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Low Power Electronic Voltage Transformer Design and Construction

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Highlights:

- Voltage sensor
- Resistive Transformer
- IEC 61689-11

Keywords:

- Voltage sensor
- Electronic voltage transformer
- Instrument transformer
- Ferroresonance
- Voltage transformer

ABSTRACT:

The use of advanced low-power sensing technologies instead of traditional solutions used in the distribution, measurement and control of the power grid has introduced core instrument transformers due to their physical limitations and other reasons. This situation has also brought about the design of low-power voltage transformers. As can be understood from here, analogue measurement and control systems used in power centres are approaching the end of their useful life. This substations need digital automation solutions and new technologies for more efficient performance. Since no iron core is used in the low-power electronic voltage transformer structure, it is robust against network disturbances such as ferroresonance and ferroresonance formation is not encountered. In this study, a low-power electronic voltage transformer is designed and performed experiments are presented. The most essential feature expected in a voltage sensor is that the conversion rate is precise and unchanging. For this reason, the temperature coefficient and leakage capacitance values of the voltage sensor have been designed to have the lowest margin of error. Performance tests were applied to the voltage sensor using mains frequency endurance, partial discharge, accuracy class, linearity and temperature distribution tests. The results of the performance tests show that it has been successfully applied for the design of a precision voltage sensor with an accuracy class conforming to the IEC 61689-11 standard.

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INTRODUCTION

Inductive voltage transformers are widely used in medium voltage measurement systems, mainly for voltage measurement. With the increasing capacity of the power system and the higher voltage of the power transmission system, the inductive voltage transformer insulation structure becomes more and more complex, high cost and heavier. Therefore, it is a more complex structure for installation. In addition, many problems arise in inductive voltage transformers, such as magnetic saturation, the formation of ferroresonance and a short circuit. As the demands of improving and improving the power system have increased, measurement and protection systems have become intelligent, computerized and digital. In the systems developed due to this, there is no need for a transformer output signal with high-rated power. The system essentially needs electronic voltage transformers. Therefore, the development and application of low-power electronic voltage transformers (voltage sensors) have become an inevitable demand. This kind of transformer uses electric voltage divider technology, without using any iron core in the structure. Electronic voltage transformers are based on the principle of resistive and capacitive voltage dividers as the working principle(Wang et al., 2009).

Knowledge of power network state variables is an essential requirement for power system stability in innovative grid systems. It uses instrument transformers to measure node voltages and currents as state variables. Due to the widespread use of distributed generation, especially at a medium voltage levels, studies on medium voltage instrument transformers are still used today. While inductive voltage and current transformers are old or traditional medium voltage instrument transformers, low-power electronic voltage and current transformers are called new generation low-power electronic instrument transformers. Low-power electronic voltage transformers (voltage sensors) have a smaller size and lighter weight than inductive voltage transformers. It also provides easier installation in harsh environments compared to inductive voltage transformers. The secondary rated voltage of the voltage sensor (3.25 V and this voltage divided by √ 3) is lower than the inductive voltage transformer (100-110-115-120-200-230 V and these voltages divided by √ 3). Therefore, considering distributed networks, voltage sensors are preferred in smart grids(Ghaderi et al., 2020).

In addition, while searching for a fault in the feeder on the grid, inductive voltage transformers in the medium voltage measuring cells give a short-circuit error when the insulation test is applied on this feeder to find out which transformer the fault originates from. For this reason, all inductive voltage transformers on the feeder must be separately controlled. This is a significant waste of time. On the other hand, when the insulation test is applied to the feeder on the grid where the voltage sensor is used, the voltage sensor will not show a short circuit feature. Thus the problem of controlling all transformers in the feeder will be eliminated.

All electrical measurements required to organise the power system are generally obtained from voltage and current signals extracted from instrument transformers. The metrological requirements of instrument transformers are unified under the IEC 61689 standard. While IEC 61869-2 and 3 chapters deal with inductive current and voltage transformers, respectively, IEC 61869-10 and 11 explain the new generation low-power electronic instrument transformer requirements for current and voltage, correspondingly. The purpose of the above standards is to express the requirements of transformers in terms of accuracy and tests to be performed for possible different operating conditions. However, standards do not always cover and address all possible existing conditions that may apply(Mingotti et al., 2020).

Recently, electronic voltage transformers have received more attention in the literature than inductive voltage transformers. One of the most important features of electronic voltage transformers is ability to perform real-time network control with the highest efficiency, speed and accuracy with smart grids and distributed energy sources. These reasons have necessitated new features for inductive voltage transformers. For the systems to work under real-time feedback control, an accurate measurement process must be performed. Regarding non-nominal frequency, the protection relays should now turn on faster than before (within a few ms instead of tens of ms). However, given that energy no longer flows in one direction (since multiple producers or consumers are now connected to the feeder on the same grid), in order to correctly divide energy production revenues and for proper reactive energy injection into the grid, accurate energy and power measurements must be made. Again, the mass placement of secondary substations and metering nodes has also caused space and size restrictions. For this reason, reducing the dimensions of all electrical apparatus and systems has become a crucial parameter (Mingotti et al., 2018).

The conversion rate, temperature coefficient and leakage capacitance of the voltage sensor are mainly taken into account in the design. For this reason, high-voltage resistors with high value and good stability have been selected compared to other voltage sensors made in the literature. A toroid-type electrode was used to ensure the accuracy of the accuracy class, the minimum size of the corona discharge and leakage capacitors. The mould design of the voltage sensor is proportional to the resistors. Thus, the electrical shielding method is also applied, and leakage capacitance and leakage currents are minimized in the mould design.

In this study, modelling, design, testing and measurements of the voltage sensor according to IEC 61689-11 standards were performed, and the obtained data were shared.

MATERIALS AND METHODS

Low-Power Electronic Voltage Transformer Modelling

Low-power electronic voltage transformers work based on the voltage divider principle. Voltage dividers with resistive or capacitive elements are used as a typical design.

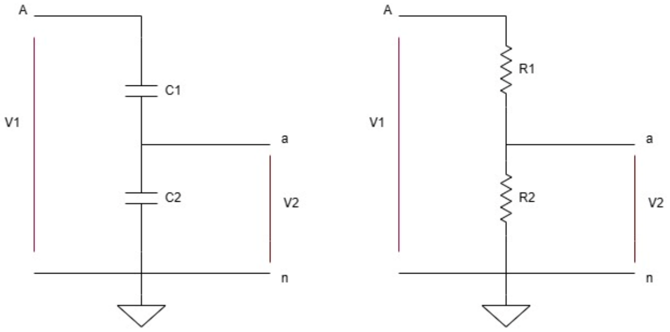

Figure 1. Working principle of capacitive and resistive low-power electronic voltage transformer

The most widely used type in the literature is the low-power electronic voltage transformer based on the resistive voltage divider principle. This structure consists of two voltage divider resistors into which the high voltage V1 (in kV orders) is divided, as seen in Figure 1. The aim here is to reach a voltage value that will represent V1 but proportionally much lower. Therefore, the resistor value R1 is chosen very high compared to R2 and is fixed according to the turn ratio requirements. The input-output relationship of a resistive transformer is as follows:

$$v_2 = v_1 \frac{R_2}{R_1+R_2} \tag{1}$$

The voltage divider principle is also valid for capacitive low-power electronic voltage transformers. However, since the capacitor resistance (capacitive reactance) is inversely proportional to the capacitance, the capacitor C2 is chosen to be larger in order to obtain a lower capacitive reactance than C1. Thus, as with a resistive electronic voltage divider, the input-output relationship of a capacitive transformer can be shown as follows (Mingotti et al., 2020).

$$v_2 = v_1 \frac{c_1}{c_1+c_2} \quad \text{or} \quad v_2 = v_1 \frac{Xc_2}{Xc_1+Xc_2} \tag{2}$$

Design

Measurement in high voltage systems is more comlicated than in low voltage systems due to the very high voltage amplitude and cannot be measured directly. Therefore, the measurement process in these systems is only possible by reducing the high voltage to the voltage level that can be measured with low voltage measuring devices. For this process, a voltage divider or a voltage measurement transformer (converting elements) is used. The high voltage value is converted into a low voltage value, and measurement is made with different measuring instruments (such as voltmeters, oscilloscopes, instruments for imaging and monitoring). The accuracy of the measurements varies according to the characteristics of the transducer elements. The output voltage of the converter elements used for high voltage measurements should be proportional to the characteristics of the value at their inputs (Ryan, 2001).

Resistive voltage dividers are the most widely used systems in the literature for high voltage measurements. The arm in which the output voltage value is measured in the resistive voltage divider is called the low voltage resistance arm, while the resistance arm in which the high voltage value is applied is called the high voltage resistance arm. Depending on the conversion ratio of the voltage divider, the values of the resistors used in the resistor arms may vary. The conversion ratio of a voltage divider must be measured with absolute accuracy. The voltage divider conversion ratio should be independent of current, voltage and temperature. As the voltage value applied in the divider increases, the resistance value can also change. According to Ohm's law, with the increase in voltage value, the current value passing through the resistor increases and a temperature increase is observed in the resistor in direct proportion to the increasing current value. With heating, the resistance value will change depending on the temperature coefficient. A change in the resistance value will cause a change in the voltage divider conversion ratio. The value of the voltage, the insulation materials used in the divider structure, and the surface and ambient conditions cause leakage currents. As the voltage value applied in the voltage divider increases, the electric field level also increases. The increase in the electric field level causes the formation of a corona. The power loss caused by the corona, on the other hand, affects the conversion rate accuracy with its effects, such as electromagnetic compatibility and heating (Kuffel et al., 2000).

The resistors used in the voltage sensor are placed in series between the high-voltage electrode and the low-voltage electrode. In this way, the irregularity caused by the voltage distribution that will occur in the low and high-voltage arms of the voltage sensor is minimized. With the toroid-type electrode used on the top of the voltage sensor, leakage currents and the effect of the corona are prevented.

Resistor selection

The resistors should be high-voltage resistors with high value and good stability. Types of resistors with these properties include solid-film resistors, metal-film resistors, single-winding resistors, and metal-oxide film resistors.

While the maximum value of the film resistors in production can only reach 10 Mega Ohm, the maximum operating voltage is 35 kV. Although the synthetic carbon film resistor can be made of a high-value and high-tensile type, its voltage stability is poor. Therefore, they are not preferred in practical use. Moreover, high-voltage and high-value metal film resistors can reach up to 200 Mega Ohms. With this feature, they look like a suitable resistance structure for maximum operating voltage. The value of wire-wound resistors can be up to 5 Mega Ohms. Therefore, the maximum operating voltage is limited to around a few hundred volts; in other words, it is not a suitable candidate for a high-voltage divider. Moreover, with the development of materials and electronic technology, resistors chosen for voltage measurement in medium voltage power systems can become high-voltage and high-value thick film resistors. Thick film resistors are made by printing resist paste on a substrate, followed by heating and drying. It consists of resistance paste, conductive materials, glass binders and some organic binders. Thick film resistors with different properties can be obtained by changing the ratio of the materials used in the resistor paste. The value of the resistors produced in this way can reach a maximum of 2 Giga Ohms, and the operating voltage can reach 40 kV. The voltage and temperature coefficient can be made lower, which can meet the design requirements of the voltage sensor. The resulting resistor size is small as can be seen in Figure 2.

Figure 2. High voltage thick film resistor

Performance analysis of voltage divider

Resistive voltage dividers have excellent dynamic properties and are suitable for measuring AC, DC voltage and impulse voltage. Moreover, there is also a measurement error caused by the resistive voltage divider. The leading cause of this error is the distributed capacitance value caused by the natural electric field between the resistive voltage divider and the surrounding earth's potential objects. In addition, the stability of the resistor element will bring errors such as corona discharge of the high voltage electrode and leakage current of the insulator support.

Effect of changes in heat or ambient temperature

The influence of temperature on the resistance value is expressed by the temperature coefficient. The transformation ratio of the voltage divider will be as shown in Equation 3 for temperature changes ΔT, where Ky and Ka are the temperature coefficients of the resistance of the high and low voltage branches, respectively.

$$k = \frac{R_1 + \Delta R_{\ 1}}{R_2 + \Delta R_{\ 2}} = \frac{R_1 + K_y \Delta T R_{\ 1}}{R_2 + K_a \Delta T R_{\ 2}} \tag{3}$$

If the temperature coefficients of the two arms are equal, that is, the resistance value of the high and low voltage arms varying with temperature is the same.

Equation 4 shows that although the temperature change causes the resistance change, after the proportional relationship, the resistance change is balanced, and the ratio of the voltage divider is not affected.

$$k = \frac{R_1 + \Delta R_{\ 1}}{R_2 + \Delta R_{\ 2}} = \frac{R_1 + K_y \Delta T R_{\ 1}}{R_2 + K_a \Delta T R_{\ 2}} = \frac{R_1}{R_2} \tag{4}$$

If the temperature coefficients of the two arms are not equal, it will cause errors in the measurement. Equation 5 shows the proportional relationship of the temperature difference between the high and low-voltage arms.

$$\Delta K = K_y - K_a \tag{5}$$

Equation 6, below shows that the temperature coefficient difference between the high and low-voltage branch resistors is directly proportional to the effect of temperature on the conversion rate.

$$k = \frac{R_1+K_y\Delta TR_{\,1}}{R_2+K_a\Delta TR_{\,2}} = \frac{R_1+K_y\Delta TR_{\,1}+\Delta K\,\Delta T\,R_1}{R_2+K_a\Delta TR_{\,2}} = \frac{R_1}{R_{\,2}}\left(1+\frac{\Delta K\,\Delta T}{1+K_a\Delta T}\right) \tag{6}$$

Voltage Sensor Technical Values

The turning ratio of the designed voltage sensor will be 20/√3 / 3.25/√3. While determining the turning ratio of the voltage sensor, the operating voltage of the product has the same characteristics as the inductive voltage transformer. The most significant difference is in the secondary rated voltage values. Secondary rated voltage values of inductive voltage transformers; 100-110-115-120-200-230 V, and these voltages are divided by √ 3. In a standard voltage sensor, the secondary rated voltage value is 3.25 V, and this voltage is divided by √ 3.

In inductive voltage transformers, the secondary rated voltage is generally preferred as 100/√ 3 V for meter counters and 100/3 V for protection devices. Therefore, the nominal values of the electronic device (measurement and protection devices) to be connected to the secondary must be of a type that can provide this voltage value. An example of this is the REF615 relay. In addition, the input impedances (2MΩ-50pF) of the measuring instruments to be connected to the secondary should be selected at the appropriate value, and the loading effects on the secondary should be minimized. Thus, measurement errors will be minimized.

As mentioned above, while the secondary rated voltage of a standard voltage sensor is 3.25 V and this voltage is equal to √3, there may be differences in this value depending on the transformer design to be requested. Depending on the demand, a voltage sensor design with the same value as the secondary rated voltage of the inductive voltage transformer is also possible. The most crucial point to be considered in such a tension sensor is that the rotation ratio can be provided with a real sensitivity. The designed tension sensor and its technical values are given in Figure 3.

Figure 3. Technical values of the designed tension sensor

Tension Sensor Structure

The designed tension sensor is shown in Figure 4. As seen in the figure, two different resistors are used in the sensor structure. These resistors have low tolerance (0.5%) and low-temperature coefficient. In order to keep the contact resistances of these resistors connected in series with each other low, copper alloy connection material is used and the formation of spikes in the connection is avoided. While the resistance on the high voltage side has a very high power (watt) in the Mega Ohm range, and due to the lightning impact effect, the resistance on the low voltage side has a low-power in the order of Kilo Ohms.

A surge arrester is connected in parallel with the resistor on the low voltage side against sudden voltages. It is aimed to minimize the error in the measurement by applying electrical shielding on the resistors due to pollution, humidity, electromagnetic disturbances and leakage currents. Necessary connections in the mould design of the transformer were made using brass blind nuts, and insulation was provided by pouring epoxy resin. A coaxial cable is used at the secondary output of the voltage sensor.

Figure 4. Design view of the transformer

RESULTS AND DISCUSSION

In this section, the tests and measurements made with the designed and built tension sensor are discussed, and the results are given.

Mains frequency voltage withstand the test

The corona effect in the voltage sensor can change the electric field distribution proportionally. Parts such as the electrodes of the voltage sensor, connecting materials and electrical components are designed in a way that does not allow a corona formation. In this section, the voltage withstands the test of the voltage divider under high voltage with mains frequency has been carried out. Since the highest mains voltage of the designed voltage sensor is 24 kV; For the insulation test, the mains frequency breakdown voltage was chosen as 50 kV, and this value was applied to the sensor for one minute. During the insulation test, a high-voltage connection was made to the primary terminal of the voltage sensor, and the secondary circuit was grounded by short-circuiting. As seen in Figure 5, no puncture, jumping or corona formation was observed in the voltage sensor applied to 50 kV for one minute.

The specified test procedure was carried out according to the standard given in Table 1, depending on the maximum voltage value that can be seen in the grid and the insulation amount of the transformer design.

Table 1. Main's frequency voltage withstands standard test values

Maximum Um voltage for hardware (Active) kV	Rated mains frequency breakdown voltage (Active value) kV
3.6	10
7.2	20
12	28
17.5	38
24	50
36	70
Operating Voltage of the Product	Breakdown Voltage of the Product

Figure 5. Insulation test image of the transformer below 50 kV

Partial discharge test

Electrical partial discharge is a general name given to the electrical discharge or sparks that occur with the dielectric material between two conductive electrodes, which cannot form a full bridge due to gaps in its structure. In summary, the energy discharged through the insulation material between two active conductors for partial discharge can also be called.

In order to make partial discharge measurements at the rated voltage of the low-power electronic voltage transformer, a high voltage laboratory a partial discharge measuring apparatus was used. While measuring, two different partial discharge measuring devices were compared. These devices are a partial discharge oscilloscope an MPD600 device, a measurement and analysis unit that allows the most precise detection, recording and analysis of partial discharge events.

Omicron's partial discharge (partial discharge - PD) measurement system, MPD series, is an innovative and high-tech product developed to determine insulation errors as accurately as possible. Thus, it detects even the weakest partial discharge signals and ensures that insulation-related failures that may occur in expensive equipment produced and commissioned at high costs are detected much earlier.

At the beginning of the partial discharge test, the measuring apparatus was calibrated at 50 PC with the partial discharge calibrator. In order to test the voltage sensor with a nominal voltage of 24 kV by the standard, voltage levels of 16.6 kV (1.2*Um/V3) and 28.8 kV (1.2 Um) should be used, and in this situation, the partial discharge values should not exceed 50 PC. It has been set that the amount of discharge originating from the test environment varies between 10 and 5 PC. After applying a voltage to the transformer, it was observed. That the partial discharge load changed between 20 and 12 PC, that is, the transformer did not exceed the maximum value specified in the standard (50PC), and a partial discharge did not occur. In Figure 6, the image of the partial discharge event seen in the MPD600 device is given.

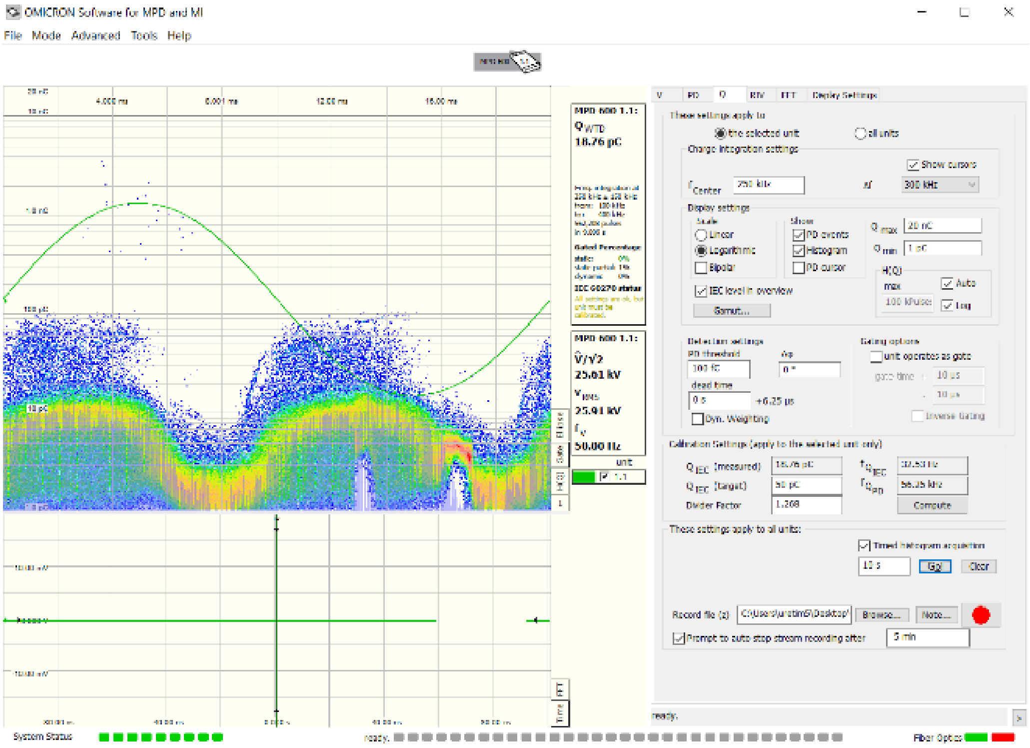

Figure 6. Image of partial discharges of the transformer at rated voltage

Accuracy class determination experiment

The most essential feature expected in the voltage sensor is that the conversion ratio is sure and unchanging. However, the conversion rate can vary depending on many factors. The most important of these factors is the voltage applied to the primary voltage sensor. For this reason, the voltage sensor was kept under a constant voltage of U1 = 20 kV for 8 hours; during this time, the output voltage value of U2 was measured every 30 minutes, and the conversion ratio value was calculated as K = U1/U2. It was determined that the conversion rate changed within the first 5 hours and remained constant between the 5th and 8th hours.

It took 5 hours to provide the current (I= U/R) passing through the voltage sensor depending on the voltage, the lost power ($P = RI^2$) and the thermal balance (W = P.t) depending on the current. It has been observed that the flat conversion rate reached at the end of the 5 hours differs from the actual conversion rate. It can be said that the reason for this is the measurement error resulting from changing the output equivalent resistance of the voltmeter with 10 MΩ impedance, which is connected to measure the U2 voltage value on the resistor on the low voltage side. The voltage at the sensor output can be measured with precision voltmeters, as this measurement affects the sensitivity of the measurement system in the medium voltage system. Therefore, a precision measuring instrument was used in the accuracy class determination experiment.

The voltage divider in the designed sensor divides voltages up to 50 kV theoretically in a ratio of approximately 20/√3 / 3.25/√3. The turning ratio of the transformer should theoretically be 6153.846.

When the primary voltage of 20/√3 kV is applied to the designed transformer, the secondary output voltage is measured as 3.242/√3 Volts. The error between the theoretical calculation and the designed transformer has been found to meet the requirements of accuracy class 0.5 for measurement purposes and accuracy class 3P for protection purposes. Thus, the 50 Hz frequency turning ratio and error class of the designed transformer are determined as follows.

$$\textit{Desired conversion rate} = \frac{20000/\sqrt{3}}{3.25/\sqrt{3}} = 6153.846 \qquad (7)$$

$$Measured\ conversion\ rate = \frac{20000/\sqrt{3}}{3.242/\sqrt{3}} = 6169.031 \tag{8}$$

$$Error\ class = \frac{(desired\ conversion\ rate - Measured\ conversion\ rate)}{desired\ conversion\ rate} * 100 = \frac{(6153.846 - 6169.031)}{6153.846} * 100 = \%\text{-}0.24 \tag{9}$$

Determination of linearity experiment

The linearity test of the low-power electronic voltage transformer was made by applying 5.3 kV, 10 kV and 15 kV to the divider and measuring the output voltage without allowing the transformer to heat up. From the test results given in Table 2, the linearity of the primary and secondary output voltages and the conversion ratio can be seen.

Table 2. Determination of linearity

Given voltage (kV)	Measured voltage (V)	Conversion rate (kV /V)
5.3	0.861	6155.63
10	1.625	6157.63
15	2.437	6155.10

Determination of temperature distribution

The low-power electronic voltage transformer was kept under a constant voltage of 20 kV for 8 hours, and temperature measurements was made every 30 minutes. The measurements made are the temperature values in the lower, middle and upper parts of the transformer. As a result of the experiment, as seen in Figure 7, it was observed that the temperature changed during the first 5 hours and remained constant at around 40°C between the 5th and 8th hours. The thermal analysis of the tension sensor was performed with the SolidWorks program, as seen in Figure 8.

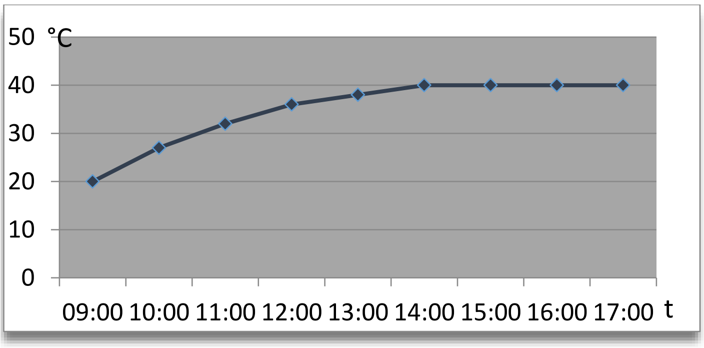

Figure 7. Temperature distribution graph of the transformer after 8 hours

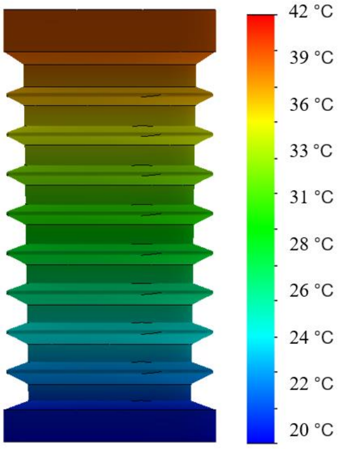

Figure 8. Tension sensor thermal analysis

Capacity and insulation loss factor measurement experiment

Power factor measurements were made to determine the insulation status of both the transformer windings to the ground and between the windings and to set an example for the measurements to be made during the operation. For dielectric loss factor measurement at the rated voltage of low-power electronic voltage transformer, a high voltage laboratory Tan Delta test device was used. In this experiment, the secondary output of the transformer was grounded by short-circuiting, and the test was carried out in GST mode by applying 10 kV from the primary. After applying a voltage to the transformer, the tan delta value was measured as 0.43%. It has been observed that the designed transformer does not exceed the maximum 2.5% insulation value determined in the standard.

CONCLUSION

In this study, the design of a low-power electronic voltage transformer produced for the first time in Turkey was carried out.

High-value resistors with good stability have been used in the voltage sensor design. In addition, the effect of the electric field on the surface of the resistance winding wires is relatively high. For this reason, resistance paste was printed on the surface, and heated resistors were selected. Since the characteristics of the resistors used in the high and low-voltage arms of the voltage sensor directly affect the conversion rate of the voltage sensor, the resistor selection was carried out taking into account some parameters. When voltage is applied to resistors, it is aimed to keep the change in resistance values at a minimum level. For this reason, resistors with sensitive temperature coefficients were selected in the high and low voltage arms compared to the studies conducted in the literature. It was ensured that the leakage capacitance value had the lowest margin of error and the accuracy class was sensitive.

The transformer network, by examining the design IEC 61689-11compliance against the standard frequency resistance, partial discharge, accuracy class, linearity and temperature distribution measurements, was made by applying tests and performance tests. The data from the performance experiments and measurements show that it has been successfully applied for a precision voltage sensor design of accuracy class that complies with the IEC 61689-11 standard.

The voltage sensor designed has compact dimensions, does not provide ferroresonance formation and does not show a short circuit fault on the feeder. For the first time in Turkey, produced and demanded by these new voltage sensors, in conjunction with various engineering companies, with domestic production through distribution companies provide significant added value, as well as to contribute to the country's economy is considered. The image of the sensor whose design has been completed is given in Figure 9. The image of the sensor whose design has been completed is given in Figure 9.

Figure 9. The final state of the designed transformer

Conflict of Interest

The article authors declare that there is no conflict of interest between them.

Author's Contributions

The authors declare that they have contributed equally to the article.

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