Axial Magnetic Field Strength Needed for a 126-kV Single-Break Vacuum Circuit Breaker During Asymmetrical Current Switching

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***Abstract*— The objective of this paper is to investigate how strong an axial magnetic field (AMF) is needed in test duty T100a for a 126-kV single-break vacuum circuit breaker (VCB) when interrupting a rated short circuit current of 40-kA rms in light of arcing contact gap, arc duration and phase shift effect. The AMF is generated by a pair of 2/3 coil-type AMF contacts. First, the accuracy of a 3-D finite element simulation of AMF is validated by an AMF measurement at a contact gap 30 mm and the error is $< 10\%$. After that test duty T100a of the 126-kV single-break VCB are carried out 18 times with arc duration from 3.3 to 19 ms at 40-kA rms. With a given opening displacement curve, the contact gap as arc extinguishes within a range from 12 to 50 mm corresponding to the arc duration from 3.3 to 19 ms. Then the AMF distribution of the 126-kV single-break VCB at each contact gap at which arc extinguished is simulated to analyze the current interrupting results. The results show that there are successful interruptions at the short-circuit current 40-kA rms in test duties T100a, with the shortest arcing contact gap window from 18 to 23 mm and the longest arcing contact gap of 44 mm. The shortest arcing contact gap window corresponds to the maximum AMF at the intermediate plane of the contact gap per kilo-ampere of the breaking peak current from 9.3 to 8.5 mT/kA. In addition, the longest arcing contact gap corresponds to the value of 6.1 mT/kA. The phase shift time at the center of intermediate plane of the contact gap ranged from 1.36 to 0.75 ms corresponding to an increase of arcing contact gap from 12 to 50 mm in the tests.**

***Index Terms*— Magnetic fields, vacuum arcs, vacuum circuit breakers (VCBs), vacuum interrupters.**

I. Introduction

VACUUM circuit breakers (VCBs) are widely used as intermediate voltage-class switching devices for their excellent features such as the ability to be switched numerous times, maintenance free, and so on [1]–[4]. In recent years, they meet the requirements of a movement toward environment protecting and are expected to be used in transmission voltage level applications [5]–[8]. In this paper, we discuss such an application, which is a kind of 126-kV single-break VCB with a pair of 2/3 coil-type AMF contacts.

In power systems, VCBs acting as protective devices, are required to switch off short-circuit currents [9]. According to an international standard IEC 62271-100 [10], VCBs should be capable to perform five basic short-circuit test duties, which relates to four symmetrical terminal fault conditions and one asymmetrical test duty: T10, T30, T60, T100s, and T100a. Therefore, the five short-circuit test duties are a series of challenges to the transmission voltage level VCBs, especially the test duty T100a. This paper presents test results of the 126 kV VCB in test duty T100a, with an asymmetrical short-circuit current of 40-kA rms.

Many methods have been proposed to increase the interrupting ability of VCBs. One method to improve the VCBs' interruption performance is to apply an axial magnetic field (AMF), B_{ax}, parallel with the arc. The B_{ax} can be produced through a pair of AMF contacts. Above a critical B_{ax}, it forces the high current arc to rapidly become diffuse and better distributed within the gap [4]. Therefore, the high current diffuse arc gives a superior current interruption performance. That is why numerous contributions share their insights on high current interruption in vacuum under an AMF in medium voltage VCBs [11]–[27].

How strong an AMF is needed in a successful current interruption? Fenski *et al.* [28] determined an effective surface as a contact surface area where the contact system provides an AMF higher than 4 mT/kA. Dullni *et al.* [29] measured the minimum AMF necessary to prevent arc constriction and contact surface melting. His results were that for a 40-mm contact diameter, a current interruption of 12 kA needed an AMF on the order of 40 mT. Morimiya, *et al.* [30] found a current interruption of 14.8-kA peak value needed an AMF $\sim$60 mT for a 45-mm contact diameter and a 30-mm gap space. Stoving *et al.* [31] proposed that for the best arc stability, the axial field should be $\sim$70 mT for a current interruption of 12 kA, with a 38-mm contact diameter and a 12-mm contact gap. Slade [32] reviewed the effect of an AMF on the vacuum arc, including earlier findings that a threshold AMF, dependent on the arcing current, is required for a diffuse arc mode to be established at high currents. Schulman *et al.* [4] established the existence of a critical AMF for a diffuse arc, B_{crit} (in mT), that is linearly proportional to the peak current (in kA) for the conditions of their experiment. However, in addition to the AMF, the current interruption

Manuscript received November 30, 2012; revised February 12, 2013; accepted March 26, 2013. Date of current version June 6, 2013. This work was supported in part by the National Natural Science Foundation of China under Project 51177122 and Project 51221005 and the State Key Laboratory of Electrical Insulation and Power Equipment Fund under Grant EIPE13304 and Grant EIPE11118.

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Digital Object Identifier 10.1109/TPS.2013.2259598

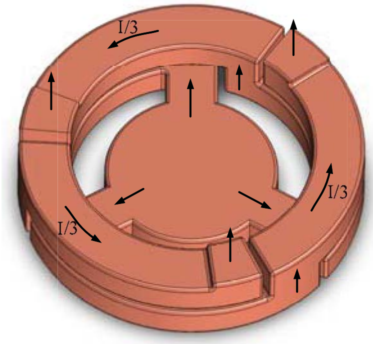

Fig. 1. 2/3 coil-type AMF contact structure.

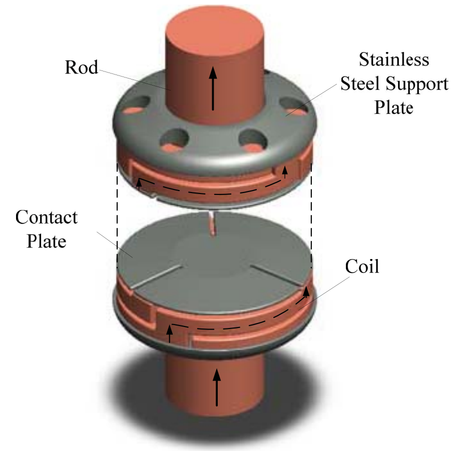

Fig. 2. Full arrangement of the 2/3 coil-type AMF contacts.

performance at a given contact gap and recovery voltage is additionally influenced by many other important impact factors, such as: 1) arc duration, contact separation length as arc extinguishes and the TRV applied between the contacts; 2) the phase shift time between the induced AMF and the source current; 3) the current waveform and its peak value, especially in an asymmetric current interruption, i.e., test duty T100a; and 4) contact diameter and contact material.

The objective of this paper is to investigate how strong an AMF is needed in test duty T100a for a 126-kV single-break VCB as interrupting a rated short-circuit current 40-kA rms in light of arcing contact gap, arc duration, and phase shift effect. The results could provide some information for 126 kV single-break VCBs' designs.

II. Experimental Setup

A. Structure of 2/3 Coil-Type AMF Contact

To investigate the AMF needed for a 126-kV single-break VCB in test duty T100a, a new type vacuum interrupter with a pair of 2/3 coil-type AMF contacts, is proposed for the 126 kV VCB [33]. Fig. 1 shows a coil structure of the 2/3 coil-type AMF contacts behind the contact plates [33]. The contact diameter is 100 mm. And the diameter of the coils is the same to the contact. Fig. 2 shows the full arrangement of the 2/3 coil-type AMF contacts with the current carrying rods, the stainless steel support plates and the slotted contact plates. And the contact plates have slots with a length of 2/3 of the contact radius. Both contacts are identical and the contact gap is 60 mm [33].

B. Magnetic Field Measurement

To study the AMF needed to test duty T100a of a 126 kV single-break VCB, the accuracy of the 3-D finite element simulation of AMF should be validated by a magnetic measurement experiment. First, the AMF is measured at a contact gap of 30 mm. The axial magnetic flux density measurement system is shown in Fig. 3. Three Hall elements are used to measure axial magnetic flux density distribution (B_{ax}). An ac of 1800-A rms is supplied to the 2/3 coil-type AMF contacts from a step down transformer. The current flowed through a pair of fixed contacts via a 30-mm length and 30-mm diameter copper conductor rod.

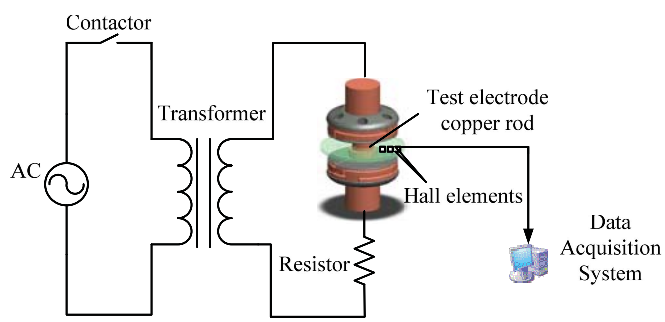

Fig. 3. Axial magnetic flux density measurement system.

TABLE I
MAIN TECHNICAL PARAMETERS OF THE SINGLE-BREAK 126-kV VCB

No.	Technical Parameters	Value	Unit
1	Rated voltage	126	kV, rms
2	Rated frequency	50	Hz
3	Nominal rated current	2500	A, rms
4	Rated short circuit breaking current	40	kA, rms
5	Rated short circuit making current	100	kA, rms
6	Rated short time withstand current (4 s)	40	kA, rms
7	Peak withstand current	100	kA, rms
8	Power frequency withstand voltage (1 min)	230	kV, rms
9	Impulse withstand voltage (1.2X50us)	550	kV, peak
10	Permissible temperature of terminal	$-40 \leq T \leq 105$	$^{\circ}$C
11	Mechanical life	2000	Operations
12	Number of rated nominal current interruption	2000	Operations
13	Contact gap	60	mm
13	Operating mechanism stroke	80	mm
14	Maximum contact erosion	3	mm

In the axial magnetic flux density measurement system, Melexis MLX90215 Hall elements are used to measure the axial magnetic field. The Hall elements are 4. 5 × 3.8 × 1.2-mm programmable linear Hall Effect sensors IC fabricated utilizing silicon-CMOS technology. As shown

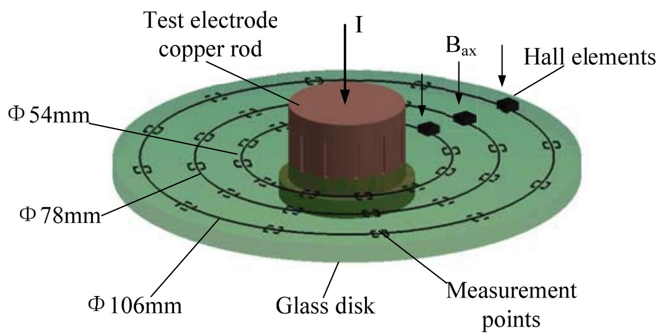

Fig. 4. Hall elements arrangement.

in Fig. 4, the three Hall elements are set on a glass disk that is installed on the intermediate plane between the two contacts. The Hall elements are set at the diameters of 54, 78, and 106 mm, respectively. The glass disk could rotate around the axis of the disk and the data of the axial magnetic flux density are recorded every 30°. This meant that the distribution of the AMF between the contacts can be measured from 36 measured points on the intermediate plane. Current is measured by a current transformer. The accuracy and linearity of the current measuring systems guaranteed the error is $<10\%$ at a frequency of 50 Hz.

III. Test Duty T100a Tests

A 126-kV/2500-A/40-kA single-break VCB with the 2/3 coil-type AMF contact is used in the test duty T100a current interruption tests. The 126-kV VCB is shown in Fig. 5. Its main technical parameters are shown in Table I. The rated voltage of the single-break VCB is 126 kV. The nominal rated current is 2500 A. The rated frequency is 50 Hz. The rated short-circuit breaking current is 40-kA rms.

To investigate the AMF needed for the 126-kV single-break VCB in test duty T100a as interrupting a rated short-circuit current 40-kA rms, the short circuit current are interrupted 18 times on T100a with different arc duration according to IEC 62271-101 Table I.1a (22.5 ms $< t <$ 43 ms, t minimum clearing time) [34]. The peak value of the transient recovery voltage (TRV) is 216 kV. And the rise rate of TRV is 2 kV/μs. An opening displacement curve is kept the one shown in Fig. 6. The maximum contact gap is 60 mm. And the contact gaps at the arc extinguishing under different arc durations, could be calculated from Fig. 6. The T100a tests of the 126-kV single-break VCB are carried out in a synthetic circuit in Xi'an High-voltage Apparatus Research Institute Co., Ltd (XIHARI), Xi'an, China.

IV. AMF Simulation

An AMF simulation is carried out with a commercial 3-D finite element analysis software. At the first step, the accuracy of the simulation result is validated by a comparison it with the measured results. We analyzed the AMF of the 2/3 coil-type AMF contacts with the same model used in the AMF measurement system, as shown in Fig. 7. There is a copper conductor rod linked between the contacts.

Fig. 5. 126-kV single-break VCB adopted to investigate the needed AMF strength in T100a.

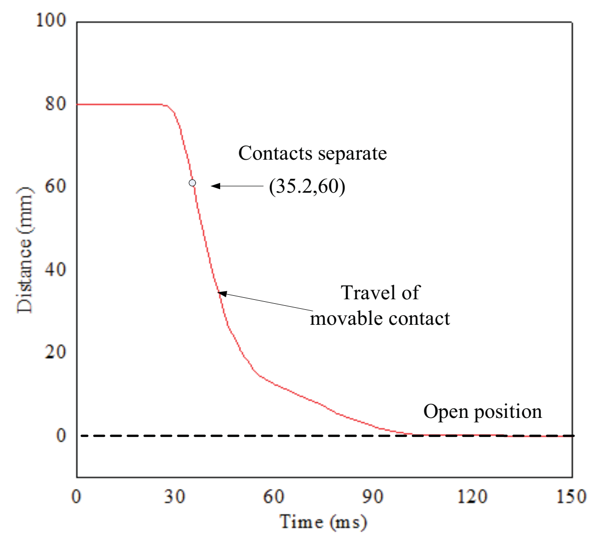

Fig. 6. Opening displacement curve of the 126 kV single-break VCB with the maximum contact gap 60 mm.

After 18 times T100a tests, AMF distribution under different arcing contact gaps according to different arc durations, are simulated to analyze the current interrupting experimental results. The AMF contact model used for the simulation is shown in Fig. 8, where the arc plasma is substituted by a conductor with the same diameter of the contacts. The conductivity of the arc plasma conductor is obtained from the arc voltage and the arc current. Table II shows the material properties of the electrode structure in the simulation.

V. Results and Discussion

A. Comparison of Measurement and Simulation of the AMF

The accuracy of magnetic field simulation is verified by a magnetic field measurement experiment shown in Fig. 7, in which ac 1800-A rms is applied under a 30-mm contact gap. Fig. 9 shows a simulated axial magnetic distribution on the

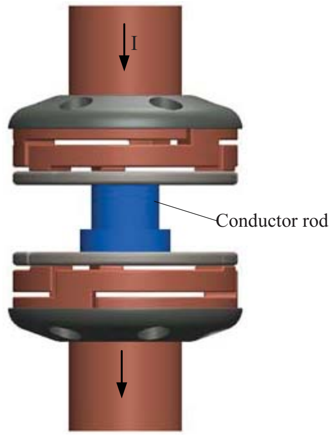

Fig. 7. Contact model for AMF measurement.

Fig. 8. Contact model for numerical AMF analysis to interrupt current interruption test results.

TABLE II
MATERIAL PROPERTIES

Parts	Material	Conductivity(Siemens/meter)
Coil	Copper	5.8e+007
Conductor rod	Copper	5.8e+007
Arc Plasma	Plasma	1579
Copper Arc	Copper	5.8e+007
Contact plate	CuCr50	1.044e+007
Background	Vacuum	0

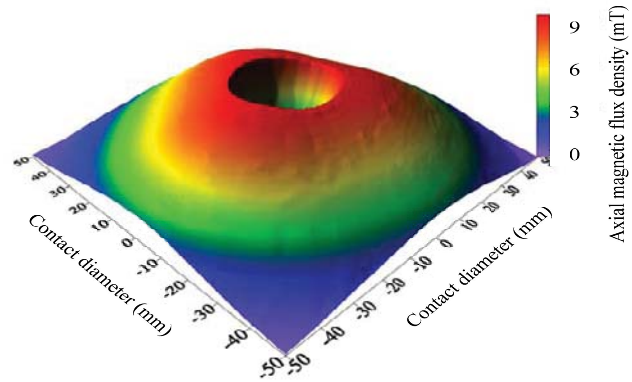

Fig. 9. Distribution of the axial magnetic flux density on the intermediate plane. Current-1800-A rms. Contact gap-30 mm. (a copper conductor rod is installed at the contact center).

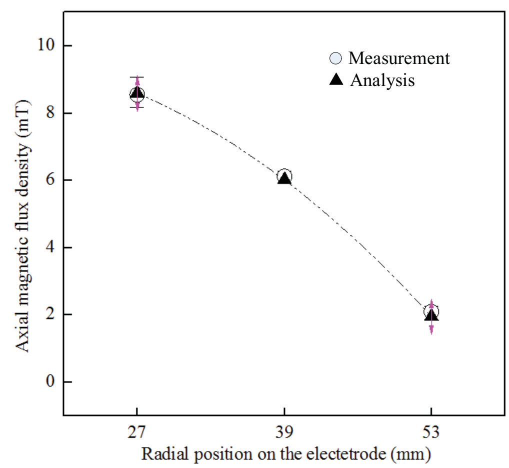

Fig. 10. Comparison of the finite element analysis results and the measurement results.

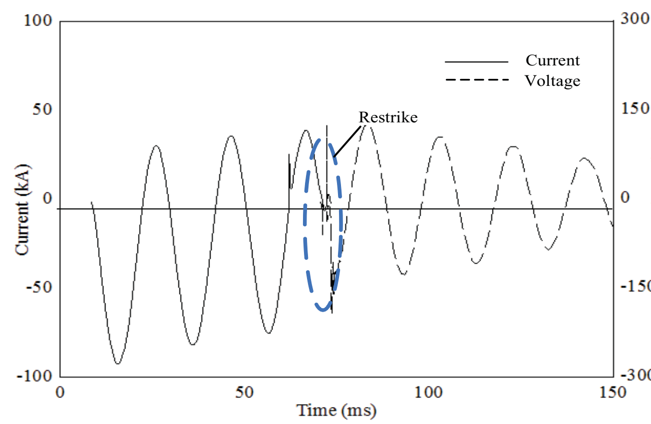

Fig. 11. Failure current interruption with arc duration 3.3 ms, breaking current 40.3-kA peak.

intermediate plane of the contacts under a contact gap of 30 mm with a copper conductor rod. And the simulation results are used to compare with the measured results.

Fig. 10 shows a comparison of the measured results and the simulation results of the axial magnetic flux density in a radial direction. And the errors are $< 10\%$. The results showed that the analytical results fitted the measured ones very well.

B. Test Duty T100a Tests

Test duty T100a tests for the 126-kV single-break VCB are carried out 18 times with the opening displacement characteristics shown in Fig. 6. In addition, the T100a test duties of the 126-kV single-break VCB are carried out with an arc duration ranging from 3.3 to 19 ms. The test results are shown in Table III, including arc durations, breaking current, contact gap at current zero, and switching results. Fig. 11 shows a typical failure interruption result with arc duration of 3.3 ms, and breaking current of 40.3 kA peak value. Fig. 12 shows a

TABLE III
TEST RESULTS IN TEST DUTY T100a OF A 126-kV VCB

No.	Arc Duration (ms)	Breaking Current (peak, kA)	Contact Gap at Current Zero (mm)	Switching Results
1	3.3	40.3	12	Failure
2	4.4	43.6	16	Failure
3	4.6	41.5	18	Success
4	5.4	44.0	19	Failure
5	5.5	42.1	19	Success
6	6.3	44.7	22	Failure
7	6.4	44.5	23	Success
8	6.6	43.0	23	Success
9	7.4	43.7	26	Success
10	7.6	45.6	27	Success
11	10.4	67.4	34	Success
12	10.7	67.0	38	Success
13	14.6	70.0	44	Success
14	15.8	67.7	47	Failure
15	16.1	71.1	47	Failure
16	17.0	70.1	48	Failure
17	17.9	67.9	49	Failure
18	19.0	72.0	50	Failure

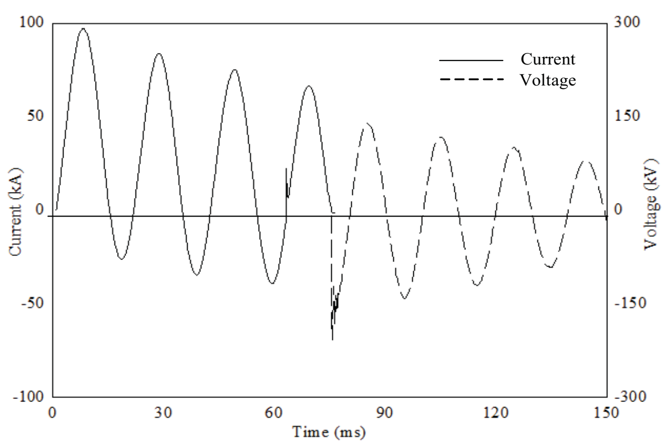

Fig. 12. Successful current interruption with arc duration 10.4 ms, breaking current 67.4-kA peak.

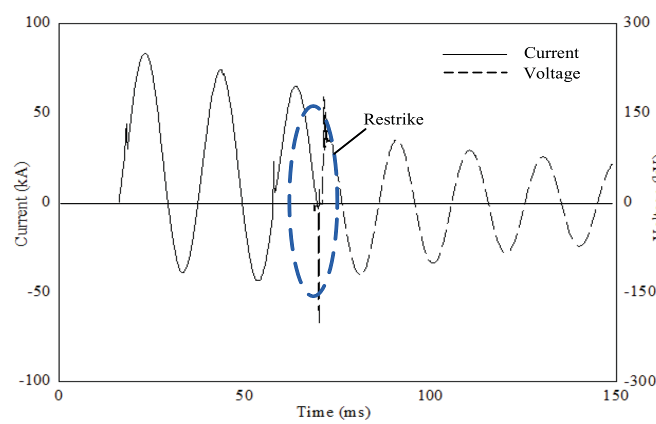

Fig. 13. Failure current interruption with arc duration 17.9 ms, breaking current 67.9-kA peak.

typical successful interruption result with arc duration 10.4 ms, breaking current 67.4-kA peak. Fig. 13 shows a typical failure interruption result with arc duration 17.9 ms, breaking current 67.9-kA peak.

To analyze AMF of the 126-kV single-break VCB in each test, the contact gap at which arc extinguished under different arc duration should be calculated. Combined with the opening displacement curve in Fig. 6, the arcing contact gaps with different arc durations could be calculated that are shown in Table III. As shown in Table III, the arc contact gaps ranged from 12 to 50 mm, with the arc durations increasing from 3.3 to 19 ms.

C. AMF Simulations

To analyze the current interruption results, the AMF distributions at current peak in the intermediate plane are simulated with contact gaps from 12 to 50 mm, according the arc duration from 3.3 to 19 ms. Figs. 14–16 show the axial magnetic flux density distribution at current peak in the intermediate plane under the different arc durations. Fig. 14 shows the axial magnetic flux density distribution at the intermediate plane with a contact gap 12 mm according with the arc duration 3.3 ms. The breaking current is 40.3-kA peak and the maximum AMF at current peak is 434 mT. Fig. 15 shows the axial magnetic flux density distribution at the intermediate plane with a contact gap 34 mm according to the arc duration 10.4 ms. The breaking current is 67.4-kA peak and the maximum AMF at current peak is 484 mT. Fig. 16 shows the axial magnetic flux density distribution at the intermediate plane with a contact gap 49 mm according to the arc duration 17.9 ms. The breaking current is 67.9 kA peak and the maximum AMF at current peak is 384 mT.

The conductors including the contact plate and the coil structure used to generate the AMF in the contact gap will cause a phase shift between the source current and the

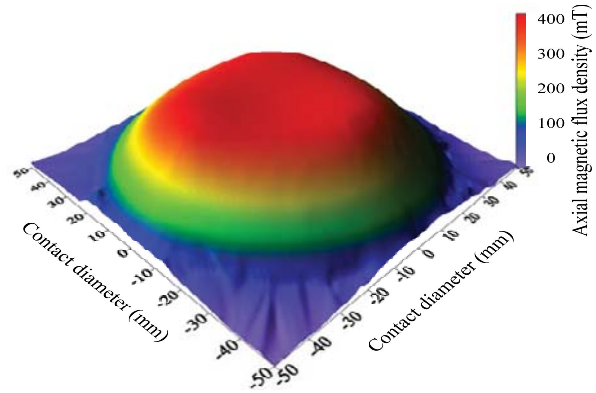

Fig. 14. AMF distribution in the intermediate plane with contact gap 12 mm. Arc duration: 3.3 ms. Maximum axial AMF: 434 mT. Breaking current: 40.3-kA peak.

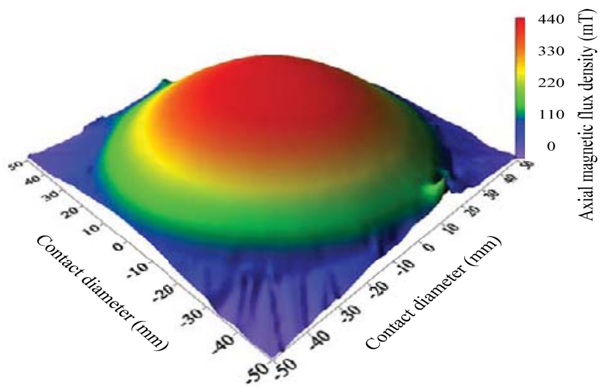

Fig. 15. AMF distribution in the intermediate plane with contact gap 34mm. Arc duration: 10.4 ms. Maximum axial AMF: 484 mT. Breaking current: 67.4-kA peak.

induced AMF. The phase shift could have a major impact on the current interruption performance, especially its influence at the current zero. A residual AMF after current zero hinders the rapid plasma diffusion outward contact gaps and it reduces the effective mean free path for ionizing collisions under the influence of the TRV [12]. The phase shift time of the proposed 2/3 coil-type AMF contact, as an important factor for current interruption performance, were shown in TABLE IV with a contact separation at which arc extinguished for the 18 times short-circuit current interruption at test duty T100a. The given shift phase time is at the center of intermediate plane of the contact gap and it is in a range from 1.36 to 0.75 ms according to an increase of the arcing contact gap from 12 to 50 mm.

TABLE IV also shows values of the maximum AMF per kilo-ampere of the breaking peak current for the 18 times of current interruption, with an indication of a failure or a successful interruption. The maximum value of the AMF was obtained as the maximum value at the intermediate plane of the contact gap (Figs. 14–16).

D. AMF Strength Needed for a 126-kV VCB in Test Duty T100a

To interrupt the high-current vacuum arc, it is necessary to ensure that it returns to the diffuse mode before current zero. Because the diffuse arc mode distributes the energy input over

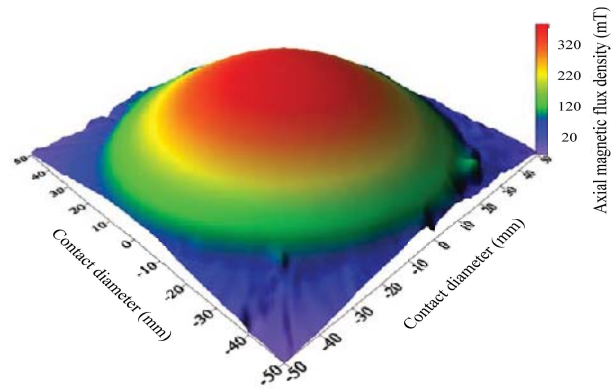

Fig. 16. AMF distribution in the intermediate plane with contact gap 49 mm. Arc duration: 17.9 ms. Maximum axial AMF: 384 mT. Breaking current: 67.9-kA peak.

the anode and cathode surfaces, leading to a significantly lower rate of contact erosion. The vacuum arc can be controlled as a diffuse mode by applying an AMF until a high current with a significant reduction in the involvement of the anode in the arcing process. Schulman *et al.* [4] studied the effect of an AMF upon the development of the vacuum arc between opening electrical contacts in a demountable vacuum arc chamber. They observed a critical (threshold) AMF B_{cirt} for producing a high-current diffuse vacuum arc mode, after the rupture of the molten metal bridge as the contacts parted.

However, one should note that a successful current interruption needs not only a strong AMF, but also many other important factors. The most important impact factors include arc duration and its corresponding arcing contact gap, and an effect of phase shift of the AMF. A good choice of contact diameter and contact material also contributes a successful current interruption. Therefore, in light of the arcing contact gap, arc duration and phase shift effect, the 18 times 40-kA rms tests of test duty T100a for the 126-kV VCB suggested the shortest arcing contact gap window is from 18 to 23 mm and the longest arcing contact gap is 44 mm. The shortest arcing contact gap window corresponded to the maximum AMF per kilo-ampere of the breaking peak current from 9.3 to 8.5 mT/kA. And the longest arcing contact gap corresponded to the maximum AMF per kilo-ampere of the breaking peak current of 6.1 mT/kA. In spite of the AMF strength needed, other mentioned impact factors for a successful current interruption will be addressed in the following.

In a current interruption in vacuum, the short arc duration is closely related to the shortest arcing contact gap. In the period of short arc duration, the contact surfaces suffer a formation and rupture of a molten metal bridge. And then the short arc duration evidences a transition from the initial bridge column arc to a diffuse vacuum arc, with a help of the applied AMF. Thus at the end of the short arc duration at which current zero, the resulted metal vapor resided between the closely spaced contacts (shortest arcing contact gap) should withstand a fast rising recovery voltage that reaches a high value. In addition, a solidification process of the local melted region on the contact surface, which is induced by the initial bridge arc, would have an impact on the dielectric recovery process that would has

TABLE IV
SIMUALTION RESULTS OF THE AMF FOR A 126-kV VCB IN TEST DUTY T100a

No.	Arc Duration(ms)	Breaking Current(peak, kA)	B_{max}/I_p (mT/kA)	Phase Shift Time (ms)	Switching Results
1	3.3	40.3	10.8	1.36	Failure
2	4.4	43.6	9.7	1.27	Failure
3	4.6	41.5	9.3	1.19	Success
4	5.4	44.0	9.1	1.17	Failure
5	5.5	42.1	9.1	1.17	Success
6	6.3	44.7	8.6	1.07	Failure
7	6.4	44.5	8.5	1.07	Success
8	6.6	43.0	8.4	1.07	Success
9	7.4	43.7	8.0	1.02	Success
10	7.6	45.6	7.9	1.00	Success
11	10.4	67.4	7.2	0.90	Success
12	10.7	67.0	6.8	0.86	Success
13	14.6	70.0	6.1	0.80	Success
14	15.8	67.7	5.8	0.78	Failure
15	16.1	71.1	5.9	0.78	Failure
16	17.0	70.1	5.8	0.77	Failure
17	17.9	67.9	5.7	0.76	Failure
18	19.0	72.0	5.6	0.75	Failure

an influence on short arc duration. In addition, the phase shift effect between the AMF and source current not only causes a time delay for applying the AMF on the vacuum arc, which has an impact on a transition from the bridge arc to a diffuse arc as the contacts part, but also causes an AMF that hinder an escaping of the charged particles from the contact gap.

The long arc duration of the 126-kV VCB could be determined by an interaction of vacuum arc and AMF applied. If the longest contact gap at which the arc extinguishes is too high, the vacuum arc tends to be unstable burning, and an anode spot has a high possibility to form at a long contact gap. Both an unstable burning arc and an anode spot would easily to lead a reigniting under a high recovery voltage value. However, by applying an AMF keeps a vacuum arc burning more stable and enhances a threshold current of an anode spot formation. Coil-type AMF contacts generates stronger AMF as the longest arcing contact gap is short. Therefore, the long arc duration is closely related to the longest arcing contact gap and the corresponding AMF strength.

In the test 126-kV vacuum interrupter, the contact material is CuCr50 (50% weight of Chromium). The choice of 50% of Chromium is not an optimum percentage for high current interruption. Contact material of CuCr25 or CuCr30 could have a better current interrupting performance. However, CuCr50 contact material could have a better insulation level than that of CuCr25 or CuCr30 contact material. This is also important if one considers a 126-kV single-break vacuum interrupter should withstand a much higher transient recovery voltage, power frequency voltage and the BIL than its medium voltage counterpart.

VI. CONCLUSION

We investigated how strong an AMF was needed in test duty of T100a for a 126-kV single-break VCB as interrupting a rated short-circuit current of 40-kA rms in light of arcing contact gap, arc duration, and phase shift effect. A 126-kV single-break vacuum interrupter was used, which had a pair of 2/3 coil-type AMF contacts with contact diameter 100 mm, contact gap 60 mm and contact material CuCr50 (50% weight of Chromium). And 18 times of current interruption tests was conducted under test duty T100a. The test results showed that:

1) The shortest arcing contact gap window existed between 18 and 23 mm and the longest arcing contact gap is 44 mm for a successful current interruption.
2) The shortest arcing contact gap window corresponded to the maximum AMF per kilo-ampere of the breaking peak current from 9.3 to 8.5 mT/kA. And the longest arcing contact gap corresponded to the maximum AMF per kilo-ampere of the breaking peak current of 6.1 mT/kA.
3) The phase shift time at the center of intermediate plane of the contact gap ranged from 1.36 to 0.75 ms corresponding to an increase of arcing contact gap from 12 to 50 mm in the tests.

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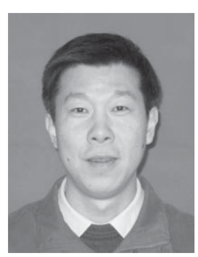

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