A Complete Strategy for Conducting Dynamic Contact Resistance Measurements on HV Circuit Breakers

Michel Landry, *Senior Member, IEEE*, Olivier Turcotte, and Fouad Brikci

***Abstract*—Dynamic contact resistance measurement (DRM) is known as an effective technique for assessing the condition of power circuit-breaker (CB) main contacts and arcing contacts. In some SF_6 gas CBs, the metallic fluorides (white or gray powder) produced during the arc quenching process mask the actual breaker contact resistance. In this case, the standard DRM method of injecting 100 A dc is no longer applicable. The following paper proposes a complete strategy for conducting DRM on high-voltage CBs based on three relevant parameters: breaker contact speed (low or rated), injected current values (100–2800 A dc), and the presence of metallic fluorides deposited on breaker contacts.**

***Index Terms*—Arc byproducts, circuit breakers (CBs), dynamic contact resistance measurement, metallic fluorides.**

I. INTRODUCTION

THE design of modern high-voltage puffer-type SF_6 gas circuit breakers (CBs) is based on the switching of two parallel contact sets. First, the low-resistance silver-plated contacts or the main contacts are specifically designed to carry the load current without any excessive temperature rise. Second, following the main contact part, the tungsten–copper arcing contacts are finally opened, thus initiating arc quenching and current interruption.

To assess the condition of the breaker contacts, the main contact resistance measurement is usually performed. However, the static resistance measured when the breaker remains in a closed position does not give any indication of the condition of the arcing contacts. To evaluate the latter's condition, an internal inspection can be done, but time-consuming and costly maintenance procedures must be followed in order to securely handle the SF_6 gas and arc byproducts. It should be remembered that excessive arcing-contact wear and/or misalignment may result in a decrease in the CB's breaking capacity.

Dynamic contact resistance measurement (DRM) at rated speed was developed more than ten years ago to assess the condition of the arcing contacts without dismantling the breaker. This method is no longer widely used since the interpretation of the resistance curve remains ambiguous. Previously published test results usually depicted several spikes [1]–[3] in the resistance curve which could be the result of a partial contact part during the contact movement involving high speed and acceleration.

After reviewing the relevant parameters for the low-contact-speed DRM method [4], the paper presents the DRM results for capacitor-bank SF_6 gas HV CBs for which metallic fluorides have a major influence on breaker contact resistance. DRMs at various current levels are also presented. Finally, based on those results, a complete strategy for conducting DRMs on HV CBs is proposed. It is based on three relevant parameters: breaker contact speed (low or rated), injected current values (100–2800 A dc), and the presence of metallic fluorides deposited on contacts that could mask the actual contact resistance for some breakers.

II. REVIEW OF THE RELEVANT PARAMETERS FOR PERFORMING DRMs AT LOW CONTACT SPEED

Reference [4] reported that DRMs at low contact speed allow reproducible curves to be obtained which are easy to analyze and interpret. Fig. 1(a) depicts a DRM curve that was recorded at the rated contact speed. Several spikes can be observed. Moreover, it is absolutely impossible to identify the main contact part. The presumed main contact part is indicated based on other measurements at low contact speed. It is estimated that this phenomenon is caused by the partial contact part due to high contact speed and acceleration during contact movement. At low contact speed, the DRM curve [Fig. 1(b)] is far smoother and the main contact part can be easily identified. It must be pointed out that the partial contact part does not occur when high current is interrupted since electromagnetic forces are exerted on the contacts, maintaining them together until final contact separation (see Section IV). Therefore, it is assumed that the low-speed DRM more adequately simulates the actual operating conditions of an inservice HV CB.

As documented in [4], when plotting contact resistance as a function of the contact travel, the following vital diagnostic parameters can be extracted:

- $R_p(\mu\Omega)$ average main contact resistance;
- $R_a(\mu\Omega)$ average arcing contact resistance;
- D_p (in millimeters) main contact wipe;
- D_a (in millimeters) arcing contact wipe;
- P_a (in millimeters) position of the breaker contacts at the arcing contact part;
- $R_a \times D_a$ (mΩ·mm) area beneath the resistance curve (during D_a) as a function of the contact travel.

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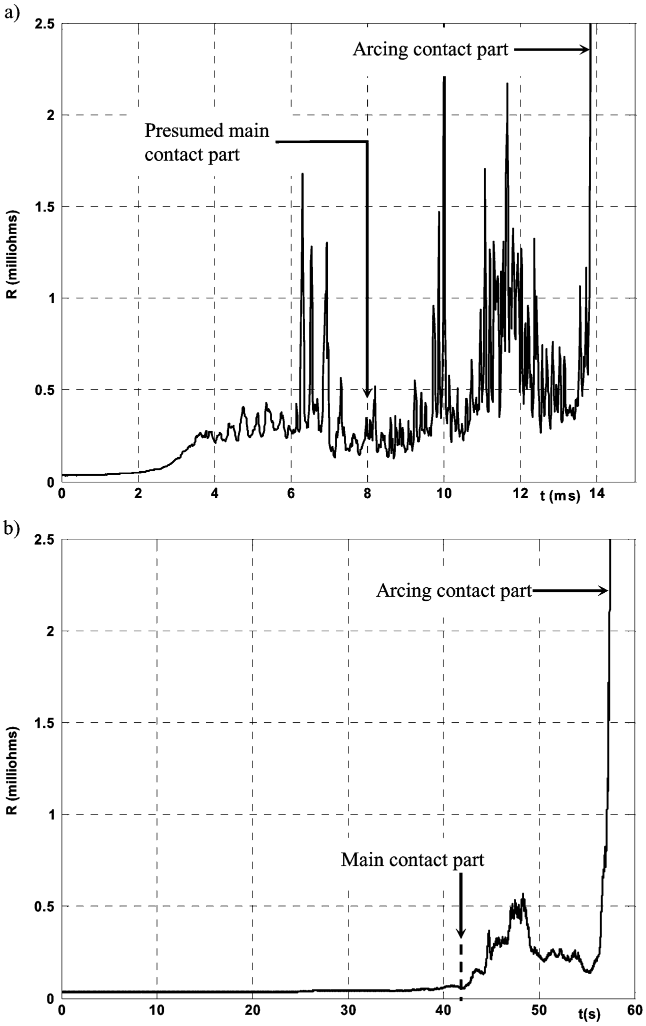

Fig. 1. Comparison of two consecutive DRMs on the same SF$_6$ HV CB with defective arcing contacts. (a) At rated speed. (b) At low speed.

The product $\mathrm{R_a} \times \mathrm{D_a}$ represents a very useful diagnostic criterion, for which a value of 3–5 mΩ·mm corresponds to normal arcing contact conditions while a value higher than 10 mΩ·mm might indicate defective arcing contacts.

DRMs during closing operations are not generally useful since the measurement must be performed during a transient state (i.e., from open to closed contacts). There are two main reasons why the measurement in this condition is impractical.

1) The abrupt resistance variation from infinity (open contacts) to the arcing contact resistance is difficult to measure, making the resistance level of the arcing contact difficult to detect.
2) The transient dc current at the moment of the arcing contact touch generates undesired noise level and, therefore, jeopardizes the measurement.

III. DRM IN THE PRESENCE OF METALLIC FLUORIDES

Metallic fluorides are usually present in the form of a nonconductive dust powder ($\mathrm{CuF_2}$, $\mathrm{AlF_3}$, $\mathrm{WF_6}$, etc.) that is deposited on the breaker contacts. Their influence on contact resistance has already been observed on medium-voltage FB4-type CBs [5] and short-circuit breaking tests have revealed that the presence of metallic fluorides does not decrease the breaker's breaking capacity. In this type of seal-for-life interrupting chamber, the current must circulate through moving roller contacts. It has been observed that arc byproducts adhere to these roller contacts and, therefore, cause an increase in breaker contact resistance. It is also well known that the circulation of a current higher than the rated current results in a decrease in contact resistance [5]–[7]. In [8, Sec. 6.1], the author mentions that high contact resistance will appear when there is no scraping or wiping motion between contacts.

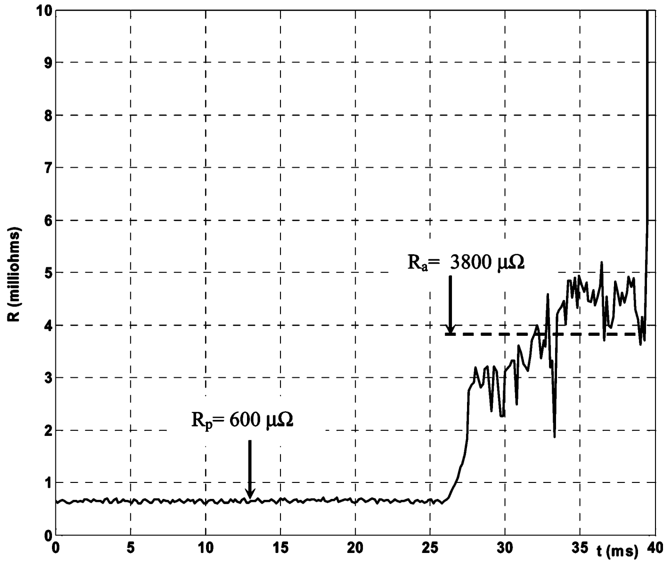

Fig. 2. DRM curve obtained for a capacitor-bank SF$_6$ gas HV CB with increased contact resistance caused by deposited metallic fluorides.

Surprisingly, this phenomenon was observed on capacitor bank CBs that had undergone 4735 operations, which is particularly high. To the author's knowledge, it was never reported on high-voltage CBs. In fact, as a first check, the substation maintenance crew performed static resistance measurements of the main contacts using conventional equipment injecting 10-A dc current. An extremely high value of the main contact resistance was measured (i.e., in the order of 4500–6000 $\mu\Omega$), which could be interpreted as defective contacts.

Furthermore, it was concluded that the usual measuring equipment at 10–100 A dc is useless in the presence of this type of metallic fluoride.

Fig. 2 shows a typical DRM curve at 100 A dc for which the breaker contact resistance is effectively very high (i.e., $\mathrm{R_p} = 600\,\mu\Omega$ and $\mathrm{R_a} = 3800\,\mu\Omega$). For the substation maintenance engineer, it is a matter of paramount importance to know the actual breaker contact condition of his or her substation CBs. Therefore, a measurement method is needed to determine whether the high resistance value is due to defective contacts or merely caused by the presence of metallic fluorides deposited on the breaker contacts. A measurement method was therefore developed with the aim of avoiding the dismantling of the breaker's interrupting chambers.

Fig. 3 illustrates the test setup that was used to perform DRM at 2800 A dc on a capacitor-bank SF$_6$ gas 120-kV CB. It is comprised of:

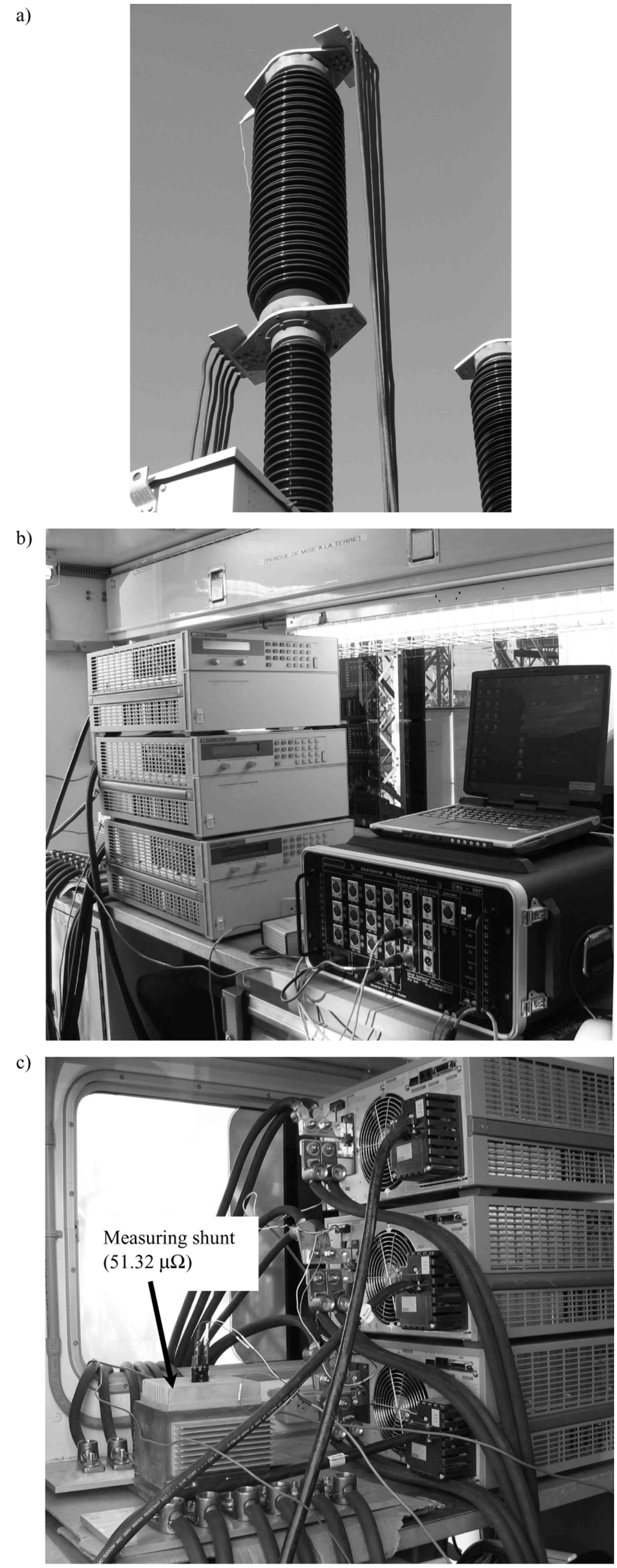

Fig. 3. Test setup for DRM at 2800 A dc on a capacitor-bank SF_6 gas 120-kV CB. (a) Connections to the breaker terminals. (b) Current sources and data-acquisition system. (c) Rear view of the current sources and measuring shunt.

- six 4/0 copper cables for carrying the high dc current from the current source up to the breaker terminals to minimize the voltage drop and not for thermal reasons [Fig. 3(a)];
- three current sources connected in parallel for delivering the measuring current of 2800 A dc [Fig. 3(b)];
- a data-acquisition system [Fig. 3(b)] for recording the relevant signals (injected current, voltage across the breaker terminals);
- a measuring shunt (51.32 $\mu\Omega$).

Due to the time available for executing the test program, the contact travel sensor was not installed. Table I presents a summary of the static and dynamic contact resistance measurements at various currents. With the breaker contacts maintained closed, contact heating intervals (i.e., 1–15 min) were also performed in order to vaporize the deposited metallic fluorides at the actual points of contact. For each phase, the most relevant test results are presented. In view of these results, the following conclusions can be made.

- DRMs at 2800 A allow acceptable contact resistance values to be obtained, typically 100 $\mu\Omega$ for the main contacts and 200–300 $\mu\Omega$ for the arcing contacts. Fig. 4 presents such acceptable DRM curves for the three phases of the tested breaker. For phase B, the DRM curve shows that the arcing contact separation flickers. In fact, the contact resistance reaches a value of more than 2.5 mΩ before collapsing to a value lower than 1 mΩ just before the final arcing contact separation. Among DRMs obtained during consecutive opening operations, it was observed that this behavior may occur a few times, and is most likely influenced by the actual surface shape and roughness of the arcing contacts. While it is an acceptable phenomenon close to final arcing contact separation, it should be emphasized that a similar pattern occurring in the middle of the arcing contact travel would be a clear indication of defective arcing contacts.
- Metallic fluorides deposited on contacts mask the actual value of the breaker main contacts and arcing contacts. At 100 A, the main contact resistance is extremely high: 863, 546, and 654 $\mu\Omega$ for phases A, B, and C, respectively.
- Current amplitudes of 1000 and 2000 A are not high enough for the metallic fluorides to decompose; to obtain acceptable contact resistance values, a current amplitude of 2800 A was required.
- To reduce the main contact resistance close to 100 $\mu\Omega$, a contact heating interval of at least 15 min. at 2800 A was required.
- For the arcing contacts, several DRMs at 2800 A during opening operations were required to reduce the arcing contact resistance to an acceptable level (i.e., at values of 200–300 $\mu\Omega$).

IV. DRM IN THE MEDIUM-CURRENT RANGE

A. *Reasons for Performing DRMs in a Medium-Current Range*

Performing DRMs at low contact speed and with an injected current of 100 A dc has the clear advantage of the resistance curve being noiseless [Fig. 1(b)] (i.e., there is no partial contact separation during contact movement). However, for some breaker mechanisms, the method is intrusive since some adjustments of the operating mechanism are required for low-speed breaker operation. There is a potential risk of damaging the

TABLE I
SUMMARY OF STATIC MEASUREMENTS AND DRMS PERFORMED AT VARIOUS CURRENTS ON A CAPACITOR-BANK SF_6 GAS 120-kV CB (THE TEST RESULTS ARE PRESENTED IN THE ORDER OF THE TEST SEQUENCE)

Phase Identification	**DC Injected current (A)**	**Contact heating interval (min.)**	**R_p (μΩ)**	**R_a (μΩ)**	**Comments**
ϕA	100	-	863	-	Static R_p at 100 A
	2000	1	122	-	Contact heating at 2000 A
		2	116		
		3	115		
		4	114		
		5	110		
		10	108		
		15	105		
	2000	-	108	341	DRM at 2000 A R_p and R_a remain high.
			136	411	
			136	364	
			139	506	
			143	539	
	2800	-	120	417	DRM at 2800 A
			110	377	
			122	376	
			123	295	
			123	313	
	2800	1	106	-	Contact heating at 2800 A
		2	100		
		3	97		
		4	96		
		5	95		
		10	93		
		15	90		
	2800	-	91	334	DRM at 2800 A
ϕB	100	-	546	-	Static R_p at 100 A
	1000	2	206		Contact heating at 1000 A
		4	201		
		6	196		
		10	175		
		15	164		
		20	162		
	100	-	619	-	Static R_p after contact heating at 1000 A
	1000	-	216	457	DRM at 1000 A R_p and R_a remain high.
			235	446	
			248	493	
			230	464	
			255	505	
	2800	1	120	-	Contact heating at 2800 A
		2	117		
		3	115		
		4	110		
		5	108		
		10	103		
	2800	-	103	317	DRM at 2800 A
			119	293	
			121	237	
			119	338	
			125	402	
ϕC	100	-	654	> 3000	DRM at various current amplitude
	460	-	342	961	
	767	-	309	627	
	939	-	276	536	
	1263	-	227	446	
	2843	-	125	235	
	100	-	235	-	Static R_p at 100 A
	2800	1	81	-	Contact heating at 2800 A
		2	79		
		3	79		
		4	79		
		5	78		

operating mechanism when restoring it back in service. For these breakers, another strategy was successfully used which consists in performing the DRMs at rated opening speed with an injected current of at least 700 A.

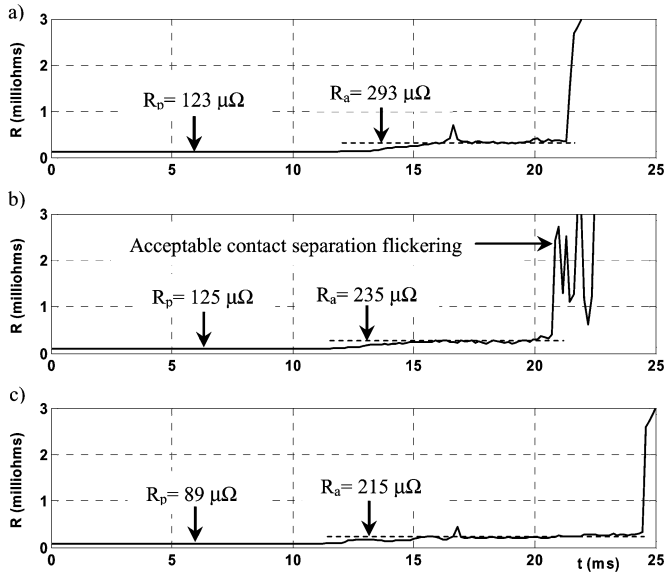

Fig. 4. DRM curve at 2800 A on a capacitor-bank SF_6 gas 120-kV CB. (a) Phase A. (b) Phase B. (c) Phase C.

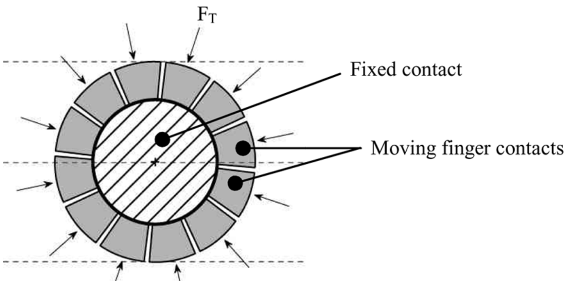

Fig. 5. Schematic of forces exerted on the fixed contact by the moving finger contacts.

B. Physics Related to Forces Exerted on the Fixed Contacts

As documented in [9], the contact resistance can be written as

$$R_c = \frac{\rho \times \sqrt{\pi \times H_k}}{2 \times \sqrt{F_T}} \tag{1}$$

where

ρ	specific resistivity;
H_k	contact hardness;
F_T	total force acting on a contact.

As can be deduced by (1), the contact resistance is inversely proportional to the square root of the contact force F_T. This force (F_T) acting on a contact [8] is made up of three components (2): the contact spring force (F_S), the attraction force (F_A), and the repulsion force (F_R)

$$F_T = F_S + F_A - F_R. \tag{2}$$

For an appropriate contact design, the repulsion force is lower than the attraction force. The attraction force increases as the current circulating through the contact becomes greater. Fig. 5 depicts a cross section of a typical fixed contact and moving finger contacts of an SF_6 gas HV CB. The moving contacts comprise 12 individual fingers. Therefore, the total injected current ($\mathrm{I_i}$) is divided into these 12 fingers and, as a result, a current $\mathrm{I_f} = \mathrm{I_i}/12$ circulates in each finger in the same direction. Electromagnetic attraction forces [10] generated by the associated magnetic-field intensity are proportional to the current square and inversely proportional to the distance (d) between fingers, as given in (3). Therefore, these forces tend to pinch the moving finger contacts on the fixed contact, thus reducing the contact resistance as predicted by (1). In addition, these forces significantly improve the wiping action on the contact surface for removing deposited metallic fluorides

$$F_A \propto \frac{\mathrm{I_f^2}}{d}. \tag{3}$$

C. Test Results on Several Circuit Breakers

To investigate the influence of the injected current, resistance measurements were performed at rated contact speed on the following CBs:

- A1, manufacturer A, hydraulic drive mechanism with energy stored in the disk spring assembly;
- A2, manufacturer A, spring-loaded mechanism;
- B1, manufacturer B, hydraulic drive mechanism with energy stored in nitrogen gas accumulator;
- B2–B4, manufacturer B, spring-loaded mechanism.

The injected current was varied from 100 to 875 A. The test results are plotted in Fig. 6(a) for the main contact resistance ($\mathrm{R_p}$) and Fig. 6(b) for the arcing contact resistance ($\mathrm{R_a}$). Based on these graphs, the following conclusions can be drawn:

- Except for breaker B1, $\mathrm{R_p}$ with an average value of 25 $\mu\Omega$ is relatively stable as the injected current varies;
- The value of $\mathrm{R_a}$ becomes relatively stable with an injected current of at least 700 A.

For breaker A2, Fig. 7 depicts DRM curves at various dc-injected currents ranging from 100 to 800 A. Based on this graph, it becomes clear that interpreting the DRM curve at 100 A may lead to a wrong diagnostic, especially for the arcing contact resistance ($\mathrm{R_a}$) that becomes clearly visible at the main contact separation which occurs at approximately 8 ms. As the injected current increases (100 to 800 A), stabilization of $\mathrm{R_a}$ can be observed, as also shown in Fig. 6(b).

In view of these results, it would be recommended to apply an injected current of at least 700 A when performing DRMs at the rated contact speed.

V. CONCLUSION

This paper demonstrated that DRMs are affected by the following parameters:

- breaker contact speed (low or rated);
- presence of metallic fluorides;
- amplitude of the dc injected current.

For some breaker mechanisms, the adjustments required for low-contact speed operations are intrusive. Consequently, DRMs must be performed at rated contact speed despite the

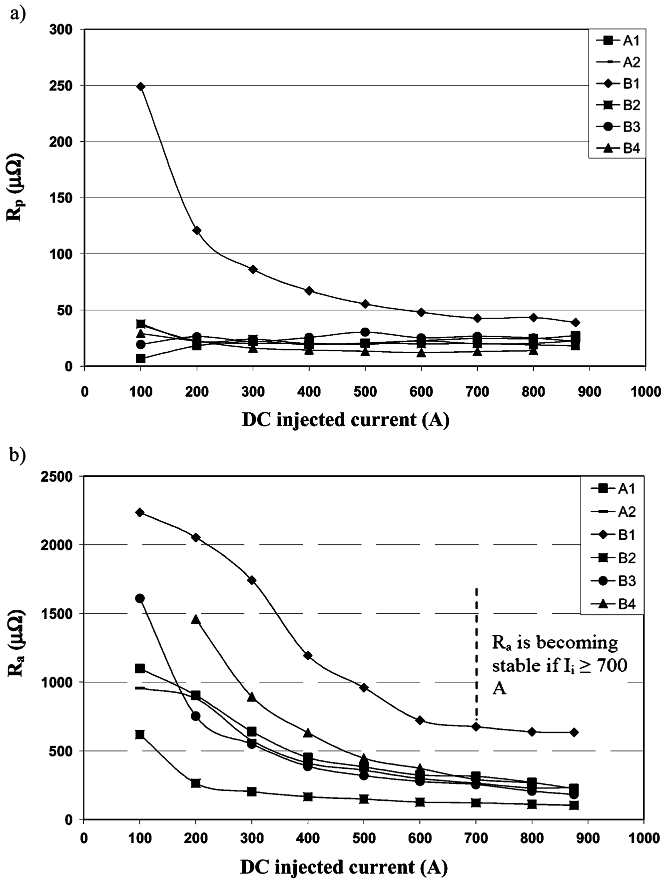

Fig. 6. Average breaker contact resistance as a function of the dc injected current. (a) Main contact resistance (R_p). (b) Arcing contact resistance (R_a).

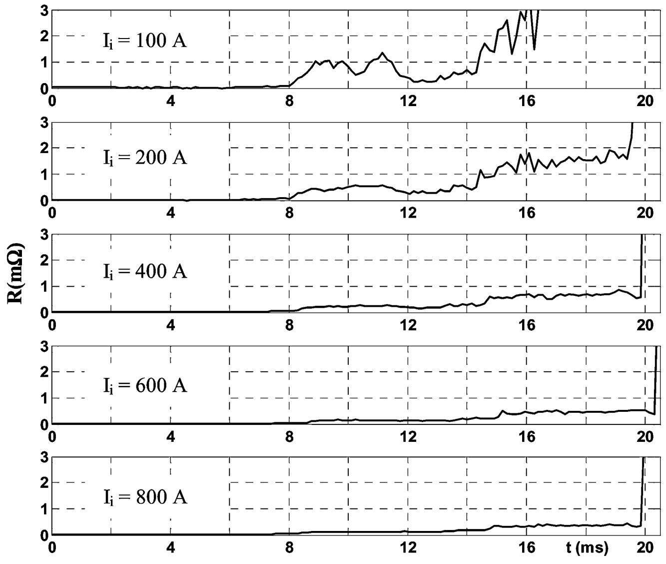

Fig. 7. DRM curves at the dc injected currents (I_i) ranging from 100 to 800 A.

undeniable advantages of low-contact-speed DRMs. Metallic fluorides deposited on the contact surface mask the actual value of the breaker contact resistance. In this particular case, conventional static measurements at 10 or 100 A and DRMs at 100 A are totally useless.

Considering all of these parameters and to avoid dismantling the breaker's interrupting chamber, the following measurement strategy can be advantageously applied:

1) For Breakers Affected by Metallic Fluorides:

- To measure the actual value of the main contact resistance, the breaker contacts in the closed position must be heated with a current of 2800 A for at least 15 min. After this period, the main contact resistance values in the order of 100 $\mu\Omega$ should be obtained.
- To obtain the actual value of the arcing contact resistance, several DRMs must be performed during opening operations in order to decrease its value to acceptable levels of 200–300 $\mu\Omega$.

2) For Breakers Not Affected by Metallic Fluorides and for Which Low-Speed Operations Can be Easily Performed: For these breakers, DRMs at low contact speed give the best results.

3) For Breakers Not Affected by Metallic Fluorides and for Which Low-Speed Operations Cannot be Performed: For these breakers, DRMs at the rated contact speed should be performed with an injected current of at least 700 A, thus avoiding possible wrong diagnoses about the breaker contact conditions.

For a thorough diagnostic of breaker contact conditions, contact travel measurement would be suggested to assess the following parameters:

- rated contact speed, which is a crucial design parameter for SF_6 gas HV CBs;
- arcing contact wear by comparing the actual arcing contact wipe to the reference one corresponding to new arcing contacts.

Moreover, the graph of the contact resistance as a function of the contact travel can be plotted to extract the six crucial diagnostic parameters as described in Section II.

Unless appropriate methods are applied for minimizing the risk of magnetizing the current transformers, this technique should be avoided for dead tank CBs with integral bushing current transformers.

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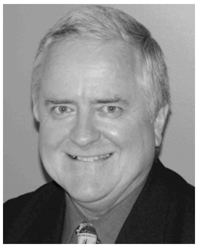

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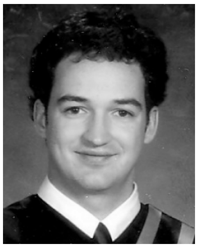
Mr. Landry worked on research related to the design of a new SF6 puffer breaker for low-temperature applications (−50 °C) from 1985 to 1990, which earned him the 1991 Méritas prize in Engineering awarded by the Ordre des Ingénieurs du Québec. He earned a prize paper award from the IEEE Power Engineering Society in 1986. He is member of the Canadian IEC Technical Committee 17 on switchgear, and a registered Professional Engineer in the province of Québec.



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