Ahmadu Bello University, Zaria

THE DIRTY DIELECTRICS: IMAGINE A WORLD OF ELECTRICITY WITHOUT IT

AN INAUGURAL LECTURE

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The Dirty Dielectrics:

Imagine a World of Electricity Without it

An Inaugural Lecture

By

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2024

Dedication

The lecture is dedicated to Prof N. I. Hariharan

Acknowledgments

I wish to express my sincere appreciation to the Ahmadu Bello University, the Vice-Chancellor, Management, staff, and students of this great University. To all the Heads of the Department of Physics since I joined the service of the university in 2005, thanks for the support.

My gratitude to all my teachers, lecturers, and instructors in the labs from the very beginning to this day. I want to seize the opportunity to express my gratitude to my Primary one teacher who taught me my first word and letter. I couldn't have gotten to this point without the excellent guidance, encouragement, sincere criticism, and valuable suggestions of these people. They have greatly influenced my academic and personal life.

To the members of the Materials Physics Research Group, I found a family in all of you. I could not have asked for a better family in the university. This is your success. Thank you for joining hands with me to get to where we are today. To my colleagues; Dr Jimoh Raimi, and Prof T. O. Ahmed, it has been a long walk together since 1993. Thanks for those fruitful discussions, they were very helpful.

I wish to acknowledge Late Prof N. Hariharan who introduced me to the world of dielectrics. He was a source of inspiration.

My appreciation to Prof John C. Fothergill, Dr. Steve J. Dodd, and Prof Len Dissado who were at the University of Leicester and Lars Lundgaard of SINTEF Norway for shaping my knowledge of dielectrics.

My humble appreciation to my parents Alhaji Adubi Abdulmalik and Hajia Habibah Abdulmalik. I forward to your names the credit of whatever I am or achieved today and anything good I do, and unto myself the negative ones because they are the outcome of my failures. My sincere appreciation to siblings, relations, and friends for their untiring support all through to this point. My special gratitude to my brother, Alhaji Abdulkarim Omuya Adubi Abdulmalik, who sacrificed everything to see me get to this point. I wonder how it would have been without you. Thank you for refusing to give up on me.

My sincere appreciation to my wife, Hajia Amina Oiza Gomina. You have been a source of blessing since you joined me at the critical point of my career in 2014. Thank you for the patience and standing by me. The same goes for my little kids.

Finally, my gratitude goes to Allah for seeing me through the course of this chosen career. I could not have achieved this without His infinite mercy and grace.

Protocols

- The Vice-Chancellor,
- Deputy Vice-Chancellors (Administration and Academic),
- The Registrar,
- The University Librarian,
- Deans, Directors,
- HODs,
- Members of the University Council,
- Members of the Senate,
- Eminent Professors and Senior Academics,
- Esteemed Teaching and Non-Teaching Staff of the University,
- Friends of the University and Invited Guests,
- Students
- Ladies and Gentlemen of the Press,
- Distinguished Ladies and Gentlemen,
- ABUSITES,
- Good Afternoon!

Preamble

I graduated from the Ahmadu Bello University, Zaria in 2000 with a BSc. degree in Physics. I then enrolled for an MSc Physics just after the National Youth Service Corp. I joined the services of Ahmadu Bello University in 2005 just as I was about to finish the program. I rose to the rank of Professor of Physics in 2020 after earning a PhD degree in High Voltage Engineering from the University of Leicester in 2012. I began my teaching and research activities at the Department of Physics.

I have participated in several Conferences, Workshops, and Technical Meetings in Italy, Mexico, Norway, the UK, and the USA. I participated in the IAEA/ICTP School on Pulsed Neutrons: Characterization of Materials, at the Abdus Salam International Centre for Theoretical Physics, Trieste (ICTP), Italy in 2007. I was also there at the Institute of Physics (IOP) Conference on Early Career Research in Electrostatics and Dielectrics, London, UK in 200. I participated in the European Electrical Insulation Manufacturers (EEIM) Seminar on Electrical Insulation for Transformers – Materials, Design, Reliability & Performance, Testing, Research & Development, University of Manchester, UK in 2010. I participated in the UK University High Voltage Network (UHVnet) Colloquium in the UK in 2010, 2011, and 2012. I participated in the IEEE/NTNU Seminar on Silicon Carbide in Power Electronics in Trondheim, Norway in 2014. I also participated in the International Topical Meeting on Nuclear Applications of Accelerators conference and the pre-conference PUFFIn (Penelope-

Based User Friendly Fast Interface for Calculating Dose Distribution in Irradiated Products) training in 2024 in Norfolk, Virginia, USA. I was one of the recipients of the 2008 Islamic Development Bank (IsDB) Merit Scholarship Award for High Technology (PhD) on the development of natural ester insulating fluid from Nigerian vegetable oil to fund my PhD from 2009 to 2012. I was among the five recipients of the 2010 IEEE DEIS Graduate Fellowship Award (5,000 USD) for Innovative Idea: Effect side branching on natural ester insulating fluid. I was a finalist at the University of Leicester's 2011 Postgraduate Festival. I won the World Academy of Science (TWAS) Individual Research Grant for Basic Sciences for the project "Nigerian vegetable oil-based fluid as an alternative drilling fluid for offshore rigs" in 2013. The award began the making of our today's materials science research laboratory in the department.

I was a postdoctoral research fellow at the Electric Power Engineering Department of the Norwegian University of Science and Technology (NTNU) Trondheim, Norway. I was part of a research team on the SINTEF Energy research project "Pressure Tolerant Power Electronics for Oil and Gas Exploitation -PRESSPACK".

As an academic mentor, I have supervised 6 PhD students and several MSc students. I have published over 40 articles on my research findings in indexed and high-impact journals. I have been a peer reviewer for Industrial Crops and Products, Radiation Physics and Chemistry, Materials Physics and Chemistry, IEEE Transactions on Dielectrics and Electrical Insulation, IET High Voltage, etc. I was recently appointed as an Associate Editor for

IEEE Transactions on Dielectrics and Electrical Insulation.

My major contribution to the advancement of dielectric physics in Nigeria and globally has been in five principal areas: (i) Properties of engineered insulation materials, (ii) integrity of high voltage insulation system, (iii) electrical ageing, degradation, and breakdown, (iv) reliability studies, (iv) "nano-dielectrics" – i.e. dielectric materials made from nanocomposites, (v) the measurement and study of partial discharges (PD). In a pioneering work, I authored work on optical PD study of the insulating system under fast transient voltage – an area in which work is still on to develop a suitable technique for PD study on converters, transformers, and penetrators under fast-rise voltage. I initiated the revival of high voltage research at Ahmadu Bello University after about 30 years of its breakdown. I was key to the upgrading of the Materials Science Research Laboratories in the Department of Physics, Ahmadu Bello University Zaria, Nigeria to include a high-voltage materials laboratory, the materials Characterization Laboratory, and the Transformer Oil Dissolved Gas Analysis laboratory. Our HV laboratory is perhaps the only functional high-voltage materials laboratory in any University in the Northern part of the country. I initiated the Materials Physics Research Group, one the functional research groups in the University.

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Fundamental of Dielectric Physics

General introduction

Energy is one of the most vital requirements for the socio-economic development of any country. The growing population has caused the demand for an increase in power generation requirements. Electricity generation and operation are built around a safe insulation system. The increasing output means an increase in electrical stress on the insulation system. Insulation systems play a vital role in the reliability of electric power systems and power electronic. Insulation failure may result in system failure and ultimately system breakdown and costly repair. As the electrical and electronic power system keeps evolving, so does the need to design insulation systems with the requirement to take care of the current power demands.

Electricity has always been a part of nature in the form of static electricity but the discovery that an electric current could be produced by passing a magnet through a loop of copper wire (Electromagnetic Induction) by the English scientist, Michael Faraday in 1831, revolutionised the concept of electricity generation. The induction ring was the first electric transformer. Nearly all the electricity produced today is from giant power plants with magnets and copper coils. This current is a flow of electrons, something we call charges, per unit time in the conductor. The human body contains various ions with the tendency to conduct electricity. That makes the human body a good conductor and electrons can flow through it when in contact with a current-carrying conductor. That is dangerous and can cause electric shock. Shock is basically a mini feeling of current passing through the body. If you have ever experienced the feeling of electric shock while opening the door of your car or coming in contact with a household appliance, you will recall that it was a scary experience. But why don't we get a similar experience when the human body comes in contact with materials such as wood? This is because wood is an insulator while metal is a conductor. Electric materials are capable of developing (conducting) electric charge or current while di-electrics are not capable of developing (conducting) electric charge or current. The insulator lacks the free electrons responsible for current flow. The electrons in insulators are "bounded" and static.

Faraday in 1836 realised that electric charges produced by a high-voltage generator could not create an electric field inside a room enclosed by a metallic sheet. This was later referred to as the Faraday cage. The electric field lines do not 'pass through' an electrical conductor. This is contrary to what happens in any non-current-carrying material such as glass or air. Faraday needed a new term to define such 'non-electrical-conducting' materials that allow the electric field to pass through them. William Whewell in 1836 invented the term *dielectric*. The word *dielectric* comes from the Greek 'dia = through' + 'electric', which for ease of pronunciation is written as 'dielectric'.

Dielectrics are materials that have no free charges but bound charges of opposing signs. For such a material, an applied electric field causes the bound electrical charges to try to separate from one another causing induced electric dipoles. The applied field causes the electron clouds of atoms to shift in position relative to their nuclei.

The extent of the separation due to the applied electric field is described by the so-called *polarization* (figure 1).

Maxwell's Equation

There are two energy bands in any material. The valence band and the conduction band. There is a third band called the band gap that separates the two bands. In dielectrics (insulators), the valence and conduction bands are separated by an energy gap with a large band gap. The conduction band is empty and there are no electrons available for electrical conduction. Electrostatics is the subfield of electromagnetics that describes an electric effect caused by static charges. Maxwell's first equation which was derived from Gauss's theorem describes the electrostatic field. The polarisation causes a local modification of the electric field inside the materials with an electric field displacement field, $\boldsymbol{D} = \varepsilon_0 \boldsymbol{E}$. The polarisation resulting from the applied field is

$$P = (\varepsilon - \varepsilon_0)E$$

Where ε is the permittivity of the dielectric material.

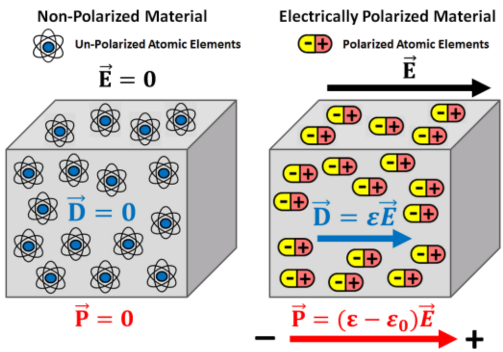


Figure 1: Polarisation of materials

Assuming a parallel plate capacitor with a dielectric between the plates, the application of an electric field deforms the distribution of charges. A displacement current is produced if the electric field changes with time. You can also have conduction current from ionised impurities in the material. The total current density through the capacitor is the sum of the conduction current which results in electrical conductivity, σ, and the displacement current.

$$J_{tot} = \sigma \cdot E + \frac{\partial D}{\partial t}$$

Len Dissado, one of my mentors, is to this day intrigued by dielectrics. His draw is their complexity. He said: “It's all materials which a friend once called ‘dirty dielectrics’. They're not nice and easy standard chemical structures. They are mixed up every things with additives you put in deliberately, things that are left over from when you formed them, and stuff you don't want in there that got in there anyway.”

The physics of dielectric materials in high voltage Engineering

Using the Poisson equation, the distribution of the electric potential *V* can be related to the space charge density, ρ, with the expression

$$\nabla \cdot E = \frac{\rho}{\varepsilon_r \varepsilon_0}$$

Where ε_0 is a universal constant of nature called the permittivity of free space and ε_r is the relative permittivity of the dielectric.

If you have two conductors in a device at a distance *d* apart, and one is carrying current while the other is neutral or grounded, the application of high voltage may be high enough to ionise the air between the conductors. It creates a conducting path through the air. At certain field strength, the number of charge carriers in the conducting path in the air between the conductors is high enough to drop the resistivity of the air. This will cause a strong current flow through it. This creates lighting (corona discharge phenomenon) that could lead to electrical breakdown. The electric field between the two potentials V_1 and V_2 is

$$E = \frac{\partial D}{\partial x} = \frac{V_2 - V_1}{d}$$

There was a need to protect users from electric shocks and the equipment from breakdown from the field of the current carrying conductors. Dielectrics (insulators) were found to be the best materials to perform that purpose and it was believed that a voltage *V* between two electrodes (current-carrying conductors) can be insulated by placing a homogeneous insulating material (dielectrics) of breakdown strength E_b. The breakdown strength of the material between these electrodes is considered a characteristic constant of the material. It is a function of the nature of the material. The thickness of the material which determines the separation *d* between the conductors can simply be calculated as $d = V/E_b$.

The first public power station was into service in London in 1882. The station was Direct current (DC) and of low-voltage. The limitation of DC led to the development of alternating current (AC). The art of the development of

AC generators and transformers was perfect and in 1890 electricity supply by AC became common. The first AC power station was commissioned in London in 1890. The generated electricity is at a limited voltage and needs to transmit the generated power over long distances to the end-users. The electric power (P) transmitted on an overhead AC line increases approximately with the surge impedance loading or the square of the system's operating voltage. Thus, for a transmission line of surge impedance Z_L (≈ 250 Ω) at an operating voltage V, the power transfer capability is approximately $P = V^2/Z_L$. The transmission experienced Ohmic losses or power loss (I^2R). This is described as the voltage drop along the power line due to the flow of current through the line. This led engineers to begin to think in terms of high system voltages. The power system is developed with the appropriate insulation and the operating voltage does not usually place severe stress on the power system's insulation except in special circumstances. However, the dimensions of the insulation of generation, transmission, and distribution equipment are determined by the operating voltage. The power system can experience voltage stresses from various sources of overvoltage. These may originate externally or internally. Lightning discharges are of high voltage and can be one of the sources of external overvoltage. This is not dependent on the operating voltage of the system. Therefore, the importance of stresses produced by lightning decreases as the operating voltage increases. Changes in the operating conditions of the power system such as switching operations, a fault on the system or fluctuations in the load or generations are the main causes of internal overvoltage. Since switching operations is the major cause of the changes in the system's conditions, these overvoltages are generally referred to as switching overvoltages.

A dielectric material is a passive component of an electrical or electronic power system whose primary function is to insulate. As it performs its function, it is subjected to electric, mechanical and thermal stress. There are different types of insulation systems:

- The air-insulated system which has a low breakdown strength of *3 kV/mm* is used in dry-insulated transformers, partially insulated switchgear, insulated busbars in air, cable termination, etc.
- The gas-insulated system which has a high breakdown strength that is 2.5 times that of the breakdown strength of air is used in gas-insulated transformers (SF_6), hydrogen-filled rotating machines, pressure gas-insulated cables, cycle breakers, etc. The major drawback is its toxicity and sensitivity to contaminants
- The liquid-insulated system has high breakdown strength. It is used in oil-filled electrical and electronic power equipment. It doubled as a coolant with good cooling properties. It has no cavity but is sensitive to moisture, particles, high loss, and thermal expansion.
- Solid insulation system has good dielectric strength and it is used in cables, generators, bushing, etc. They are easy to shape, low cost, low weight, and good temperature resistant. But they are sensitive to moisture, and cavities and unlike liquid have no self-healing properties.

Dielectrics are characterised by properties such as relative permittivity (the ease of charge storage), loss tangent (the ease of charge transport), and dielectric breakdown (the voltage endurance capability). Dielectric permittivity characterises the degree of electrical polarization. It is the ratio of the electric field and the corresponding electric displacement.

There are different types of polarisation and this is a function of the operating frequency. Charge transport in dielectric materials leads to DC conductivity. Polarisation due to displacements contributes to the leakage current. The dipole moment induced in molecules on the application of an electric field results from a slight displacement of its electron cloud with respect to the nuclei. This is known as electronic polarisation. The applied field also leads to the relative displacement of polyatomic molecules to each other. This is referred to as atomic or ionic polarization. Molecules carrying a permanent dipole moment in addition to electronic and atomic polarization suffer a torque in an electric field E that tends to orient the dipole in the field direction leading to orientation polarization [Von Hippel, 1957]. Thermal agitation, on the other hand, tends to maintain a random distribution as a result there will be a time-averaged orientation in the direction of electric field, E.

Electrical Breakdown in Dielectrics

Failure of Electrical Insulation Properties (flow of current) of an Insulator or Dielectric is referred to as a breakdown. Dielectrics can be gas, liquid, vacuum, or gas and the breakdown mechanisms are different. In a gas, free electrical charges under a sufficiently high force can produce ionization and avalanche breakdown by hitting other atoms. The breakdown theory of liquid is yet to be well established. However, the experimental relationship has been derived between the electrode voltage difference and the inter-electrode distance. To use a vacuum as real insulation, it must be at very low pressure. Only pressure lower than 10^{-2} mbar can be considered to provide real dielectric insulation. Vacuum under high pressure can create ideal conditions for electrical discharge. Breakdown in solid can be classified into two fundamental types: there is the electronic breakdown where above the critical field, sufficient energy electrons can transit from the valence and cross the forbidden gap to the conduction band. This can result in the creation of a collision phenomenon with other electrons. This can lead to a breakdown. There is the avalanche breakdown similar to the theory of breakdown in gases. Above a critical field, the application of sufficient energy can make conduction electrons gain enough energy to liberate electrons from the lattice atoms by collisions.

High Voltage: Physics or Engineering?

High voltage engineering is a multi-disciplinary area in electrical engineering that incorporates physics, chemistry, and engineering. It considers the effects of electric fields on the properties of dielectric materials, especially when high voltage is applied. It is the science of designing the insulation coordination of high-voltage devices to ensure reliable operation. The concept of a complete insulator does not exist. Even a good insulator can conduct under High Voltage as charge carriers are mainly injected from the electrical contacts or other external sources. High voltage science and engineering is the knowledge of the behaviour of dielectrics or electrical insulation when subjected to high voltage. It studies the electrical phenomenon occurring in various mediums at high voltages. It develops and optimises operating characteristics of internal and external insulators of electrical and electronic power devices. The science of planning, operating, and testing high-voltage devices is known as the high voltage engineering. This field brings experts from various fields to work together and as such, it is referred to as the materials science of electric power engineering.

Applications of Dielectrics

Electrical power

Electricity generation is a network (Figure 2). The generated electricity by the Power plants in Nigeria is between 11.5 – 16 kV. This generated electricity cannot be transported over a long distance else it will be lost due to Ohmic loss. To sustain the generated electricity, it is first stepped up to 330 kV with a step-up transformer at the Power stations. The 330 kV is then transported along transmission lines (conductors) to the next transmission substation. The electricity is stepped down by a transformer to 132 kV at the substation. The 132 kV is further transported along the transmission lines to Injection substations where another set of transformers stepped it down to 33 kV. The transmission stopped at this point and electricity distribution began. The 33 kV is stepped down by a step-down distribution transformer to 11 kV. This is further stepped down to 0.415 kV (415 V) phase to phase or 240 V phase to ground. The 240 V is transported to our homes or offices.

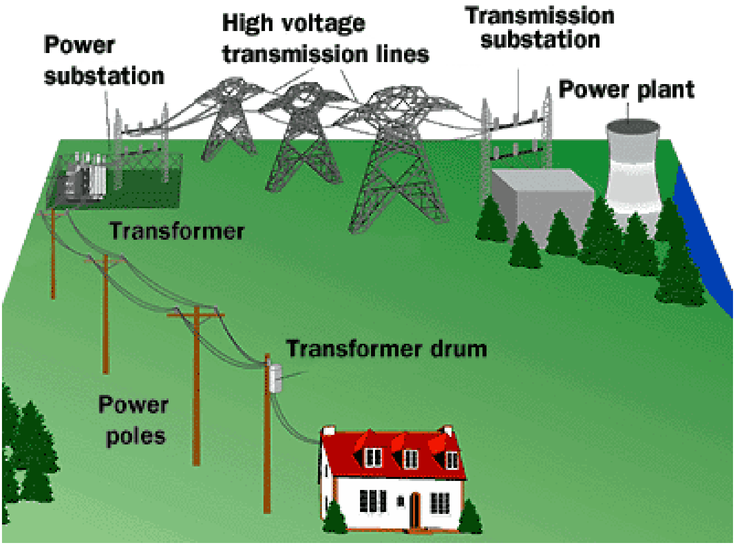


Figure 2: Electricity network

Power transformers are built around the insulation system (Figure 3). They cannot survive for a second without the insulation system. The insulation system of an oil-filled transformer consists of oil and cellulose (paper and pressboard). The cellulose which is the solid insulation serves as dielectrics to store electric charge when energised, isolate the components in the transformer, and serve as mechanical support. The oil provides the required dielectric strength and sufficient cooling, fills the voids in the solid insulation to preserve the core and coil, and protects the solid insulation from contact with oxygen. The connecting high-voltage cables are insulated with polymers (Figure 4).

Figure 3: The inside of a transformer with solid insulation

Figure 4: High Voltage cable

Electric power transformers and high voltage rotating electrical machines used for power generating equipment which is built around their insulation system are vital components of electrical generation, transmission, and distribution networks. The insulation system plays a vital role in their reliability. Unlike the active components such as conductors and magnetic steel in power equipment (motors, generators, transformers, cables, etc.), the insulation in power equipment is passive. It does not contribute to the magnetic field or guide its path.

The designers of power equipment would have loved to eliminate the electrical insulation, since it increases equipment size and cost, and reduces efficiency. Insulation is "overhead," with the primary purpose of preventing short circuits between the conductors or to ground. However, without the insulation, copper conductors would come in contact with one another or with the grounded part, causing the current to flow in undesired paths and preventing the proper operation of the machine. In addition, power equipment that requires a coolant requires the insulation to be a good thermal conductor, so that the copper conductors do not overheat. The insulation system must also hold the copper conductors tightly in place to prevent movement. Therefore, the reliability of the insulation system is a key element for the reliable operation of the transmission and distribution power equipment and rotating machines for power generation.

Power Electronics

Power electronics have advanced thanks to the development of power semiconducting technology. This has facilitated the development of renewable energy and DC power lines. A power converter is an electrical circuit that transforms the electric energy from one form into the desired form optimised for the specific load. Electronic switching devices are increasingly used at high voltage for various applications. The critical components in a power electronic module are power semiconductors, DC-link capacitors, and drivers. The development of Insulated Gate Bipolar transistors (IGBTs) with a voltage range of 300 V to 6.5 kV that is commonly insulated with silicone gel influenced the evolution of power electronics. It generates a voltage sinewave at the desired frequency using pulse width modulation (PWM). The slew rate of fast-rise pulse voltage influences the partial discharge inception voltage (PDIV) of the insulation system. This has applications in pressure-tolerant power electronics for subsea oil and gas exploration, electric vehicles, and electric aircraft.

Despite the fact Direct current (DC) electricity was developed before alternating current (AC) electricity, it was abandoned for AC because the transmission of DC power at low voltage over long distances was not possible. The rapid development in power electronics in the 1990s gave birth to the development of the insulated-gate bipolar transistor (IGBT). This opened the gateway to a new HVDC transmission system technology. HVDC transmission became a reality with the development of high-voltage semiconductor valves. This made it possible to simplify the converter station. The High voltage DC (HVDC) system's core component is the power converter. HVDC is the preferred system for use in a variety of transmission applications, using submarine cables, land cables and overhead lines

Subsea oil and gas exploration

Oil exploration in deep waters poses a new challenge that requires new technology. Motors with electronic variable speed drivers (VSD), also known as variable frequency drivers (VFD), are used in pumping technology for subsea oil and gas exploration. The most popular type of VFD is a pulse-width modulated (PWM) frequency converter. Transistors in the electronic converter provide the motor with power. The "Insulated Gate Bipolar Transistor" (IGBT) is a popular transistor choice for contemporary VFD. It drives the motor using "pulse width modulation" (PWM) at the specified frequency. This system operates at atmospheric pressure. Exploration takes place at a depth down to 5000 m (Figure 5). Today's converters are in 1 bar cubicle with conventional technology. To compensate for the pressure in the deep waters, the wall of the cubicle is made to be able to withstand the pressure. This led to a thick and heavy cubicle. This calls for the need to develop pressure-tolerant technology to reduce the weight and wall thickness of the converter cubicles.

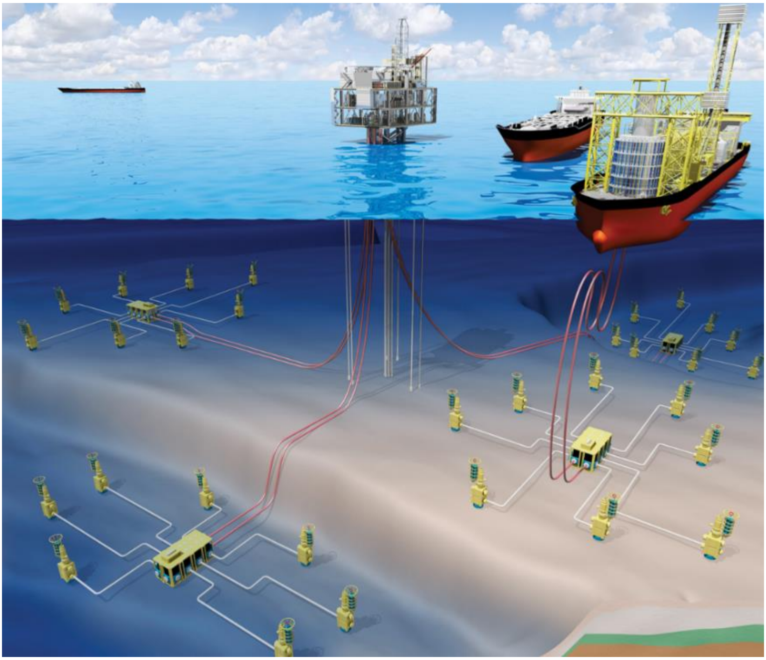


Figure 5: Subsea oil exploration

Satisfactory operation of these critical components needs to be guaranteed. There are two main parts in power electronic converter modules: The active components consist of the power semiconductors (IGBT, diodes), interconnections, etc. The insulation system which serves as the base structure and protects the conducting parts makes up the passive component. The modules used different fluid for insulation (Figure 6).

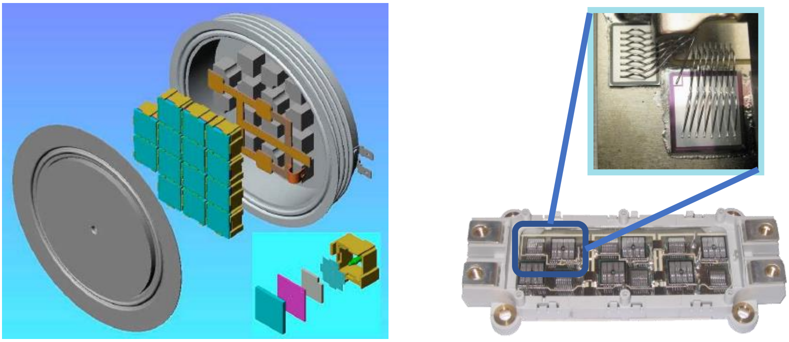


Figure 6: (a) ***Presspack modules*** *with e.g. SF6, (b)* ***Planar modules*** *with silicone gel protection above copper an AlN-substrate*

The increase in blocking voltage results in a strong local electric field stress along the edges of the semiconductors and the metallization along the trench at the top of the ceramic substrate. The partial discharge inception voltage (PDIV) of the insulation system is influenced by the slew rate of fast-rise rise pulse voltage in this power electronic module. A diverging field can cause partial discharge to start at low voltages. As its slew rate rises, the driving voltage behind discharge will also rise. The magnitude of the discharge increases as the driving voltage behind PD increases.

Electric cars

The electric cars (Figure 7) development can be regarded as a major solution towards achieving zero-carbon in modern communities. One of the most important components that also form the core of an electric and hybrid car is the electric motor. The currently available electric cars have 400 V as the on-board power supply.

The electric car motors are built with an insulation system to protect the motor. The insulation materials have good thermal conductivity to help dissipate the heat generated in the system. There is ongoing work on the vehicle for tomorrow with higher voltage to improve the efficiency of the current electric vehicles. A vehicle with an onboard voltage of 800 V or higher is anticipated. Increasing the voltage of electric cars from 400 to 1,000 V reduces the battery charging time, increases the battery efficiency, longer driving autonomy, reduces the weight, and, consequently, the price of the vehicles. Again, increasing the slew rate in the new generation of power electronic switching devices can reduce switching losses.

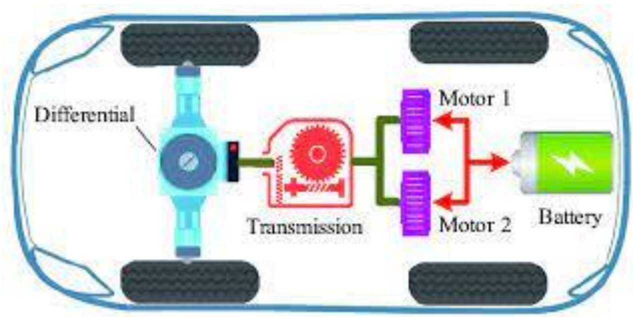


Figure 7: Electric car

However, increased stress on the drive-fed motor creates a new challenge with the insulation system´s and e-drive motor´s performance. The current insulation system cannot withstand the new voltage demand. Using a pulse-width modulated inverter with a high voltage level (800 V and higher) in electric cars increases the possibility of Partial discharge (PD) generation and power of PD, leading to premature insulation failure. PDs are small electrical arcs in voids inside or on the surface of the insulation excited by high electrical fields. The new system required an appropriate insulation system, or else the partial discharge may cause significant damage during the lifetime of the machine. To achieve this, there will be the need to introduce new insulating materials to meet that high voltage requirement.

Electric Airplanes

Achieving zero-carbon emission is everyone's dream and zero-carbon emission has got to an advanced state. The aviation industry also has decarbonisation ambition but electric aircraft was considered a fantasy till recently (Figure 8). However, technological advancement has helped make possible short-distance electric air travel. They utilise electrifying motors. The electric motors create thrust by passing current through large amounts of copper wiring and steel to create magnetic fields that can turn a rotor. The motor is built with appropriate dielectrics as insulators. The electric motor cannot survive without proper insulation. The high-voltage equipment and cables must be shielded.

The current electric aircraft used motors are capable of producing only hundreds of kilowatts of power. This is too little to power larger aircraft. To power a large aircraft, efforts are ongoing to develop an electric motor that can generate 1 megawatt of power. The current commercial aircraft operate at voltages below 1 kV. There has been extensive study on the electrification of aircraft and a voltage level of at least 6 kV is envisaged. Higher voltage levels translate into higher electric stress on the insulation system. These projected voltages and power systems will not operate satisfactorily without the proper electrical insulation system. However, such an insulation system must not interfere with its lifting capability. The insulation packaging must be compact while maintaining electrical system integrity during operation. Designing an appropriate insulation system to keep the volume and weight of space power systems low is key to the success of electric aircraft.

Figure 8: BETA Electric Aircraft made its first international flight on September 27, 2023

Research contributions

Engineered Insulation Materials

Mineral-based insulation oil has performed well over the years. However, in a situation where there is accidental leakage in a transformer, the oil could constitute an environmental hazard because it is toxic and non-biodegradable. This has shifted attention towards new insulating materials that are biodegradable and sustainable, and hence mitigate environmental issues. Seed oil was identified as a viable alternative fluid for oil-filled power equipment and there are already commercially available natural ester insulating fluids. The FR3 insulating fluid and Midel EN insulating fluid are in the market and there are existing transformers filled or retro-filled with these fluids. Despite the promising potentials of natural ester, it has certain drawbacks like high viscosity, low pour point, and poor oxidative stability. There are ongoing research activities toward improving the properties of the natural ester-based insulating fluid.

The major contributions are as follows:

My contribution is attempting to perform a chemical modification of non-food grade seed oil to improve its properties for use as an insulating fluid. Extracted crude oil samples from the seeds were purified and the purified oil samples were transesterified to separate the ester from the glycerol (Figure 9). The transesterification lowered the viscosity of the oil to a value below mineral oil. The ester samples were then passed through an epoxidation reaction for the structural modification of the oil to eliminate the unsaturated carbon-carbon double bond which is responsible for the poor oxidative instability of vegetable oil. The introduced epoxy ring on the structure was then opened to attach the side-branched chain. The side chain was to prevent easy crystalization of the liquid, thereby decreasing the pour point. With chemical modification, the dielectric material's behaviour becomes complex and the properties become function of things that are left over from when they were formed, and unwanted things that are not wanted but got in there anyway.

Some test cells were designed and fabricated for the measurement of the dielectric properties of the oil (Figure 10). A bespoke ageing vessel (Figure 11) was also designed and fabricated for the accelerated ageing test of the fluid samples and their compatibility with the adjacent materials. The compatibility and ageing behaviour of Kraft papers (insulating papers) in the presence of ageing catalyst were evaluated.

In an article to celebrate 50 years in the development of insulating liquid and published by IEEE Insulation Magazine in 2013, the palm kernel oil ester based insulating fluid was mentioned among the recently developed insulating fluids.

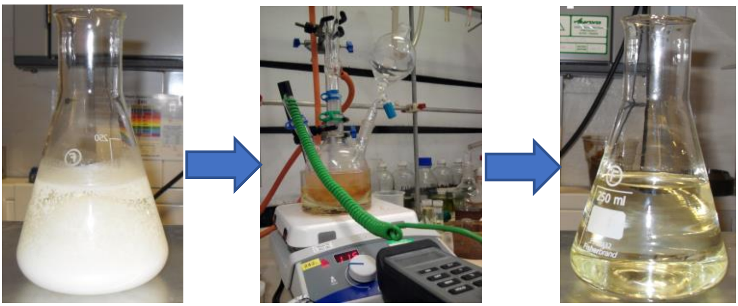


Figure 9: Natural ester fluid sample processing

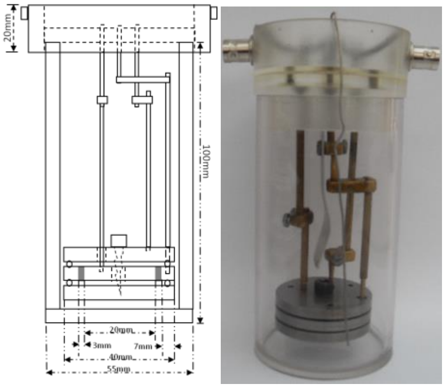


Figure 10: Dielectric test cell

Figure 11: Bespoke Ageing Test Vessel with ageing components

i. A.A. Adekunle et al., Journal of Molecular Liquids, 391B, 2023.
ii. S.O. Oparanti et al., Waste and Biomass Valorization, 14, 1693-1703, 2023.
iii. S.O. Oparanti et al., Biomass Conversion and Biorefnery, 2190-6823, 2022.

iv. A.A. Abdelmalik, et al, Journal of Physical Science, Vol. 29(1), 1-16, 2018.
v. S. Umar et al., Industrial Crops & Products 115, pp. 117–123, 2018
vi. A.A. Abdelmalik, IEEE Transactions on Dielectrics and Electrical Insulation, 22(5), 2408-2414, 2015.
vii. A.A. Abdelmalik, Sustainable Materials and Technologies, 1, 42-51, 2014.
viii. A.A. Abdelmalik, IEEE Transactions on Dielectrics and Electrical Insulation, 21(5), pp. 2318-2328, 2014.
ix. A.A. Abdelmalik, Current Journal of Applied Science and Technology, 4(2), 371-386, 2013.
x. A.A. Abdelmalik et al., Proceedings of the IEEE International Conference on Solid Dielectrics, 541-544, 2013.
xi. A.A. Abdelmalik et al., IEEE Transactions on Dielectrics and Electrical Insulation, 19(5), pp. 1623-1632, 2012.
xii. A.A. Abdelmalik et al., Industrial Crops and Products, 33, pp. 532-536, 2011.
xiii. A.A. Abdelmalik et al., Proceedings of the IEEE Conference on Electrical Insulation and Dielectric Phenomena, 2, pp. 415-418, 2011.
xiv. A.A. Abdelmalik et al., Proceedings of the IEEE Conference on Electrical Insulation and Dielectric Phenomena, 1, pp. 183-186, 2011.
xv. A.A. Abdelmalik et al., Proceedings of the IEEE International Conference on Dielectric Liquids (ICDL), 2011.

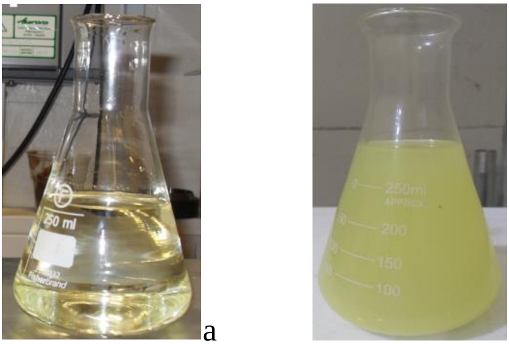
Nano-insulating fluid with nanotechnology

The characteristic breakdown field of the synthesised ester is very high compared to mineral oil and the other properties indicate that the fluid is suitable to be tested in full-size transformers. However, the low viscous synthesised ester was found to have higher DC conductivity when compared with the base fluid and mineral oil. This can cause thermal breakdown due to dielectric heating. Because of this, further investigation of the ester was considered to reduce the electrical conductivity to avoid the possibility of dielectric heating.

However, the concept of nanotechnology was introduced by Feynman in 1959 and Choi and Eastman proposed the homogeneous dispersion of nano-sized particles in base fluid in 1995. It has been reported that the dispersion of nanoparticles in an insulating base fluid enhanced the dielectric and thermal characteristics of transformer oil. The concept was employed in the laboratory to improve the dielectric properties of the synthesised ester-insulating fluid.

The major contributions are as follows:

We attempted to improve the physicochemical properties, dielectric loss, and breakdown strength of our non-food grade vegetable oil methyl ester samples using nanoparticles. However, dispersed nanoparticles often sediment a few hours after dispersion. The challenge now becomes the development of nanofluid that will be stable within its useful lifetime without sedimentation. We succeeded in functionalising the nanoparticles to ensure their stability when suspended in the base fluid. The functionalised semiconducting and insulating nanoparticles were introduced into the methyl ester and a comparative study on the physicochemical, dielectric, and breakdown characteristics of the prepared nanofluids was done. A stable nanofluid was developed from the base methyl esters and functionalised nanoparticles (Figure 12). Stability was maintained after several weeks of sample preparation. The dispersion of the nanoparticles at a certain proportion led to an improved dielectric loss and breakdown strength.



a b

Figure 12: (a) Natural ester fluid (b) Natural ester nanofluid.

i. F.R. Tambuwal et al., The International Journal of Advanced Manufacturing Technology, 2022.

ii. S.O. Oparanti et al., The International Journal of Advanced Manufacturing Technology, 2021.

iii. S.O. Oparanti et al., Materials Chemistry and Physics, 259, 12396, 2021

iv. S.O. Oparanti et al., Materials Chemistry and Physics, 277, 125485, 2022.

v. S. Oparanti et al., Annual Report IEEE Conference on Electrical Insulation and Dielectric Phenomena, 2022.
vi. S. Oparanti et al., Annual Report IEEE Conference on Electrical Insulation and Dielectric Phenomena, 2021.
vii. S. Oparanti et al., Annual Report IEEE Conference on Electrical Insulation and Dielectric Phenomena, 2020.

Power Electronics Insulation Integrity and Diagnostics

Power electronics are evolving with higher voltages and electronic switching devices are increasingly used at high voltage for various applications. The slew rate of fast-rise pulse voltage influences the partial discharge inception voltage (PDIV) of the insulation system. This has applications in pressure-tolerant power electronics for deepwater oil and gas exploration, electric vehicles, electric aircraft, etc. The increasing voltage means an increasing stress on the insulation system. The ideal insulation for higher voltage systems in power electronic applications should be light, chemically stable, and a good corona suppressor. It should withstand high voltages, have low dielectric loss, and have good thermal conductivity. One of the currently considered features is that it should be self-healing in case of electrical discharges. That led to dielectric liquids being proposed as insulation for power electronic converters at sea depths of up to 5000 m. Studying the discharges under pulse voltage is challenging. The capacitive current constitutes noise in the measurement of electrical discharges. Measurement of light emission from the discharge is thought of as an alternative technique to explore.

The major contributions are as follows:

A working partial discharge setup was developed with the capability of varying pulse slew rates (Figure 13). The optical PD detection system was successfully utilised to record partial discharges under various voltage shapes and fast transient voltage (±100 kV).

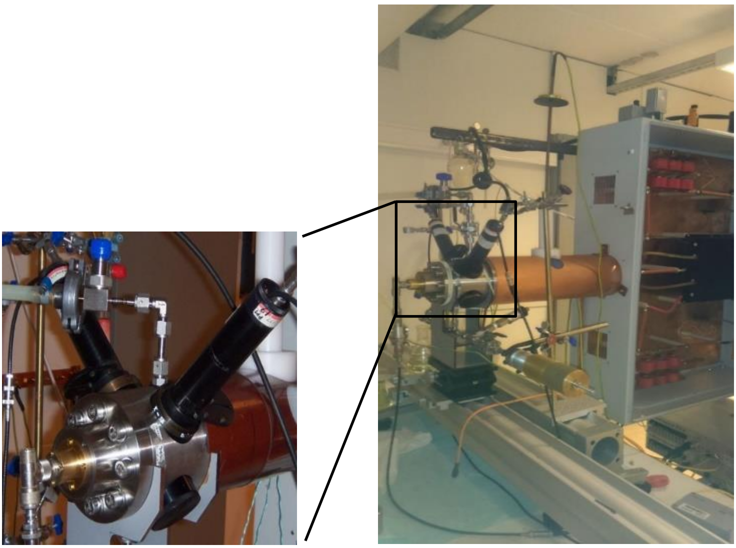


Figure 13: Optical Partial Discharge test set with different voltage sources

The experimental setup was used to evaluate the performance of liquid as insulation in pressure-tolerant power electronics under sinusoidal and square voltage. Examine the influence of voltage shape on Partial Discharges in High Voltage Insulation. Examined the Influence of liquid nature on the PD and breakdown of the trench of Insulated Gate Bipolar Transistor (IGBT). Examined the influence of encapsulating the IGBT module with the combination of polymer and insulating liquid on partial discharges on the surface of the IGBT. The results revealed that voltage slew rate dominates over other factors that influence PD inception and magnitude. Pressure increase suppresses PD activity thereby leading to an increase in PD inception voltage and a reduction in PD magnitude as well as the PD rate. Encapsulation of the IGBT power module with liquid indicates that the breakdown phenomenon is sensitive to the nature of the liquid. Coating with Parylene (polymer) raised the withstand voltage. Fast transient square voltage significantly reduced partial discharge inception and breakdown voltages.

i. A.A. Abdelmalik et al., Journal of Physical Science, 31(3), 1-15, 2020
ii. A.A. Abdelmalik et al., High Voltage, Vol. 3(1), 31-37, 2018.
iii. A.A. Abdelmalik et al., IEEE Transactions on Dielectrics and Electrical Insulation, 23(4), 2303-2310, 2016.
iv. A.A. Abdelmalik et al., IEEE Transactions on Dielectrics and Electrical Insulation, 23(2), 1119-1125, 2016.

v. A.A. Abdelmalik et al., IEEE Transactions on Dielectrics and Electrical Insulation, 22(5), 2770-2778, 2015.

vi. A.A. Abdelmalik et al., Annual Report IEEE Conference on Electrical Insulation and Dielectric Phenomena, 31-34, 2014.

Initiation of asset management research in ABU

Nigeria has been struggling with frequent power failures and the government of Nigeria initiated the process of privatizing the electricity industry in 2013. Experience shows that most of the power failures are related to insulation failures. Successful electricity industries are very much concerned about asset management and they invest in research and development towards developing new ideas and finding a solution to their challenges. But high voltage engineering was practically non-existent in the country. Asset management in the Nigerian power industry is still mostly based on the traditional so-called *"corrective maintenance"* technique where equipment is allowed to fail and then gets repaired or replaced. There is still no emphasis on detailed scientific analysis of the invisible damage on some of the insulation components of the equipment and/or developing a suitable diagnostic model to minimise avoidable failures.

The major contributions are as follows:

We are studying the rate of growth of the ageing signatures in transformers in Nigeria's electricity network (Figure 14) We have collected the oil samples from thirtyfive in-service power and distribution transformers for diagnosis. A computer code was developed to this effect. This is to demonstrate to the electricity industries and stakeholders the benefits of a preventive maintenance system for oil-filled power equipment on the grid network. This, we hope, will help to reduce outages in distribution systems due to insulation failure, save asset management costs, and prolong the effective and useful life span of in-service power equipment. It should also ensure the provision of better service delivery to electricity end-users if adopted as a future maintenance technique.

i. Development of a diagnostic tool for the analysis of insulating fluid in transformer, Nasiru Yunusa, MSc thesis, 2023
ii. Condition monitoring of some distribution transformers of ABU Zaria 11 kVA feeder, Umar Lawali, MSc thesis, 2023.

Figure 14: Dr Yusuf M. Abubakar working with the DGA facilities

Polymeric insulating materials

Polymeric materials are part of insulating materials. They are used in cables, bushing, encapsulation of power electronics, etc. Our effort is toward the modification of the polymer with nanoparticles for enhanced insulation performance. Several metal oxide particles (micro and nano-sized) have been studied as fillers in the insulating nanocomposite, and nanoparticles from natural sources such as clay were also considered as fillers. Aside from clay, other naturally occurring resources such as animal shells and eggshells can serve as cheap resources when used as fillers.

Power plant cannot survive without insulation. The power equipment contains many insulation materials and polymeric materials are some of the materials used for electrical insulation. Polymeric materials in nuclear power plants when exposed to ionizing radiation for a long time can undergo some changes in properties. These changes can have negative effect on the insulating properties of the polymeric materials.

The major contributions are as follows:

My contribution in this area is the examination of the influence of nanoparticles on the insulating behaviour of epoxy polymers when exposed to neutron flux from Nigeria Research Reactor I (NIRR-I) the filling of the epoxy with nanoparticles led a radiation induced degradation that is lower than the percentage of degradation of the irradiated epoxy sample without nanoparticles.

i. A.A. Abdelmalik et al., Radiation Physics and Chemistry, 198, 110230, 2022.
ii. A.A. Abdelmalik et al., Radiation Physics and Chemistry, 179, 109215, 2021
iii. A.A. Abdelmalik et al., Journal of Physical Science, 31(1), 1-14, 2020
iv. A.A. Abdelmalik et al., SN Applied Sciences 1, 1238, 2019.
v. A.A. Abdelmalik et al., SN Applied Sciences 1, 373, 2019.

The making of the Cubicle (High Voltage Materials Research Laboratory)

My first stint on research in dielectric physics was during my MSc Physics research at Ahmadu Bello University Zaria (ABU Zaria) in 2002 and it was introduced by my supervisor, Prof. Narayana I. Hariharan. The search for literature on dielectrics in 2002 made me realise that there were ongoing research activities on natural ester as an alternative insulating fluid for oil-filled power equipment. In the course of the work, I often visited the university library to search for previous works on the subject. There I found a research report on the investigation of groundnut oil for use as transformer oil in the university as far back as 1980. It was an MSc dissertation from the Department of Electrical Engineering, ABU Zaria (ABUDEE) in 1980. All the characterisations including the breakdown strength test were done in a high-voltage laboratory of the department. I was elated that all the characterizations required for my MSc research work can be done within the university. I reached out to the department and, to my surprise, the gigantic high voltage (HV) laboratory that was established in the 70s was not in operation for the past two decades. That left me heartbroken. Further efforts to find facilities in nearby institutions to carry out the measurements needed were also disappointing.

Meanwhile, the first commercially available natural ester transformer oil was introduced in the year 2000. That means, if the high voltage laboratory in Ahmadu Bello University that was established in the 1970s had not broken down and had sustained the 1980 research on the feasibility of using groundnut oil as an alternative insulation fluid, the university might have patented vegetable oil-based transformer oil even before the commercially available natural ester transformer fluid that came out around 2000- a product of research and development that started in the early 1990s in North America.

The frustration of getting facilities for HV research within the country informed my determination to have a high voltage laboratory to continue the research in alternative natural ester insulating fluid from non-food grade oil in Nigeria. That gave birth to the journey to having an HV laboratory that started in 2012. The journey started without an idea of how I would make that happen and where the funds would come from.

To attract funds from any organisation, you must have something on ground to excite their interest, research experience, and track record, but I had none. I was just a fresh PhD with no post-PhD experience. This led to the development of the first proposal on "power transformer life management" which was ready by 2013. Even though

I was disappointed with the lack of feedback from the submission of the proposal, that did not discourage me from developing and submitting another proposal on electrically conducting nanofluid from vegetable oil this time targeting foreign grants. Luckily, the proposal won a 12,000 USD TWAS (The World Academy of Science) research grant for basic sciences. This became a source of succor and the turning point that renewed my hope for the establishment of the High Voltage Materials Laboratory (HVML). That grant was used to acquire a Rhode & Schwarz HM8118 programmable LCR Bridge with a frequency range of 20 Hz to 200 kHz, RBD Picoammeter, Brookfield digital viscometer, vacuum oven, hotplate magnetic stirrer, etc.

The sourcing of funding continued but there were little or no funding opportunities from the industry due to a weak link between Nigeria's industry and academia. So, there was no hope of getting a grant from the industry. I was handicapped and the dream stagnated for five years. I almost gave up due to frustration by the end of 2017. Then, an idea came up.

There was advice to reach out to our friends and close associates that know how passionate I am about the university and research and float a crowdfunding exercise within that cycle and see how it goes. So, I sent messages across that cycle of friends. Within a few months, about 1.5 million naira was raised which was used to purchase some equipment that includes a 35 kV HVDC source, a 5 kV HVAC source, a high voltage probe, a digital oscilloscope, and an Infrared thermal imager. These became our first HV sources and we improvised a Faraday cage from an abandoned metal cabinet which led to the completion of our first high-voltage experimental setup in Figure 15 after a successful installation of the earth rods and a perfect connection for grounding. At this point, our joy could not be overemphasised.

Figure 15: Dr Abdulsalam I. Galadima working with the 35 kV HVDC experimental set-up

Then, I realised that it was time for us in materials physics to come together to work as a team. I initiated the Materials Physics Research Group in 2018. We developed a working document and I served as the pioneer leader from 2018 to January 2022. Among the efforts in 2018 were emails sent to senior colleagues in Europe. I requested any of their old HV sources and measurement kits in their store that they considered obsolete but still work that they are willing to donate. I received an encouraging response from some of them. Prof. John C. Fothergill (my PhD supervisor), who had left Leicester, forwarded the email to Dr. Stephen D. Dodd who was still at Leicester. This resulted in a gift of a Glassman 400 kV HVDC source from the University of Leicester to ABU

Zaria in 2019. Also in 2019, we submitted a grant application to Nigeria's tertiary education trust fund (TETFund) for a national research fund (NRF) grant on which I served as the Principal Investigator, and the application was successful.

We won a grant of about 32.5 million naira and that was a gigantic breakthrough. We were able to purchase a 10 kVA 100 kV PD-free transformer system installed and tested in Figure 16, a Diael partial discharge measurement test kit (Fiure 17), and a Dissolved gas analysis system. With a 400 kV HVDC generator, a PD-free 100 kV AC generator, and a partial discharge measuring system with HFCT and UHF sensors, our small high-voltage laboratory is good to go. We also acquired a Tensile testing machine and Hioki LCR frequency analyzer that can measure dielectric parameters at lower frequencies (1 mHz to 200 kHz) from the TETFund NRF Grant.

Figure 16: Installation and testing of the 100 kV HVAC system

Figure 17: Dr. Abdulsalam I. Galadima working with the Diael MS Pico partial discharge measuring system

In addition, the university later acquired an additional programmable LCR Bridge with a frequency range of 20 Hz to 5 MHz and a UV ageing chamber (Figure 18) through TETFund intervention.

Figure 18: A Postgraduate student using LCR Bridge for dielectric measurement

Now, the laboratory has the capability of conducting several tests such as capacitance measurement, resistance measurement, impedance measurement, tan δ measurement, and loss factor test, etc, within the frequency of 1 mHz to 5 MHz with our LCR Bridge. We can perform AC and DC breakdown characterisations on insulation materials, and a partial discharge test using Diael MS Pico partial discharge setup. Our DGA system which we are yet to finish the setup due to a funding issue when completed can detect the seven key gases in transformer oil. We can also measure the dynamic viscosity of both Newtonian and non-Newtonian fluids and the tensile strength of papers and polymeric materials. We can measure the pH and have a setup to measure the acid value of insulating fluids.

Research grants attracted

i. A.A. Abdelmalik, A.I. Galadima, Tertiary Education Trust Fund (TETFund) Institutional Based Research (IBR) Grant: Assessment of ageing signatures in transformers in Kaduna electric distribution network. 1.58 million Nigerian naira, 2022 – 2023.

ii. Y.M. Abubakar, A.A. Abdelmalik, Tertiary Education Trust Fund (TETFund) Institutional Based Research (IBR) Grant: Influence of radiation sterilization on polymeric medical devices. 1.89 million Nigerian naira, 2022 – 2023.

iii. A.A. Abdelmalik, N. Chalashkanov, Z. Ladan, A. Aliyu, A.A. Khaleed, A.T. Salawudeen, Tertiary Education Trust Fund (TETFund) National Research Fund (NRF) Grant: Reliability model for the safe operation of oil-filled power equipment in Nigeria electricity grid network, 32.8 million Nigerian naira, 2019 – 2022.

iv. A.A. Abdelmalik, The World Academy of Science (TWAS) Individual Research Grant for Basic Sciences: Nigerian vegetable oil-based fluid as an alternative drilling fluid for offshore rigs. 12,000 USD, 2013 – 2015.

v. A.A. Abdelmalik, 2010 IEEE DEIS Graduate Fellowship Award for Innovative Idea: Effect side branching on natural ester insulating fluid. 5,000 USD, 2010 – 2011.

vi. A.A. Abdelmalik, Research Grant from National Grid, UK: Feasibility of using a vegetable oil-based fluid as electrical insulating oil. 5,000 GBP, 2009 – 2011.

vii. A.A. Abdelmalik, 2008 Islamic Development Bank (IsDB) Merit Scholarship Award for High Technology (PhD): Development of natural ester insulating fluid from Nigerian vegetable oil. Fully funded PhD. 2009 - 2012.

Summary, Conclusion, and Recommendations

Summary

Electrical and electronic power has become an indispensable part of modern-day life. Our work, leisure, healthcare, economy, and livelihood depend on electricity supply. The electrical and electronic power industry has evolved over the last decades and dielectrics and electrical insulation played a great role in the success of the evolution. The "Dirty Dielectric" has made it possible to increase the operating voltage of the power system without failure. Designing an appropriate insulation system that will not interfere with the integrity of the power systems is key to the success of electric aircraft.

Dream they said is the tiny seed from where beautiful tomorrow grows. We had a dream and we were able to realise the dream. We proudly have an active high-voltage research facility in the University. While interacting with a senior colleague at National Grid, UK, in 2018 about our plans to turn an empty space into an HV materials laboratory in my university, he said, "You don't take on easy challenges, do you? You really seem to have given yourself quite a tough job setting up an HV research facility from almost nothing." Establishing an HV laboratory from nothing is truly a tough job, and I do like to take on tough challenges. We were determined to achieve the dream of reviving HV research at ABU Zaria, Nigeria. It becomes tougher when it is in a country where universities are not well funded, there is little available funding for research, and there is a wide gap between the industry and academia.

We proceeded on the tough job and succeeded in establishing an HV laboratory. The HV laboratory was referred to as a cubicle by a senior colleague. We liked the name and decided to call the laboratory “The Cubicle” (Figure 19).

Figure 19: The Cubicle

Conclusion

The Cubicle is still small, and we need to do more. We hope to win more grants, aid, and international collaborations to be able to improve on what we have at the moment. We are presently collaborating with Kaduna Electric Distribution Company (KAEDCO) and Transmission Company of Nigeria (TCN), though without any financial commitment at the moment. We hope to leverage on the outcome of our current research activities and engage more electricity-related industries.

We hope to be a strong force in solution development for Nigeria's electricity industry and possibly the neighbouring countries.

Recommendations

Research on groundnut oil as a possible alternative transformer oil started in the university as far back as 1980 at the Department of Electrical Engineering, ABU Zaria (ABUDEE). The research was discontinued when the high voltage laboratory became inactive. Meanwhile, the first commercially available natural ester transformer oil was introduced in the year 2000- products of research and development that started in the early 1990s in North America. Environtemp FR3 Ester and Midel EN fluids were produced from some seed oils. Cargill was in Ghana a few years ago to market FR3 ester fluid for Ghana's electricity industry. If we had sustained this 1980 research, Nigeria may have produced a vegetable oil-based transformer oil even before the commercially available natural ester transformer fluid that came out around 2000- a product of research and development that started in the early 1990s in North America. There are plenty non-edible seeds with high oil yield. There is the need to intensify our effort on research and development on seed oil based tranformer oil. We can have a Nigerian produced ester transformer oil in a few years.

Growing pressure over the handling of efficient electricity supply and customer satisfaction is placing asset engineering in a background role in electricity transmission and distribution. Power equipment failure is an expensive event. Some of the faults are manufacturing faults from the factory. There should be Federal Government regulation to perform integrity tests on power equipment such as electrical rotating machines for generation and power transformers before installation. The government should support the university in establishing a power equipment diagnostic centre to achieve that. Electricity companies prioritise monitoring of transformer conditions and identification of inception of faults prior to failure for better service delivery.

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