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Development of Epoxy-MgO Nanocomposite Material for High Voltage Electrical Insulation

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Abstract: This paper investigates the dielectric properties of epoxy-MgOnanocompositematerials,focusingontheirdielectric constant and breakdown strength. The synthesis of epoxy-MgO nanocompositeswithvaryingnanoparticleconcentrationsusing magneticstirring ,ultrasonication and thermalcuring willbe done. Keyparametersincluding dielectric constantandbreakdownstrength, willbeevaluatedthroughhighvoltagetesting toassessperformanceofthematerialunderelectricalstress. Thisproject will also evaluatethecost-effectiveness ofepoxyas a polymer matrix, being more affordable and accessible than other polymers; making it suitable for large-scale applications. Additionally,theeffectsofnanoparticledispersionandinterfacial interactions on dielectric characteristics will be explored to identifyoptimalloadingconditions.Theresultingnanocomposites with enhanced dielectric properties could make them promising candidates for high voltage electrical insulation, where high dielectric strength and thermal stability are critical.

Index Terms: Epoxy resin,nanocomposites,high voltage elec- trical insulation,interparticle distance

I. INTRODUCTION

Then an ocompositesareadvancedmaterialsconsistingof a base matrix reinforced with nanoparticles, nanotubes, or nanofibers, leading toenhancedmechanical,thermal, electrical, and optical properties. Engineered at the nanoscale, these materials exhibituniquecharacteristicsduetothehighsurface area and aspect ratio of nanofillers, making them superior to conventionalcomposites.Theirapplicationsspanaerospace,
automotive,andelectronics.

In high-voltage insulation and energy storage, nanocom- positesofferimproveddielectricproperties,higherbreakdown strength, and reduced dielectric losses, enhancing power systemefficiencyandreliability.Epoxy-magnesiumoxide(MgO) nanocomposites,inparticular,integrateepoxyresinwithMgO nanoparticles, enhancing mechanical strength, thermal stability,anddielectricperformance.Theseadvancementscontribute tothedevelopmentofdurableandefficientinsulationmaterials for power transmission and distribution.

II. THEORETICAL MODEL OF DIELECTRICNANOCOMPOSITE

A. Inter Particle Distance

Theinterparticledistancedependsontheamountoffiller added.Thefillerparticlesaresphericalinshapeandtheyare arrangedinasimplecubic latticethentheinterparticledistance can be calculated as:

$$D - {}^{*}\ \pi\rho_n \frac{100}{6}\ \frac{1}{\rho}\ \frac{\quad}{wt\%}\qquad \frac{wt\%}{100}1 - \quad \frac{\rho_m}{\rho}^{1/3}\qquad -1\quad d \tag{1}$$

D-istheinterparticledistance
d-isthediameterofthenanoparticle
ρ_n-isthedensityofepoxy
ρ_m-isthedensityofMgO

Table 1 presents the interparticle distance of epoxy- magnesium oxide (MgO) nanocomposite at various weight percentages of MgO. The interparticle distance quantifies the spacingbetweenparticlesinthecompositematerial,expressed in nanometers (nm). The data in the table illustrates the rela- tionship between interparticle distance and weight percentage of filler ratios.

TABLEI

CALCULATEDINTERPARTICLEDISTANCED FORDIFFERENTWEIGHTPERCENTAGESOFMGONANOPARTICLES(20NMDIAMETER).

WeightPercentage(%)	InterparticleDistance(nm)
1	87.47
2	65.11
5	42.28
10	28.86
15	22.17
20	17.84
25	14.67
30	12.19
35	10.15

Analysis of the data reveals that as the weight percentageof the filler increases, the interparticle distance decreases, indicatingthattheparticlesarepositionedclosertogether.This relationship is visually represented in Fig.1 The methodology and findings shed light on the interparticle distance as a key factorindeterminingthecomposite'sproperties.Astheweight percentage of MgO nanoparticles increases, the interparticle distancedecreases,indicatingacloserpackingofparticles,

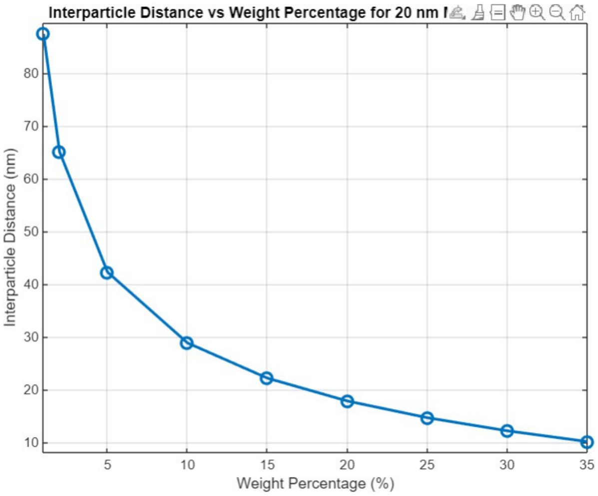

Fig.1.InterparticledistanceVsWeightPercentage

which may influence the dielectric properties. These findings arecriticalforoptimizingthedesignofepoxy-MgOnanocom- posites, as understanding the particle dispersion and spacing will aid in tailoring the material's dielectric performance for applications in electronics and insulation. The comprehensive simulation and testing approach offers valuable insights into thedesignanddevelopmentofhigh-performanceepoxy-based nanocomposites.

B. Simulation

SimulationoftheepoxyMgOnanocompositeisdone using COMSOL Multiphysics software. It investigates the distribution of the electric field within the nanocomposite material under high voltage conditions. The simulations were conducted using the Finite Element Method (FEM) with COMSOL Multiphysics V6.0.

COMSOLdividesthenanocompositegeometryintoafinite number of mesh elements which are symmetrically identical and solves problems by approximating derivatives using fi- nite differences. In COMSOL multiphysics, the electrostatics modulewasusedtocomputethedistributionofelectric field inside the nanocomposite. Polymers and fillers were assumed as isotropic materials. It was expected that uniform dispersion of nanoparticles existed in polymer matrix. It was thought that the connection between the particles and epoxy was perfect. The geometry considered is a nanocomposite samplewithelectricfieldstressthathasbeensubjectedto itandauniformthickness.Unitcelltechniqueisemployed to model the nanocomposite. Based on filler concentration which corresponds to inter-particle distance,the unit cell sizeis determined.

The sum of the nanoparticle diameter and the inter-particle distance is chosen for each side of the unit cell (cube) shown in Fig. 2 The top face of the block receives voltage while the bottom face is grounded. The other faces are untouched, making the geometrylooklikeaparallel-platecapacitor.Meshingisone of the important steps as it divides the geometry into finite number of elements.

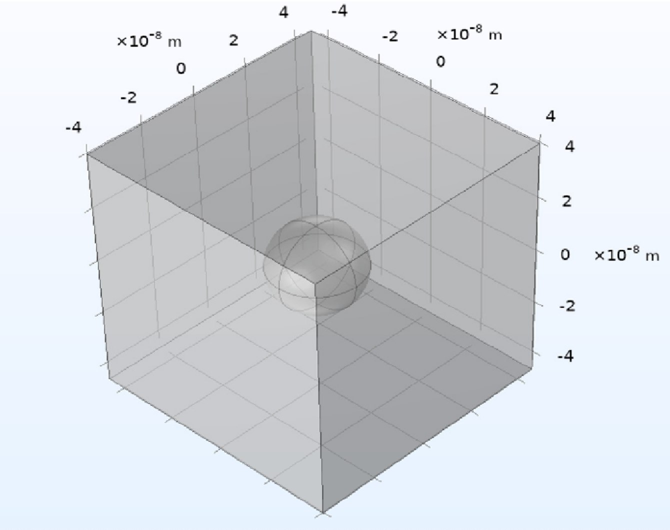

Fig.2.SingleunitcellofNanocompositeModel

C. *Electric Field Distribution Analysis*

Upon obtaining the computation results, it is noted that if the material were solely epoxy, the electric field distribution would be uniform throughout the block. However, adding MgOnanoparticlesintroducesnon-uniformelectricfielddistribution.Toanalyzethiseffect,apotentialof1.75Vwasapplied tothetopfaceofthenanocompositeunitcellinthesimulation model, with the bottom face grounded. At 5 percent MgO concentration,thisvoltagegeneratedabreakdownstrength of 42.4 kV/mm, which aligns closely with the breakdown strength of pure epoxy. When the same voltage was appliedto nanocomposites with increasing MgO concentrations, the breakdown strength progressively improved, indicating that higher MgO content enhances dielectric strength and break- downresistance.ThesefindingshighlighthowMgOdispersion and concentration can modify the electric field landscape within nanocomposites, thereby increasing their effectiveness for high-voltage insulation applications.

1) *MgOat2%weightratio:*Afterapplyingapotentialof 1.75V at top face of the unit cell, the electric field distribution of the MgO nanocomposite at 2% weight ratio is shown inFig. 3. From this figure we can infer that the breakdown strength is 30.6 kV/mm at 2% weight ratio.
2) *MgOat5%weightratio:*Afterapplyingapotential of 1.75V at top face of the unit cell as shown in Fig. 4, the electric field distribution of the MgO nanocomposite at 5% weight ratio is shown in Fig. 5. From this figure we can infer thatthebreakdownstrengthis42.4kV/mmat5%weightratio.
3) *MgOat10%weightratio:*Afterapplyingapotentialof 1.75V at top face of the unit cell, the electric field distribution oftheMgOnanocompositeat10%weightratioisshown

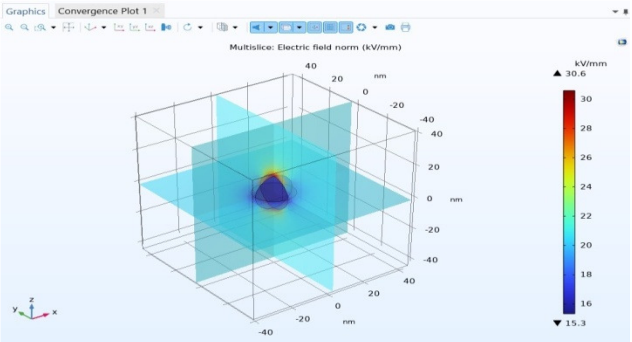

Fig.3.ElectricalPotentialDistributioninNanocomposites

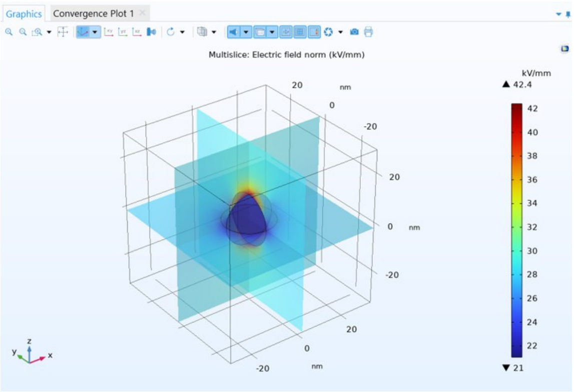

Fig.4.ElectricalPotentialDistributioninNanocomposites

inFig.6.Fromthisfigurewecaninferthatthebreakdown strength is 53.9 kV/mm at 10% weight ratio.

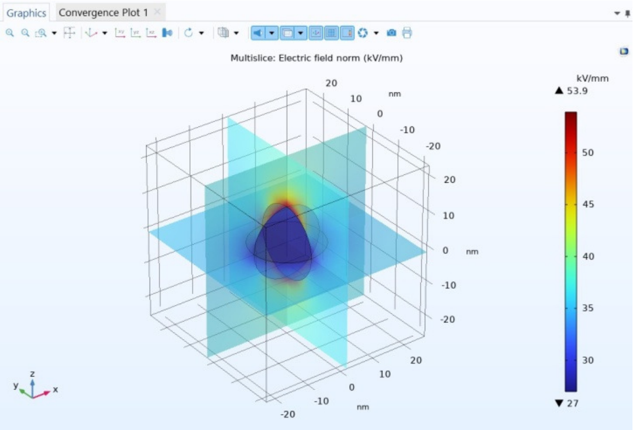

Fig.5.ElectricalPotentialDistributioninNanocomposites

The results from the COMSOL simulations indicate that epoxy nanocomposite materials are suitable for high voltage insulation applications. The incorporation of MgO nanoparti- clessignificantlyenhancesthematerial'sresistancetoelec- trical breakdown, particularly when the nanoparticles are evenly distributed throughout the epoxy matrix. The sim- ulationfindingsdemonstratethatastheweightpercentage ofMgOnanoparticlesincreases,thebreakdownvoltageof the nanocomposite also rises, thereby improving its overall dielectric strength.

III. SAMPLE PREPARATION

A. *Preparation Procedure*

The base polymers utilized were Bisphenol-A-Epoxy resin (CY1300) and the corresponding hardener (HY956), both supplied by Haksons. To shape the samples into round discsof specified dimensions, a stainless steel mould was custom- built for this purpose. The mould consist of 4 circular disc of diameter 6 cm and a thickness 1 mm in a rectangular sheet made of stainless steel. This design was chosen for its afford- ability and practicality in accommodating the testing device. The testing device is specifically designed to accommodate round discs, aligning with the circular form of the mould.This configuration was chosen based on considerations of cost-effectiveness and functionality. The mould's volume is calculated using a formula,

$$\pi\times r^2\times h \qquad (2)$$

where'r'istheradiusand'h'isthethickness.Inthedirectdis- persionmethodemployedforcreatingpureepoxysamples,the process initiates by taking appropriate amounts of Bisphenol- A-epoxy resin (CY1300) in a beaker. The required percentage weight of nanomaterial MgO is measured and added to the pure epoxy resin. Subsequently, manual stirring is conducted for 5 minutes, followed by 8-10 minutes of stirring using a magnetic stirrer in a water bath maintained at 60°C. If the mixturebecomeshighlyviscous,heatingisappliedduringthis stage. Ultrasonication is then performed for 8-10 minutes.

1) *Magnetic stirring:*A magnetic stirrer is a widely used laboratory apparatus having either a rotating magnet or a sta- tionary electromagnet and hence produces a rotating magnetic field.

Its main function is to mix solutions by introducing abar which spins within it. A rotating magnet or stationary electromagnet inside the device creates the required magnetic field thereby enable efficient mixing quickly among liquids in industrial laboratories.

2) *Ultrasonication:*An ultrasonicator is a versatile device commonlyusedinscientific,medicinalandindustrialfieldsfor tasks like cell disruption, sample preparation, and emulsifica- tion. A sonicator harnesses the power of ultrasonic waves to create cavitation bubbles within a liquid medium. These bub- blesformduetotherapidalternationofhighandlow-pressure wavesproducedbythesonicator.Whenthesebubblescollapse, they generate intense pressure and temperature gradients, cre- ating micro-jets and shockwaves that physically disrupt cells, tissues,orotherobjectsinthesample.Thecomponentsof a typical sonicator include a generator which produces high- frequency electrical signals, a transducer that converts these signals into mechanical vibrations and a probe or horn that transmitsthesevibrationsintothesample.Theprobeisusually submergedintheliquidmedium containingthesample.During sonication, the sample is placed in a container such as a test tube or beaker covered with a suitable liquid medium. The sonicator probe is then immersed in the liquid and activated producing high-frequency sound waves. These waves cause the liquid to vibrate, creating cavitation bubbles throughoutthe sample. As the bubbles rapidly expand and collapse, they generate intense pressure and temperature gradients, leadingto the disruption of the sample at the microscopic level. This disruption is crucial for various applications such as cell lysis, particle size reduction, and homogenization.
3) *Heatinginoven:*Themouldsareputtogetheronto anOHPsheetwithalittlegreaseappliedbetweenthem. Next, the mixture is poured into the moulds. These assembled mouldsarethenplacedinsideapreheatedovenat60°Cfor a period that lasts four hours without interruption. After this time period, one has to carefully remove the samples from the oven. This step helps in both solidifying of the mix as well as removing air bubbles from the composite material.

Perfect samples can only be obtained through proper exe- cution of these steps. If insufficient hardener is added to the mixture, it may turn out slimy which makes it improper for furthertestingprocedures.Also,iftherequiredtemperatureof thematerialisnotachievedwhileitisbeingheatedinanoven during processing, it can set wrong, fail to achieve complete setting and as a result become slimy. Attention to these things helps to remove samples from OHP sheet successfully and a perfect sample can be obtained as shown in Fig.7

Fig.6.Preparedsamples

Epoxy-MgO samples are prepared by mixing a suitable amount of hardener with the resin. The samples are molded as 6 cm diameter discs with a thickness of 1 mm. They undergoa series of preparation stages, including magnetic stirring, ultrasonication, and oven curing. These processes are crucial for achieving a uniform dispersion of the epoxy matrix.

IV. BREAK DOWN ANALYSIS

This chapter focuses on the DC breakdown analysis of nanocomposite samples. The test done is very much similarto conventional High voltage breakdown test except that the sample material is immersed in insulating oil. Transformer oil is used as an insulating oil because it exhibits good insulating properties. Prepared samples undergo DC breakdown studies. It is through the use of high voltage DC testing apparatus as showninFig.7thatthevoltageatwhichbreakdownoccurs is measured.

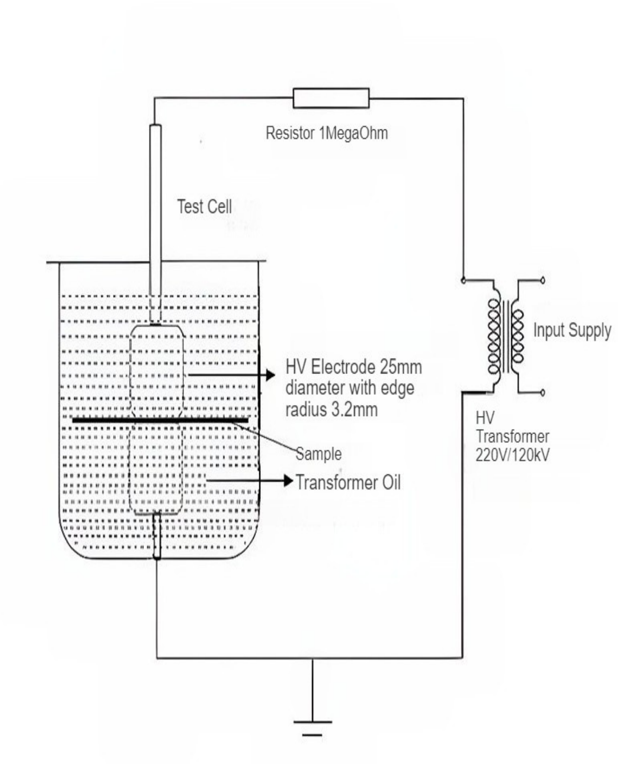

Fig.7.ExperimentalSetup

A. *DC Break Down Test*

ThesampleissubjectedtoaDCbreakdowntestwhere a voltage higher than that of an operational system fails it electrically. With this process one can be able to find out how much voltage the sample can take before it starts conducting electricity. In order to prevent flashover on its surface during testing, electrode setup was completely submerged inside a container full of transformer oil The electrodes used are made of copper and had diameter 25 mm with edge radius of 3.2 mm.

They were connected to the high voltage side of the transformerthatconverts220Vto120kVinDC.Atthe last stage, the voltage was introduced on the high voltage electrode till a point where failure occurred. The sample failures were puncture ones. These samples have an average thickness between 1mm and 2 mm measured using a digital vernier caliper before testing. $E=V/d$ is applied in calculating DC breakdown strength, where V represents the breakdown voltage and d means thickness of sample at failure point.

Onincreasingweightpercentageupto8%tremendouslyim- proves breakdown strength by giving 65% increase compared with pure epoxy sample. However, beyond this optimal con- centration,specificallyat10%weight, thebreakdownstrength rapidly falls. This suggests that there is a threshold for weight percentage that necessitates optimization of concentration at 8% in order to maximize breakdown strength.

TABLEII

BREAKDOWNPROPERTIESUNDERDCCONDITIONS

Weight%	Thickness(mm)	BreakdownProperties	
		Voltage(kV)	Strength(kV/mm)
Pureepoxy	1.28	43.89	34.28
2%MgO	1.57	52.75	33.59
5%MgO	1.33	54.39	40.89
8%MgO	1.47	77.88	52.97
10%MgO	2.19	71.87	32.82

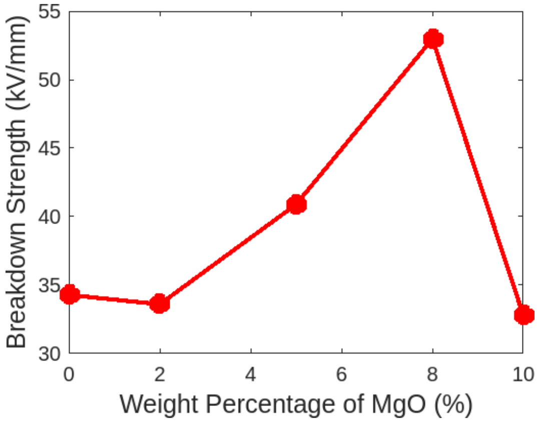

Fig.8.breakdownstrengthvsweightpercentage

V. CONCLUSION

Improvement of dielectric properties of Epoxy-MgO nanocomposites is investigated. Multiple samples of Epoxy- MgO nanocomposite at different filler loadings are prepared. HighVoltageDCbreakdowntestswereconductedtoevaluate the dielectric strength of the material at different filler con- centrations.DCbreakdownstrengthsof5wt%and8wt% arefoundtobegreaterthanthatofunfilledepoxy,while for 10 wt% the breakdown strength decreases. The maximum value of DC breakdown strength was obtained as 52.89 kV/mm at 8% filler loading. The improvement in breakdown strength is about double as that of pure epoxy. Simulation studiesalsowereconductedusingCOMSOLMultiphysics to analyse the electric field distribution in the matrix. The studyshowshowMgOnanoparticlescangreatlyimprove the electrical insulation capabilities of epoxy resins. Further research should be conducted in order to validate whether these kinds of nanocomposites can withstand long-term appli- cations in industry. Nevertheless, promising results have been obtained on these materials, which suggest that epoxy-silicon nanocomposites could transform high voltage insulation area by developing more effective and reliable materials.

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