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Effect of Temperature Rise on Leakage Current and Breakdown of Power Cables.

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EFFECT OF TEMPERATURE RISE ON LEAKAGE CURRENT AND BREAKDOWN OF POWER CABLES

By

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Abstract :

The present work reports an experimental investigation of the effect of temperature rise on the leakage current and thermal breakdown in power cables. An empirical equation was found to give the relation between the leakage current and the temperature of the insulation. It was found that the thermal breakdown occurs when the heat generation in the insulation is larger than the heat dissipation in the surrounding soil. The variation of leakage current with the temperature was well investigated and it was found that the leakage current increases with increasing of insulation temperature.

Leakage current in power cable predicts the critical breakdown voltage in high-voltage cables. It was anticipated that a significant of deterioration could be detected by measurement of leakage current at the operating temperature especially if the deterioration had progressed to a point where the cable failure is imminent .

1- Introduction :

Underground cables are an indispensable intermediate stage in practically all power systems, either to transmit electrical

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energy to overcrowded metropolitan areas where overhead lines are impossible to string, or to form connections between the different electrical components in the switch-yard .

The rate of increase of installed capacity all over the world is rather high, but still too low to follow the higher rate of increase of demand. A representative figure for this rate is 7% per year, which means doubling the power energy about every 10 years. This means more generation, including nuclear stations, more transmission and distribution of energy. For example, the total energy consumption of Manseura Zone is 260 Mln KWh, having maximum demand 73 MVA on 1981, from which 118 Mln . KWh industrial load, 15 Mln.KWh rural load and 115 Mln.KWh municipalities consumption. The corresponding values on 1973 were 70.4 Mln. KWh and 18.6 MVA as maximum demand. For the realisation of the scheme recomendations, it is necessary to install 195 new distribution transformer 11/0.4 Kv and laying 133 Km of new 11 Kv cables. The cable, if of poor efficiency, may form a bottle-neck in the process of energy flow in a power system.

In the design of a cable there are electrical, thermal and mechanical considerations, in addittion to the economical ones. These factors vary according to the specifications of the materials used. Higher voltage necessitates a thicker insulation, and higher current necessitates a bigger cross-section of the conductors. The heat dissipated from the cable has to travel through the insulation, sheath and serving and then through the ground to the atmosphere.

For high-voltage cables, the thermal parameters are closely connected with electrical parameters, since a part of the energy is dissipated in the dielectric and converted into heat leading to the heating of the cable itself . Heating of the cable reduces its electrical strength, increases the power factor of the insulation and increase the leakage current. Heat flow from cable to the surrounding soil depends on the ambient temperature, so the worst conditions for certain loading are in summer where the ambient temperature is maximum.

The temperature rise of cable is mainly due to copper losses which will be transmitted to the soil. The power transmission and distribution capability of power cables suffers from thermal restrictions imposed by four inherent physical properties of the cable insulation, viz. the permissible operating temperature, the dielectric power factor, the leakage current and the dielectric constant. With direct buried power cables carrying a heavy load continuously, drying out of the soil immediately surrounding the cable occurs in the summer months and the thermal resistivity may rise to value in excess of that adopted for current loading calculations with the possibility of the conductor unduly high temperatures, or even thermal breakdown occuring.

2- Cable Construction and Test Equipments :

There are many various types of cables used in Egypt in AC power transmission. Different types of cable were selected such as impregnated paper and polyethylene cables. To control the conditions affecting the leakage current and breakdown in power cables, cable samples were prepared for testing in HV-laboratory. These cable samples had a total lenght of 3 m. The samples were taken to cover a wide range of cross-sectional areas used in the distribution of electrical power in Egypt. Table (1) Shows the main dimensions, conductor materials and type of insulation of the cable samples under test .

Sample	Conductor materials	Insulating materials	Cross-Sectional Areas, sq.mm
A	Alum.	Impregnated paper	3 x 150.
B	Copper.	Impregnated paper	3 x 70 .
C	Alum.	Impregnated paper	3 x 70 .
D	Alum.	Impregnated paper	3 x 70 .
E	Alum.	Polyethylone (XLP)	3 x 240.

To investigate the effect of temperature rise on leakage current and breakdown of high voltage cable, many samples have been used throughout the tests. These cable samples were located in a wooden box of dimensions 1 x 0.75 x 1 meters. The bottom of the box was totally earthed by metal sheets. The height of cable from the ground metal sheet is 0.7 m. The box is well filled with sandy soil.

The equipment used consists essentially of a high voltage unit with a step-up transformer of 8 KVA and 220/80000 V, control unit, smoothing capacitor and HV-rectifier unit.

A direct reading AC and DC voltmeter with a suitable range of reading is also provided. The applied voltage can be measured by means of a resistive potential divider and an electrostatic voltmeter .

Leakage currents were measured in the HV-side by means of a multi-scale, micro-ammeter having full measuring scale of 100μA, which can be multiplied to indicate a current of 50 mA.

The temperatures of insulation were measured by using an thermocouple potentiometer. Accurate results were obtained by using a copper-constantan thermoelectric pyrometer, glued into wall flush with the surface of the cable cores.

The insulation of the cable was heated by allowing the full load current to flow in the cable cores using a current transformer of type TUR Rusian made, having a current range of up to 1000 A .

3- Results and Discussions :

To study the effect of temperature rise on the leakage current and breakdown of power cables numerous tests were carred out. In all tests the leakage current was measured by means of multiscale, microammeter as mentioned before. Readings were recorded after dying away of charging currents.

The leakage current in a power cable under applied voltage flows in a special path through the insulation, sheath and armouring to the ground. Therefore the leakage current depends on many factors associated with all the components of the whole path .

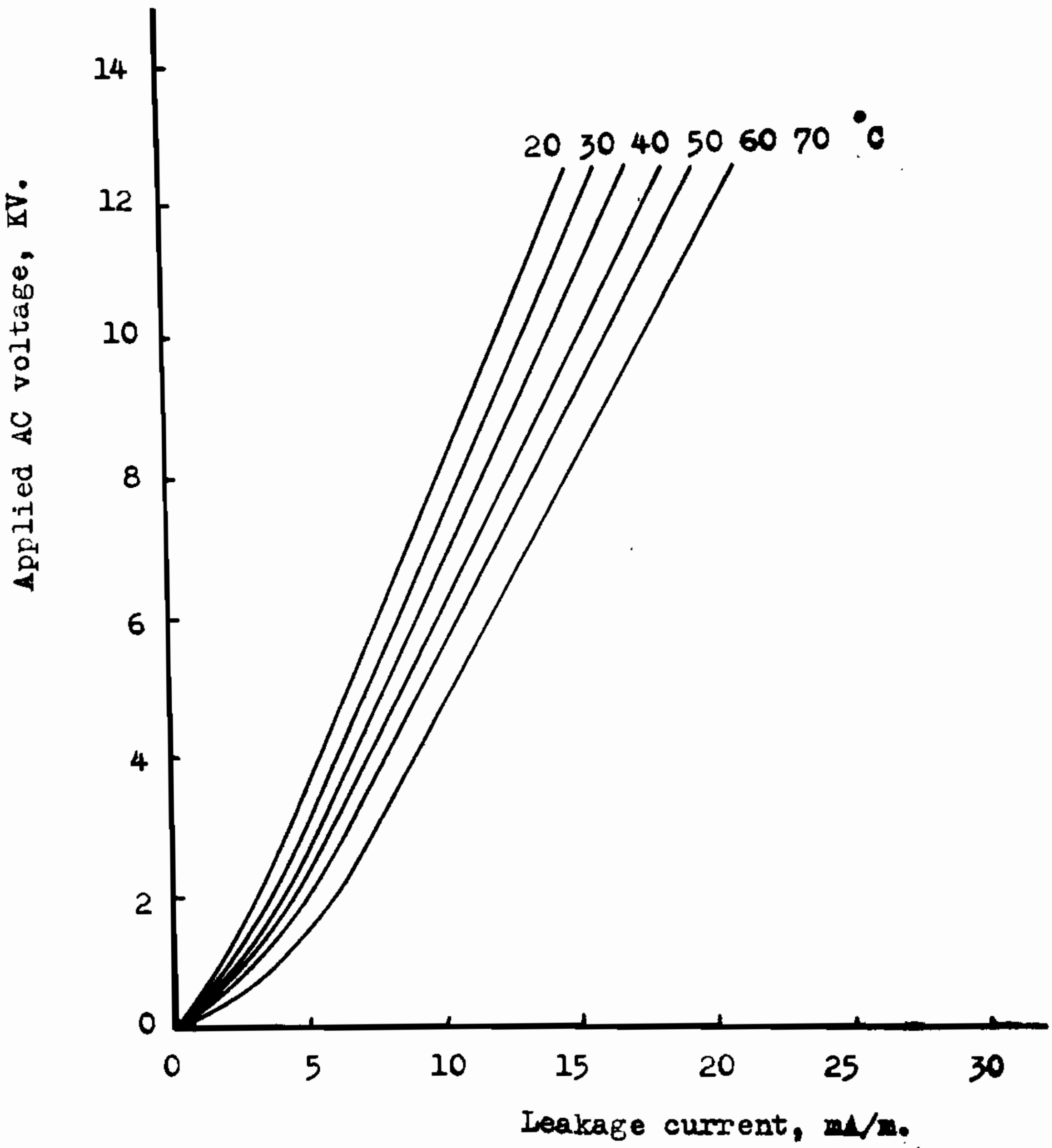
Among these factors the temperature rise represents the most serious factor affecting the cable operation and even the cable life and safety .

A number of cable samples were experimentally investigated under well-controlled conditions in High-Voltage Laboratory , Faculty of Engineering, Mansoura University. Each value of the leakage current shown in the given figures represents the mean value of 5 successive measurements after intervals of 15 minutes to avoid any recharging of the cable under test. The standard deviation of the measurements was found to be dependent on both cable type and applied voltage. In all obtained results, it was in the order of up to 15 % .

3-1 Effect of Insulation Temperature on Leakage Current

The temperature regime of power cables has an important significance. As a general rule, the leakage current in power cables should increase with increasing of operating temperature. To investigate this effect, measurements were carried out at different insulation temperature in the range of up to 80 °C . This range of temperature was obtained by preheating the cable by flowing the rated-full-load current through its cores, using TUR current-transformer, having a current range up to 1000 A. The current transformer was supplied from a low-voltage supply through a 3-phase Troidac supplied from 3-Ø, 380 V-supply. The leakage current in cable samples, was recorded under applied test voltage of up to 20 KV .

To get-the leakage, current-temperature characteristic of a cable sample, it was preheated and the insulation temperature was measured using a Thermocouple-Potentiometer. Fig.(1) shows the effect of operating temperature on the leakage current of cable sample B, under AC applied voltage. It is clearly seen from Fig.(1) that the leakage current increases with increasing of insulation temperature. As a comparative example, the leakage current per unit length increased from 15 mA to 21 mA as the temperature was increased from 20 °C to 70 °C at the same applied voltage. The leakage current depends also on the type of applied



Fig(1) : The effect of operating temperature on the leakage current of power cables under AC. voltage between cores and sheath.

voltage. Fig.(2) shows the variation of leakage current with the operating temperature under DC voltage of both positive and negative polarities. Under DC voltage the leakage current per unit length in power cables is very small in the order of microamperes per meter. It is clearly seen in Fig.(2), that the leakage current of power cables increases with the increasing of insulation temperature under DC voltage of both polarities. Negative polarity DC voltage gave higher current than the same voltage of positive polarity. As a comparative expample, the leakage currents at 30°C and 70°C, under applied voltage of 20 KV of positive polarity are 5.5 μA/m and 30.5 μA/m respectively. The corresponding values at the same voltage of negative polarity 9 μA/m and 34 μA/m respectively. It is clearly seen that the leakage current is increased to about 5 times its initial value as the temprature is raised from 30°C to 70°C .

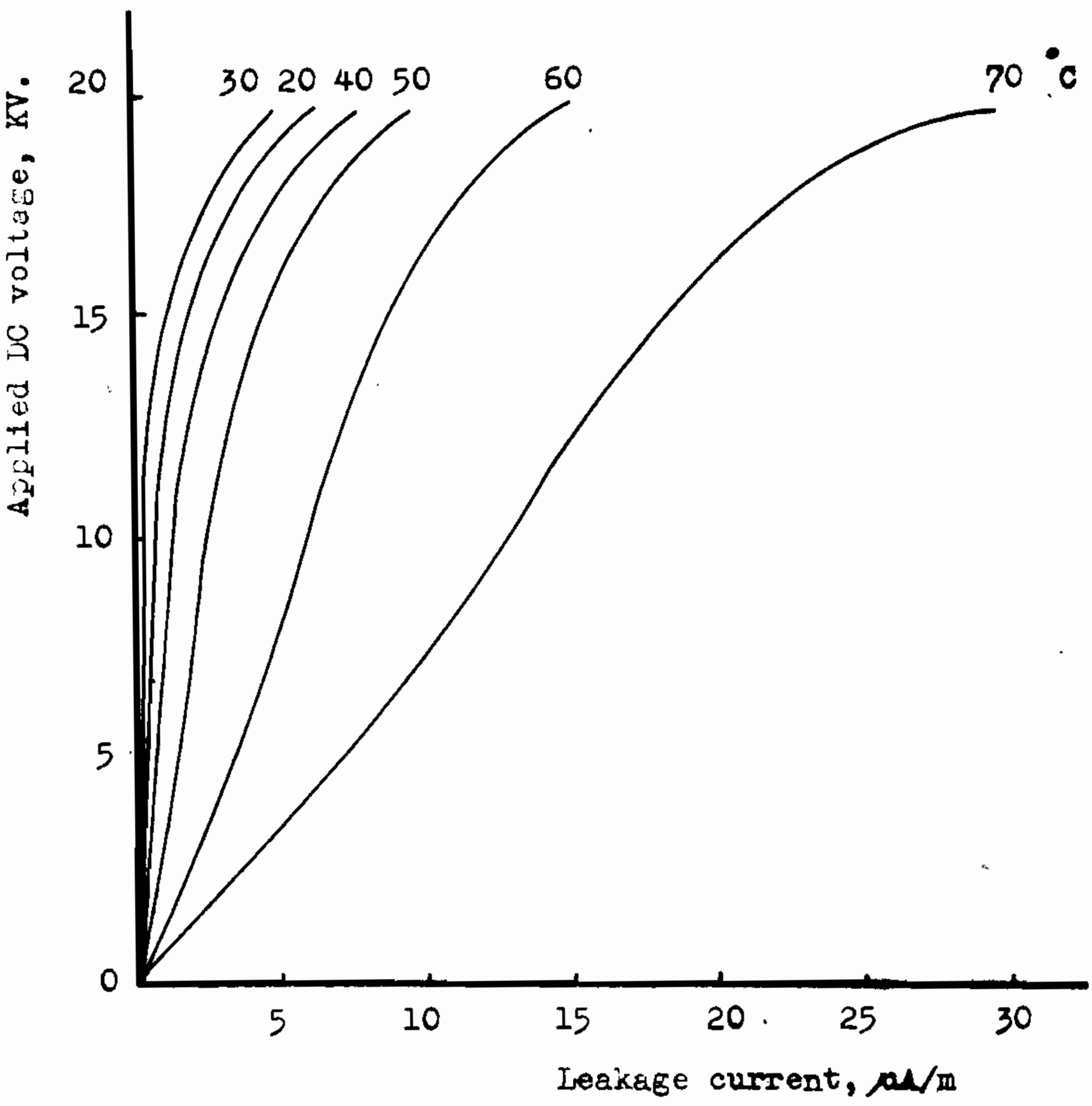
The dependence of the leakage current on the operating temperature of different cable samples was will investigated under different applied voltages, namely A.C. and D.C. voltages. This dependence was formulated as mathimatical relationships with the aid of the obtained experimental results. These analytical expressions give the leakage current of given power cable in terms of the temperature difference .

Beginning with the AC voltage, the relationship between the leakage current and the insulation temperature may be approximated to a straight line, having slope depending on the cable type and applied voltage. This expression was found from the results shown in Fig.(3), which shows the leakage current temperature characteristic of cable samples under AC voltage of different values. This characteristic can be expressed by the following equations:-

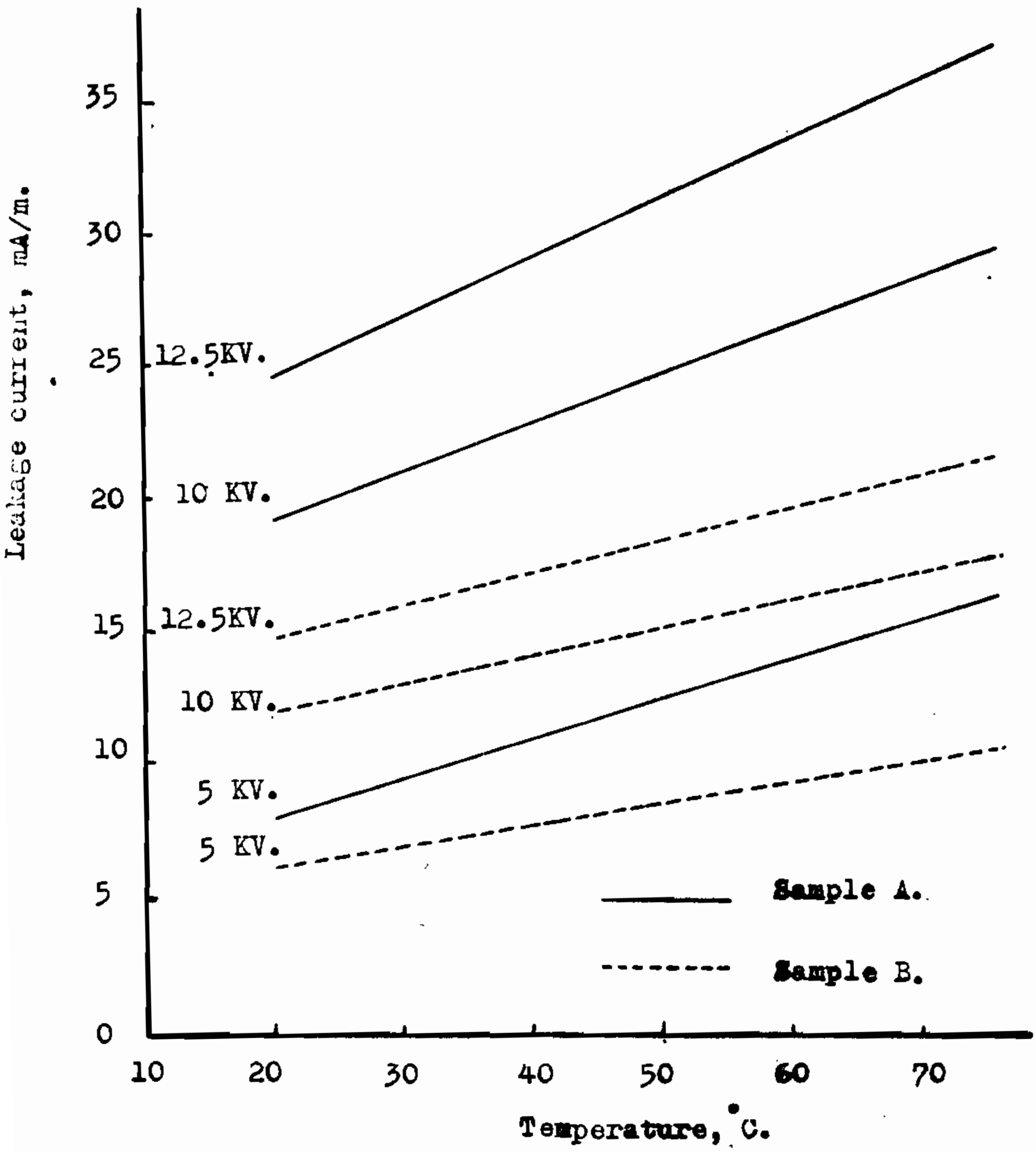
$$I_t = I_o + k \ (\Delta t) \qquad (1)$$

Where :

I_t = Leakage current at temperature t°C in mA/m



Fig(2): Core to sheath leakage current at different operating temperature under DC voltage of positive polarity.



Fig(3): The effect of operating temperature on the leakage current of power cable from core to sheath under different applied AC voltage.

I_o = Leakage current at 20 °C mA/m

Δt = temperature difference °C

k = Constant depending on the cable type

The numerical values of constant K for the two cable samples A and B, as example, are 0.22 and 0.12 respectively. The current I_o depends of course on both the cable type and applied voltage. Cable sample A gave leakage current per meter at 20 °C of 8 mA , 19 mA and 25 mA at respective applied voltage of 5 KV, 10 KV and 12.5 KV. The leakage current of cable sample A at the rated-voltage namely 10 KV, can be calculated as

$$I_t = 19 + 0.22\ (t - 20)\ \ \text{mA/m} \qquad (2)$$

A similar set of equations was found to estimate the leakage current of power cables under the rated-voltage and different operating temperatures. These equations can be applied in practice to determine the leakage current in the different power cables with sufficient accuracy. Under DC voltage, the leakage current differs from that under AC voltage. This is produced beeause DC leakage current is pure resistive instead of capacitive-resistive leakage current under AC voltage. The variation of leakage current with the operating temperature was well investigated and shown in Fig.(4) under different DC applied voltage, for cable samples A and B. It is clearly seen in this figure, that the leakage current of sample A under DC voltage of is higher than that of sample B at the same applied voltage. It is also clearly shown that, there is a decrease in leakage current of underground cable at low temperature up to 35°. The possible explanation for this phenomenon in leakage current is that the water in the impergnating oil would be absorbed by the paper insulation, produced through the process of extruding, moulding, heating and cooling. This process leads to a drying of the impregnating oil and finally to a decreasing in the leakage current. It is displayed in contrary behaviour, because of a large quantity of polar radicals created owing to decomposition of the insulating papers under severe heating at high temperature. The polar radicals cause the increase in leakage current at low temperature, but it decreases at temperature nearly 35 °C by catching ionized materials, such as metalions. At higher temperature up to 40 °C the oil would be able to dissolve more water, and hence the water in the insulating paper will tend to diffuse into the oil forming micro-voids in the insulated paper. The latter may increase the leakage current due to polarization microdischarges inside the formed voids. Water in impregnating oil will be distributed partly as emulsified and partly as a molecular phase .

The conduction in this case will be due to the presence of water and impurities in the impregnating oil. These move into the high-field region leading to an increase in leakage current. In addition the viscosity of the oil decreases at high temperatures given the impurities more mobility to move. Impurities in the oil can be created as deterioration products of the oil itself . Deteriorated oil has iron sludge particles, hydrogen gas and carbon particles.

Additionally the insulating paper can be considered as a rich source of cellulose fibres in the oil. These are polar and can be easly ionized under the action of an electric field forming induced ions, which increase the leakage current.

The conduction in power cable may be raised by gas bubbles formation . Gas bubbles may be formed in the cable by one of a number of possible mechanisms. They may be created either from gas dissolved in oil, coming out of solution in regions of high field stress, or they may be formed due to vaporization of the oil itself. They may be present from the time of manufacture of oil impregnated paper .

All these factors introduce a dependence of the leakage current on the concentration of water, gas bubbles and impurities in the impregnating oil .

At a certain field stress all these impurities will be ionized and become conductive depending on their sorts and permittivities. They gather at the place of maximum electric stress and finally form a conducting channel leading to a very high conducting currents.

This may be followed by a breakdown of cable insulation across this channel

It is clearly seen in Fig.(4), that the variation in leakage current under DC voltage is exponential . An exponential expression was found with the aid of the obtained experimental results, giving the leakage current of power cable with insulated paper in terms of the operating temprature under applied DC voltage. This can be expressed in the following exponential form as :

$$I_t = I_o \exp (\alpha x \Delta t)$$

Where :

I_t = Leakage current at temperature t °C, μA/m

I_o = Leakage current at 20 °C, μ A/m

α = constant depends on the applied voltage and cable type

Δt = temperature difference C°

The numerical values of I_t and I_o , at 20 KV, for the two mentioned cable samples namely A and B were found to be :-

For A $\alpha = 0.03$, $I_o = 8$ μA/m
For B $\alpha = 0.033$, $I_o = 7.5$ μA/m

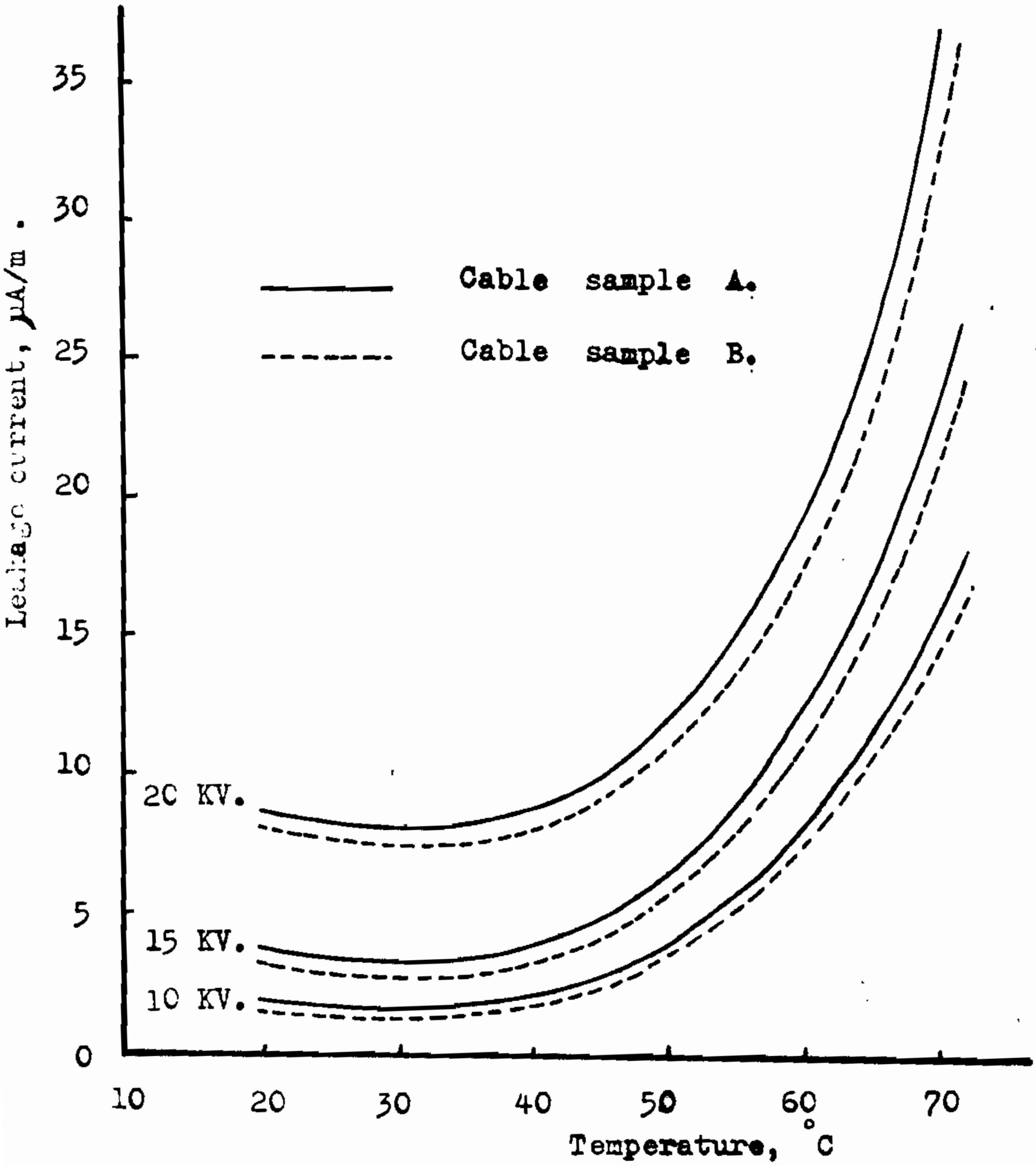
By means of the above equation , the leakage current can be calculated very close to the corresponding experimental values. The calculated values by means of these equations are in a good agreement to those obtained experimentally.

It can be used in practice to determine the leakage current in power cables at any operating temperature up to the maximum allowed operating temperature, namelly 80 °C.

Beyond this range the leakage current increases rapidly and continuous to increase till the dielectric material is damaged. This is resulted beacuse any increase in temperature increases the heat generation in the dielectric, and this in turn produces a further rise in temperature .

3-2 Leakage Current as Pridictor at Breakdown in Power Cables :

The voltage required to breakdown a certain insulation depends on many factors such as the duration and magnitude of the applied voltage, the insulation thickness, cable length and size.



Fig(4): The effect of operating temperature on the leakage current of power cable under different DC voltage of positive polarity, between core and sheath.

It depends also on the maximum temperature attained in the cable, the oil pressure in the dielectric and the presence of moisture or gaseous cavities . The last factor is very dangereous on the power cables during operating. Under high dielectric stresses corona phenomena are produced in the cavities which in the course of time will lead to deterioration of the cable insulation and even to breakdown.

The elimination of cavities in impregnated paper cable can be achieved by three alternative methods explained as follows:-

i) Introduction of an inert gas at high pressure within the lead sheath and in direct contact with the dielectric.

ii) The use of low viscosity mineraly oil for impregnation of the dielectric.

iii) The application of external pressure to solid type cable.

Insulation breakdown takes place at a point where applied stress exceeds its own breakdown stress. Such point, that is breakdown at first, can be defined as the weakest point.

The breakdown voltage of insulation depends on its thickness, the thicker is the layer of a given electrical insulating material, the higher is its breakdown voltage .

Fig.(5) and (6) show the increase of leakage current in power cable samples C,D and E with the DC applied voltage, leading finally to the breakdown.

From this figures, it is clearly seen that at the same applied voltage, the breakdown voltage for a new cable sample D is always higher than that for identical cable sample C withdrawn from the field after serve operating for many years.

As a comparative example the old cable gave breakdown voltage of 80 KV while the new sample gave 120-KV-DC voltage of positive polarity, both had 1.5 mA leakage current just before breakdown. This current increases rushly exceeding the allowed current and operating the protective relay of the control unit. The old cable gave breakdown voltage of 57 KV and 1.2 mA leakage current while the new sample gave 84 KV-DC voltage of negative polarity and 1 mA leakage current. The decrease in the breakdown voltage of cable after long use is mostly attributable to the deterioration of insulating material .

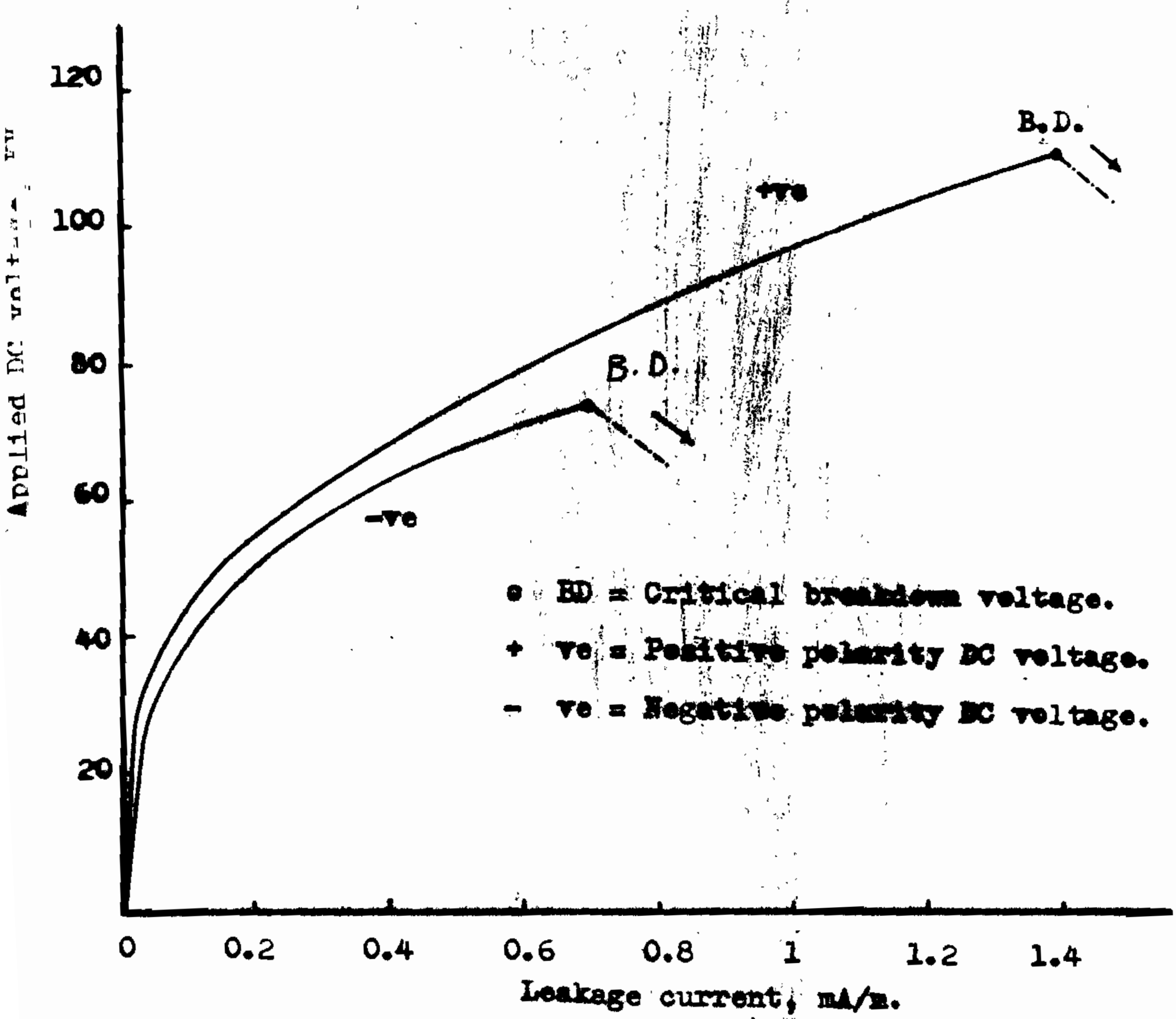
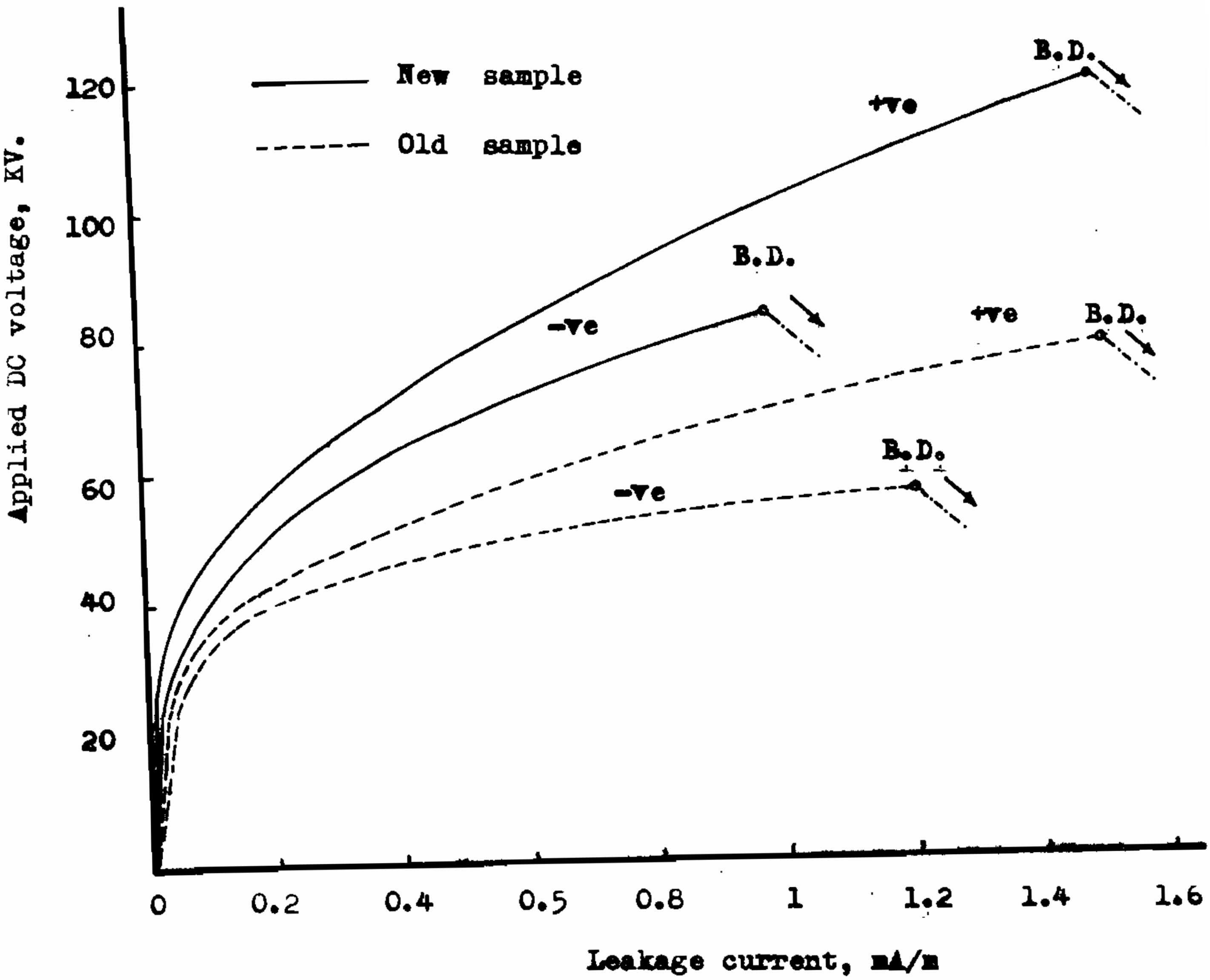


Fig (6): The increase of leakage current in XLP cable with the DC applied voltage leading finally to the breakdown.



Fig(5): The increase of leakage current in underground, impregnated-paper cable with the DC applied voltage, leading finally to the breakdown.

Also it is clearly demonstrated that the breakdown voltage of XLP cable sample (E) takes place at 110 KV. DC applied voltage of positive polarity and at 74 KV-DC applied voltage of negative polarity. The corresponding leakage currents just before breakdown, were 1.4 mA and 0.7 mA respectively.

At the point BD. on the graph Fig.(5) :

$$\frac{dI}{dv} \longrightarrow \infty \qquad (11)$$

where :

I = Leakage current.

V = Critical breakdown voltage.

This point corresponds to the moment of a breakdown . The subsequent reduction in voltage can be explained by a decrease in the insulation resistance . A strongly conductive breakdown channel formed during a breakdown practically produces a short circuit between core and sheath. The maximum voltage applied to an insulation at the moment of breakdown as the breakdown voltage of insulation .

Different phenomena were occurring in insulation after a breakdown and can be determined both by the nature of electrical insulating material and a higher leakage current. The breakdown voltage generates a spark or an electric arc which can fuse , burn and crack the dielectric and even the sheath. After the voltage is taken off a solid dielectric may exhibit a trace of breakdown in the form of a punctured, fused or burnt-through hole of an irregular shape. If voltage is again applied to a punctured solid insulation the breakdown occurs in most cases at the a ready punctured spot even at a rather lower voltage. At DC voltage the ions flow very slowly due to the conductivity of ionisation of cavities, forgein particles present in the insulation and even of the insulation itself. These ionisations are less intense and take place much rarely than under AC voltage. Therefore the possibility of formation of the branched discharge is practically eliminated.

Besides, under DC voltage the potential distribution along the thickness of insulation is determined by the conductivities of its sections. Since the conductivity of the impregnated paper is always of a few times less than the conductivity of oil, the highest field intensities are formed in the paper. This is favourble, since the electric strength of impregnated paper is higher than that of oil films .

Under AC voltage the distribution of potential is determined by both the capacitances and conductivities, and the greatest field intensities occur in the oil films which have smaller dielectric permittivity. Therefore, the working field intensity in case of the cables with viscous impregnation under DC voltage can be increased to about 5-7 times in comparison with amplitude of the intensity at AC voltage . This permits to use the cables with viscous impregnation for electrical energy under DC voltage up to 500 - 750 KV .

The obtained results, showed that the DC breakdown voltage is higher with positive polarity than with negative polarity. This is due the streamer mechanism and the increase in leakage current, which describe the development of the spark discharges. These will take place quicker than in the case when the core is positive with respect to the sheath.

Breakdown voltage of polyethylene insulated cable is hardly affected by the number of microvoids present in the insulation. The major cause of generation of microvoids in polyethylene is steam permeating into the insulation at the time of valcanization, even if vulcanization is carried out with a heat medium other than steam. It is quite difficult to reduce the microvoids to zero. However it may be possible to reduce the number of voids through degassing of material or high pressure extruding.

The weakest point of XLP cables consists of projection on semiconductive layers extending into insulation or defects in insulating material. If the breakdown of XLP cables is caused by a projection on the conductor screen , the cable size effect should be related to maximum stress.

Weak-points of XLP cables broken-down consist of defects, such as contamination, void and other inhernt defects orginated from XLP crystalline-amorphus structure. It is anticipated that such defects exist at random in the insulation and breakdown stress at each position differs .

From the above discussion it will be realized that the measurements of the applied voltage and corresponding leakage current in insulating materials are very important and give a fair indication as to comparative dielectric strengths of such materials.

A growth in the voltage applied to an insulation increases the leakage current, the charge formed by the capacitance of the insulation and the energy dissipation in the insulation. The last increases the temperature of the insulation, leading to a temperature rise in the cable.

In conclusion, under the assumption that the increasing of the applied voltage does not change the properties of the insulating material, the leakage current increases generally leading finally to a breakdown of the material.

If the voltage applied to an insulating is progressively increased the leakage current increases rapidly and continuous to increase till the dielectric material is damged. In this case the leakage current flowing through the insulation will sharply increase, predicting to the breakdown in the cable.

3-3 Breakdown Mechanism and Thermal Breakdown in Power Cables

The breakdown in power cables of paper oil insulation may be produced by the partial discharge in the micro-voids or gas bubbles formed between the different layers. The appearance of partial discharges is related to the accumulation of impurities in the oil which in turn depends strongly on its past history. Under AC stresses, the cable is heated up by different power losses such as copper loss in the cores, sheath and metalic covering losses, dielectric loss in insulation, eddy current and hysteresis loss in steel armouring .

The temperature distribution in power cables as well as known is quite complex and can be determined according to Poisson's equation as reported elsewhere . It is also well known that the difference between the conductor temperature and ambient temperature is nearly proportional to the power loss. Power losses in power cables cause temperature rise and unstable condition can result the so-called thermal breakdown.

Temperature rise also brings about an acceleration of chemical deterioration so that thermal breakdown may well result from a combination of thermal and chemical processes. Electrochemical deterioration is dependent on the presence and mobility of ions in the insulation. Ionic leakage currents also are an important source of energy loss and can be responsible for thermal breakdown. In fact, final breakdown resulting from electrochemical deterioration is often thermal .

The heat generation in the insulation paper can be approximated by the average temperature of the insulation. The conditions of thermal breakdown are given as follows :

$$G_T > W_T \tag{1}$$

$$G_T = W_T \tag{2}$$

$$\frac{\partial G_T}{\partial T_c} \geqslant \frac{W_T}{T_c} \tag{3}$$

Where :

T = the insulation temperature , °C.

T_c = the conductor temperature , °C.

G_T = the heat generation, W per m.

W_T = the heat dissipation, W per m.

Condition (1) indicates that the heat generation in the insulation is larger than the heat dissipation , resulting in the development of thermal breakdown.

Conditions (2)and (3), indicate the state when the cable is in its thermal steady state and subjected to small thermal disturbance, caused by an increase of the voltage or current or by decrease of the thermal dissipation propertiesof the soil. The rate of the heat generation with respect to the temperature variation is larger than the rate of the heat dissipation. This results in heat storage inside the cable leading to temperature rise and finally to thermal breakdown. The unstable thermal state of the cable is mainly resulted due to the temperature characteristics of the dielectric loss of the insulation.

An insulation is thermally stable when the increase of dissipable heat due to any cause is greater than the corresponding increase in power losses.

Thermal breakdown occurs when the heat generation in an alternating electric field exceeds the heat dissipated from the cable to the surrounding soil. Accordingly it depends upon the thermal dissipation characteristics of the soil. In other words if the soil surrounding the cable dries out, the thermal dissipation properties of the cable will be very poor and will lead it to thermal breakdown .

As a general rule, the leakage current in power cables should increase with increasing of operating temperature and increase in corresponding dielectric losses. These, rise and produce more heat and the temperature will be built up from the small initial temperature, causes an increase in insulation temperature and produce finally a thermal breakdown.

4. Conclucions

The present work was planned to study the factors affecting the operation of power cable. Among these factors, the temperature rise forms the most important factor affecting the operation and even the life of power cables.

From the previous results obtained throughout this work which was carried out to investigate the effect of temperature rise on the leakage current and breakdown in power cables, the main results can be summerized in the following conclusions :

1) The insulation temperature has a great effect on the leakage current of the power cables.
   This current should increase with increasing of operating temperature.
2) The leakage current-Temperature characteristics of the power cables under applied AC voltage can be approximated to a straight line, having a slope (K) depending on the corres - ponding cable type and applied voltage. This can be explained from the obtained relation-ship expressed as :

   $$I_t = I_2 + K.\Delta t \quad ......$$

3) An exponential expression was found for the leakage current of the power cable under applied DC voltage. This can be experssed in the following form :

   $$I_t = I_o \exp(\alpha . \Delta t).$$

4) The breakdown voltage under applied DC voltage with positive polarity is greater than that under DC voltage with negative polarity for the power cables.

5) Measurements of the leakage current can be considered in practics as main predictor of breakdown in the power cables and generally recognized as the most reliable guide to the quality and codition of the power cable.

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