Rev.Adv.Mater.Sci. 21(2009) 75-89

MONITORING OF LEAKAGE CURRENT FOR COMPOSITE INSULATORS AND ELECTRICAL DEVICES

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Received: December 03, 2007

Abstract. Electrical insulation is an important part of all electrical systems. The level of insulation safety provided by an insulator depends on the amount of leakage current flowing on its surface. Actually increased leakage current causes a part of high voltage to appear at dead end of insulator. This voltage may sometimes be of order of 1000 to 5000 Volts depending upon weather conditions. Such a level of leakage current causes hazards to public safety as well as losses. So to monitor and keep the leakage current low is an important parameter to be considered by designers and electric supply companies. This paper highlights the concepts and importance of leakage current for insulators and general electrical devices. In addition, different methods of measurements of leakage current are reviewed. Particular focus has been made on leakage current monitoring of composite insulators. Feasibility of these methods for some particular environments has also been discussed.

1. INTRODUCTION

1.1. What is leakage current

Any current flowing from hot conductor to ground over the outside surface of a device is called leakage current. In case of insulators on a transmission line, it is the current that flows over the surface of insulator, and, if no ground exists, the current flowing from a conductive portion of a device to a portion that is intended to be non conductive under normal conditions [1].

1.2. Importance of leakage current for electrical devices

In case of commercial electrical systems and household appliances, the leakage current is directly related to public safety. To understand this fact, consider an electric motor with weak winding insulation. Due to long time running, heating or some other factor, insulation may wear at some point. The voltages at that point will be transferred to core of motor. The core is connected to motor body; so, a voltage will appear at outer surface of motor body. If the body is grounded, this voltage will cause a net current flow to ground. This current is drawn directly from point of insulation failure. The magnitude of this current depends only on the resistance of ground. Depending on ground resistance there can be two cases.

Case 1. The total resistance between the point of insulation failure and the ground is of the order of 1 to 10 ohms. In this case, very high current can flow and it can cause winding of motor to burn or tripping/opening of safety device if attached. The safety device can be a circuit breaker, fuse, *etc.*

Case 2. Total resistance between point of insulation failure and the ground is higher than 100 ohm or more, the current here will be limited to safe value. This will be called leakage current. Safety device may not operate at this value of current. In this case the body of motor will be having a considerable amount of voltage and may cause a shock to a person who touches it.

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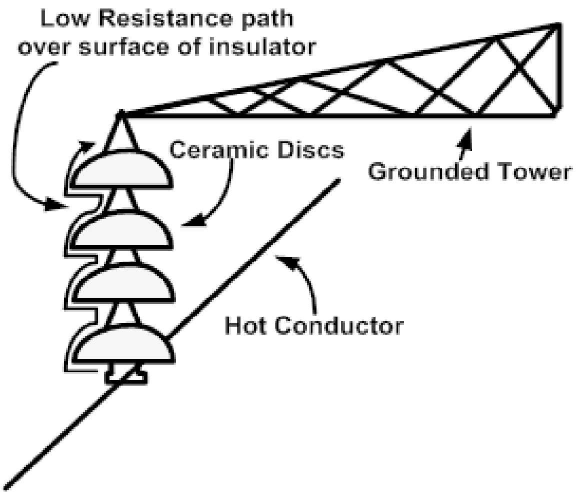

Fig. 1. Low resistance path over the surface of an insulator.

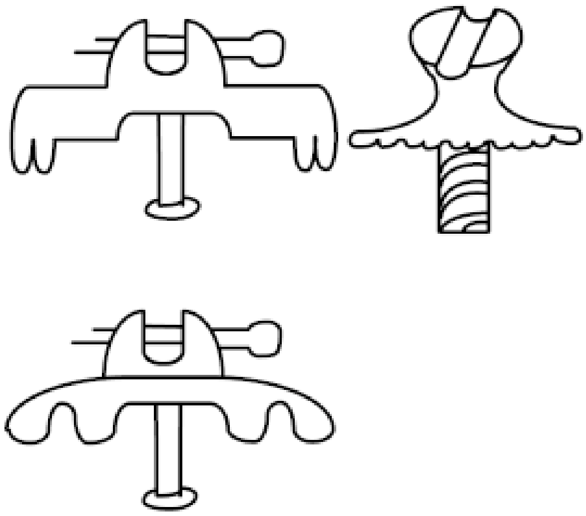

Fig. 2. Ceramic insulator shapes with increased leakage resistance.

It is quite clear that the leakage current either for a device or for insulator is drawn from the main supply and it never contributes to developing any useful power in the load and hence causes wastage of power. That's why it is very important to minimize leakage currents in all electrical and electronic devices/loads. This is also needed to eliminate safety hazards. The standard manufacturing procedures use special test equipment called HIPOT tester; it is discussed in Section 3.2.

1.3. Importance of leakage current for insulators

1.3.1. Importance of leakage current for ceramic insulators

In case of insulators, the leakage current may not always pose a public safety hazard. Still it becomes a very important factor to consider in design, selection, and installation of a transmission line. The reason for this is the insulator itself whose performance is drastically affected with increased leakage current.

The current cannot pass inside the insulator, but a path of relatively low resistance exists over the surface as shown in Fig. 1. This is actually the interface between insulator surface and the air. This path has low resistance than the air around insulator. This is more accurately called surface leakage current path.

A small amount of leakage current flows over this path and can never be eliminated at all. However, very low levels of leakage currents have been achieved in modern insulator designs. Before invention of polymeric insulators, the ceramic insulators with reasonably low leakage current were common. Such insulators are still available in form of discs of different sizes and diameters as shown in Fig. 2; these insulators can be attached together to make an insulator for any voltage level.

The lower side of discs (see Fig. 2) has the grooves. These are meant to increase the surface leakage path and, hence, leakage resistance. The leakage resistance is directly proportional to length of surface of insulator from energized end to dead end. The increase in leakage resistance decreases the leakage current. If we don't use such a grooved structure then we have to increase the overall length of insulator string by adding more discs; this approach is not cost effective. But the more severe problem is the increase of the swing of conductors attached to it. It may result is sever conductor vibration and even breaking of conductor. Another question arises is why not to use these grooves on upper side of discs also. This has been tried in past a long ago and resulted in severe pollution accumulation on upper side creating bowel like structure upward that easily fills with dust and salt pollutants and never be washed with rain. Hence, no ceramic insulator today has grooves on top side. The shape shown in Fig. 2 is final after many research and field experiences.

Because of increasing pollution deposits, the leakage current of all ceramic insulators increases

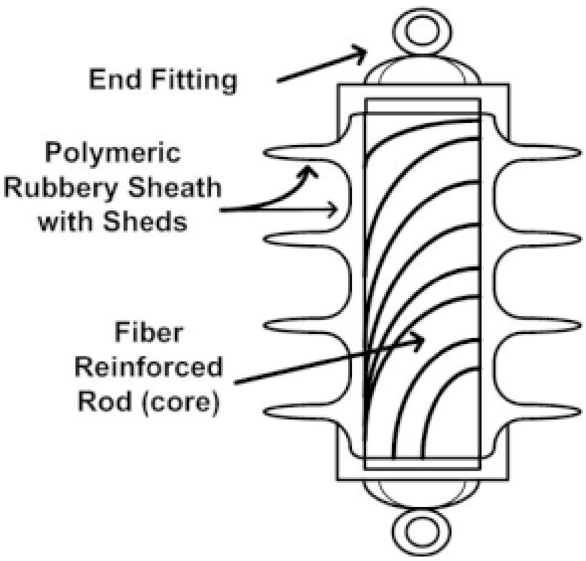

Fig. 3. Polymeric insulator with rubber sheds.

with time gradually. This continues until they reach a point of maintenance or damage by flash over. Maintenance is always required for keeping it at safe levels. The leakage current also varies temporarily due to environmental changes like rain, humidity, temperature, *etc*. But in most cases, these changes don't require attention unless pollution deposits increase considerably.

1.3.2. Importance of leakage current for composite insulators

For composite insulators which have been introduced commercially about 25 years ago, the leakage current is also an important factor to consider. However, the design of these insulators is such that they offer a very high surface leakage resistance. This structure has a fiber reinforced rod as the main strength member, which is covered on outside by a polymeric rubber. The whole structure is then fitted with two end fittings to make a complete insulator in one assembly. This is the reason they are called composite insulators since the complete insulator is one unit as shown in Fig. 3.

The rubber covering the rod is not straight but molded to give a shape of what is called a weather shed. Many types of polymeric rubber have been used by different manufacturers of polymeric insulators. But since all them belong to rubber family, so they have good leakage current suppression ability. The beautiful feature of these insulators is their uniform distribution of electric field and, hence, the stress over their surface. This is due to the fact that all insulator surface from energized end to dead end is of same material and molded in one cast.

Increasing pollution deposits with time do not always increase the leakage current of composite insulators. Instead there is a complex phenomena involved in it.

Composite insulators are made up of polymeric materials which are organic in nature. All organic compounds decay in natural environment. So do the composite insulators also. This process is called aging of insulators [2]. The leakage current of insulator depends on surface resistance which, in turn, depends on its hydrophobicity. These insulators have shown a cyclic decrease and then the recovery of hydrophobicity with time. Even if pollution deposits become heavy, these insulators make them hydrophobic by transfer of LMW [3,4]. Due to this reason leakage current does not increase continuously. In fact, it may happen that leakage current first increases for about a year and then starts decreasing. As an example for a composite insulator, you can expect a leakage current of 5 mA after one year of service and a leakage current of 2 mA after 2 years of service.

So the obvious advantage of these insulators is that without maintenance and even under heavy pollution deposits they maintain safe values of leakage currents for long time. However, temporary variations in leakage current due to environmental changes for these insulators are similar to that for ceramic ones.

2. TYPES OF LEAKAGE CURRENT

There are two types of leakage current:
1) DC leakage current;
2) AC leakage current.

2.1. DC leakage current

It can be caused when a source of DC voltage is shorted directly or with a very low resistance onto itself; it usually applies only to appliances using high DC voltages only. Many consumer appliances use low voltage DC levels below 48 volts, at these voltages leakage current is not an issue to consider. For example, a radio using 6 V DC from AC gets developed a partial short path between its DC voltage and neutral of step down transformer. Such a fault will only cause a few milliAmperes of current to flow. Such a flow will be called DC leakage current because it will be only one directional and constant in magnitude. This may not even cause any effect on working of radio and user cannot even detect it.

But it does not mean that DC leakage current is always harmless or unimportant. To understand its importance, consider a CRT picture tube with high voltage fly back transformer. A worst nature of DC leakage current can occur if the voltage from output of fly back finds a low resistance path to its own ground. In most cases, a small amount of current flowing to such a short will burn the fly back itself. In worst cases, it can cause a fire or shock a person due to appearance of a very high voltage at mounting screws of CRT.

DC locomotives also have some issues related to DC leakage current, but they are mostly obsolete these days. In places where it is used, satisfactory results have been achieved, especially after the commercial introduction of twin disc polymeric insulators. Few problems or accidents are ever reported due to leakage current in other DC systems.

2.2. AC leakage current

AC leakage current is very common phenomena and applies to many electrical devices and insulators. It will be discussed separately for electrical devices and insulators.

2.2.1. AC Leakage current in electrical devices

AC is the current that is caused by parallel combination of leakage capacitance and DC resistance between a voltage source and grounded conductive parts of a device. In all electrical devices, leakage current caused by capacitance dominates over the leakage current caused by DC resistance. The reason is that DC resistance is made sufficiently high during design to minimize DC leakage current. So, we can say that major source of AC leakage current in electrical device is leakage capacitance.

However, capacitances aroused there between hot and grounded parts of electrical devices are sometimes intentional and sometimes not. Intentional capacitances are due to use of capacitive filters. Unintentional capacitances arise at places like between two adjacent tracks in a PCB, insulations between semiconductors and heat sinks, *etc*.

The insulation failure is always unintentional and causes a flow of either leakage current or short circuit current. The short circuit current can not flow for long time, because it either burns out the appliance or operates safety breakers. The leakage current, however, can not be detected easily. That's why some times called "silent current". When leakage current is due to insulation failure, it is independent of capacitances.

Table 1. Leakage current values from IEC950 standards.

Device Insulation Type		Maximum Safe Leakage Current
Double Insulated		0.25 mA
Grounded	Hand Held	0.75 mA
	Movable	3.5 mA
	Stationary (Not Mounted)	4.0 mA
	Stationary (Permanently Mounted)	5.0 mA

2.2.1. AC Leakage current in insulators

The major part of leakage current in insulators is contributed by DC resistance of the surface. This is contrary to case of electrical devices where capacitive leakage current dominates. The reason is that insulators are used at power frequencies. The power frequency is not higher than 60 Hz anywhere. At this frequency, the skin effect and capacitance are low and constant; the change occurs only in resistive component of leakage current. Therefore, in most of research regarding characteristics of insulators, only surface resistance and resistive portion of leakage current are taken into account [5-7].

2.3. Safe levels of leakage current for electrical devices

For all consumer and medical devices, safe values of leakage currents are specified by IEC950 safety standard; values for double insulated and grounded devices are listed in Table 1.

2.4. Allowable levels of leakage current for insulators

The leakage current values for insulators are not fixed and yet not defined strictly by any standards

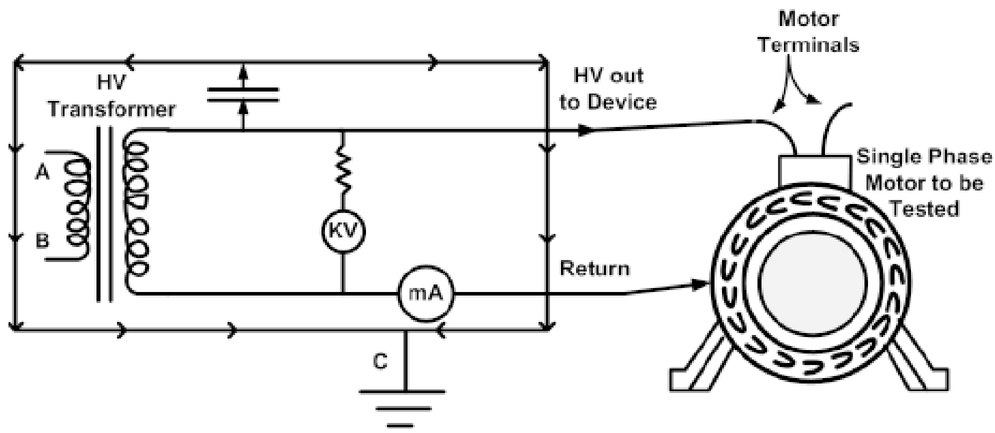

Fig. 4. Basic Circuit of a HIPOT tester and connection to test a motor insulation.

organization. The major reason is that insulators are always mounted at height; therefore, their leakage current limit is set according to reliability of operation rather than safety. So we can not state an exact value of maximum leakage current for any insulator. Instead, a limit is defined by power companies; this limit also varies from country to country and even sometimes within a country. For any transmission line, this limit is defined regarding the type of insulators used, voltage rating, and quality of service required and limits of losses for that line.

However, the maximum limit in any case is 100 mA, although observed values in dry weather lie from a few microamperes to 5 mA. In wet weather, the leakage currents spikes of up to 50 mA or so are considered safe and OK.

In service, online leakage current monitoring system developed at Monterrey, Mexico [5], have shown leakage current peaks of even 450 mA on actual insulators in outdoor environment just after two months of installation. However, this was a rare case and never happened again after those faulty insulators were replaced.

3. LEAKAGE CURRENT MEASUREMENT OF ELECTRICAL DEVICES

3.1 Direct measurement [1]

In most cases, direct measurement has sufficient accuracy and a meter specially designed for measuring leakage currents is used. The current flowing in the ground conductor is measured by connecting the meter in series with the grounding connection of the device concerned. For information processing equipment, the ground connection is opened and the current flowing to the neutral side of the power line is measured. For medical equipment, the current flowing to ground is measured. The meter may also be connected between the outputs of the power supply and ground. The test conditions include swapping the AC line and neutral connections, and turning power switches off and on while monitoring the current. The test is performed after the equipment has warmed to normal operating temperature and, in some cases, following certain tests that cause abnormally high temperatures within the equipment. The intent is to identify and measure the worst-case leakage current [1].

For very low leakage currents, the meter is replaced with a network consisting of either a resistor or a resistor and capacitor combination. The voltage drop across the network is then measured using a sensitive AC voltmeter. Ungrounded or double-insulated equipment is checked by connecting the meter between any touchable conductive part and ground. In the case of nonconductive housings, a copper foil of a specific size is placed on the housing, and the current flowing from it to ground is measured.

3.2. HIPOT leakage current testers [8]

The HIPOT test also called Dielectric Withstand Test is a routine test that is performed in electrical production industry. This is a high voltage test that stresses the insulation of an electrical product far beyond what it will encounter in normal operation throughout its life. If the insulation of product can withstand a much higher voltage for a given time then it can withstand normal voltage for its whole life.

The basic function of HIPOT tester is to monitor excessive leakage current to ground. The excessive leakage current flowing to ground indicates a fault in insulation. Hipot tester applies a high voltage across the insulation of device that is tested. This voltage is usually greater 1500 Volts or so to test a device that is intended to be used on 220 Volts, a typical circuit and test connections are shown in Fig. 4. Terminals A and B are connected to supply voltage of 220 or 110, terminal C is grounded, return lead is floating as shown here. The device to be tested should be placed on some insulating surface separated electrically from ground and device is connected between return lead and HV out terminal. Connection for testing a motor is shown in Fig. 4. Motor's case is isolated from ground, one lead from winding is connected to HV out probe and return lead to motor body. This applies high voltage across winding and case. If winding is weak or short at some point to case a current will flow to return lead and mA meter will show that current. Almost all HIPOT testers have an over current trip to protect the tester itself. This is necessary in case if device is totally shorted to its body and excessive current flows on application of high voltage from HIPOT tester.

Some older designs of HIPOT testers had their return lead also connected to transformer core and ground. This causes a potential problem since a certain capacitance is always present between transformer windings and core. This capacitance also causes a leakage current to flow to return lead and hence pass through the mA meter. For this reason, the device will show leakage current without any device connected. Alternately, we can say that device will monitor its own internal leakages; this causes an error in actual current what user is attempting to measure. In past solution to this was to offset the internal leakage current by an offset circuit, but this approach too has many drawbacks. Most of HIPOT testers come with floating return as discussed above.

It is also very important to keep in mind that a HIPOT tester HV probe and return should never be connected across both terminals of a device, *e.g.* two motor terminals in above case. This will obviously burn the device and/or damage the tester itself.

3.3. Leakage current monitoring of surge arrestors and HV devices.

A common technique is to employ a unity value resistor is series with surge arrestor and take samples of voltage across it. The samples can be taken at fixed interval or depending upon value of sample. In second method, samples are also taken at regular intervals, but only a value greater than a preset is recorded and all others are discarded. This results in samples of increased and abnormal values only. Such a scheme has been used in many researches [9-11], more detail on surge arrestors leakage current characteristics is given in [12,13].

4. IMPORTNACE OF LEAKAGE CURRENT FOR INSULATORS

In any service environment where insulators are used, pollution exists. In some areas level of pollution is low and does not requires maintenance and cleaning of insulators even for long times. But in majority of environments like coastal and industrial areas, insulators get severe pollution deposit. These deposits upon wetting can discharge and dry band arcing over surface. This causes degradation and may lead to flashover [14].

Flashover is formation of arc over surface of insulator. This arc may sustain for long duration to cause insulator break down or for short duration to cause dips in transmission voltage. It is quite necessary to prevent flashovers in all conditions of weather. This requires regular checking of pollution deposit on every insulator and cleaning/replacement of dusty/faulty insulator respectively. But it is very difficult to examine energized insulators due to their height, voltage across them, and their location. Transmission lines pass through mountains, terrains, and horrible places. The idea of monitoring insulators on them physically/manually is totally out of scope.

So we need to detect when a certain string of insulators or all insulators in an area require cleaning/replacement. The surface pollution changes two major characteristics of insulators which are Hydrophobicity and Leakage Current.

All methods of hydrophobicity measurement [2] require human intervention close to insulators, which is obviously not possible on energized insulator on a transmission line. The leakage current measurement, however, is very feasible. It is thus very popular and widely adopted all over the world for condition monitoring of energized transmission line insulators. Usually, a hardware that measures and transmits the value of leakage current is installed on a few towers and readings are observed in substation at remote area. Depending upon these values of leakage, current maintenance is scheduled. The methods developed for this in different areas of world will be discussed in Section 5.

The leakage current is directly proportional to surface pollution deposit. As the pollution layer becomes thick, it traps more water under rain or wetting conditions. The more water on surface, the less is surface resistance and more is the leakage current. However, a temporary rise in leakage current value is not taken as indication of maintenance required. The reason is that it can only be due to increased humidity around insulator. Such a condition can be guessed by analyzing decreasing values of leakage current for few hours after an increase has been observed.

The behavior discussed above applies in general to all types of insulators. But polymeric or composite insulators may show a deviation. It means that a composite insulator can have a low value of leakage current even with heavy pollution deposit. If this happens, the reason is that composite insulators have Low Molecular Weight components (LMWs), which are highly mobile and responsible for surface resistance. Pollution deposits reduce surface resistance, but with passage of time, some of the LMW in bulk of insulator migrate to pollution layer [3,4,15]. This makes pollution layer more resistive and, hence, enables composite insulators to maintain low leakage current values even in presence of pollution layer.

Many setups for leakage current monitoring of energized ceramic and composite insulators have been developed, they will be reviewed now.

5. LEAKAGE CURRENT MEASUREMENT IN SERVICE INSULATORS

5.1. 275 KV transmission line insulators leakage current monitoring setup [6]

This setup was constructed by Queens Land Electric Company (QEC), Australia in 1978 to investigate long and short term outdoor performance of insulators. Initially, it was without leakage current monitoring. After several failures, QEC initiated a project to develop leakage current monitoring in late 1980's. The test site chosen was a highly polluted industrial area with coal burn offs and saltish pollution. The industrial pollution in that area also contains sulphates. The sulphates under wet conditions are more conductive than chlorides which are also found in coastal areas [6]; this was the reason to choose industrial area for this testing.

This setup consists of ceramic and composite insulators installed in bridging positions on the on the tension tower at each of three cross arm levels. Composite insulators were main concerns which were installed in series with good quality ceramic insulators. The purpose of ceramic insulator was to get leakage current reading. Transducers for monitoring leakage current were attached in parallel to these ceramic insulators. One may think that presence of ceramic insulator in series reduced the actual leakage current of composite insulator. This is true, but not leading to false results. The reason is that the change in leakage current under different weather and pollution conditions is more important than to monitor installed value of leakage current [16]. It is obvious that ceramic insulator in series will cause a less leakage current than if composite insulator was present alone. But this will not stop the changes in the value of leakage current that composite insulator will cause due to environmental factors.

The values from all twelve transducers on four towers go to data center. The data center has an A/D converter, signal conditioner, and a multiplexer. The signal after passing from these devices is given to a fiber optical emitter and conveyed to swan bank power station in Australia over fiber cable. At this station, leakage current data is continuously analyzed taking 20 minute average base.

The results indicate best leakage current suppression capability of Silicon Rubber (SiR) insulators. Decreasing length of a certain SiR insulator from 6112 mm to 4801 mm only caused a very slight increase in leakage current. The EPDM was found to come next with 2 to 3 times the leakage current of SiR. However, after every prolonged rain, these current levels decreased. It was observed that rain did not remove pollution from composite insulators sufficiently; still these insulators preserve good leakage current suppression. The reason for this is LMW transfer to pollution layer making it hydrophobic [17].

From the results of this site, it was also noted that strings of porcelain performed reliably but have poor leakage current suppression compared to composite insulators under wet and contaminated conditions.

5.2. Setup to predict leakage current from wind velocity [18]

In this study a mathematical relationship between leakage current and wind velocity has been found. The relationship provides a good resemblance with actual measured values of leakage current.

The leakage current of polluted insulators depends on exposure time, insulator weight, static arc constant, and wind velocity. The effect of all these factors was monitored by aging the insulators on 275 kV line in YTL power station, Malaysia. Leakage current was measured using an electrode near first dead end shed of insulator. The highest leakage current peaks were monitored along with wind velocity. Using all this data and dimensional analysis technique, a relationship was found that is expressed as

$I = D_c (Wv)^b$,

where I= Leakage Current, Wv =Wind Velocity, D_c= Dimensional Constant, b=exponent, more details can be found in [18].

5.3. On-line leakage current monitoring of 400 KV line insulators in Mexico [5]

A system for measurement of leakage current and surface resistance of insulators was developed in Monterrey, Mexico. This system was installed on several towers along the 400 kV line as a diagnostic tool to monitor the surface condition of polluted insulators.

In this setup, the leakage current was measured by using a Current Transformer (CT) with high permeability core. Primarily, the CT was connected directly between the first and second bell of the ceramic insulator string (on dead end) and six turns of wire on CT window as shown in Fig. 5.

Secondary, the CT was given to data acquisition system (DAS) using a coaxial cable. The DAS had three stages. First stage measures the basic value of leakage current using a full wave rectifier to give maximum peak. The second stage measures highest leakage current peak at each semi cycle of signal and the third stage registers and stores data using a microcontroller circuit and memory.

The results showed values from 50 to 150 mA in first two months of installation. But such high values never appear again when some of faulty insulators were replaced once. The authors suggest that cleaning or replacement of insulators is necessary when peaks of 250 mA or more are observed in rainy season [5].

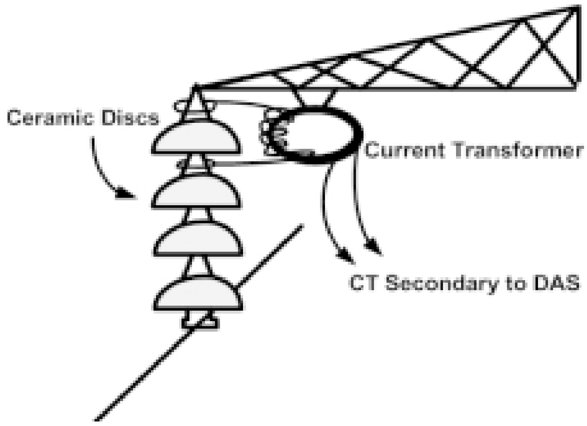

Fig. 5. Current Transformer used as Leakage Current transducer.

5.4. Leakage current monitoring setup for composite insulators in Pakistan [2]

This setup was developed in University of Engineering and Technology, Taxila, to investigate the behavior and performance of composite insulators in the extremely polluted and hot areas of Pakistan. A field test site was also developed in a polluted industrial area in which a facility for fixing the insulators in open atmosphere at height of about 15 meter from ground is available. On this test stand, insulators of various kinds and sizes are attached and energized with high voltage provided by a 10 kV, 1 kVA Commercial High voltage transformer.

A leakage current monitoring system includes a current transducer and a microcontroller based circuit. The current transducer was also installed in series with insulators at dead end and voltage across it was sampled by a precision operational amplifier circuit. This voltage then passed through a signal conditioner and isolator and then given to microcontroller circuit which exports it to computer on RS232 protocol. A simple VB program in the computer stores these values at every 20 minute interval and any value greater than 5 mA that ever occurred.

The composite insulators are energized in this setup since 2005 and still under monitoring. Up till now, satisfactory results on the performance of these insulators have been achieved except two major flashovers which occurred in rainy season of 2006.

5.5. Leakage current monitoring system in Victorian Power Station, Australia [19]

This system was based on computer aided leakage current measurement, recording, and analysis. The notable feature of this system is that it optically isolated the leakage current sensor from measuring and recording electronics. The system comprises of a leakage current collector resistor and optical isolator, electro-optical conversion, optical fiber link, optical to electrical conversion, microcomputer based metering, and recording facility.

The leakage current is collected by a copper ring connected in series between a resistor and grounded insulator end. The AC voltage across this one Ohm resistor is converted into DC by an RMS to DC converter. This DC voltage is then fed to a voltage controlled oscillator which gives a square wave pulse signal. The frequency of this pulse varies in accordance with AC voltage across resistor connected with insulator and hence with leakage current. This pulsating signal is given to optical fiber emitter which does light modulation. The light modulated signal travels over optical fiber and is received by an optical fiber detector at remote end where a computer based data acquisition, analysis, and storage system is present. The problem of transmitting the weak electrical signals over large distance with minimum noise and distortion is successfully solved by use of optical fiber link. Link distances of up to 4 kilometers were demonstrated with this system.

The received signal is given to a Multi-channel Input Card (MIC) whose main purpose is to count the incoming pulses and transfer the result to the computer. Software program converts the output data from the card into actual leakage current values. The sampling rate can be changed from software. This allows changing data rates. A fast sampling rate allows capturing every peak when heavy current surges are occurring, while a slow sampling rate reduces the data and saves memory space when there is low discharge activity. A number of tests were performed on the 66 kV post insulators with various degrees of conductive pollution on its surface. From the results authors have given a relationship for calculation of pollution layer thickness (S) as

$$S = p(r_2^2 - r_1^2),$$

where r_1 = radius of insulator and r_2 = radius of insulator + pollution layer.

5.6. Leakage current monitoring setup for composite insulators in coastal area [14]

This system was established by Chalmers University of Technology in Sweden on west coastal area. In this system a glass insulator is added between the HTV silicon insulator and the tower to allow the measurement of the leakage current. System monitors a total of 20 insulators at a time. The signal across cap insulator is conducted through a coaxial cable along the tower. In case of a flashover the discharge current passes through a lightning arrester flash counter which records the flashover.

The detectors are designed to measure the pulse peak value and consist of four parts: an emitter follower, a comparator, a logic control circuit, and a sample and hold (S/H) circuit. The input voltage is compared with the voltage held at the S/H circuit. This means that the registered pulse amplitude corresponds to the highest value of the pulse peaks arriving to the detector during the sampling interval. All units are monitored by a digital data acquisition system. It is known that the leakage current below 1 mA does not produce significant arcing [20-22]. Therefore, for leakage current values up to 1 mA, the leakage current data is registered every 30 minutes. For values between 1 and 5 mA, the data is registered once every 10 minutes and the recording is done at rate of one per minute for currents higher than 5 mA. All this data is stored in the main computer located at the Chalmers High Voltage laboratory.

The results show that HTV silicone rubber insulators with creepage distance of 27.6 mm/kV showed maximum current leakage current of 2 mA. The same insulator with creepage distance of 17.3 mm/kV showed currents exceeding 25 mA. The maximum current pulses recorded on the porcelain insulator with 30 mm/kV is also 25 mA. So it can be considered that composite HTV silicone insulators maintained high surface resistance under severe salt storm conditions of Swedish west coast. Insulators did not develop any continuous dry band arcing, degradation or erosion even after 7 years of exposure in this environment

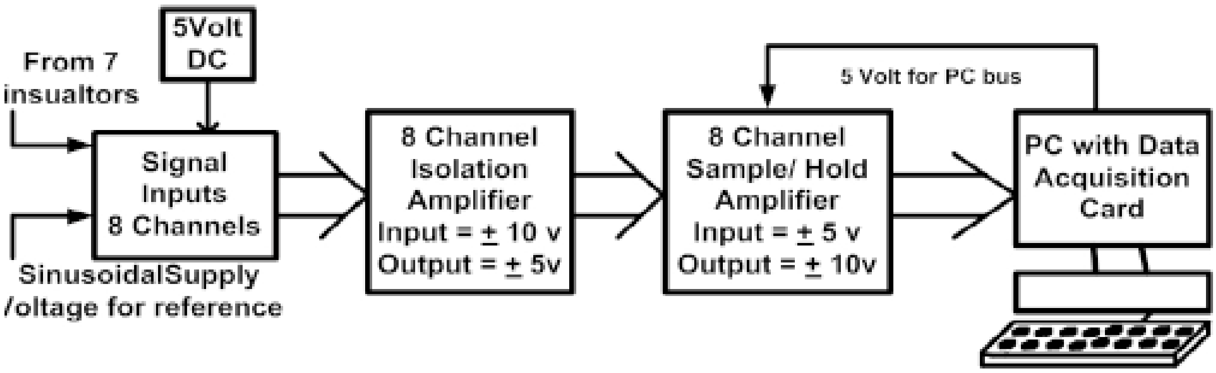

Fig. 6. Block Diagram of MCIC system [data from 7].

5.7. An advanced leakage current monitoring setup for RTV coated composite insulators [7]

A multi channel current integrator-cum peak classifier for on line Leakage current measurement of RTV coated insulators was developed mutually by central power research institute, Uppal and Bangalore in India [7].

It is designed to monitor leakage currents in a maximum of seven insulators. The eighth channel is used to give a reference sinusoidal signal to system. The system uses this signal to detect half cycle duration. This eight-channel system consists of a set of input signal conditioners and a PC-based plug-in multifunction card for digitizing the eight input signals. A Windows-based MCIC software program developed in Lab VIEW controls the digitizing hardware.

The MCIC system has been fabricated by the following components: (1) sample and hold register, (2) isolation amplifier, and (3) data acquisition system. These components, along with other support components, were integrated on a printed circuit board (PCB) to form a data acquisition system. A block diagram of the MCIC hardware configuration is shown in Fig. 6. The MCIC system accepts eight analogue voltage inputs with input isolation up to 1500 Volts.

The MCIC system analyses the leakage current online and stores the values of average leakage current, peak leakage current, pulse count, charge, and current squared integral.

Samples of porcelain and RTV coated insulators were aged in a chamber for about 70 hours. Leakage current, accumulated charge, and pulse count (any leakage current peak greater than 50 mA) were monitored using MCIC system. The other test conditions are given in [7]. The results show that the RTV coated insulators have conducted much less leakage current, accumulated less charge, and less pulse count as compared to the porcelain insulators. The low leakage current of RTV coated insulators is due to hydrophobicity of the coating, which also results in less charge accumulation and less pulse count.

5.8. Leakage current measurement by wavelet transformation and instantaneous sampling methods [23].

This setup was developed in Japan by Chubu University. The setup was actually developed for many other purposes including leakage current monitoring of Composite insulators [24]. Salt fog ageing tests were conducted in this setup according to the specifications given by CIGRE WG 15-06 [25].

The research described in [23] was done to investigate what kind of leakage current is most influential on aging deterioration of polymeric insulators. How different leakage current measuring methods give results and what is the effect of UV radiation on leakage current.

Insulators were subjected to salt fog test in chamber. The leakage current was measured by measuring voltage across a 100 Ohm resistor placed in series between the insulator sample and ground. This voltage was converted into digital value by an A/D converter and then given to computer via RS232 interface for recording. Half samples were aged without UV radiation and half with UV radiation of 15 mW/cm^2. All specimens were of 250 mm length and 30 mm diameter. Leakage current was measured by two different methods [26].

Method 1: This method was adopted to see the effect of UV on leakage current. In this method, the wavelet transformation of leakage current measured by sampling rate of 10000 per second was determined. Leakage current was divided into three components: conductive, dry band, and pulsive. Most of degradation among these components is caused by dry band arcing [27].

Conductive components are components which have the shape providing voltage supply with minimum distortion. Pulsive component appears like surges on conductive current shape, and the dry band arc component is that lags more than $\pi/10$ from supply voltage.

The results show that samples exposed to UV radiation have smaller values of leakage currents than those which were not exposed to UV. The reason could be drying of surface due to heating caused by UV. The dried surface also has more hydrophobicity. Accumulative charge was also less on samples exposed to UV as compared to others [23].

Method 2: This method was adopted to see the effect of UV radiation on aging deterioration. In this method the instantaneous magnitude of leakage current was measured by sampling rate of 1000 per second and accumulated charge was calculated. Minimum measurable value of leakage current is 1 mA. The occurrences of 10, 50, and 100 mA surges were also counted every minute.

The results from this method did not show any count of leakage current pulses of 10, 50, or 100 mA for silicon rubber samples. Only surges of 10 mA were observed on porcelain insulators. But even porcelain did not have any surge count of 50 or 100 mA. Based on these authors claim that surge counting levels of 10, 50, and 100 mA are too high and meaningless, when trying to investigate aging deterioration of composite insulators.

5.9. Transmission of leakage current reading using RS-485 protocol [11]

This system was designed for continuous leakage current monitoring of metal oxide surge arrestors on many towers and its transmission over RS-485 bus to a single computer. However, the same system can be used for insulators also. The leakage current signal is taken from surge arrestor by inserting a series resistance and measuring voltage across it. This voltage is given to data sampling unit that transforms it into RS-485 protocol which can be transmitted over to a PC at comparatively long distance, more details can be seen in [11].

5.10. Software algorithms for leakage current monitoring systems

Reference literature contains a small number of works on the software aspect of systems for leakage current monitoring. A good work has been presented in [28]; in this paper, algorithms are developed for detection of leakage faults from monitoring data. These algorithms are developed on the base of fault lists, they help to find out a fault condition by analyzing previous fault lists. Further details can be seen in [28].

6. ELATIONSHIP BETWEEN LEAKAGE CURRENT AND OTHER FACTORS

6.1. Leakage current and degradation of composite insulators [27]

A correlation between progressive degradation and the changes of leakage current components was investigated in this study. Leakage current was monitored by a data acquisition system (DAS) with 12-bit, 8-channel analog/digital (AD) converter. The DAS consisted of a 12-bit, 8 channel AD converter which sampled the leakage current on all insulators continuously. The sampling rate of the AD converter was 12.5 kHz. A microcomputer was used to get peak and average values and the integral of the current to yield cumulative charge from sampled values. The numbers of leakage current pulses in the range of 10, 10 to 30, 30 to 50, and >50 mA were measured.

The most important result of this research is that degradation can be observed from waveform of leakage current. A distorted waveform of leakage current is a sign of degradation. The extent of distortion can be found quantitatively by measuring the ratio of Peak to RMS value of leakage current.

6.2. Leakage current and hydrophobicity.

Leakage current is directly proportional to hydrophobicity loss, especially for composite insulators. The more is the loss of Hydrophobicity, the more the leakage current becomes; this fact has been reported in many studies [23,29-31]. The leakage current monitoring requires no need to use complex image processing softwares to estimate surface deterioration. The measurement of leakage current just needs the computer to record its values after a certain time intervals or after some certain changes in value of current as discussed in Section 5.6.

6.3. Leakage current and EQ. Salt deposit density (ESDD)

This relationship was investigated in [5] and also reported by [32]. Leakage current was found directly proportional to ESDD. The lower is the leakage current, the lower is the ESDD and vice versa. The same behavior was also observed in aging of composite insulators in Pakistan [2]. The surface resistance is inversely proportional to ESDD.

6.4. Leakage current and flashover voltage

The flashover voltage decreases with ESDD increase [32,33]. But ESDD is directly proportional to leakage current, so we can conclude that as the leakage current increases, the voltage at which flashover will occur decreases. In other words, leakage current is inversely proportional to flashover voltage.

6.5. Leakage Current and Humidity

Leakage current increases as the humidity increases [2,23,30].

6.6. Leakage current and UV radiation.

UV radiation applied on composite as well as ceramic insulators causes a reduction in value of leakage current [2,23].

6.7. Leakage current and insulator length

Increasing of the surface creepage distance of ceramic insulator helps to reduce the leakage current, the same is valid for composite insulators; however, the composite insulators in some places have shown a very slight effect of surface creepage resistance on leakage current. Investigation on decreasing in the length of a certain SiR composite insulator from 6112 mm to 4801 mm caused a very slight increase in leakage current only [6].

6.8. Leakage current and temperature

Temperature changes produce negligible effect on leakage current value.

6.9. Effect of fillers adding on leakage current of composite insulators

Effect of ATH (alumina Tri-hydrate)adding was investigated in [12]. It was seen that adding ATH up to 50 pph decreased leakage current value, but adding a very high amount of ATH again increased it. So a low amount of filler is suggested helpful if one is wishing to make a material with reduced leakage currents. Adding to much filler destroys the purpose.

6.10. Leakage current, corona, and dry band arcing [12]

Under a case when a small dry band arcing starts, the leakage current becomes resistive in nature and its waveform becomes non-linear. This waveform shows distortion from the basic sinusoidal shape. Leakage current waveform also has spikes which correspond to occurring of corona.

7. DISCUSSION

The significance of leakage current for all electrical devices and insulators can never be ignored. Leakage currents flowing towards grounded parts of electrical devices directly pose a public safety hazard. Insulation weakness/failure is only reason for this. The ordinary measurements of leakage currents can be done using µA meters.

Leakage current in case of high voltage insulators are important to consider even they may not always pose safety hazard for public. The reason is that insulators are also affected a lot with the amount of leakage current flowing on their surface. Increase in leakage current causes a net generation of heat on surface. This heat damages the insulator surface and also causes a slightly burned path with low resistance over the surface. Such a path gives rise to dry band arcing. This can lead to failure or flash over of insulator. Ceramic insulators can shatter upon excessive dry band arcing and composite insulators although will never shatter, but are affected in a more complicated way as the heat of excessive dry band arcing causes scission and loss of the low molecular weight components (LMW) chains in silicon rubber layer of composite insulators. The loss of LMW's causes a reduction in surface resistance. Even it was found in [34] that ceramic insulators coated with thin layer of silicon rubber performed excellent in contaminated conditions. The reason is transfer of LMW from rubber layer to surface of pollution deposit same as it occurs in case of composite insulators.

The other diagnostic techniques currently in use for accessing insulator surface degradation are surface conductivity test, hydrophobicity measurement, equivalent salt deposit density (ESDD), method of measurement of flashover voltage (FOV), leakage current monitoring, *etc*. Among these, leakage current monitoring is considered most suitable as it is easy and possible while insulators are energized on-line [27].

The major environmental factors effecting leakage current are humidity, rain, and salt/pollution deposits. On newly installed insulator, leakage current is low but as the pollution deposits on the surface and insulator is wetted by humidity/rain, the leakage current increases. The initial values of leakage current for SiR composite insulators were observed approximately half of those for the EPDM and quarter of those for ceramic insulator. For composite insulators, there is a small variation in leakage current values observed with time.

Generally, it is known that the leakage current is divided into three parts, first one caused by dry band arcing, second by presence of some electrolyte on surface which cause conductivity and third one is pulsive. Pulsive part is contributed due to lightening and other switching surges and lasts only for short times and least dangerous. The current caused by electrolytic conductivity is not considered dangerous because heat generated by it is transferred to the surface indirectly from the liquid film. Only dry band arcing is considered most dangerous because it directly heats the surface and thus results in larger degradation. Visual inspection results from leakage current sites have shown that the degraded surface is divided into two different areas depending on the erosion level; less eroded grounded top area and significantly eroded energized bottom area [27].

To create best insulator designs, it is necessary to study in detail the establishment of dry-band arcing current on material samples and full size insulators. Many studies are still in progress at different areas of world. The aging cycles simulated in laboratory setup sometimes apply too much simultaneous stresses which are never encountered in filed. Such tests yield a failure of insulator but are not realistic.

8. CONCLUSION

To detect leakage current levels accurately for production line equipments, HIPOT tester with floating return is a good choice.

The most common approach, used at many sites of leakage current monitoring, is to measure leakage current by inserting a precision unity value resistor or special purpose current transducer(e.g. a CT with high permeability core) in series with insulator and to measure voltage across it. This voltage is then translated to actual values by some microcontroller and/or computer system and software.

Ceramic insulators are known to increase their leakage current with increasing surface pollution deposits. The same does not exactly applies to composite insulators which are well known for their degradation and then recovery of surface resistance [3,4,15,27,35,36].

Before developing a laboratory aging cycle, it is necessary to conduct outdoor leakage current monitoring effect of dry-band arcing on actual insulators. The dry band arcing has been found major degradation factor.

In general, it is reported form many sites that leakage current values are lower in actual field conditions, as compared to those obtained in laboratory aging cycles. Based on this, we can say that periods of maintenance predicted from laboratory aging tests can be increased for in service insulators [36].

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