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Grain size effects on the behavior of silicone rubber high voltage power cables using seagull optimization algorithm

Shaymaa Ahmed Qenwy[1], Saud Abdulaziz Aldossari[2], Kareem AboRas[2], Loai Saad Eldeen Nasrat[3], Ahmed Hossam-Eldin[2]
[1]Department of Electrical Power Engineering and Control, Pyramids Higher Institute for Engineering and Technology, Giza, Egypt
[2]Department of Electrical Engineering, Alexandria University, Alexandria, Egypt
[3]Department of Electrical Engineering, Aswan University, Aswan, Egypt

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ABSTRACT

High voltage insulation is one of the most important components of electrical power systems. Polymeric materials have lately supplanted ceramic materials as insulating materials due to their low weight, straightforward structure, high mechanical strength, good performance in the presence of pollution, ease of transportation, and ability to enhance voltage. The purpose of this thesis is to add micro and nano-sized aluminum oxide (Al_2O_3) fillers to silicone rubber (SIR) to enhance its electrical characteristics. Micro Al_2O_3 filler with contents of 10wt%, 20wt%, 30wt%, and 40wt% was combined with nano Al_2O_3 with contents of 1wt%, 3wt%, 5wt%, and 7wt% to create samples of SIR composites. The composites' dielectric strength is evaluated in a variety of environments, including dry, wet, low-salt wet, and high-salt wet circumstances. In order to boost the insulator's dielectric strength under diverse environmental conditions, this research aims to develop a weight ratio composition for such a composite. The ideal concentration of nano or micro Al_2O_3 fillers has been calculated using the whale optimization algorithm (WOA) and seagull optimization algorithm (SOA).

Corresponding Author:

Shaymaa Ahmed Qenwy
Department of Electrical Power Engineering and Control
Pyramids Higher Institute for Engineering and Technology
Fardoos, Giza, Egypt
Email: shaymaa.qenawy@yahoo.com

1. INTRODUCTION

High voltage insulators come in a variety of shapes and sizes, including pin, suspension, and pressure insulators, but their primary purpose is always to keep the tower's columns from coming into direct contact with the ground [1]. Polymeric materials have recently supplanted inorganic materials used in manufacturing, including insulators like glass and ceramics [2]. Polymeric materials have lately supplanted ceramic materials as insulating materials due to their light weight, straightforward construction, high mechanical strength, good performance in the presence of pollution, ease of transportation, and ability to enhance voltage. Despite these benefits, there are some drawbacks as well. For example, it might be challenging to determine a product's life expectancy and to identify defective insulators because it is hard to check for flaws or damage [3]. Exposure to chemical changes on the polished surface and to dry tape arcing or flash are two additional drawbacks.

For applications requiring external insulation, silicone rubber (SIR) utilization has increased steadily. SIR provides advantageous properties for exterior insulation compared to traditional materials like glass and porcelain [4]–[6]. Simpler installation, less weight, and strong performance against pollution are a few examples of advantages [4], [5]. The hydrophobic surface property, in particular, avoids wetting and increases robustness against pollutants [6].

The addition of various fillers to base SIR has been contemplated as a remedy for tracking problems [7]–[12]. According to reports, these fillers could boost the resistance to tracking by enhancing polymeric materials' thermal conductivity [7] and thermal stability [8], [9] characteristics. The addition of micro-sized alumina tri-hydrate (ATH) or silica particles to SIR has frequently been thought about [7], [10], [13] for tracking resistance enhancement. The enhanced heat conductivity relative to pure SIR has been used to explain the higher tracking resistance of such SIR micro composites [13].

The demand for of nanocomposites, a brand-new class of reinforced polymers made by incorporating nanoparticles into a polymeric matrix, has grown during the past ten years [14]. Nanoparticles are responsible for the distinctive and extraordinary features of nanocomposite coatings due to their high reactivity and vast specific surface area. Utilizing nanoparticles sparingly can enhance the hydrophobicity, flame resistance, and ultraviolet (UV) resistance of coatings [15]–[17]. These coatings can be applied to any surface to treat it as well. The choice of the base polymer, the nature of the nanoparticles (both in terms of size and quantity), the optimization of the production process, and the verification of the homogeneous dispersion of nanoparticles within the polymeric matrix are challenges that are frequently encountered during the development of nanocomposites [18].

The level of nanoparticle aggregation in a sample is an indication of how well the particles were dispersed. The capacity to create production procedures that encourage the homogenous and repeatable dispersion of nanoparticles inside nanocomposites is one of the constraints on the development of nanocomposites. The number and size of the aggregates grow with poor dispersion, degrading the materials' characteristics [19]–[21].

Nanoparticles may be added to the underlying polymer to improve various properties of the silicone rubber and cut expenses. These particles can be added to the composite silicone to increase its relative permittivity, surface hydrophobicity, and electrical conductivity [22], [23]. Semiconductor materials like titanium dioxide (TiO_2) or zinc oxide (ZnO) nanoparticles can help ensure the homogeneity and dispersion of electric fields on the insulators in order to reduce the surface flashover of insulators [19].

Considering this, the current work examines the dielectric behavior of SIR reinforced with varying levels and sizes of aluminum oxide (Al_2O_3). The goal of this research is to develop a weight ratio composition for such a composite that will increase the insulator's dielectric strength under various environmental circumstances. The ideal concentration of micro and nano Al_2O_3 filler has been estimated using the whale optimization algorithm (WOA) and seagull optimization algorithm (SOA) approaches.

Based on the literature review, it is clear that many studies have been devoted to SIR micro and nanocomposites. However, less attention has been given to algorithms in optimizing the filler ratio to improve the electrical properties of the insulator. Previous studies on SIR focused on tracking and corrosion [4], [5], [8], [9], [19], hydrophobicity [6], [7], and dielectric properties [11], [13], [17], [23]. Therefore, in this contribution, due to the high raw materials (micro, nano Al_2O_3, and SIR), algorithms were used to find the ideal concentration of filler material. In this research, two types were used: WOA and SOA.

2. MATERIALS AND METHOD OF PREPARATION

2.1. Material

Many chemical components were used in this research. In the preparation of composite insulating materials, SIR was chosen as the polymeric matrix. Al_2O_3 was chosen as the filler material. The following are the materials used in this paper:

i) Sonax (A. Faroon Egypt S.A.E.), a German company, provided the SIR. High molecular weight polymers and rather long polymer chains can be found in solid SIR.
ii) A filler with a particle size of less than 20 m is utilized to improve several desired qualities.
iii) Nano Al_2O_3, a filler with a particle size of 20±5 nm, is employed to enhance several desired qualities.
iv) Nanotech Egypt provided the micro and nano fillers.

2.2. Composite preparation

To make SIR composites with different ratios of Al_2O_3 filler in micro and nano size filler (17wt%, 37wt%, 57wt%, and 7wt%), (107wt%, 207wt%, 307wt%, and 407wt%), respectively, all the formulae listed in Table 1 were combined. A sample of pure SIR is gathered for comparison. In a laboratory setting, the mixture is fed through a two-cylinder mill with a diameter of 470 mm and an operating distance of 300 mm. 1 mm is the constant distance between each cylinder. The samples are then vulcanized on a heated plate for 10 minutes at a temperature of 150°C and a pressure of 40 kg/cm^2.

Table 1. The mixing formulation of SIR with different micro and nano Al_2O_3 filler percentages

Material	Filler wt (%)	Acronym
Pure SIR	0	P
SIR+micro Al_2O_3	10wt%	SIR10
	20wt%	SIR20
	30wt%	SIR30
	40wt%	SIR40
SIR+nano Al_2O_3	1wt%	SIR1
	3wt%	SIR3
	5wt%	SIR5
	7wt%	SIR7

2.3. Dielectric strength test

The dielectric strength of a material is commonly expressed in voltage gradient measures such as voltage per thickness (kV/mm), and it is the maximum electric field strength that a material can withstand without degrading or failing to maintain its insulating properties [24]. Alternating current (AC) voltage has been used to prepare and test sets of composite samples. To reduce inaccuracy, the average score from 3 samples of each test has been used. To ensure the accuracy of the results, each sample has undergone various tests. For the dielectric strength test, samples are made into discs with a diameter of 5 cm and a thickness of 1 mm. The samples were examined under various meteorological circumstances that can be categorized as:

i) AC voltage was used to examine the initial sample set in dry conditions.
ii) In order to use AC voltage to simulate rain and other atmospheric moisture, the second set of the sample was submerged in distilled water.
iii) To mimic coastal environments, the third group was submerged in sodium chloride solution. Two volumes of saline, 30,000 s/cm and 50,000 s/cm, were produced for this experiment.

The main board supplies the single-phase high voltage auto transformer (Terco type HV 9105), which has a primary output of 100 kV-5 kVA-50 Hz, with high-voltage AC power as shown in Figure 1. Variac (0-220 V) controls the main board. A resistor was connected to the secondary winding of the high voltage testing transformer in order to protect it from the test's high current. The sample and a brass cylindrical electrode with a 25 mm diameter are both attached to the transformer. The electrodes' faces were parallel and free of any blemishes or other flaws. The cylindrical electrode is depicted in Figure 2.

Figure 1. High voltage auto transformer used in dielectric strength test

Figure 2. Cylindrical electrode with a diameter of 25 mm used in dielectric strength test

A (0-250 V) variac, which controls the voltage delivered to the transformer's primary winding, is used to control the output voltage of the transformer through a control desk as illustrated. The desk includes operational and signal components for the test equipment's control circuit for warning and safety. The measurement devices (peak, impulse, and direct current (DC) voltmeters) are made to be stored on the control desk. The usual test sample thickness is 1 mm, and it should be in the shape of a disc. A sphere with a diameter of 20 mm on the high voltage side and a sphere with a diameter of 20 mm on the low voltage side made up the electrode composition (the test technique followed IEC 60156).

2.4. Whale optimization algorithm

A swarm-based intelligent algorithm called WOA is suggested for challenges involving continual optimization. Recent meta-heuristics techniques have demonstrated that it performs better [25]. For instance, it is simple to construct and reliable compared to other swarm intelligence techniques, which makes it comparable to several nature-inspired algorithms. The method requires fewer control settings; only one parameter, the time interval, needs to be changed. Figure 3 illustrates how the WOA's humpback whale population looks for food in a multidimensional space. Despite the fact that each whale's position is represented as a unique decision component, the distance between a humpback whale and its food correlates to the value of objective cost. It should be highlighted that three operational processes are used to detect the time-dependent location of a whale individual: shrinking encircling prey, bubble-net attacking method (exploitation phase), and search for prey (exploration phase) [25].

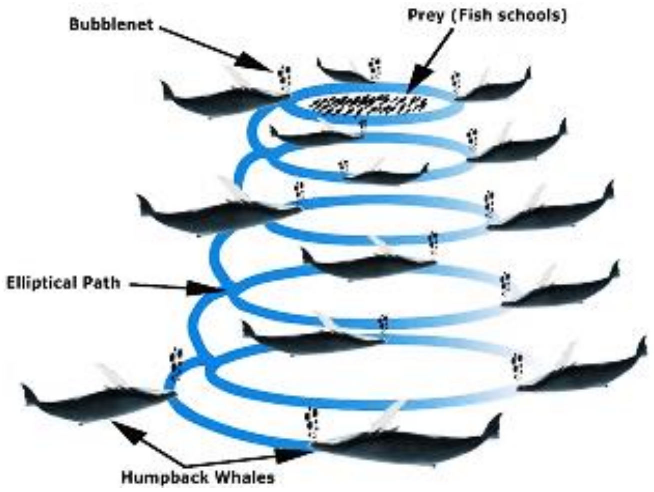


Figure 3. Humpback whale feeding practices using bubble-nets

2.5. Seagull optimization algorithm

Seagulls can migrate and attack on their own volition. Seasonal long-distance travel from one location to another is called migration. To prevent collisions when moving, seagulls start out in various spatial locations. When migrating in groups, the seagull with the best circumstances takes the lead, and the other seagulls follow to update their current location. Foraging is how the attack seems, with a spiral motion similar to that used to attack the prey. By continuously updating the seagull positions, SOA was utilized to develop a mathematical model for these two behaviors and repeatedly look for the best answer. A brand-new metaheuristic called the SOA was put forth by Dhiman and Kumar [26] and simulates the natural behavior of seagulls, including migration and attack.

3. RESULTS AND DISCUSSION

3.1. Dielectric strength test

One method for describing the electrical properties of SIR composites is the dielectric strength test. To investigate the electrical characteristics of composite materials, the dielectric strength test is used to micro and nanoscale composite samples [27]. The highest electric field strength that an insulating material can withstand without degrading, or failing to maintain its insulating qualities, is known as its dielectric strength. Although SIR is an insulator, adding filler will improve the material's electrical, mechanical, physical, and thermal characteristics. The filler that offers the optimum electrical properties is determined by the dielectric strength test for several composite samples. SIR composites are made into discs with a diameter of 5 cm using a lathe machine and manual labor. The concentration is added at a rate of 1wt% to7 wt% for nanofillers and 10wt% to 40wt% for microfillers. The dielectric strength test, which is destructive in nature since current is delivered through the sample between two electrodes, perforates it. Prior to deterioration, the samples were monitored for status by measuring their dielectric strength under AC voltage. Each sample was examined three times, and the average was used to eliminate error to ensure the results were accurate. The dielectric strength of micro and nano Al_2O_3 composite materials investigated in a dry environment is represented experimentally in Figure 4. The procedure employed to check on the samples' condition before they degraded was to measure their dielectric strength under an AC voltage. Each sample was tested three times, with the average being calculated to decrease error and ensure the correctness of the results. Experimental results for micro and nano Al_2O_3 composite materials tested in a dry environment are shown in Figure 4.

Figure 4 shows that after adding SIR with 7wt% Al_2O_3, the highest dielectric strength value was 38.49 kV/mm. While the dielectric strength of pure SIR is at least 26.04 kV/mm. Additionally, it is evident that the dielectric strength of the micro and nano composite samples rises with increasing Al_2O_3 concentrations up to percentages of 30wt% for micro Al_2O_3 to reach 33.95 kV/mm and 7wt% for nano Al_2O_3, but falls when percentage increases higher than 30wt% for micro Al_2O_3. The concentration of micro and nano-Al_2O_3 filler increases, which increases the dielectric strength. The dielectric strength of SIR composite with nano Al_2O_3 filler is higher than SIR with micro Al_2O_3 filler. SIR without fillers exhibits a lower dielectric strength than SIR supplied with micro and nano Al_2O_3. This occurred because the chemical bonds in empty SIR broke down more quickly, creating a gap [28].

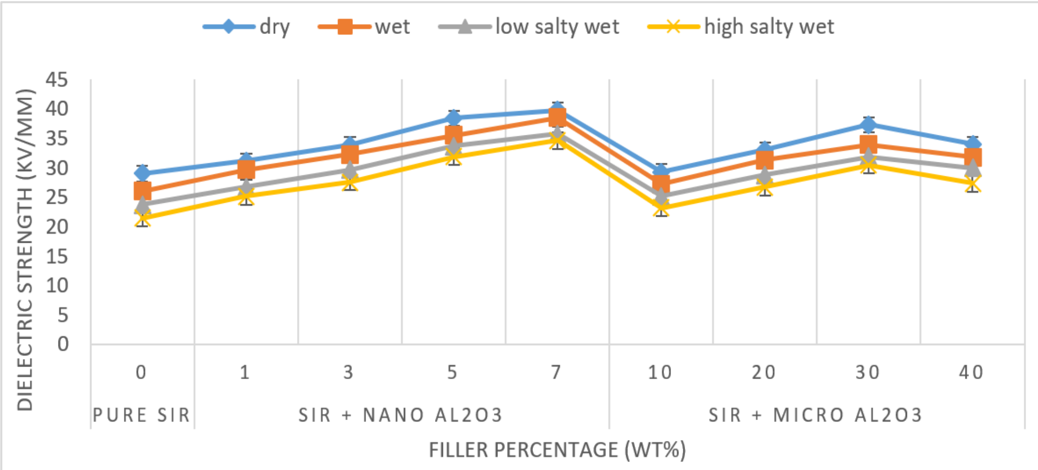


Figure 4. Dielectric strength (kV/mm) of SIR with different nano and micro Al_2O_3 filler percentages in different weather conditions

3.2. Optimization techniques

Although the experimental data is precise at certain points, it was nevertheless optimized to get the best filler value possible. The WOA and SOA simulation models are discussed in this portion in order to estimate the dielectric strength for the ideal concentration of micro and nano Al_2O_3 filler that might boost the dielectric strength of SIR. Experimental values of dielectric strength test must be entered the algorithm code, but algorithms deal with polynomial equations, not values. Therefore, MATLAB curve fitting has been used to find the polynomial equations, and then insert the equations into the code to find the best ratio of filler. Table 2 is a detailed explanation of the work steps.

To create a polynomial equation with the minimum squared error possible, the laboratory data from the practical experiment described in the preceding section was first imported into the MATLAB curve-fitting toolbox. Second, this polynomial equation is used to predict the ideal Al_2O_3 filler concentration to enhance the dielectric strength features of SIR in the WOA and SAO m files in the MATLAB software. A total of 100 iterations were included in the simulation for the algorithm for all test functions. The polynomial equations that were produced from the MATLAB curve-fitting code are shown in Table 2 so that they may be entered into the MATLAB optimization code to determine the ideal percentage of filler spread in SIR in various weather conditions.

Table 2. The polynomial equation obtained from curve-fitting

Material	Test condition	Polynomial equations	
SIR+micro Al_2O_3	Dry weather	$y = -0.2213x^4 + 1.7342x^3 - 3.1588x^2 + 0.9558x + 29.7$	(1)
	Wet weather	$y = 0.0479x^4 - 1.2158x^3 + 7.5621x^2 - 13.714x + 33.36$	(2)
	Low salty wet weather	$y = -0.0754x^4 + 0.3125x^3 + 1.0754x^2 - 2.8225x + 25.25$	(3)
	High salty wet weather	$y = -0.2171x^4 + 1.8942x^3 - 5.0429x^2 + 6.8858x + 17.92$	(4)
SIR+nano Al_2O_3	Dry weather	$y = -0.2617x^4 + 2.8233x^3 - 10.113x^2 + 16.662x + 19.9$	(5)
	Wet weather	$y = -0.1063x^4 + 1.3375x^3 - 5.8688x^2 + 13.438x + 17.24$	(6)
	Low salty wet weather	$y = -0.1604x^4 + 1.7642x^3 - 6.5646x^2 + 12.721x + 15.98$	(7)
	High salty wet weather	$y = -0.2767x^4 + 3.2983x^3 - 13.518x^2 + 25.327x + 6.61$	(8)

3.2.1. Applying WOA for micro Al_2O_3/SIR composite samples

Where x is the proportion of Al_2O_3 filler content in the samples and y is the dielectric strength value (kV/mm) under all possible situations. Applying WOA by adding (1) to (4) to the program's WOA code in various weather scenarios. Figure 5 shows WOA results for the optimal value of dielectric strength for micro Al_2O_3/SIR samples under different weather conditions. The greatest result for dielectric strength was 39.5140 kV/mm at 32.5400wt% of micro Al_2O_3 filler under dry conditions, as illustrated in Figure 5(a). As illustrated in Figure 5(b), the highest ideal result for dielectric strength was 35.947 kV/mm with 32.4712wt% of micro Al_2O_3 filler in a moist environment. The optimal dielectric strength value is 33.8520 kV/mm at 32.6462wt% of micro Al_2O_3 filler under low salty wet conditions as illustrated in Figure 5(c), and the optimal finding for dielectric strength is 32.0946 kV/mm at 32.1664 wt% of micro Al_2O_3 filler under low salty wet conditions as illustrated in Figure 5(d).

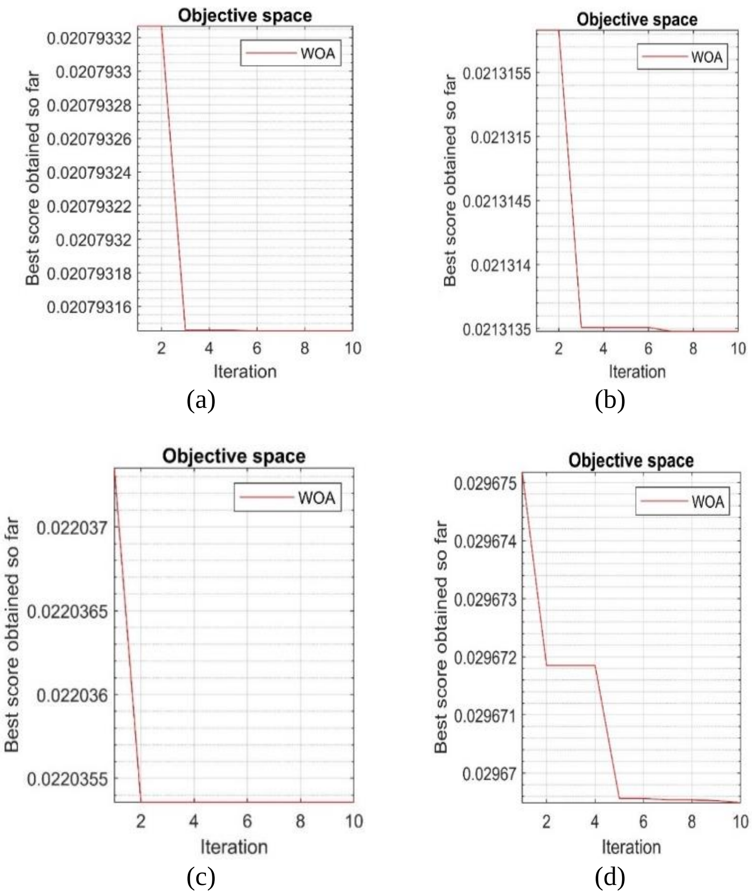
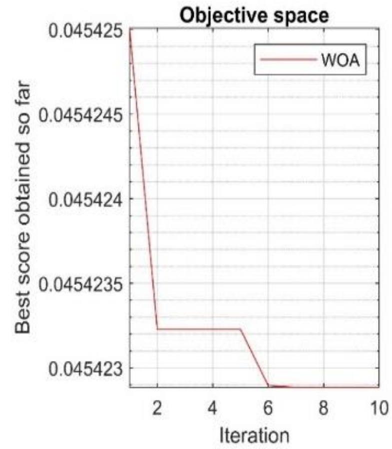


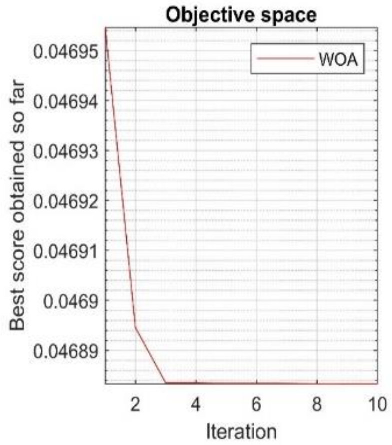
Figure 5. WOA findings for the best value of dielectric strength for micro Al_2O_3/SIR samples under; (a) dry condition, (b) wet condition, (c) low salty wet condition, and (d) high salty wet condition

3.2.2. Applying WOA for nano Al_2O_3/SIR composite samples

Where x is the proportion of Al_2O_3 filler content in the samples and y is the dielectric strength value (kV/mm) under all possible weather conditions. Applying WOA by adding (5) to (8) to the program's WOA code in various weather scenarios. Figure 6 shows WOA results for the optimal value of dielectric strength for nano Al_2O_3/SIR samples under different weather conditions. The highest ideal result for dielectric strength 42.2564 kV/mm at 6.0223wt% of nano Al_2O_3 filler under dry conditions is illustrated in Figure 6(a). As illustrated in Figure 6(b), the best ideal result for dielectric strength was 40.5493 kV/mm at 6.562wt% nano Al_2O_3 filler under wet conditions. The optimal dielectric strength value is 36.9792 kV/mm at 6.0238wt% of nano Al_2O_3 filler under low salty wet conditions, as illustrated in Figure 6(c), and the optimal finding for dielectric strength is 36.0454 kV/mm at 6.0109wt% of nano Al_2O_3 filler under low salty wet conditions as illustrated in Figure 6(d).



(a)



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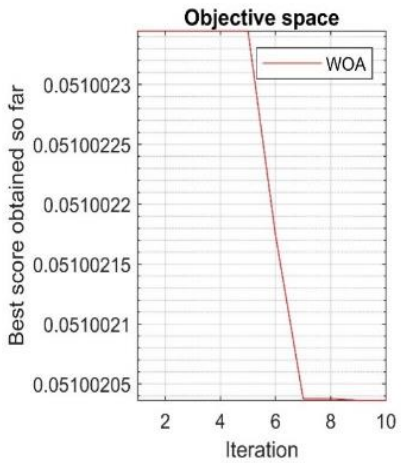
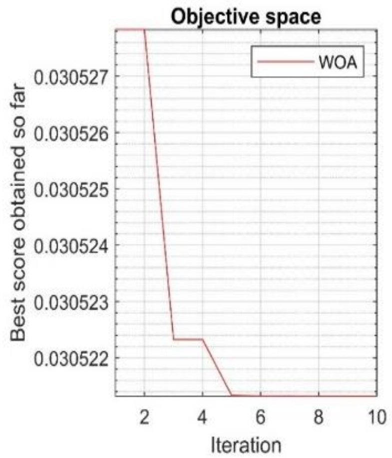


(c)



(d)

Figure 6. WOA findings for the best value of dielectric strength for nano Al_2O_3/SIR samples under; (a) dry condition, (b) wet condition, (c) low salty wet condition, and (d) high salty wet condition

3.2.3. Applying SOA for micro Al_2O_3/SIR composite samples

Applying SOA by adding (1) to (4) to the program's SOA code while varying the weather. Figure 7 shows SOA results for the optimal value of dielectric strength for micro Al_2O_3/SIR samples under different weather conditions. The greatest result for dielectric strength was obtained at 32.2208wt% of micro Al_2O_3 filler under dry conditions, as illustrated in Figure 7(a), and it was 40.2340 kV/mm. The best result for dielectric strength, as illustrated in Figure 7(b), was 34.8479 kV/mm with 32.8857wt% of micro Al_2O_3 filler in a wet environment. The best result for dielectric strength was 34.8479 kV/mm at 32.7698wt% of micro Al_2O_3 filler under low salty wet conditions, as shown in Figure 7(c), and the ideal dielectric strength value was 33.1256 kV/mm at 32.1792wt% of micro Al_2O_3 filler under high salty wet conditions, as illustrated in Figure 7(d).

3.2.4. Applying SOA for nano Al_2O_3/SIR composite samples

Applying SOA by adding (5) to (8) to the program's SOA code while varying the weather. Figure 8 shows SOA results for the optimal value of dielectric strength for nano Al_2O_3/SIR samples under different weather conditions. The greatest result for dielectric strength at 5.0223wt% nano Al_2O_3 filler under dry conditions is 42.9865 kV/mm, as illustrated in Figure 8(a). As illustrated in Figure 8(b), the highest ideal result for dielectric strength was 40.6861 kV/mm at 5.962wt% nano Al_2O_3 filler at wet conditions. And as shown in Figure 8(c), the best result for dielectric strength is 37.4796 kV/mm at 5.988wt% of nano Al_2O_3 filler under low salty wet conditions, and Figure 8(d) shows the optimal dielectric strength value of 36.9525 kV/mm at 6.0109wt% of nano Al_2O_3 filler under high salty wet conditions.

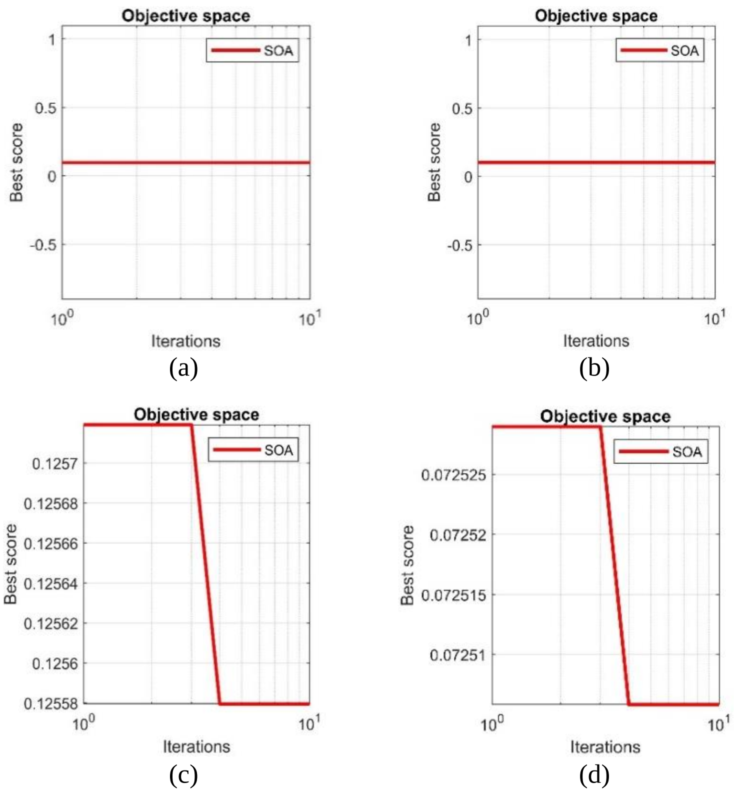


Figure 7. SOA findings for the best value of dielectric strength for micro Al_2O_3/SIR samples under; (a) dry condition, (b) wet condition, (c) low salty wet condition, and (d) high salty wet condition

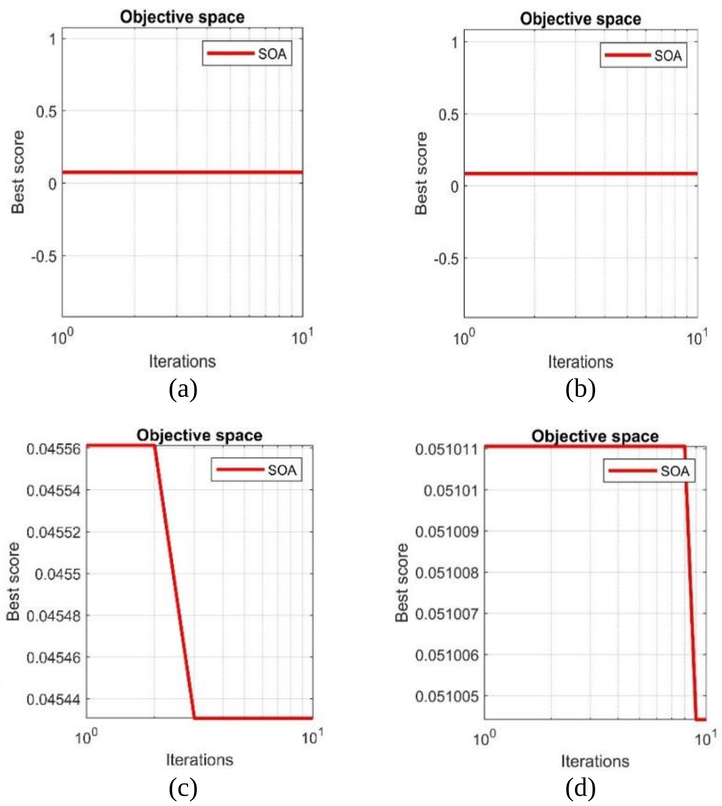


Figure 8. SOA findigs for the best value of dielectric strength for nano Al_2O_3/SIR samples under; (a) dry condition, (b) wet codition, (c) low salty wet condition, and (d) high salty wet condition

3.2.5. Comparison between different optimization techniques at different weather conditions

Figure 9 shows a comparison between WOA and SOA optimization techniques in different weather conditions. Many previous studies used methods such as the gray wolf algorithm and other algorithms [29]–[36]. In this research, two methods of algorithms were selected and compared to find the best percentage of the filler, as well as to find the highest value of the dielectric strength. A comparison between WOA and SOA strategies is shown in Figure 9 in order to determine which optimization method produces predicted dielectric strength values that deviate from actual values by the least percentage for measurements made in the lab under various weather conditions. From Figure 9, it can be inferred that the SOA is the best optimization strategy because it yields high dielectric strength values and has the lowest deviation percentages.

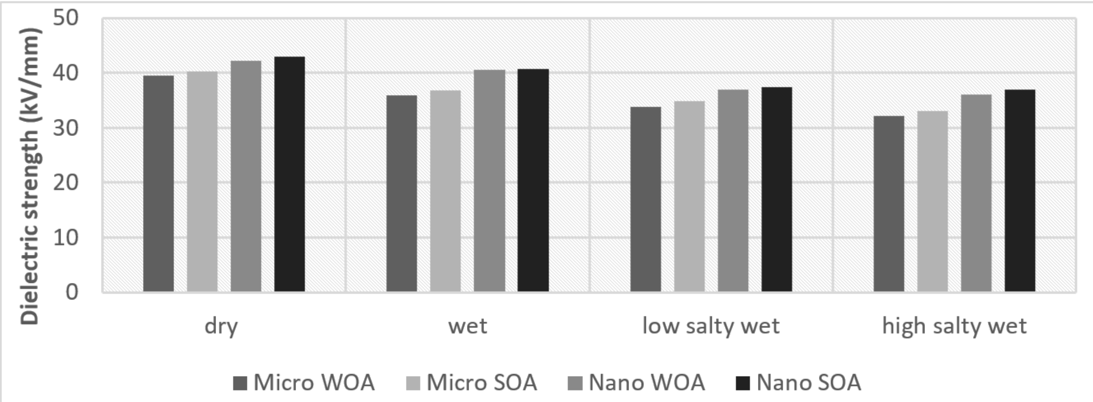


Figure 9. Comparison between WOA and SOA optimization techniques in different weather conditions

4. CONCLUSION

Fillers have been used to improve specific processing features or improve the physical properties of the polymeric base material. The purpose of this paper is to use optimization techniques to investigate the electrical performance of SIR insulators composites. Two types of algorithms, WOA and SOA, were used to find the best filler ratio to obtain the highest dielectric strength value. The findings indicate that the dielectric resistance is lower in wet conditions than it is in dry settings. The presence of the salt water solution greatly lowers the dielectric strength. Up to a certain point depending on the salinity of the water, loading the SIR with an Al_2O_3 filler increases the dielectric qualities. After this point, any additional Al_2O_3 filler additions will impair the dielectric capabilities, and the lowest dielectric strength value can be seen in pure SIR. The dielectric strength of SIR loaded with nano fillers of about 7wt% Al_2O_3 is at its highest level. The models also show good ingenuity in estimating the dielectric strength at the insulator surfaces. The findings demonstrate that the Seagull optimization algorithm approach may be utilized to assess the dielectric strength of SIR composite insulators and to forecast the ideal filler concentration that can preserve higher dielectric strength under various adverse weather conditions.

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BIOGRAPHIES OF AUTHORS

Shaymaa Ahmed Qenwy was born in Luxor, Egypt, in 1990. In 2012, she graduated from Elshorouq Academy's higher institute of engineering with a B.Sc. in electrical engineering. In 2016, she graduated with an M.Sc. in electrical engineering from Aswan University's Faculty of Engineering's Electrical Engineering Department. In 2020, she also earned a Ph.D. in electrical engineering from Ain-Shams University in Cairo's Faculty of Engineering's Electrical Engineering Department. At the Pyramids Higher Institute for Engineering and Technology in Giza, Egypt, she is currently a teacher. She can be contacted ar email: shaymaa.qenawy@yahoo.com.

Saud Abdulaziz Aldossari was born in Wadi Addwaser, Saudia Arabia, on September 1995. He received the B.Sc. degree in Electrical Power and Machines Engineering in 2019 from college of Engineering at Wadi Addwaser, Prince Sattam Bin Abdul Aziz University. He can be contacted at email: soud_502@hotmail.com.

Kareem AboRas received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the Faculty of Engineering, Alexandria University, Alexandria, Egypt, in 2010, 2015, and 2019, respectively. His doctoral study focuses on improving the efficiency of renewable energy conversion systems. He is currently an Assistant Professor with Alexandria University's Faculty of Engineering's Electrical Power and Machines Department. Power electronics, control, drives, power systems, smart grids, microgrids, power quality, optimizations, electric vehicles, machine learning, modeling, fuel cells, HVDC, and renewable energy systems are some of his areas of interest in study. He can be contacted at email: kareem.aboras@alexu.edu.eg.

Loai Saad Eldeen Nasrat is a professor at Aswan University, Faculty of Engineering, Electrical Engineering Department. In the field of HV engineering, he has actively participated in both basic and applied research. His areas of interest in study include aged oil transformers, nano polymeric materials, high voltage cables, and environmental investigations. More than 60 publications on HV polymeric insulating materials and Nano insulating materials have been written and published by the author or a co-author in technical journals and conference proceedings on a national and international scale. He is a participant in CIGRE's Egyptian Sub-Committee. He can be contacted at email: loaisaad@yahoo.com.

Ahmed Hossam-Eldin received the B.Sc. (Hons.) and M.Sc. degrees in electrical engineering from Alexandria University, Egypt, in 1965 and 1969, respectively, and the Ph.D. degree in electrical and electronic engineering from Heriot-Watt University, Edinburgh, United Kingdom, in 1972. Since 1983, he has served as a professor of electrical materials and power engineering. He serves as a consultant for 160 public and private projects in the areas of electrical, energy, and the environment. He served as the social development fund's (SDF) consultant. He is listed as a 2004 UNESCO expert in water desalination using renewable energy. He has received widespread acclaim for his academic accomplishments and general leadership contributions to his community and the rest of the world. 325 of his papers have been published in journals and conferences around the world. He is the author of five worldwide books on instrumentation and logic circuits, electrical circuits, electrical materials, and HV engineering. He serves as the Chair of the ASRT's Top National Awards Engineering Committee. He edits and reviews for numerous international magazines. He can be contacted at email: a.hossamudn@alexu.edu.eg.