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Investigation on Flashover Performance of 25 kV Traction System Section Insulator Assembly in DMRCL System

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This paper describes the failure analysis of a section insulator assembly at one of the depot of Delhi Metro Rail Corporation Limited (DMRCL). Frequent breaker tripping at Saritavihar depot of DMRCL due to flashover of the section insulator assembly was observed; the cause of failure of the section insulator was investigated and presented in this paper. As a first step laboratory tests on new and used section insulator assemblies were conducted to make comparative analysis, and then simulation studies were carried out to estimate the possible over voltages during different switching operations and their relationship with the test voltages used in the experimental investigation. This paper presents the laboratory experiments and simulation studies for the failure analysis of section insulator assembly of DMRCL.

Keywords: *Section insulator, Electric traction, Insulation level and Impulse testing.*

1.0 INTRODUCTION

Metro rail has become an important mode of transport in all of the metro cities in India because of obvious reasons. The DMRCL is a rapid transit system serving Delhi, Gurgaon, Noida and Ghaziabad in the National Capital Region of India. The network consists of 6 lines with a total length of 189.63 km with 142 stations of which 35 are underground. It has a combination of elevated, at-grade and underground lines. The DMRCL uses 25 kV AC overhead lines on the ground-level and elevated routes, and uses rigid catenary or overhead power rail, in the underground tunnel sections [1–2].

In general, in India, the substations supplying power to the traction system are fed from 132 kV systems. To minimize unbalance in the system, each traction substation is powered from different phases of the system. The two overhead supply feeders generally originating from two different substations are separated by section insulator assembly, so that the train- loco will change over smoothly from feeder of one substation (phase of supply) to another. In the DMRCL traction supply system the feeders originate from the same phase and even then the feeders are separated by section insulator assembly. DMRCL encountered power supply interruptions at their Saritavihar depot due to flashover of one such section insulator. Central Power Research Institute (CPRI) took up the investigation to find out root cause for the flashover. Figure 1, shows the top and front views of section insulator assembly in 2D. The section insulator assembly comprises two composite insulators, arcing horns on two sides of the insulator to protect the insulators from physical damage due to flashover. A section insulator should possess the strength to withstand the electrical, mechanical and environmental stresses which it is going to face on site. But in present case, the failure of the section insulator assembly is mainly attributable to electrical stresses, hence this investigation is

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confined to evaluation of the electrical strength of the insulator by laboratory experiments and electromagnetic transient simulation studies to estimate the possible electrical stresses which it may encounter in the network while in service.

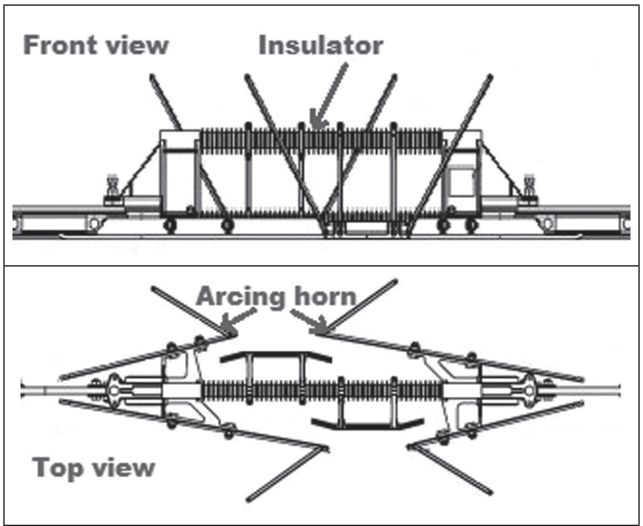

FIG. 1 TYPICAL SECTION INSULATOR ASSEMBLY USED IN DMRCL

The voltage stresses are classified by suitable parameters such as the duration of the power-frequency voltage or the shape of an over voltage according to their effect on the insulation or on the protective device.

In general the type tests are envisioned to confirm the foremost characteristics of an insulator which depend mainly on its design. They are generally carried out on a small number of insulators and only once for a new design or manufacturing process of insulator and then successively reiterated only when the design or manufacturing process is changed. The results of type tests are certified either by test certificates accepted by the purchaser or the test certificates confirmed by a qualified organization [3]. But in this case, as a part of failure analysis we have carried out all the dielectric type tests on a new and an old section insulator (removed after 9 months in service) assemblies to check the key characteristics and aging effect.

2.0 LABORATORY STUDIES

As the traction system voltage is 25 kV (Phase to ground), the section insulator shall have voltage rating of above 43 kV. This is closer to the standard system voltage of 52 kV; insulation level of the insulator shall correspond to 52 kV. The following tests are conducted on the section insulator:

1. 50% Lightning Impulse (LI) voltage flashover test, as per IEC 60060-1 standard [4].
2. LI voltage withstand test, as per IEC 60060-1standard [4].
3. Power frequency voltage tests as per IEC 60060-1 standard [4]
   i. Power frequency voltage flashover test (Dry).
   ii. Power frequency voltage withstand test (Dry).
   iii. Power frequency voltage flashover test (Wet).
   iv. Power frequency voltage withstand test (Wet).
4. Both side power frequency voltage under very high polluted conditions, and
5. Bias test (one side power frequency and other side LI voltage).

2.1 50% Lightning Impulse Voltage Flashover Test

For all LI tests, a standard impulse voltage having a front time of 1.2 μs ± 30% and a time to half value (tail time) of 50 μs ± 20% which is described as 1.2/50 μs was used.

The 50% flashover voltage is the prospective voltage which has a 50% probability of producing a flashover across the insulator. After making the test setup, twenty number of LI voltage shots were applied to the sample by following the up and down method (voltage level for each succeeding shot was increased or decreased by a small amount which is 1.5–3% of previous shot peak value; if the insulator flashovers at precious shot then the voltage value for next shot shall be decreased otherwise the value shall be increased), and the average of the peak values of all the twenty shots is 50%

LI flashover voltage under actual atmospheric conditions [4, 5].

The 50% LI flashover test was conducted on both used and new samples with positive and negative polarity of test waveforms; these values are corrected to standard reference atmosphere and tabulated in Table 1. It is inferred from the test results that the 50% flashover voltage of the used sample is significantly lower than the new sample.

TABLE 1

RESULTS OF 50% LI FLASHOVER TEST

Polarity	Test Voltages in kV (Peak)			
	New Sample	Used Sample	Manufacturer's Specification	52 kV System requirement
+Ve	168	136	155	≥ 260
-Ve	175	127	162.5	≥ 260

2.2 Lightning Impulse Voltage withstand Test

As the air insulation is self-restoring insulation the LI voltage withstand test value was evaluated from the 50% LI flashover voltage by using statistical method (50% LI flashover voltage = 1.04* maximum withstand voltage). Fifteen impulses each of positive and negative polarity with maximum withstand voltage were applied to the sample. The atmospheric corrected results are tabulated in Table 2 [4]. No flashovers were observed during the test. However, once again it was noticed there is some degradation in the used sample which shows lesser value as compared to new sample.

TABLE 2

RESULTS OF LI VOLTAGE WITHSTAND TEST

Polarity	Test Voltages in kV(Peak)			
	New sample	Used sample	Manufacturer's specification	52 kV System requirement
+Ve	160	129	149	250
-Ve	165	121	156	250

2.3 Power Frequency Voltage Tests

Power frequency voltage flashover and withstand tests were carried out on both new and old samples under dry and wet (rain) conditions [4].

For flashover test the power frequency voltages is applied and increased continuously, until a flashover occurs on the sample. The same procedure has been repeated for five times and the average of these five trails recorded values has been taken as flashover voltage. Withstand test has been conducted at 95% of flashover voltages applied to the sample for one minute and the test voltage is further reduced by 5% if flashover occurs at any instant during the test. Resistivity of the water used to simulate rain for wet tests is 8–10 kΩcm. The atmospheric corrected values of power frequency voltage tests are tabulated in Table 3 [3–5].

The test results indicate similar to the case of LI tests, that the power frequency flashover and withstand voltages of used sample are lower than that for the new sample.

TABLE 3

RESULTS OF POWER FREQUENCY VOLTAGE TESTS

Type of test	Flashover Voltages in kV(rms)			
	New sample	Used sample	Manufacturer's specification	52 kV system requirement
Dry	85	62	95.5*	> 105
Wet	61	53	73.5*	≥ 105
	Withstand Voltages in kV(rms)			
	New sample	**Used sample**	**Manufacturer's specification**	**52 kV system requirement**
Dry	78	55	85.0* 95.5**	>95
Wet	50	45	66.0* 73.5**	95

*Results provided by supplier as per test report.
**As per claim in the insulator assembly drawing.

2.4 Pollution Test

In case of section insulators, there is likely hood of the insulator being subjected to differential voltages proportional to phase of the feeder voltages at both ends. It could be zero or 60° (electrical). The severe case of potential difference considering phase difference of 60° (electrical) is simulated in the tests carried out at CPRI as zero phase difference results ideally, in no voltage across the section insulator.

Pollution test by salt fog method on the section insulator assembly at heavy and very heavy contamination condition have been conducted. The test specimen is placed in a chamber of dimension 3 m × 3 m × 3.5 m. Salt fog is generated as per the requirement of IEC 61109 and the test setup is shown in Figure 2. High voltage AC of 25 kV is applied to one end of the section insulator assembly.

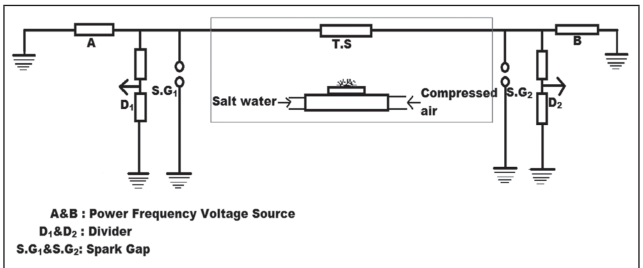

FIG. 2 TEST SETUP FOR POLLUTION TESTS.

The other side of section insulator was energized by another transformer whose output voltage was varied from 18 kV–25 kV in steps of 1 kV. The duration of the test at each voltage level was 15 minutes. This is not a usual procedure but followed to simulate exact field conditions encountered by the insulator assembly. The severity of pollution was 80 kg/m³ and 224 kg/m³ which imply the heavy and very heavy pollution conditions respectively. Flashovers were not observed on the section insulator assembly at all the applied test voltages and at both the severities of pollution. This implies that the pollution accumulation on the section insulator assembly when energized with differential voltage as considered in the tests do not lead to the flashover observed in the field. Additionally, test was repeated with the section insulator energized to 25 kV at one end and the other end being grounded. The section insulator assembly withstood a salinity of 80 kg/m³ and 224 kg/m³ further confirming that pollution is not the primary cause of the reported flashover while in service [6].

2.5 Bias Test

Bias test is normally carried out on longitudinal insulation (like open contacts of circuit breakers) for their performance at open condition. The section insulator in traction system encountered similar service conditions. So the insulator has to withstand a differential voltage due to system nominal voltage on one side and LI withstand (Line-Ground) voltage on the other side. This simulates a condition in which one of the feeders associated with the section insulator is energized to normal system voltage and the other feeder is de energized and a lightning caused over voltage is appearing on it. The test setup is shown in Figure 3.

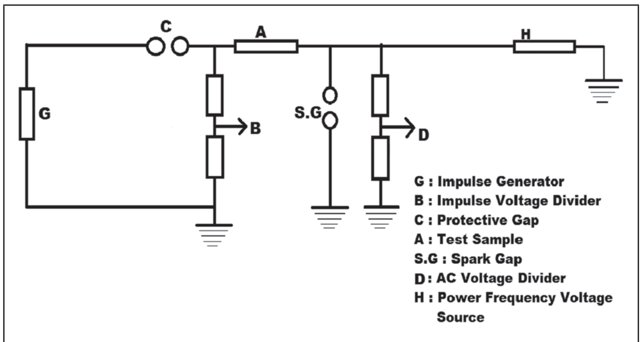

FIG. 3 TEST SETUP FOR BIAS TEST

One side of the section insulator assembly is applied with power frequency voltage of 37.5 kV peak corresponding to nominal feeder voltage of 25 kV(rms). From LI withstand test the maximum impulse withstand voltage is obtained as 165 kVp. The bias test voltage (voltage appearing across the sample) is chosen as the difference between the maximum LI with stand voltage and peak of the power frequency voltage. This works out to 127.5 kVp. Hence the other terminal was subjected to a negative LI voltage of 127.5 kVp initially at positive peak of the power frequency voltage. It is expected that the section insulator assembly will withstand the resultant differential voltage.

In order to check the influence of instantaneous power frequency voltage on the insulation withstand characteristic of the section insulator assembly, the angle of application of impulse voltage with reference to the power frequency voltage was varied point on from +90⁰ to 0⁰. The test was repeated with positive polarity impulse at corresponding power frequency voltage angles of –90⁰ to 0⁰.

Waveform of impulse and power frequency voltage at different angles of impulse application are shown in Figures 4(A) and 4(B). The application of the negative impulse voltage of magnitude 127.5 kVp at positive peak of the power frequency voltage resulted in flashover of the section insulator assembly. Varying angle of application of impulse to reduce the effective differential voltage (switching angle varied from +90° to 0) also resulted in flashover till a small angle close to the zero (above 10° before voltage zero).

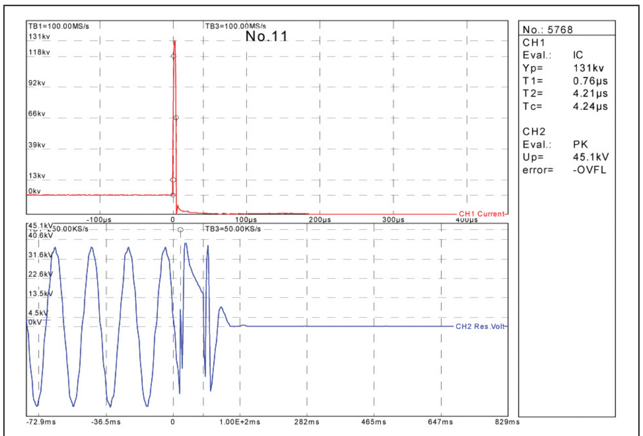

FIG. 4(A) POSITIVE LI APPLICATION ON NEGATIVE HALF CYCLE OF POWER FREQUENCY VOLTAGE RESULTING IN FLASHOVER ON THE NEW SAMPLE.

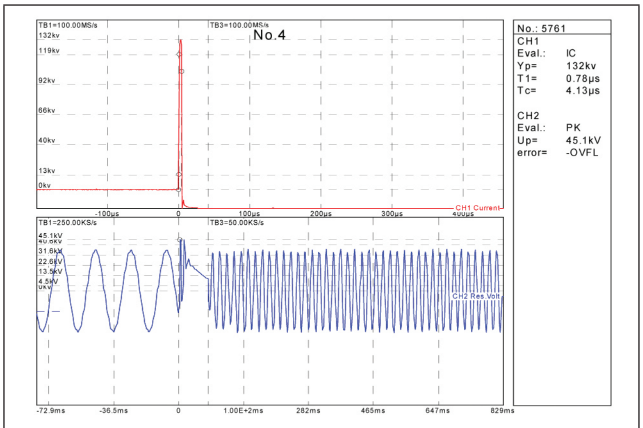

FIG. 4(B) POSITIVE LI VOLTAGE APPLICATION ON NEGATIVE HALF CYCLE OF POWER FREQUENCY VOLTAGE (AT CLOSE TO ZERO CROSSOVER) STILL RESULTING IN FLASHOVER ON USED SAMPLE.

The above observations bring out a phenomenon showing that comparatively small transient voltage that can appear on the de-energized side of the section insulator trigger flashover across the air gap of the hardware associated with the section insulator assembly.

One possibility is that the non-linear air gap of the hardware is in the state of ionization, may be due to corona and a relatively small transient voltage could trigger the spark over of the gap. This is probable as the facing edges of the gap of the hardware are found, on physical inspection, to have reasonable undulations which could produce corona when energized to 25 kV.

This phenomenon is undesirable as any insulation isolating two different circuits (could be of same phase or different phase or one side energized and the other side de-energized) shall withstand the differential voltage caused by system nominal power frequency voltage on one side and lightning impulse voltage of magnitude equal to system Basic Insulation Level (BIL). In such a case, the section insulator assembly used by DMRCL shall withstand a lightning impulse voltage of magnitude 155 kV on one side of the terminals when the other side is energized to power frequency voltage of 25 kV (rms), the impulse voltage polarity being opposite to the polarity of the power frequency voltage and impulse voltage is applied at the peak of the power frequency voltage. If this test is not included in the specification of section insulator assembly DMRCL shall include this requirement.

3.0 SIMULATION STUDY

The simulation studies on equivalent network which is shown in the Figure 5 were carried out to estimate the possible transient over voltages across the section insulator due to switching operations. The simulation studies are carried out by using the PSCAD software which has been extensively used in the industry and results of software are acceptable universally. The severe two operating conditions are presented in this paper as two case studies.

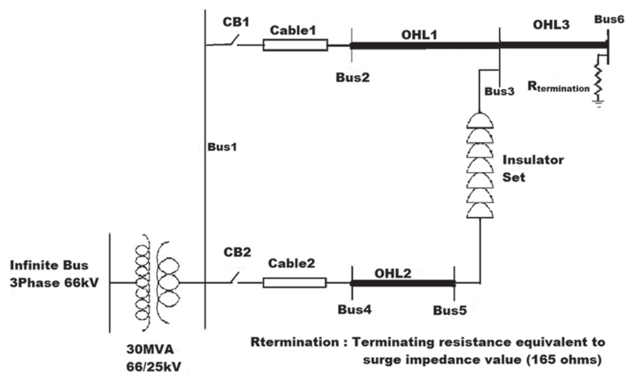

FIG. 5 SYSTEM EQUIVALENT NETWORK FOR SIMULATION STUDIES.

CASE 1: Energizing the Overhead line 1 (OHL1) by Switching on the circuit breaker 1 (CB1) under the condition that Overhead line 2 (OHL2) is already energized (i.e. energizing one side of the insulator assembly when another side was already energized) at positive peak of the voltage on the OHL2.

CASE 2: Energizing the Overhead line 2 (OHL2) by Switching on the circuit breaker 2 (CB2) under the condition that Overhead line1 (OHL1) is already energized (i.e. energizing one side of the insulator assembly when another side was already energized) at positive peak of the voltage on the OHL1.

For the above two cases the simulations are done and the highest voltage at each critical bus are tabulated in Tables 4 and 5. The overhead line 3 (OHL3) is terminated with surge impedance (165 ohms) of traction feeder at bus no. 6 to minimize the system modeling and computational complexities. The transient voltages at all the buses are more under case 2 but the transient voltage across the insulator is approximately same for the both the cases.

TABLE 4

OVER VOLTAGES AT CRITICAL BUSES FOR CASE 1

Bus No.	Switching over voltage	Figure No.
1	1.174 p.u. (41.52 kV)	6(A)
3	1.405 p.u. (49.7 kV)	6(B)
5	1.762 p.u. (62.3 kV)	6(C)
Across insulator	1.67 p.u. (59.2 kV)	6(D)

TABLE 5

OVER VOLTAGES AT CRITICAL BUSES FOR CASE 2

Bus No.	Switching over voltage	Figure No.
1	1.72 p.u. (61.03 kV)	7(A)
3	1.83 p.u. (64.78 kV)	7(B)
5	2.23 p.u. (78.7 kV)	7(C)
Across insulator	1.64 p.u. (58.9 kV)	7(D)

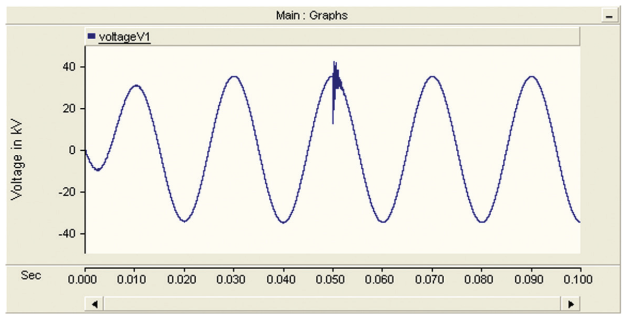

FIG. 6(A) VOLTAGE WAVEFORM AT BUS 1 FOR CASE 1.

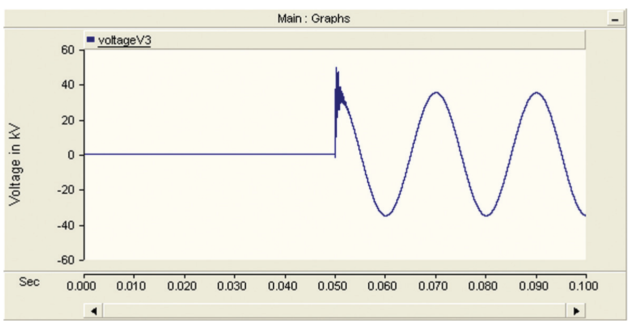

FIG. 6(B) VOLTAGE WAVEFORM AT BUS 3 FOR CASE 1.

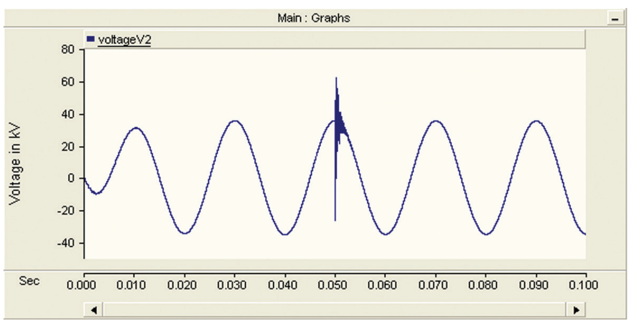

FIG. 6(C) VOLTAGE WAVEFORM AT BUS5 FOR CASE 1.

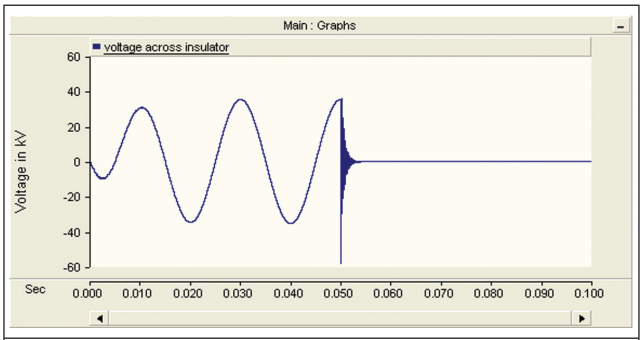

FIG. 6(D) VOLTAGE WAVEFORM ACROSS THE INSULATOR FOR CASE 1.

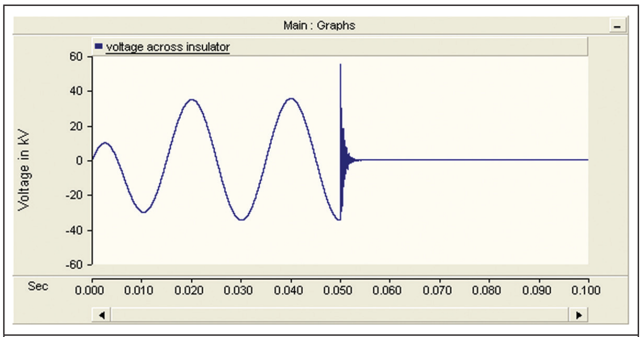

FIG. 7(D) VOLTAGE WAVEFORM ACROSS INSULATOR CASE 2.

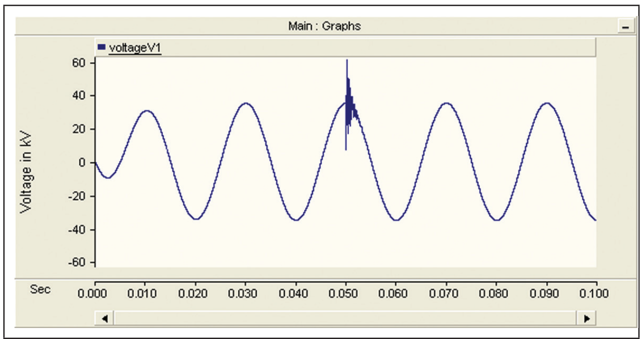

FIG. 7(A) VOLTAGE WAVEFORM AT BUS 1 FOR CASE 2.

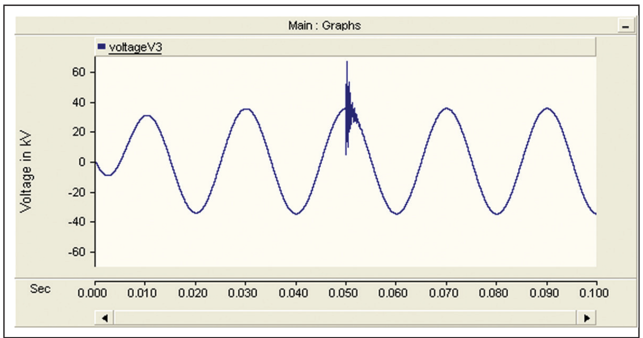

FIG. 7(B) VOLTAGE WAVEFORM AT BUS 3 FOR CASE 2.

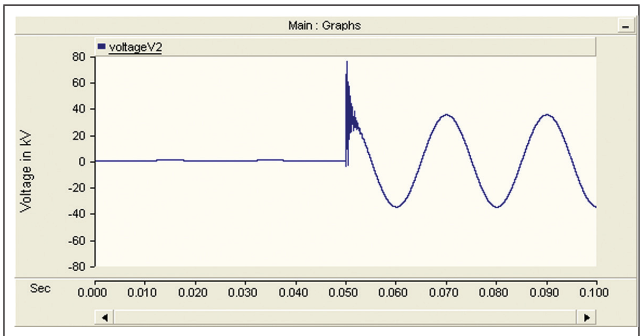

FIG. 7(C) VOLTAGE WAVEFORM AT BUS 5 FOR CASE 2.

4.0 CONCLUSIONS

Laboratory tests on new and used section insulator assemblies of DMRCL were carried out to verify the insulation characteristics claimed by the supplier and to check any degradation in insulation level while in service. By observing the 50% LI voltage flashover test results and the lightning impulse strength of the used (9 months) sample is considerably less than the new sample (~19% for positive polarity and ~27% for negative polarity). The power frequency voltage performance of the used insulator is poor compared with the new insulator (~29% under dry condition, ~13% under wet condition). The used section insulator assembly performs significantly poorer under both lightning and power frequency voltages. This is a matter of concern as the used insulator was only for a period of 9 months in service when compared to its expected life span of about 25 years.

The section insulator assembly performed well under polluted conditions, indicating that pollution is not the primary cause of the reported flashover while in service. The bias test has thrown up an interesting observation that even for a relatively small transient voltage on the un-energized end of the section insulator, while the other end is energized to the nominal system voltage results in the flashover of the air gap in the hardware associated with the section insulator assembly. This is an indication of presence of ionized air environment in the gap. Physical inspection of the part of the hardware for point-point air gap geometry showed that it is conducive for corona generation due to presence of not too smooth surface.

In insulation withstand studies; systems are classified into two ranges based upon the system nominal operating voltage. In Range-I (1 kV < system nominal operating voltage, Um ≤ 245 kV), the standard short-duration power-frequency or the lightning impulse withstand voltage should cover the required switching impulse withstand voltage [7]. A switching transient over voltage of magnitude of the order of 1.67 p.u. (equivalent lighting impulse voltage of 1.77 p.u.) computed across section insulator connected to the de-energized feeder getting charged, could result in a flashover of the section insulator assembly. Laboratory tests have shown that such over voltages occurring when one feeder is energized and transient over voltages of low magnitude could trigger section insulator flashover.

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