THE BEHAVIOUR AND PERFORMANCE OF METAL OXIDE VARISTOR UNDER THE APPLICATION OF MULTIPLE LIGHTNING IMPULSES

MOHD MUHRIDZA BIN YAACOB

UNIVERSITI TEKNOLOGI MALAYSIA

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MOHD MUHRIDZA BIN YAACOB

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ABSTRACT

The behaviour and performance of lightning protective devices such as the metal oxide varistor (MOV) under the application of multiple lightning impulse are different from that of the standard single stroke test. Since the MOV is the most common, economical and reliable device for low voltage and telecommunication systems lightning protection, a precise method of testing has to be adopted based on natural characteristics of lightning to accurately determine its performance and capability. In this work, a Multiple Lightning Impulse Generator (MIGe) with new electronic delay triggering technique with a voltage capability of 5 kV and a current capability of 1 kA has been designed, constructed and developed in the laboratory to conduct impulse testing based on natural lightning parameters. The generator can produce up to five sequences of impulse voltage and current with variable characteristics such as impulse waveshapes and time interval between impulses. This system also incorporates an electronic triggering and delay circuit to initiate and delay the breakdown process of the sphere gaps. Laboratory studies are then being carried out on 2 kV and 5 kV voltage and 1 kA current ratings metal oxide varistors. The electrical and thermal responses of the device are then being analyzed to determine the effect on the varistor characteristics. From the results it has been found that material degradation has occurred on the MOV test samples when multiple lightning impulse are being subjected as compared to the standard testing procedures. The degradation is shown by reduction in the electrical characteristics where the DC voltage at 1 mA current value reduces more than the tolerable limits of ±10%. The other parameters being studied which are the temperature, insulation resistance, capacitance and partial discharge also showed a considerable effect whereby the percentage change is significant when the multiple impulse is applied.

ABSTRAK

Gayalaku dan sambutan peranti perlindungan kilat seperti varistor logam oksida (MOV) terhadap dedenyut berbilang kilat adalah berlainan dari pengujian piawai yang menjanakan dedenyut tunggal. Disebabkan (MOV) adalah merupakan peranti perlindungan kilat yang paling banyak digunakan, paling ekonomi, serta berkeupayaan tinggi bagi sistem voltan rendah dan telekomunikasi, maka satu kaedah pengujian yang bertepatan dengan ciri-ciri semulajadi kilat perlu dijalankan bagi menentukan keupayaan dan gayalakunya. Dalam kajian ini, sebuah Janakuasa Dedenyut Berbilang Kilat (MIGe) berkadaran 5 kV dan 1 kA dengan teknik pemicuan lengah elekronik yang baru telah direkabentuk, dibina dan dibangunkan di dalam makmal bagi menjalankan pengujian dedenyut berdasarkan parameter semulajadi kilat. Janakuasa ini mampu menjanakan sehingga lima dedenyut voltan dan arus dengan ciri-ciri sebenar kilat seperti bentuk gelombang yang berbeza serta masa lengah antara denyut yang boleh diubah. Sistem ini juga menggabungkan litar lengah dan pemicuan elektronik bagi mengawal dan melengahkan proses pecahtebat pada sela sfera. Pengujian makmal telah dijalankan ke atas MOV yang mempunyai kadaran voltan 2 kV dan 5 kV serta kadaran arus 1 kA. Kesan elektrik dan terma apabila peranti tersebut dikenakan dedenyut kilat dengan parameter semulajadi juga dianalisa. Keputusan dari pengujian makmal telah menunjukkan bahawa penurunan kualiti bahan telah berlaku pada MOV tersebut apabila dedenyut berbilang kilat dikenakan dibandingkan dengan prosedur pengujian piawai. Penurunan kualiti bahan ini ditunjukkan dengan pengurangan terhadap cirri-ciri elektrik di mana nilai voltan DC pada arus 1 mA berkurangan lebih dari had limit ±10%. Lain-lain parameter yang dianalisa iaitu suhu, rintangan penebatan, kapasitan dan nyahcas separa juga menunjukkan kesan yang besar di mana peratus perubahan yang tinggi berlaku ke atas MOV bila dikenakan dedenyut berbilang.

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LIST OF SYMBOLS

μs	-	Microsecond
LIV	-	Lightning Impulse Voltage
t_f or t_1	-	Front time
t_t or t_2	-	Tail time
T_1	-	Time taken for waveform to rise to peak value
T_2	-	Time taken for waveform to decay to half peak value
γ	-	Voltage Index
v	-	Voltage
T_C	-	Critical Temperature
C	-	Capacitor
R	-	Resistor
L	-	Inductor
α	-	Damping factor
C_C	-	Charging capacitor
R_C	-	Charging resistor
S	-	Sphere gap
T	-	Triggering circuit
D	-	Time delay circuit
R_1	-	Front resistor
R_2	-	Tail resistor
t_d	-	time delay
SCR	-	Silicone Controlled Rectifier
^oC	-	Degree of Celsius
E		Applied voltage

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CHAPTER 1

INTRODUCTION

1.1 Background

The stability of power systems is very critical in effective transmission and distribution of electrical energy. If the system is not stabilized, it can result in electrical power system failure. Normally breakdown occurs due to the voltage or current surges resulting from lightning strikes. Breakdown causes loss in productivity and cost. On top of that it may cause great inconvenience to the consumers. A stabilized system will lead to minimization of system failure, continuity of production, uninterrupted output and continuous supply of electricity to consumers.

Lightning strikes have been the most severe problem in the protection of electrical power transmission and distribution. Surges that result from lightning impulses propagate into the transmission or distribution systems and lead to system breakdown. It has been proved that lightning is the single largest cause of power system outages. From studies that have been made, nearly 50% [1] of the outages on systems of 300 kV or above are due to lightning. Lightning also contributes to 26% of the outages on 230kV circuits and 67% of the outages on 345 kV circuits [2,3]. An extensive work which has been carried out in the past has revealed that one of the most important causes of insulation failure is the lightning striking the nearby ground or directly the lines [4,5]. It is also accepted that in the medium voltage (MV) tower lines, the overvoltages induced by the lightning strokes to the nearby ground are the most frequent cause of the insulation failure [6,7]. A recent extensive survey has also confirmed that more than 50% of the faults in the MV lines rated at 10 – 20 kV are caused by lightning [8].

The over-voltage or over-current resulting from a lightning incident will propagate not only into the power line but also into the low voltage systems such as the telecommunication system. These surges of exceptional severity could cause damage to the highly sensitive equipment and also danger to the telephone user. Proper protection system has to be employed in order to prevent these surges from causing major problem to the equipment.

It has been the concern of many protection and insulation engineers on how to protect the transmission, distribution and telecommunication systems from severe lightning surges. Various protective devices have been designed and installed to such systems to withstand the surges resulting from lightning, thus preventing system outages and damage to the equipment. Since the beginning of ac transmission, lightning protection of transmission equipment has been provided by gaps and non-linear resistors. As transmission voltage increases, lightning arresters or surge arresters have been extensively used to replace the conventional method of protection. Surge arresters are applied to protect equipment against the effect of lightning or other surges conducted by system to the equipment being protected. It is used at sub-stations and at line terminations to discharge the lightning over-voltages and short duration switching surges. These are usually mounted at the line end at the nearest point to the sub-station and connected in parallel with the apparatus to be protected. One end of the arrester is grounded and also bonded to the case of the equipment being protected, while the other end is connected to the electric conductor. It reduces the transient system over-voltages to levels compatible with the terminal-apparatus insulation. For protection of lower voltage systems such as the telecommunication system, metal oxide varistors are widely used to suppress the over-voltage or over-current from damaging the equipment. In order to determine the performance and capability of the devices, laboratory tests based on standard procedures are applied before it is being installed. These tests are used as a proof test to the new prototype equipment, whether it can be manufactured or not.

1.2 Natural Lightning Characteristics And Standard Testing Procedures

1.2.1 Natural Lightning Characteristics

Lightning is the flow of electrical charge over a short duration which occurs as the result of atmospheric electrical disturbances. The discharge is associated with the dielectric breakdown of the air as a result of potential differences attained between opposing charge centers. This occurs between clouds and also from cloud-to-earth. The total energy transfer consisting of a number of multiple strokes normally takes place in less than 0.1 second [9].

Lightning strikes can stress electrical equipment by subjecting it to surge voltage and current. Electrical overstress due to lightning is a major cause of insulation breakdown which leads to interruption of power supply. Some parameters concerning the natural event of lightning are as follows:

1. Positive or negative polarity.
2. Associated with downwards or upwards stepped leader.
3. Single stroke or multiple strokes.

4. Current magnitudes vary between a few kA to hundreds of kA.

5. Waveshapes can have rise-time from fractions to tens of μs and decay time duration from 10's to 100's of μs.

It has been found that no standard lightning stroke occurs in nature and the current produced after stroke contact varies over wide range. A natural lightning generates simple unidirectional double-exponential impulses which are complex and oscillatory with multiple strokes in one flash [10]. Theoretical studies and experimental surveys relevant to overvoltage induced on power lines by lightning strikes have also shown that the waveshapes are different from that of the standard impulse in the presently adopted standards [11,12].

A considerable amount of analysis has been made on the frequency of the multiple stroke of lightning. It has been shown that between 60% to 70% of ground flashes have more than one stroke [11,12,17,19-37]. On average there is 3 or 4 strokes/flash and the possibility of more than 10 strokes/flash is about 5%. A multiple stroke ground flash is a sequence of multiple pulses separated by time intervals of tens of milliseconds. These multi-stroke flashes can impose surges of exceptional severity on service equipment such as distribution surge arresters, insulators, etc. In natural lightning discharges, a multi-stroke negative flash is liable to higher energy and there is a higher probability of a continuing current.

1.2.2 Standard Lightning Impulse Testing On Protective Devices

Lightning impulse voltage is defined as a unidirectional voltage which rises rapidly to a maximum and then decays rather more slowly to zero [13]. The waveshape of a standard lightning impulse voltage (LIV) waveform as defined by the testing standard for equipment testing is shown in Figure 1.1 [14]. It is known as a t_l/t_2 or waveform t_f/t_t .

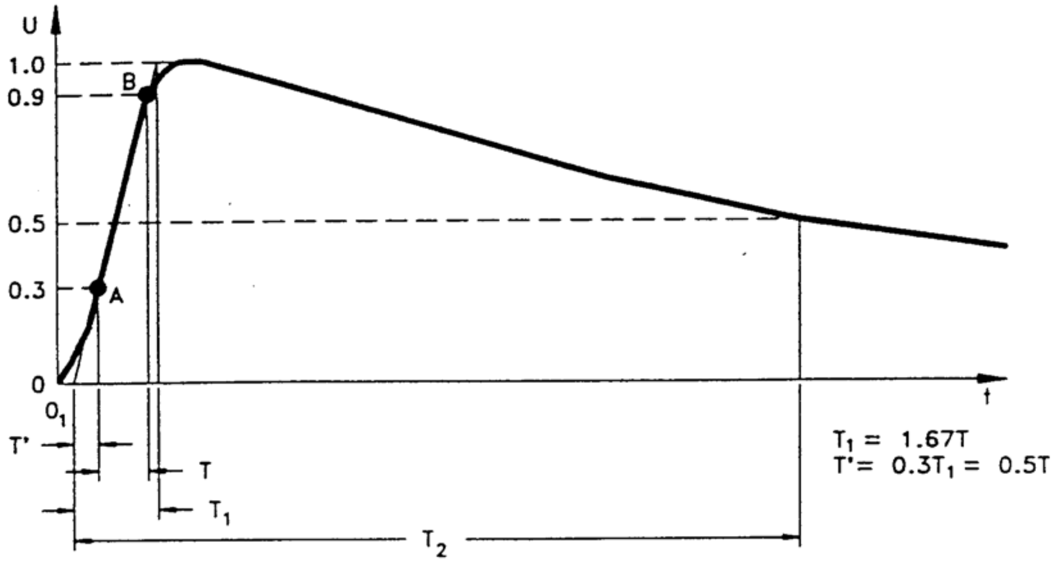

Figure 1.1 Standard lightning impulse voltage

From Figure 1.1, T_1 is the time taken for the waveform to rise from 10% to 90% of its peak value which is known as the rise time. T_2 is the time for the waveform to decay to its half of the peak value. For standard testing, waveshape of 1.2/50 μs and 1/1000 μs is generated in the laboratory for impulse voltage and 8/20 μs for impulse current.

According to the standards [15], the lightning impulse test on surge arresters can be categorized into:

1. Lightning Impulse Sparkover Test
    - i. Application of five positive and five negative polarities of impulses with time interval of 1 minute between impulses.
    - ii. 1.2/50 μs voltage wave shape.

iii. Time interval between start of the wave and the instant of sparkover is immaterial.

2. Lightning Impulse Current Withstand Test
   i. Test on three new samples of complete diverters, sections or non linear elements only.
   ii. Test samples have not been subjected previously to any test except those specified for evaluation purposes.
   iii. The rated voltage of test samples shall, be at 3 kV and not exceed 6 kV.

   a. High current impulse test
      i. Application of two 4/10 current impulse waveshapes.
      ii. The peak values of the impulse current depend on the rating of the diverters.
      iii. For 10 kA rating the peak current is 100 kA.
      iv. For 5 kA rating the peak current is 65 kA.
      v. For 2.5 kA rating the peak current is 25 kA.
      vi. For 1.5 kA rating the peak current is 10 kA.
      vii. Test samples should be permitted to cool down between impulses.
      viii. Time intervals between impulses are determined by the ambient temperature of surrounding environment.
      ix. Examination of the test samples shall reveal no evidence of puncture or flashover of the non-linear resistor or significant damage to the series gaps.

   b. Long duration impulse current test
      i. Application of twenty discharge operations to the test samples.
      ii. Operation on each test sample will be divided into 4 groups of 5 impulses.
      iii. Time intervals between operations shall be 50 sec to 60 sec and between groups shall be 25 min to 30 min.

3. Operating Duty Test
    1. Service condition is simulated by the application to the diverter of a stipulated number of specified impulses.
    2. Application of an 8/20 μs current impulse waveshape having a peak value equal to the nominal discharge current of the diverter.
    3. Twenty impulses shall be applied in 4 groups of 5 impulses.
    4. Time intervals between impulses shall be 50 sec to 60 sec and between groups shall be 25 min to 30 min.
    5. It is not required that the test piece be kept energized between impulses or between groups of impulses.

For low voltage telecommunication system lightning protection, the protective device such as MOV has to be subjected to 1/1000 μs impulse voltage and 8/20 μs impulse current [16].

1.2.3 Comparison Between Natural Lightning Parameter And Standard Testing Procedure

From the testing standard in Section 1.2.2, the difference between lightning impulse testing and natural lightning in the field can be defined as follows:

Lightning Impulse Testing: A single impulse is applied followed after a time interval of many seconds by repeated application of statistically independent impulses.

Natural Lightning in the Field: Multi-stroke ground flashes are a sequence of multiple pulses, three or four on average and are separated by time intervals of tens of millisecond.

Test procedures for determining impulse withstand voltages for equipment with non-self-restoring insulation do consider the possibility of progressive deterioration with repeated voltage applications [17]. Repeated impulse voltage applications will result in temperature rise of the arrester block and heat transfer to other internal components of the arrester which can lead to arrester failure. It has been shown that little or no guidance has been given by standards on high voltage testing to acceptable time intervals between successive applications of impulses.

From standards [18], insulation systems of an apparatus of high voltage structures can be classified into:

1. Self-restoring Insulation
   Insulation which completely recovers its insulating properties after a disruptive discharge caused by the application of test voltage.

2. Non-self-restoring Insulation
   Insulation which loses its insulating properties or does not recover them completely after a disruptive discharge caused by the application of test voltage.

From these definitions, “What will be the response of insulation or equipment if tested with a sequence of multiple impulse applied with time intervals of less than that defined in the standards?”. Daverniza et al [19] concluded that there should be an effect if the test object is non-self-restoring type which retains a memory of the preceding impulse. In this case, multiple impulses will have a very significant effect on the performance and capability of the equipment.

1.3 Previous Studies on Multiple Lightning Effect on Lightning Protective Devices

Procedures in the existing standard to predict lightning performance of systems for the first stroke are well developed [17]. However the effect of subsequent strokes on lightning protectives devices is not catered for. Test and analysis have shown that this effect is a critical factor in lightning protective equipment testing because it will affect the performance and reliability of the device and equipment [12,17,19-37]. A serious consideration should be given to include the testing procedures for subsequent strokes in the existing standard.

The effect of multiple negative strokes lightning to lightning protective equipment and device is unclear. It was suggested that only 30% of the equipment operations show multiple components [20]. However, all field data suggest that subsequent components are more than ample to cause arrester operation. On the other hand, the average of the highest of subsequent components is roughly half that of the first component [21].

A considerable amount of studies have been made on the effect of multiple lightning impulse on lightning protective equipment and device. Melton [22] has conducted a study on the effect of repetitively pulsed operation on metal oxide varistor (MOV). Experimental tests were done to determine the appropriate energy ratings for zinc oxide varistors for pulsed conditions from 10 to 20 ms long. Tests were first performed on single MOV unit which were forced to fail in a small number of shots. Then several sets of matched pairs were operated under identical conditions to investigate current sharing and the statistics of failure. The initial tests were conducted to determine the maximum single pulse energy capacity at different pulse lengths. Test results show that the standard rating method used by the manufacturers relating to peak current, pulse length and expected lifetime are adequate, but somewhat conservative. Failure mode for the MOV’s is found to be different between long and shot duration pulses, where the former produced a lower failure rate. Repetitive application of pulses also resulted in higher failure rate where all the MOV tested failed the test when subjected to 20 shots or less.

Sargent et al [23, 24] performed experimental tests on zinc oxide varistors by applying single or multiple impulse at the rated current of the varistor with a waveshape of 8/20 μs. The multiple current pulses consisted of six current pulses within one second and were applied using a multipulse generator. A microstructural examination and measurement of voltage at 1 mA current flowing of both pulsed and unpulsed varistors were carried out. Results of the test reveal that both single and multiple pulses caused degradation in the breakdown voltage of the varistors. The specimens which had been subjected to multiple pulses showed a significantly greater amount of degradation. The varistors also became appreciably hot and the plastic surrounding the device inflated during application of the multipulses. It was also found that all pulsed specimens contained cracks extending between the two contact surfaces of the varistor. Multiple pulses were seen to be much more detrimental to the stability of a zinc oxide varistor than the single pulse of the same magnitude.

Another work by Darveniza et al [25] which examines the effects of multiple stroke lightning current on low voltage zinc oxide varistors. Multipulse lightning currents were applied to three different types of varistors which are used as the low voltage lightning protection. The dc voltage required to pass a current of 1 mA, often referred as the dc reference voltage was measured for each device before and after the varistor being applied with single and sextuple 8/20 μs impulse currents. This measurement is used as an indication of any changes in the device characteristics. From the test results, the application of sextuple currents of magnitude 75% of the maximum rated current caused a large change in the dc reference voltage and other device characteristics. The main reason for this to happen is the absorption of the incoming transient pulse energy by the varistor. At the end of the second pulse of the sextuple, each device had already absorbed a mean of 68% more than the rated maximum energy. This additive energy absorption was seen to lead to severe degradation of characteristics or destruction. The application of multipulse currents also caused three types of physical damage which is the swelling of the plastic encapsulation surrounding the zinc oxide disc, damage to the disc in the vicinity of the metallised electrodes and complete shattering of the MOV. They also suggested that further work need to be carried out on the multiple lightning effect on MOV.

In another work by Darveniza et al [26, 27], experimental studies were carried out on MOV to investigate the surface flashover mechanisms when subjected to multiple impulse current. Five different types of varistors were used in the test and were subjected to single and multiple impulse current with four successive impulses. The results show that the multipulses are more damaging than the single pulse. Plasma enhancement and varistor surface coating were found to play a dominant role in surface flashover of the device. Bartkowiak et al [28] has made a study on the failure modes and energy absorption capability of zinc oxide varistor by looking into the thermal and mechanical behaviour. The zinc oxide varistors were simulated with current pulses of various magnitude and duration. The purpose of the simulation is to identify failure processes and determine the energy absorption capability of varistor elements. Results of the simulation are found to be in excellent aggrement with the experimental studies. It provides a fundamental explanation of the energy handling depending upon the current surge intensity and duration.

Madhira et al [29] has conducted systematic experiments with the purpose to determine the degradation effect of single and multiple current pulses on the microstructure of MOV. The MOV used in the test were artificially degraded by the application of single or multiple 8/20 μs lightning impulse currents. The electrical degradation of the specimens were monitored before and after the impulse being applied using the diagnostic test. Results have shown that degradation has occurred on the varistors which were subjected to the multiple lightning current where the grain size of the zinc oxide material appeared to be smaller as compared to a new sample. This is due to the non-uniform temperature distribution in the material because of the development of localized hot spot during the multipulse current activity.

Another work carried out by Perrot et al [30] studying the influence of mixed multi-impulse and AC 50 Hz conditions on the operating characteristics of zinc oxide varistor. Results of the test show that non-uniform conduction takes place within the varistor element in the pre-breakdown region and can lead to severe degradations subjected to the mixed multi-impulse and AC 50 Hz conditions. Unlike single impulse testing, dramatic leakage current increase and irreversible breakdown of the material was found to occur under those conditions. Darveniza and Saha [31] also concluded that the application of multiple 4/10 μs and 8/20 μs impulse currents to metal oxide varistor blocks has resulted in severe effect. It has been found that the multipulse current causes surface flashover which is not evident with standard single-pulse test.

Based on data collected from lightning field studies in South Africa, Flugum and Kalb [10] have concluded that the possibilities which may adversely affect surge arrester performance are:

1. The extremely high number of multiple strokes in a flash.

2. Short time interval between strokes.

The median value of the number of strokes in Southern Africa lies between 3 and 4. About 20% of the discharges have a number of strokes which exceeds 6 and the maximum number on record is 25 on the other hand, the median value of the time interval between strokes is 35 ms and a mean value of about 60 ms [10]. Surge arrester duty under the above conditions is much more severe. If a repetitive rate of impulse test is applied to the distribution arresters at a time interval of 50 or 60 ms, if any, arresters would survive more than 5 to 6 such operations. Although laboratory tests are an attempt to simulate natural events, they are always modified by assumptions made by tester in the design and construction of the circuit. From this conclusion, can we expect that modern surge arresters might be able to survive tests based on natural events of lightning?

A study of the performance of distribution surge arresters made by Cleveland Electric Illumination Co. [32] clearly shows that a re-evaluation of distribution arrester standards is required. According to their analysis on field data, lightning causes 33% of permanent distribution outages on power system, which equal to about 2000 outages per year. These lightning-caused equipment failures represent 50% of all fuse blowing, transformer failures and arrester failures, the effect of lightning on the reliability of distribution system is significant, and so are related costs associated with service restoration. Distribution lines with appropriate lightning protection will significantly improve performance and the most economical method of protection is using surge arresters on all phases. In order to verify that the application of arresters on all phases would actually result in the expected improvement in lightning performance, the company has initiated an arrester-testing program on an existing 10 kV distribution-class arrester design. A group of seven utilities was invited and finance extensive and severe tests. The purpose of this testing program was to verify manufacturers' published data regarding the arresters' characteristics and to obtain information about arresters durability and capability. Much of this testing made is beyond the present arrester standards requirements. When subjecting the arresters to the two 65 kA surges utilizing an 8/20 μsec wave, three different arrester designs showed evidence of internal flashover in which one arrester exploded. The results of the more severe non-standard test pointed out important areas on concern on distribution arresters:

1. The fault-withstand test indicated that essentially all standard arrester design have an unsafe failure mode.

2. Wide variation in the surge capability of the various designs when subjected to duty-cycle destructive tests using 20, 40 and 60 kA surges.

Another analysis done by the Cleveland Electric Illumination Co. was on two 13.2 kV rural distribution feeders where they made an inspection on 54 failed arresters from these feeders. On these failures, it was found that 43 were subjected to one to four repetitive lightning surges of 10 to 90 kA and surge durations of up to four times that of the standard 8/20 μsec wave. From the inspection they have made a conclusion that the failure of the arresters was due to the high current magnitude and long duration of the surge resulting in energies in excess of distribution arrester capability. It should be noted that the same arresters have pass the standard design tests before being installed to the system. Based on the author's experience, tests and analysis of surge arresters, it was concluded that existing 10 kV distribution-arrester performance and the standards that perpetuate this performance are inadequate. In order to improve arrester quality, standards must be upgraded such as the application of repetitive of impulses.

Another study was undertaken by Woodworth and Fletcher [33] on the inherent weakness of silicon carbide arresters. From the studies he made a conclusion that the failure of this type of arrester is due to the degradation which occurs to the gap and block structure due to repetitive surge duty. Discharge voltage of silicon carbide arrester increased significantly after a duty cycle or high-current/short duration tests. Gap structure deteriorates with repetitive surge duty due to the relatively high magnitude of power follow current during impulse operation. This deterioration leads to arresters failure by:

1. Sparkover under normal system voltage application.
2. Failure to reseal during an impulse operation.

With the development of metal oxide surge arresters in recent years, many studies have been made on the performance of such arresters. Schei and Ekstrom [20] have made several tests to determine the effect of temporary and transient over-voltages on metal oxide arresters. It is found that temporary and transient over-voltages are stressing conventional arresters with series gaps. Under a sequence of lightning over-voltages, these arresters may conduct a current high enough to cause considerable heating of zinc oxide resistor blocks. This causes a lower protection level and higher discharge energy to the arresters. Results of single impulse tests show that the stresses resulting from application of high impulse current could lead to arrester failure. These stresses can be large considering that one lightning flash consists of more than two strokes. Further more that it has been shown that the energy absorption value for the first and second stroke are found to be similar.

Another work by Ishikawa et al [34] proved that multi-stroke flashes in natural lightning discharges should be regarded as more dangerous than a single-stroke flash. In this work, an entirely new type of impulse generator has been designed which can produce 3-successive impulse voltages to simulate multi-stroke lightning flashes. Although tests were applied on animals, the same effect is expected if the same tests were made on service equipment. This is because a very high energy is absorbed and a higher probability of a continuing current under the application of multi-pulse lightning impulses. Most of the distribution arresters are likely to operate satisfactory under these types of conditions.

To prove that a multiple lightning impulse has a significant effect on electrical insulation and service equipment, a multiple impulse generator was designed and constructed by Sargent et al [24]. The generator can produce up to 6 consecutive lightning impulse voltages of up to 100 kV or of currents up to 10 kA with inter-pulse time intervals between 20 to 130 ms. Preliminary tests were carried out on a number of insulation configurations representative of distribution equipment and distribution surge arresters and fuses. For the electrical insulation, conventional and multiple breakdown test were conducted on:

1. Sphere-sphere air gaps.

2. Rod-plane air gap.

3. Polythene coaxial cable termination.

4. Rod-ring on Perspex.

5. Rod-ring/plane on Perspex.

The first two are air insulation while the others solid insulation. From the results obtained, it was shown that multiple lightning impulses do not produce any effects on the breakdown strengths of the air gaps. For the three different types of solid insulation an observation was made on which particular pulse(s) in the sextuple sequence that caused breakdown. It was found that the most of the breakdown occurred on the first pulse, except for the cable termination, breakdowns often occurred on one of the following pulses, eg. no. 4, 5 or 6. From these results, it seem that multiple lightning impulse has an effect on solid insulation and is worthy of more detailed study.

Multiple duty cycle tests were then applied to distribution surge arresters. The aim of the study is to assess whether the application of multipulse to the arresters causes them to respond differently from the standard duty cycle tests. A small number of used and unused surge arresters were subjected to standard lightning impulse tests and also a multiple lightning impulse test. Results of these preliminary tests show that:

1. Changes occurred in impulse spark-over voltage and discharge residual voltage under the application of the multiple test.

2. Arrester which is damaged by multiple testing may not always reveal their condition when standard tests are repeated.

3. High values of accumulated energy were absorbed during multiple testing which could lead to arresters failure.

From these preliminary tests, it can be concluded that multiple lightning impulse has a significant effect on distribution surge arresters.

To verify their preliminary tests Darveniza and Mercer carried out another multiple lightning impulse test on distribution arresters [19]. A group of 24 distribution arresters including new used arresters were subjected to the tests. The arresters used for the tests include:

1. 21 of gapped silicon carbide type where 8 of them were new.

2. 3 new metal oxide arresters.

The voltage ratings of the arresters ranged from 7 kV to 12 kV and the current ratings are 5 kA and 10 kA. Preliminary operating duty tests were carried out as follows:

1. Single-impulse operating duty tests, in which six 5 kA, 8/20 μsec current impulses were applied at time intervals of 1 minute.

2. Multiple operating duty tests, in which a sextuple train of impulses were applied at time intervals of 35 ms.

Results of the preliminary tests show that some unexpected changes occurred in the arrester characteristics. After the tests have been conducted on all of the arresters, it was found that 8 out of 24 arresters were severely damaged. These 8 arresters were 4 of the used silicon carbide type and 3 of new silicon carbide arresters and 1 new metal oxide arrester. Arresters which failed during the tests were then dismantled and it was observed that there was an increase in the internal gas pressure and extensive burning of the gap components and block interfaces.

A preliminary test of temperature rise was then carried out on one metal oxide and two silicon carbide arresters. A sextuple train of 5 kA, 8/20 μsec current impulses was discharged through the arresters and the temperatures of the arresters were noted. Results of the tests show that:

1. A maximum rise of approximately 14°C above the ambient temperature and required 170 minutes to return to ambient for the silicon carbide arresters.

2. An increase of 35°C above ambient and required 175 minutes to return to ambient for the metal oxide arrester.

As mentioned earlier, the increase in temperature of the arresters valve element is one of the major cause that will lead to the arresters failure.

From these tests, the authors have concluded that:

1. Change in arrester characteristics, such as an increase in lightning impulse sparkover voltage which results in less effective performance of the arrester and not operating at its rated voltage.

2. Multiple current testing caused more damage than the standard impulse current tests and this damage was not always readily detected by standard impulse tests.

RA Ghani [35] has done preliminary studies on the effect of multiple lightning impulses on metal oxide varistor. In his work, investigation has been made on the single and multiple standard 1.2/50 μs and 8/20 μs lightning waveshape effect on the V-I characteristic of the MOV and the thermal response. It has been found that the multiple standard impulse voltage and current waveshapes have given a significant effect on the electrical and thermal characteristics of the MOV.

Another work by N D Mohamed [36] on the application of standard 1/1000 μs and non standard multiple impulse voltage on the MOV. The parameter being studied is the MOV V-I characteristics and the breakdown voltage when the multiple impulse being applied. From the experiment being conducted, it has been found that the breakdown voltage reduces very significantly when the multiple and standard impulse voltage is applied.

These results also show that the effect of multiple lightning impulse is worth further detailed study. The authors also urged that serious consideration would have to be given to incorporating such tests into the standards.

Since most of the modern arresters using either gapped silicon carbide or gapless metal oxide, the existing standards are not sufficient to determine the capability and performance of the arresters under multiple lightning impulse conditions. Results surveyed have a very significant effect on these arresters.

From the literature review, it can be concluded that further study on the effect of multiple lightning impulse on protective device is necessary. Since existing standards do not consider the effect of multiple lightning impulse, serious consideration should be given to incorporating such tests into the standards.

1.4 Research Methodology

1.4.1 Introduction

Literature study has shown that multiple lighting impulse is one of the factors which leads to the failure of distribution surge arresters. When they are subjected to multiple lightning tests, it was found that their response was different from the standard tests. Although preliminary studies have been done on the effect of multiple lightning impulse on high voltage equipment [19,24,34], more tests based on natural characteristics of lightning have to be conducted to protective devices used for low voltage lightning protection device such as the telecommunication equipment. Preliminary work initiated by Darveniza et al [19] is a good starting point on studying the effect of multiples lighting impulse on distribution surge arresters. From this work, the parameters that they used in testing program are as follows:

1. Six successive multiple lighting impulse operation.
2. Magnitude of current is 5 kA.
3. 8/20 μsec waveshape.
4. Constant time interval impulse which in 35 ms.

The device that they used in the testing program are:

1. Distribution expulsion fuses.
2. Distribution surge arresters:
    - Used and unused silicon carbide.
    - Unused metal oxide arrester.

From this testing program, it is found that there are some limitations in the parameters of the lighting impulse which are as follows:

1. Magnitude of impulse applied to the test objects.
2. Constant time interval between impulses.

3. Standard waveshapes.

Apart from the above, the devices being used for the testing programs are only distribution surge arresters.

In order to simulate the natural lightning characteristics, one has to consider the actual parameters that occur during a lightning incident; for example, the time interval between successive impulses should not be taken as a constant value. Field study on lighting parameters has also shown that the time interval between impulses is ranging between 10 to 100 ms [12]. Data collected from field studies of lightning parameters can be listed as follows:

1. Average ground flashes are 3 or 4 stroke/flash.
2. Magnitude of current varies between a few kA to hundreds of kA with a median value of 25 kA [10].
3. Unidirectional double exponential impulses which are complex and oscillatory.
4. Time interval between impulses in the range of 10 ms to 100 ms.

Data analysis collected by the Flugum and Kalb [10] has proved that most of the failures of distribution arresters are due to:

1. Repetitive rate of an operation up to 4.
2. High current magnitude of up to 90 kA.
3. Long duration waveshape of four times the standard 8/20 μs.

It is the purpose of this work to conduct tests according to the actual parameters of lightning. The proposed work can be listed into the following categories:

1. Test is to be made on metal oxide varistor used as protective device in telecommunication system.
2. Sequence of 1 to 4 multiple impulses.
3. Time interval between successive impulse is 40 ms.
4. Standard and natural impulse voltage and current waveshapes.
5. Measurement of parameters such as V_{dc}, temperature, insulation resistance, capacitance and partial discharge to determine the effect during an application of multipulses.

In this study, a comparison between the existing testing procedure and natural characteristics of lightning will be done. Some important parameters of lightning which affect the performance of metal oxide varistor will also be analyzed. These parameters can be listed as follows:

1. Number of strokes/flashes.
2. Time interval between strokes.
3. Impulse current and voltage magnitudes.
4. Current and voltage waveshapes.

With the knowledge of these parameters, a multiple impulse generator will be designed and constructed. This generator will be designed such that it can generate an impulse which has the same characteristics as the natural lighting impulse. Tests will then be conducted on new samples of metal oxide varistor and the effect of applying the multiple lighting impulse will be analyzed. At the end of the work, a new procedure for MOV lightning impulse testing will be proposed.

Previous research and tests have shown that breakdown due to lightning is a main problem to power transmission and distribution systems. It has been the study of many researchers of how to minimize the frequency of failure and damage by installing a reliable protection system. To install a proper protection system, a precise method of testing the equipment based on natural characteristics is important. Since surge arresters are most commonly used equipment for protecting the distribution system from lightning strikes, the present test procedures have to be reviewed. This in turn requires the multiple lightning impulse tests to be employed.

1.4.2 Objectives of Study

The following are the objectives of this study:

1. To compare the standards of lightning impulse testing and the natural characteristics of lightning.

2. To design and construct a multiple impulse generator.

3. To conduct experimental tests on metal oxide varistor based on standard and natural parameters of lightning.

4. To compare the performance of the varistors between the standard tests and multiple impulse testing.

5. To propose a new procedure for metal oxide varistor lightning impulse testing.

1.4.3 Research Problem and Hypothesis

1.4.3.1 Research Problem

Is multiple stroke lighting impulse testing more effective in determining the performance and reliability of metal oxide varistor than the single stroke test?

From this research problem, some research questions can be asked as follows:

1. What is the effectiveness in the performance of metal oxide varistor when the multiple tests are being employed?
2. Is there a significant difference in the performance and capability of the varistor when single stroke testing is replaced by multiple stroke testing?

1.4.3.2 Hypothesis

The multiple lighting impulse tests can determine the performance and capability of metal oxide varistor precisely.

1.4.4 Scope of Study

The scope of this study will be focused on the following aspects:

1. Multiple impulse generator which is capable to generate 5 kV and 1 kA and simulate the natural lightning parameters will be designed and constructed.

2. Application of multiple lighting impulse tests with four successive impulses of time interval 40 ms between impulses on metal oxide varistor with 2 kV and 5 kV voltage ratings and 1 kA current rating will be conducted to study the effect of a multiple stroke lightning.

3. Laboratory work will be conducted using the simulated lightning impulses.

1.4.5 Significance of Findings

The immediate benefit by conducting this research is to spark research activities in the area of multiple lighting impulses testing on high voltage equipment and protective devices. This work is giving a new direction towards research in multiple lightning. This research also introduces a new concept of lightning impulse testing on MOV adopting the multiple lightning characteristics. This will lead to a better protection system under lightning occurrence, thus resulting in less system failure.

1.5 Thesis Organisation

The thesis is organized as follows:

Chapter 1. The natural lightning characteristics and standard lightning impulse testing procedures are reviewed and comparisons are made between the difference in parameters. Previous studies on the effect of multiple lightning impulse on protective devices are also being reviewed. The research methodology are presented in this chapter.

Chapter 2. This chapter reviewed the microstructure, operation mode, electrical characteristics and failure mode of the metal oxide varistor as the surge protective device for low voltage telecommunication systems. Methods of lightning propagation into the low voltage telecommunication system such as the resistive, inductive and capacitive couplings are also reviewed and presented.

Chapter 3. The design, construction and principle of operation of the MIGe are shown with details of every components of the test system. A new triggering technique of the generator which employs an electronic delay circuit is presented. The commissioning of the generator in no-load condition to simulate the required impulse voltage and current waveshapes of 1/1000 μs, 1/500 μs, 1.2/50 μs, 1.2/25 μs, 8/20 and 8/10 μs are shown.

Chapter 4. In this chapter, the experimental procedures and test samples selection are reported. The sequence of tests and the different waveshapes applied to the test samples are listed. The diagnostic tests procedures and parameters measurement instrumentation are detailed.

Chapter 5. Results of the diagnostic tests conducted are presented. Analysis are done to determine the effect of applying single and multiple standard and non-standard waveshapes. Discussions on the effect of the application of standard and non-standard lightning impulse are done based on the parameters measurement before and after the tests being conducted.

Chapter 6. This chapter presents the contributions, conclusion and suggestion for further studies that can be done in the related research area.

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