Modeling of the Electric Field in Mineral Oil-Based Nanofluids used in Power Transformers by Comsol Multiphysics Software

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Abstract - In high-voltage equipment containing insulating oils, the dielectric rigidity of these oils linked to the knowledge of the electric field and the method of controlling electrical stresses. In recent years, the use of nanofluids (NFs) in electrical devices has increased due to the improved capabilities of electrical insulation and thermal cooling. This increase in dielectric strength is due to the modification of the distribution and intensity of the electric field when nanoparticles (NPs) are added to the insulating liquid. In this work, we modeled the electric field distribution of NFs based on mineral oils (MO) using the finite element method (FEM) to understand the effect of the presence of NPs on the intensity and distribution of the electric field, we use conductive (Fe_3O_4) and semiconductor (TiO_2) nanoparticles at different volume concentrations (0% w/w, 0.01% w/w, 0.018% w/w, 0.024% w/w). The results showed a difference in the electric field distribution with the presence of NPs, and the volume concentration and type of NPs had a major role in determining the value of this electric field. It was observed from the results that the mixture of conductive nanoparticles (Fe_3O_4) and MO submitted greater electric field values than the mixture consisting of semiconductive nanoparticles (TiO_2) and MO.

Keywords - COMSOL Multiphysics; electric field, mineral oil, modeling, nanofluids, nanoparticles, transformer oil, volume concentration.

I. INTRODUCTION

In the electrical network, the reliability of high-voltage equipment is considered one of the most important requirements that must be met to ensure the transportation and distribution of energy to consumers in good conditions [1, 2]. The power transformer is the most important and expensive element in the electrical network plays a sensitive role in raising the electrical voltage to ensure the transmission of electricity with the least possible losses. Any malfunction of this device leads to interruptions in the power supply and consequently significant economic losses [3].

In large capacity transformers that contain oils, the oil is used as a means of insulation and cooling [4], since it transfers the heat generated by the internal parts to the outside of the transformer to maintain this device, because any deterioration of the insulating fluid leads to a reduction in dielectric strength and the subsequent appearance of partial discharge, which negatively affects the shelf life of this vital element [5-7].

There are many dielectric fluids used in electrical equipment, including oils such as mineral and vegetable oils. To increase the efficiency of these oils, researchers added nanoscale particles in different quantities, shapes, and types, and studied the electrical and thermophysical properties of these insulating media, where the results showed a notable improvement in their power transformer capabilities by applying nanotechnology. Several mineral oil-based nanofluids mixtures have been prepared by adding different types of NPs to the base fluid (conductive, semi-conductive, and dielectric). The distribution of these NPs increases dielectric strength and thermal conductivity [8, 9].

Numerous researches have indicated that insulation failure is the most common cause of major failure of electrical transformers. It is important that the insulating fluid withstands the applied electric field. The presence of NPs in the dielectric fluid causes a variation in the distribution of the electric field thanks to the trapping of electrons on the surface of the NPs, which ultimately leads to delaying the electrical breakdown [1, 3].

A thorough analysis of the electric field distribution in and around electrical equipment is of great importance in determining the voltage withstand capability of liquid insulators. Liquid insulation for power transformers is designed to withstand electrical stresses with sufficient reliability. Controlling the electric field distribution of liquid insulators by adding NPs would increase insulation resistance [3].

This paper presents a numerical model to study the effect of the presence of NPs on the electric field distribution of mineral oils used in transformers, using the finite element method to highlight the effect of the volume concentration and type of NPs on the intensity and distribution of the electric field.

II. NANOFLUIDS

Dielectric fluids are considered one of the main components of high voltage transformers as they have two basic functions: insulation and cooling [10]. Dielectric fluids have evolved technologically due to the constant need for reliability and efficiency of high voltage equipment. The limited electrical performance of the dielectric system forced engineers to look for ways to improve it by using different nanoparticles suspended in insulating oils to form nanofluids [11].

The NFs concept was introduced by Choi at Argonne National Laboratory, USA, in 1995, where he demonstrated the possibility of increasing the thermal properties of the fluid using nanoparticles with high thermal conductivity [12]. Since then, this nanofluids concept has been taken into consideration in high voltage applications, and several investigations have reported significant improvement in the performance of conventional dielectric fluids by adding nanoparticles in terms of cooling and dielectric capacity. NFs are mixtures of small particles of nanometer-sized materials (nanoparticles, nanowires, nanotubes, nanofibers, nanorods, or nanosheets) that are mixed with a carrier fluid such as oils used in transformers in varying amounts, types, and shapes [10]. Many NPs additives have been investigated so far with the aim of enhancing the dielectric properties of liquid insulators. These NPs can be classified according to their electrical properties into three main groups [13]:

- Conductive NPs: ZnO, SiC, Fe_3O_4, Fe_2O_3
- Semiconductor NPs: Cu_2O, CuO, CdS, TiO_2
- Dielectric NPs: SiO_2, BN, Al_2O_3

A) Nanofluid preparation methods

After selecting the NPs and carrier fluid, the method of preparing the NFs is an important issue in the process of producing NFs. Methods of preparing NFs can be classified into one-step or two-step methods [13].

- **One-step preparation process:** The one-step process involves the simultaneous synthesis and dispersion of nanoparticles in the base fluid [11].
- **The two-step preparation process:** NPs of different sizes and shapes are synthesized as powders and then dispersed using a magnetic stirrer or ultrasound in the host liquid [11, 13].

III. MODEL CONFIGURATION AND METHODOLOGY

A 2D model (Fig. 1) was developed using by the finite element method by the COMSOL Multiphysics software to study the presence of NPs on the electrical behavior of the cooling fluid used in power transformers, the system is composed of electrodes of parallel-plate copper with an electrical conductivity is 5.998×10^7 S/m and the relative permittivity is 1. The space between the electrodes is filled with dielectric oil-based nanofluids and the NPs are homogeneously dispersed in this oil. The dielectric used in this modeling is mineral oil [3, 9]. The properties of this oil such as thermal conductivity, density, dynamic viscosity, specific heat capacity, electrical conductivity and relative permittivity are shown in Table I [14]. The NPs chosen for the study are conductive nanoparticles (Fe_3O_4) and semiconductor (TiO_2) spherical shape and radius of 10 nm with an electrical conductivity of 10^4 S/m and 10^{-11} S/m respectively [15].

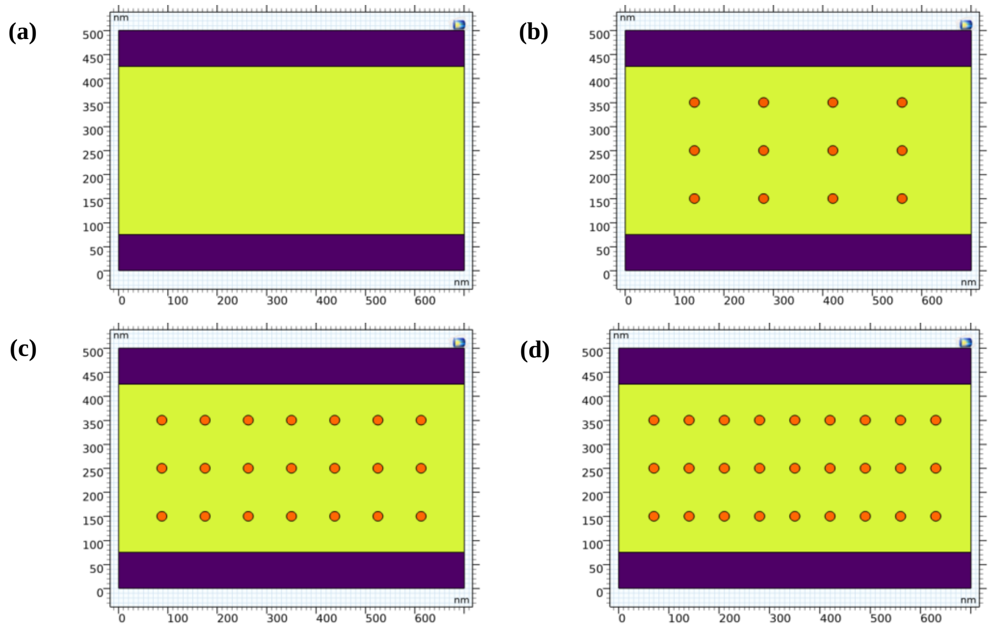


Fig.1. Geometry of the model studied for each sample used: (a) MO + 0% NPs, (b) MO + 0.01% NPs, (c) MO + 0.018% NPs, and (d) MO + 0.024% NPs

Table I. Properties of mineral oil [3] [14]

Parameters	*Mineral oil*
Electrical conductivity σ (S/m)	*1×10^{-12}*
Relative permittivity ε_r	*2.2*
Density ρ ($kg.m^{-3}$)	*1098.72 – 0.712T*
*Thermal conductivity **k** ($W.m^{-1}.K^{-1}$)*	*$0.1509 - 7.101\times10^{-5}T$*
Dynamique viscosity μ ($kg.m^{-1}.s^{-1}$)	*$0.08467 - 0.0004T+5\times10^{-7}T^2$*
Specific heat capacity C_p ($J.kg^{-1}.K^{-1}$)	*807.163+3.58T*

Where ρ is the material density (kg/m^3), C_p is the heat capacity (J/(kg.K)), T is the temperature (k), **μ** is the dynamique viscosity (kg/(m.s)), k is the thermal conductivity (W/(m.K)), σ is the electrical conductivity (S/m), ε_r is the relative permittivity.

In our study, we relied on conductive (Fe_3O_4) and semiconductor (TiO_2) NPs, using a Only one concentration at a time to study the effect of NPs presence on the electric field of NFs. A high DC voltage of 10 kV is applied to the electrodes to generate a high electric field in the space between them, and the electric field distribution is observed in the dielectric space with and without NPs to study the application of NPs-reinforced dielectric fluids in high voltage DC applications.

A) *Mathematical formulation*

The calculation of the electric field of NFs in COMSOL Multiphysics software is based on the electric current model. In the electric current model, the physical interface solves a current conservation equation based on Ohm's law, using the scalar electric potential as the dependent variable through the following equations [16]:

$$\nabla.J = Q_{j.v} \tag{1}$$

$$J = \sigma E + J_e \tag{2}$$

$$E = -\nabla V \tag{3}$$

Where J is the current density (A/m^2), J_e is the externally generated electric current density (A/m^2), σ is the electric conductivity (S/m), E is the electric field in (V/m), V is the electric potential (V), $Q_{j.v}$ is the volumetric current source (A/m^3).

IV. RESULTS AND DISCUSSION

The simulation results to understand the electric field variation of nanofluids are presented in this section. The present study was conducted using COMSOL Multiphysic software. Fig. 2 and 3 show the distribution of the electric potential after applying a high DC voltage of 10 kV to give the electric field of the NFs at the y-axis. The experiment is conducted at different volume concentrations of the NFs (0%, 0.01%, 0.018%, and 0.024%).

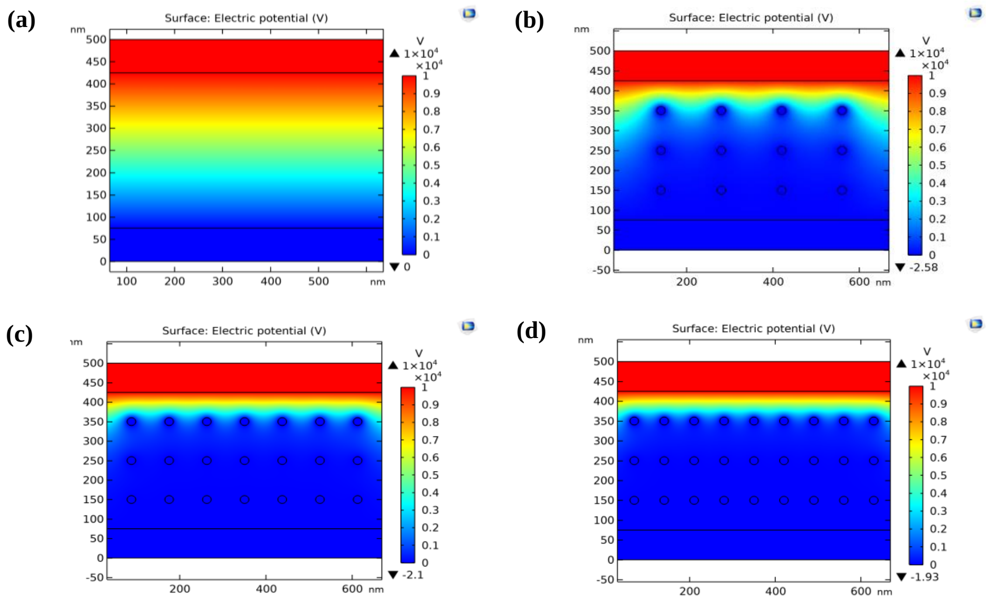


Fig. 2. Electrical potential distribution within the electrodes gap for conductive nanoparticle-based nanofluids: MO + 0% Fe_3O_4, (b) MO + 0.01% Fe_3O_4, (c) MO + 0.018% Fe_3O_4, and (d) MO + 0.024% Fe_3O_4

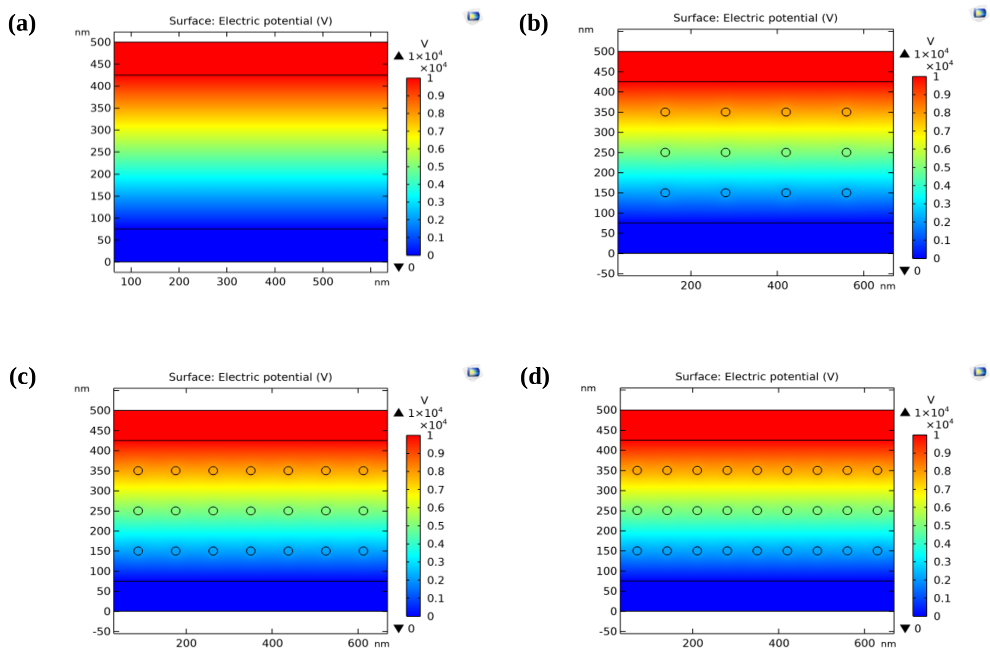
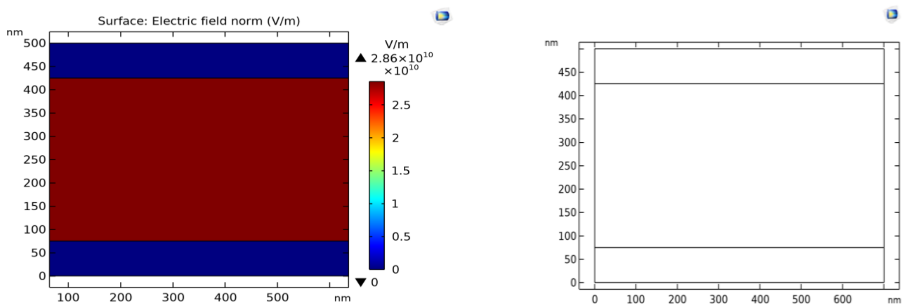


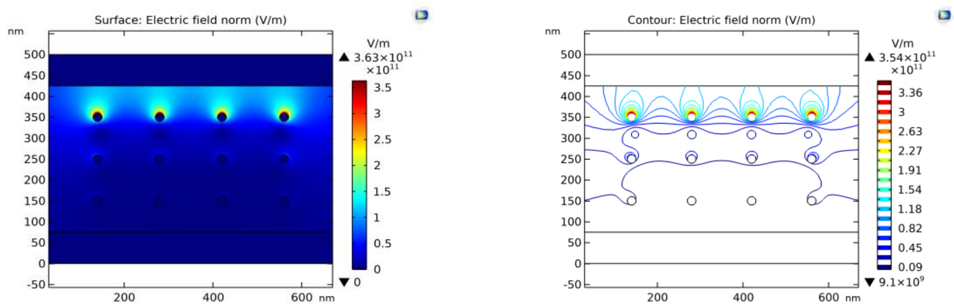
Fig. 3. Electrical potential distribution within the electrodes gap for semiconductor nanoparticle-based nanofluids: MO + 0% TiO_2, (b) MO + 0.01% TiO_2, (c) MO + 0.018% TiO_2, and (d) MO + 0.024% TiO_2

The electric field intensity across space was illustrated in 2D for each sample (Fig. 4 and 5). the electric field distribution inside dielectric oil gets changed when the dispersion of NPs which has a high relative permittivity compared to MO, It was observed that the maximum electric field intensity is around the NPs (the interface between the nanoparticles and the dielectric oil). The electric field observed when there are no NPs in the mineral oil is 2.86×10^{10} V/m. On the other hand, the presence of NPs modified this electric field value. The highest values were recorded at a concentration of 0.01%, While the conductive NPs with an electrical conductivity of 10^{4} S/m increased the electric field intensity to a maximum of 3.63×10^{11} V/m, while the semiconductor NPs with an electrical conductivity 10^{-11} S/m also increased the electric field intensity to a maximum of 5.33×10^{10} V/m. Furthermore, as the volume concentration increases, the electric field intensity values of the samples decrease.

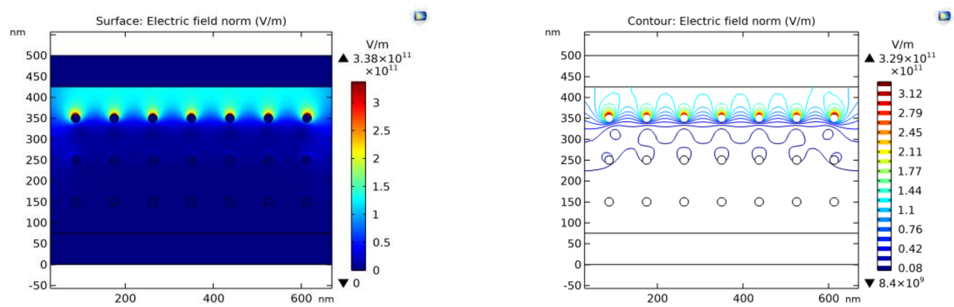
(a) MO + 0% Fe_3O_4



(b) MO + 0.01% Fe_3O_4



(c) MO + 0.018% Fe_3O_4



(d) MO + 0.024% Fe_3O_4

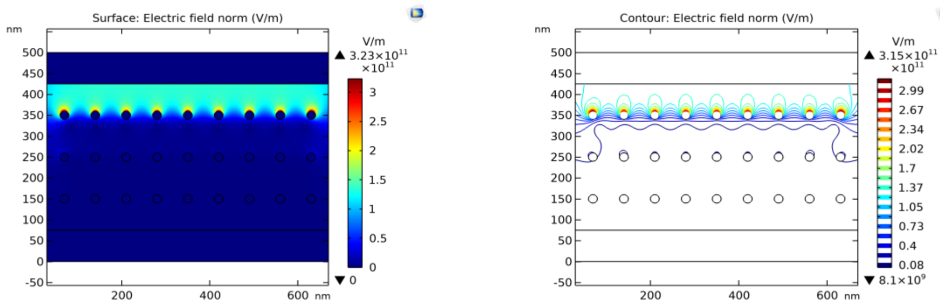
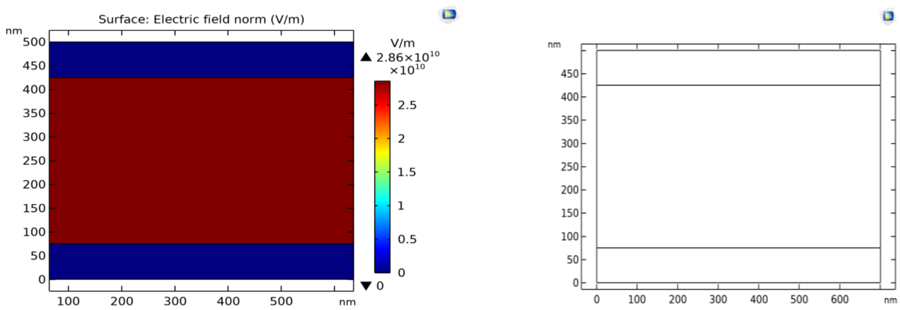
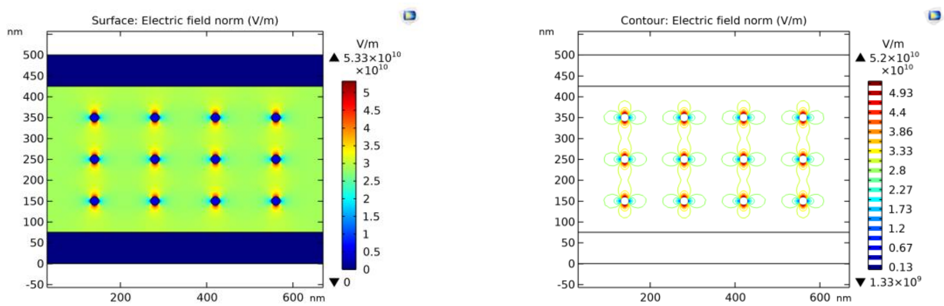


Fig. 4. Electric field distribution and contour in nanofluids based on conductive nanoparticles (Fe_3O_4): MO + 0% Fe_3O_4, (b) MO + 0.01% Fe_3O_4, (c) MO + 0.018% Fe_3O_4, and (d) MO + 0.024% Fe_3O_4.

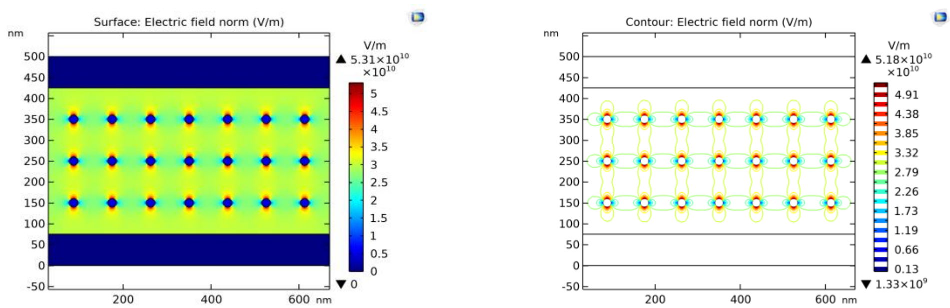
(a) MO + 0% TiO_2



(b) MO + 0.01% TiO_2



(c) MO + 0.018% TiO_2



(d) MO + 0.024% TiO_2

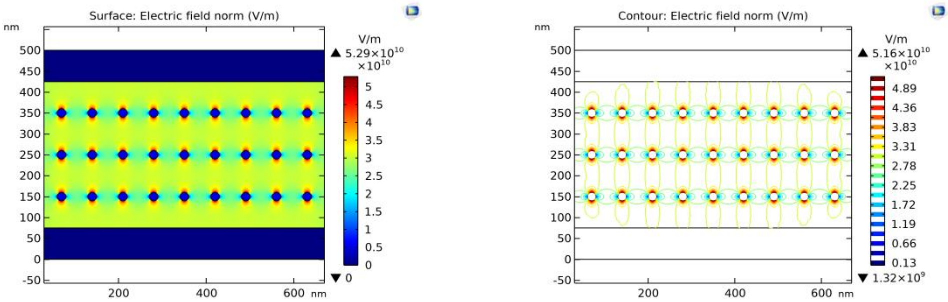


Fig. 5. Electric field distribution and contour in nanofluids based on semiconductor nanoparticles (TiO_2): MO + 0% TiO_2, (b) MO + 0.01% TiO_2, (c) MO + 0.018% TiO_2, and (d) MO + 0.024% TiO_2

Moreover, the type of NPs played an effective role in determining electric field values, as NFs based on conductive NPs showed higher electric field values than samples based on semiconductor nanoparticles as shown in Fig. 6.

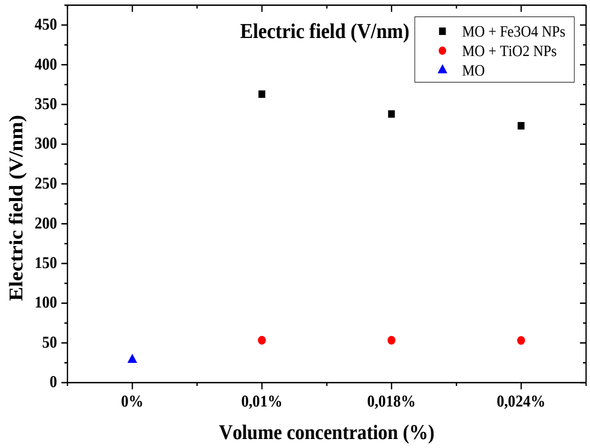


Fig. 6. Effect of the types and volume concentration of NPs on the electric field of the NFs

V. CONCLUSION

In this work, a comparative study was carried out on the influence of NPs at different weight percentage ratios (0% w/w, 0.01% w/w, 0.018% w/w, 0.024% w/w) on electric field performance in mineral oils by developing a model 2D using COMSOL Multiphysics software. The most important findings are summarized as follows:

- The electric field intensity of the insulating oil changes with the addition of the NPs, and this is due to the high relative permittivity of the NPs compared to the base liquid.
- The highest electric field intensity values were recorded at the interface between the NPs and the dielectric oil.
- The electric field of NFs based on conductive NPs is greater than that based on semiconductor NPs
- The intensity of the electric field of NFs is linked to the distribution of the electrostatic field.
- With increasing volume concentration, the electric field intensity of the samples decreases.
- The highest values of the electric field of the NFs were recorded at a volumetric concentration of 0.01 %, while the lowest values of the electric field were at a volumetric concentration of 0.024 %.

Dielectric nanofluids are considered one of the most promising solutions for use in high-voltage devices, due to their positive results in terms of increasing electrical insulation strength and thermal conductivity compared to traditional insulating oils.

VI. REFERENCES

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