EE3036 SUSTAINABLE AND ENVIRONMENTAL FRIENDLY HV INSULATION SYSTEM

UNIT-I

SUSTAINABLE AND ENVIRONMENTAL ENERGY AND PRODUCTS

Introduction:

Sustainable and Environmental

Sustainable:

- ✓ That can continue or be continued for a long time.
- ✓ Involving the use of natural products and energy in a way that does not harm the environment.
- ✓ Causing, or made in a way that causes, little or no damage to the environment and therefore able to continue for a long time.
- ✓ **Sustainable energy** comes from renewable sources, so it respects natural resources, and its production process does not generate an environmental impact or the emission of greenhouse gases or other pollutants.

Environmental Friendly:

- ✓ Not harmful to the environment, or trying to help the environment
- ✓ The production system must be economically and socially acceptable, and also nature- and *environment-friendly*.

Sustainable and environmental friendly insulating materials:

- ✓ Sustainable and environmentally friendly insulating materials are continuously substituting conventional insulating items in the market place. These are favourable to traditional insulating materials, due their superior functionality. The also offer explicitly security and eco-friendly advantages.

HV Insulation System:

- ✓ The primary function of high voltage insulators is to insulate, i.e., prevent the flow of electric current and to keep oppositely charges conductors mechanically separated during all service conditions.

- ✓ This means that the insulation of a power apparatus is designed to withstand any electrical, thermal, and mechanical stress likely to occur during manufacturing, testing, and the long-expected service lifetime of 30 years or more.

List out the high voltage apparatus:

- ✓ Bushings, capacitors and power transformers, Distribution Transformer, circuit breakers, Instrument transformer (current transformer and potential transformer).

CARBON PRINT:

A carbon footprint is the total amount of greenhouse gases (including carbon dioxide and methane) that are generated by our actions.

A **carbon footprint** (or **greenhouse gas footprint**) is a calculated value or index that makes it possible to compare the total amount of greenhouse gases that an activity, product, company or country adds to the atmosphere. Carbon footprints are usually reported in tonnes of emissions (CO_2-equivalent) per unit of comparison. Such units can be for example tonnes CO_2-eq per year, per kilogram of protein for consumption, per kilometre travelled, per piece of clothing and so forth. A product's carbon footprint includes the emissions for the entire life cycle. These run from the production along the supply chain to its final consumption and disposal.

The carbon footprint concept makes comparisons between the climate impacts of individuals, products, companies and countries. A carbon footprint label on products could enable consumers to choose products with a lower carbon footprint if they want to help limit climate change.

CARBON PRINT CALCULATION:

To accurately calculate your carbon footprint as a business, you must first convert the collected data into values that are compatible with an 'emission factor'. The common equation to do this is GHG emissions = data x emissions factor.

GLOBAL WARMING POTENTIAL:

Greenhouse gases (GHGs) warm the Earth by absorbing energy and slowing the rate at which the energy escapes to space; they act like a blanket insulating the Earth. Different GHGs can have different effects on the Earth's warming. Two key ways in which these gases differ from each other are their ability to absorb energy (their "radiative efficiency"), and how long they stay in the atmosphere (also known as their "lifetime").

The Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years. GWPs provide a common unit of measure, which allows analysts to add up emissions estimates of different gases (e.g., to compile a national GHG inventory), and allows policymakers to compare emissions reduction opportunities across sectors and gases.

- CO_2, by definition, has a GWP of 1 regardless of the time period used, because it is the gas being used as the reference. CO_2 remains in the climate system for a very long time: CO_2 emissions cause increases in atmospheric concentrations of CO_2 that will last thousands of years.
- Methane (CH_4) is estimated to have a GWP of 27-30 over 100 years. CH_4 emitted today lasts about a decade on average, which is much less time than CO_2. But CH_4 also absorbs much more energy than CO_2. The net effect of the shorter lifetime and higher energy absorption is reflected in the GWP. The CH_4 GWP also accounts for some indirect effects, such as the fact that CH_4 is a precursor to ozone, and ozone is itself a GHG.
- Nitrous Oxide (N_2O) has a GWP 273 times that of CO_2 for a 100-year timescale. N_2O emitted today remains in the atmosphere for more than 100 years, on average.
- Chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are sometimes called high-GWP gases because, for a given amount of mass, they trap substantially more heat than CO_2. (The GWPs for these gases can be in the thousands or tens of thousands.)

Global Warming Potential Example:

For example, the GWP100 for nitrous oxide (N_2O) is 273. This means that 1 tonne of N_2O causes the same amount of warming as 273 tonnes of CO_2 (in this case over 100 years).

Causes Global Warming Potential:

Burning fossil fuels, cutting down forests and farming livestock are increasingly influencing the climate and the earth's temperature. This adds enormous amounts of greenhouse gases to those naturally occurring in the atmosphere, increasing the greenhouse effect and global warming.

ENVIRONMENT REQUIREMENT FOR ANY PRODUCT AND SYSTEM.

Environmentally friendly design for electrical insulation system:

Introduction:

Two governing factors have been normally considered in a conventional design of electrical systems, these are low cost and reliable performance.

Since the environmental issue becomes increasingly important, the associated design guidelines and legislations have been proposed and implemented in more and more countries.

Therefore, it is imperative to fully consider environmental friendliness in design of an electrical system and in its manufacture in order to comply with the codes and regulations. At the same time people’s demand on the environmental friendly products is growing and producing such a product or system becomes more competitive.

Material selection:

- ✓ Material selection is a key step in the design of an electrical insulation system.
- ✓ It also forms a basis to appraise its environmental friendliness.
- ✓ Selecting an insulation material that will cause minimum damage is critical in achieving an environmentally friendly design (***Ecodesign***).
- ✓ Apart from using environmentally friendly insulation materials, a design of environmental friendly system needs to extend to its whole life cycle.

Influence factors of environmentally friendly design:

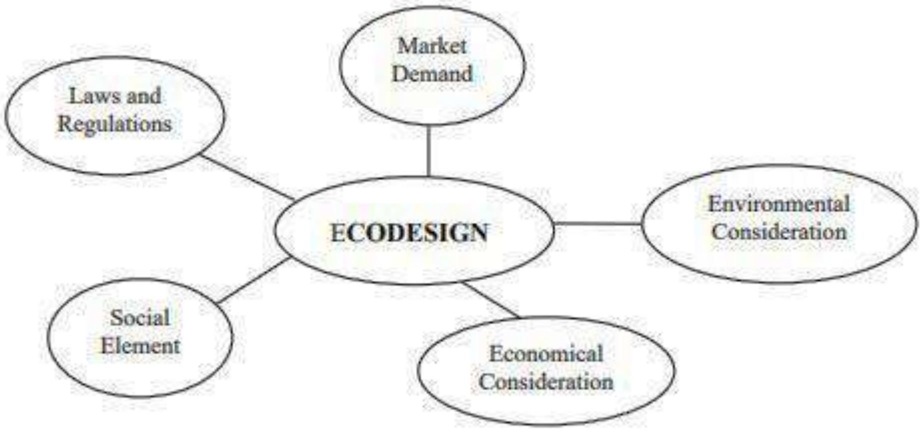

Fig: Influence factors of environmentally friendly design

(a) Law and Regulations

Globalisation of the world economy has forced companies in each country to participate in the process of relevant code development, standardisation and implementation.

For instance (example), the Montreal and Tokyo agreement, European standard on environment, a standard specifically for electrical equipment known as WEEE (Waste from Electrical and Electronic Equipment), and most importantly ISO 14000.

(b) Market Demand

Since environmentally friendly products are favoured and thus competitive, they are not only beneficial to customers but also to manufacturers themselves.

(c) Environmental Consideration

Such products can significantly reduce the damage to environment.

(d) Economical Consideration

For example, an ecodesign that uses less raw materials and consumes less energy can reduce its overall cost. From the life cycle point of view, such a design is economical.

(e) Social Consideration

Electrical products of Eco design can gain easy acceptance from the general public.
It can influence society. Assessment of this influence is a complicated project and it can provide more employment opportunities.

UNIT-II

ALTERNATE GREEN GASEOUS INSULATORS

SF6 gas and its hazardous environmental effects:

- Sulfur hexafluoride (SF6) is an anthropogenically produced compound, mainly used as a gaseous dielectric in gas insulated switchgear power installations.
- It is a potent greenhouse gas with a high global warming potential, and its concentration in the earth atmosphere is rapidly increasing.
- During its working cycle, SF6 decomposes under electrical stress, forming toxic by-products that are a health threat for working personnel in the event of exposure.
- During its working cycle, SF6 decomposes under electrical stress, forming toxic by-products that are a health threat for working personnel in the event of exposure.
- SF6 is an anthropogenically produced slow reacting gas with a relatively high molecular weight. It exhibits excellent arc extinction properties and this gives rise to its high applicability in power technology.
- In its normal state it is chemically inert, non-toxic and non-flammable. Because of its inertness and non-toxic characteristics it has been treated as an environmentally safe and acceptably non-toxic material, in the sense that it does not react unfavourably with the biomass.
- However, when dissociated under high-pressure conditions in an electrical discharge the pure SF_6 may readily reform toxic by-products.

Toxic by-products of SF_6 in the Working Environment:

- In the presence of an electrical discharge such as an arc, spark, or corona, a portion of the SF6 decomposes into lower fluorides of sulfur that can react to form a number of chemically active by-products.
- Much effort has been spent in identifying the species, the generation rates, and some of their properties, under laboratory or practical operating conditions in GIS power systems.

- The possible formation of SF4, SF2, S2F10, SO2, SOF2 SOF4, SO2F2, SOF10, S2O2F10, HF, and H2S during degradation of SF6 is now well documented and widely accepted by workers in this field.

- The compounds formed include not only gaseous sulfur fluorides and sulfur oxyfluorides but also metal fluorides formed by the reactions with electrode materials and spacers.

- Recent experimental work has established that the production yield of some of the contaminants (i.e., S2F10) may be affected by the presence of water, oxygen, or even surface reactions originating by the presence of organic insulates, for example poly tetra fluoro ethylene [PTFE], under corona, spark, and arc discharges).

- In addition, high energy photons and high energy X-rays lead to decomposition of gaseous SF6 forming corrosive oxyfluoride by-products comparable to the ones obtained during corona discharge occurrence.

- The most important toxic by-products, as well as their common concentrations observed during the working cycle of SF6 as an insulant, are summarized in Table 1.

Table 1. SF_6 decomposition byproducts and their typical concentrations during repeated sparking. A 16kJ total energy deposition in 70 cm^3 SF_6 gas is examined.[33, 34]

Product	Approximate Concentration (% by volume)
SOF_2 (SF_4)	0.5
SOF_4	0.085
SF_4	0.085
S_2F_{10}	0.025
SO_2F_2	0.006
SO_2	0.002
HF	1.0

- During the maintenance or repair of SF6 insulated or irradiated equipment, the handling of these gaseous as well as solid by-products is a matter of concern because of their toxic nature.

- The toxic by-product generation rates strongly depend upon the type of the electrical stress (i.e., corona, spark discharge) and the overall operating conditions (i.e., humidity levels, nearby surfaces that can act catalytically, X-ray radiation, or high energy photons, surface to volume ratio, polarity effect).

- Table 2 provides typical net production yields for several SF6 decomposition products formed during electrical discharges.

Table 2. Corona and spark production net yields of SF_6 decomposition byproducts.[37]

Species	Corona Discharge (nmol/J)	Spark Discharge (nmol/J)
SOF_4	0.90	0.2
SOF_2	0.54	1–3
SO_2F_2	0.25	0.02
S_2F_{10}	0.5	0.04–0.37

- Alternative to SF6 for use in transmission equipment. A suitable, environmentally sustainable solution has not been found- until now, that is—because of the numerous, very stringent HV switchgear specifications it has to meet. These include:

✓ high dielectric strength;

✓ good arc quenching capability;

✓ low boiling point;

✓ high vapor pressure at low temperature;

✓ high heat dissipation;

✓ compatibility with switchgear materials;

✓ design compactness, etc.

- It also has to meet health and safety prerequisites such as low toxicity and non-flammable. And, of course, environmental requirements such as:
  - ✓ low GWP;
  - ✓ no Ozone Depletion Potential (OD P); and minimal environmental impact.

ALTERNATE GASES:

- Grid Solutions, a GE and Alstom joint venture, has identified a fluoronitrile based gas mixture dubbed ‘g3—green gas for grid’ that is such a alternative.

- Environmental considerations are increasingly taking a front seat in all arenas of our daily lives— political, industrial and societal.

- Not least among the major concerns are global warming and the greenhouse gases that contribute to it, as their concentration in the air reaches new heights.

- Hence the power industry’s focus on sulfur hexafluoride (SF6) and the need to find a suitable alternative for it in industrial applications.

- Grid Solutions, a GE and Alstom joint venture, has identified a ***fluoronitrile based gas mixture dubbed ‘g3—green gas for grid***’ that is such a alternative.

- Currently the first SF6-free high voltage equipment are available offering the same performances and footprints that SF6 insulated equipment provide at similar and affordable economic conditions. GE’s Grid Solutions business fluoronitrile based gas mixture dubbed ‘g3— green gas for grid’ has been proven as a suitable replacement for SF6.

g3—Green Gas for Grid:

- Pure 3M™ Novec™ 4710 Dielectric Fluid has liquefaction at a low temperature which means that it cannot alone replace SF6.

- On further investigation, it was found that the best solution was to mix it with CO_2—for the latter’s arc quenching capability—to create a gas mixture suitable for disconnector and circuit breaker applications.

- The resulting mixture was dubbed ‘g3—green gas for grid’. Depending on minimum operating temperature and maximum filling pressure, g3 can be based on 4%vol, 6%vol or 10%vol Novec™ 4710 fluid.

- These three mixtures allow covering the majority of the specification for indoor and outdoor application.

Gaseous mixtures and other sources and its properties:

A whole battery of laboratory and application tests examined the different characteristics and performance of g3. The power frequency dielectric strength of g3 was measured on 145 kV GIS using Novec™ 4710 fluid ratios ranging from 0 to 20% by volume. For a 0%v mixture, that is, CO_2, the dielectric strength is about 40% of the SF6 value. With an 18% to 20%v Novec™ 4710 fluid content, the dielectric strength of the mixture is equivalent to SF6, as shown on Figure 3. Taking a typical GIS as an example, the dielectric strength of g3 for a minimum operating temperature of –25°C is about 90% of the SF6 value.

The remaining 10% can be made up by a moderate CO 2 overpressure combined with a relatively minor design adjustment.

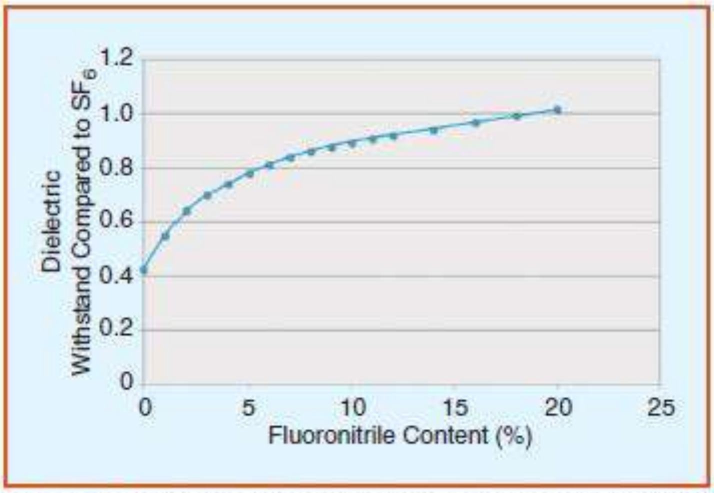

figure 3. Dielectric strength master curve for Fluoronitrile/CO_2 mixtures.

Like the heptafluoro-iso-butyronitrile itself, the toxicity of g3 was also compared to the EU 1272/2008 CLP regulation dealing with Classification, Labelling and Packaging of chemicals and the European Agreement concerning the International Carriage of Dangerous Good by Road (ADR)—where the toxicity of a gas mixture (LC50) is calculated by taking into account the toxicity (LC50*i*) and the mole fraction or volume fraction (*fi*) of each substance: LC50 (mixture) = 1/(R*fi*/LC50*i*).

Then the LC50 of g3 can be derived from the previous formula and goes from approximately 100,000 ppmv to 190,000 ppmv for 10% to 4% Fluoronitrile respectively. These figures were confirmed by tests performed by independent and accredited toxicological lab. Additional toxicity measurements made after current interruption test demonstrate that used g3 is basically slightly less toxic than used SF6.

The heat dissipation capability of g3 was determined by temperature rise tests on a 420 kV busbar arrangement filled with the gas mixture at 5.5 bar for a minimum operating temperature of –25°C. The results were then compared to a system filled with SF6 at 5.5 bar as a reference. The test setup was equipped with temperature sensors to monitor the temperature rise.

Considering that the heat dissipation within a GIS arrangement is mainly driven by convection, Vermeer's constant was determined. Vermeer's constant is linked to the gas's physical properties, such as density *t*, thermal conductivity *m*, specific heat capacity *Cp* and dynamic viscosity *h* using the following formula:

$$C = 0,1683\left[\frac{\rho^2\lambda^2 C_p}{\eta}\right]$$

and was found to be equal to 13.8 for heptafluoro-iso-butyronitrile. This means that the pure gas has a higher heat dissipation capability than SF6. Then the convection constant of g3 can be derived from the gas mixture formula *C*mix = *C*1(*x*1)0.75 + *C*2(*x*2)0.75, where *Ci* and *xi* stand for the convection coefficient and volume fraction of gas *i*. The heat dissipation of g3 is a little lower than pure SF6 but still higher than CO2.

It was ascertained that with g3 the Global Warming Potential can be brought down by over 98% compared with SF6 depending on the application. The GWP of g3 was calculated according to the F-gas regulation4 where the total Global Warming Potential of a mixture that contains fluorinated greenhouse gas is calculated as a weight average, derived from the sum of the weight fractions of the individual substances multiplied by their GWP. For an example, the gas mixture used in the 420 kV GIB present a GWP of about 330 which is less than 1.5% the GWP of an equivalent SF6*i* insulated GIB.

The g3 mixture is also non-flammable, non-ozone-depleting and remains homogeneous over long periods of time, even if it cools down to the minimum temperature rating of the switchgear.

Testing on Equipment:

Under application conditions, the dielectric performance of different g3 gas mixtures were tested on a typical 145 kV SF6 GIS arrangement with a disconnector/earthing switch connected to a cable end box. The performance of the mixtures was compared to SF6 under lightning impulse and power frequency. Table 1 shows the insulation performance relative to SF6 assuming a 50% probability of flashover in negative polarity—which is the worst polarity for both SF6 and the alternative gas mixtures. The dielectric performance of the tested mixtures at pressures of 6.7 to 8.2 barabs is between 87 %–96% of that of pure SF6 at 5.5 barabs.

table 1: Dielectric performance of g^3 compared to SF_6 under lightning impulse measured on a 145 kV GIS.						
No.	Gas Mixutres	Pressure at 20 °C (bar_{abs})	Desingn Pressure (bar_{abs})	Application (°C)	Standard Deviagtion (kV)	$\frac{U_{50}(test)}{U_{50}(SF_6)}$
1	100% SF_6	5.5	7	-30	15	1
2	Fluoronitrile/CO_2	6.7	8	-15	14.5	0.94
3	Fluoronitrile/CO_2	6.7	8	-25	14.3	0.87
4	Fluoronitrile/CO_2	7.7	9.5	-25	15.4	0.92
5	Fluoronitrile/CO_2	8.2	~10	-22	12.5	0.96

It should be noted that the standard deviation measured on the gas mixtures is essentially the same as for SF6, or even lower. The small difference in dielectric performance can be compensated by design adjustments or with a dielectric coating in high stress electrodes. For power frequency tests, all the mixtures withstood 300 kV for one minute.

Temperature rise tests were performed on a fully equipped three-phase encapsulated 145 kV GIS bay containing a circuit breaker, a current transformer, two busbar disconnectors/ earthing switches, a line disconnector/earthing switch and a cable end box. The conductors were equipped with about 200 temperature sensors to monitor temperature rise
for different gas formulations.

A temperature rise difference of some 5 K to 6 K was observed. This can be compensated by adequate design improvements. The switching bus-transfer current capability at 1600 A and 20 V was tested over 100 close/open operations on a 420 kV disconnector designed for SF6 at 5.5 bar.

The disconnector was filled with a g3 mixture for a minimum operating temperature of –25°C at a total pressure of 5.5 bar. Arcing time proved to be stable over the 100 operations with average arcing time comparable to those that are typical for SF6.

This means that the gas mixture tested is eminently capable of switching bus-transfer current and can be used as a substitute to SF6 for this application. Arcing contacts presented electrical wear similar to SF6.

g3 in Action:

All these exhaustive laboratory and equipment tests provided conclusive evidence that g3 is an effective and highperforming substitute for SF6. This meant that it is now Possible to deliver switchgear that responds to the demand for more environmentally sustainable high-voltage electrical equipment.

However, while developing a more environmentally sustainable alternative to SF6 in power equipment is a breakthrough, building products incorporating such a brand new technology is another matter—one that requires even more development effort and further exhaustive testing. GE's Grid Solutions business has now made two g3-compatible products commercially available: current transformers and gasinsulated busbars.

A third, a 145 kV circuit breaker, is in the final stages of development and will soon be ready for the market.

g3 for Full 145 kV GIS Including:

Circuit Breaker

GE Grid Solutions business decided to adapt their last generation of 145 kV GIS to g3 technology. This involved testing the GIS bay in its entirety including the circuit breaker. With a customer interested in a pilot project for a 145 kV GIS using g3.

Currently the first SF6-free high voltage equipment are available offering the same performances and footprints that SF6 insulated equipment provide at similar and affordable economic conditions. GE's Grid Solutions business fluoronitrile based gas mixture dubbed 'g3— green gas for grid' has been proven as a suitable replacement
for SF6.

The first applications will be commissioned soon and the extension of Grid Solutions g3 portfolio is underway. As environmental concerns become an increasing focus of governments, regulators and consumers, the development of g3 adds momentum to the on-going quest for a more sustainable high-voltage switchgear equipment solution. By adopting g3 solutions for their new assets final users of high voltage equipment may anticipate and protect themselves from possible increasing regulatory and customer pressure to reduce their environmental footprint. The advent of g3, as a ground-breaking step towards a greener industry, will help them satisfy that requirement.

UNIT III

ALTERNATE GREEN LIQUID INSULATORS

Green Liquid Insulators:

Green insulating liquids Vegetable insulating liquids are a potential alternative to mineral insulating oil for application in HV apparatus, but they also fulfil environmental and health demands, for instance, nontoxicity, biodegradability, recyclability, and non-hazardousness.

Undoubtedly, VOs are abundantly available as a natural resource and thought to be green and reasonable insulator.

The liquid insulation system is applied both as an insulator and a coolant in several elements of the HV network comprising cables, switchgear and transformers.

Hazardous effects of existing liquid dielectric materials:

Mineral oil (MO)- Mineral transformer oil is exposed to mechanical and electrical stresses when transformers are running and the oil is stable at higher temperature, but it exhibited low thermal conductivity. As the time passes by, the oil gets contaminated with impurities and properties of the oil are degraded and so it is discarded as a waste. The impurities present in waste transformer oil such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), harmful gases and heavy metals etc. contaminate the environment and has hazardous impact on land, water, air and on living beings
Mineral transformer oil spills occur in the environment when a power transformer is damaged.

Toxins of waste transformer oil:

The pollutants present in waste transformer oil are polychlorinated biphenyls (PCBs), heavy metals, polycyclic aromatic hydrocarbons and hazardous gases etc. which makes the oil more toxic and adversely affect the environment and living beings.

The transformer oil during use gets contaminated with PCBs and becomes hazardous and hence it is discharged. During the discharge of this waste transformer oil the environment is the recipient. It goes into the environment through incineration of PCBs containing wastes, leakage of oil from old electrical equipment, through runoff, improper disposal of waste oils, volatilization

transformer oils and found that mineral transformer oil are hazardous to environment having low biodegradability, contaminate the waterways and soil if spilled or leakage occurs and transformer mineral oils consists of complex mixture of hydrocarbons and PCBs components. Since the base fluid of transformer oil is the mineral oil hence some of the toxic effects are listed below in Table.

Toxic effects of mineral base fluid of transformer oil

Standard	Properties	Mineral Oil
OECD Method 301 F	Biodegradability	$< 9.8\%$
OECD 203	Acute marine toxicity	Noxious
OECD Methods	Toxicity to the soil	Noxious/ toxic products are formed
OECD 420	Acute oral toxicity	Noxious
ASTM D1275-06 Method B	Corrosive Sulphur	Non-Corrosive

The transformer oil impacted soil contaminated with heavy metals is due to anthropogenic activities and it has adverse effect on human health if the significant amount of its daily dosage occurs with long term exposure. Since it also contains persistent organic pollutants (POP) which are hazardous substances can cause serious environmental effects. As compared to adults' children are more vulnerable to contaminated environmental pollution.

Hence mineral oil, silicon liquids are classified as hazardous and will damage the environment.

Alternate Sources of Environmental Friendly Liquid Such as Ester Oil, Vegetable Oils Dielectric and its Properties.

Natural ester oil:

Natural esters developed in the early 1990s in the USA as a “green” and environmentally friendly alternative due to enhanced environmental issues associated with traditional MO and silicon liquids.

Natural ester liquids indicated adequate dielectric traits, superior chemical stability and lower pour point. They manifested outstanding properties as compared with MO, for instance, higher fire and flashpoint temperatures and superior biodegradability conduct.

Lastly, most contemporary development of insulating liquids for HV applications is the renewable, sustainable and environmentally friendly natural esters and pentaerythritol tetra fatty acid natural which usually evolved as a gradually general MO substitute in HV applications mainly in high-fire-risk applications such as indoors or onshore, because of their small volatility and extraordinary fire point.

These also have a smaller pour point, high humidity tolerant and enhanced operation at elevated temperature, and these are toxic-free and freely decomposable.

VOs also termed as NEs or bio-based liquids are commonly extracted from contemporary entities and derived from plants yields usually sunflower, rapeseed and soybean.

The first transformer prototype with VOs as an insulating medium was developed in 1996; however standard fabrication of transformer immersed with VOs initiated in 1999.

Timeline events in the development and applications of NEs insulating liquids are given in Figure.

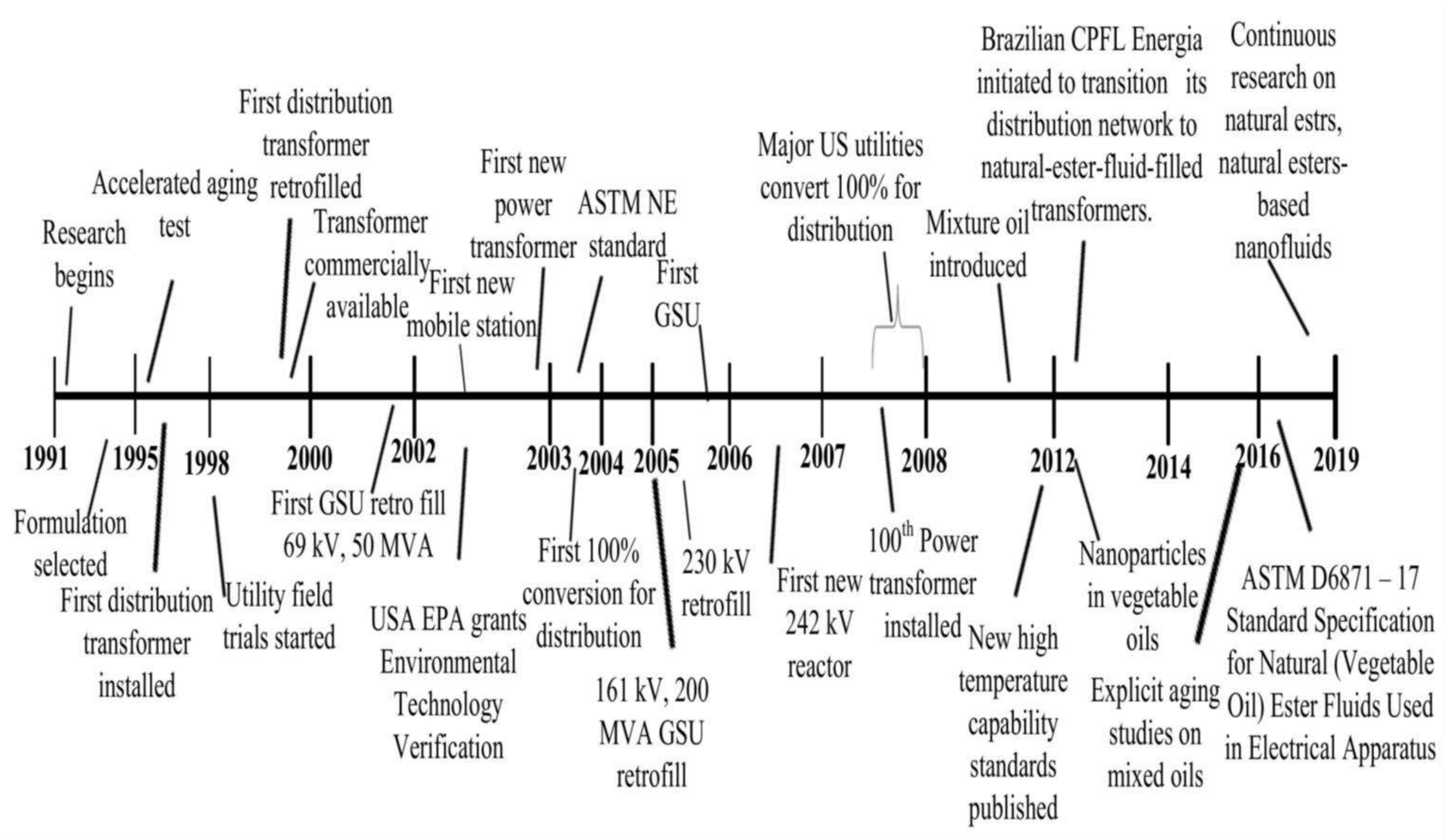

Figure: Timeline of proceedings in the development and application of natural-ester insulating fluids.

Natural esters are obtained from different plant-based seed oils. Their physical and chemical traits rely on their sources of origin, chemical configuration and saturation/unsaturation proportion of fatty acids.

The contaminants (moisture, particles, gases) existing in the oil highly impact dielectric strength, which results in the trend to compare them with traditional MOs by observing the contamination level.

Water absorption of natural esters and MOs makes a huge deference among them in terms of humidity-absorbing ability; NEs possess more excellent moisture-absorbing capability (20–30 times more) in comparison to MOs which affects the impact of moisture on BDV.

On the subject of security, environmental concerns and thermal characteristics, natural esters ensure better features in comparison to MO. They are categorized as extraordinary fire point liquids with self-quenching traits and appropriate for several industrialized applications.

Thermal features and relationship with cellulose insulation contribute toward extended insulation lifetime and permit greater or prolonged overloads, over a longer period without unusual failure of dielectric structures.

Natural esters are deliberated as the suitable substitute of MOs in the applications where fire protection, ecological vulnerabilities or better insulation qualities are necessary. Fire safety is one of the main concerns of today's research community due to the applications of insulating fluids in some sensitive areas for instance, subway channels, ships, offices, shops, workplaces, etc.

There are multiple examples of equipment explosion leading to exterior fires that are very hard to quench and may cause the extension to atmospheres due to the seepage of oil. Typical characteristics of natural ester and MO are given in Table.

Summary of characteristics of insulating fluids applied in HV equipment [5].

Features	MO	Silicone Fluid	Synthetic Ester	NE
Category	Filtered from crude petroleum	Synthetic	Synthetic	Refined vegetable oil
Major component	Composite combination of hydrocarbons	di-alkyl silicone polymer	Pentaerythritol tetra ester	Plant-based natural ester
Origin	Refined from oil	Prepared from chemicals	Developed from chemicals	Derived from crops
Biodegradability	Slowly biodegradation	Really slow to biodegradation	Readily biodegradable	Readily biodegradable
Oxidation stability	Good stability	Outstanding stability	Outstanding stability	Normally oxidation vulnerable
Moisture saturation at ambient (ppm)	55	220	2600	1100
Flash point, °C	160–170	>300	>250	>300
Fire point, °C	170–180	>350	>300	>350
Fire categorization	O	K	K	K

Note: O-flash point < 300 °C, K-flash point > 300 °C as per IEC 61100 standard VOs categorized as low-flammability liquids as per IEC standards.

Electrical Properties:

Insulating characteristics of insulating fluid differ depending on several dynamics for example moisture content, temperature, applied voltage, frequency level, polarity, electrode configuration, particulates, etc. The application of NEs as an alternative to MOs has multiple benefits.

The dielectric constant of natural ester influences the dielectric constant of paper insulation impregnated with ester liquids that are superior to that of MOs.

Because of the closer permittivity values of natural esters and impregnated paper insulation, a greater stress is undergone on paper insulation in the case of natural esters liquids than MOs.

To choose appropriate insulating fluids, it is essential to identify the dielectric characteristics: breakdown strength (BDV), dielectric constant, dielectric dissipation factor, etc.

The dielectric features of various sorts of insulating fluids are presented in Table.

Electrical features of natural ester fluid and mineral oil (MO).

Electrical features	**MO**	**NE Fluid**
Dielectric strength (BDV), kV	54.9	56.7
Dielectric dissipation factor	0.081	0.45
Specific resistance, 10^{12} ohm cm–1@80 ºC	220	**3**
Gassing tendency, µL/min	**-5**	**-79**

Dielectric Breakdown Voltages (BDVs):

The dielectric strength (DS) of insulating material is a measure of its capability to endure electrical stress without collapse. The BDVs of an insulating structure (liquid and solid insulation) is one of the key factors for the electrical structure of HV equipment. It may be defined as the lowest voltages at which there occurs electric conduction that leads to a dielectric rupture. BDV is also termed dielectric strength or striking voltage.

The insulation system provides insulation up to a specific voltage extent beyond which insulation BD happens. The voltage at which BD happens is called BDV or DS of insulation.

This BDV signifies the electrical insulation competency of the insulation system; thus, a small value manifests that the insulation system is not a good insulation system.

The DBV is influenced by the physicochemical properties of materials used, and it is sensitive to humidity and particulate content. Unlike conventional insulation systems (MOs), in which BDV considerably affected by humidity level, environmentally friendly insulation (synthetic and natural esters) retain its dielectric capability at higher humidity levels.

All the insulation systems for HV equipment must fulfil AC withstand voltage, lightning impulse (LI) and switching impulse test standards. Numerous investigations have been conducted by multiple researchers to observe the BDV, discharge properties of various insulation systems.

Impulse BDV Test:

The impulse strength of the insulation system specifies its capability to endure HV transients of a very short period, for instance, those it may be exposed to through lightning strikes.

The standard lightning impulse (LI) specifies simulating lightning shots and usually uses 1.2µs surge for a wave to achieve a 90% amplitude and decline down to 50% amplitude after 50 µs. The LI BDV is generally examined by IEC 60897 standard.

Physical Properties:

Every insulating fluid has extensively different physical traits—particularly viscosities, density, pour point, interfacial tension and flashpoint, as indicated in Table.

Evaluation of physical characteristics of natural esters (NEs) and MO.

Physical Characteristics		MO	NE liquid
Viscosity, cSt	@40 °C	7.800	35.12
	@100 °C	2.240	8.010
Density, @ 25 °C/Cg/cc		0.855	0.924
Pour point, °C		−40	−21
Flash point, °C		145	275
Interfacial tension, mN/M		40	30

Vegetable oil:

Vegetable oils and their esters are being investigated as potential substitutes for mineral insulating oils used in medium-voltage electrical equipment like transformers, due to their environmental advantages like biodegradability and renewability.

Properties like breakdown voltage, pour point, and viscosity were measured for several seed oils and their esters and compared against IEC standards for mineral oils and synthetic esters.

Some seed oils like rapeseed oil and their esters were found to meet or exceed the dielectric, viscosity and pour point requirements after chemical modifications like esterification.

Vegetable oil-based dielectrics also showed advantages like higher flash/fire points, better thermal properties like heat capacity and conductivity, and lower expansion coefficients compared to mineral oils.

Oxidation stability is a concern but can potentially be improved by additives. Sealed transformer designs help limit air exposure.

The biodegradability, non-toxicity, renewability and disposal advantages of vegetable oils make them environmentally favourable dielectric fluids if technical performance can be validated through further testing.

Long-term assessments in actual transformers and code recognition are needed for commercial adoption of these vegetable oil-based dielectric fluids.

In summary, the promising initial results for vegetable oil-based dielectric coolants as greener substitutes for traditional mineral oils in distribution transformer.

Properties Measured:
Breakdown voltage (IEC 60156)
Pour point (ISO 3016)
Viscosity at 40°C (ISO 3104)

Key Results:

Untreated seed oils and esters showed breakdown voltages up to 70-99 kV, meeting IEC requirements after accounting for higher moisture saturation limits.

Untreated seed oil viscosities (41-261 mm2/s at 40°C) exceeded IEC limits, but esterification reduced viscosities to 5-16 mm2/s, meeting requirements.

Untreated seed oil pour points (-15 to -27°C) didn’t meet the -40°C limit, but esters from larger alcohols had pour points < -38°C, meeting the limit.

Vegetable Oil Advantages:

Flash points 315-328°C and fire points 350-360°C, higher than mineral oils (100-185°C).

Thermal conductivities 0.16-0.17 W/m.K, similar to mineral oils (0.11-0.16 W/m.K).

Volume expansion coefficients 5.5-5.9 x 10^-4 K^-1, lower than mineral oils (7-9 x 10^-4 K^-1).

Biodegradability & Aging:

- Vegetable oils are inherently biodegradable unlike mineral oils.
- Oxidation inhibitors and metal passivators may be needed as additives to improve oxidative stability.
- Sealed transformer designs limit air exposure to slow oxidation:

Vegetable Oil Composition:

Vegetable oils are primarily made up of triglycerides, which are esters formed from glycerol and three fatty acid molecules. The fatty acids can have different carbon chain lengths (typically 8-22 carbons) and varying degrees of saturation (saturated, mono-unsaturated, poly-unsaturated). The specific fatty acid composition affects the properties of the vegetable oil.

Esterification Process:

To improve properties like viscosity, the authors performed esterification on the vegetable oils. This involves breaking down the triglyceride molecules into three separate fatty acid esters by reacting with an alcohol like methanol or isopropanol.
This reduces the molecular size/weight, lowering the viscosity

Breakdown Voltage:

While untreated vegetable oils had high moisture contents (150-200 ppm), their high saturation limits mean this absolute moisture corresponded to relatively low relative humidities of ~27%. This is comparable to typical mineral oil moisture levels after dehydration treatment, explaining why the vegetable oils could still achieve the required breakdown voltage performance.

Low Temperature Performance:

The high viscosities and pour points of untreated vegetable oils are due to their long fatty acid chains solidifying at low temperatures. Esterification helps reduce molecular sizes/weights, improving low temperature fluidity. Using larger alcohol molecules in esterification further reduced pour points.

Thermal Properties:

The thermal conductivity, heat capacity and low expansion coefficient of vegetable oils are advantages for heat transfer capabilities in transformer applications compared to mineral oils. Their high fire/flash points also make them much more fire-resistant.

Environmental Benefits:

Being bio-derived and biodegradable are the key environmental advantages of vegetable oils over mineral oils. Their renewability from crops and lack of toxicity are also beneficial. However, oxidative aging remains a challenge that may require food-grade antioxidant additives.

Overall, through chemical modifications like esterification, the authors demonstrated vegetable oil formulations that could potentially meet the key dielectric and fluid property requirements for transformer applications while providing environmental benefits over mineral oils.

Here are some of the key benefits of using vegetable oils as substitutes for mineral insulating oils in electrical equipment like transformers, as highlighted in the paper:

Technical Benefits:

1. High Fire Safety – Vegetable oils exhibited much higher flash points (315-328°C) and fire points (350-360°C) compared to mineral oils, making them more fire-resistant.
2. Good Thermal Properties – Vegetable oils had similar or better thermal conductivities, heat capacities and lower volume expansion coefficients beneficial for heat transfer performance.
3. Vegetable oil-based dielectric fluids provide an environmentally-friendly alternative to mineral oils while also offering technical performance benefits like higher fire safety and potential economic benefits, making them promising candidates for transformer application.

Mineral oil and Natural ester (Rice bran oil and Sunflower oil) are analysed and from the analysis, it is concluded that vegetable oils have better breakdown voltage, flash point, fire point, Density of oil, than the mineral oil.

UNIT IV

ALTERNATE GREEN SOLID INSULATORS

SOLID INSULATORS:

- Solid insulator means the insulating coating of wiring harnesses, provided in order to cover and prevent the high voltage live parts from any direct contact.

- SOLID DIELECTRICS USED IN PRACTICE Solid insulating materials are used in all kinds of electrical circuits and devices to insulate one current carrying part from another when they operate at different voltages. A good insulator should be of low dielectric loss, having high mechanical strength, free from gaseous inclusions and moisture, and should also be resistant to thermal and chemical deterioration.

- **Solid insulation**
  Insulating paper

Insulation paper mainly includes : plant fiber paper.

Plant fiber paper includes cable paper, capacitor paper, winding paper, etc.

Example: paper and polymer are organic materials.

Solid dielectrics vary widely in their origin and properties. They may be natural organic substances, such as paper, cloth, rubber, etc.

HAZARDOUS EFFECTS OF EXISTING SOLID DIELECTRIC MATERIALS.

Some key environmental effects on the dynamics and life-time of ceramic and polymeric insulators. That high pollution levels are non-uniformly distributed and are correlated with, for example, industrial and marine regions. In these regions, the pollution, aging and degradation of insulator materials is accelerated compared to relatively unpolluted regions, where the degradation is more predictable over time. The rate of the environmental pollution of HV insulators depends on the weather conditions, surface roughness wettability, and insulator geometry. The mechanism of pollution of HV insulators is mainly governed by the gravity, wind forces, electrostatic forces, humidity, particle size and mass, and chemical properties of the insulators. The analyses indicate that the presence of pollutants on insulator surfaces leads to different types of electrical discharge such as corona, partial discharge and dry band arching which result in the accelerated degradation of insulators and the surrounding infrastructure and ultimately can cause flashover and blackouts. Although multiple methods were devised to improve the material surface of insulators, the surface pollution associated with aerial deposits and electromagnetic radiation cannot be totally avoided.

Environmental-friendly solid insulating materials:

Solid environmental-friendly insulating materials, have shown great advantages and potential as insulating materials for HVDC cables, including environmental friendliness, high temperature resistance and high breakdown strength.

Environmental-friendly insulating materials are expected to play a more important role in future cable insulation systems.

The environmental-friendly insulating material should have mechanical flexibility, high temperature integrity, excellent insulating properties and low cost. Particular attention should be paid to the mechanical and electrical properties of materials at extreme temperatures to overcome the challenges of low temperature brittleness and stark decrease in electrical properties at high temperatures.

The insulation system generally applied in HV apparatus solid cellulose insulation (paper/pressboard) and liquid insulation for stable functioning.

In the electricity sector, this is acknowledged that the lifespan of the HV apparatus is primarily based upon used insulation arrangement (usually liquid and solid insulating materials) status. This arrangement forms the main insulating constituent of the insulation system executing the threefold operation of the electric barrier, mechanical backing and heat outflow route.

The major insulating media for HV equipment generally comprises of greatly solid insulation.

The BDVs of an insulating structure (liquid and solid insulation) is one of the key factors for the electrical structure of HV equipment. It may be defined as the lowest voltages at which there occurs electric conduction that leads to a dielectric rupture. BDV is also termed dielectric strength or striking voltage. The insulation system provides insulation up to a specific voltage extent beyond which insulation BD happens. The voltage at which BD happens is called BDV or DS of insulation. This BDV signifies the electrical insulation competency of the insulation system; thus, a small value manifests that the insulation system is not a good insulation system. The DBV is influenced by the physicochemical properties of materials used, and it is sensitive to humidity and particulate content.

The oxidation of liquid insulation is a critical matter since it leads to the development of derivatives, e.g., acids and sludge, which in turn originate issues in the apparatus by decreasing dielectric features of solid insulating material.

The effect of low-energy and high-energy exhausts on the operational performance of NE liquids in deficiency of solid insulation must furthermore be explored.

ALTERNATE SOURCES OF ENVIRONMENTAL FRIENDLY SOLID DIELECTRIC AND ITS PROPERTIES.

Thermosets are widely used for insulation protection of electrical equipment and play notable roles in advanced electrical systems for their excellent electrical properties, thermal stability and mechanical properties. Conventional electrical insulating thermosets are processed complicatedly and unfriendly to environment during manufacture, operation, and maintenance and recycling. The advancement of green power grids and the promotion of sustainable development have spurred considerable interest in environmental-friendly electrical insulating thermosets. Green synthesis technology and design of recyclable molecular structure are emerging technologies for preparing environmental-friendly electrical insulating thermosets. Environmental-friendly electrical insulating thermosets and mainly introduced bio-based electrical insulating.

Thermosetting electrical insulation materials provide insulation protection for electrical equipment Protection is an important basic material for manufacturing electrical equipment and is widely used It is used in the production of various electrical equipment such as cables, motors and transformers. Thermosetting electrical insulation materials include thermosetting resins and their composite materials, According to different chemical structures, they are divided into cross-linked polyolefins, phenolic resins, Epoxy resin, polyurethane and silicone, etc. with thermoplastic electricians Compared with insulating materials, the molecular chains of thermosetting electrical insulation materials are composed of covalent Bonded to form a three-dimensional network structure, it is heat-resistant and Solvent, arc resistance, tracking resistance, dimensional stability and mechanical properties, etc. are significantly improved. For example, low-density polyethylene (LDPE) cross-linked. The upper limit of use temperature of the final cross-linked polyethylene (XLPE) is raised from 70℃ up to 90°C and resistant to creep, environmental stress cracking and impact.

Green preparation of thermosetting electrical insulation materials Greening agents and solvents. Catalyst in the polycondensation of thermosetting phenolic formaldehyde, Curing of epoxy and chain extension of PU and other thermosetting electrical insulation materials plays an important role in the preparedness response. The development of new catalysts is not only It can improve catalytic efficiency and reduce catalyst toxicity, and is often accompanied by Converting more low-value waste materials as new synthesis routes emerge It is a thermosetting electrical insulation material. Use organic catalysts instead of gold Catalysts are an important means to achieve green catalysts. Solvent is often as reaction medium and diluent, its greening is conducive to reducing water body pollution, reduce energy consumption and improve air quality, etc. Use water as a solvent It is the main development of using agents instead of organic solvents to produce thermosetting electrical insulation materials.

UNIT V

EVOLVING STANDARDS FOR GREEN INSULATION SYSTEMS

As power systems continue to evolve and demand for electricity increases, power system equipment faces higher operating demands. One critical aspect of power system equipment is insulation, which plays a crucial role in ensuring the safe and efficient operation of electrical infrastructure.

Understanding the Challenges

Higher operating demands in power systems result from factors such as increased power consumption, renewable energy integration, and the electrification of various sectors. These demands put additional stress on power system equipment, including transformers, cables, and switchgear. Traditional insulation materials may struggle to withstand the increased temperatures, electrical stresses, and environmental conditions associated with these higher operating demands.

Enhanced Thermal Performance

To address the challenges posed by higher operating demands, insulation materials have evolved to offer enhanced thermal performance. New materials, such as advanced polymers and composite insulators, exhibit improved thermal conductivity and can withstand higher temperatures without compromising their insulating properties. These advancements allow power system equipment to operate at higher loads and temperatures, increasing their overall efficiency.

Improved Electrical Insulation

Higher operating demands also require improved electrical insulation to ensure the safe and reliable operation of power system equipment. Insulation materials with higher dielectric strength and lower dielectric losses have been developed to minimize electrical stress and prevent breakdowns. Additionally, advancements in nanotechnology have led to the development of nanocomposite insulation materials, which offer superior electrical insulation properties and enhanced resistance to partial discharges.

Environmental Considerations

As the world becomes more environmentally conscious, insulation technologies for power system equipment have also evolved to address sustainability concerns. Traditional insulation materials, such as oil-based products, are being replaced with eco-friendly alternatives. For instance, bio-based insulating oils derived from renewable sources are gaining popularity due to their reduced environmental impact and improved fire safety characteristics.

Enhanced Durability, Reliability and Testing.

Higher operating demands necessitate insulation materials that can withstand harsh environmental conditions and prolonged service life. Manufacturers are incorporating additives and modifiers into insulation materials to enhance their durability and resistance to aging. Additionally, advanced testing and monitoring techniques, such as partial discharge measurements and thermal imaging, are being employed to assess the condition of insulation in real-time, allowing for proactive maintenance and replacement strategies.

Evolving Standards of Management

The standards suggest the use of the previous insulation system as a reference in the qualification process of a new insulation wall.

Many standards exist and provide procedures and test methods for estimating the lifetime of an insulating system submitted to thermal stress (Ul-746, UL-1446, IEC-60216, IS-11182, etc.). Many other factors cannot be well-quantified and should be studied later. For example, the customer does not always know how many times his machine will operate under overvoltage or overload conditions as well as their duration. Studies periodically confirm that thermal aging is responsible for the greatest number of outages and subsequently, a good method to initiate the design of electrical insulation is to first deal with the effect of thermal aging. Thermal aging does not apply to all elements of an insulation system. All the elements or materials used do not have the same behavior in front of this constraint. Hence, it may be possible to increase the expected lifespan of an insulation system by modifying only one of its components: the weakest one. The constitution of insulation wall must be examined, and, in particular, the arrangement of the insulation layers in machines which should have a high service life. These machines are essentially high voltage machines.

The standards, IEC and IEEE, request that turn insulation must be able to withstand a surge pulse. In observing the IEC standard, the test voltage is 0.65 times the surge voltage (4 Un + 5 kV) and the rise time is around 0.2 μs. The surge test also takes into account the main insulation; it must be able to withstand a surge (4 Un + 5 kV) rise time 1.2 μs.

Thermal Ageing in Front of Standards

Hence, thermal aging is a phenomenon which is understood and documented. About the resin, standards exist and are useful in determining the lifetime of a polymeric material used in electrical equipment. The UL and IEC standards give a relationship between the thermal aging of an insulation material and its lifespan.

The standards provide any indication about the combination of constraints. However, the standards do not provide any indication about the combination of constraints. Moreover, many stresses are out of the scope: mechanical stress, moisture, starting conditions, etc. Manufacturers are aware of these limits and believe that existing standards need to be improved.

Standards Evolutions and Experimental Aspects

Standardized tests that are able to provide information on the status of the insulation.

During the standard ageing test, the coils are not powered and are not submitted to mechanical stresses. Moreover, the standards suggest that any added mechanical stress or electrical stress, should not introduce any significant additional aging during the thermal aging test.

Major applications and standards

The dielectric, mechanical, and thermal properties of some biobased materials and their possible applications are introduced in following paragraphs.

Bio-based thermoplastic polymers in polymeric insulation. PLA, which is derived from corn, sorghum, and plant roots, is a bio-based material with good electrical performance. To assess the feasibility of PLA as a dielectric insulation, the volume resistivity, relative permittivity, and dielectric loss tanδ of PLA are measured.

The volume resistivity (4.9–5.5 × 1017 Ω·cm), dielectric constant (3–3.8), and tanδ (0.02–0.022) of polylactic acid (PLA) are slightly greater than those of cross-linked polyethylene (XLPE).