Rev. Adv. Mater. Sci. 44 (2016) 33-45

# ADVANCED MATERIALS FOR POWER ELECTRONICS PACKAGING AND INSULATION

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*Received: May 22, 2015*

**Abstract.** Insulation is an important part of any electrical and electronic system. More and more insulation materials are being introduced to cope with the high speed electronics and integrated circuits. Different types of insulation materials have different applications in industry. Power electronics devices have a higher trend towards integration and increase in density nowadays. Main motives towards evolution of power electronic devices are to increase the reliability, thermal and electrical performances by achieving hybrid integration. In this paper, we have reviewed different insulation materials essential for protection of electrical and electronics system, factors that result in degradation of insulation materials i.e. power electronic convertors and adjustable speed drives, designs used to improve the power quality of medium voltage grid stations and effect of transient frequency on service life of insulation materials. Moreover the degradation of insulation materials and factors affecting insulation are also been discussed.

## 1. INTRODUCTION

The Insulation materials have very high resistivity. These materials oppose the flow of electric current due to high resistance. Insulating materials play an important part in various electrical and electronic circuits. There are certain factors that affect the insulation materials including. There are various factors that results in degradation of insulation materials and hence lifetime. Major factors are temperature, moisture, applied voltage, aging, corona effect and bad dielectric medium used etc. As the aging proceeds, the insulation properties of the materials are affected. Similar is the effect of moisture. With the passage of time materials also absorb water. This degrades its performance. The material used for insulation must be hydrophobic i.e. water repellent.

Different types of insulation materials have different applications in industry. Some are more suitable for the use in avionics; some are more suited for the PCBs while some have proved to be the best for the applications where insulation has to bear severe vibrations like motors and generators.

Insulation materials have found wide spread applications everywhere in transformers, electric switches and circuit breakers.

In Electrical and Electronic systems, specifically polymeric insulating materials are used widely. These polymeric materials include polyethylene (PE), poly tetra-flouro ethylene (TEFLON), polyester, poly vinyl chloride (PVC), polyethylene- 2, 6-Naphthalene Di carboxylate (PEN), poly amides, poly propylene and many others.

Researchers are heading towards newer and reliable materials in field of insulation. More and more insulation materials are being introduced to cope with demands of high speed switching in electronics and integrated circuits. In past, the key feature considered was solely the ‘technology’ but nowadays key parameters that are to be encountered

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are quality, reliability and environmental factors along with technology. This trend has changed the basic goal of manufacturing of insulation materials. Earlier wire splices were used either without insulation or they were just wrapped by tape in order to protect. But later sealed splices based on dual wallet heat shrink tubing came to market when the automobiles became more reliant on electronics and wire splices failed to provide desired reliability. Critical thing related to this type of insulation is sizing and installation of tubing over the splice. New technique based on procured gels is recently developed because it's very difficult to create sealed splice as it requires huge amount of heat and availability of huge heat sink is not that much easy. Gel can be manufactured chemically from large variety of elastomers like butyl, polyurethane, silicones and fluorosilicates. Silicones and fluorosilicates act as best temperature resistant and solvent at extreme conditions. Gel shows great sealing capabilities and it's easy to handle it. Aromatic polymer systems are not always suitable as insulating components although they provide resistance to chemical and high temperature environments [1].

Since, one can simply understand the importance of insulation in the reliability of a system, so several tests are also used to test the insulation materials. One of such tests is Surface Insulation Resistance (SIR) Test. Surface insulation resistance (SIR) represents the electrical resistance between two electrical conductors separated by some dielectric material under the artificial aging conditions like medium heat and high humidity. Reasons to perform an SIR test are to classify or qualify a product, to evaluate and control a process and to compare materials or processes. Besides such tests, thickness of insulation also plays an important role in the reliability of an electrical system. Many tools are being developed to measure the thickness of the insulations to a greater precision and to ensure its reliability and strength under extreme situations. Moreover, work is also being done to develop high quality substrate materials for use in the PCBs besides commonly used material epoxy to support much higher frequencies and clock speeds. In this scenario, Thermount and Polyamide are the two materials that appear to be a better choice for such applications and provide low CTE, high Tg and low dielectric constant along with many other added benefits.

Nowadays addition of nano composites have largely strengthen the insulating properties of insulators by increasing the resistance of the materials. Dielectric breakdown strength, treeing life, partial discharge resistance, tracking resistance, thermal conductivity and glass transition temperature have been greatly changed by incorporating nano composites in the polymers.

Major problem in high power electronic is failure of thin dielectric insulation. Several standard test procedures are available for measuring the quality of insulation or causes which lead to the failure of insulation materials. Harmonization between different standards is essential in order to reduce the cost and time delay in testing the components and devices to multiple standards. Standard test procedures available for evaluation of electronic power transformer insulation are based on accelerated thermal aging. In this study various test procedures proposed by IEEE standard test guidelines for insulation have been conferred in detail.

We will further discuss the effects of harmonics on lifetime of insulation. Electrical Networks are shifting towards the smart grids which make the use of more and more smart components in power quality assessment. We will also discuss the scope of insulation in optical electronics where high voltage signal is first converted into optical signal and then transmitted over fiber.

## 2. POLYMER INSULATION MATERIALS AND THEIR APPLICATIONS

Considering the use of polymer insulation materials widely in the applications where the different materials are in contact with one another, the electronic properties of the polymer interfaces are worth giving importance while dealing with charge injection/extraction processes. C. Laurent et al. in [2], discussed the case of polyethylene (PE) when used in different applications like HVDC insulated systems, dielectric barrier discharges resulting from the cold plasma processes used in surface treatment of UV-VUV sources and situations where dielectrics are subjected to ionizing radiations and particle fluxes. In PE surface, the impurities may concentrate on the surface of PE and chemical attacks like oxidation may begin there. Author performed AC luminance modeling of PE interfaces. The measurement of current emission from charged surface of PE was made by exposing it to plasma. It was observed that energy trapped in the sites over the surface of PE in form of charge follows an exponential distribution. Measurement of the emission current, once a known quantity of charge has been deposited on the sample surface, into the vacuum can provide a spectroscopic method to infer the distribution in charge trapping sites.

Due to vast advantages of polyethylene (PE) in electric and mechanical properties and as it can withstand up to 100 kV/mm high electric stress, it is widely used in insulating power cables and for electrical energy transmission. Premature failure of insulation can occur by exceeding the voltage stress which in turn increases the dielectric stress on insulation. Stress due to AC voltage cause reduction of insulation resistance by amount of several order continuously. Crossed linked polyethylene (XLPE) cables can withstand more electric stress under DC field than under AC field. Reason of reduction of insulation resistance of XLPE cable are moisture absorption, moist environment, carrier transfer and charge accumulation under AC stress. X. Zhang et al [3] examined two specimens of XLPE cables and measured the effect of DC voltage on them by using Scanning Electronic Microscopy (SEM) and dielectric loss tangent measurements. First sample was aged in service for one year and second one was virgin XLPE sample. Electrical tree formation was examined by SEM. Results show that the electrical tree formation in case of aged sample is longer than virgin. Dielectric loss tangent (tan$\delta$) of aged sample is 30% higher than virgin. Electrical conductivity increases with temperature. Author concludes that application of DC voltage to any cable insulation results in enhanced electric stress whereas, application of AC voltage increases the moisture absorption. So in order to produce the worst combination of stresses those encountered in power electronic components due to harmonics, a combination of AC and DC voltages should be applied to XLPE cable and other insulation materials intended to be used in HVDC systems.

Polymers are getting popular day by day. Thermoplastics is a group of insulation material that are widely used in electrical and electronic systems. Polyethylene- 2, 6- Naphthalene Di carboxylate (PEN) is a member of this group of polymers. J. F. Chavez and J. J. Martinez-Vega [4] have researched for the effect of high electric field on PEN along with the influence of morphology. Under the influence of low electric field, amorphous PEN samples showed high current density as compared to crystalline PEN samples. Due to semi crystalline morphology, current density at high fields is limited. In HV domain, dielectrics are not reliable as there are defects in microscopic volume that arises from degradation of materials. This results in micro voids leading to rapid aging. Semi crystalline samples are less conductive and create more opposition to charge carriers. For the thicker films, deeper traps were observed as compared to thin film. So it was observed from experimental results that crystalline form is more resistant to degradation.

Polymer insulation materials have found wide spread applications in last decade in all fields of electrical engineering. Polymer materials with addition of nano particles form nano composites. Nano composite materials are commonly used now a days in outdoor, indoor insulation and manufacturing of electronic components. Nano composites exhibits functional performance as flame retardancy, bio degradability, gas barer effect and paint performance. Some of the effects of adding nano particles to polymers include reduction in polarization, permittivity, space charge, partial discharge, tracking resistance and increase in thermal conductivity. The shape of the nano particle mixed with polymer is assumed to be spherical but any other shape also works. Formulation of methods for development of industry standard polymer nano composites is required. The finished product can be characterized by advance analytical methods such as small angle X-ray scattering (SAXA), energy dispersive X-ray spectroscopy (EDX), wide angle X-ray diffraction (WAXD) and transmitting electron microscopy (TEM), etc. [5]

Polymers are widely used as a based substrate material for many field effect transistors. Drain/ source terminals are the most vulnerable points in this aspect as they have to suffer all the stresses of conducting current and open circuit voltages. Plastic electronics refer to cheap and simple mass production using solution processing as compared to expensive techniques like vacuum deposition or photolithography and spin-coating or printing. Huge work is done till now to improve the field-effect mobility of organic layers. High width to length (W/L) ratio is required to compensate the low field-effect mobility operating with channel length less than 10 $\mu$m. Till now resolution of range 100 $\mu$m in case of screen printing of conductive inks have been achieved but it’s not that much satisfactory and lateral resolution of 10 $\mu$m. Field effect mobility of 1.5 $cm^2/Vs$ for pentacene have been observed as compared to hydrogenated amorphous silicon TFTs. E. Becker and coworkers [6] explain patterning technique using selective electro-polymerization (polymerization under the influence of electric current) of doped positive substrate. Polymerization is carried out by creating a potential difference between anode and cathode. Film thickness is adjusted by monitoring the amount of charge per area. Film pattern can be transferred easily to an insulating polymer. Authors proposed a patterning technique that is straight-forward and require wet-chemical procedure. That proposed technique is fast and material efficient, anode can be reused many times. Manufacturing cost of the pattern of polymer films is independent of the expenses of patterning technique. This technique is also applicable in industrial production.

Parylene is also a member of polymer series. Parylene is a chemical vapor deposited poly xylylene polymers. Parylene conformal coating is used for protection of devices, components and surfaces. It is a vacuum deposited plastic that has the ability to deposit in a uniform nature hence provides dielectric behavior. In the paper, R. Olson [7] has described certain applications of Parylene. It is used for environmental protective coating due to its low dissipation factor, high dielectric and mechanical strength and excellent noise and chemical barrier properties.

Y. Cao and P. C. Irwin [8] studied the effects of nano filler on properties of polyimides using Short circuit thermally stimulated current (TSC). The transformation from main thermally stimulated current peak to high current indicates deeper trapping due to incorporation of nano fillers. These nano fillers effect the properties and the study on polyimides showed that addition of nano fillers results in decreased conductivity, improved discharge resistance, mechanical robustness and heat dissipation. Electrical conductivity of polyimides filled with nano fillers reduces for high temperatures.

Nano composites have an intercalated structure. Molecules of resin are inserted in the spaces between each layer. This property results in an increase in insulation breakdown strength of epoxy resin as compared to that of epoxy resin without layered silicate. Epoxy resin is mixed with micro scale inorganic material particles like silica or alumina. T. Imai et al [9] elaborated experiments for the measurements of insulation properties of epoxy layered silicate nano composite. The time for breakdown has been measured and the results showed that nano composites have approximately twice the time of the break down as compared with epoxy resin. Similarly, process of electrical treeing was observed in case of nano composites and epoxy resins. In case of epoxy resins electrical treeing appeared more frequently but in case of nano composites treeing pattern appears at higher electrical fields as compared to epoxy resin. So, Epoxy layered silicate nano-composite has better insulation properties as compared to non-layered structure.

In power electronics involving high voltage, substrates are important part of components as they have to bear all peak inverse voltages. Ceramics are usually employed to make substrates. Alumina and aluminum nitride are most commonly used for this purpose because of their superior mechanical strength and electrical properties.

T. Lebey [10] investigated the use of aluminum nitride for making substrate of different power electronic components. This study helps in proper designing of new generation power electronic components. The author suggests that to increase the reliability, electrical performance, thermal endurance and to decrease the cost, hybrid integration is a good approach. Hybrid integration can be achieved using multi-layer ceramic construction which combines different ceramic materials in a layer by layer three dimensional architecture. There are two further approaches which can be employed to do this integration. First approach realizes construction of a high voltage switch through a serial connection of low voltage switches which can be glued together using an epoxy resin. Second approach is to use a mixture of different ceramic materials in a way to achieve the strength required for a high voltage switch. However this process needs a very precise design and control to achieve a reliable product.

## 3. POWER ELECTRONICS AND ELECTRICAL INSULATION SYSTEMS

Presence of distorted voltages or currents due to low frequency and high frequency harmonics and non-sinusoidal voltage on network and load side cause significant reduction in quality and reliability of instruments' insulation. Current distortion in instruments cause acceleration of aging phenomenon resulting in power loses and overheating of insulation and conductor. The main cause of (current and voltage) these distortions are extensive use of PEC (power electronics convertors). PECs are used to control speed and power in low and medium voltage ac-rotating machines. Inorganic insulated wires used for electrical machines (frequency range 50-60 Hz) show premature breakdown due to use of ASD (Adjustable speed drives). ASD is basically generate impulsive waveforms i.e. waveform (width-modulated impulses having high slew rate) generated by PEC using fast electronic switches. Power convertors manufactured using SCR has been replaced by BJT due to continuous development in technology, producing square waveform. This improvement in technology cause reduction in switching losses and improves the reliability and stability, but still a lot of work is needed to investigate the phenomenon occurring in the insulation of machines with these reliable PECs [11].

A. Cavallini and coworkers [12] have discussed the dominant factors which accelerate the aging of insulation materials being used in equipment having power electronic convertors (PEC). Two major factors of over voltage i.e. switching and lightening cause huge increase in stress resulting in insulation failure due to the fact that it can exceed the breakdown strength of insulation material. Low frequency harmonic component existence increases the actual slope, peak voltage and decreases dielectric and thermal properties of insulation material. Lifetime of insulation decreases by a factor of 2 to 4 with increase in dielectric loss that in turn cause increase in temperature up to 10-20 °C but increase in peak voltage even only by few percent can drastically reduce the lifetime by several order. On the other hand, high frequency harmonic components due to the use of PEC can cause exceed in amplitude of fundamental voltage and this uneven voltage distribution along motor windings results in increase in inter turn insulation electric stress and can cause premature failure. That electric stress results enhanced partial discharge (PD) activity. PD can severely affect the windings of motors that are made up of organic insulated magnetic wires i.e. polyamide-imide (PI). Composites of organic/inorganic materials working together can sustain more PD activity than organic insulation materials acting alone. Uneven voltage distribution also accelerate the insulation degradation. PD measurement is necessary so that during operation using PEC, PD remain in safe limit. The dominant factors which age up the insulation include low and high frequency harmonics, PD, thermal stress and dielectric loss.

As PD activity drastically effects the organic insulated motors, so it is necessary to guarantee the insulated motors as PD free. Contrary to this motors having composite organic/inorganic insulation can withstand high PD activity. A. Cavallini and coworkers [13] examined the insulation conditions during motor operation and PD activity. Parameters of PD like amplitude and repetition rate accelerate the aging mechanism along with space charge accumulation. In order to prevent from premature breakdown of insulation materials, PD measurement is very useful and indicative tool. It must be performed as a part of quality control. Use of multilevel converters can reduce the electric stress offering to insulation material and also cause reduction in over voltages. Improvement in electrical apparatus design by strengthening the inter turn insulation and phase of rotating machines can prevent from situation that lead to the overstress between turns.

## 4. INSULAION IN LITHIUM-ION BATTERIES

Among the energy storage sources used in electronic devices, most popular is Lithium ion battery. It has benefits like high energy density, smooth discharge characteristics and able to work in a sealed environment. In spite of all these advantages, there are some serious concerns related to the use of Lithium ion batteries. Among them, most important is fire hazard. In order to reduce this fire hazard, separator materials used in the construction of Li-ion batteries should be highly stable against thermal stress. This separator is a polymer insulation paper which has the pores to allow free movement of Li ions without electrically shorting the negative and the positive layers. B. N. Pinnangudi [14] have presented a detailed overview of different separator materials used in li-ion batteries. Author reports that commonly used separators are polyethylene (PE), polypropylene (PP), blends of PE and PP, high density PE and ultra-high molecular weight PE. Other materials used include polyamide, poly-tetra-fluro-ethylene (PTFE or Teflon), polyvinyl chloride and polyesters. In recent years, separators made up of blends of polymer and ceramic materials are also being used. These materials combine the advantages of flexible polymers and high temperature ceramics. The important characteristics of separators are chemical stability, uniform thickness, high porosity, high permeability, wettability and less thermal shrinkage. The author investigated 1 amp-hour Li-ion cells supplied by five different manufacturers under application of over-charge stress. The over-charge was brought to a point where the cell temperature rises to about 500 degree Celsius. Many reasons were found for thermal runaway. Among these one was failure of separator resulting in shorted cell; another was an application of an incorrect voltage to charge the cell. Over charging it turned out to be a reason for thermal runaway.

## 5. IMPORTANCE OF INSULATION IN MOTORS

Motors are an essential part of domestic and industrial load. It is estimated that almost 70% of the electrical energy produced in the world is consumed by motors for a vast majority of applications. Many of these motors don't require to be operated at full power all the time. Therefore, speed control is very important. Among the techniques used for the speed control of induction motors, most efficient is adjustable or variable speed drives. These kinds of drives employ chopping of voltage along the time axis which results in lossless speed control [15]. However, one drawback of this scheme is that steep fronted voltages are applied to the motors. The steep-fronts in the voltage when applied to motors generate high voltage surges. These surges weaken the motor's stator and rotor insulations. The high frequency of these steep-front voltages result in applications of thousands of short duration high voltage surges to motor winding insulation. This results in larger circulating currents through the coil which in-turn melts the copper and causes burning of insulation. The author concludes that medium voltage motor insulation may not be effected widely by high frequency variable speed drives used in high speed electronics.

## 6. INSULATION APPLICATIONS IN OPTICAL ELECTRONICS

Measurement of high voltages, conduction and leakage currents in service by direct methods is rarely feasible. For this purpose many indirect methods are available. Commonly used techniques involve capacitive or resistive voltage dividers as transducers. The low voltage obtained from these transducers is then frequency or light modulated and transmitted over air or optical fiber. L. H. Christensen [16] proposed a new design in which an optical voltage modulator is used. This voltage modulator transforms the electric field of line into a corresponding light signal. This eliminates the need of capacitive or resistive voltage divider (as voltage transducer) which is the previously used approach. The optical voltage transducer (OVT) presented in this research consists of two electrodes connected to ground and HV terminal which have electric field between them. Pockel's crystal ($Bi_4Ge_3O_{12}$) is connected with grounded electrode. Pockel's crystal when exposed to electric field, generates a light corresponding to field strength. This results in formation of an optical voltage transducer for 132-150 kV. This scheme provides an OVT with adjustable transformation ratio and less weight as compared to conventional PT. The temperature dependent error of this optical transducer is between ±1.3 percent. Using this system increases the noise immunity, measurement bandwidth and connectivity with digital equipment.

Electrical Networks are shifting towards the smart grids which make the use of more and more smart components to measure quality and consumption of energy efficiently. Capacitive or resistive voltage dividers are commonly used as transducers to measure high voltages, leakage and conduction currents in service. The electrical signal thus obtained is converted into optical signal and transmitted via fiber. Commercial instrument transducers that have already been used in power transmission have limitation of operational frequency. D. Gallo and his coworkers [17] proposed a design of realized voltage transducer (RVT) for medium Voltages with fiber optic insulation. This voltage transducer transforms the input signal into a corresponding light signal proportional to it and resulting light signal is transmitted over optical fiber which solves the problems of bandwidth limitation and errors of measurement transformers.

The input stage of RVT is a resistive Voltage divider with an op-amp for impedance adjustment. The attenuation of voltage divider and maximum dissipated power are limited to 17000 and 1 W, respectively; so that the load effect on network and its cost are lower. This is done by choosing proper resistance values. The transmission stage includes voltage/current converter, the optical transmitter with optical fiber and optical feedback part. Voltage/current converter transforms the incoming bipolar voltage into corresponding unipolar current. Op-amp used in this stage has higher gain bandwidth product which increases the overall bandwidth of transducer by improving optical feedback and impact of parasitic components are minimized by its low input resistance. Plastic optic fiber is used for transmission of light signal because it does not oxidize and damage in presence of rain and works well in presence of vibrations. Fourier analysis and AC analysis performed shows that the RVT reduces the harmonics, limits the attenuation to 84.86 dB, provide good accuracy and bandwidth. As simple electronic components are used in its construction so it has low cost. All these specifications can be more beneficent for mass scale deployment in future smart grids.

The enhancing demand for power quality assessment in medium voltage grids opted by spiking amount of diffusion of distributed generation sources empower to employment of transducers to convert and obtain voltage signal with better and convalesced accuracy. Conventional potential transformers used for power quality analysis have limitation on frequency bandwidth and linearity. Capacitor and resistor voltage dividers are used to resolve these issues but have disadvantage of absence of galvanic insulation. G. Aurilio and his companions presented a design of medium voltage insulated divider (MVID) [18]. MVID is composed of high impedance voltage divider (VD) and electronic insulation interface (EII). Resistive-capacitive voltage divider is used to step down the high line voltages to the voltages that are needed by electronic components. To provide suitable insulation, divider is filled with resins. The low voltage attained is then converted to optical or light signal using an infrared light emitting diode (LED) and transmitted over plastic optic fiber. Optical to electrical conversion is then takes place using a photodiode, which is used in closed loop scheme with infrared LED. AC and spectral analysis shows that proposed design provides better linearity, very large bandwidth and high accuracy, it has error ratio of 12% at 100 KHz. The magnitude and phase variation is ±0.1% and ±60 mrad until 100 KHz.

## 7. IMPORTANCE OF INSULATION AND HIGH QUALITY SUBSTRATE MATERIALS IN PCBs

The manufacturers of polymer materials have to face the increasing frequencies of electronic devices, therefore more and more polymer materials are expected to emerge in the coming years. In the field of aeronautics, polymer materials are also widely used to make cables and PCBs protection etc. For such applications, we have to choose the dielectric material by considering its insulation resistance, dielectric strength, loss characteristics and the aging rate over a wide range of environmental conditions. The authors in [19] investigated the dielectric properties of 12 μm thick polyurethane conformal coating. This is one of the highly used materials in aeronautics for the protection of different modules. Such coatings are made to protect PCBs and other related equipment from chemical and environmental hazards such as fuel vapors, oxidative agents, temperature and humidity. Impedance measurement was performed on the test specimen under artificial aging conditions like high temperature, humidity and frequency range from 0.1 to 10 MHz. It was observed that impedance measurement is one of the best methods to test the dielectric materials because it permits the investigation of degradation of polymers in real aeronautics environment by simulating the artificial aging conditions with a better sensibility than infrared methodologies. The author suggests investigation of polyurethane and other organic insulation materials at further higher frequency bands and under different environmental conditions.

The design and fabrication of multilayered, high speed and high density printed circuit boards (PCB) requires the high quality substrate materials. The manufacturers have decreased the pin pitch from 1.27 mm to less than 0.5 mm over the years. Moreover, to use the high temperature soldering processes and multilayered PCBs, there is need for the materials with high glass temperature (Tg) and low thermal expansion coefficient (CTE). In such situation, Thermount and Polyamide are the materials that can replace the glass epoxy composite laminate, FR-4 which was previously used as a substrate in the manufacturing of PCBs. Thermount has several performance benefits over the standard materials: low CTE, high *Tg*, low dielectric constant, dimensional stability along with the benefit that it enables high speed laser microvia formation, however it absorbs more moisture than FR-4 when subjected to high humidity and that could severely affect its electrical properties. Similarly, Polyamide also provides certain benefits: low *z*-axis CTE, high *Tg* but similar to Thermount, it also absorbs more moisture when exposed to high humidity. The electrical properties of these materials are guaranteed under the standard normal conditions but they can be affected severely when exposed to a single or the combination of different environmental factors, therefore, A. Bulletti et al. in [20] investigated the surface resistivity (*Rs*) of these base laminates (epoxy, thermount, polyamide) when they are subjected to the certain environmental factors like relative humidity, temperature, solder flux contaminations, corona discharges and outgassing phenomenon in vacuum and concluded that surface resistivity of polyamide PCB is slightly higher than those for epoxy and thermount PCBs, however when these boards were subjected to humidity and then dried, there was no change in surface resistivity. Exposure to vacuum slightly increased the *Rs* of polyamide but has little effect on thermount and epoxy. When these boards were subjected to flux contamination and then passed through standard cleaning, there came a large drop in the surface resistivity which indicates that these boards absorb ionic matter from the flux. Hence the author concluded that flux contaminations should always be removed and it is essential to bake the boards to expel moisture that would have been absorbed by board substrates during cleaning procedure.

## 8. POWER SUPPLIES WITH HIGH INSULATION CAPABILITY TO BE USED IN ELECTRONICS

In the Medium Voltage (1 kV to 36 kV) power distribution market, the need for the smart intelligent control systems, sensors, actuators and communication equipment is growing fast. These applications are usually located on the high voltage potential side and can be supplied with an auxiliary power of few watts or less. This auxiliary power requires the need of a power supply that is able to handle a very high input voltage. Hence to feed the electronics on the high potential side of MV distribution lines, the major challenge is to achieve high partial discharge voltage which has to be above the operational voltage of the insulation devices. Moreover, a low leakage current through the connection has to be ensured under steep transients and a low coupling capacitance is necessary. To fulfill these requirements, a low volume, resonant switch mode power supply with special transformer design has been proposed by L. Heinemann, J. Mast, and G. Scheible in [21] by making the use of parasitic elements of transformer as resonant elements. The electrical properties of the transformer like leakage inductance, magnetizing inductance, coupling coefficients and winding losses etc. are mainly dominated by parasitic elements which mean that if the transformer is operated in the conventional switched mode power supply, then only a low power transfer is possible. Therefore, in order to transfer significant amount of power using transformer, the leakage inductances have to be compensated for using the series of connected capacitances. For simplicity, a power circuit similar to class E-converter was chosen. To keep the leakage inductances and compensation capacitors close to resonance despite of component tolerances, the control circuit must be able to adjust the switching frequency. As obvious from the above discussion that the main element of the proposed MV-isolating DC-DC converter described is the high frequency transformer with high insulation voltage, low coupling capacitance, excellent mechanical properties and low volume along with simple manufacturing process. The transformer simply consists of simple distributed windings. The electric field in the transformer is controlled by simple insulation section in order to achieve a higher insulation capability and low coupling capacitance. Moreover, the transformer is encapsulated with epoxy that serves as a simple epoxy block for the primary and secondary sided terminals to connect to the electronics. The power supply thus presented is able to transfer 2.5 W over an isolation barrier usually required for MV electrical power distribution. It guarantees a partial discharge free insulation voltage of more than 50 kV along with insulation test voltage of more than 80 kV.

## 9. INSULATION FAILURE IN ELECTRICAL CONNECTORS

Connectors play a vital role in all electrical and electronic systems. The two important factors which dictate the functioning of the connector or contact are resistance and insulation between different contact points. The minimization of contact resistance is usually investigated by a lot of manufacturers in order to make their product reliable. However research on failure of insulation within a connection is very limited. Xin Xi Zhang, Kun Li, and Jun Xu [22] investigated failure modeling of insulation in a connector and its effect on signal transmission. The main aim of this research was to investigate the insulation strength between two contacts in one part of a connector in presence of water. The surface of contact was covered with a thin layer of water and salt in order to simulate the pollutants encountered in harsh service environments. It was observed that a leakage current is setup between the two contacts which affects the low voltage signal being carried in that contact. It was observed in this research that smaller the insulation resistance between two contacts, greater the voltage drop and distortion of signal. This distortion also effects the adjacent contacts in terms of interference generated towards them.

## 10. DEGRADATION OF INSULATION MATERIALS

Accumulation of water on insulations is more damaging as compared to the effects of high humidity in the atmosphere. Degradation of electrical insulation and coatings in presence of moisture greatly increases. The situation is worst in case of marine environment where salt particles get deposited on the surface of insulator. H. R. Baker and R. N. Bolster [23] studied the effect of moisture on insulation material and measured the surface resistivity. Hydrophilic substances are more prone to degradation as they allow water to make contact with themselves. But in case of hydrophobic materials, they don’t allow water to make contact hence water doesn’t forms a continuous film. Hydrophobic materials are less vulnerable to surface degradation and have higher surface resistivity as compared to hydrophilic materials. Due to high contact angles, lesser area of insulator is covered by water hence small leakage current will flow. By increasing the roughness of material, the hydrophobicity property of material can be increased. More hydrophobic surfaces show lesser surface resistivity.

A. Brockschmidt [24] has listed the factors which cause the degradation and breakdown of insulation material in power electronics; these key factors include corona, heat and harmonics. In this particular paper the effects of corona are discussed in detail. Corona is a state in which an insulation gas is just before its breakdown point. Failure of capacitors filled with liquid impregnation has been reported in literature. An idea proposed to prevent failure from corona was manufacturing and use of ovular capacitors. Transformers that are not properly designed experience corona at high voltage peaks or altitude between windings. Electric field cause ionization of gases and thus accelerates the electrons of ionized gases. Acceleration of electrons results in formation of more photons due to frequent collision of electrons with gas particles. Recombination of electrons with positive ions is faster in case of light or low electric field then in case of high electric field. Electrons continuously recombine with ions at anode side thus resulting in glow as neon lamp. Recombination of electrons with positive ions also generates electromagnetic interference. Large number of gases is used to prevent from breakdown but $SF_6$ has higher breakdown and corona voltage then other gases. Corona effect varies from DC to various AC frequencies. Lifetime and reliability of insulation in power electronic circuits is highly dependent upon the switching frequencies, corona inception voltages and corona extinction voltages.

Modern high power electronic uses thin dielectric insulation. Insulation material fails with passage of time under certain specific conditions. The cause of failure could high voltage and high frequency transient. These factors cause breakdown of materials. W.J. Sarjeant [25] has discussed in detail the factors that cause the degradation of insulation materials used in modern power electronics. Author highlights the processes which lead to breakdown. The dielectric insulation material under consideration is polypropylene (PP) because of low power dissipation and broad applications. A number of life tests were performed at different voltages and different repetition rates to measure the number of pulses that cause on failure of PP film. High voltage pulse causes the breakdown of air which in turn damage the surface of insulation material leading to the failure of material.

The need of Power electronic devices for conversion between AC and DC waveforms becomes clear in modern power grids. The switching between AC and DC waveforms results in repetitive transients which reduces the lifetime of insulation. Repetitive transients have high slew rate, high repetition frequency and high magnitudes. Each of these have drastic effect on lifetime of insulation. J.J. Smit [26] addressed the effect of repetition frequency on life time of insulation. Author used oil impregnated paper as test sample. MOSFET was used for switching. A number of life tests were performed by varying the repetition frequency between 1 KHz and 10 KHz. The results show that the degradation of paper increases with increase in AC voltage magnitude. As the frequency of transients increases, deterioration of paper increases. This decrease in life time of paper occurs as a result of faster deprivation of dielectric properties of cellulose. When high frequency is applied to paper, the cellulose molecules aligned themselves according to polarity. The molecules re-aligned themselves as the polarity changes. This will create a free space around molecules in which molecules can move freely until break down occur. Higher the rate of polarization, lower the life time of insulation. Heat is another factor causing the degradation of insulation.

## 11. TESTS AND INSTRUMENTS TO MEASURE INSULATION QUALITY

Harmonization of multiple standards is the need of hour because testing of materials, components and equipment according to multiple standard increases the cost and time delay which is not desirable in industry. Harmonization is a step by step procedure which includes categorizing standards of same scope, comparison of test procedures, pointing out the differences, resolving the differences by agreeing on same contract and identifying the remaining differences if any.

R.F. Weddleton and coworkers [27] has presented a comprehensive overview of the efforts of IEEE standards Coordinating Committee 4 (SSC 4) to harmonize electrical insulation test procedures and standards between IEEE and IEC. The aim of this effort is to write IEEE standards as international standards so that these standards are accepted as IEC standards. SSC 4 works by developing a harmonization strategy after comparing IEEE electrical insulation standards with IEC standards.

Harmonization can be achieved using several routes depending upon goal for harmonization.

Two goals are discussed in the paper

1. Keeping both IEEE and IEC standards. Identifying the similarities and differences between them. Testing is required twice only for non-common areas.
2. Having a single standard.

After setting the goal for harmonization, next step is to choose the route through which harmonization is attained. Two of which are conferred in the paper.

- Comparing scope, test procedures, units of measure etc. of both standards, identifying the difference and resolve the differences by selecting the better one.

· Choosing one of the standard for fixed time period.

Authors of the paper compared ANSI/IEEE-1-1986 "General principles for temperature limits in the rating of electric equipment and for evaluation of electrical insulation" with IEC 85-1984 "thermal evaluation and classification of electrical insulation". And the areas with non-common points were addressed. Author suggests that a lot of efforts are required to harmonize different standards into a single set of standards. In order to achieve this goal industry support through participation in standard laying committee like IEEE, IEC and ASTM is mandatory.

Surface Insulation Resistance (SIR) is an important property of any insulation material. It represents the resistance between two electrical conductors separated by some dielectric material. SIR testing is usually done by exposing the material under test to artificial aging conditions. This test is basically performed on different insulation materials to find out their long term reliability and that whether the material, when used in an assembly would produce the unacceptable amount of leakage currents. M.Pantazica et al. in [28] carried out the experiment to determine the effects of protective coating on the SIR of the specially designed printed circuit boards with laminate FR-4 epoxy glass. These boards were coated with five different types of solder pastes and then the measurements of SIR were made after exposing them to the artificial aging conditions. The results showed that the average SIR for the coated board dropped to 48% of the initial value while the average SIR for the uncoated board dropped to nearly 35% of its initial value, therefore it can be concluded that coating is bringing obvious improvement in the values of SIR.

Insulation thickness is an important factor in the servicing and manufacturing of electrical devices and components, that is why it is needed to measure the insulation thickness accurately and with high precision. Therefore, J.H.S.R. De Silva in [29] describes the working and design of an efficient, user-friendly and cost effective length measuring tool named "Smart Logger". This instrument consists of three parts namely digital micrometer, auto tool and processing unit. This instrument can be used to measure the curvature of arcs, spherical surfaces along with the small lengths conventionally measured by a micrometer screw gauge. The processing unit is the most important part of the Smart Logger which handles all its functions. It has a digital display from where readings can be directly read along with the keypad and memory to store the measurements. Smart Logger 2.0 is the software, designed using the Microsoft Visual Basic 6.0 software and it has the capability to be connected with computer through serial port as well as it has the extra advantage to be connected with any length-measuring device such as calipers and traveling microscopes without concerning about the least measurements and coincided amounts.

There are various standard test procedures available for evaluation of electronic power transformer insulation. Most popular among them are listed by IEEE 350 hours, 1000 hours, 3000 hours, 5000 hours multi-stress tests . Most of these tests are based on accelerated thermal aging. There are certain drawbacks in some standard test procedures like recommended test temperature often exceeds the chemical stability temperature of various components inside that transformer. Some test techniques produce severe gassing of water vapors due to elevated temperature which otherwise would never be encountered in real service of that transformer.

E.N. Henry [30] has presented a detailed overview of different test methods used for evaluation of electronic power transformer insulation. Author highlights special precautions and procedures which must be considered during accelerated thermal evaluation of power transformer insulation.

Various test procedures proposed by IEEE standard test guidelines for insulation have been discussed in detail in this study along with the limitation put by each test on the system. All the units which failed before 50 hours of operation had many common phenomenon occurring in them. For example, failure was originated in hotspot area in most of the cases. There was mechanical damage due to gas pressure in all the cases. Failure was always accompanied with splitting of encapsulation with corresponding gas oozing. Excessive heat, turn to turn insulation failure and coil to coil insulation failure was observed in most of the samples. Cellulose insulation transformer generates water due to chemical breakdown under normal conditions. Therefore, applying IEEE test procedures without preconditioning causes premature failure in sealed electronic power transformer. So the test will depict an unrealistic evaluation of insulation. In lieu of this fact it is recommended that before accelerated thermal evaluation of any electronic power transformer insulation following factors must be kept in mind.

1. In first 80 hours of operation transformer should be operated with minimum start up voltage with resistive load only which circulated load current without saturation. This will ensure dryness before any further tests.
2. After 80 hours of operation water escape path should be sealed in order to avoid any further moisture absorption from air.

Results of any tests conducted after this 80 hours drying procedure should still not be used for direct assessment of insulation life. Rather it should be critically analyzed to compare the performance of test specimen with those used in actual service. Insulation systems without cellulose may not require the above set of procedures but it may require certain other precautions for its realistic evaluation. So a lot of investigation is needed for other kinds of insulation systems in order to develop a set of procedures which can realistically evaluate these systems.

Ungrounded insulated terrestrial power networks have floating live and neutral. If any of the phase gets shorted i.e. first fault occurs no hazardous current will flow through it. Capacitive coupling to ground occurs in the case. Usually the amount of current flowing due to first fault is not very large so do not activate circuit breakers and system remains functional. If second fault occurs large current flows and system has to be turned off by a fuse or circuit breaker. The currents due too first fault needed to be measured so that it can be corrected before second fault. P. V. Vugt and coworkers [31] in this paper have explained certain insulation monitoring devices. A device needs to be installed to detect the insulation fault IMD- Insulation Monitoring Device or PIM- Power Insulation Monitor. There are three methods for capacitance handling. First being DC method that cannot handle more capacitance. DC method uses a DC voltage that is injected into the phase and then the current that is returned through ground is measured. Second is Pulse measurement method has limited capacity of handling capacitance but has disadvantage of too long detection times. Pulse measurement method uses pulses of positive and negative voltages. Third is AMP Adaptive Measuring Pulse measurement method adapts the length of pulse due to changing RC and it can handle more capacitance and detects fault on time.

## 12. DISCUSSION

Main motives towards evolution of power electronic devices are to increase the reliability, thermal and electrical performances by achieving hybrid integration. Parylene is a chemical vapor deposited polyxylylene polymers. Parylene conformal coating is used for protection of devices, components and surfaces. Nano fillers have a great impact on dielectric properties of polyimides. Epoxy layered silicate nano-composite has better insulation properties. Epoxy resins are also considered excellent electrical insulators with good thermal and mechanical properties and are used in the insulation of heavy electrical equipment like transformers, current transformers etc. However, it is observed that the epoxy resins made by adding fillers (like Aluminum Nitride) have better thermal stability than the simple epoxy resins.

Wide range of insulation materials are known like Parylene conformal coating, PEN, polyimide nano composites, epoxy layered silicate nano composites etc. PEN- polyethylene 2-6 Naphthalene Di-carboxylate a member of thermoplastics has the properties of mechanical and thermal resistance along with dielectric and insulating characteristics. Nano composites are multiphase solid material where one of phases has 1, 2 or 3 dimensions of less than 100 mm polymer nano composites are 2$^{nd}$ generation of filled resins i.e. it consists of polymers filled with large amount of micron sized in organic fillers.

Surface electrical leakage on insulations and coatings in the presence of moisture condensation greatly deteriorates the material. Accumulation of water on insulations is more damaging as compared to the effects of high humidity in the atmosphere.

Connectors are one of the basic component of electrical and electronic systems. Major factor that degrade the functionality of contacts are insulation and resistance between contacts. Leakage current gets established between two contacts and effects the low voltage signal being carried out in that contact.

Low and high frequency harmonics, non-sinusoidal voltages at network and load side results in significant reduction of insulation life time. Another major reason of degradation of insulation material is extensive use of PEC and ASD. Power convertors made up of SCR has been replaced by BJT. PEC made up of BJTs has improved the stability and reliability.

For any reliable system, system must be isolated from ground. So, a first fault do not results in tripping or interruption. Maximum allowed capacitance to ground is the disadvantage as the detection of first fault to ground is obstructed by these capacitances. For this purpose, Insulation Monitoring Device and Adaptive Measuring Pulse measurement AMP methods are used.

Many tools are being developed to measure the thickness of the insulations to a greater precision and to ensure its reliability and strength under extreme situations. Moreover, work is also being done to develop high quality substrate materials for use in the PCBs besides commonly used material epoxy to support much higher frequencies and clock speeds. In this scenario, Thermount and Polyamide are the two materials that appear to be a better choice for such applications and provide low CTE, high $T_g$ and low dielectric constant along with many other added benefits.

PD is another major factor that results in degradation of insulation material. PD activity highly damage the organic insulated motors whereas motors having composite organic/inorganic insulation have the capability to withstand high PD activity.

Earlier wire splices without insulation or tapped were used, later sealed splices were used but now Gel shows great insulating property.

## 13. CONCLUSION

Distorted waveforms magnitude, harmonics, over voltages because of resonance, impedance mismatch, repetition rate, slew rate, polarization and uneven potential distribution play important role in degradation of insulation reliability, quality and lifetime and causes increased electrical and thermal stress on insulation systems and increased dielectric and joule losses and operating temperature. Increase in electric stress and PD is the main cause of accelerated insulation degradation. Life time of insulation material is directly related to the degradation dielectric properties of material.

Power electronics devices have a higher trend towards integration and increase in density nowadays. Different insulation materials with different characteristics are known nowadays. Presence of moisture and accumulation of water greatly affects these insulation materials.

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