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Parametric change in Insulation Resistance and Breakdown Voltage of Underground PVC Cables under Accelerated Multistress Aging Conditions

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Abstract- **PVC is widely used as an electrical insulation for low-voltage indoor wiring and underground cabling. These cables are attacked by contaminants and chemicals present in the soil. The elevated temperatures and pressures inside the soil also adds up to stresses and deteriorates their insulations and sheaths and this eventually goes on damaging the conductors. So their performance in the contaminated service environment should be investigated considering extreme conditions in order to predict and ensure reliable service life. In this research 4 different PVC cable samples (2 core 10 mm^2, 4 core 10 mm^2, 4 core 120 mm^2 and 4 core 240 mm^2) were subjected to mechanical (via small punches), thermal, chemical and electrical stress over each core of the cable. Electrical stress was applied with 1 kV AC transformer. These samples were aged for 1000 hours under International Electrotechnical Commission (IEC) 1000 hours multistress aging conditions. Visual inspection and electrical characterization was done by Breakdown Voltage and Insulation Resistance Test for insulation and sheath at different intervals to investigate early stage degradation and reduction in lifetime. The results were compared with the characterizations already reported in the literature. Physical appearance and chemical degradations were apparent from the visual inspection of end aged samples. Quantitatively the results also indicated the continual decline in the breakdown voltage and insulation resistance over the aging time. Our findings inferred that the depreciation in quality of PVC cables (insulations and sheaths) is likely due to the chemical stresses which also instigates all other stresses.**

Index Terms-- **1000 Hours Multistress Aging, Breakdown Voltage, Insulation Resistance, PVC Cables, Visual Inspection**

I. INTRODUCTION

Over the last 2 decades there has been a significant increase in the use of underground supply system. Although they are little too expensive and complex as compared to the overhead but there are certain factors which encourage the installation of such cables [1]. Having underground cables lied beneath the ground in the tunnel it avoids human contact and prevents any electric shock and arcs. Underground cables are more durable as they are least effected by any environmental and external mechanical stresses. These cables are most suitable for the supply of electricity to high rise buildings, hotels, universities, factories, and Government Departments [2]. In developed countries such cables are also used for long distribution and transmission but they are not recommended to operate above 66 kV because of economic constraints and insulation difficulties [3]. Underground system has become a matter of interest especially in congested urban areas where it is made free of any kind of interruptions out of environmental havocs (i.e. lightings, thunderstorms, strong winds, etc.). These cables have several layers of protection for pure conductor starting from insulation, PVC Sheath, armoring and over sheath (for Armored Cables) [4]. Such a cable would have an extended lifetime, protection, elastic modulus and maximum electrical conductance but it’s capital cost accumulates to the outstanding price of 3 to 4 times more than that of overhead system, however its operating and maintenance costs are comparatively lower to overhead system [5].

Every insulation has its own advantages and drawbacks when it comes to underground cable insulation therefore no insulating material possesses all recommended qualities. Selection of cable is totally dependent on the condition on which it is going to be installed incorporating all the above factors beholding economical perspective and electrical stress range [6]. But due to the presence of contaminants in the surrounding of a chemically active soil inside the earth these cables insulation are readily attacked by chemicals (moisture, salts, acids, alkalis, etc.) with high temperature and pressure deteriorating their sheath and core insulation. This deterioration of insulation causes leakage current and electrical discharges and then eventually would run on damaging the conductors [7]. All these factors cause the physical and chemical changes in the insulation material. However the change in electrical properties is the most important one as these cables are used underground in low-medium voltage distribution [8]. So for a long term investigation on their performance in service environment should be carried out to estimate their lifetime considering extreme conditions. Proposed research is aimed towards the accelerated aging of PVC Insulated cables in a multistress environment and enquiring into the parametric changes occurred in its insulation resistance and breakdown voltage characteristics. Visual observation has also undertaken for each cable to monitor the physical changes over different time intervals due to thermo-chemical stresses.

A. PHYSICAL AND CHEMICAL PROPERTIES OF PVC

PVC is a thermoplastic synthetic compound made by the polymerization of a powdered form of acetylene. It is a polymer of vinyl chloride monomer. Its properties are such that it can be used both as cable jacketing and wire insulation in general to insulate the cables. There are two main types of PVC insulated cables; PVC insulated power cables and PVC insulated sheath cable [9]. Some of the PVC properties identified by researchers are:

- PVC exhibits good resistance to UV radiation, water, and inertness to other chemicals (acids, alcohols, alkalis, etc.) that makes it durable.
- It has a good dielectric strength (40 kV/mm for Rigid PVC).
- It is highly flexible and is oil and flame retardant [10].
- PVC is economical and it has notable aging properties that exceeds its age by 25 – 30 years of service life.
- It has a maximum operating temperature rating of 85°C but with some compounds it can sustain from -45°C to 105°C temperature.

With its exceptional withstanding capabilities it has now almost completely taken the place of rubber and paper insulation range up to 1 kV. Although it is lightweight and easier to shape with a tolerable flexibility range but still there is minimum bending radius of 8D (according to standard IEC 60227) [11] which shouldn't be violated taking in consideration a longer run life. PVC insulated cables and sheaths have low corona resistance that's why it is best suited preferably for low voltage or for the medium voltage stresses. Furthermore it can be cut, plastic-welded and reshaped without any curtailment in its lifetime [12]. To enhance its various properties it has to be modified with the fillers (i.e. $CaCO_3$), plasticizers (i.e. 30% DOP: that makes a gel), lubricants and other ingredients. Stabilizers (i.e. lead stearate) in PVC prevents thermal and chemical degradation to a great magnitude and counteract cracks formation. With these additives now they have become suitable to be used as an insulating material in underground cables. Decreased amount of plasticizers inflict hardness in the PVC so that it can be used for wire covering, sheaths, for railway vehicles exterior, etc. [13].

Every insulation and sheathing industry put into effect some important physical properties including: Tensile Strength (N/mm^2), Specific Gravity (gm/cm^3), Insulation Resistance (Ω), Volume Resistivity (Ohm. m), Elongation at Break (% EAB), Loss of Mass (mg/cm^2) etc. [14]. PVC/PVC cables have an insulation and sheath both of PVC but sheath material is a recycled PVC. Most commonly used PVC cables are manufactured for low voltage 0.6/1 kV range starting from 1 core to 5 cores generally [15].

II. PREVIOUS RESEARCH

PVC is used currently in lots of engineering applications. Low and medium voltage underground PVC cables insulations are exposed to various stresses like chemical, mechanical, ultraviolet, thermal, etc. that brought about the degradation of these cables. Researchers in recent times has adopted natural aging methods alongwith several combinations of these stresses to tune with the soil environment. A great amount of research has been done on the natural and early stage accelerated aging of PVC polymer. Some of the studies has shown various PVC physical and mechanical parameters variation to observe the aging effects. These researchers have adopted many quantitative and qualitative techniques based upon the nature of aging. Various researches on field and laboratory aging of PVC and other polymers have recorded and compared the effects of natural / accelerated degradation on the Dielectric strength and IR values of PVC polymer.

Some earlier studies has made known the process involved in the thermal degradation of PVC as: Dehydrochlorination, loss of plasticizers, and oxidation [16] leading to current leakage between cores [17] and eventual failure. Any degradation is more remarkable for samples those are buried in the shallow places. In [18] six different polymers that had been buried under soil for 32 years, has induced a great amount of biodegradation. Natural aging of plasticized PVC for 15 – 30 years has shown a considerable loss of mass and additives in a process called photo-aging. TGA, UV spectrophotometry, and chromatography analysis has graphically shown the loss of plasticizers and dehydrochlorination [19]. If the aging is done in low temperatures either natural or controlled environment then the predominant process of accelerated aging is mass loss. Shrinking, mass loss and discoloration after aging was observed because of two degradation stages: loss of plasticizer at early stage and the progressive loss of stabilizers at the prolonged time followed by discoloration and HCl emission. Mechanical precautions must be attentively done during handling to protect the sheath and to reduce the intermittent faults. Reasons are the eroded cables and the accumulation of dust and particles in the duct and over the cable makes a conductive path in the presence of humidity and start producing arcing currents that can even reach tens of amperes. This arc can be produced inside or outside of the cable core [20] and this short term overload bring forth the increase in temperature of core insulation [21]. Thermal degradation is carried out owing to the combined process of heat and light in the presence of oxygen but it can only be made faster with temperature rise [22]. As proven from this research that plasticizer are evaporated at the start of degradation process and to the mass loss of stabilizers and change in color. At the next step HCl starts releasing from it in a process called dehydrochlorination or pyrolysis and the samples starts getting shrinked and cross-linked [23].

In 2000, Mihai Brebu et al. [24] addressed the characterization of high voltage cable insulation waste and jacket (PVC 0.6/1 kV) and are naturally aged for 18 years were grounded by cryogenic procedures. The base polymer and extracts were analyzed by elemental analysis, GPC, viscometry, IR and 1H-NMR spectroscopy, TG, DSC, and several standard methods which indicated that only 2 wt% of plasticizer was lost during natural aging and obtained a thermal stability order: PVC waste jacket < PVC cable insulation < virgin PVC < PVC cable formulation. Plucking out of plasticizers is an indication of reduction in insulation resistance, loss factor, dissipation factor, permittivity and increase of AC volume resistivity confirmed by the discoloration and stiffness of samples. Durability and reliability of cable insulation will get decreased as it depends on all of these factors [25]. Induced Current method uses these physical properties variations while thermal degradation characterizes the dielectric properties of electrical insulation [26]. Voltage response method can also measure the dielectric strength. In 2009, Tamus et al. [27] studied that the steepness of decay voltage for PVC and PE increases with the thermal aging and is proportional to conductivity of insulation.

Aged PVC samples for 6.6 kV in a frequency range of 1 mHz to 1 kHz shows a resistive behavior and conductivities are high due to the accumulation of charges in insulation so that polarization also increases as shown by IR micro-spectroscopy, DSC and TMA [28]. It is natural that in a wet environment sheath get damaged because of high temperature and other penetrations. Moisture starts rinsing into the core which starts the lower level transients with the increase of temperature. Current reaches 10 mA and with the sudden increase of temperature these discharges reaches level of sporadic discharges in days and then into intermittent arcs within hours to cross 100 mA just before an ultimate breakdown of cable. So gradual increase of temperature could curtail this arcing phenomenon inside the core [29].

Any loose connection of Cu/Al conductors can also put on the degradation with overheating and will lead to embrittlement and structural loss of PVC insulation. Chemically active soil with sulfate ions also lead to degradation alongwith the thermal stresses [17]. Lifetimes of insulation deteriorated significantly because of thermal stress and even other stresses are related proportionally with it [30] so much that for every 10°C rise in temperature causes a reduction in lifetime to half. There is another degradation because of the manufacturing problems which would not directly degrade the polymer rather its poor IR of 50 MΩ.km before installation and 0.6 – 2.73 MΩ.km after installation measured by parallel electrical, mechanical and chemical examinations causes this rapid degradation. Compound with low stabilizers content proved to be the major degradation parameter for polymers [31]. These parallel methods are somehow more accurate and precise when one of them is used [32].

In 2015, Pierre Quennehen et al [33] dissected different decreases of electrical resistivity by setting out two set of single core cables with PVC insulation and by virtue of which they determine the aging mechanism responsible for this decrease of electrical properties. In 2017, Paula Magioni et al [34] concludes that aging index, a low-cost test, to evaluate the thermal degradation of LV electrical cables insulated by PVC. They determined eight consecutive aging cycles of 16 days (400 hours). In the experiment PVC insulated LV cables, copper conductors, 4 mm^2 cross section, 750 V voltage class, 70°C temperature class is assessed to evaluate their degradation. In 2020, Y. Koga et al., [35] the authors applied the SP test to evaluate the validity of SP test for PVC cables lifetime prediction. The degradation of PVC resin was analyzed using Fourier Transform – Infrared Spectroscopy (FT-IR), Tensile Testing, and SP Testing. The activation energies and estimated lifetime obtained from the Arrhenius method were compared. The activation energy obtained from the apparent elastic modulus using SP testing was the smallest and the predicted lifetime was the shortest (390 years) of all mechanical properties. SP test came out to be an excellent minimally destructive lifetime prediction method that can estimate early deterioration [6]. In 2019, Koga Yasutomo et al. [36] analyzed chemical changes observed in PVC cables via SP test and made the correlation with IR. They employed Size Exclusion Chromatography (SEC) to analyze molecular weight change for each aging time thereby analyzed chemical structure by FT-IR which shows how polymer chains are cut based on IR result. Experimental results concluded that the molecular weight change affects the mechanical properties of PVC by SP test irrespective of its effectiveness in evaluating residual life predictions having its damage modeling.

In this research the unarmored PVC insulated cables were stressed in an accelerated multistress environment for 1000 hours under International Electrotechnical Commission (IEC) 1000 hours multi stress aging conditions divided into 7 cycles (summer and winter) to bring about the early aging of insulation. It was visually observed at various aging times to study the major influencing factors behind every apparent and physical changes. Its dielectric properties and insulation state was assessed and characterized with insulation breakdown test and HVDC Megger test respectively. These tests results were compared with the characterizations already reported in the literature to estimate the performance of these cables.

A. REQUIREMENTS FOR A CABLE INSULATION

Some of the main requirements of the insulating materials used for the cable are that it should sustain severe acid and alkalis attacks for extended temperature range (i.e. 15°C to 95°C). To avoid the leakage current it must have high IR and this high resistance will be having high dielectric strength that would help to avoid electrical breakdown. Environment under the ground is very humid and has high level of moisture content. Underground cables are very much prone to different concentrations of soil and varying degrees of humidity the entire time so their insulation must have to be non-hygroscopic as DS deteriorates with increase of moisture content (in that case sheath covering with excellent elasticity and temperature resistance is preferred to enfold the insulation). Other recommended features for an underground cable insulation is to be non-inflammable, chemical, heat and pressure resistant, capable of withstanding high rupture voltages and made up of a material with high Tensile Strength, low permittivity and low coefficient of thermal expansion.

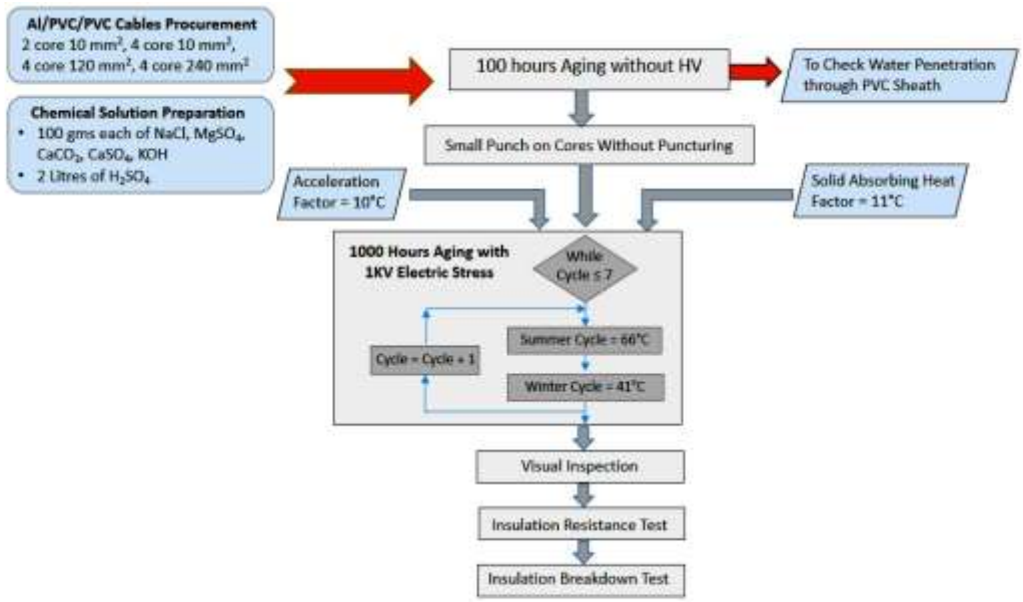


FIGURE 1. Flow Chart of the whole scheme of Aging and Characterization

III. METHODOLOGY

This study was focused on the electrical and chemical characterization of different PVC Cables. Four different Al/PVC/PVC cables samples were laboratory aged and then their degradation (after every cycle) was compared with the virgin samples and the characterizations already reported in the literature. The procedure adopted is shown in figure 1. Four unarmored PVC cables (i.e. 2 core 10 mm^2, 4 core 10 mm^2, 4 core 120 mm^2 and 4 core 240 mm^2) of similar lengths were procured. Several chemicals were acquired (i.e. salts, acid and alkalis) for the application of chemical stress and small punches were applied to mechanically stress the insulation without puncturing. The study was first carried out with 100 hours aging (to notice the quantity of water penetration) followed by the 1000 Hours aging in multistress environmental chamber. These cables were exerted with a continuous effect of electrical, thermal, mechanical and chemical stresses during this 1000 hours aging period. Parametric changes are characterized by qualitative and quantitative techniques during each aging cycle to find the end results.

IV. EXPERIMENTAL SETUP

Experimental setup consisted of four environmental chambers made with HDPE Pipes in order to completely immerse the cable samples under investigation. Aging started with 100 hours aging to check the water penetration which was an important step to see any perforations and to assure the quality of PVC sheath against the applied electrical and thermal stresses. After this time PVC insulations were exposed to measure the amount of water seepage and then small punches were carefully applied all over the cores of insulation to provide mechanical stress without damaging it. These cables were then immersed in these HDPE chambers with their conductor edges evicted out of pierced holes. Measured holes must be created according to the diameter of cable to leave no vacant space for the discharge of gases. The immersed cables samples were chemically stressed with the solution consisting of various chemicals dissolved in the water to make a real life situation encountered in underground cables. One end of the conductor of each cable was connected to 1 kV HVAC by a step up transformer to provide them with electrical stresses. Thermal stress was applied with the electrolysis powered with 220 VAC across the Stainless Steel (SS) electrodes and the chemical solution acted as an electrolyte. In each chamber the electric thermostats and 4 A circuit breakers were connected in series with electrodes to maintain the temperature to a specified limit. These samples were then aged for 1000 hours multi-stress aging conditions divided into 7 cycles (categorized into alternate summer and winter cycles). 11°C rise in temperature was added to cater the effect of heat trapped by solid and additional 10°C was added to accelerate the aging up to 18 times in both cycles. During the multistress aging, all the samples of these cables were taken after each cycle and then analyzed by different techniques.

A. MATERIALS AND METHODS

SELECTION OF CABLES AND HDPE PIPES

Field aging requires the underground installation of cables to comply with all insulation layers for a HV setup to lay them down beneath the middle of sand bed of the trench. But in a LV case there is a 2 layer insulation comprising core and outer sheath. In low voltage case (below 11 kV) these cables are laid directly into the soil or inside an RCC/PVC pipe. In this laboratory aging experiment unarmored PVC insulated cables of different dimensions were taken each of similar length. For applying stress and to properly examine and characterize the core insulation, the cables selected were unarmored Al/PVC/PVC. Based on the literature review, in experiments with high temperatures and vigorous chemicals the polymer must have to be contained in a chamber that is both mechanically stiff and lightweight and it also exhibits greater resistance against concentrated salts, acids, alkalis and hydrocarbons [37]. It should sustain high pressure without breaking or bursting. So the four chambers made up of 16-PN High Density Polyethylene Pipes (HDPE) pipes were employed with a wall thickness of 4 mm and inner diameter of 5 inches. It has zero leak rate even after jointing and possess all above properties befitted its use in the multistress HV experiment.

UNDERGROUND PVC CABLES – Al CONDUCTOR

Four different Al/PVC/PVC cables were employed as shown in figure 2. These cables have a melting point of 85 – 95°C and a service life of 25 – 30 years. Its construction and testing standards are IEC 60228, IEC 60502-1. By its flame retardant property, it follows the standard IEC 60332-1-2 and EN 60332-1-2. Table I shows the cables selected for experiment and their respective properties.

TABLE I
UNDERGROUND PVC CABLES PROPERTIES

Cables	**Voltage Range (kV)**	**Current Capacity (A)**	**Weight Per km (kg/km)**	**Resistance DC (Ω)**	**Resistance AC (Ω)**	**Overall Diameter (mm)**
2 Core 10 mm^2	0.6-1	22	210	1.91	2.45	18.6
4 Core 10 mm^2	0.6-1	19	450	1.91	2.45	21.6
4 Core 120 mm^2	0.6-1	173	2660	0.253	0.325	39.6
4 Core 240 mm^2	0.6-1	300	4750	0.125	0.163	55.1

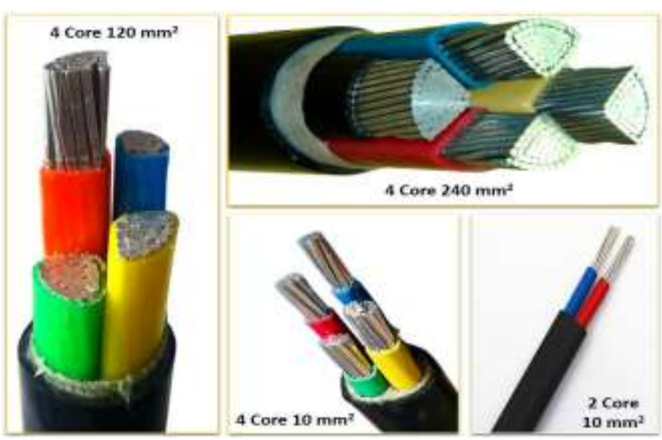


FIGURE 2. 2 core 10 mm^2, 4 core 10 mm^2, 4 core 120 mm^2 and 4 core 240 mm^2 PVC cables

B. CHEMICAL SOLUTION

Generally soil in underground environment is moist and contains acids, alkalis, metallic and non-metallic salts. Metals, non-metals and semiconductors are also present in underground environment (soil). So the selection of chemicals was made by reviewing literature that was focused on the most abundant soil chemicals in various underground environment all over the world [38]–[40]. Furthermore the soil chemicals having the most adverse effect on PVC cables lifetime were chosen to bring about accelerated aging. After reviewing the literature following materials were selected: i) Sodium Chloride (NaCl) ii) Magnesium Sulfate ($MgSO_4$) iii) Calcium Carbonate ($CaCO_3$) iv) Calcium Sulfate ($CaSO_4$) v) Potassium Hydroxide (KOH) and vi) Conc. Sulfuric Acid (H_2SO_4). These chemicals were mixed together in distilled water. Chemical reaction with the presence of heating and electrolysis within the solution produces other products which have their own effects on insulation. In present study a solution of 30 litres was prepared with all of the chemicals mentioned below in the Table II with their specified quantities and concentrations.

TABLE II
SPECIFIED QUANTITIES AND CONCENTRATIONS OF CHEMICALS USED

Sr. No	**Chemicals**	**Solubility (g/100 ml)**	**Density (g/cm^3)**	**Quantity**	**Concentrations**
1	Sodium Chloride (NaCl)	35.7	2.16	100 g	Pure Form (Processed)
2	Magnesium Sulfate ($MgSO_4$)	18.2	1.68	100 g	Hydrated Crystalline
3	Calcium Sulfate ($CaSO_4$)	0.26	2.32	100 g	Anhydrous
4	Calcium Carbonate ($CaCO_3$)	0.013	2.71	100 g	Anhydrous
5	Potassium Hydroxide (KOH)	138.3	2.12	100 g (varying)	50% Conc. Hydrated
6	Sulfuric Acid (H_2SO_4)	232.7	1.84	2 Ltr (varying)	1.835 Specific Gravity 60% Conc.

With the continuous evaporation due to heating and exothermic reactions caused the reduction in sulfuric acid and potassium hydroxide concentrations which subsequently has reduced the stress and electrolytic current so it has to be continuously filled after each cycle to maintain the defined proportion.

C. ACCELERATED AGING AND AGING CYCLES

Aging or accelerated aging is the application of real time aging in aggravated conditions (Sunlight, UV light, thermal stress, electrical stress, chemicals, pressure, punches, vibrations, etc.). Using aging test, expected levels of stress and its effects for a long term can be determined within a shorter time in laboratory. This test is mainly used to observe how a certain product is changing and deteriorating over the time in an expedited manner and is also used to find out the lifetime of a product when actual lifetime is unknown. Accelerated aging should be carried out below glass transition temperature of a polymer. 100 Hours aging and 1000 Hours multistress aging is done for different purposes, explained in sub-sections below.

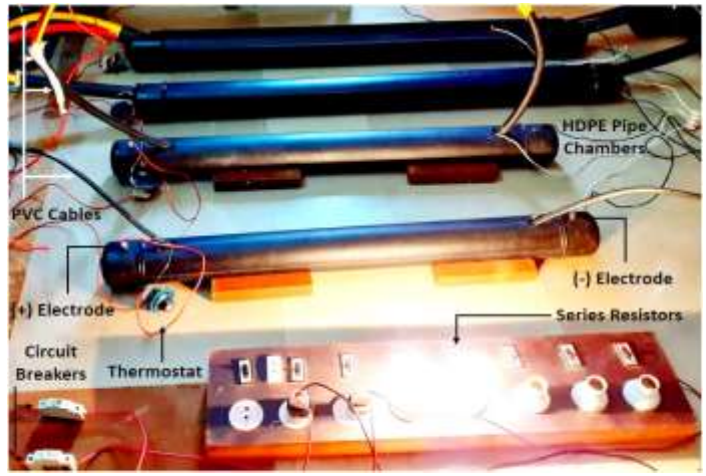
100 HOURS AGING

Before kicking off the Multistress aging experiment it was advisable and appropriate to check the quality of sheath and then the PVC insulation. There are microscopic excavations, small pores and cavities in the sheath membrane that allows the water ingress from sheath to core. The ingress of water into the cabling system can have a serious effect on its electrical and dielectric properties. When the cables got wet, its dielectric performance changes which affects the impedance and the related parameters of LC, modulus of elasticity, TS and service life. Figure 3 shows the conditions of four cables after 100 hours thermal aging in water. All four cables were provided with 220 V electrical stress via unit transformer. In chemical stress only heated water was present at 80°C. Electrolytic heating was also done with a 220 VAC source through SS electrodes and water as an electrolyte to bring down the PVC cable's mechanical, electrical and thermal properties to check the resistivity of sheath. Following is the picture of PVC Sheath cut up parts after 100 hours aging was done. As the sheath is made up of impure / recycled PVC so it has passed much water onto the core for this 100 hours period as shown in figure 3. But PVC core is made up of pure, cavity less and tough PVC material that would not lose its resistivity properties with water and moisture prematurely. On removing these 6 inch sheath window, it can be seen that little amount of water has been seeped through it.

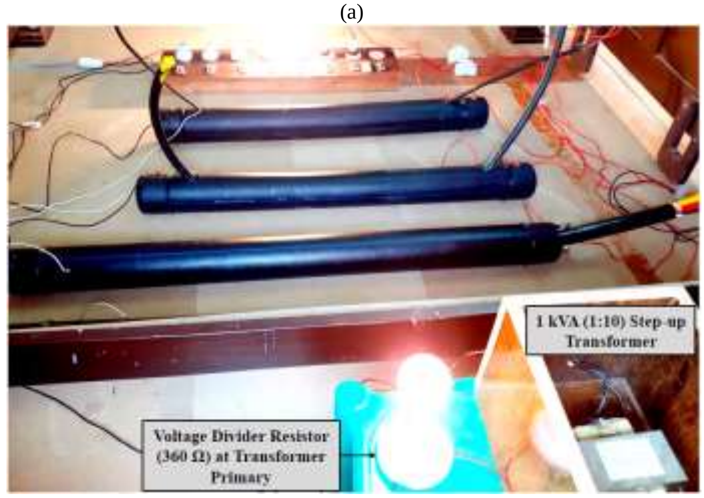
FIGURE 3. Carved out Sheaths window after 100 Hours Aging

MULTISTRESS AGING FOR 1000 HOURS

This is the final Aging setup where four specified cables were aged mechanically, electrically, thermally and chemically. Figure 4(a) reveals the whole experiment including four cables stationed inside the chambers of HDPE pipe. These four cables were inserted inside the pipes in such a fashion that a minimum of 3 feet must be immersed completely into the solution. For a multistress system electrical stress was provided by connecting one end of these cables to the secondary of a High Voltage Transformer. Having divided the voltage by a 360 Ω resistor connected in series with the primary of a (1:10) 1 kVA step-up transformer the output came out to be 1000 V approx. at secondary as shown in figure 4(b). At primary, 0.384 A was flowing but at the secondary all four cables were showing a leakage current of 20 – 30 mA (5 – 7 mA each). In case of any anomaly or overcurrent 2 A circuit breaker was connected in series with the primary alongwith a 360 Ω resistor so that the breaker must trip it within milliseconds. But if CB went faulty then the resistor would play its role by limiting the current to 0.384 A even if transformer secondary connections are shorted. Transformer before use was properly earthed by connecting its body to earth terminal to avoid hazardous situation. This earth connection was also connected to each cable's outer sheath and was dipped in to the solution as well.



(a)



(b)

FIGURE 4. Experimental Setup of 1000 Hours Multistress Aging (a) Front View (b) Transformer Side View

For stressing mechanically these cables were already small punched and also their strain and TS were varied with a little bending within MBR limit. To stress chemically all the pipes were filled with the same concentration of solution as mentioned in section (*chemical solution*). These chemicals responded very differently at higher temperatures w.r.t their resistivity, affinity, reactivity, solubility, etc. Thermal stress was applied via electrolytic heating following 7 cycles comprised of alternate summer (66°C) and winter cycles (41°C) for 42 days with each cycle of 6 days as shown in Table III. Electric Thermostats and 4 A circuit breakers were installed for the protection against over temperature and over current respectively across each chamber. The multistress aging cycle consisting of thermal, mechanical, chemical and electrical stresses is in accordance with IEC 61217, IEC 60507 and IEC 60815 standards. The aging process was implemented for 1000 Hours according to a standard D876-00.

TABLE III
DISTINCTION IN THE PARAMETERS OF SUMMER AND WINTER CYCLES

Entities	Summer Cycle	Winter Cycle
Number of Cycles	4 (Alternate)	3 (Alternate)
Days per Cycle	6	6
Thermal Stress (°C)	66°C	41°C
Temperature Error (°C)	± 4°C	± 2°C
Electric Stress (AC)	1000 V	1000 V
Chemical Stress	$NaCl$, $MgSO_4$, H_2SO_4, KOH, $CaCO_3$, $CaSO_4$	$NaCl$, $MgSO_4$, H_2SO_4, KOH, $CaCO_3$, $CaSO_4$
Small Punches on Core	13 MPa	13 MPa
$H_2SO_4 + H_2O$ Refilling	Twice in each cycle	Once per cycle
Electrodes Rusting	60%	30%
Electrolytic Current (min)	0.8 – 1 A	0.8 – 1 A
Electrolytic Current (max)	1.7 – 2.3 A	1.1 – 1.6 A

V. RESULTS AND DISCUSSIONS

A brief overview of each of the techniques of analysis used in this study is given below. The following parameters were monitored during the experiment.

1. Qualitative Analysis
    a) Visual Inspection
2. Quantitative Analysis
    a) Insulation Resistance Test
    b) Insulation Breakdown Test

A. QUALITATIVE ANALYSIS

TABLE IV
PHYSICAL CHANGES IN PVC INSULATION AND SHEATH

Cables Sample	100 Hours	1000 Hours Multistress Aging						
		1st Cycle	2nd Cycle	3rd Cycle	4th Cycle	5th Cycle	6th Cycle	7th Cycle
INSULATION								
2 Core – 10 mm^2	-	-	D	D	D,H,A	D,H,A,C	D,H,C,A,S	D,H,A,S,T,C
4 Core – 10 mm^2	-	-	D	D	D,H,A	D,H,A,C	D,H,A,C,S	D,T,H,A,S,C
4 Core – 120 mm^2	-	-	D	D	D,H,A	D,H,A	D,H,A,C,S	D,H,A,S,C
4 Core – 240 mm^2	-	-	D	D	D,H,A	D,H,A	D,H,A,S	D,H,A,S
SHEATH								
2 Core – 10 mm^2	D	D	D	D,H	D,H,A	D,H,A,C	H,A,C,S	H,A,S,C
4 Core – 10 mm^2	D	D	D	D,H	D,H,A	D,H,A,C	H,A,C,S	H,A,C,S
4 Core – 120 mm^2	D	D	D	D,H	D,H,A	D,H,A	H,A,S,C	H,A,S,C
4 Core – 240 mm^2	D	D	D	D,H	D,H,A	D,H,A	H,A,S	H,A,S

Note: H: Hardness, D: Discoloration, C: Cracks and Patches, A: Salts Accumulation, S: Sulfur Deposits, T: Torn out

VISUAL INSPECTION

All the PVC insulation and sheath samples were visually inspected during the multistress aging (after every cycle). Physical damages like protrusions, bruises, patches and cracks, chemical damages like discoloration, dryness and salts depositions and thermal changes like volume resistivity, hardness and flexibility all were observed for every aging cycle and compared with each other over the time of 1000 hours. Some major physical, chemical and thermal changes those were observed for the timespan of accelerated multistress aging is shown in Table IV. Discoloration started at the very first cycle with sheath started exuding the blackish green colored mass from its surface. Scraped out samples exhibited the hardness starting after 4^{th} cycle till the end cycle. It is almost 4^{th} cycle after which salts deposition started increasing to both the surface of insulation and sheath because of the voids created out of continuous heating. Sheath of 10 core cables started cracking after 5^{th} cycle and after 6^{th} cycle the hair cracks or trees started appearing on the insulation of all cables and have been cleaving out till then the aging completed except for 240 mm^2. There was a sulfur layer deposition after 6^{th} cycle and at the end of aging it was found that some of the insulations of 10 core were damaged completely and its conductor was almost eaten away by the acidic solution.

Among the insulations the 4 core 10 mm^2 insulation has shown the highest degradation even one of its core was torn out because of much higher LC and the lowest was observed for 240 mm^2 insulation. Among the sheaths the highest degradation was observed for the sheaths of 2 core and 4 core 10 mm^2 cables and the lowest was speculated for 240 mm^2. At the very first cycle of aging discoloration began because of the dehydrochlorination of PVC started at higher temperature which led to the formation of polyene sequences and the bubbling of acetylene and chlorine gases. Other physical and molecular changes observed on the sheath surface was the loss of DOP and migration of plasticizers that could even start at lower temperature (20 – 50°C) which was the main reason of lifetime controlling mechanism. Temperature rise has caused the Young's modulus and activation energies to increase which were the root causes of plasticizer migration. This plasticizer loss was faster for sheath rather than for core insulation. The multistress aging has imparted structural relaxation into the polymer chain via segmental motion in the amorphous region due to variations in glass transition temperature.

Figure 5 and 6 displays the physical demonstration of how all the stresses have imparted changes on the PVC insulation cores and sheaths respectively over the multistress aging stages. Intrinsically because of oxidation, dehydrochlorination and loss of plasticizer insulations lost their tensile strength, flexibility and softness [41]. They went darker and were covered with sulfur and salts deposits. 2 core 10 mm^2 and 4 core 240 mm^2 cables sheath has shown the maximum of these deposits. These figures correlated the picture more accurately such as the virgin samples were clear with no surface damage. 500 hours aged sheaths were covered with a layer of salts such as for 4 core 10 mm^2 and 4 core 240 mm^2 sheaths it became very prominent.

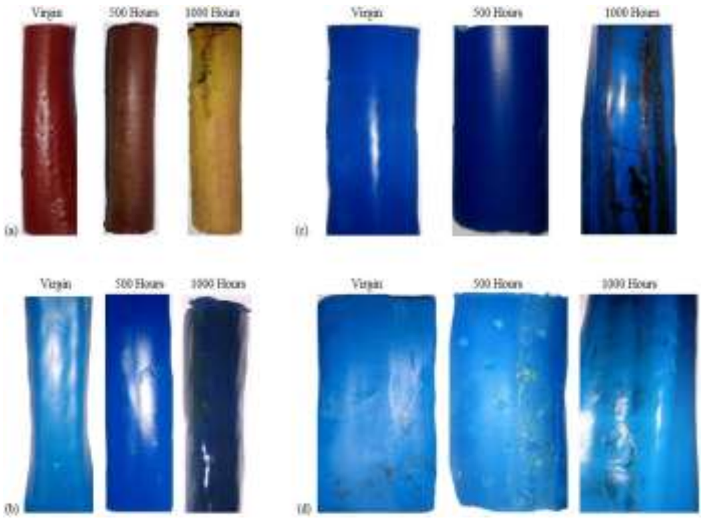


FIGURE 5. Insulation samples of virgin, 500 hours aged and 1000 hours aged PVC cables a) 2 core 10 mm^2, b) 4 core 10 mm^2, c) 4 core 120 mm^2 and d) 4 core 240 mm^2

However at the end of this cycle all the by-products were filtered at bottom and significantly the sulfur were spattered all over the surface of these sheaths owing to the emission of SO_2 and H_2O from sulfuric acid at higher temperature.

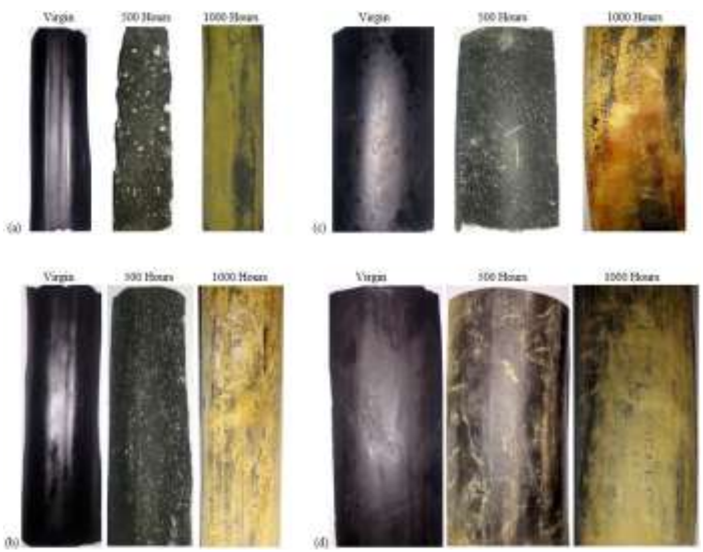


FIGURE 6. Sheath samples of virgin, 500 hours aged and 1000 hours aged PVC cables a) 2 core 10 mm^2, b) 4 core 10 mm^2, c) 4 core 120 mm^2 and d) 4 core 240 mm^2

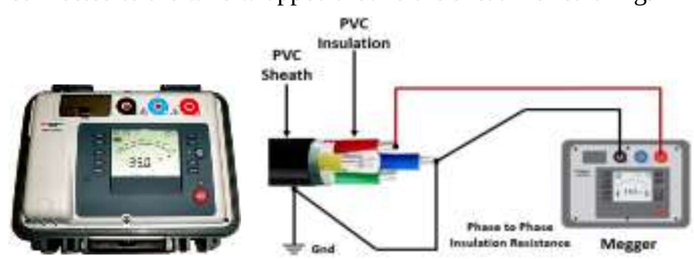
B. QUANTITATIVE ANALYSIS

Quantitatively the insulation and sheath of bigger cable would be least effected as compared to other ones which can be proved from the results of quantitative analysis techniques and tests.

INSULATION RESISTANCE TEST

Underground cables are provided with thick insulating protection encasing the conductor to avert them from environmental damages and it provides a buffer in between conductor and anything outside the insulation to avoid the direct contact. It also avoids the contact with other conductors and omits the leakage current to flow through it. It is the most commonly used parameter for health assessment of cables. IR values of a cable depends upon insulation material, its size, length, type and thickness of its insulation alongwith insulation temperature and humidity. Over the time the chemicals under the ground, heat, moisture and other mechanical stresses impart negative impact onto the insulation and degradation occurs. It effects its mechanical and electrical properties and also decreases its resistance [42], [43]. Owing to such situations it is very necessary to measure insulation resistance of a cable to ensure its longevity. Normally IR is measured with the megger (megaohmmeter) according to International standard IEC 60501-1 which are basically of two types: Operated and Manual Type – Hand Operated and Electronic Type – Battery (as shown in figure 7(a)). A common rule of thumb says that IR changes by a factor of 2 for each 10°C change.

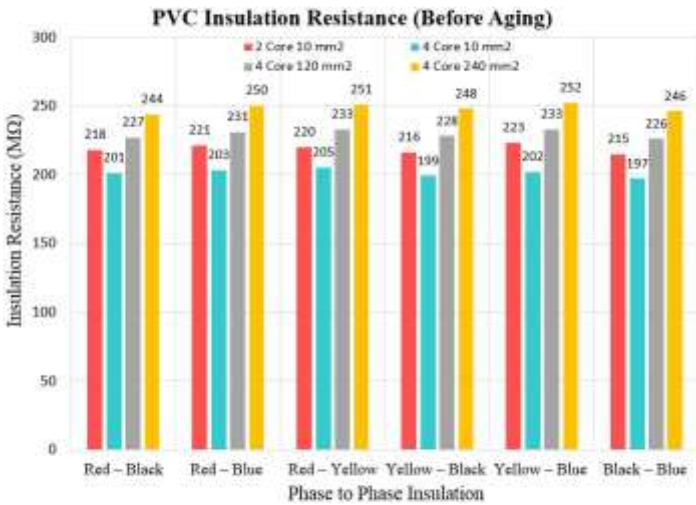
For phase to phase IR measurement line and guard terminals of megger were connected to conductors of two cores and the one of these conductors was connected to guard terminal and was earthed through cable's sheath as shown in figure 7(b). This guard terminal acted as a shunt. Earth terminal of megger could also be connected to the wire wrapped around the sheath for earthing.



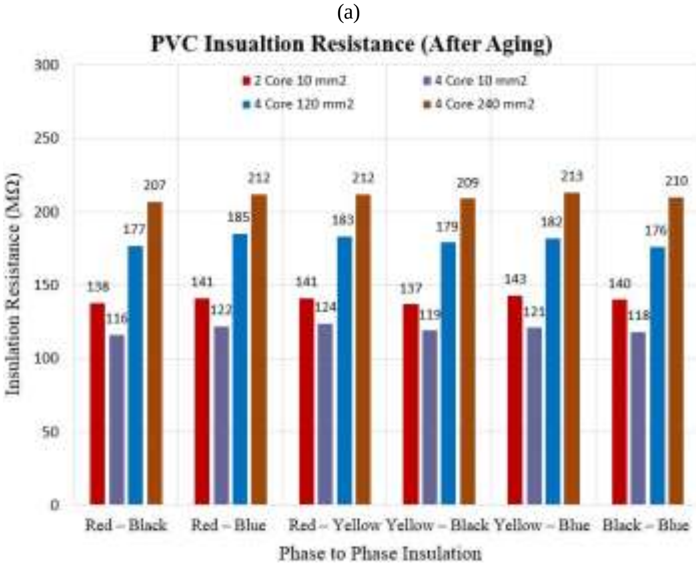
(a) (b)

FIGURE 7. (a) Megger 10 kV (b) Insulation Resistance Test (Between Blue and Red cores phases)

Phase to phase IR readings of four cables were measured via 10 kV Megger as shown in figure 7(b). Every insulation when upon heated can maintain its IR to the same level after the applied thermal stress is removed without causing any permanent damage. But on the long run and at higher temperatures molecular vibrations causes the permanent change in the structure incepting minor to major cracks with curtailing the IR to a very lower value and even can bring about the dielectric breakdown. Similarly the IR values in the graph shown in figure 8 hasn't been reversed to original state. Phase to phase IR values were highest for 4 core 240 mm^2 and it has been decreasing with the size of cables except for insulations of 2 core 10 mm^2 cables which exhibited slightly higher IR values contrary to 4 core cables insulations of same area (before and after aging). That was because of the 2 core cables has much more surface area in between its cores (inside its sheath) than to the four core cables of same size to help the heat (that was generated) inside the core to transfer it to the air. That was the reason for slightly higher current rating for 2 core 10 mm^2 as compared to 4 core 10 mm^2.



(a)



(b)

FIGURE 8. Insulation Resistance of PVC insulations (Phase – Phase) (a) Before Aging (b) After Aging

On an average 2 core 10 mm^2 insulation's resistance was 219 MΩ and 4 core 10 mm^2 IR value was 201 MΩ which resulted in an 8% lesser value recorded before aging. Same phenomenon accounted for after aging and got 14% reduction with 139.5 MΩ and 120 MΩ were the average IR values of 2 core 10 mm^2 and 4 core 10 mm^2 insulations respectively as shown in bar graphs of figure 8 (a, b). 120 mm^2 insulation has almost 1.8 – 2.0 times the thickness as opposed to 10 mm^2 but its mean IR value was just 230 MΩ i.e. a meager 5% more than that. The 240 mm^2 insulation has reached almost 2.2 – 2.5 times of 10 mm^2 thickness and got the mean 248.5 MΩ IR which is only 13% greater to it. It can be seen that the cable with thinnest insulation has dealt with the most deterioration after multistress aging and got the least IR value when evaluated against the other. The aged 4 core 10 mm^2, 2 core 10 mm^2, 4 core 120 mm^2 and 4 core 240 mm^2 insulations got the depreciated mean IR values of 120 MΩ, 139.5 MΩ, 180 MΩ and 210.5 MΩ respectively and suffering the percentage reductions of 40.3%, 36.3%, 21.74% and 15.29% respectively, illustrated in figure 8(b). Aside from the homogeneity in between all core's insulation resistance the phase to phase IR value containing black core were showing somewhat smaller values to their average values. (i.e.1.5 – 2% for virgin and 1.8 – 3% for aged) as the phase to neutral IR values are smaller as compared to phase-phase IR values.

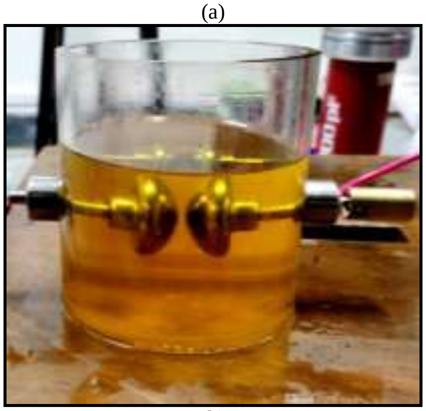
INSULATION BREAKDOWN TEST

Insulation or dielectric breakdown is the point at which the flow of current is stopped. A point just before when the breakdown starts to happen is actually the breakdown strength of that insulation. When that breakdown voltage is achieved then failure of insulation occurs and the material is no longer an insulator as it starts conducting. HIPOT (High Potential) Tester is employed there to check whether the insulation is maintained and if the current is flowing or not. This is the most widely used test for assessing the insulation quality and to test its integrity. Its purpose is to stress the dielectric properties of material under test. It involves a high potential setup with a "Box type and Dry Transformer" or a "Table type and Gas Transformer" or "Cabinet Type and Oil Transformer" and a test specimen is placed in between two electrodes and voltage is raised from zero until breakdown following the guidance in IEC 60243. Measurement conditions are 20 – 25°C temperature and 25 – 27% relative humidity. Breakdown of any material depends chiefly upon its intrinsic properties alongwith other factors such as electrode configuration, surrounding medium, environmental conditions and contact pressure. This phenomenon corresponds to the degradation of insulating properties and also the mechanical deterioration. Figure 9(a) depicts the breakdown test setup.

While testing, the AC high voltage was supplied to 100 kV setup from single phase transformer (220 V / 100 kV, 5 kVA, 50 Hz) with rate of voltage rise of 1 kV/s. The HV supply was connected to the test chamber through a vertical bushing. A 10 MΩ current limiting resistor was connected at the output of the HV supply to protect it from damage during sample breakdown. The sample to be tested was clamped between movable mushroom shaped brass electrodes in the presence of oil (as shown in figure 9(b)) and the other end of this electrode was grounded. The whole schematic of BD test is shown in figure 10.

The mushroom shaped brass electrodes must be of equal length and its contact must be smooth and facing exactly each other which is normal to plane of test sample to avoid any flash outside of the specified area of sample due to irregularities [44]. Electrode chosen were of 20 mm diameter following the standard IEC 60243-1. Sample holder can move back and forth and can be lowered easily in transformer oil as shown in figure 9(b). Oil bath is mandatory otherwise breakdown procedure could lead to many bigger partial discharges and flashovers leading to bigger puncture. Testing in air would cause the breakdown of air as well and it might not cause the intrinsic breakdown of insulation. Every breakdown voltage is displayed on HV measuring unit. The process initiated with some fewer voltage levels and then linearly increasing it where the current (known as Leakage Current) started flowing at a certain voltage level (depending upon the health of sample) across the test points of HIPOT Tester [45]. Voltage was increased until the breakdown happened and a current ceased to flow. Dielectric strength can be calculated by dividing the B.D voltage by the insulation thickness. It is measured in volts per mil or kilovolts per inch (or kilovolts per millimeter).

(a)



(b)

FIGURE 9. (a) Insulation Breakdown Test Equipment (b) Mushroom – Shaped Brass Electrodes in Transformer Oil

Breakdown characteristics of all four PVC cables insulations and sheaths were determined with the dielectric breakdown test which is similar to the leakage current test. Again the samples taken were constituting the one before aging (Un-Aged), after 100 Hours aging and then during the course of 1000 hours multistress aging.

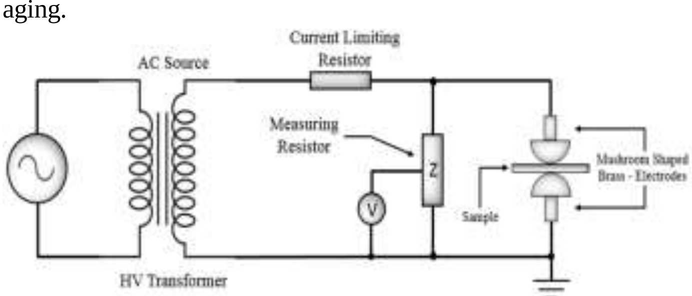
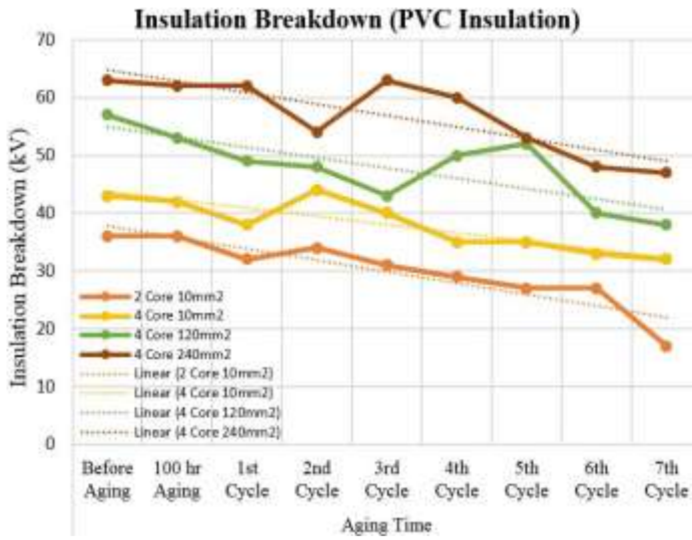
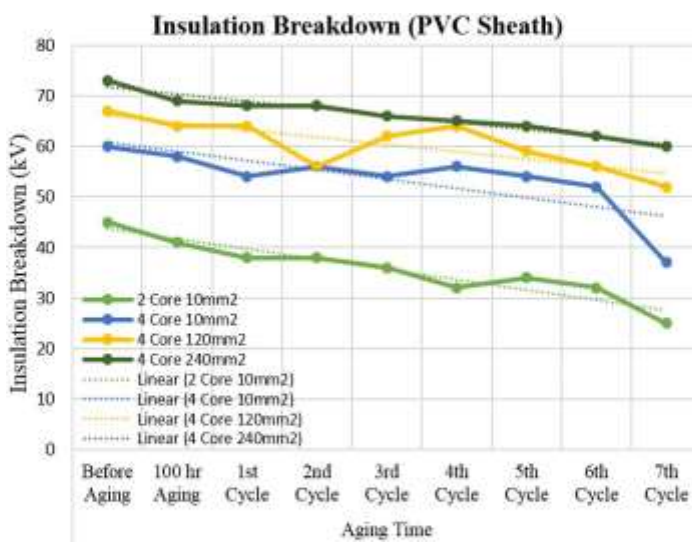


FIGURE 10. Schematic Diagram of Breakdown Test

Dielectric Breakdown of sheaths and insulations of four cables were plotted in figure 11 (a, b) for different aging times. It was certain that sheaths materials were more rigid and thicker as compared to their insulations inside that's why they could sustain more electric stress but their DS values are not necessary linear with the thickness for all cases [46]. For un-aged samples sheath BD voltages were 45 kV, 60 kV, 67 kV and 73 kV for these four cables while for insulations these were 36 kV, 43 kV, 57 kV and 63 kV respectively. It was observed that for same cables sheath showed 15 – 40% more dielectric and breakdown strength when evaluated against their core insulations before aging and 25 – 50% after aging.



(a)



(b)

FIGURE 11. Breakdown Voltages of (a) PVC Insulations and (b) PVC Sheaths

However, there was a symmetrical decreasing trend observed for every cable's insulation and sheath throughout the aging except at some points for example for 4 core 240 mm^2 insulation the BD voltages were averaging at 62 kV and it slumped to 54 kV at 2nd cycle following the rise in 3rd cycle to 63 kV as shown in figure 11(a). Similar asymmetry was observed in case of 4 core 120 mm^2 sheath and insulation both at different positions. Also for finally aged samples bigger cables insulations were least effected when compared with smaller ones from electrical perspective i.e. 240 mm^2 insulation has shown a 25.4% reduction in BD voltage and 120 mm^2 insulation resulted in a 33.33% decline but for 2 core 10 mm^2 insulation this decrease has gone from 36 kV to 17 kV (52.78%) in contrast to the fresh samples.

This difference in percentage reduction became more narrowed for sheaths where 240 mm^2 cable presented a 17.8% reduction in its BD voltage and 120 mm^2 cable's sheath displayed a 22.39% decline and 2 core cables marked a 44.44% reduction. Black powder was formed upside the breakdown point with mostly carbon concentration [47].

It was also inferred that after summer cycles (with 66°C) the alleviation in BD voltages was little more than the reduction in BD voltage after winter cycle which showed that the temperature played a greater role in the whole aging process and in decreasing the dielectric strength.

C. COMPARISON OF PROPOSED ACCELERATED MULTISTRESS AGING CONIDTION WITH OTHER AGING CONDITIONS

Parametric changes observed in PVC cables insulation in case of proposed 1000 hours multistress aging environment are compared with its theoretical/ manufacturer's values and also are compared with other aging conditions mentioned in previous researches as listed in Table V.

TABLE V
COMPARISON OF RESULTS WITH OTHER TECHNIQUES

Ref., Year	Technique	Aging	% Red. in IR	% Red. in BD
[10], 1992	Improved Performance of FRLA Materials	14 days	47.06	25
[22], 2006	Accelerated Thermal Aging Test	5000 h	67.27	28
[48], 2010	Accelerated Thermal Aging Test	24300 h	94	-
[49], 2014	Dunnett's Method of Heat Aged Samples	28 days	-	81.26
[50], 2015	IR/PI Variations Dependency	1000 h	6.67	-
[51], 2015	HALST Condition	21 h	66.67	-
[32], 2016	Slow Polarization in VR Measurement	14 days	40	-
[52], 2017	"Procedure Aging" in Water and Heat	40 days	36.36	32.69
[15], 2017	Accelerated Aging in Brine	60 days	4.47	-
[53], 2017	Individual Temperature Correlation	-	82.22	-
[25], 2017	Water Impact in Damaged Integrity	28 days	65.22	87.5
[27], 2017	Voltage Response Measurement	1000 h	-	11.11
[8], 2019	Field Aging in Thermal Stresses	50 h	-	17.24
[54], 2020	Induced & Accelerated Aging	89 h	82	-
[55], 2021	OIT, XRD, FTIR, SCM, DC Breakdown	1000 h	-	10.11
Proposed Model	**Accelerated Aging in Multi-Stress Environment under SP Test**	**1000 h**	**40.3**	**52.78**

In previous research various techniques have been employed to get the desired results. Some techniques were destructive to bring about early aging in fewer aging cycles and shorter time and to quantify the swiftly decremented parameters. Aging with longer times from thousands of hours to months were somehow degrading with moderate speed because of their parametric reduction and fact-finding for aging mechanism were more focused on their variations in the intervening period through the aging rather than the realistic results. Various researches were centered on thermal and electrical stresses, however some have stressed with the combination of electrical, mechanical and thermal.

The proposed model is converged on least destructive and realistic aging method to assess the degradation of end results as well as the samples conditions in the lapse of aging cycle's time. The corresponding characterizations techniques (of Insulation Resistance Test and Breakdown Test) were also following the IEC standards. This method have used multiple stresses for a complete 1000 hours aging (electrical, mechanical, chemical and thermal stresses) to correlate with real-life underground soil stresses. The findings in this research as compared to previous studies are more optimum and more identical to real-life results i.e. 40.3% reduction in IR and 52.78% reduction in BD is closely equivalent to 25 years natural aging (in dry condition) results of PVC cables in field.

VI. CONCLUSION

In this study the electrical and chemical characterization of different sizes of Low Voltage (0.6/1 kV) Al/PVC/PVC cables were investigated. The key characterizing parameters were the visual inspection of PVC sheaths and insulations, Insulation Resistance and Breakdown voltage. Visual inspection of PVC samples during the aging clearly revealed the thermo-chemical effects over the aging intervals which made it evident the emergence of depositions, cavities, protrusions, cracks, voids etc. Chemical effects got double folded with the presence of high temperature and has made the cable insulation and sheaths more vulnerable to their effects and their reaction products. Electrolytic heating got faster in summer cycles alongwith the conductor corrosion (Aluminum conductor and SS electrodes) as well.

Breakdown voltages decreased eminently because of persistent thermal effects but it had originated by means of electrolytic heating of vigorous chemicals at first place which had multiplied the chemical harshness as well as the temperature in a short stretch of time. Intensely affected cable was 2 core 10 mm^2 which got a 52.78% descent in its insulation BD voltage and 44% downturn in its sheath contrary to the fresh samples while the 4 core 240 mm^2 has shown the lowest percentage reduction. Graphically the results implicated the incremented reduction in summer cycles than in winter cycles. Even electric stress of 1 kV has drawn out an increased leakage current of 5 mA in summer cycle as opposed to the 3 mA in winter cycle.

Insulation resistance of 4 core 240 mm^2 cable insulation has expressed the higher IR values as compared to the others and it was exerted with the least percentage curtailment in IR. Unusually in the case of IR the most affected insulation was of 4 core 10 mm^2 cable (instead of 2 core) because of its comparably little likelihood of heat rejection and 4 core 240 mm^2 has resulted in highest IR value . IR values were following the order: 4 core 10 mm^2 IR < 2 core 10 mm^2 IR < 4 core 120 mm^2 IR < 4 core 240 mm^2 IR. Similarly their percentage reductions in IR came to follow the sequence of depreciated IR (DIR) after multistress aging as: 4 core 10 mm^2 DIR > 2 core 10 mm^2 DIR > 4 core 120 mm^2 DIR > 4 core 240 mm^2 DIR. From IR values and BD voltages it is deduced that the sheaths and insulations acted differently against different stresses.

So it is concluded that the electrolytic heating has made the chemical stress more intrusive and aggressive towards insulation and sheath. Furthermore this chemical stresses has also triggered off all other stresses which aggravated their effects exponentially high. Surface hardness, cracks formation, salts and sulfur depositions has mounted up progressively. BD voltages and IR values also got declined mainly as a consequence of thermo-chemical stresses. In view of this the chemical stresses distinctly has been deemed accountable for the alleviated parametric characterizations of Polyvinyl Chloride cables (insulations and sheaths). Leakage Current and Volume resistivity characteristics of cables insulations in accelerated multistress aging conditions would be the prospect of further investigation which could lead to a better estimation of electrical properties and the prediction of cables lifetime as derived from their corresponding degradation curves.

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