Capacitive Current Switching of Vacuum Interrupters and Inrush Currents

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Abstract- **Capacitive current switching has become increasingly necessary for power factor correction in distribution systems. However, Restrikes are potentially dangerous as they could cause overvoltage which can be harmful to the power system. The dielectric strength of the Vacuum Interrupter (VI) in a capacitive current switching is strongly determined by a condition of the contact surfaces modified by an inrush current. But the influence of the inrush current on restrike phenomenon of VIs is still not well understood. The objective of this paper is to understand the restrike characteristics of VI under the inrush currents of different amplitudes. The peak values of inrush currents are set at 0kA, 2kA, 5kA and 10kA. VIs with a rated voltage of 7.2kV are used. For the each testing operation, VI suffers an inrush current during a making operation. Then a DC recovery voltage appeared across the vacuum interrupters after a switching current (lower than 1 A) is interrupted. The experimental results show that a higher inrush current induces more damages to the contact surfaces, which result in more restrikes. The restrike probabilities are 4.6%, 17.9% and 30.4% on average at the inrush current of 0kA, 2kA and 5kA respectively. VIs cannot be opened after several test operations by a welding at the inrush current of 10kA. The inrush currents with higher amplitude induce the restike occurring earlier than that of lower amplitude during the recovery voltage.**

I. INTRODUCTION

Vacuum Interrupters (VIs) are frequently used for reactive power compensation. The capacitor banks are switched perhaps once or twice a day [1-3]. Bonfanti et al [1] show that 60% of all the capacitor banks are switched up to 300 times a year and a further 30% are switched up to 700 times a year. So VI with long mechanical life is suitable for this duty. However, Restrikes may occur occasionally, which may cause overvoltage to do harm to the power system [4-5]. Thus a reliable dielectric strength of VI is essential for capacitive switching.

The capacitive current switching performance of a VI is mainly determined by the condition of the contact surfaces modified during the prestrike process. Dullni et al [6] show that restrike phenomenon is correlated with the prestrike process during the making operation. Juhsasz et al [7] find that the frequency of restrikes is dependent on the energy of the prestrike arc. Koochack Zadeh et al. [8] observe that the amplitude of the inrush current has a large influence on the field emission current. However, research so far has not sufficiently clarified the relationship between prestrike and restrike phenomenon. Many studies have investigated other factors which may influence the restrike phenomenon. For example, the study by Delachaux et al [9] shows that slower closing speed can result in higher restrike probability. Yokokura et al [10] have found that CuW is the best materials for capacitive current switching compared with CuTeSe, CuBi and CuCr. Körner et al [11] show that the spiral type contacts have a better dielectric behavior than the flat contacts as the erosion areas caused by pre-arcing are larger. Therefore, the impact of the inrush current during the prestrike process on restrike phenomenon is still not well understood.

The objective of this paper is to understand the restrike characteristics of VI under the inrush currents of different amplitudes. First, we investigate the impacts of the inrush current of 0kA, 2kA, 5kA and 10kA (peak value) on the restrike probabilities. And then we study how the inrush currents influence the occurring time of the breakdowns. Finally, the conditions of the contact surfaces under the inrush currents of different amplitudes are also analyzed.

II. EXPERMENTAL SETUP

A synthetic test for evaluating the capacitive current switching performance of VI is shown in Fig. 1. This test circuit is composed of three parts: an inrush current source, a current source and a voltage source. The inrush current source supplies a current of up to 20kA peak value at a frequency of 3800Hz by discharging a capacitor C2 over an inductance L2. The current source is similar to the inrush current source, which can provide a power frequency current of up to 2kA (50Hz). The voltage source can produce a recovery voltage with the wave shape of (1-cosωt) by a high voltage transformer T through a voltage source capacitor C1.

A test operation is composed of a making operation and a breaking operation. All the experimental apparatuses are given in Fig. 1. Before the start of the test, the inrush current source capacitor C2 and the current source capacitor C should be pre-charged to a

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required voltage. When the phase angle of U_{AC} is zero, the test sequence is triggered by a signal. Then a vacuum circuit breaker (VCB) SW_{inrush} is closed. When the test vacuum circuit breaker SW_{test} is closed, a high frequency inrush current will flow through a test VI. After the $SW_{current}$ and $SW_{voltage}$ are closed, a small capacitive current I_v is applied to the test VI. And then the SW_{inrush} is opened to isolate the inrush current circuit from other two circuits. At an appropriate time, a synchronous vacuum circuit breaker SW_g is closed to keep the power frequency currents I_c and I_v in a same phase. When the switching current I (I_c + I_v) is interrupted by the VCB $SW_{current}$ and SW_{test}, a recovery voltage is applied to the test VI. The whole test sequence is stopped after a recovery voltage is applied.

Fig. 2 shows a typical oscillogram of making operation. The upper trace is a contact travel and the lower trace is an inrush current. Fig. 3 shows a successful breaking operation oscillogram of the test VI. The lower trace represents the switching current I. After the switching current zero, a recovery voltage (the upper trace) is applied to the test VI.

In this research, test VIs of the rated voltage 7.2kV are used without conditioning. The contact diameter is 30 mm and the contact material is CuCr25. The contact gap is adjusted to 4mm.

To evaluate the capacitive current switching performance of the test VI, a series of 80 making and breaking operations is executed for each one. The detail test conditions are listed in Table 1. Eleven 7.2kV VIs are used for the whole experiment. According to the different amplitudes of the inrush current of 0kA, 2kA, 5kA and 10kA, the experiment is composed of four test series a, b, c and d. And each test series uses 3 VIs for test series a - c. The test condition is set in the worst case (the switching current is less than 1A) as the switching current of hundreds amperes has a conditioning effect [5-11]. And the peak value of the recovery voltage is about 15kV ($2U_m$). The full period of recovery voltage application is 500ms.

TABLE 1. CONDITIONS FOR CAPACITVE CURRENT SWITHCING TEST

Inrush current	Series a	$U_m(1 - \cos\omega t)$	Series d
	0kA	$U_m = \frac{7.2\ kV \times \sqrt{2}}{\sqrt{3}} \times 1.25$	10 kA
	Frequency: 3800Hz		
Switching current	< 1A		
Recovery voltage			
	Duration: 500ms		
Test duty	C – O: 80 times		

III. EXPERMENTAL RESULTS

Restrikes and non-sustained disruptive discharges (NSDDs) are two common phenomena after the capacitive current switching by using vacuum interrupters in power system. Restrikes are defined as a resumption of the current, whereas the NSDDs do not result in current in the main load. Since the capacitive current switching test is executed by using a synthetic test circuit, which is not equal to a direct test or a field running in power system [9]. Thus we do not distinguish the two kinds of breakdowns and both of them are referred to restrike in this paper.

Fig. 4 shows a typical oscillogram of the restrike. The recovery voltage is applied to the contact gap after the switching current is interrupted. When the VI cannot withstand the high voltage in the third crest of the recovery voltage, a restrike occurs and a restrike current is established at the same time. There are also several restrikes occurring later in the same figure

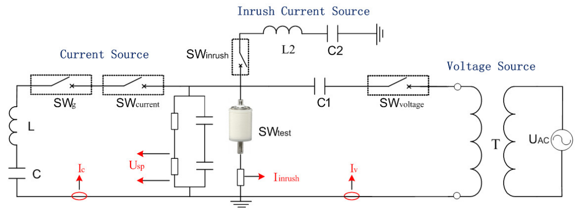


Fig. 1. A synthetic test circuit for capacitive current

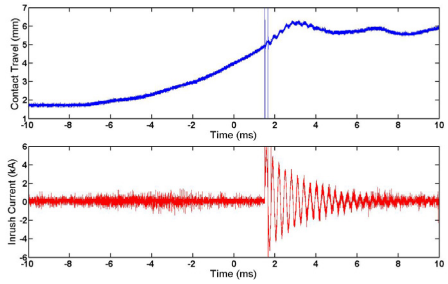


Fig. 2. A typical oscillogram of a making operation

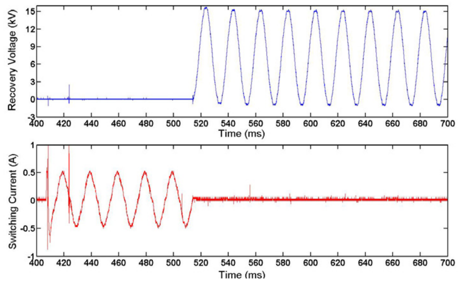


Fig. 3. A typical oscillogram of a breaking operation

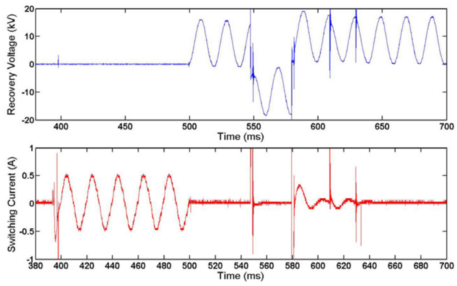
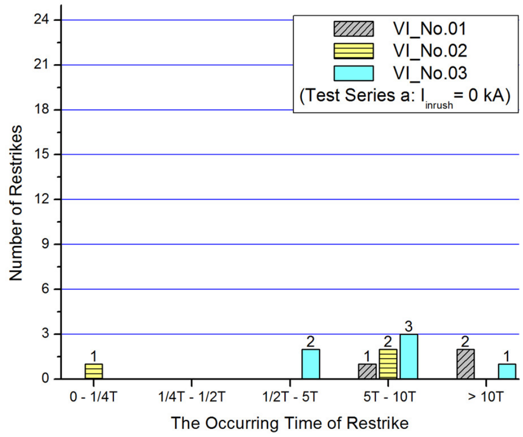
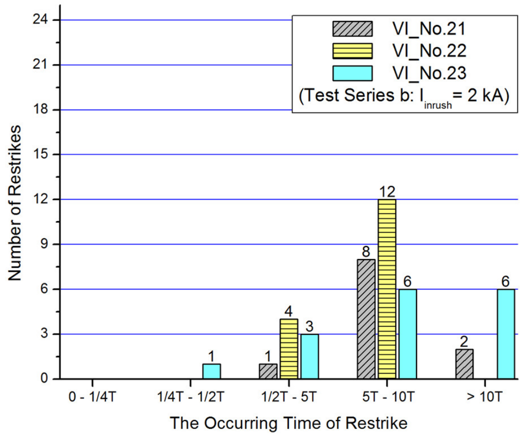


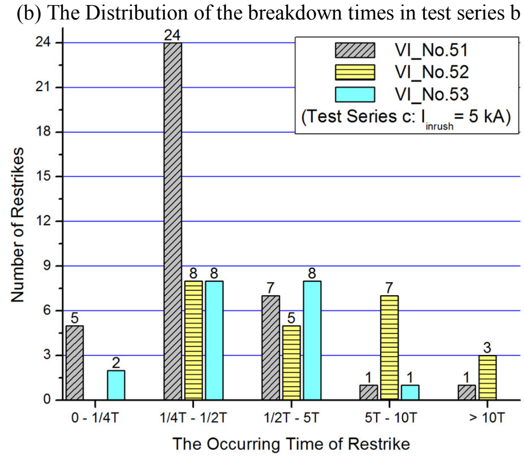
Fig. 4. Restrike oscillogram of vacuum interrupters after switching current zero



(a) The Distribution of the breakdown times in test series a



(b) The Distribution of the breakdown times in test series b



(c) The Distribution of the breakdown times in test series c

Fig. 5. The Distribution of occurring time of breakdown under different amplitudes of the inrush currents

Table 2 shows the restrike probabilities of all test VIs for four test series a, b, c and d (restrike is referred to the breakdown which occurs after 1/4T of the recovery voltage). It is obviously that the restrike probability is closely related to the amplitude of the inrush current. And a higher inrush current produces more restrike phenomena in the capacitive current switching test. In test series a, the restrike probability of the test VI is 4.6% on average. In test series b, the restrike probability of the test VI is 17.9% on average. And the average value of restrike probability in test series c reaches 30.4%, which is nearly 1.7 times of that in test series b. In test series d, the restrike probability cannot be accounted, as the contacts are welded and the test VI cannot be opened after less than five operations at the inrush currents of 10kA.

TABLE 2. RESTRIKE PROBABILITY FOR FOURTEST SERIES

Test series	Test VI	Restrike probability	Average value
a I_{inrush} = 0kA	No.01	3.8%	4.6%
	No.02	2.5%	
	No.03	7.5%	
b I_{inrush} = 2kA	No.21	13.8%	17.9%
	No.22	20.0%	
	No.23	20.0%	
c I_{inrush} = 5kA	No.51	41.3%	30.4%
	No.52	28.8%	
	No.53	21.3%	
d I_{inrush}=10kA	No.101	Welding less than 5 test operations	
	No.102		

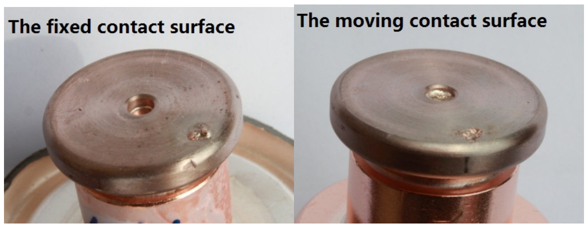


Fig. 6. The photograph of the contact surfaces of VI_No.22 after 80 operations in test series b

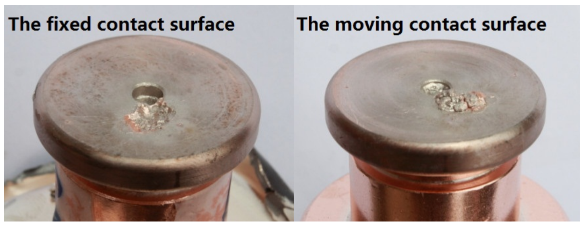


Fig. 7. The photograph of the contact surfaces of VI_No.52 after 80 operations in test series c

Fig. 5 shows a distribution of occurring time of breakdowns (reignitions and restrikes) for each test VI. In the abscissa axis, the T is the cycle of the recovery voltage (20ms) and zero represents the instant when the recovery voltage is applied to the VI. Fig. 5 indicates that the inrush current amplitude can strongly influence the occurring time of the breakdowns. Fig. 5 (a) shows that most of the breakdowns occur after 5T (100ms) with no inrush current applied. Fig. 5 (b) shows that the occurring time of breakdowns mainly distributes from 5T (100ms) to 10T (200ms) and some breakdowns occur before 5T (100ms) at the inrush current of 2kA. Fig. 5 (c) shows that the majority of breakdowns occur before 1/2T is in at the inrush current of 5kA (some breakdowns even occur before 1/4T). Thus, the retstrike occurs significantly earlier with the amplitude of inrush current increasing.

Fig. 6 and Fig. 7 show photographs of the contact surfaces after 80 making and breaking operations in test series b and test series c, respectively. Both the test VIs have a damaged surface with a macroscopic protrusion. And in the meanwhile a crater is formed on the opposite contact surface. Fig. 6 shows that the height of the protrusion is 0.7mm and the area of the crater is about $10mm^2$ for the test VI (No.22) in test series b. Fig. 7 shows that the height of the protrusion is 1.3mm and the area of the crater is about $31mm^2$ for the test VI (No.52) in test series c. so it can be seen that the damages on the contact surfaces exhibit strong difference depending on the amplitude of the inrush currents.

IV. DISSCUSSION

During the capacitive current switching test by VIs, the inrush current flows through the contacts and the arc foot of the prestrike arc on either electrode melts the contact surfaces locally, which may finally cause contact welding after two contacts touch together. When the contacts are opened again, the dielectric strength of the contact gap in the vacuum interrupter is influenced by the variation of the contact surface conditions [5-11].

The inrush currents can modify the contact surfaces of VIs during the making operations [11]. A macroscopic protrusion is formed on a contact surface and a crater is formed on the opposite contact surface at same time. So the contact gap may be influenced significantly by this protrusion and crater. And then the macroscopic electric field in contact gap can be influenced significantly by these damages located on a particular area on the contact surfaces as shown in Fig. 6 and Fig. 7. Thus, the prestrike process during making operation can directly reduce the dielectric strength of the vacuum gap. And more serious damages are produced on the contact surfaces (higher protrusions and larger areas of the craters) in the case of I_{inrush} = 5kA, which induced more restrike phenomena.

It is suggested that the electric field is not determined by U/d where U is the voltage impressed across a contact gap d, but is given by βU/d [2]. The enhancement factor β increases quickly due to a growing damage caused by the pre-arcing, which may result in field emission current during the period of recovery voltage application. And the inrush currents with higher amplitude have a significant influence on the field emission current. Koochack Zadeh et al. [8] observed that restrike may happen after a high value of field emission current or the field emission current increases continuously during the recovery voltage until a breakdown occurs. It means that field emission current can influence the occurring time of breakdown under the recovery voltage. Thus, with the amplitude of the inrush current increasing, the field emission becomes higher to generate the restrike occurring earlier during the recovery voltage.

V. CONCLUSION

The impact of the inrush currents with different amplitudes during the making operation on the restrike characteristics of VIs after switching capacitive current is studied in this paper. The experimental results show that higher protrusions and larger areas of the craters are produced on the contact surfaces with the amplitude of inrush current increasing. Due to the amplitude of the inrush currents increasing from 0kA, 2kA and 5kA, respectively, the restrike probabilities of VIs are 4.6%, 17.9% and 30.4% on average in the test series a, b and c. The contacts are welded and cannot be opened after several test operations (less than 5) in test series d with an inrush current of 10kA. The inrush current with a higher amplitude induces the restrike occurring earlier during the recovery voltage.

REFERENCES

[1] I. Bonfanti, C. Guilloux, G. Damstra, R. Smeets, "Shunt Capacitor Bank Switching Stresses and Test Methods," Electra, No. 183, pp. 12-44, 1999.

[2] P.G. Slade, "The Vacuum Interrupter: theory. Design and Application," CRC Press Taylor & Francis Group, 2008.

[3] S. Griot, A. Moreau, "Vacuum Circuit breaker's Electrical Life for Shunt Capacitor Switching," 24th International Symposium on Discharges and Electrical Insulation in Vacuum, Braunschweig, pp. 194-197, 2010.

[4] R. P. P. Smeets, A. G. A. Lathouwers, "Capacitive Currents Switching Duties of High-Voltage Ciruit Breakers: Background and Practice of New IEC Requirements," Proc. IEEE Power Engerneering Society Winter Meeting, Singapore, Vol. 3, pp. 2123-2128, 2000.

[5] G. Sandolache, U. Ernst, X. Godechot, S. Kantas, M. Hairour, and L. Dalmazio, "Swithcing of Capacitive Current with Vacuum Interupters," 24th International Symposium on Discharges and Electrical Insulation in Vacuum, Braunschweig, pp. 129-132, 2010.

[6] E. Dullni, Wenkai Shang, D. Gentsch, I. Kleberg and K. Niayesh, "Switcing of Capacitive Currents and the correaltion of Restrike and Pre-ignition Behavior," IEEE Trans. on Dielectr and Electr. Insul., vol. 13, No. 1, pp. 65-71, 2006.

[7] A. Juhsasz, W. Rieder, "Capacitive Switching with Vacuum Interrupters," Proceedings of the 10th International Conference on Gas Discharges and Their Applications, pp. 62-65, 1992.

[8] M. Koochack Zadeh, V. Hinrichsen, R. Smeet and A. Lawall, "The Impact of Capacitive Bank Inrush Current on Field Emission Current in Vacuum," 24th International Symposium on Discharges and Electrical Insulation in Vacuum, Braunschweig, pp. 210-213, 2010.

[9] T. Delachaux, F. Rager, D. Gentsch, "Study of Vacuum Circuit Breaker Performance and Weld Formation for Different Drive Closing Speeds for Switching capacitive current," 24th International Symposium on Discharges and Electrical Insulation in Vacuum, Braunschweig, pp. 241-244, 2010

[10] K. Yokokura, M. Matsuda, K. Atsumi, T. Miyazawa, S. Sohma, E. Kaneko and I. Ohshima, "Capacitor Switching Capability of Vacuum Interrupter with CuW Contact material, " IEEE Trans. on Power Delivery, vol. 10, No. 2, pp. 804-809, 1995.

[11] F. Körner, M. Lindermayer, M. Kurrat and D. Gentsch, "Swithcing Behavior of Different Contact Materials under Capacitive Switching Conditions," 23rd International Symposium on Discharges and Electrical Insulation in Vacuum, Braunschweig, pp. 202-205, 2008.

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