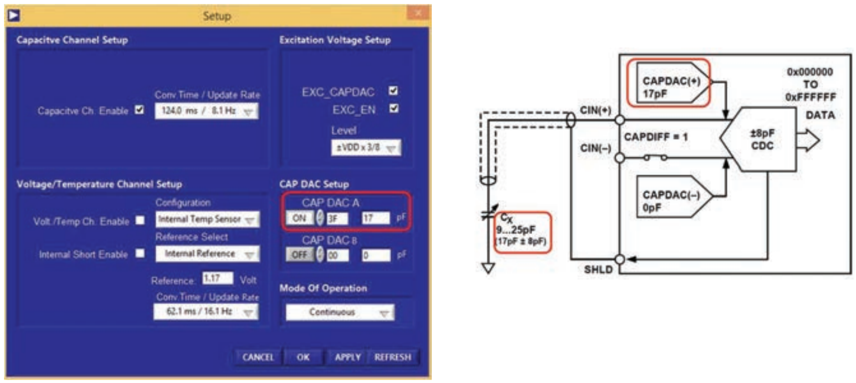
Figure 6 Block diagram of the test setup.

5 Experimental Setup and Results

Figure 5 depicts the photograph of the experimental setup used to test the proposed measurement system. The proposed setup has been tested for a line voltage (Vx) range of 200 to 250 V, at 60 Hz. The test signal Vx was obtained and measured from a highly accurate variable isolating transformer and power multimeter from Lucas-Nuelle [22].

The voltage Vx from the Variable transformer was supplied to an insulated cable (see Figure 1). A block diagram representation of the experimental set-up is shown in Figure 6.

At different voltage levels, the capacitance (C_B) of the fabricated sensor was measured with the help of AD 7747 evaluation board [21]. AD7747 is a high resolution, 24 bit sigma delta capacitance to digital converter from Analog devices. It is specially designed for grounded capacitive sensors (sensors with one plate connected to ground). The board can measure the capacitance in the range of ±8 pF (changing), and it can extend up to 17 pF (fixed), which can be tuned by a programmable on-chip digital-to-capacitance



(a) (b)

Figure 7 CAPDAC setup for programmable shifting of the input range.

converter (CAPDAC). Resolution and accuracy of the board 20 aF and 10 fF respectively. The update rate was configured to 8.1 Hz. This board was found highly suitable to interface the fabricated capacitive sensor.

In this work, CAPDAC has been configured to shift the input range (to provide offset capacitance). Figure 7(a), depicts the picture of the setup to configure the CAPDAC to 17 pF. The block diagram in Figure 7(b) shows how to provide offset capacitance and shift the capacitance input range, up to 25 pF absolute value of capacitance connected to the CIN (+).

The capacitive sensor consists of two concentric ring-shaped copper electrodes, *A* (inner) and *B* (outer). The sensor electrodes A was connected to the input capacitance terminals Cin terminal of the AD7747 board, whereas the terminals *B* was kept at ground potential as shown in Figure 1. The terminals of the sensor were connected to board by using a high quality shielded cable (RG316) of length ≈5 cm via SMB connectors to minimize the effect of parasitic capacitances.

When a line voltage was change, the capacitance corresponding to voltage was also changed and were acquired continuously by AD7747 CDC and provide real time data on PC with 8.1 Hz update rate as shown in Figure 8. Figure 9 shows the variation of the sensor capacitance (C_B) when the voltage was varied from 200 to 250 V. It is clearly shown in the Figure 9 that the capacitance (C_B) linearly increases with increase in the line voltage. The maximum nonlinearity error noted was −0.42%.

By using AD7747 evaluation software, three types of data (Hex code, capacitance value and user defined value) can be acquired as shown in Figure 8. Here, line voltage is the user defined value. Also, acquired capacitance

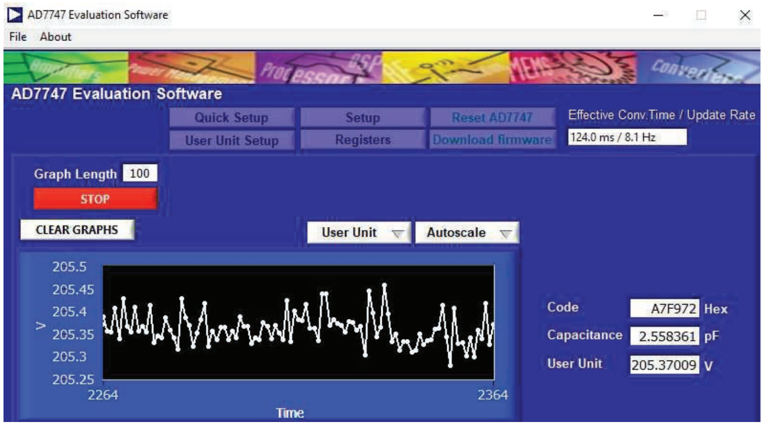


Figure 8 AD7747 evaluation software window, showing capacitance value and calibrated voltage value.

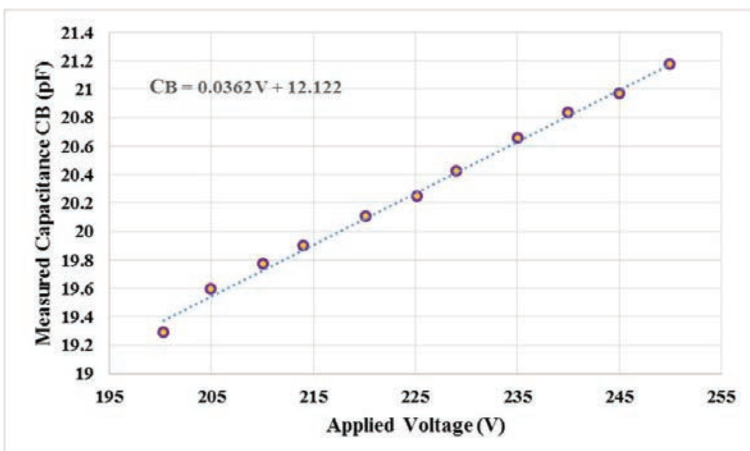


Figure 9 Measured capacitance using the prototype w.r.t to applied voltage from 200 to 250 V, 60 Hz.

has been calibrated in terms of line voltage by setting up the user unit setup (see Figure 10). In user unit setup, value of offset and range can be written by using the linear equation shown in Figure 9.

After configuring the user unit setup, line voltage was again varied from 200 to 250 V at a period of 5 V and recorded the measured value (user unit) by using AD7747 evaluation software (see Figure 8). Also, applied voltage and

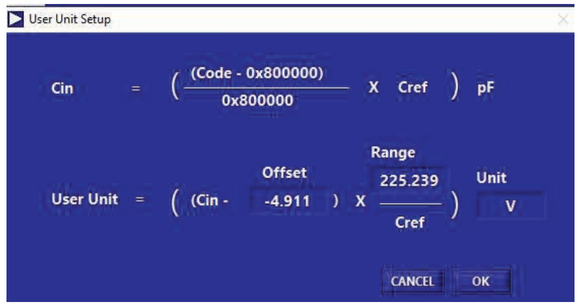


Figure 10 AD7747 evaluation software window, showing how to setup user unit (line voltage in this work).

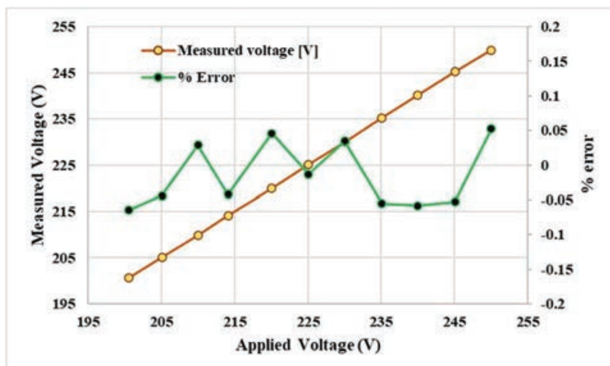


Figure 11 Measured voltage using the prototype w.r.t to applied voltage and the percentage relative error from 200 to 250 V, 60 Hz.

the measured voltage readings were plotted along with the associated relative errors as shown in Figure 11. The maximum relative error was recorder as 0.064%.

Also, analysis has been done for calibrated voltage inside the AD7747 evaluation software as shown in Figure 12. In analysis window tab in Figure 12, it is shown that the average voltage is 205.34 V with 0.0745 V rms noise and 0.282 V p-p noise. Recorded rms resolution and p-p resolution are 12.6 bits and 10.6 bits respectively. Analytical parameters are also shown in Table 1. After observing the analysis part, one can say that the proposed system is highly accurate.

A comparison table of the existing nonintrusive a.c voltage measurement scheme and the proposed scheme are listed in Table 2. As shown in Table 2, the first three schemes require direct operator contact to the power system

Table 1 Analytical parameters of the measurement system

Parameters	Value
Non-linearity error* (%)	−0.42%.
Maximum relative error** (%)	0.064%
Root mean square noise$^{\&}$ (rms)	0.0745 V
Peak-to-Peak noise$^{\&}$ (p-p)	0.282 V
Root mean square resolution$^{\&}$ (rms)	12.6 bits
Peak-to-Peak resolution$^{\&}$ (p-p)	10.6 bits

*Capacitance output w.r.t applied voltage,
** In the measurement of calibrated line voltage
$^{\&}$For measured voltage

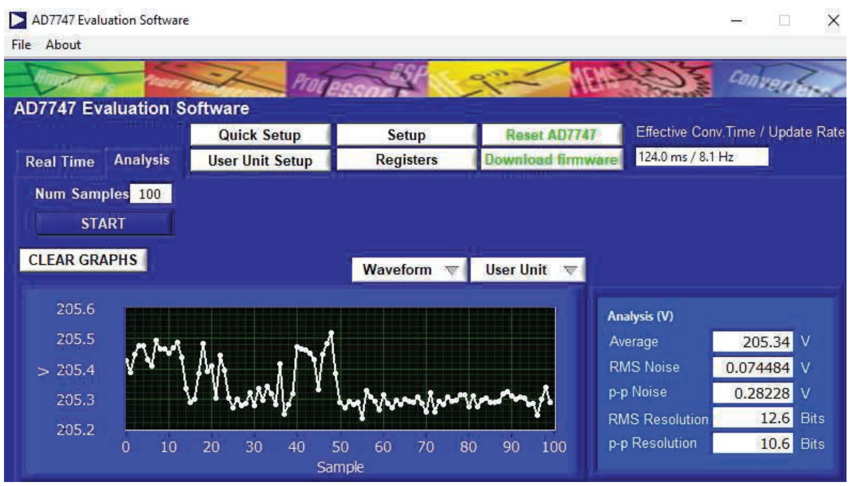


Figure 12 AD7747 evaluation software window, showing analytical data of calibrated voltage.

Table 2 Comparison of various nonintrusive a.c voltage Measurement schemes

Scheme	Compulsory Ground Contact
[16] FFT Magnitude	Yes
[17] Dual slope	Yes
[18] Self Balancing	Yes
[19] FFT Magnitude & Phase	No*
This work-Sigma-Delta	No*

*Body contact between circuit part and ground potential is compulsory.

ground. Whereas, the 4th and the proposed scheme does not require any connection operator and ground.

6 Conclusion

With the increasing requirement for inexpensive, accurate, and contactless measurement system for the detection a.c voltage, an efficient, nonintrusive capacitive coupling sensor was simulated, fabricated and tested successfully in this paper. In contrast to the earlier capacitively coupled schemes, the proposed system will not require any power system ground. The CDC AD7747 used in this system was obtained a capacitance value which is proportional to the root mean square value of unknown voltage. The proposed scheme was first realized in COMSOL Multiphysics simulation software. After that, an experimental setup was developed and tested in order to validate the proposed measurement system. The capacitance output w.r.t to applied voltage of the developed sensor exhibits good accuracy and high linearity. The developed system was tested for a pure sinewave voltage signal at 60 Hz frequency. The recorded worst-case error was less than 0.064% and shows good linearity (−0.42%) over the range of 200 to 250 V input voltages. Due to the above-mentioned advantages, we believe that the presented scheme will find numerous monitoring applications in the modern electric power system.

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Biographies

Anwar Ulla Khan received the M. Tech degree from Aligarh Muslim University, Aligarh, India, in 2011. He has Ph.D. degree from the Jamia Millia Islamia (Central University), New Delhi, India, in 2017. He is currently working as an Assistant Professor in the Department of Electrical Engineering Technology, College of Applied Industrial Technology (CAIT), Jazan University, Jazan, Kingdom of Saudi Arabia. His research interests include sensors, microcontroller-based signal conditioning circuits, health monitoring of electrical assets in smart grid and Internet of things (IoT).

Mashhood Hasan received the B.Eng. degree in electrical engineering from Jamia Millia Islamia University, India, in 2003 and the M.Tech. and Ph.D. degrees in electric power engineering from same university, in 2009 and 2016, respectively. Currently, he is an Assistant Professor at the Department of Electrical Engineering, College of Applied Industrial Technology (CAIT), Jazan University. His research interests include renewable energy, power quality, high quality utility interface, power electronics, power generation, power grids, power supply quality, power transmission reliability, and artificial intelligence applied power system.

Mohammad Ehtisham Khan received doctorate degree in Chemical Engineering from Yeungnam University, the Republic of Korea in 2017 and presently working as an Assistant Professor and Head of the Department in Chemical Engineering Technology at Jazan University, Kingdom of Saudi Arabia. Dr. Khan is working in the cutting-edge area of nanosciences and nanotechnology, especially inorganic materials, such as, the fabrication of metal-metal oxides and carbon-based nanoparticles/nanocomposites for sensing, dyes degradation, and water treatment application. Dr. Khan has 35 publications in international peer-reviewed journals, conference proceedings, and Editing 3 books in Elsevier, 12 book chapters.

Wahid Ali received doctorate degree in Chemical Engineering from Yeungnam University, Rep. of South Korea in 2018. He did his Master of Technology in 2011 and Bachelor of Technology in 2007 both from Aligarh Muslim University, Aligarh India. Dr. Ali is currently serving as an Assistant Professor in the Department of Chemical Engineering Technology, College of Applied Industrial Technology (CAIT) Jazan University, Jazan, Kingdom of Saudi Arabia. His research work belongs to the Process System Engineering area. His research interests are Process modelling & simulation of chemical processes, optimization, and surrogate modelling.

Waleed Al Hazmi received the Master of Engineering degree from Australian National University, Australia, in 2007. He has Ph.D. degree from Polytechnic University in Madrid, Spain, in 2017. He is currently working as an Assistant Professor in the Department of Mechanical Engineering, Jazan University, Jazan, Kingdom of Saudi Arabia. His research interests include solid mechanics.

Waleed Zakri joined Mechanical Engineering Department at Jazan University in 2009. Before getting his PhD from The university of Akron in 2018, he served their as a research assistant and completed more than 10 peer-reviewed research articles in the top-tier reviewed journals and majors international conferences. His research expertise is in engineering power and energy systems.