ISSN 2664-4150 (Print) & ISSN 2664-794X (Online)
South Asian Research Journal of Engineering and Technology
Abbreviated Key Title: South Asian Res J Eng Tech

| Volume-6 | Issue-2 | Mar-Apr- 2024 | DOI: 10.36346/sarjet.2024.v06i02.002

Original Research Article

Zinc Oxide Filler Effect on Dissipation Factor of High-Density Polyethylene

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Article History
Received: 14.01.2024
Accepted: 23.02.2024
Published: 15.03.2024

Abstract: Polymer Nano-composites (PNC) are efficient materials that consist of polymer matrix and nanoparticles to create a new generation with excellent properties. In this paper a PNC filler-based Zinc oxide (ZnO) is used for enhancing the dissipation factor (DF) or Tan δ of the obtained polymer compared to the individual polymer material and improving the electrical properties of high-density polyethylene (HDPE). The electrical properties of HDPE are investigated under different concentrations of zinc oxide including (0, 10, 20, 30, and 40 wt.%) as well as under different conditions including the variations of temperature (25-150 Celsius) and frequencies (0.1 kHz to 1 MHz). The simulation results reveal that inclusion Zinc oxide as filler can improve the electrical properties of HDPE. In addition to that the minimum value of dissipation factor and the best electrical properties can be obtained at concentration 10 % loading compared to the other concentration levels. Curve fitting solutions were performed to determine the best fit for the experimental results. African Vultures Optimization Algorithm (AVOA) was used to determine the optimal value of zinc oxide filler percentage to obtain the best optimal value of dissipation factor.

Keywords: Polymer Nano-Composite (PNC), Zinc Oxide Filler (ZnO), Dissipation Factor (DF), African Vultures Optimization (AVOA), high-density polyethylene HDPE.

1. INTRODUCTION

Underground cable is an essential part of the electric power system that provides the required power from generation systems to the electric loads or from the system to another system in the electric grid. Thus, the underground cables should be well insulated and protected to ensure the reliability and stability of the power systems [1]. Insulators play a vital role in insulating the conduction apparatus in power systems like cables, transformers and generators where the performance of these parts depends on the strength of the insulation [2]. Scene 50 years ago, oil-impregnated and paper-insulated cables were used but nowadays polymer insulators are wildly used [3]. Polyethylene (PE) is one of the most important insulation polymers materials that can be utilized for cable insulation including low, medium, and high voltage underground cables due to its efficient properties such as excellent electrical breakdown strength electrical and it has high chemical resistivity of alkalis and acids and it wildly uses due to its low-cost compare to ceramic insulators [4, 5]. It is worth mentioning here that there are two types of PE including Low-density polyethylene (LDPE) and High-density polyethylene (HDPE) [6]. In addition to that LDPE is mostly used for LV cables while HDPE is mostly used for HV cables.

Several efforts have been presented to improve the electrical properties of the polymers by adding nanofillers or nano-composites where [4]. Clay-Nanofiller was added to improve the dielectric properties of HDPE with different concentrations of the samples at different frequency ranges. The dielectric strength of nano-composites was examined which consisted of polystyrene (PS)-polycarbonate(PC)/Cobalt oxide(III) nanoparticles (Co_2O_3 NPs)- Silicon carbide nanoparticles (SiC NPs) [7]. In [8], Silicon dioxide and graphene oxide nano-materials (SiO_2–GO) were added to improve the probabilities of ternary blend polymer. The Nano-silver-coated porous clay heterostructure (PCH) was employed for enhancement of the dielectric strength of poly(lactic acid) (PLA) [9]. $BaTiO_3$ particles with the epoxy polymer were investigated including the chemical and the dielectric properties [10]. The J.I. Hong *et al.*, added and investigated the influence of zinc oxide nano-composites on LDPE [11]. The thermal, and electrical properties of the HDPE were invest aged by incorporating expandable graphite (EG) and flake graphite (FG) [12]. In [13], the electric properties of the LLDPE 324CN were studied by adding Nano fillers which consist of SiO2 and Al2O3. The electric properties of the LDPE were observed under different types of nano-fillers like the Clay Alumina (AhO3), Fumed Silica, and the Silica (SiO2) [14]. The aim of this paper is to investigate of inclusion the zinc oxide filler on the electrical properties of the HDPE under different concentrations levels of this filler.

2. EXPERIMENTAL AND PROCEDURES

2.1 Blend Preparation

Zinc oxide has many benefits such as harmlessness, inexpensive cost and good electrical characteristics. Zinc oxide is a common ingredient in many different types of materials including plastics [15]. The specimens were prepared by mixing inorganic filler (ZnO) into HDPE as the base polymer, the concentrations of filler were taken as a percentage of the total weight of the base polymer. The mixture between HDPE and ZnO nano-filler is prepared in the lab,and five blend samples with varying weight percentages of ZnO have been prepared and tested as follows:
(100/0), (90 / 10), (80/20), (70 / 30) and (60/40) wt%.

2.2 Dissipation Factor Test

Dissipation factor (DF) test is an important test in electric sectors that can be used for judging the insulation quality of cables, capacitors, transformers and other components [16]. This test is also known as Tan δ test. The aim of this test is measuring energy lost as heat (dielectric losses) and gives indication if there is degradation, moisture or contamination in insulators which can provided earlier warning of insulation failure [17]. It is worth mentioning here that the dissipation factor represents the ratio of a power loss in insulators to the total power transmitted through the dielectric. This measure is the tangent of the loss angle [18]. Dissipation factor or Tan δ can be determined from the equivalent circuit and the phasor diagram of Figure (1) as follows:

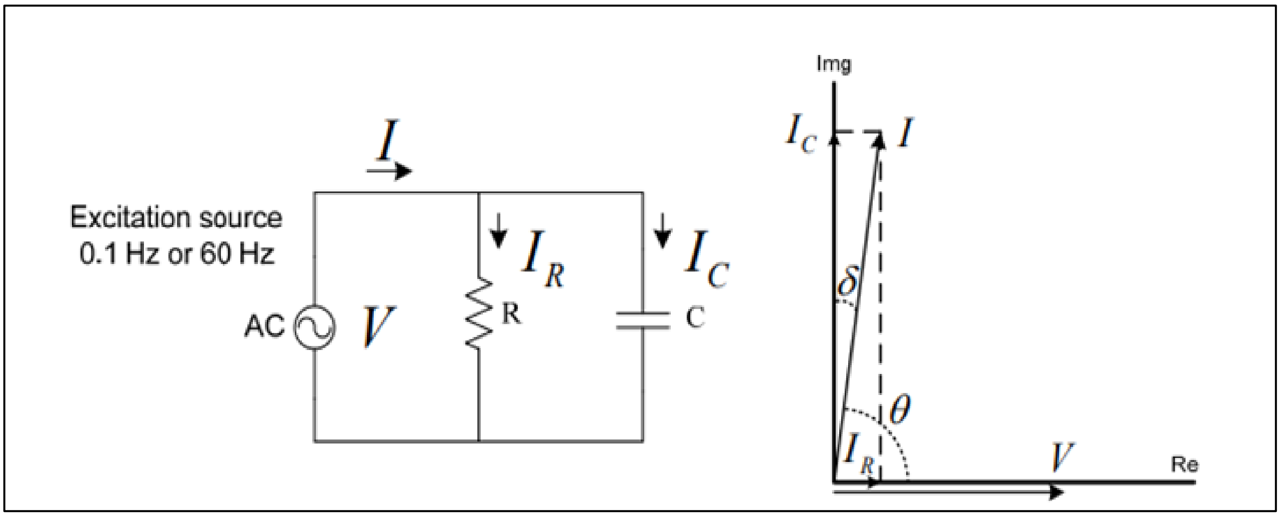

Figure 1: The phasor diagram and equivalent circuit of Tan δ

$$DF = \frac{I_R}{I_C} = \frac{\sqrt{I^2 - I_C^2}}{I_C} \text{ ………………….. (1)}$$

$$DF = tan\,(\delta) = \frac{I_R}{I_C} = \frac{V/R}{V/(1/\omega C)} = \frac{1}{\omega RC} \text{ …………….. (2)}$$

Where:
C : equivalent parallel capacity
R : equivalent parallel resistance
δ : loss angle

3. RESULTS AND DISCUSSION

3.1 Dissipation Factor Measurements

The dissipation factor test acts as an indication for the rate of the deterioration state. The variation of dissipation factor as a function of frequency in hertz and temperature in Celsius, for five composite samples (0, 10, 20, 30, and 40 wt.%), The test was repeated 4 times for each sample with different temperature (25,50,100, and 150 °C) and was tested under frequency range from (0.1 kHz to 1MHz). The dissipation factor of HDPE/ZnO composites has been evaluated as depicted in Table (1).

Table 1: Summary of dissipation factor measurement results of HDPE/ZnO composites

Temperature °C	filler percentage %	Tan δ $\times 10^{-4}$				
		10^2 Hz	10^3 Hz	10^4 Hz	10^5 Hz	10^6 Hz
25	0	3.11	3.76	2.88	2.35	1.84
	10	2.81	3.02	2.52	2.06	1.51
	20	7.1	7.63	6.24	5.52	4.7
	30	16	16.56	15.88	15.01	14.1
	40	14.31	14.87	13.21	12.8	11.01
50	0	2.1	2.28	1.76	1.44	0.83
	10	1.44	1.89	1.37	1.19	0.62
	20	5.01	5.92	4.89	4.2	3.61
	30	13.01	13.59	12.44	11.67	10.01
	40	10.12	11.4	10	9.21	8.33
100	0	1.31	1.48	1.09	0.93	0.13
	10	0.74	0.91	0.87	0.65	-0.01*
	20	2.81	2.99	2.42	1.93	1.2
	30	9.28	10.11	9.01	8.33	7.91
	40	7.55	8	7.13	6.44	5.73
150	0	0.5	0.61	0.34	0.22	-0.07*
	10	0.25	0.4	0.2	0.17	-0.12*
	20	1.59	1.99	1.37	0.96	0.51
	30	6.21	6.83	5.98	4.88	4.01
	40	5.01	5.67	4.8	4.32	3.7

* The negative Dissipation Factor reading; indicates the insulation failure this may occurred because the samples concentrated moisture, and carbonization.

Table 2: Average of dissipation factor of HDPE/ZnO Composites samples with different temperatures

Tan δ ×10-4				
ZnO filler %	**25 °C**	**50 °C**	**100 °C**	**150 °C**
0	2.788	1.682	0.988	0.32
10	2.384	1.302	0.632	0.18
20	6.238	4.726	2.27	1.284
30	15.51	12.144	8.928	5.582
40	13.24	9.812	6.97	4.7

Table (2) provided that, for 30% ZnO filler concentration, is the highest loss of insulation also for 10% ZnO filler concentration, is the lowest loss of insulation.

3.2 Soft Program (MATLAB) Results

Curve fitting is applied to find the best fit curve for experimental data points.

$y = a0 + a1x + a2x^2 + a3x^3 + a4x^4$ ....…........... (3)

Eq. (3) represents the Polynomial y model of 4th degree as an example of curve fitting used to get the relation between single input and single output.

Where:

The input (x)**:** represented the percentage of ZnO filler concentrations in sample.

The output (y): represented value of the Tan δ (dissipation factor)

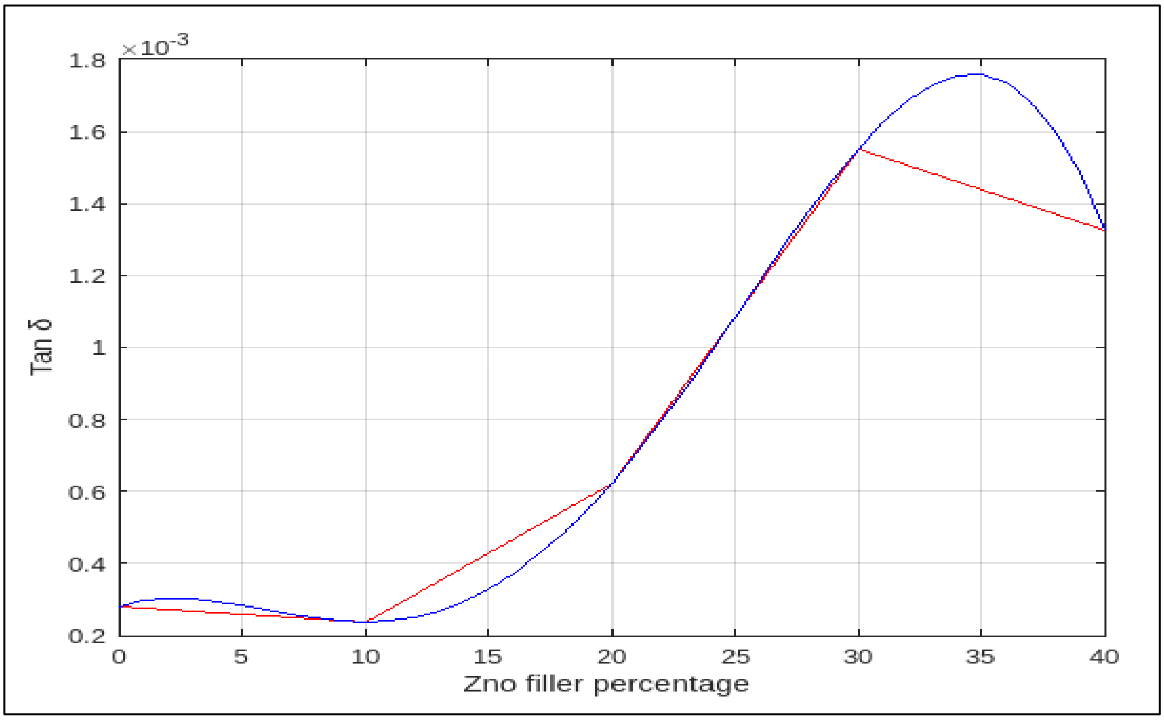

Figure 2: Curve fitting results of Tan δ for HDPE/ZnO samples at (25 °C)

Figure (2) illustrated the curve fitting for DF results of the HDPE samples with different ZnO filler percentages at 25°C, the obtained 4th degree polynomial equation is;

y = (0.0002788) + (2.383 e-05) X+ (-6.755 e-06) X^2 + (4.723 e-07) X^3 + (-7.550 e-09) X^4

a4= -7.550 e-09, a3= 4.723 e-07, a2= -6.755 e-06, a1= 2.383 e-05, a0= 0.0002788

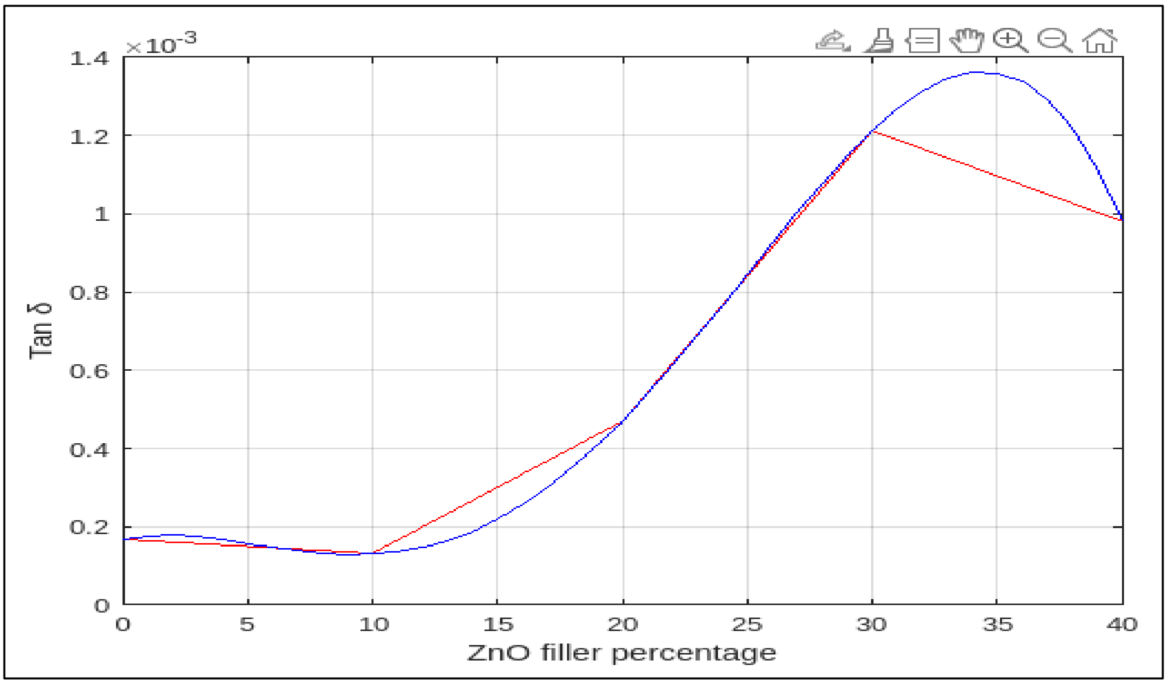

Figure 3: Curve fitting results of Tan δ for HDPE/ZnO samples at (50 °C)

Figure (3) illustrated the curve fitting for DF results of the HDPE samples with different ZnO filler percentages at 50 °C, the obtained 4th degree polynomial equation is;

y = (0.000168) + (1.264 e-05) X + (-4.579 e-06) X^2 + (3.515 e-07) X^3 + (-5.805 e-09) X^4

a4= -5.8005 e-09, a3= 3.515 e-07, a2= -4.579 e-06, a1= 1.264 e-05, a0= 0.000168

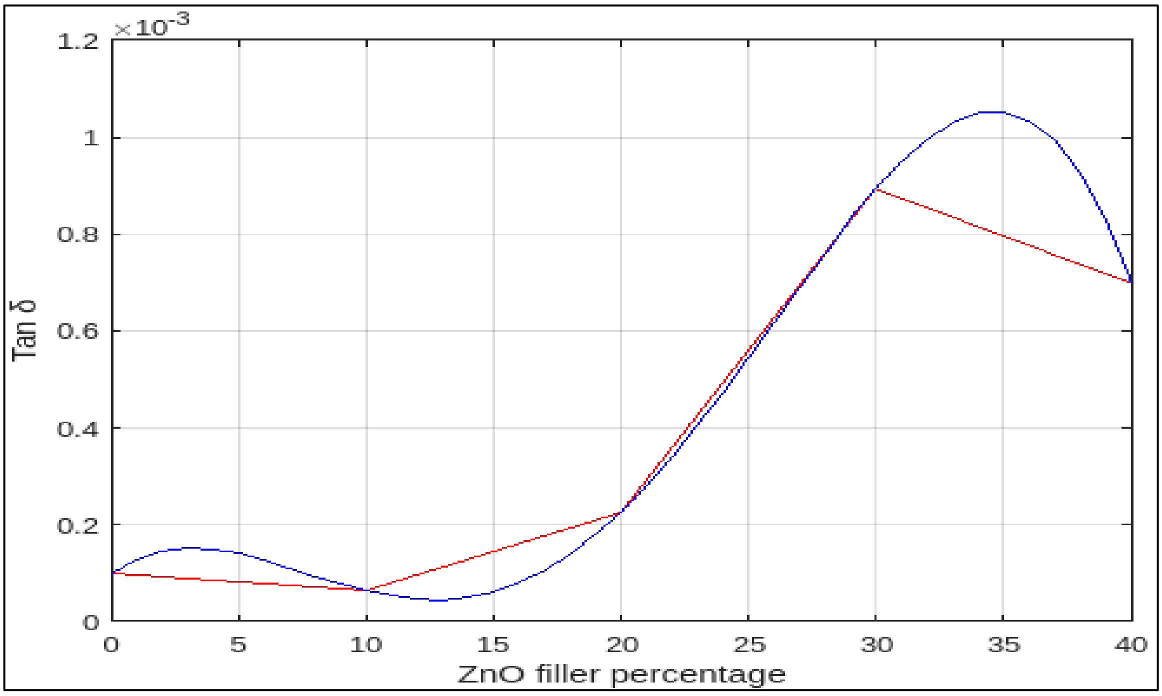

Figure 4: Curve fitting results of Tan δ for HDPE/ZnO samples at (100 °C)

Figure (4) illustrated the curve fitting for DF results of the HDPE samples with different ZnO filler percentages at 100 °C, the obtained 4th degree polynomial equation is;

y = (9.880 e-05) + (3.821 e-05) X + (-8.152 e-06) X^2+ (4.669 e-07) X^3+ (-6.942 e-09) X^4

a4= - 6.942 e-09, a3= 4.669 e-07, a2= - 8.152 e-06, a1= 3.821 e-05, a0= 9.880 e-05

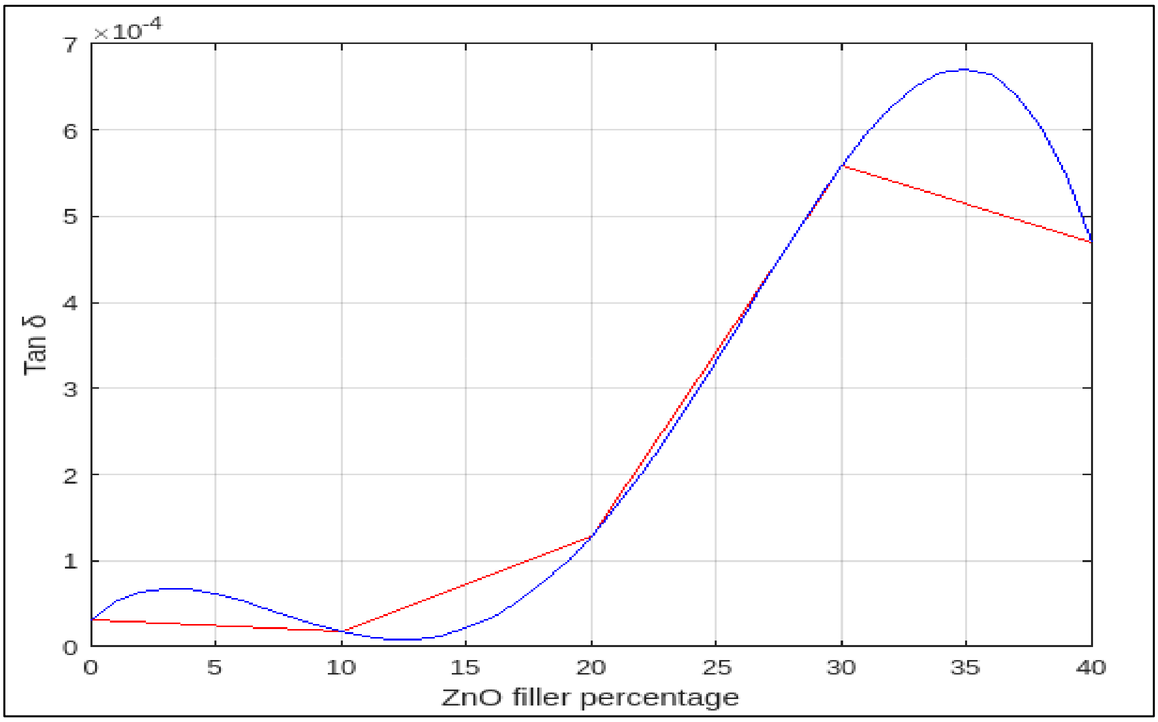

Figure 5: Curve fitting results of Tan δ for HDPE/ZnO samples at (150 °C)

Figure (5) illustrated the curve fitting for DF results of the HDPE samples with different ZnO filler percentages at 150 °C, the obtained 4th degree polynomial equation is;

y = (3.200 e-05) + (2.468 e-05) X + (-5.084 e-06) X^2+ (2.906 e-07) X^3+ (-4.301 e-09) X^4

a4= -4.301 e-09, a3= 2.906 e-07, a2= -5.084 e-06, a1= 2.468 e-05, a0= 3.200 e-05

Figures 2 through 5 illustrate the variation in the dissipation factor for HDPE under different concentrations of zinc oxide filler for all samples. An important observation is that Tan δ decreases with decreasing the concentrations of ZnO-nano filler at 10% filler concentration then it further increases at 20% and 30% filler concentrations this means that at 10% ZnO filler concentration is the lowest dielectric losses due to increasing the insulation of the base polymer material and at 30% ZnO filler concentration is the highest dielectric losses due to decreasing the insulation of the base polymer material also can be observed that at 30% sample, Tan δ values are higher than those of the 40% sample. However, when filler content is 40%, Tan δ values are higher than those of the pure material. This means that ZnO-nano filler improves the dissipation factor for HDPE polymeric material.

The variation of dissipation factor as a function of frequency, and temperature, respectively for 10% zinc oxide filler sample judging from (Figures 6 & 7). It can be seen that the dissipation factor increases in the frequency range (10^2 to 10^3 Hz) then it further decreases gradually in frequency range (10^3 to 10^6 Hz) also the dissipation factor increases with decreasing in temperature.

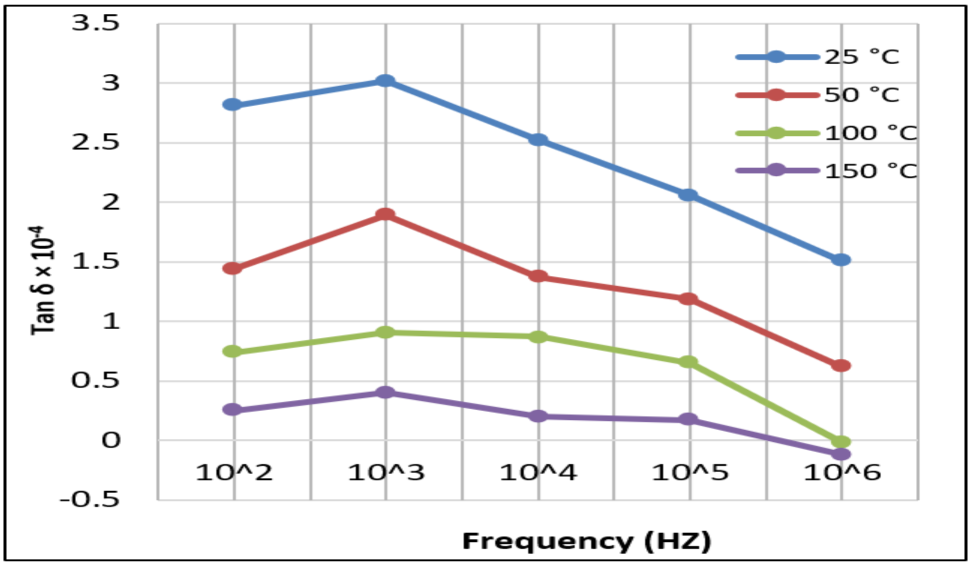

Figure 6: Frequency dependence of Tan δ under different temperature conditions for 10% ZnO sample

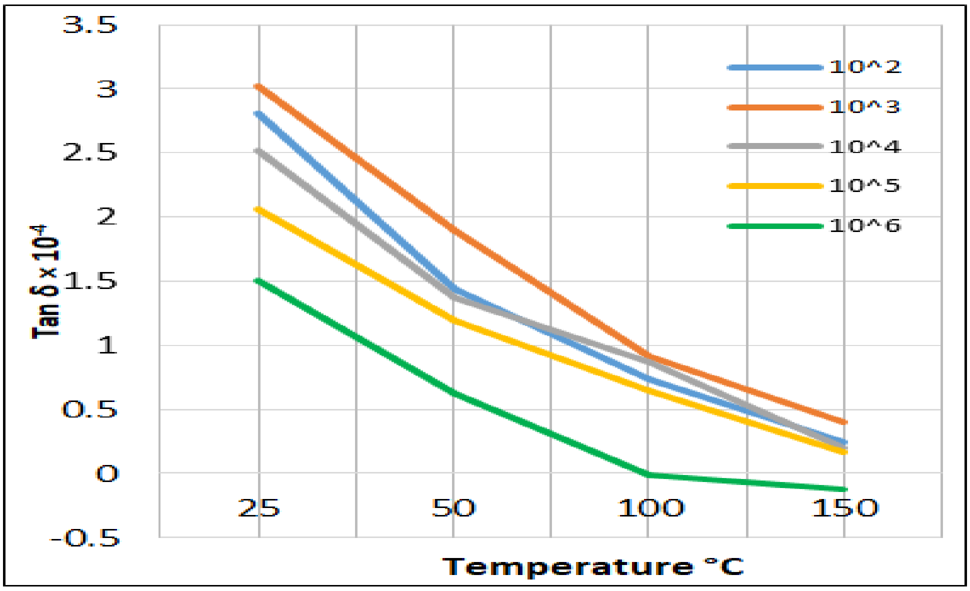

Figure 7: Temperature dependence of Tan δ under different frequency range for 10% ZnO sample

3.3 African Vultures Optimization Algorithm (AVOA) Results

African Vultures Optimization Algorithm (AVOA) is very important Algorithm, it was developed to handle applications where it performed properly, it has been widely used to solve engineering optimization problems, and many enhanced strategies of AVOA have been offered in recent published research [19].

Applying the optimization algorithm method for HDPE/ZnO composites, the concentrations of modified ZnO filler were added from 0 to 40 wt% into the base polymer material the set data is as follows**:**

- Lower boundary = 0
- Upper boundary = 40
- Number of variables = 1
- Maximum iteration = 100

The effect of different amounts of ZnO filler into the base polymer (HDPE) on the dissipation factor was studied and simulated by the African Vultures Optimization Algorithm the best vulture_x (represents zinc oxide filler concentration) and the best vulture_F (represents the value of dissipation factor) results as follows:

1. The best vulture_x is 9.9623% which gives the best vulture_F is 2.384 e-4 at 25 °C.
2. The best vulture_x is 9.3001% which gives the best vulture_F is 1.2907 e-4 at 50°C.
3. The best vulture_x is 12.6644 % which gives the best vulture_F is 4.5083 e-05 at 100°C.
4. The best vulture_x is 12.4489% which gives the best vulture_F is 8.6721 e-6 at 150°C.

4. CONCLUSIONS

This paper presented a deep investigation including the influence of addition the ZnO filler to HDPE for electrical properties improvement in terms of the dissipation factor (Tan δ) under different concentrations of zinc oxide, temperature and frequencies variations. The experimental outcomes authenticate that:

- The addition of the ZnO filler to HDPE can improve the dissipation factor of the polymer composites considerably.
- The value of the Tan δ increases with decreasing the temperature.
- Tan δ increased with increasing the frequency from 10^2 to 10^3 Hz, then it further decreases gradually from 10^3 to 10^6 Hz with increasing the frequency.
- The increment percentage illustrates how dissipation factor can be improved by ZnO filler percentage for 10 wt% due to increasing the insulation of the base polymer material.
- The best filler concentration that provides the best dissipation factor is 10% ZnO filler while the worst filler concentration is 30% ZnO filler.
- African Vultures Optimization Algorithm (AVOA) performed to determine the optimal value of the zinc oxide filler percentage to obtain the best optimal value of dissipation factor value.

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