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Investigation of the Effects of Additives on the Electrical and Magnetic Properties of Polyester Resin

Salih Nişancı[1], Mehmet İpekoğlu[2], Muhammet Hilmi Nişancı[3], Mustafa Karhan[4], Mukden Uğur[5]

[1]Department of Electrical-Electronics Engineering, Turkish-German University, Faculty of Engineering, İstanbul, Turkey
[2]Department of Mechanical Engineering, Turkish-German University, Faculty of Engineering, İstanbul, Turkey
[3]Department of Electrical and Electronics Engineering, Sakarya University, Faculty of Engineering, Sakarya, Turkey
[4]Department of Electronics & Automation, Çankırı Karatekin University, Çankırı, Turkey
[5]Department of Robotics and Intelligent Systems, Turkish-German University, Institute of Science and Engineering, İstanbul, Turkey

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ABSTRACT

Polymers are widely used as insulation materials in the electrical industry because their existing electrical and mechanical properties can be altered by adding different types of additives. Successful prediction of the service life of the insulators used in the electrical industry is important for the reliability of the system. For this purpose, insulating materials are subjected to tests according to various standards.

In this study, unlike the literature, a polymeric insulator was produced by adding 3 wt.% zinc oxide (ZnO), magnetite (Fe_3O_4), and nickel (Ni) into the polyester. The produced samples were subjected to the inclined plane test in accordance with ASTM (American Society for Testing and Materials) D-2303 standards. In order to analyze the electric and magnetic field distributions formed on the samples during the inclined plane test, first, the current flowing on the samples during the test was measured. Following this, analyses were carried out by creating a simulation model of the samples.

Studies found in the literature mainly focus on two-dimensional investigation of the electrical field distribution. This study concentrates on the three-dimensional examination of the electrical field also considering the magnetic field distribution. Results of this study showed that prior numerical analysis gives insight into information about the real-life behavior of the samples.

***Index Terms*—**Polyester, zinc oxide, magnetite, nickel, insulator, inclined plane test

I. INTRODUCTION

The demand for electrical energy has been increasing day by day since the beginning of the use of electricity in the 19th century with the increase in the world population and the acceleration of technological developments. In order to meet this increasing demand, new transmission and distribution lines are established and the power levels of the existing lines are further increased. Increasing the power levels utilized in the lines causes problems in insulation, which forms the basis of the electrical network. The most common approach to overcome this problem is changing the type of insulating material. The aim is to produce electrically and mechanically more efficient equipment in this manner [1].

While a small number of materials such as porcelain, glass, and mica were used as insulating materials at first, the number of potential insulating materials reached thousands with the use of polymers as insulating materials in the 1960s [1, 2].

Owing to the advantages they have over other insulation materials, polymers are widely used as insulation materials. These advantages include being lightweight, having higher strength-to-weight properties, higher resistance to breakdown resistance, higher thermal conductivity, and the ability to change their physical and chemical properties by doping with other inorganic materials [3, 4]. Commercial interest in polymeric materials has increased due to these advantages, and this has led to more research activities in this area [5].

Despite having many advantages, it is not common to use polymers alone as insulating materials [1]. Therefore, they are either used by mixing with other polymers or doping with different inorganic materials to form composite materials.

Corresponding author:
Salih Nişancı

E-mail:
salih.nisanci@tau.edu.tr

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Compared to traditional materials, composite materials are preferred more due to their high mechanical strength, thermal resistance, and resistance to chemicals and water [6]. Composite materials are widely used in many areas such as rail systems, aerospace, construction, and food packaging and are also used in the electrical industry due to their superior electrical properties [7-10].

Composite materials used in the electrical industry are subjected to various electrical and mechanical stresses throughout their service life, and this stress can cause deterioration of composite materials [11-14]. The performance of composite materials under these stresses during their service life varies depending on the type of material from which they are made, their design, and most importantly, the type of additive in it [15]. Literature survey shows that aluminum trihydrate (ATH) and silicon dioxide (SiO_2) are widely used as additives, while zinc oxide (ZnO), borax ($Na_2[B_4O_5(OH)_4]8H_2O$), and barium titanate ($BaTiO_3$) are also used as additives [16-22].

Several methods have been studied and then standardized to evaluate the properties of composite materials under electrical and mechanical stress [14]. Among those standards, IEC 60587 and ASTM D2303 standards, which have slight differences from the former one, are used to compare the surface resistance of insulation materials that are used under harsh environmental conditions [23].

In this study, the effects of different additives incorporated into polyester on the electric and magnetic field distributions of the produced composite materials were investigated by experimental and simulation methods through the inclined plane experiment. Literature reports the use of various additives such as ATH, SiO_2, and $Na_2[B_4O_5(OH)_4]8H_2O$. The conducted study expands this knowledge by further evaluating the effect of ZnO, Fe_3O_4, and Ni as potential additives. In comparison to the two-dimensional numerical examinations found in the literature, the current study examines three-dimensional electric field distributions and further takes magnetic field distributions into account. Based on the outcomes of the current research which showed that the maximum value of the electric field distribution formed on the sample is inversely related to the test endurance times of the samples, it may be suggested that the use of numerical electric field distributions is a time-conserving and cost-effective method to predict the test endurance times of the samples.

First, the inclined plane test method, the numerical modeling, and the measurement of the relative permittivity and permeability values of the produced samples are introduced in this study. Following this, outcomes of the numerical analysis of two- and three-dimensional electric and magnetic field distributions are reported and discussed.

II. MATERIALS AND METHODS

A. Inclined Plane Experiment

Inclined plane test was first proposed by Mathes and Gowan in 1961 and accepted as ASTM D2303 standard in 1964. In the following years, the IEC (International Electrotechnical Commission) 587 standard was developed, which is based on the same theory as this test standard contains some differences [24].

Samples are exposed to a large amount of surface wear in the inclined plane test, and such severe testing conditions are usually unlikely to occur in daily life [24]. During the test, a voltage of a certain magnitude is applied to the produced sample, and an evaluation is made about the electrical properties of the sample by examining the behavior of the sample under the applied voltage. When the voltage source is turned on, a dry band forms on the sample and electrical discharges in the form of arcing occur near the ground electrode. These localized discharges cause an increase in temperature on the sample surface. The temperature rise depends on the magnitude of the leakage current, the thermal properties of the material, and the environment, as well as the discharge time that occurs at a particular location. If the carbon in the polymeric material cannot be removed from its surface in the form of compounds of the carbon element, a conductive path is formed on the polymeric materials because of high-power discharges and the resulting temperature increase. This carbon path is called tracking [1].

However, no trace formation is observed on the materials in which the carbon can be separated from the sample surface by physical or chemical means. For example, in polymers such as polyester and epoxy, carbon is formed on the deteriorated surface, while in other polymers such as silicone rubber, carbon is removed as a by-product with gaseous CO_2 [24]. In such materials, erosion occurs instead of tracking.

Erosion and tracking resistance depend on the chemical composition of the polymer. Added polymeric insulators are produced by adding suitable inorganic fillers to the base material in order to increase the resistance of the polymer against the formation of tracking and erosion. Although the most commonly used additives are alumina trihydrate and quartz, other material types can also be used as additives [25].

While the addition of inorganic additives can affect some properties of the added polymeric insulator positively compared to its pure state, it can also change some properties negatively. Generally, the tensile strength of the newly formed material increases depending on the amount of additive added, while the hydrophobicity of the material decreases [24].

To test the reliability of the results statistically, the current ASTM D2303 standard requires the test results of five samples should be similar to each other. Although sample production takes place under the same conditions, there may be some inconsistencies between samples due to production instabilities. In such cases, the standard states that the number of samples should be increased from 5 to 15 to ensure the reliability of the experiments [25,26].

The tests of the samples can be done separately as well as simultaneously. If samples are to be tested simultaneously, the voltage source must be strong enough. In the previous studies in literature, it has been observed that if the voltage source is not strong enough while testing more than one sample at the same time, a large amount of voltage drop occurs and the arc goes out due to the voltage drop during the test [24].

B. Sample Preparation

To ensure the homogeneous dispersion of the accelerator in the polyester before solidification begins and to prevent the formation of air bubbles, cobalt, which is the accelerator material, was added to the polyester and the mixture was then stirred using a plastic rod during the sample production. After this process was completed, methyl ethyl ketone peroxide was added under vigorous stirring conditions. After further removal of the air bubbles, the prepared mixture was poured into silicone molds. In the production stage of compound specimen (polyester with additive), the additive material is added to the pure polyester just before the accelerator is added.

Fig. 1. Electrically connected sample which is covered on its two wide surfaces with conductive tape

Fig. 2. Measurement of the hollow coil.

The major drawback of this process is the formation of lumps within the polyester. In order to prevent this, the additive was first powdered in an agate mortar and then mixed with the polyester piece by piece. Next steps of the production process of filled polyester samples are exactly the same as the production of pure polyester samples.

A PET (Polyethylene terephthalate) film was placed on the molded polyester to prevent traces on the polyester and to achieve a smooth surface. The samples were then kept at room temperature for 24 hours and further cured in an oven at 80°C for 5 hours in an open atmosphere in order to facilitate cross-linking of the polyester.

C. Calculation of Relative Dielectric Constant Values of Samples

While the conduction parameters of the samples at high frequencies can be measured by vector network analyzers, these devices cannot be used for measurements at 50 Hz network frequency. Therefore, a literature survey was conducted about the measurement methods of the dielectric constant at the operating frequency and it was found that the parallel plate method was widely used [27-29].

The sample is placed between two conductive plates and the capacitance of the sample is measured with the help of an LCR meter (Inductance (l), Capacitance (C), and Resistance (R)) meter in the parallel plate method. Then, using the measurement data, the relative dielectric permittivity of the sample is calculated analytically using (1), which is widely used in the literature for the calculation of the capacitance value formed between parallel plates.

$$\varepsilon_r = \frac{Cd}{A\varepsilon_0} \tag{1}$$

where A is the surface area of the conductive plates in m², d is the distance between the plates in meters, C is the capacitance value in Farads, ε_r is relative dielectric permittivity of the material, and $\varepsilon_0 = 8.85 \times 10{-}^{12}$ F/m is the electrical permeability of the free space.

Since the produced samples are bent in shape as a result of heat treatment, conductive tape is used in the parallel plate method in order to minimize the air gap between the plate and the sample. Samples with dimensions of 50 mm × 50 mm × 5 mm were produced for this purpose and then both surfaces of the samples were covered with conductive tape. In order to ensure the electrical connection between the LCR meter and the samples, cables of equal

TABLE I. AVERAGE VALUES AND STANDARD DEVIATIONS OF RELATIVE DIELECTRIC CONSTANT VALUES OF PURE POLYESTER AND POLYESTER SAMPLES PREPARED WITH 3 WT.% ADDITIVES.

Relative Dielectric Constant	Pure Polyester	Polyester with 3 wt.% Nickel	Polyester with 3 wt.% Magnetite	Polyester with 3 wt.% Zinc Oxide
Average	4.53	3.37	3.18	4.50
Standard deviation	0.12	0.22	0.23	0.28

TABLE II. AVERAGE VALUES AND STANDARD DEVIATIONS OF RATIO OF RELATIVE PERMEABILITY COEFFICIENT VALUES OF PURE POLYESTER AND POLYESTER SAMPLES PREPARED WITH 3 WT. % ADDITIVES.

Relative Permeability Coefficient	Pure Polyester	Polyester with 3 wt.% Nickel	Polyester with 3 wt.% Magnetite	Polyester with 3 wt.% Zinc Oxide
Average	0.99	1.24	1.16	1.09
Standard deviation	0.01	0.07	0.04	0.01

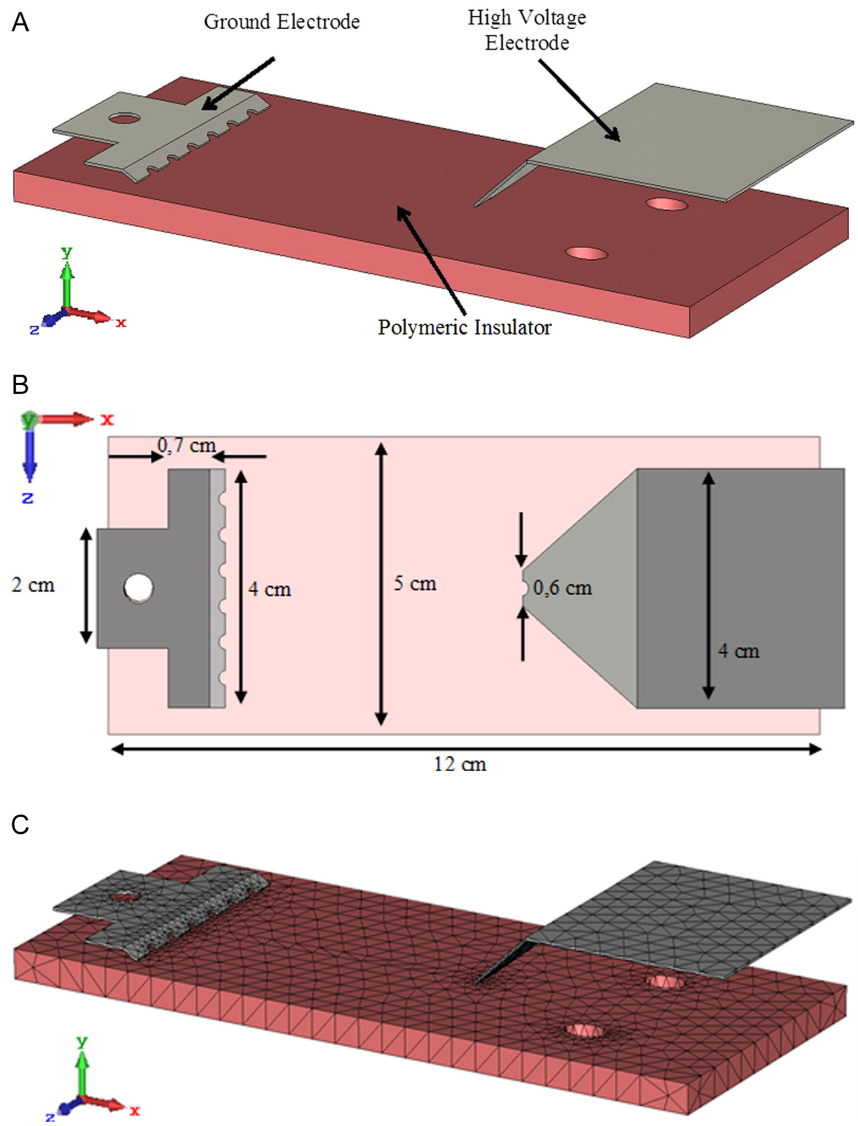

Fig. 3. Schematics of the sample designed for numerical investigations with the high voltage and ground electrodes placed on top; (a) oblique view, (b) top view, (c) mesh pattern.

length having a cross-sectional area of 0.75 mm^2 were soldered to the sample surface covered with conductive tape. Finally, capacitance values of the samples were measured using an LCR meter (GWINSTEK LCR-8110G), which is capable of making measurements in the frequency range of 20 Hz to 10 MHz, as shown Fig. 1.

Measurements were repeated ten times for each sample in order to increase the accuracy of the results. It has been determined that the dielectric constant values calculated using the capacitance measurement result of pure polyester vary between 4.48 and 4.58, with the average value of 4.53 and the standard deviation of 0.122. The obtained results were found to be consistent with the study by Fimberger et al., and therefore, this method was used when calculating the relative dielectric constant coefficients of the following samples [30]. The average values and standard deviations of the measurement results for the relative dielectric constants of pure and added polyester samples are given in Table I.

D. Calculation of Relative Permeability Coefficients of Samples

While the relative permeability coefficients of materials can be measured with the help of analyzers at high frequencies, it is very difficult to make this measurement at 50 Hz mains frequency. Therefore, the relative permeability coefficients of the samples at 50 Hz were found by calculating the inductance. The inductance is calculated as in (2). Using this and by simplifying the length, cross-sectional area, relative permeability coefficient of free space, and the number of windings for the samples, the ratio of the relative permeability coefficients of the two materials with the same physical dimensions and equal number of windings is found to be the ratio of their inductances as shown in (3).

$$L = \frac{\mu_r \mu_0 N^2 A}{l} \quad (2)$$

$$\frac{\mu_{r1}}{\mu_{r2}} = \frac{L_{r1}}{L_{r2}} \quad (3)$$

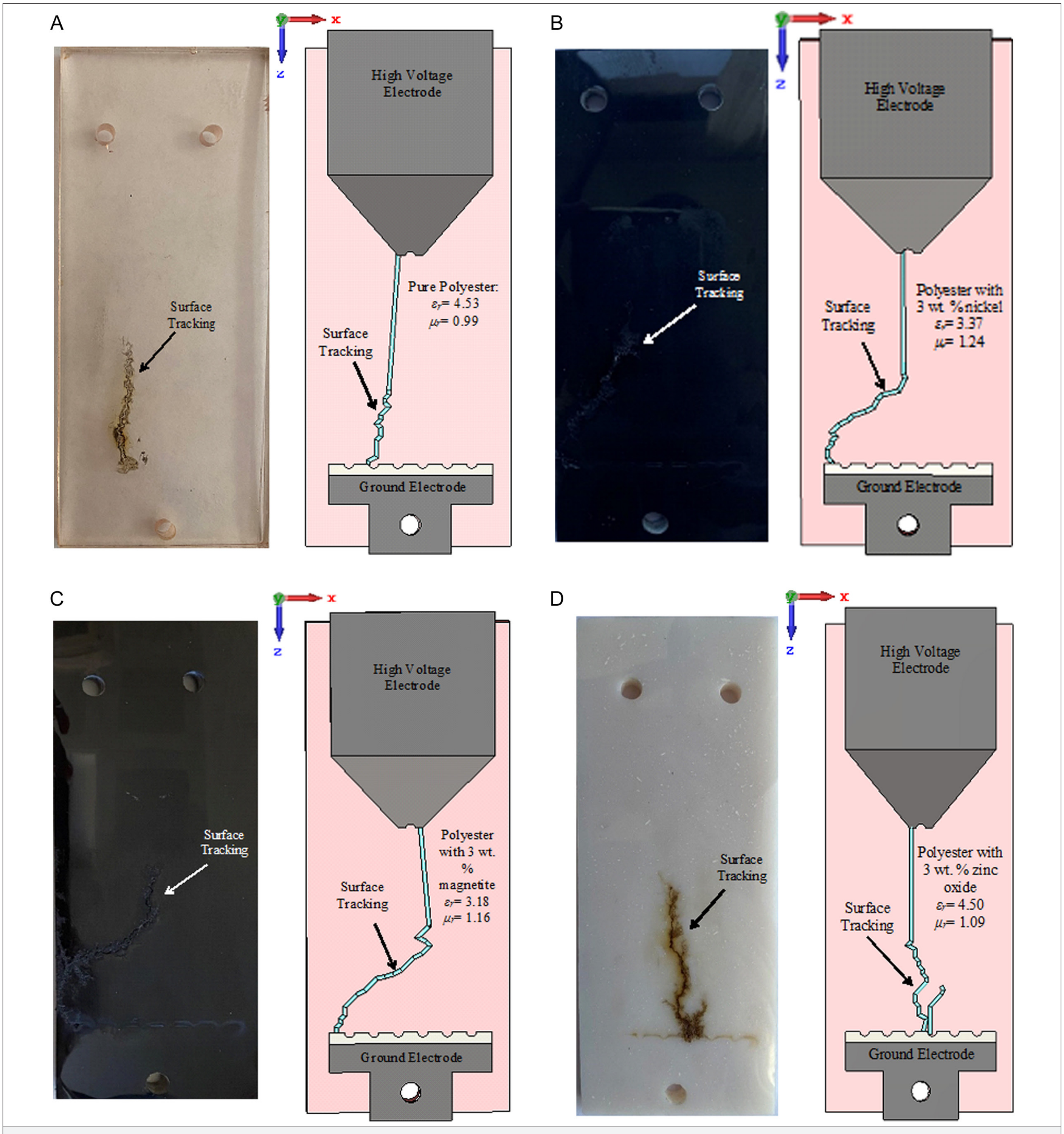

Fig. 4. Images of the trace formation on the surface of the samples and the results of the simulations; (a) pure polyester sample, (b) polyester sample with 3 wt.% nickel, (c) polyester sample with 3 wt.% magnetite, and (d) polyester sample with 3 wt.% zinc oxide.

In order to calculate the ratio of relative permeability coefficients using (3), a hollow coil was wound with equal cross-sectional area as the sample, and its inductance was measured using an LCR meter (Gwinstek LCR-8110G digital) capable of measuring in the frequency range of 20 Hz to 10 MHz as in Fig. 2. Measurements were repeated five times and were averaged to increase the accuracy of the measurement results.

Equation 3 was used to determine the ratio of two inductance values in order to calculate the ratio of relative permeability coefficients of

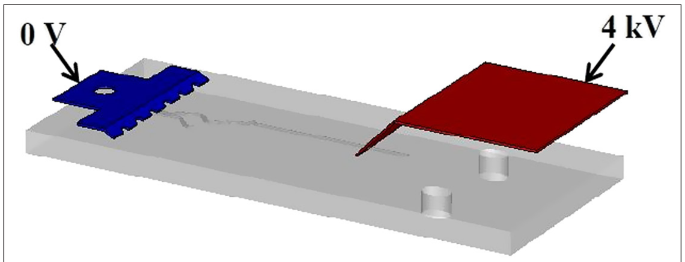

Fig. 5. Excitation of samples with test voltage for numerical analysis of electric field distribution.

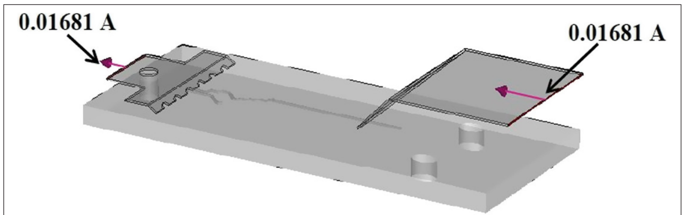

Fig. 6. Excitation of the electrodes with the current port for the numerical analysis of the magnetic field distribution formed on the samples.

the samples. The resulting average values and standard deviations are given in Table II.

E. Modeling of Inclined Plane Experiments

To simulate the electric field distribution on the sample during the inclined plane test, the relative permittivity and permeability constant values of the samples at 50 Hz operating frequency were calculated and then simulations were carried out using the commercial three-dimensional full-wave electromagnetic simulation software (CST Studio Suite) using the obtained values [31]. The simulation model of the samples and electrodes produced in accordance with the standard and subjected to the inclined plane test was created in the CST Studio Suite program as in Fig. 3. Since the simulation model includes complex surface shapes, a mesh pattern consisting of a total of 42 687 triangular elements with side lengths of max. 1.88 cm and min. 0.34 mm were used during the numerical analysis. The designed sample and the mesh pattern structure of the sample created by using triangular elements are given in Fig. 3.

After the samples were modeled geometrically, the relative permittivity value of each sample was defined in Table I, and the relative permeability coefficient was defined in Table II to further conduct numerical analyses. To simulate the trace formation on the sample during the experiments, a conducting line was created between the high voltage and the ground electrodes, and the dielectric constant

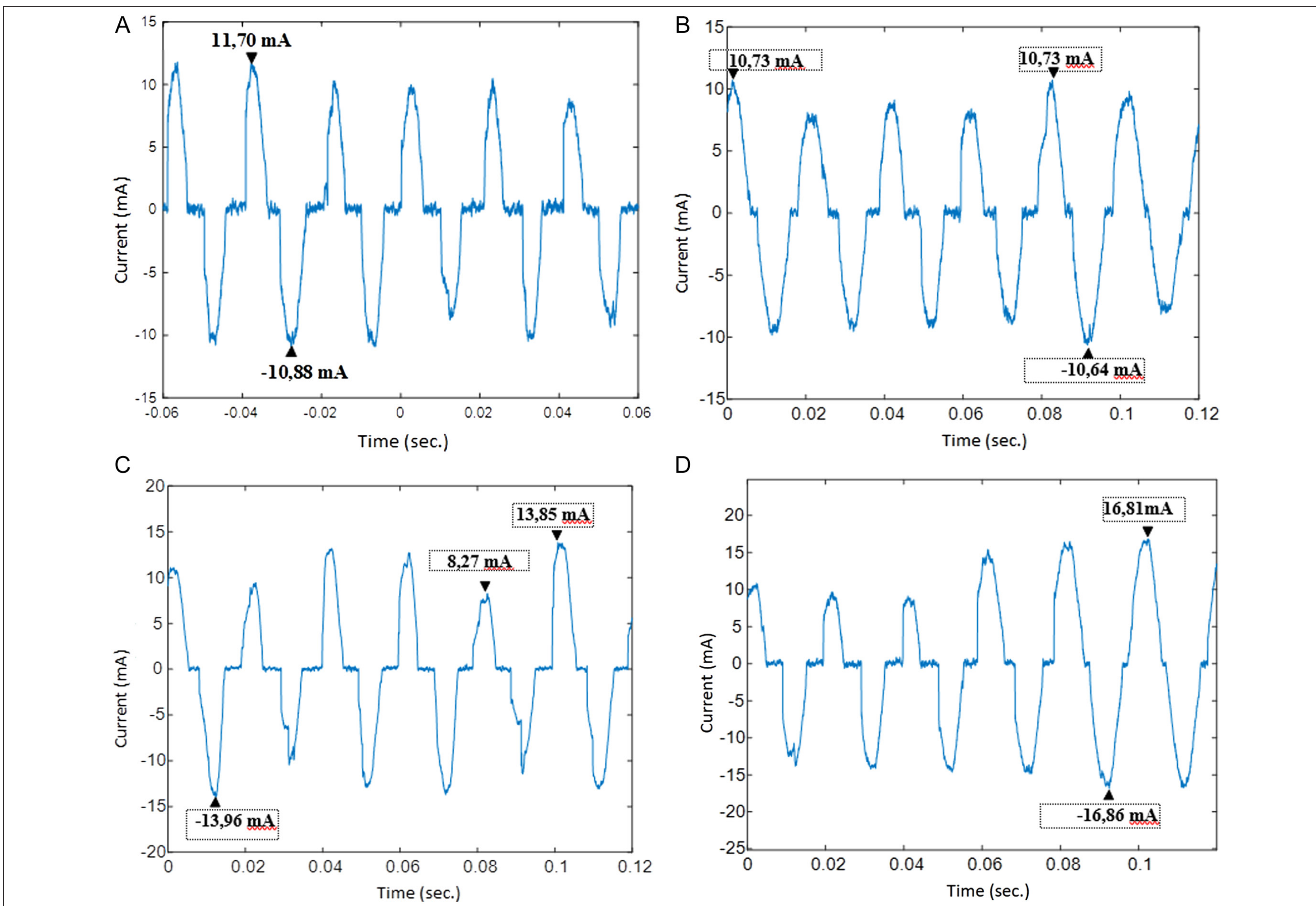

Fig. 7. Plots of leakage current signals flowing through the sample during the experiment. (a) Pure polyester sample, (b) polyester sample with 3 wt.% nickel, (c) polyester sample with 3 wt.% magnetite, and (d) polyester sample with 3 wt.% zinc oxide.

of the line was defined as 100, the relative permeability coefficient as 1, and the electrical conductivity as 0.253 S/m according to the values found in the literature [1, 32, 33]. The conductive paths formed on the samples at the end of the test and the results of the simulation model are given in Fig. 4.

In order to examine the electric field distribution on the sample as specified in the ASTM D2303 standard, high voltage electrode was excited with 4 kV AC for all samples, as presented in Fig. 5.

In order to examine the magnetic field distribution, high voltage electrode for each sample was excited with the current port representing the largest value of the current flowing through the sample, as shown in Fig. 6, when no electrical discharge occurs during the experiment.

The voltage value formed on a 100 Ω resistor was measured by establishing a voltage divider circuit and then the current was calculated by dividing the measured value by 100. Obtained results are given in Fig. 7. After that, all samples were excited with the maximum value of the current flowing over them in order to simulate the maximum magnetic field distribution on the samples. These current values are given in Table III.

TABLE III. CURRENT VALUES AT WHICH THE HIGH VOLTAGE ELECTRODE IS EXCITED FOR MAGNETIC FIELD DISTRIBUTION ON PURE POLYESTER AND POLYESTER SAMPLES PREPARED WITH 3 WT.% ADDITIVES.

Sample	Pure Polyester	Polyester with 3 wt.% Nickel	Polyester with 3 wt.% Magnetite	Polyester with 3 wt.% Zinc Oxide
Current (mA)	11.70	10.73	13.85	16.81

III. RESULTS

The three-dimensional views of the potential, electric field, and magnetic field distributions on the pure polyester obtained from the

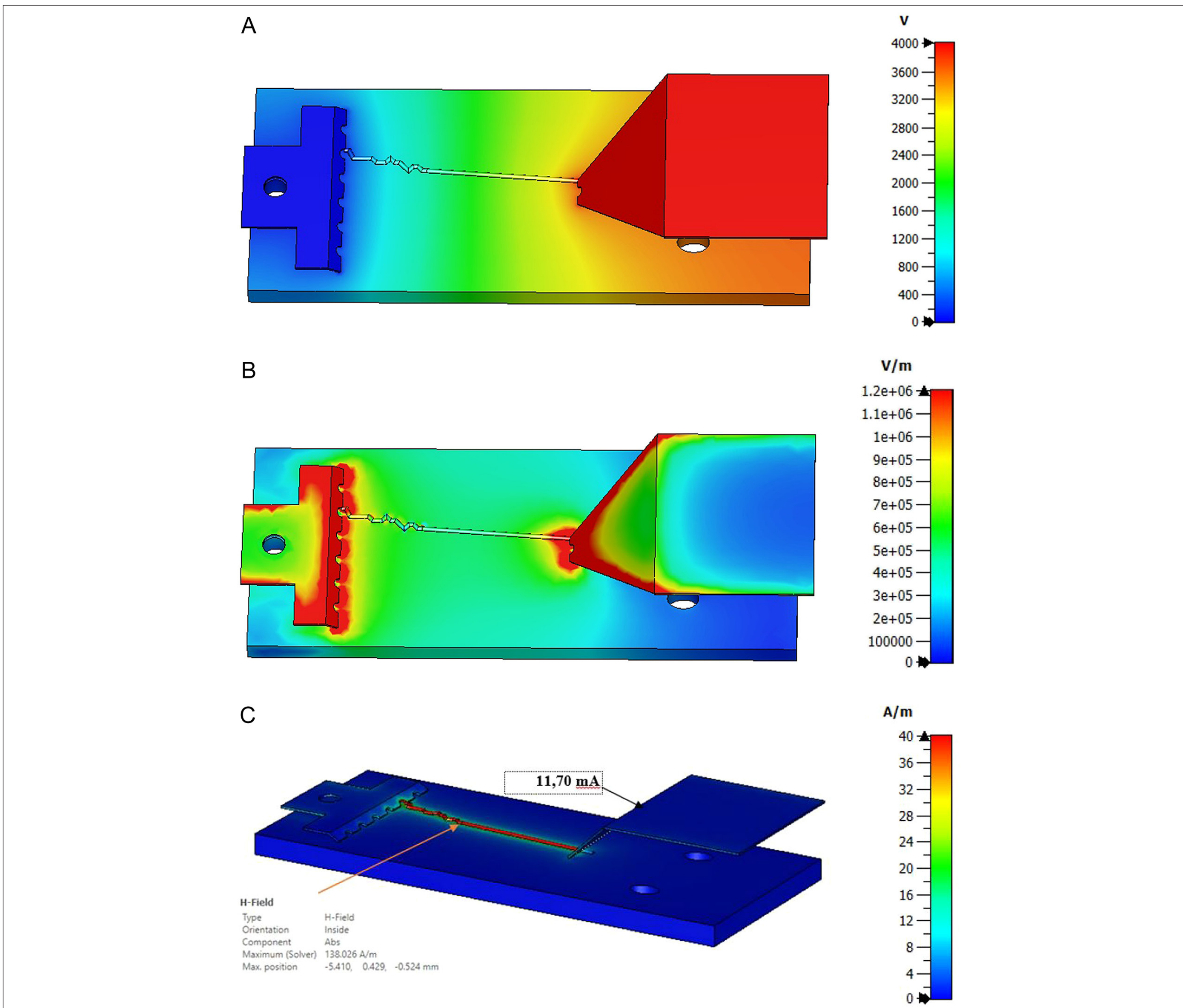

Fig. 8. Three-dimensional visualization of (a) potential, (b) electric field, and (c) magnetic field distributions on pure polyester.

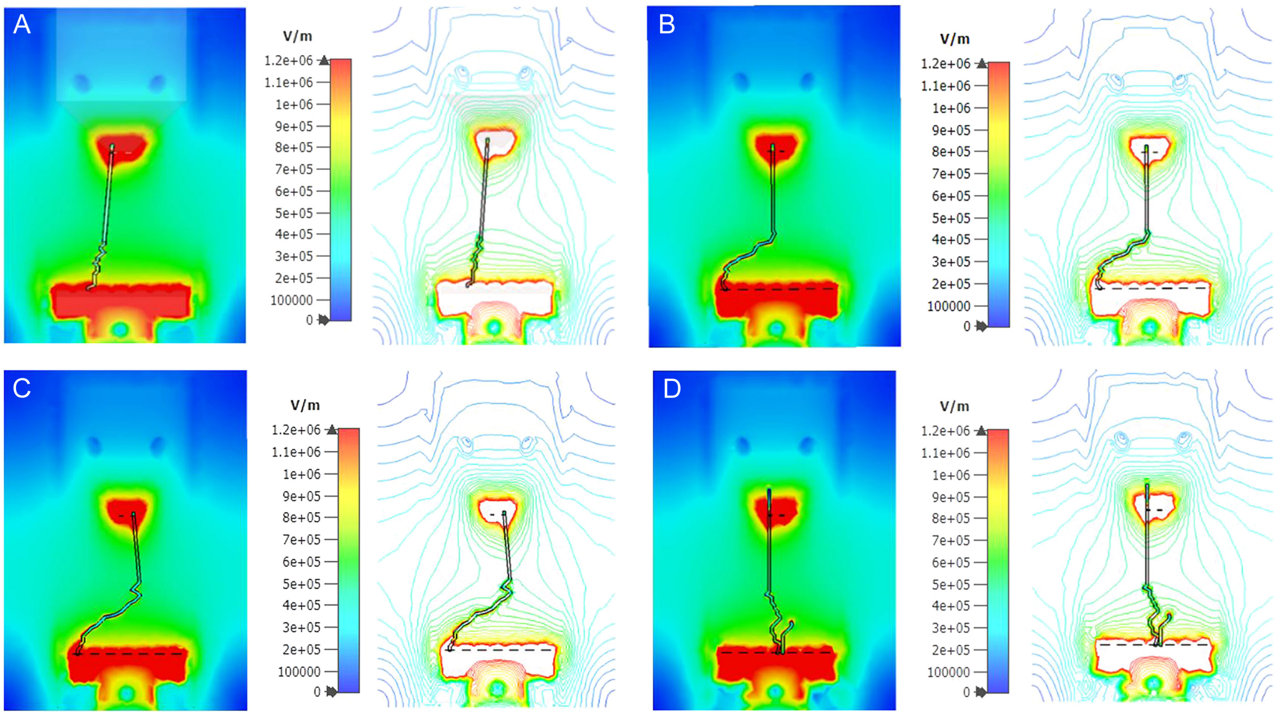

Fig. 9. Two-dimensional visuals and isoline drawings of the electric field distribution on the surface of the samples for (a) pure polyester, (b) polyester with 3 wt.% nickel, (c) polyester with 3 wt. % magnetite, and (d) polyester with 3 wt.% zinc oxide.

simulations based on the finite element method are given in Fig 8. The maximum values of the color scales were selected as 4×10^4 V, 1.2×10^6 V/m, and 40 A/m, respectively, in order to better visualize the potential, electric field, and magnetic field distributions.

It is known that there are no free charges ($\rho_v = 0$) in the interior of the conductors. Therefore, the surface of the conductors has the same electrostatic potential and provides an equipotential surface under static conditions [34]. This can be clearly seen in Fig. 8a where the

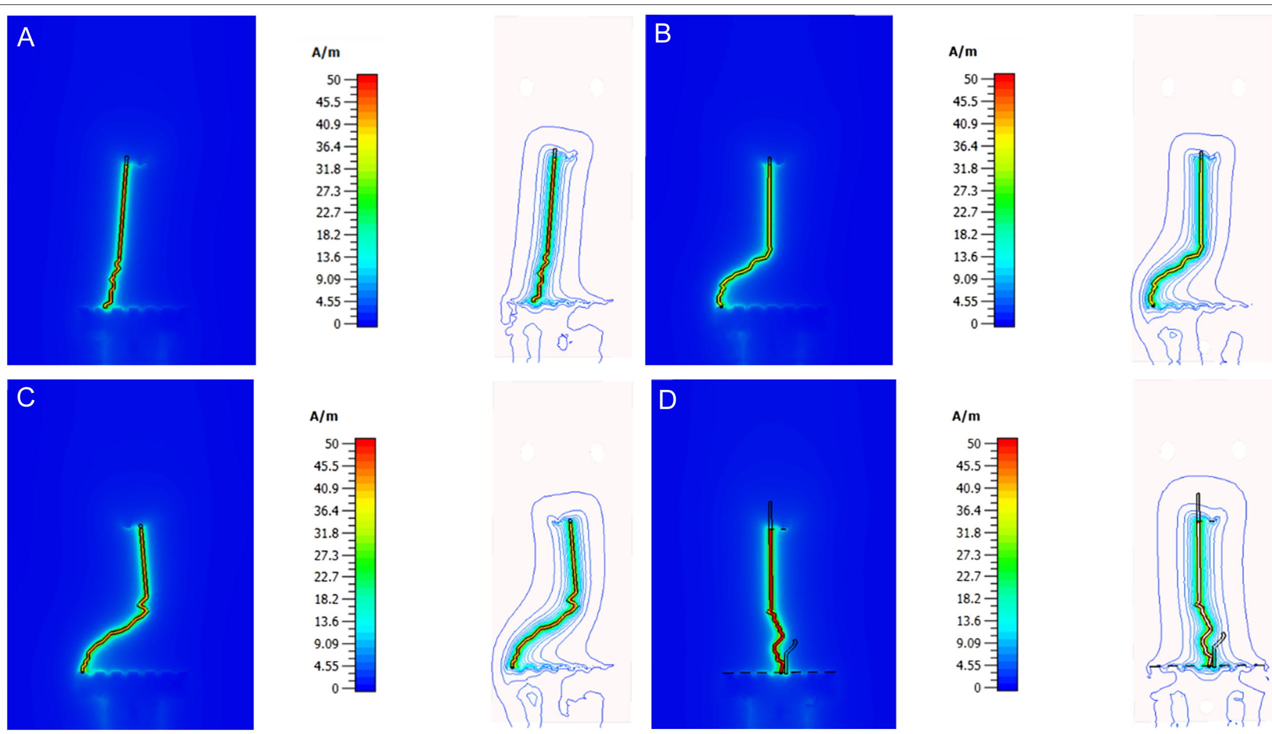

Fig. 10. Two-dimensional visuals and isoline drawings of the magnetic field distribution on the surface of the samples (a) for pure polyester, (b) polyester with 3 wt.% nickel, (c) polyester with 3 wt. % magnetite, and (d) polyester with 3 wt.% zinc oxide.

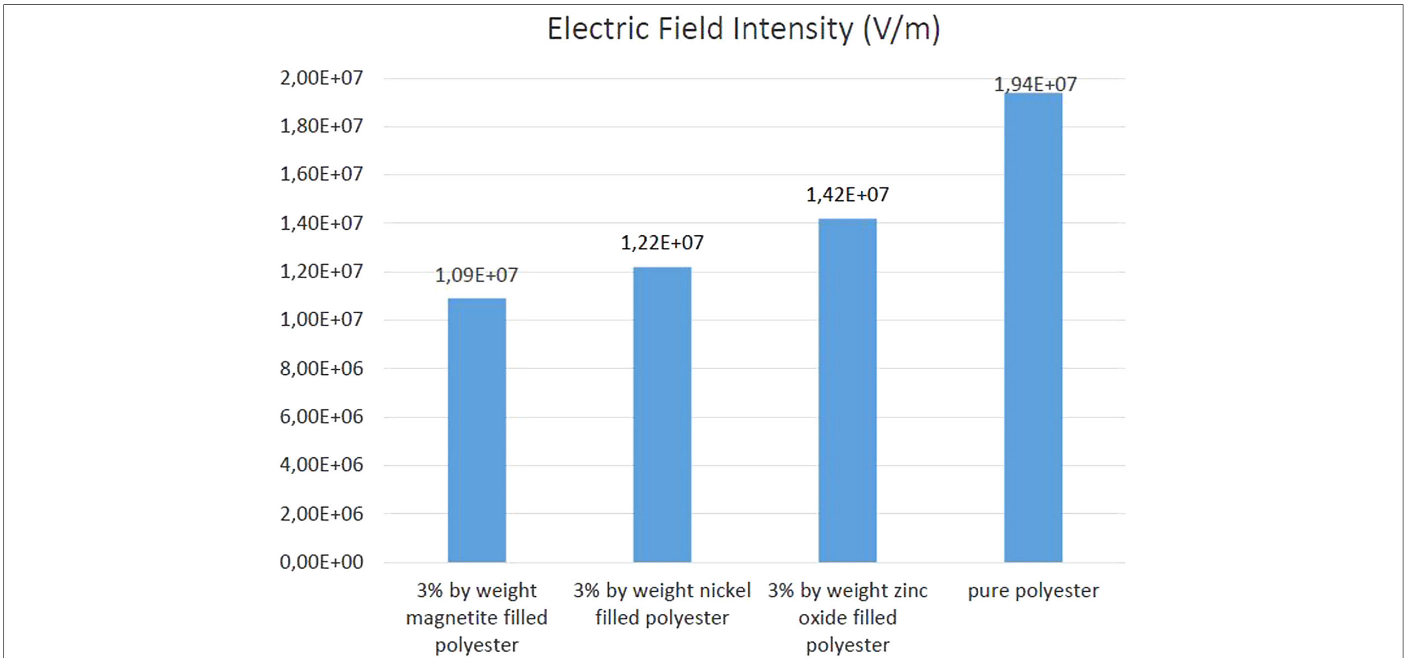

Fig. 11. The maximum electric field intensity on the sample during the test.

surface of high voltage electrode has 4 kV potential, whereas the surface of ground electrode has 0 V potential. Fig. 8b confirms that the electric field distribution has a higher amplitude around the electrodes, especially at the spikes, and its amplitude values decrease as it moves away from the electrodes. This can be explained by considering the conductor-free space boundary conditions. As known, the surface charge density (ρ_s) depends on the geometrical shape of the conductor surface. Therefore, the variation of surface charge density changes the normal component of the electric field at the interface of free space and a conductor [34]. Finally, it is seen that the magnetic field distribution is along the trace formation as shown in Fig. 8c.

In order to show the effect of the conductive additives on the electric and magnetic field distributions, the simulation results of pure polyester and the samples prepared with 3 wt.% additives were compared as shown in Figs. 9 and 10, respectively. Finally, the maximum field values obtained from the simulation results are compared graphically in Figs. 11 and 12.

Figure 11 shows that the maximum electric field level is highest for pure polyester, while the 3% by weight Fe_3O_4-filled polyester is the lowest. It is apparent from the comparison given in Fig. 12 that the maximum magnetic field level of the polyester sample with 3 wt. % ZnO is the highest, whereas the maximum magnetic field level of the polyester sample with 3 wt.% Ni is the lowest.

Observation of Fig. 11 showed that the sample with 3 wt. % Fe_3O_4 has a lower electric field density compared to its counterparts which may imply that Fe_3O_4 addition might increase the service life of polyester in electrical applications.

IV. CONCLUSIONS

Analysis of the obtained data revealed that the dielectric constant values of all samples produced by using additives are lower compared to pure polyester. It was observed that the dielectric constant of the composite material obtained by adding 3% ZnOresulted only in a slight change compared to pure polyester, while the dielectric

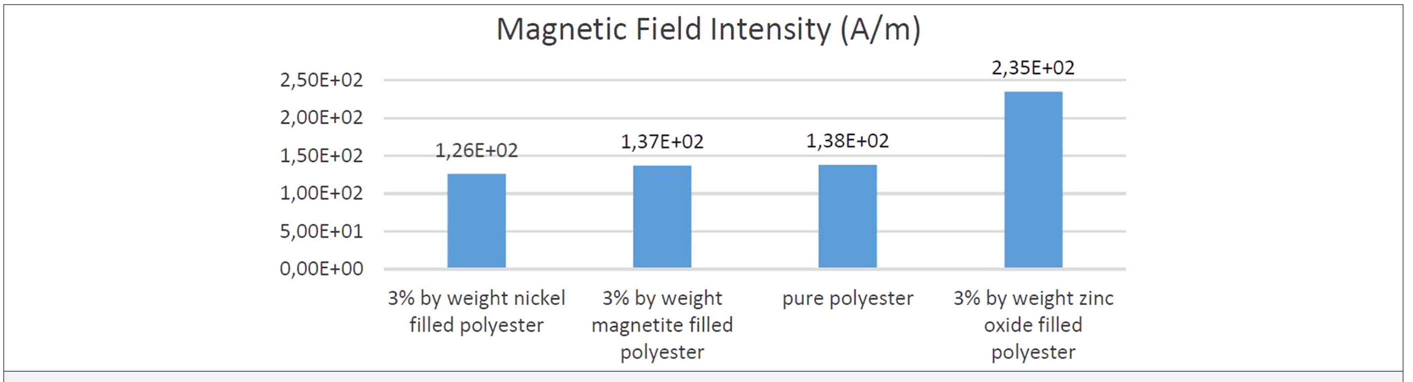

Fig. 12. The maximum magnetic field intensity on the sample during the test.

constant of the composite material was obtained by adding 3% Fe_3O_4 decreased by 30%.

It was observed that the relative permeability coefficients of all samples produced by incorporating additives to pure polyester decreased in comparison to pure polyester. The relative permeability coefficient of the samples produced by adding 3 wt.% ZnO decreased by 10% compared to the relative permeability coefficient of pure polyester, while the relative permeability coefficient of the sample was produced by adding 3 wt.% Ni decreased by 25%.

When the electric and magnetic field distribution formed on the samples during the test is examined, it is seen that the electric field distribution is higher at the points close to the electrodes, while the magnetic field distribution is the highest around the points where the current flows, as expected. While the maximum value of the electric field distribution was obtained for the pure polyester sample, it can be determined that the amount of electric field decreases up to 43.8% of the maximum value in all samples obtained by incorporating additives to the pure polyester. It is observed that the greatest magnetic field was formed on the 3 wt.% ZnO-added sample, on which the current flows the most, and the smallest on the sample with the Ni additives. Evaluating the current values flowing through the samples in Fig. 9 and the maximum amount of magnetic field formed on the samples in Fig. 12 together shows that the maximum value of the magnetic field is related to the current flowing through the sample.

Future studies are planned to investigate the effect of additives on the wettability and mechanical properties of the produced samples.

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S. Nisanci was born in Isparta, Turkey, in 1993. He received the B.S. and M.S. degrees from University of Istanbul, Istanbul, Turkey, in 2017 and 2021, respectively, both in Electrical and Electronics Engineering. Since 2020, he works as a research Assistant at the Department of Electrical and Electronics Engineering, Turkish-German University, Istanbul, Turkey. He is currently pursuing his Ph.D in Telecommunications at Istanbul Technical Universy, Istanbul, Turkey. His research interests include polymeric materials, high voltage techniques, and electromagnetic theory.

Mehmet İpekoğlu graduated from Istanbul German High School in 1997. He completed his undergraduate, graduate, and doctorate studies in Mechanical Engineering at Boğaziçi University in 2001, 2004, and 2011, respectively. He worked as a research assistant at Boğaziçi University Materials and Manufacturing Laboratory between 2002 and 2012. Mehmet İPEKOĞLU, who worked at Turkish-German University, Faculty of Engineering, Department of Mechatronics Engineering between 2012 and 2019, has been working in the Department of Mechanical Engineering since 2019.

M. H. Nisanci was born in Istanbul, Turkey, in 1983. He received the B.S. and M.S. degrees from Suleyman Demirel University, Isparta, Turkey, in 2006 and 2009, respectively, both in Electronic and Telecommunication Engineering and the Ph.D. degree in Electrical Engineering at University of L'Aquila, L'Aquila, Italy, in 2013. Since November 2013, he has been working as an Associate Professor at the Department of Electrical and Electronics Engineering, Sakarya University, Sakarya, Turkey. He was involved in the research activities at the UAq EMC Laboratory from February 2007 to March 2009, L'Aquila, Italy. His recent research has focused on electromagnetic band-gap structure design and modeling of the biphasic composite structures containing spherical or cylindrical inclusions. In addition, he has developed several numerical techniques allowing the fast evaluation of Debye parameters from well-known Maxwell Garnett mixing rule, which have potential applications in numerical electromagnetic simulators, especially time-domain algorithms. He is also extending his research to include grooved covers and/or cavities design.

Mustafa Karhan received Ph.D. degree in Electrical and Electronics Engineering from Istanbul University, Turkey, in 2017. From 2008 to 2012, he worked as a research assistant in the Electronics and Communication Engineering Department at Namık Kemal University. From 2012 to 2013, he worked as a lecturer in Electronics and Automation Department at Bingöl University. From 2013 to 2018, he worked as a lecturer in Electronics and Automation Department at Çankırı Karatekin University. He is currently working as an Assistant Professor in Electronics and Automation Department at Çankırı Karatekin University. His research interests include the aging of polymeric insulators, dielectric materials, image processing, machine learning, high voltage, dielectric phenomena, and wettability behavior.

Mukden Uğur is a professor at the Robotics and Intelligent Systems Department of Turkish-German University, Istanbul, Turkey. He graduated from Yıldız Technical University, Department of Electrical Engineering in 1991. In 1993, he received a M.Sc. Degree from UMIST and obtained his Ph.D. in Electrical Engineering in 1997 from the University of Manchester, UK. From 1995 to 1996, he worked as a research assistant for the National Grid Company in the subject of analyzing the breakdown process in transformer boards. Between 1998 and 2018, he worked in the Electrical & Electronics Department of Istanbul University. His main research interests are electrical insulation, dielectric materials, power systems protection, fractal modeling, and statistical evaluation of breakdown. Dr.Uğur has published more than 30 research articles in international journals and 60 conference proceedings and also supervised 6 PhD and 11 MSc theses.