International Conference on Lightning Protection
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

Investigation of the Effects of Multi-waveform Multi-pulse Impulse Currents on MOV for Class I SPD Through Operating Duty Tests

Yuwei He, Zhengcai Fu, Jian Chen
Key Laboratory of Control of Power Transmission and Conversion, Ministry of Education
Shanghai Jiao Tong University
Shanghai, China
hywdiandian@sjtu.edu.cn

***Abstract*—In order to evaluate the performance of class I SPDs under more close to practical operating situation, operating duty tests (ODT) with multi-waveform multi-pulse impulse currents are carried out on MOVs for class I SPDs. The multi-waveform multi-pulse currents consist of quadruple impulse currents with one 10/350 μs impulse simulating first return stroke current, one 2 ms rectangular impulse simulating long duration current between return strokes, and two steep impulses simulating subsequent return stroke currents. The test results show that all the MOV samples could pass the standard ODT according to IEC61643-11 without degradation, while the electrical and physical properties of MOVs under multi-waveform multi-pulse operating duty tests (MODT) would significantly deteriorate. The MOVs with high limiting voltage have better withstand capability under MODT. The main failure modes for MOVs after MODT include the crack on the plastic encapsulation, the punctures close to the edge of varistors, and shattering of the varistor. Some interesting phenomena are also observed, such as, the MOVs would be more easily damaged if the first return stroke is directly followed by subsequent return stroke without interval current, the tested MOVs that could pass the MODT under time interval of 100 ms between the multiple currents all failed in the tests under time interval of 20 ms. The microstructural examination indicates that after the MODT, the grain size of the punctured ZnO materials would become smaller and the quantity of the white intergranular phase between grains significantly increases.**

Keywords-operating duty test; multi-waveform multi-pulse impulse currents; metal-oxide varistor; lightning return stroke current components; micostructure

I. INTRODUCTION

Surge protective devices (SPDs) mounted on low-voltage distribution lines are used to protect sensitive equipment against surge currents in electrical and electronic systems [1-2]. The class I SPDs, installed at the points of high exposure in buildings and distribution systems, are more vulnerable to lightning strokes [3-4]. The discharge currents and residual voltages on SPDs installed at the entrance terminals, which were caused by multiple lightning strokes, have been measured by Shaodong Chen et al. at Guangdong area of China [5]. The operational experience in American also shows that the multiple lightning strokes are the main cause of arrester failures [6]. Therefore, further experimental investigations on the performance of class I SPDs under multiple stroke currents are necessary.

IEC and IEEE standards have suggested the operating duty tests (ODT) to demonstrate the performance of SPD in response to surges that can be expected at the service equipment [3-4]. The ODT is carried out with 15-20 current impulses with waveform of 8/20 μs applied on the SPDs. However, the single impulses of 8/20 μs currents, with time interval of 50-60 s between two impulses, could not simulate the effects of realistic multiple lightning strokes that contain average 3 or 4 strokes with time interval of average 30 to 40 ms between the strokes [7]. The effects of multiple impulse currents on the metal-oxide varistors (MOVs) of distribution arresters have been investigated by M. Darveniza et al. [8-11], B-H Lee et al. [12-13] and T. Haryono et al. [14-15]. Christof Drilling et al. used the multiple lightning currents combined with follow current to test the spark-gap type SPDs [16]. Alain Rousseau et al. also carried out the tests with multiple shots up to 10 impulses to evaluate the performance of MOV-type SPDs [17-18]. Their results showed that multiple impulse current tests are more close to practical operating situation than single impulse current tests, which have a stronger degradation effect on the electrical and physical properties of MOVs than single impulse. Moreover, M. Darveniza et al. also suggested the introduction of multi-pulse in the ODT [10].

The previous researches [8-21] still have some deficiencies. For example, successive 8/20 μs impulse currents are adopted in most of the multiple impulse currents tests. However, the impulse current of 8/20 μs waveform could not represent the typical currents of lightning return strokes, which also has large difference with the discharge currents measured on distribution line arresters stroke by natural lightning [22-24]. In addition, natural lightning flashes include four main current components including first return stroke current, subsequent return stroke current, intermediate current and long-duration continuing current [7]. In existing literatures, the combinations of 8/20 μs+ 4/10 μs+ rectangular impulse currents [19], the combination of 28/53 μs+ 10/25 μs impulse currents [20] or two rectangular impulse currents [21] were considered to simulate the different current components, which still could not represent the full-scale current components in ground flashes. Taking account the above shortcomings, a set of multi-waveform multi-pulse impulse current generators (MWMP ICG) were developed by High Voltage Laboratory of Shanghai Jiao Tong University to simulate the effects of full-scale lightning currents. The effects of single and multiple simulated lightning impulse currents on metal-oxide arrester blocks used for distribution line arresters were investigated by Anfeng Jiang et al. [25]. However, the operating duty test, which is the reflection of field conditions likely to occur on distribution systems in service, was not considered yet.

In order to evaluate the performance of class I SPDs under more close to practical operating situation, operating duty tests with multi-waveform multi-pulse simulated lightning impulse currents (MODT) are carried out on the MOVs of class I SPDs in this paper. The influence of different MOV types, the amplitudes of the impulse currents, the time interval between two impulses, and the sequences of multiple impulses are investigated. In addition, the standard ODT according to IEC61643-11 is also carried out for comparison. Moreover, the microstructural examination is conducted on the failed varistor after the MODT to find out the differences of the microstructures and the cause for varistor failure.

II. LAYOUT OF THE EXPERIMENTS

A. The multi-waveform multi-pulse impulse current generator (MWMP ICG)

The multi-waveform multi-pulse impulse current generator (MWMP ICG) with the current amplitude and time interval between the pulses adjustable is shown in Fig. 1. The multi-waveform multi-pulse currents (MC) used for the tests are quadruple impulse currents including one 10/350 μs impulse current to simulate the first lightning return stroke, one 2 ms rectangular impulse current to simulate the continuing current of interval stroke, and two steep impulse currents with front time less than 1μs (abbreviated as '1μs steep current') to simulate the subsequent lightning return strokes. Since the current amplitudes, time intervals, and sequence of the impulses are adjustable, different possible combinations of multiple lightning strokes are simulated in the laboratory.

Figure 1. Photograph of the MWMP ICG

B. Measurements

Four independent Pearson coils are adopted to measure the quadruple impulse currents on the tested MOVs. The voltage divider with ratio of 25.62 is used to measure the residual voltages on MOVs. A four-channel digital oscilloscope of TEK DPO3014 is adopted to record the experimental waveforms.

C. Test samples

Three types of MOVs of class I SPDs from EPCOS are adopted in the experiments. Their electrical properties are shown in Tab. I.

TABLE I. ELECTRICAL PROPERTIES OF MOVS SUBJECT TO ANALYSIS

MOV type	Nominal discharge current (8/20μs) (I_n)/ kA	Impulse Current (10/350μs) (I_{imp})/ kA	Max. operating voltages (U_c)/ V	DC 1mA reference voltage (U_{DC1mA}) / V	Residual voltage at I_n (U_r)/ V
V230	20	6.5	230	350	935
V275	20	6.5	275	418	1090
V460	20	6	460	720	1760

D. Proposal for the single and multi-waveform multi-pulse operating duty test

According to IEC standard 61643-11 [4], the complete ODT include an ODT and an additional duty test for class I SPDs. The ODT contain three groups of five impulses of 8/20 μs current impulses with positive polarity when the tested MOV is energized at U_c. The interval between the impulses is 50 s - 60 s, the interval between the groups is 30 min – 35 min. The additional duty test consists of five 10/350 μs current impulses in steps up to I_{imp} after the ODT, which is especially added for the class I SPDs. Compared with the multiple impulses ODT, such standard ODT could be described as single impulse ODT (SODT).

The multi-waveform multi-pulse operating duty tests (MODT) is implemented by applying three groups of quadruple impulse currents when the MOV is energized at U_c. The interval between the successive impulses is 30 ms, the interval between the groups is 30 min. For the MODT of class I SPDs, whether the additional duty test is still necessary should be thought over, since its effect may be not that significant compared with the effect of multi-pulse currents. The difference between the results with or without the additional duty test is discussed later.

The amplitudes for the MC used in MODT include different amplitudes in steps up to I_{imp} for 10/350 μs current, I_n or $0.5I_n$ for 1μs steep current, and 600A, 800A, 1000A for 2 ms rectangular current recommended by the manufacture. The influence of different amplitudes for MC on the test results would be investigated later.

The pass criteria for the ODT, according to IEC 61643-11, indicate that the SPD should achieve the thermal stability after each impulse of the ODT. Both the voltage and current records, together with a visual inspection, shall show no indication of puncture or flashover of the samples. In addition, the IEEE Std. C62.62 suggested the posttest measured U_r (MOV residual voltages at I_n) shall not deviate more than 10% from the pretest measured U_r. The Std. IEC 60099-4 [26] also requires that the U_{DC1mA} should not deviate more than 5% after the impulse tests.

E. Test procedure

The experiments of SODT and MODT are carried out on the MOV samples respectively. The flowchart of the experimental procedure is shown in Fig. 2.

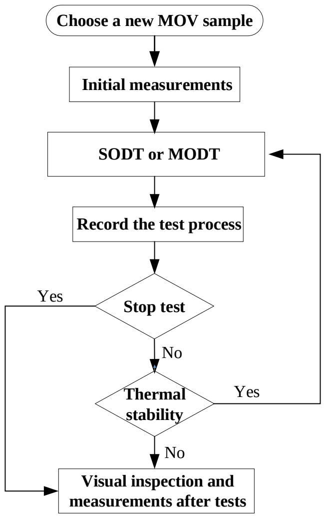


Figure 2. Flowchart of the SODT and MODT procedure

(1) Initial measurements: The MOV samples are characterized with the DC 1mA reference voltages (U_{DC1mA}), the residual voltages at nominal discharge current (U_r), and photographs at the beginning of the tests.

(2) SODT or MODT: Determinate the impulse current amplitudes, time intervals, and impulse sequences for the experiments. Adjust the charging voltage of the MWMP ICG to output the demanded impulse currents.

(3) Record the test process and check the thermal stability of the MOVs after each impulse applied. Record the measured waveforms of the MOV currents and voltages.

(4) Visual inspection and measurements after tests. Check the surface of the MOV for puncture or flashover. Measure the U_{DC1mA} and the U_r after the tests. Take photographs of the damaged MOVs after the tests.

III. RESULTS UNDER SINGLE IMPULSE OPERATING DUTY TESTS

The SODT, followed the IEC 61643-11, is carried out on the three types of MOVs, respectively. The 8/20 μs impulse current with nominal amplitude is adopted in the ODT. After that, the additional duty test of 10/350 μs current with amplitudes in steps up to I_{imp} is carried out. The change ratio for the posttest measured U_{DC1mA} and the U_r is defined as:

$$U_{cr} = \frac{U_{at} - U_{bt}}{U_{bt}} \times 100\% \tag{1}$$

where, U_{cr} represents the change ratio of the measured values. U_{at} represents the value measured after the tests, and U_{bt} represents the value measured before tests.

The test results under SODT are shown in Tab. II, where 'Pass' means no visual damage (puncture or flashover) appear on the tested MOV samples after the test.

TABLE II. RESULTS UNDER SINGLE IMPULSE OPERATING DUTY TESTS

MOV Type	Thermal Stability	U_{cr} for U_{DC1mA}	U_{cr} for U_r	Visual Inspection
V230	Yes	2.86%	1.43%	Pass
V275	Yes	3.48%	3.05%	Pass
V460	Yes	-1.69%	0.33%	Pass

Tab. II shows that the three types of MOVs could stay thermal stability and the changes of U_{DC1mA} and U_r are minor. The visual inspection also shows no damage on the tested MOVs. Therefore, it can be concluded that the three types of MOVs all pass the SODT without degradation. However, such tests could not simulate the effects of realistic lightning stroke on class I SPDs. More strict tests with multiple impulse currents should be considered.

IV. MULTI-WAVEFORM MULTI-PULSE OPERATING DUTY TEST RESULTS

A. The difference between the results with or without additional duty test in MODT

Compared with class II or class III SPDs, the class I SPDs need additional duty test for complete ODT recommended by IEC [4]. However, such additional test may not be that necessary in MODT. The MODT with or without additional duty test are carried out on the three types of MOVs to compare the difference. The quadruple impulse currents of 10/350 μs impulse + 2 ms rectangular impulse + 1 μs steep impulse + 1 μs steep impulse are adopted in MODT. The time interval between successive impulses is 30 ms. Then the additional duty test with five 10/350 μs current impulses in steps up to I_{imp} is carried out after the multi-pulse currents are applied. The test results with or without the additional duty tests are shown in Tab. III, where 'F0.25Iimp' means the 10/350 μs current with amplitude of 0.25Iimp. 'R800' means the 2 ms rectangular impulse current with 800 A amplitude. 'S10' means the 1 μs steep current with 10 kA amplitude. 'I' means the results without additional duty test. 'II' means the results with additional duty test.

TABLE III. TEST RESULTS WITH OR WITHOUT ADDITIONAL DUTY TEST IN MODT

Test item	MOV Type	Thermal stability		U_{cr} for U_{DC1mA}		U_{cr} for U_r		Visual inspection	
		I	II	I	II	I	II	I	II
F0.25Iimp+R800+S10+S10	V230	Yes	Yes	4.00%	2.29%	3.47%	3.96%	Pass	Pass
F0.5Iimp+R800+S10+S10	V275	Yes	Yes	1.24%	-4.31%	1.08%	1.83%	Pass	Pass
F0.25Iimp+R800+S10+S10	V460	Yes	Yes	-1.39%	-0.69%	1.27%	1.14%	Pass	Pass

It can be seen from Tab. III that all the tested MOVs could pass the MODT no matter the additional duty test is carried out or not. For V460, the U_{cr} of U_{DC1mA} and U_r under complete MODT are even less than that without additional duty test. That is to say, compared with the significant effects of multiple impulse currents, the additional duty test has little influence on the test results. Therefore, the test procedure of MODT could be simplified and the additional duty test could be neglected in the following sections.

B. Effect of the Amplitude for Multiple Impulse Currents

The variable impulses sequences, current amplitudes, and time intervals between quadruple impulse currents could represent different combinations of multiple lightning strokes on the class I SPDs. The effects of these factors, as well as different MOV types, are also investigated in the tests.

In order to evaluate the effect of the amplitude of multiple impulse currents in MODT, three groups of quadruple impulse currents with sequence of 10/350 μs impulse + 2 ms rectangular impulse + 1 μs steep impulse + 1 μs steep impulse are carried out on the three types of MOVs, when the MOVs are energized at U_c. The interval time between the two impulse currents is set as 30 ms. The amplitude of 10/350 μs impulse current is selected from $0.25I_{imp}$, $0.5I_{imp}$, $0.75I_{imp}$, and I_{imp}. The amplitude of the 2 ms rectangular impulse current is selected from 600A, 800A, and 1000A. The amplitude of the 1 μs steep current is selected between 10 kA and 20 kA. The test results are shown in Tab. IV to Tab. VI, where the “Minor crack” and “Major crack” mean the minor or major cracks appeared on the plastic encapsulation of the varistor, the “Puncture” means the plastic encapsulation is broken and the ZnO material is punctured on surface, the “Shattering” means the ZnO material is shattered in pieces.

Based on the above results, the following outcomes were achieved.

(1) The MODT with multiple impulse currents has much stronger degradation effect on the electrical and physical properties of MOVs than single pulses. For example, the V230 could pass the SODT that consist of fifteen 8/20 μs impulse currents with amplitude of 20 kA and five 10/350 μs impulse currents with amplitude in steps up to I_{imp}. However, the V230 could not pass the three groups of quadruple impulses with amplitude of $0.75I_{imp}$ for 10/350 μs impulse current since major cracks appear on the plastic encapsulation of V230, as shown in Tab. IV

(2) The increase of the current amplitude for first lightning return stroke and 2 ms rectangular wave have serious degradation effect on the MOVs. For example, the V230 could not withstand the 10/350 μs impulse current with amplitude more than $0.75I_{imp}$ nor the 2 ms rectangular impulse current with amplitude 1000 A. However, the amplitude effect of the 1 μs steep current is relative small.

(3) The V460, which has higher limiting voltage than other two types of MOVs, has better withstand performance than V230 under same test items. Comparing the V275 with V230 under same test items, the V275 also shows better performance because the V275 could pass the test ‘F0.75Iimp+R800+S10+S10’ where the V230 failed. It can be concluded that MOVs with high limiting voltages have better performance under MODT.

TABLE IV. RESULTS ON V230 WITH DFFERENT AMPLITUDES FOR MULTIPLE IMPULSE CURRENTS

Test item	Thermal stability	U_{cr} for U_{DC1mA}	U_{cr} for U_r	Visual inspection
F0.25Iimp+R800+S10+S10	Yes	0.28%	0.96%	Pass
F0.5Iimp+R800+S10+S10	Yes	-0.86%	-0.42%	Minor crack
F0.75Iimp+R800+S10+S10	Yes	-5.71%	3.78%	Major crack
F0.5Iimp+R600+S10+S10	Yes	2.58%	0.54%	Pass
F0.5Iimp+R1000+S10+S10	Yes	5.56%	2.86%	Major crack
F0.5Iimp+R800+S20+S10	Yes	-4.69%	3.47%	Pass
F0.5Iimp+R800+S20+S20	Yes	1.43%	0.89%	Pass

TABLE V. RESULTS ON V275 WITH DIFFERENT AMPLITUDES FOR MULTIPLE IMPULSE CURRENTS

Test item	Thermal stability	U_{cr} for U_{DC1mA}	U_{cr} for U_r	Visual inspection
F0.5Iimp+R800+S10+S10	Yes	0.24%	0.46%	Pass
F0.75Iimp+R800+S10+S10	Yes	-3.11%	0.92%	Pass
FIimp+R800+S10+S10	No	-	-	Shattering
F0.75Iimp+R600+S10+S10	Yes	-3.11%	0.92%	Minor crack
F0.5Iimp+R1000+S10+S10	Yes	4.78%	0.33%	Minor crack
F0.75Iimp+R800+S20+S10	No	-	-	Puncture
F0.75Iimp+R800+S20+S20	Yes	4.78%	4.59%	Pass

TABLE VI. RESULTS ON V460 WITH DIFFERENT AMPLITUDES FOR MULTIPLE IMPULSE CURRENTS

Test item	Thermal stability	U_{cr} for U_{DC1mA}	U_{cr} for Ur	Visual inspection
F0.25Iimp+R800+S10+S10	Yes	-1.39%	1.14%	Pass
F0.5Iimp+R800+S10+S10	Yes	-3.89%	-2.57%	Pass
F0.75Iimp+R800+S10+S10	Yes	3.98%	0.57%	Minor crack
F0.5Iimp+R600+S10+S10	Yes	2.78%	1.33%	Pass
F0.5Iimp+R1000+S10+S10	Yes	-2.78%	-2.46%	Pass
F0.5Iimp+R800+S20+S10	Yes	2.08%	1.35%	Pass
F0.5Iimp+R800+S20+S20	Yes	4.19%	-0.57%	Pass

(4) Visual inspections indicate that the plastic surrounding the device inflated during application of the multipulses. Cracks appeared on the plastic encapsulation initiated from surrounding of the electrodes. For more serious cases, some varistors were punctured and shattered and could not stay thermal stability after the MODT. The photograph for the major cracks on V230 under the test of ‘F0.75Iimp+R800+S10+S10’ is shown in Fig. 3a with the first group of recorded multipulse voltage and current during the MODT shown in Fig. 4. Fig. 3b shows the shattered piece of V275 under the test of ‘FIimp+R800+S10+S10’. Fig. 3c and Fig. 3d show the punctures on varistors.

(a) Major cracks (b) Shattered piece

(c) Punctured on specimen No. 1 (d) Punctured on specimen No. 2

Figure 3. Main failure modes appear on varistors

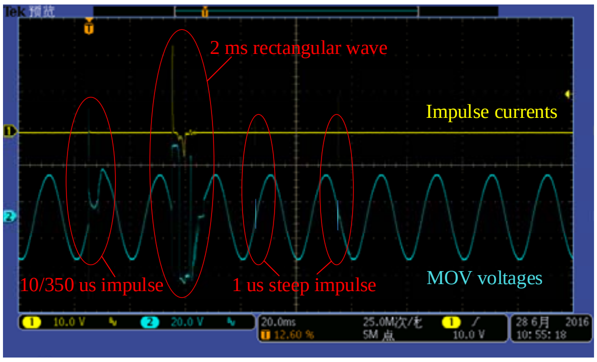


Figure 4. The current and voltage waveforms on V230 under MODT

Interesting phenomenon is that punctures, as one of the main failure modes, always appear close to the edge of varistors, instead of near the electrodes, as shown in Fig. 3c and Fig. 3d. Obvious ablation is also observed around the punctured hole. The most serious failure mode is shattering. Since two ditches are observed on the shattered piece in Fig. 3b, it can be speculated that shattering is very likely developed from the puncture.

C. *Effect of the Sequences for the Multi-wave Multi-impulse Currents*

The natural multiple lightning stroke currents are composed of different current components and sequences. In order to evaluate the effect of different sequences of multiple currents, some V275 samples are adopted in the MODT. Two groups of current amplitudes are adopted in the multiple impulse currents. The test results under different sequences of multiple impulse currents in MODT are shown in Tab. VII.

It can be seen from Tab. VII that under relative large current amplitude for 10/350 μs impulse current with $0.75I_{imp}$ amplitude, the V275 could pass the MODT under the impulse sequences of ‘F0.75Iimp+R800+S10+S10’. However, the V275 failed under the other two sequences where the steep currents appear before the 2 ms rectangular impulse. It means that the MOVs would more easily be deteriorated if no interval stroke occurs between the first lightning return stroke and the subsequent lightning return stroke. The degraded voltage waveforms on V275 under the test of ‘F0.75I_{imp}+S10+R800+S10’ are shown in Fig. 5.

TABLE VII. TEST RESULTS UNDER DIFFERENT SEQUENCES OF THE MULTIPLE IMPULSE CURRENTS

Test item	Thermal stability	U_{cr} for U_{DC1mA}	U_{cr} for Ur	Visual inspection
F0.75I_{imp}+R800+S10+S10	Yes	-3.11%	0.92%	Pass
F0.75I_{imp}+S10+R800+S10	No	-	-	Puncture
F0.75I_{imp}+S10+S10+R800	No	-	-	Puncture
F0.5I_{imp}+R800+S20+S10	Yes	3.68%	2.76%	Pass
F0.5I_{imp}+S20+R800+S10	Yes	4.78%	3.75%	Pass
F0.5I_{imp}+S20+S10+R800	Yes	1.20%	0.98%	Pass

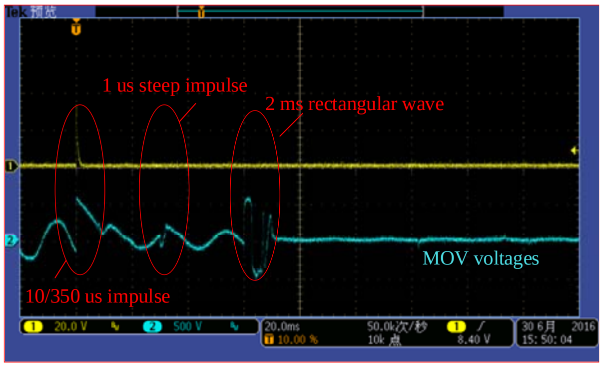


Figure 5. The degraded voltage waveforms on V275 under MODT

Another group of current amplitudes adopt $0.5I_{imp}$ for 10/350 μs impulse current and 20 kA for one of the 1 μs steep current. Under such current amplitudes, the V275 could pass MODT under any impulse sequences of multiple impulse currents. It can be concluded that the effect of different impulse sequences is not that obvious when the current amplitudes are relative low. In addition, the increase of the amplitude for first lightning return stroke current would more threaten the MOVs than the increase of the amplitude of subsequent lightning return stroke current, though the latter current has much steep wave-front and higher amplitude.

D. *The Impactt of Interval Time Between Impulse Currents*

Investigations by B-H Lee et al. have suggested that the time interval between multiple impulses can be a critical cause of failure for MOVs [12-13]. In order to evaluate the effect of interval time on the results of MODT, different time intervals (20 ms, 30 ms, 60 ms, 100 ms) between two impulses are adopted during MODT. The MC of ‘F0.75Iimp+R800+S10+S10’ are adopted. The test results on the three types of MOVs are shown in Tab. VIII.

Tab. VIII shows that when the time interval decreases to 20 ms, the tested three types of MOVs are shattered and fail in the MODT. On the other hand, the MOVs could pass the test when the time interval is more than 100 ms. The type

V230 and V275 also fail in the MODT under time interval of 30-60 ms, while V460 has better performance and pass the test. This phenomenon also confirms the conclusion that the MOVs with high limiting voltages have better performance under MODT. The current and voltage waveforms on V460 under interval of 60 ms are shown in Fig. 6.

TABLE VIII. TEST RESULTS UNDER DIFFERENT TIME INTERVALS BETWEEN IMPULSE CURRENTS

MOV Type	Interval time (ms)	Thermal stability	U_{cr} for U_{DC1mA}	U_{cr} for U_r	Visual inspection
V230	20	No	-	-	Shattering
	30	No	-5.71%	3.78%	Minor crack
	60	No	-10.53%	-11.56%	Minor crack
	100	Yes	0.35%	1.12%	Pass
V275	20	No	-	-	Puncture
	30	No	-	-	Major crack
	60	No	-	-	Minor crack
	100	Yes	0.48%	1.33%	Pass
V460	20	No	-	-	Shattering
	30	Yes	3.98%	0.57%	Minor crack
	60	Yes	-3.06%	1.14%	Pass
	100	Yes	0.97%	1.03%	Pass

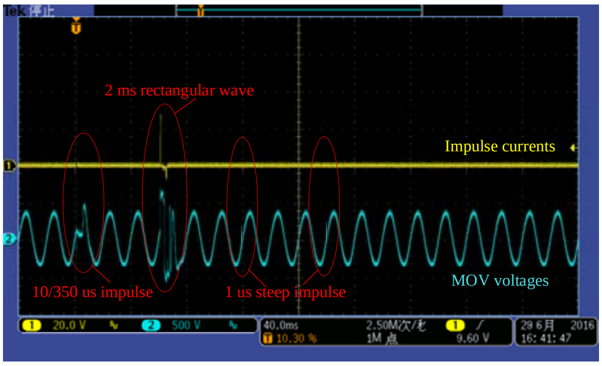
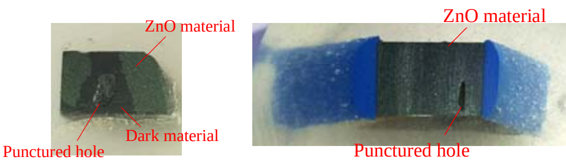


Figure 6. Current and voltage waveforms on V460 under 60 ms interval

V. ANALYSIS ON THE MICROSTRUCTURES OF FAILED ZNO VARISTORS

The above results show that the failure modes for MOVs after MODT include the crack on the plastic encapsulation, the punctures on the varistor, and shattering of the varistor.

Microstructural examination was carried out on the punctured pieces of specimen No. 1 and specimen No. 2. The specimens were firstly sectioned perpendicular to the contacts to expose the internal punctured hole. After the specimens were ground, polished, and etched, the cross sections of the punctured pieces are shown in Fig. 7.

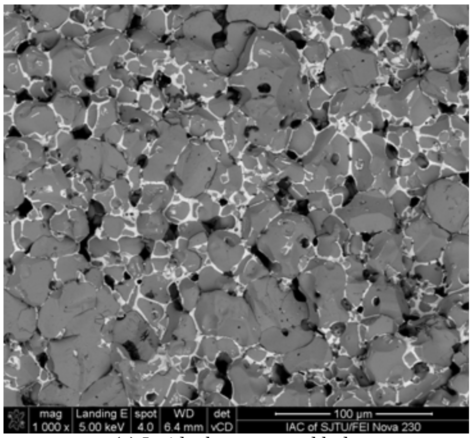


(a) Specimen No. 1 (b) Specimen No. 2

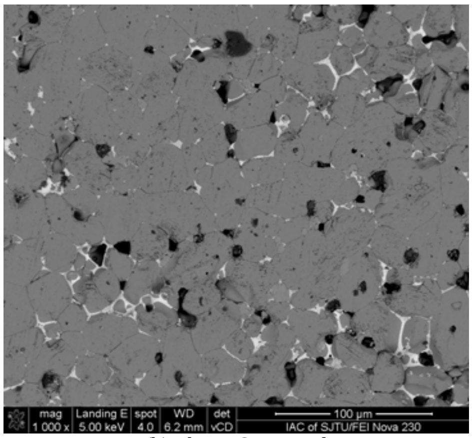
Figure 7. The cross sections of the punctured pieces

It can be seen from Fig. 7a that the punctured hole in specimen No. 1 is surrounded by dark materials instead of the ZnO materials, while the nature of the dark materials is unknown. However, the punctured hole in specimen No. 2 is surrounded by the ZnO materials, as shown in Fig. 7b.

The micrographs for the specimen No. 1 under scanning electron microscope (SEM) are shown in Fig. 8.



(a) Inside the punctured hole



(b) The ZnO material

Figure 8. Micrographs for specimen No. 1 under SEM

It was observed from Fig. 8a that the grain size is smaller in the punctured hole, compared with that in the ZnO material as shown in Fig. 8b. In addition, the quantity of the white intergranular phase in the punctured hole is much more than that in the surrounding ZnO material.

The difference of the microstructures between the punctured hole and the surrounding ZnO material indicates that the multiple lightning stroke currents would cause the grain size become smaller and the white intergranular phase increase, resulting in the ZnO material significantly deteriorated and even shattering.

VI. CONCLUSIONS

In order to evaluate the performance of class I SPDs more realistically, operating duty tests with multi-waveform multi-pulse simulated lightning impulse currents are carried out on the MOVs of class I SPDs in this paper. Some conclusions are achieved.

(1) All the tested MOVs could pass the SODT without degradation. However, such tests could not simulate the effects of realistic multiple lightning strokes that have much stronger degradation effect on the electrical and physical properties of MOVs than single pulses.

(2) The increase of the current amplitude for first lightning return stroke and interval stroke have serious degradation effect on the MOVs, while the effect for the amplitude of subsequent lightning return stroke current is little. The MOVs with high limiting voltages have better performance under MDT.

(3) The tested MOVs would be more easily damaged if the first return stroke is directly followed by subsequent return stroke without interval current. Different sequences of the multiple impulse currents have influence on the MOVs especially when the current amplitudes are relative large.

(4) With the decrease of the interval time between the impulse currents, MOVs would suffer more stress from the multiple lightning currents during MODT. The tested MOVs that could pass the MODT under time interval of 100 ms between the multiple currents all failed in the tests under time interval of 20 ms.

(5) The main failure modes for MOVs after MODT include the crack on the plastic encapsulation, the punctures on the ZnO material, and shattering of the varistor. The punctures appear close to the edge of varistors. The shattering is developed from the puncture.

(6) The microstructural examination indicates that the multiple lightning stroke currents would cause the ZnO grain size become smaller and the white intergranular phase between grains significantly increases, resulting in the ZnO material deteriorated and even shattering.

REFERENCES

[1] Metwally I., Heidler F. H., "Enhancement of the SPD residual voltage at apparatus terminals in low-voltage power systems," IEEE Trans. on Power Deliv., April, 2007, vol. 22, no. 4, pp. 2207-2213.

[2] He J., Yuan Z., Wang S., Jun Hu, Shuiming Chen, Rong Zeng "Effective protection distances of low-voltage SPD with different voltage protection levels," IEEE Trans. on Power Deliv., Jan., 2010, vol. 25, no. 1, pp. 187-195.

[3] "Test specifications for surge-protective devices for use on the load side of the service equipment in low-voltage (1000V and less) AC power circuits," IEEE Std C62.62™-2010.

[4] "Low-voltage surge protective devices -Part 11: Surge protective devices connected to low-voltage power systems –Requirements and test methods," IEC61643-11,2011.

[5] Chen Shaodong, Zhang Yijun, Yang Shaojie, et al. "Characteristics of induced overvoltage generated by triggered lightning in the low voltage power supply system," High Voltage Engineering, Dec. 2009, vol 35, no. 12, pp.2944-2952.

[6] T.A. Short,Electric power distribution handbook, CRC Press, New York, 2004, Section.12.4.5 Arrester reliability and failures.

[7] He Y., Fu Z., Jiang A., "On the simulation of lightning current for the application in lightning arrester and material ablation tests," in Proc. Int. Conf. Asia-Pacific Symposium on Electromagnetic Compatibility, Taiwan, China, May 2015, pp. 428-431.

[8] Darveniza M, Tumma L R., "Laboratory and analytical studies of the effects of multipulse lightning current on metal oxide arresters," IEEE Trans. on Power Deliv.,1994, vol. 9 no. 2, pp.764-771.

[9] Sargent R A, Dunlop G L, Darveniza M., "Effects of multiple impulse currents on the microstructure and electrical properties of metal-oxide varistors," IEEE Trans. on Electrical Insulation, 1992, vol. 27 no. 3, pp.586-592.

[10] Darveniza M, Tumma L R, Richter B, Roby, D.A. "Multipulse lightning currents and metal-oxide arresters," IEEE Trans. on Power Deliv., July. 1997, vol. 12 no.3, pp.1168-1175.

[11] M. Darveniza, D.R. Mercer, "Laboratory studies of the effects of multipulse lightening currents on distribution sugre arresters,", IEEE Trans. on Power Deliv., July, 1993, vol. 8 no.3, pp.1035-1044.

[12] Lee B H, Kang S M., "Properties of ZnO varistor blocks under multiple lightning impulse voltages," Current Applied Physics, 1997, vol. 12, no.3, pp.1168-1175.

[13] Lee B H, Kang S M, Eom J H., "Effect of Multiple Lightning Impulse Currents on Zinc Oxide Arrester Blocks," in Proc. 27th, Int. Conf. Lightning Protection, Avignon, France, 2004.

[14] Haryono T, Sirait K T, Tumiran K, Z Xiao. "Effect of multiple lightning strikes on the performance of ZnO lightning arrester block," High Voltage Engineering, vol. 37, no. 11, 2011, pp.2763-2771(in Chinese).

[15] Haryono T, Sirait K T, Tumiran K, Hamzah Berahim, "The Damage of ZnO Arrester Block Due To Multiple Impulse Currents," TELKOMNIKA, vol. 9, no. 1, 2011, pp.171-182.

[16] Christof Drilling, Markus Droldner, and Ernst Günther Jordan., "A new generator for testing of SPD's using multiple lightning current impulse for combined tests with follow currents," in Proc. 24th Int. Conf. Lightning Protection, Birmingham, England,1998.

[17] Alain Rousseau, Xuyun Zang, Lihua Zhang, Ming Tao, "Multiple shots on SPDs - Test Methods and Results," Proc. 31th Int. Conf. Lightning Protection (ICLP), Vienna, Austria, 2012.

[18] A. Rousseau, X. Zang, L. Zhang, and M. Tao, "Multiple shots on SPDs - test methods and results," in Proc. 32th Int. Conf. Lightning Protection, Shanghai China, pp. 997-1001, 2014.

[19] C. Heinrich, S. Wagner, B. Richter, W. Kalkner, "Multipulse Tests on Surge Arresters for Medium and Low Voltage Systems," in Proc. 24th Int. Conf. Lightning Protection, Birmingham, England, pp.790-794, 1998.

[20] B. Vahidi, K. Cornick, D. Greaves, "Effects of Multiple Stroke on ZnO Surge Arresters," in Proc. 24th Int. Conf. Lightning Protection, Birmingham, England, pp.960-963, 1998.

[21] M. N. Tuczek, V. Hinrichsen, "Recent Experimental Findings on the Single and Multi-Impulse Energy Handling Capability of Metal-Oxide Varistors for Use in High-Voltage Surge Arresters," IEEE Trans. on Power Deliv., April, 2013 vol. 22 no. 4, 196–205.

[22] K. Nakada, H. Sugimoto, S. Yokoyama, "Experimental facility for investigation of lightning performance of distribution lines," IEEE Trans. Power Del., Jan., 2003, vol. 18, No. 1, pp. 253-257.

[23] J. Schoene, M.A. Uman, V.A. Rakov, et al., "Direct Lightning Strikes to Test Power Distribution Lines—Part I: Experiment and Overall Results," IEEE Trans. Power Del., vol. 22, No. 4, 2007, pp. 2236-2244.

[24] P.P. Barker, R.T. Mancao, D.J. Kvaltine, D. E. Parrish, "Characteristics of lightning surges measured at metal oxide distribution arresters," IEEE Trans. Power Del., Jan, 1993, vol. 8, No. 1, pp. 301-310.

[25] Jiang A, Fu Z, Sun W, Jian Chen, Guoli Wang, Ruihai Li., "Experimental and analytical studies of the effects of multiple lightning impulse currents on metal-oxide arrester blocks," in Proc. 32th Int. Conf. Lightning Protection, Shanghai China, pp. 681-687, 2014.

[26] "Surge arresters-Part 4: Metal-oxide surge arresters without gaps for a.c. systems," IEC60099-4, 2006.