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Enhancement of Dielectric Characteristics of Transformer oils with Nanoparticles

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Abstract

There is a wide range of applications of nanocrystalline manganese nickel ferrites in electrical devices, however, such nanocrystalline compositions are not applied beforehand for enhancing the dielectric withstand voltages of the transformer oils. In this paper, nanofluid for power transformers examined toward enhancing the oil dielectric characteristics. The nanofluid is prepared using the synthesized nanoparticles of manganese nickel ferrite concerning substitution of 20% and through the oxalate precursor route annealed at 1000°C. The nanostructure of $Mn_{0.2}Ni_{0.8}Fe_2O_4$ is evaluated and verified by the scanning electron microscopy (SEM) and x-ray diffractometer (XRD). Nanofluid dielectric characteristics are examined by applying the standard impulse voltage waveform using pin-hemisphere test cell. Different concentrations of nanocrystalline manganese nickel ferrite in the transformer oils such as 0.02, 0.04, and 0.06 g/l are experimentally tested to ascertain the enhancement of using the proposed nanocrystalline particles. The dielectric withstand voltage is enhanced by around 40% with using the proposed nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ powder.

Keywords: Nanofluids, nanocystalline manganese nickel ferrite, power transformers.

INTRODUCTION

Enhancing the performance of the mineral oil that uses as insulation and coolant material in power transformers is the main request of the mineral oil suppliers. For this reason, the researchers in last decades tried to seek about the additive nanoparticles that improve the thermal and dielectric properties of the oils which results in reducing the volume of the high voltage equipment and increase their power densities [1].

The nanoparticles were categorized into conductive, semi-conductive, and dielectric particles where these nanoparticles enhanced the dielectric strength of the oils by trapping and de-trapping the free electrons that generated due to the thermal and electrical stresses on the insulation oils [2]. Additionally, the interfacial zones (the interphase regions) were developed around the filler particles between the oil and nanoparticles [3].

As the nanofluids is used to enhance the dielectric strength of the transformer oil, adding and dispersing nanoparticles in the oils constructed the oil-based nanofluids and the metal oxides were considered the most known nanoparticles [4]. Several metal oxides nanoparticles such as zinc oxide (ZnO) [5-7] titanium dioxide (TiO_2) [4-6]-[8-9], silicon dioxide (SiO_2) [4,10], aluminum oxide (Al_2O_3) [4], magnetite (Fe_3O_4) [1], [11-13], and hematite (Fe_2O_3) [14] were added to the oil to develop the nanofluids.

In [14], the Fe_2O_3 and SiO_2 nanoparticles are added to natural ester oil to enhance its dielectric properties. The results demonstrated that the performance of the oil with Fe_2O_3 is better than that with SiO_2 but beyond a threshold value of the nanoparticles concentration, the breakdown voltage will decrease. In [4], the thermal transport properties of the transformer oil with nanoparticles (Al_2O_3, SiO_2, and TiO_2) at different concentrations was investigated. In [15], the AC breakdown strength of the transformer oil was enhanced using plasma treated silica nanoparticles to obtain plasma treated nanofluids. The results illustrated that the breakdown strength of the plasma treated nanofluids increased comparing with pure oil and untreated nanofluids. The AC, DC, and impulse voltage waveforms were applied to the transformer oil with TiO_2 to investigate the performance of the nanofluids according to ASTM standard.

Nanocrystalline manganese nickel ferrites are the famous substitution ferrite system providing promising electrical properties exploited in the industry. The manganese nickel ferrite system was represented as $Mn_xNi_{1-x}Fe_2O_4$ and it was crystalized in an inverse spinel structure. Controlling the substitution factor x that is defined inversion parameter was assessed during the preparation process and heat treatments [16-19]. Completely inversion could be done for the factor x, in which it could be changed from zero to one. This provided a chance of a wide enhancement of the physical, magnetic, electric, and electronic properties. Although these wide prosperities were attained for the nanocrystalline manganese nickel ferrite systems, it was not applied for enhancing the dielectric characteristics.

In this paper, the nanocrystalline manganese nickel ferrite powder concerning substitution degree of 20 % ($Mn_{0.2}Ni_{0.8}Fe_2O_4$) introduced in [16] is used to enhance the dielectric withstand voltages of the transformer oils. The nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ was synthesized via the oxalate precursor route. Based on analyses using XRD and SEM provided the nanocrystalline evidences. Different concentrations of the nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ grams per oil litre (g/l) are considered. The nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ is distributed in the oil using the sonicator considering concentrations of 0.02, 0.04, and 0.06 g/l. The experimental measurements using the impulse generator confirmed the dielectric enhancement of incorporating the nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ into the transformer oil.

Preparation and Evaluation of Nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ Powder:

Nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ powder introduced in [16] was prepared using the oxalate precursor method. The principles of oxalate precursors technique depended on chelating the cations with the aid of oxalic acids. This method of nanocrystalline powder synthesis achieved uniform distribution cations based on the designed ratio after the drying process. The synthesized powder has advantages such as homogenous nanostructure and uniform shape processed at appropriate annealing temperatures.

The chemical organic sources used for the preparation process were ferric chloride, manganese chloride, nickel chloride, and oxalic acid anhydrous. For precisely producing nanocrystalline of $Mn_{0.2}Ni_{0.8}Fe_2O_4$, the stoichiometric ratio is adjusted of these organic sources. Then, the laboratory processes such as chemical organic mixing solution, magnetic stirring, evaporation, thermal heating and precursor drying fixed at annealing temperature were accomplished. These laboratory processes to synthesize the nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ powder were informatively discussed in [16]. However, it is important to mention that the 0.2 mol (molecular weight unit) of manganese chloride, 0.8 mol of nickel chloride, 2 mol of ferric chloride, and 4 mol of oxalic acid were considered in the mixture charging.

In [16], a wide range evaluation of the nanocrystalline formation, size, as well as morphology and magnetic properties was reported using tests such as thermal analyzer, X-ray diffractometer (XRD), scanning electron microscopy (SEM), and vibrating sample magnetometer (VSM). Based on the presented application in this paper, only the XRD and SEM results are discussed in this section where these results are used to confirm the nanocrystalline synthesis of manganese nickel ferrite system based on 20 % substitution ($Mn_{0.2}Ni_{0.8}Fe_2O_4$).

For different annealing temperatures in a range 400 to 110 ^{o}C, ref [16] presented the XRD patterns of the nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ powders. It was found that the different annealing temperatures produced different nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ powders. For annealing temperatures less than 800 ^{o}C, there were impurities that could negatively influence on the transformer oil dielectric characteristics. For annealing temperatures equal to and greater than 800 ^{o}C, a single phase nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ was synthized. However, the higher annealing temperatures increased the nanocrystalline sizes. Compromising between the avoiding of impurities at low annealing temperatures and avoiding of high nanocrystalline sizes produced at high annealing temperatures, the nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ annealed at 1000 ^{o}C is selected in this paper to enhance the dielectric withstand voltages of the power transformer oils as discussed in the following section. This is to exploit the advantages of dispersing the single-phase nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ in the transformer oils. The other observation was that the $Mn_{0.2}Ni_{0.8}Fe_2O_4$ annealed at 1000 ^{o}C was had the highest lattice parameter comparing with the other annealing temperatures.

Figure 1 shows the XRD patterns examined for $Mn_{0.2}Ni_{0.8}Fe_2O_4$ ferrite annealed at 1000 ^{o}C. From the curve this figure, a single-phase nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ powder was produced. Furthermore, the nanocrystalline size was found 161 nm for the nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ ferrite annealed at 1000 ^{o}C.

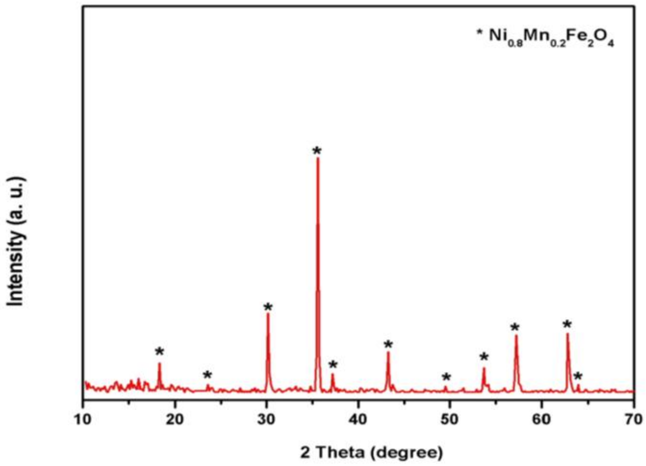
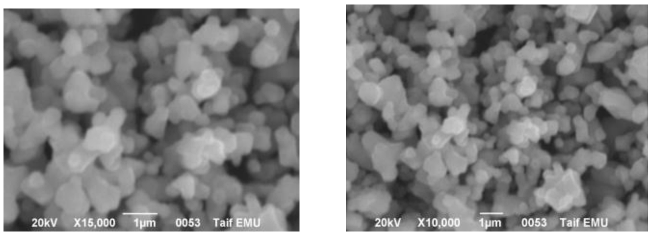
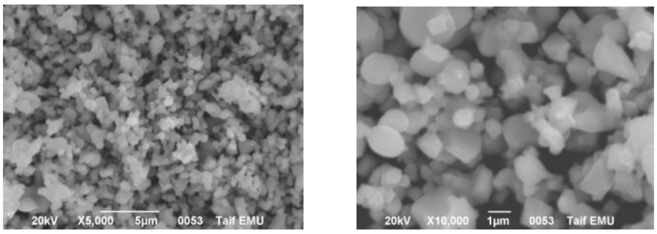


Figure 1: XRD patterns of $Mn_{0.2}Ni_{0.8}Fe_2O_4$ solution annealed at 1000 ^{o}C for 2 hr.

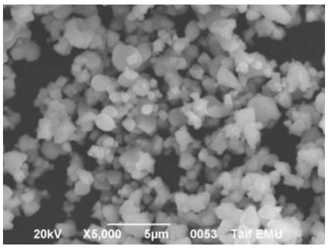
Using the synthesized nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ annealed at different annealing temperatures for 2 hr, Ref. [16] presented the results obtained by the scanning electron microscopy at Taif university. It was found from the SEM results that the nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ treated at annealing temperature less than 800 ºC had incomplete nanosturtucture. However, annealing temperatures equal to and greater than 800 ºC possessed better nanocrstalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$. For annealing temperatures 900, 1000, and 1100 ºC, better homougenous microstructures were found. Accordingly, the selection of utilizing nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ annealed at 1000ºC could be appropriate to enhance the dielectric withstand voltages of the transformer oils. Figure 2 depicts the measured micrographs at different areas and different scales to show the morphology of the synthesized nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ powder. From these figures, the homogeneity of nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ was ascertained. The average grain size was found in the range of 1 to 1.5 μm as addressed in [16].



(a) Area 1. b) Area 2.



(c) Area 3. (d) Area 4 [16].



(e) Area 5.

Figure 2: SEM micrograph.

The selected nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ is utilized in this paper to enhance the dielectrics of the transformer oil. This study is extended in the following section using the 140 kV impulse generator.

HV Impulse Tests

In this section, the oil dielectric characteristics are evaluated by applying the high voltage (HV) impulse standard waveform when the nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ powders were added to enhance the oil characteristics. These experimental tests were accomplished at the high voltage laboratory, electrical engineering department, college of engineering, Taif university, Saudi Arabia. A single stage impulse generator 140 kV depicted in Figure 1(a) was utilized to generate the standard waveform of the impulse voltage. A test cell of pin-hemisphere electrodes was used as shown in Figure 3(b) where the pin and hemisphere diameters are 0.36 cm and 3.6 cm, respectively. The gap distance between the pin and hemisphere was adjusted at 1.66 mm. The point behind utilizing a test cell of the non-uniform field and a gap distance less than the standard value was to advisedly use lower impulse amplitudes applied on the test samples and therefore a reliable impulse testing was achieved. In other words, the test cell was not damaged. A 0.4 ltr of either pure oil or nanofilled oil was considered to fill in the test cell. The uniform dispersion of the nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ in the oil was achieved using the sonicator for one hour. Then, the impulse waveforms were applied on the test cell until achieving the dielectric breakdown.

(a) Impulse generator.

(b) Pin-hemisphere test Cell with a gap distance 1.66 mm.

Figure 3: Laboratory test setup.

The experimental impulse waveforms were measured using four channels digital storage oscilloscope, 100MHz, 2 GS/s, model TDS2014C. Using the Matlab program, the scaling factor is considered to draw waveform samples in its real values. Figure 4 shows an example of generated impulse waveform applied on the test cell filled by pure transformer oils. The parameters of the impulse waveform shown in Figure 4 were found 42.2 kV and 1.2/50 μs. When the impulse amplitude was gradually and slightly increased until the breakdown occurred, Figure 5 shows the corresponding voltage waveform. The impulse amplitude was 43.4 kV. This value was considered in this study as the reference value to measure the enhancement of using the nanocrystalline manganese nickel ferrite.

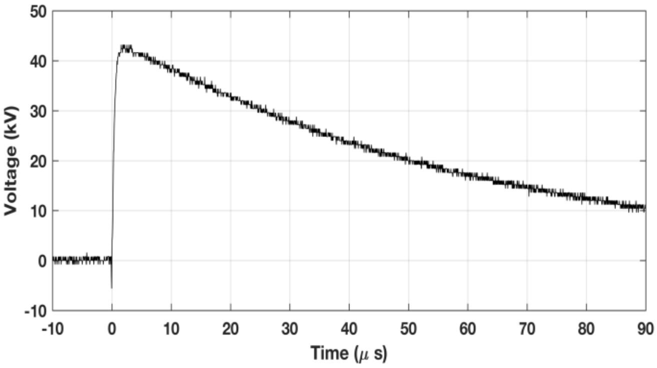


Figure 4: Impulse waveform applied on pure oil without dielectric breakdown.

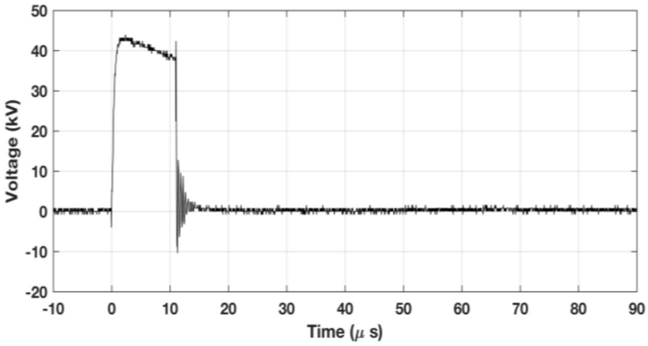
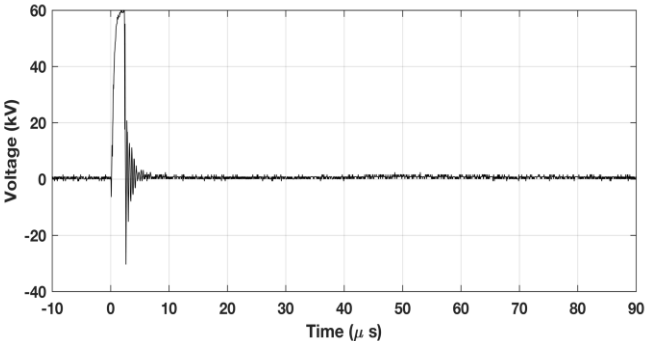


Figure 5: Breakdown impulse waveform of pure oil.

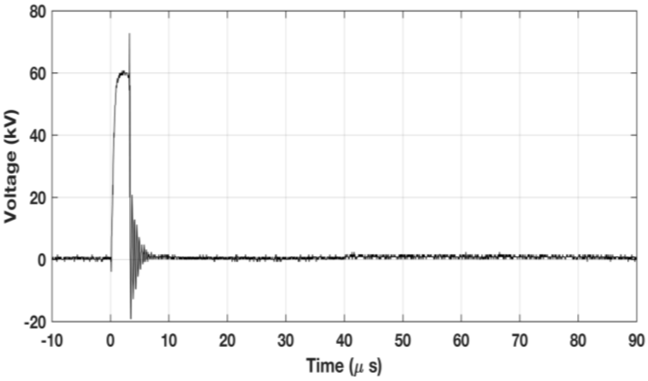
Figure 6 shows the measured breakdown impulse voltage for different nanocrystalline concentrations of nanofluid. Comparing Figures 5 and 6, higher breakdown voltages of the transformer oil have been attained due to adding nanocrystalline manganese nickel ferrite (nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$). Table 1 summarizes the percentage enhancements where the higher increase in the breakdown voltage is 42.3 % when the nanocrystalline concentration is 0.04 g/l.

Table 1: Enhancing the transformer oil dielectric using nanocrystalline manganese nickel ferrite with a substitution degree of 20%.

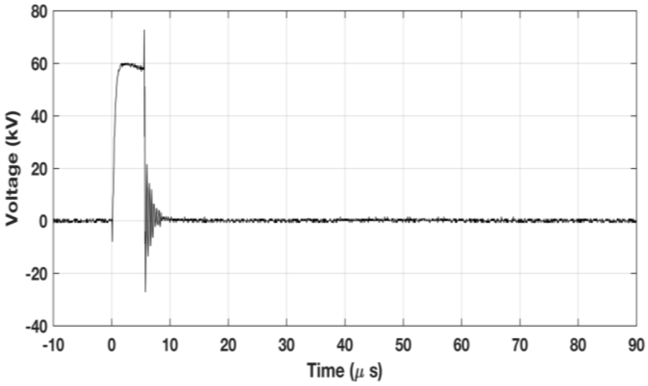
Nano concentration	Breakdown Voltage	Enhancement
Pure oil	43.4 kV	-
0.02 g/l	59.8 kV	37.7 %
0.04 g/l	61.8 kV	42.3 %
0.06 g/l	60.4 kV	39.1 %



(a) 0.02 g/ltr.



(b) 0.04 g/ltr.



(c) 0.06 g/ltr.

Figure 6: Breakdown impulse waveforms of nanofluid oils at different concentrations.

CONCLUSIONS

The nanocrystalline manganese nickel ferrite was prepared where during the synthesis process the nickel was substituted by 20 % manganese ($Mn_{0.2}Ni_{0.8}Fe_2O_4$). The nanocrystalline $Mn_{0.2}Ni_{0.8}Fe_2O_4$ ferrite were dispersed in the transformer oil with the aid of sonication process for one hour. By evaluating the dielectric withstand voltage of the transformer oil, higher breakdown voltages were attained especially at nanocrystalline manganese nickel ferrite system-based concentration of 0.04 g/l. More than 40 % enhancement of the impulse breakdown voltage was ascertained. The laboratory evaluations confirmed the nanocrystlline manganese nickel ferrite enhancement of the transformer oil dielectric characteristic.

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