UDC 621.315 https://doi.org/10.20998/2074-272X.2026.2.11

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Influence of zinc oxide nanoparticles on flashover voltage of unsaturated polyester resin-based composites for electrical insulators

Introduction. *Polyester-based composites are increasingly used in electrical applications for their insulation, mechanical, and thermal properties. Nanofillers have shown promise in enhancing the properties of polymer-based composites.* ***Goal.*** *This study aims to improve the flashover voltage of unsaturated polyester resin (UPR)-based composites by incorporating zinc oxide (ZnO) nanoparticles.* ***Methodology.*** *UPR/ZnO nanocomposites were prepared with various ZnO nanofiller ratios (0 %, 1 %, 3 %, 5 %, and 7 % by weight) with different sample lengths (0.5, 1.5, 2, and 2.5 cm). The flashover voltage was measured for the pure UPR sample and each composition of the studied filler ratios at various sample lengths. X-ray diffraction analysis was performed. A curve-fitting method was applied to estimate the flashover voltage of UPR/ZnO nanocomposites containing intermediate filler ratios between those experimentally tested.* ***Results.*** *Incorporation of ZnO nanofillers significantly enhanced the flashover voltage of polyester-based nanocomposites. The pure UPR sample exhibited the lowest flashover voltage, whereas the composite with 7 wt.% ZnO nanofiller demonstrated the highest. Notably, increasing the sample length further improved flashover voltage.* ***Scientific novelty.*** *This study examines the influence of ZnO nanoparticles on the flashover voltage of UPR-based composites.* ***Practical value.*** *The obtained findings can contribute to the development of polyester-based nanocomposite insulators with enhanced flashover voltage.* References 26, tables 3, figures 6.

Key words: **unsaturated polyester resin, zinc oxide, filler, nanocomposites, flashover voltage, curve fitting technique**.

Вступ*. Композити на основі поліестеру все частіше використовуються в електротехніці завдяки своїм ізоляційним, механічним та тепловим властивостям. Нанонаповнювачі виявилися перспективними для покращення властивостей композитів на основі полімерів.* ***Мета****. Це дослідження спрямоване на підвищення напруги пробою композитів на основі ненасиченої поліефірної смоли (UPR) шляхом включаючи наночастинок оксиду цинку (ZnO).* ***Методика****. Нанокомпозити UPR/ZnO були виготовлені з різними масовими частками нанонаповнювача ZnO (0 %, 1 %, 3 %, 5 % та 7 % за масою) з різною довжиною зразків (0.5, 1.5, 2 та 2.5 см). Напругу пробою вимірювали для чистого зразка UPR та кожної композиції з досліджуваними концентраціями наповнювача при різній довжині зразків. Було проведено рентгенівський дифракційний аналіз. Метод апроксимації кривих було застосовано для оцінки напруги пробою нанокомпозитів UPR/ZnO з проміжними концентраціями наповнювача між експериментально дослідженими.* ***Результати****. Включення нанонаповнювачів ZnO суттєво підвищило напругу пробою поліефірних нанокомпозитів. Чистий зразок UPR продемонстрував найнижчу напругу пробою, тоді як композит із 7 мас.% нанонаповнювача ZnO показав найвищу. Примітно, що збільшення довжини зразка додатково підвищувало напругу пробою.* ***Наукова новизна****. У дослідженні розглянуто вплив наночастинок ZnO на напругу пробою композитів на основі UPR.* ***Практична значимість****. Отримані результати можуть сприяти розробці поліефірних нанокомпозитних ізоляторів із підвищеною напругою пробою.* Бібл. 26, табл. 3, рис. 6.

Ключові слова: **ненасичена поліефірна смола, оксид цинку, наповнювач, нанокомпозити, напруга пробою, метод апроксимації кривої.**

Introduction. Insulators are crucial to the safety and reliability of power networks [1, 2]. As power systems continue to evolve to meet increasing energy demands and incorporate renewable energy sources [3–8], the selection of suitable insulation materials becomes critical to ensuring high performance and long-term reliability [9–12].

Traditional insulation materials such as ceramic, glass, and porcelain have been widely used since the late 1880s due to their high electrical resistance and dielectric properties. However, these materials exhibit several drawbacks, including fragility, brittleness, high weight, susceptibility to environmental factors, complex manufacturing processes, high production costs, aging effects, and, in the case of porcelain, water absorption [13].

To address these challenges, researchers have investigated polymeric-based insulators [14]. These polymeric-based insulators offer significant advantages over conventional ceramic insulators, including enhanced hydrophobicity, lighter structures that facilitate easier installation, and greater resistance to environmental degradation [15, 16].

Unsaturated polyester resins (UPRs). UPRs are widely used in electrical insulation due to their excellent physical properties, ease of processing, and cost-effectiveness. Upon curing, these resins form a solid structure with outstanding durability and mechanical strength [17–19].

Micro- and nanoscale inorganic fillers are widely used to enhance the performance of polymeric materials. Their incorporation improves mechanical strength [20], thermal stability, and dielectric properties, making polymeric-based composites highly suitable for advanced electrical insulation applications [13, 21, 22].

Goal. This study aims to improve the flashover voltage of unsaturated polyester resin (UPR)-based composites by incorporating zinc oxide (ZnO) nanoparticles.

UPR/ZnO nanocomposite samples were fabricated with different ZnO ratios (0 %, 1 %, 3 %, 5 %, and 7 % by weight), and their flashover voltages were measured for samples with various lengths (0.5, 1.5, 2, and 2.5 cm).

X-ray diffraction (XRD) was used to characterize the structural properties of the prepared samples.

A curve-fitting approach was employed to predict the flashover voltage of UPR/ZnO nanocomposites with intermediate filler ratios between the studied filler ratios.

Materials. The following materials were used:

- UPR, supplied by Egyptian British Co.
- ZnO nanoparticles, obtained from Nano Tech Egypt, with an average particle size of 30±5 nm.
- Ethyl alcohol (70 %), used as a reactive diluent.
- Methyl ethyl ketone peroxide (MEKP), which served as the hardener and was utilized as an initiator

agent. It has a density of 1.18±0.005 g/cm^3 and a viscosity of 23–25 mPa·s.

- Cobalt naphthenate, used as an accelerator.

To ensure accurate composition ratios, all weight measurements for UPR and ZnO were performed using a Sartorius analytical balance with a precision of 0.1 mg.

Preparation of pure UPR samples. UPR was dissolved in 70 % ethyl alcohol using a magnetic stirrer for 8 min. Subsequently, MEKP was added as an initiator, and the mixture was stirred for an additional 8 min. Cobalt naphthenate was added as an accelerator to initiate the curing process of the polyester resin before reinforcement. The mixture was stirred to ensure homogeneous distribution of the catalyst and initiator within the matrix, without any filler. The samples were molded into cylindrical rods (1.5 cm diameter) with lengths of 0.5 cm, 1.5 cm, and 2 cm at an ambient temperature of 25 °C [17].

Preparation of the UPR/ZnO nanocomposite samples. UPR/ZnO nanocomposites with various ZnO nanoparticle ratios were prepared by first dispersing ZnO nanoparticles in ethanol. This dispersion was subjected to ultrasonic vibration at 1500±50 rpm for 30 min, while also using mechanical agitation. ZnO nanoparticles were added to the UPR matrix at weight fractions of 1 %, 3 %, 5 %, and 7 %, relative to the total composite weight. After this, UPR and the initiator (MEKP) were gradually added to the solution. The mixture was then stirred vigorously for 10 min. Then, the accelerator (cobalt naphthenate) was added, and the mixture was stirred further to ensure even dispersion of ZnO throughout the resin. The resulting compositions were poured into cylindrical plastic molds with lengths of 0.5 cm, 1.5 cm, and 2 cm and a fixed diameter of 1.5 cm. After curing, the samples were prepared for each testing technique [17]. Preliminary trials showed that ZnO ratios above 7 wt.% caused a significant increase in viscosity. This made casting difficult and hindered uniform dispersion due to nanoparticle agglomeration.

The curing process was carried out at ambient temperature (~ 25 °C) using 1 wt.% MEKP and 0.5 wt.% cobalt naphthenate. No significant mass loss was detected before or after curing (< 0.1 %). This indicates that no low-molecular-weight decomposition products were released during the crosslinking process.

UPR weight ratios and ZnO nanofiller weight ratios, and the corresponding sample names are listed in Table 1.

Table 1

UPR weight ratios and ZnO nanofiller weight ratios, and the corresponding sample names

Sample name	% ratio of UPR by weight	% ratio of ZnO nanofiller by weight
P (Pure UPR)	100 %	0
Z1	99 %	1 %
Z3	97 %	3 %
Z5	95 %	5 %
Z7	93 %	7 %

XRD analysis. X-ray Diffraction (XRD) analysis was performed to assess the dispersibility of ZnO nanoparticles in the different prepared samples. XRD analysis was performed using an EMMAO 143 X-ray diffractometer (GBC, Australia) with a Bragg's angle (2θ) scanning range of 0°–80°. The XRD patterns of pure polyester, ZnO nanoparticles, and UPR/ZnO nanocomposites are shown in Fig. 1.

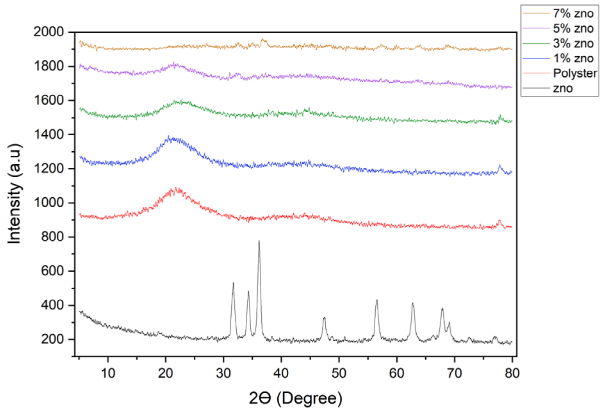

Fig. 1. XRD of pure polyester, ZnO nanoparticles and UPR/ZnO nanocomposites

According to Fig. 1, the presence of crystalline ZnO was confirmed by reflections at 2θ angles of 31.8°, 34.4°, 36.3°, 47.5°, 56.6°, and 62.8° [23]. The pure polyester intensity peak at 22.66° decreased as the ZnO content increased, indicating a uniform dispersion of ZnO nanoparticles [24, 25].

Flashover test. The flashover test is a critical method for evaluating the electrical properties of materials, particularly for outdoor insulators [15]. This test provides key characteristics of the studied UPR/ZnO nanocomposites, assessing their ability to withstand applied voltages.

Testing apparatus for flashover voltage. The AC flashover voltage test was performed using a high-voltage (HV) transformer (Terco HV 9105), which operates at 100 kV, 5 kVA, and 50 Hz. The voltage applied to the transformer's primary winding was regulated using a variac (0–250 V) controlled by a smooth control panel. Two electrodes were securely fixed on the samples, ensuring parallel alignment without defects. The transformer's LV side incorporated a safety circuit to disconnect the supply and prevent excessive current during flashover. The tests were conducted in the HV laboratory at Aswan University. To protect the HV transformer from high current surges during flashover, a 2.8 MΩ resistor was connected in series with the secondary winding of the transformer. The schematic diagram of the implemented flashover test platform is illustrated in Fig. 2 [26].

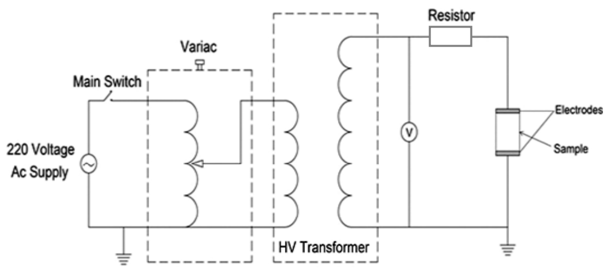

Fig. 2. Schematic diagram of flashover voltage test platform

Results and discussion. Flashover voltage measurements were conducted on the studied samples, with different sample lengths (0.5 cm, 1.5 cm, 2 cm, and

2.5 cm), at room temperature (25 °C) under normal dry weather conditions. The AC voltage increased steadily at 0.5 kV/s until breakdown occurred. Each sample was tested 10 times to ensure accuracy; the mean flashover voltages were calculated and listed in Table 2.

Table 2
Mean flashover voltage for the studied samples with different lengths

Sample	Sample length			
	0.5 cm	1.5 cm	2 cm	2.5 cm
	Mean flashover voltage, kV			
P	7.379	27.692	34.482	40.097
Z1	7.386	28.463	35.647	41.113
Z3	8.011	30.163	37.613	43.960
Z5	9.124	32.051	39.764	46.048
Z7	12.000	35.752	43.350	47.928

For all samples with different lengths, results showed that the flashover voltage increased directly with the increase in the ratio of ZnO filler. Sample Z7 exhibited the highest flashover voltage, whereas pure polyester had the lowest value. Additionally, the results showed that the flashover voltage increased directly with the increase in sample length.

For samples 0.5 cm in length, sample Z7 achieved an improvement in the flashover voltage of 62.624 % over pure polyester. For samples 1.5 cm in length, Z7 achieved an improvement in flashover voltage of 29.1 % compared to pure polyester.

For samples 2 cm in length, sample Z7 achieved an improvement in flashover voltage of 25.72 % compared to pure polyester. For samples of 2.5 cm in length, Z7 achieved an improvement in the flashover voltage of 25.72 % compared to pure polyester.

Curve fitting and flashover voltage prediction. Accurate prediction of flashover voltage for UPR/ZnO nanocomposites is essential due to the high cost of raw materials. To address this, 3rd- and 4th-degree polynomial regressions were implemented using MATLAB to estimate the flashover voltage of UPR/ZnO nanocomposites with intermediate ZnO ratios between the studied ratios, which were not prepared. These models were developed using the experimental results of the studied samples with various weight ratios of ZnO nanoparticles (0 %, 1 %, 3 %, 5 %, and 7 %) across four lengths (0.5, 1.5, 2, and 2.5 cm). Based on the root mean square error (RMSE) criterion, the 4th-degree polynomial showed the optimal fit, providing the highest accuracy and minimal deviation across all sample dimensions.

Flashover voltage of UPR/ZnO nanocomposites for various samples by the curve fitting technique. The following 4th-degree polynomial equation represents the best curve-fitting model for the dataset:

$$y = P_1 X^4 + P_2 X^3 + P_3 X^2 + P_4 X + P_5, \quad (1)$$

where y is the flashover voltage; X is the percentage ratio of the ZnO nanofiller; $P_1 - P_5$ are the coefficients. Detailed results for each sample length are next.

Flashover voltage of 0.5 cm length samples. *Mathematical model*: coefficients of (1) would be: P_1= 0.0049613095, P_2= –0.0528184524, P_3 = 0.248610119, P_4= –0.1937529762, P_5= 7.379.
Statistical indicators: RMSE = 0.0 kV, R^2 = 1.0.

Figure 3 shows that the fitted curve accurately represents the flashover voltage data for the samples of 0.5 cm in length.

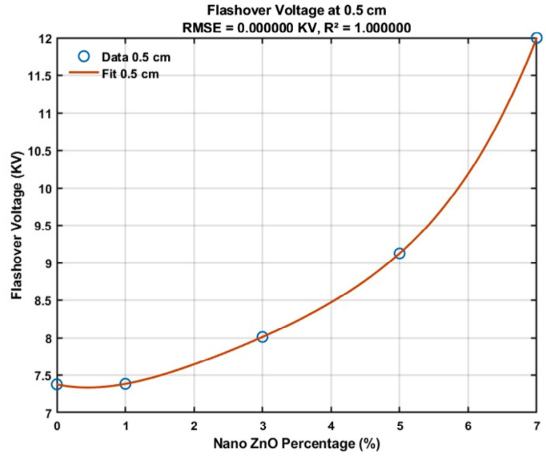

Fig. 3. Fitted curve results for the flashover voltage versus various weight percentages of nano ZnO filler for 0.5 cm length samples

Flashover voltage of 1.5 cm length samples. *Mathematical model*: coefficients of (1) would be: P_1= 0.0049172619, P_2 = –0.0448220238, P_3 = 0.1416970238, P_4 = –0.6692077381, P_5 = 27.692.
Statistical indicators: RMSE = 0.0 kV, R^2 = 1.0.

Figure 4 shows that the fitted curve accurately represents the flashover voltage data for the samples of 1.5 cm in length.

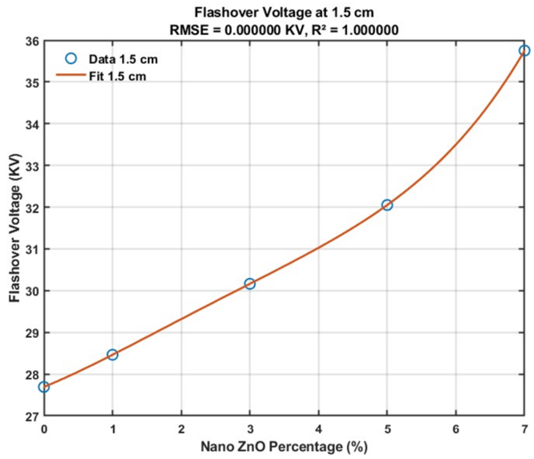

Fig. 4. Fitted curve results for the flashover voltage versus various weight percentages of nano ZnO filler for 1.5 cm length samples

Flashover voltage of 2 cm length samples. *Mathematical model*: coefficients of (1) would be: P_1= 0.0013261905, P_2 = 0.004822619, P_3 = – 0.097197619, P_4 = 1.2560488095, P_5 = 34.482.
Statistical indicators: RMSE = 0.0 kV, R^2 = 1.0.

Figure 5 shows that the fitted curve accurately represents the flashover voltage data for the samples of 2 cm in length.

Flashover voltage of 2.5 cm length samples. *Mathematical model*: coefficients of Eq. (1) would be: P_1= 0.0082315476, P_2= – 0.1202255952, P_3= 0.5097255952, P_4 = 0.6182684524, P_5 = 40.097.
Statistical indicators: RMSE = 0.0 kV, R^2 = 1.0.

Figure 6 shows that the fitted curve accurately represents the flashover voltage data for the samples of 2.5 cm in length.

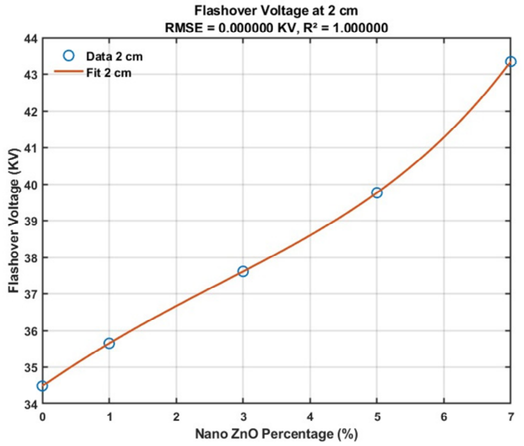

Fig. 5. Fitted curve results for the flashover voltage versus various weight percentages of nano ZnO filler for 2 cm length samples

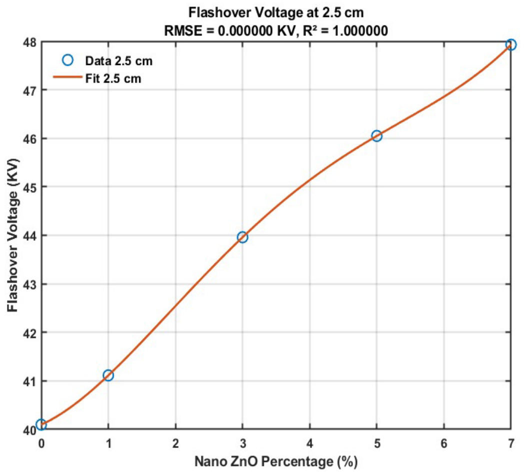

Fig. 6. Fitted curve results for the flashover voltage versus various weight percentages of nano ZnO filler for 2.5 cm length samples

Prediction of flashover voltage. Using the best-fit equations obtained from the curve-fitting technique, the prediction of flashover voltage for unmanufactured samples with intermediate ratios of nano ZnO filler (in the range of 0 % to 7 % by weight) is presented in Table 3.

Table 3

Predicted flashover voltage for several intermediate ZnO nanofiller ratios

Sample length, cm	% ratio of ZnO nanofiller by weight	Predicted flashover voltage, kV
0.5	2	7.643
1.5	2	29.317
2.0	4	38.599
2.5	6	46.856

Conclusions. This study investigated the impact of incorporating ZnO nanofiller on the flashover voltage of unsaturated polyester resin (UPR)-based nanocomposites. To evaluate the effect of ZnO, UPR/ZnO nanocomposites were prepared with different ZnO nanofiller ratios (0 %, 1 %, 3 %, 5 %, and 7 % by weight) and various sample lengths (0.5, 1.5, 2, and 2.5 cm). Experimental trials indicated that preparing UPR/ZnO nanocomposites with ZnO contents exceeding 7 wt.% was extremely challenging due to the significant increase in viscosity, which hindered proper casting and promoted filler agglomeration. XRD analysis confirmed the successful incorporation and adequate dispersion of the ZnO nanofiller within the polymer matrix. Flashover voltage measurements were conducted under identical dry conditions to ensure consistency. A curve-fitting approach based on 3rd- and 4th-degree polynomial regressions was implemented to predict the flashover voltage of unprepared UPR/ZnO nanocomposites of intermediate ZnO ratios between the studied ratios. Based on the RMSE criterion, the fourth-degree polynomial model provided the highest prediction accuracy with minimal deviation. The key findings can be summarized as follows:

1. Pure polyester exhibits the lowest flashover voltage among all tested samples.
2. Incorporation of nano-ZnO filler significantly enhanced the flashover voltage of UPR/ZnO-based nanocomposites.
3. Flashover voltage increased proportionally with increasing ZnO filler content up to 7 wt.%.
4. UPR/ZnO composites containing 7 wt.% nano ZnO filler demonstrated the highest flashover voltage among all the prepared samples for all sample lengths.
5. Flashover voltage increased with increasing sample length.
6. The polynomial regression model proved to be an effective predictive tool, minimizing the need for additional costly experimental investigations.

Conflict of interest. The authors declare that they have no conflicts of interest.

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Received 08.04.2025
Accepted 06.10.2025
Published 02.03.2026

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How to cite this article:
Rihan M., Ghazzaly A., Ebnalwaled A.A., Fahmy A.H., Nasrat L.S. Influence of zinc oxide nanoparticles on flashover voltage of unsaturated polyester resin-based composites for electrical insulators. *Electrical Engineering & Electromechanics*, 2026, no. 2, pp. 84-88. doi: https://doi.org/10.20998/2074-272X.2026.2.11