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Evaluation of Electrical degradation in High Voltage Circuit Breaker Monitoring

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1 SUMMARY

From the III Cigre International Enquiry High Voltage Equipment 2004-2007, it emerged that, although the reliability of High Voltage Circuit Breakers is primarily influenced by wear and aging, only a few percentage of surveyed breakers made use of condition based maintenance.

To achieve a more efficient asset management, matching cost reduction with improved reliability, the asset managers focused the investment on implement condition monitoring on transformers first. The same maintenance concept is expected to spread out to other assets. The condition monitoring of circuit breakers should consequently become more and more applied in the coming future. The assessment of the mechanical condition of the operating mechanism and circuit breaker can be easily put in relation to the number of operations. The estimation of electrical wear is normally carried out using the integral of the square value of the interrupted current (I2t), which provides only a rough indication of the electrical degradation. The available knowledge of the nozzle ablation and contact erosion as a function of the injected arc energy could provide a more precise electrical wear estimation.

The mechanism of performance degradation caused by nozzle ablation is easy to follow in principle, but difficult to quantify without a deep knowledge of the specific interrupter. Since the needed cooling power is subjected to fault typology, a wear limit tailored on the specific installation conditions would be possible. The contact erosion impacts primarily on the available interval for commutation, which depends on the current but it is independent from the fault typology. Unlike for the nozzle ablation, it is possible to directly assess the contact condition, with an off-line dynamic contact resistance measurement. The definition of the wear limits also implies a good knowledge of the specific interrupter.

A more precise assessment of the electrical degradation of the circuit breaker would allow a more efficient use of the circuit breaker, avoiding useless maintenance without impairing the reliability. This is technically achievable, but it requires more information of specific erosion mechanisms and the definition of acceptable limits for the specific circuit breaker. This is going to be the next challenge of the modern maintenance concept.

2 KEYWORDS

Interrupter Wear
Erosion, Ablation
Fault current
Arcing contact
Nozzle

3 INTRODUCTION

Although the CIGRE TB 167 from 2000 provides a wide guide how to apply monitoring and diagnostic techniques to high voltage circuit breakers [1], from III CIGRE inquiry on reliability of high voltage equipment for the years 2004-2007 [2], surprisingly, only 8% of the circuit breakers in the survey made use of base condition maintenance. For the rest of population, the maintenance was still time based. On the other hand, looking at the survey outcome, it is evident that aging and wear are by far the main driving factors impacting on circuit breaker reliability being responsible for more than 43% of major failures and 55% of minor ones. To achieve a more efficient asset management matching cost reduction with improved reliability, condition based maintenance and monitoring of circuit breakers is expected to catch up becoming more and more applied in the coming years. The active CIGRE WG A3.32 working on non-intrusive diagnostic and monitoring systems confirms the interest for these topics.

Besides early detection of minor miss functions, which could evolve in major failures, the estimation of mechanical and electrical degradation of performance is crucial for an efficient preventive maintenance.

For the evaluation of mechanical wear many monitored parameters are available. The banal count of operations can already by itself provide a quite significant parameter to put in correlation to mechanical degradation of the circuit breaker. Travel curve analysis, coil current observation, thermal imaging (hot spots), vibration, partial discharge and sound diagnostic methods can additionally provide a quite complete variety of diagnostic tools for assessing the mechanical condition of a circuit breaker.

Coming to electrical performance, the evaluation of performance degradation is less simple. The cumulated interrupted current in form of integral of square current is presently the only available choice.

A thorough analysis of every breaker operation and having a more accurate accounting of the resulting contact and nozzle wear will enable maintenance managers to sort out and specifically target circuit breakers that require repairs before there is an outage causing devastating revenue losses, expensive equipment damage and possibly personnel safety issues caused by a breaker failure.

In the following, the main root causes for electrical degradation of a circuit breaker are analyzed pointing out the difficulties of a reliable assessment and the need of improvements for both estimation methodology and limit definition.

4 Electrical wear and Interruption process in a circuit breaker

It is common practice to estimate the electrical wear of a high voltage circuit breaker by means of the “let through” energy function (1), which defines a direct dependency from the Joule energy as the interrupting chamber would be modelled by a constant equivalent resistance.

$$Wear \sim \int_{o}^{t_{arc}} \cdot I^2 \cdot dt \qquad (1)$$

An IEEE paper [3] suggests 1.8 as best fitting exponent instead of 2 to cover interruptions with high and low current, trying to define a general rule applicable to every circuit breaker.

The “let through energy” concept, is simple and consistent with the stress estimation applied for other assets like cable or transformer windings. Although the wear estimation is rough, it stated a significant step ahead if compared to time based maintenance. A more precise assessment of electrical degradation is actually possible, but requires a deeper knowledge of the specific interrupter, not always easily available.

Starting from interruption process, some considerations can be made about possible improvement and difficulties to implement them.

In Figure 1 a principle representation of an interrupting chamber is shown in both close and open position. The insulating nozzle made of Polytetrafluoroethylene (PTFE) defines the interrupting region placed between the arcing contacts made of sintered Tungsten-Copper (WCu) material.

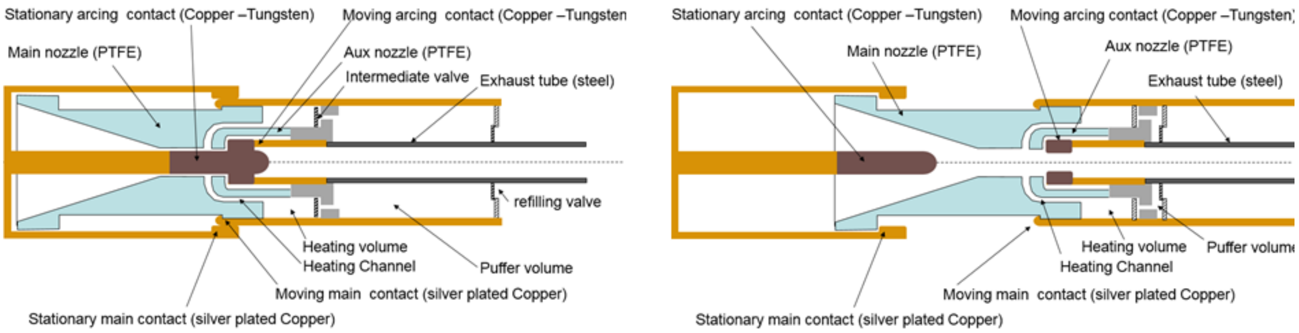

Figure 1 Principle geometry of Circuit Breaker Interrupting Chamber
On the left shown in CLOSE position
On the right shown in OPEN position.
Main contacts (Cu), arcing contacts (WCu) and nozzles (PTFE) are visible

The interrupting sequence during an opening operation is schematically shown in Figure 2. In fully close position, main and arcing contacts are both engaged and the current flows mainly through the main contacts due to their much lower resistance. While opening, the current commutates first from main to arcing contact system. The gas is compressed in the puffer volume and pushed through the heating channel in the nozzle throat where the interruption will take place. At contact separation, an arc starts burning between the arcing contacts. The released arc power heats up the gas in the contacts gap, increasing the pressure and causing a gas flow towards the heating volume.

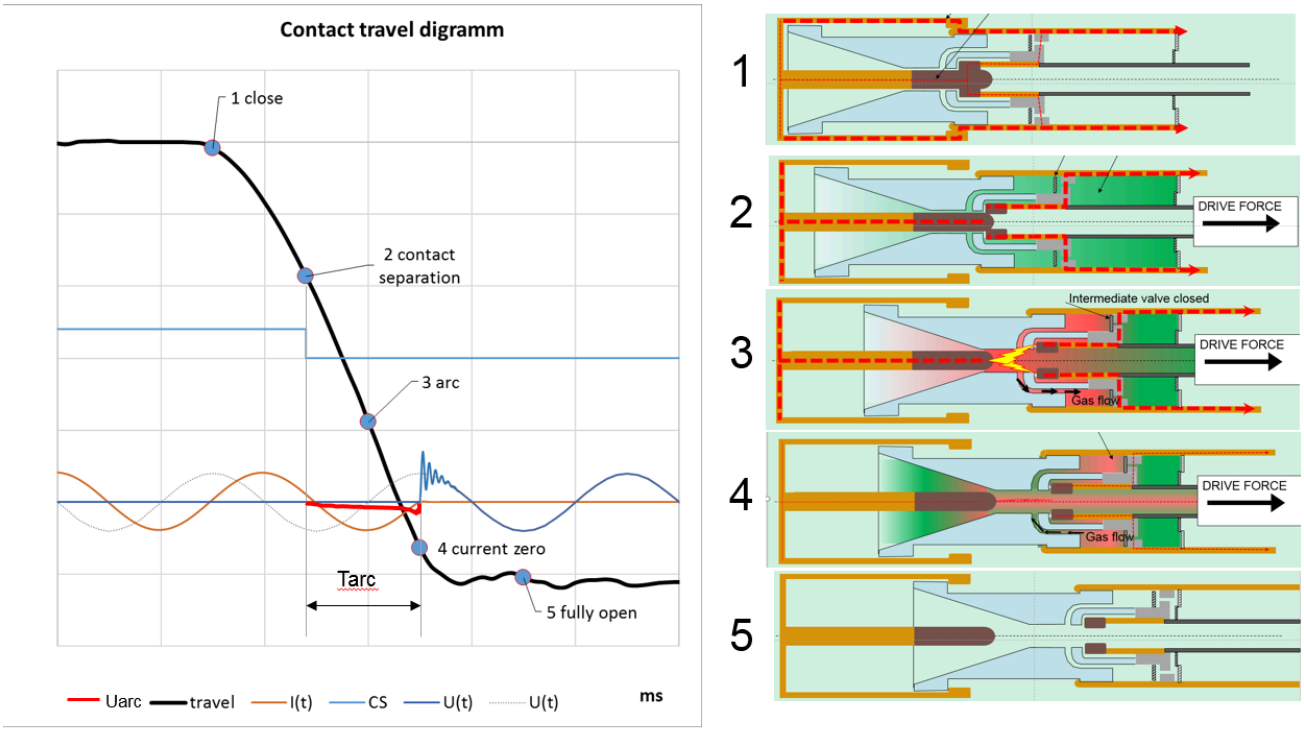

Figure 2 Interruption sequence.
On the left an oscillogram showing the contact position (travel), current, voltage and arc voltage.
On the right five key positions of the contact in the interrupting chamber:

1) Fully close position. The Current flows almost through main contacts only.
2) Separation of arcing contacts. An arc starts burning on the contacts gap
3) Back heating in the high current region. The pressure generated by the arc "charges" the heating volume
4) Around Current zero. Gas flows from heating volume to contact gap region providing cooling power.
5) Fully open position after successful interruption.

The pressure in the heating volume builds up and the valve facing the puffer volume closes preventing a high force reaction to the operating mechanism. The pressure generated by the arc keeps on "charging" the heating volume. Approaching the current zero the pressure generated in the nozzle throat is lower than one in the heating volume. The gas reverses its flow and the pressure in the heating volume pushes a gas blow towards the arc region cooling it down. If the pressure build up is enough to provide the required cooling power, at current zero the gas turns from plasma status back into dielectric medium. The current is cleared

Just after current zero, if the gas density is high enough and its dielectric strength is sufficient, also the transient recovery voltage can be withstood. The interruption is successfully over, and the circuit breaker, in open position, can guarantee the isolation between the two sides of the grid.

During every current switching, the arc energy causes material sublimation in nozzles and contacts. The resulting geometrical changes constitute the wear of the interrupting chamber known as Nozzle ablation and Contact erosion (see Figure 3).

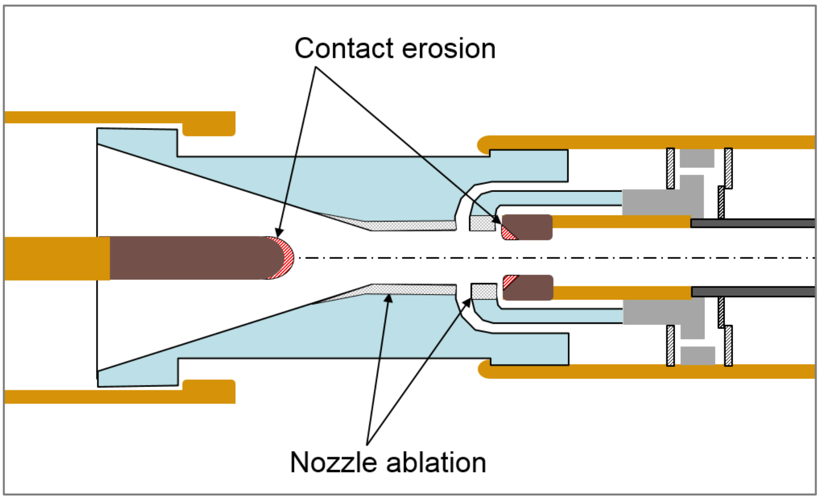

Figure 3
Wear of the interrupting chamber caused by arc energy:
- Ablation of the nozzles mainly concentrated in the nozzle throat
- Erosion of arcing contacts Plug and Tulip

The impact on circuit breaker performance are treated in the following paragraphs.

5 Nozzle ablation

The nozzle ablation is caused by the arc radiation and from the hot gas flow during the interruption. As such it is a function of the arc energy dissipated during the interruption process.

The sublimated PTFE material contributes to the pressure build up supporting the current interruption process itself. On the other hand, the geometrical change in the nozzle system from one shot to the next one makes the blowing less and less efficient.

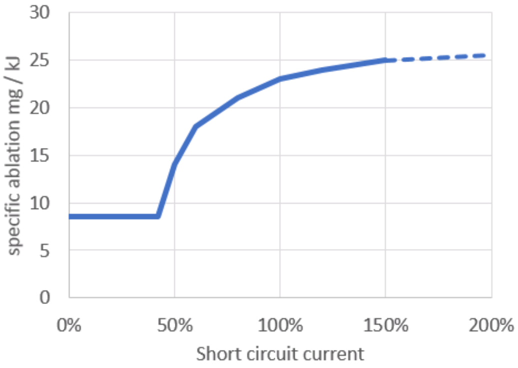

Figure 4
Principle diagram of specific ablation as function of short circuit current

The specific ablation, amount of sublimated PTFE per kJ of arc energy, remains constant only for “low current” values. For higher current, the specific ablation increases tending to a new constant value, three times higher, for interrupting current approaching the rated short circuit value [4] as shown in Figure 4.

The boundary between “Low” and “High” depends from the specific interrupter geometry, but for a general case it can be set to ~ 40% of rated short circuit current, what would correspond to ~20kA for a 50kA circuit Breaker.

Knowing the arc energy, it would be possible to estimate the ablated material from the nozzle system at every interruption, if the principle diagram shown in the Figure 4 were available for the specific interrupting chamber.

5.1 Arc energy, arc voltage

The arc energy is the integral value of the product of current times arc voltage.

$$Earc = \int_{o}^{t_{arc}} U_{arc} \cdot I \cdot dt \qquad (2)$$

Unless than for lab tests, measuring the arc voltage is a quite difficult task. The typical arc voltage is in the region of 1-2 kV. A normal voltage transformer installed in a substation, meant for measuring 245 kV or 420 kV, does not have enough resolution to detect it. In a breaker installed in a substation the arc energy must be estimated based on current measurement only.

The arc voltage increases with the arc length and gas pressure, but is rather constant within a wide range of current. For a first approximation, a constant arc voltage independent from the current could be considered rather than a linear proportionality as it would be in case of constant resistance [5].

The dependency of contact distance could also be considered, provided the travel measurement is available. As consequence, the arc energy results in a linear function of the current integral and contact distance *d* (see equation 3)

$$E_{arc} \sim k(I) \cdot d \cdot \int_{o}^{t_{arc}} \cdot I \cdot dt \qquad (3)$$

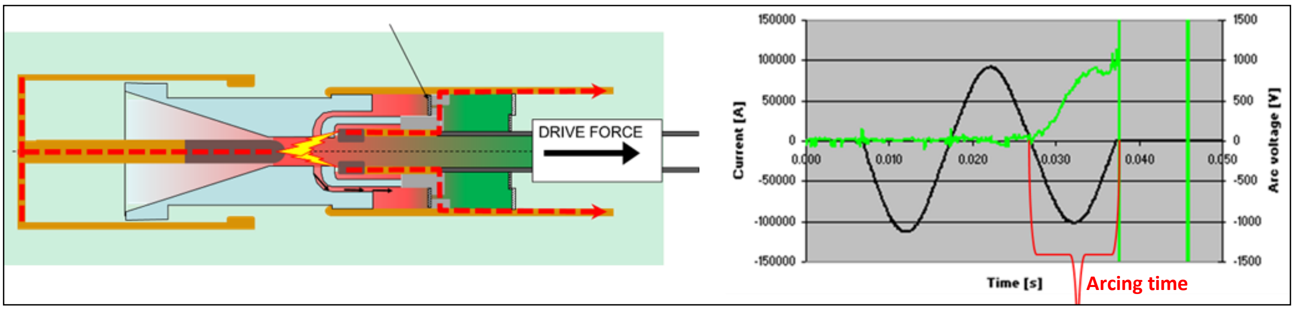

Figure 5 On the left Arc between contacts burns from contact separation until cleared current zero.
On the right, an oscillogram example showing the current (black) and arc voltage (green). The arc voltage shape increases at the beginning due to increase e of contact distance *d*, and tends to remain constant also when the current reduces towards zero.

If the travel curve of the circuit breaker is not measured, a linear dependency of current integral is the best choice. Under the a.m. conditions the three following interruption cases with different current and arcing time would provide the same arc energy:

- 10 kA@30 ms → E~10 x 30
- 15 kA@20 ms → E ~ 15 x 20
- 30 kA@10 ms → E~ 30 x 10

For a 40-kA circuit breaker, according to ablation diagram in Figure 4, the first and the second shot would cause the same PTFE ablation. The third one, although it has the same energy, would cause twice as much sublimation of material since the current is higher and ablation mechanism different.

Nozzle ablation means geometrical changes in the nozzle (see Figure 6).

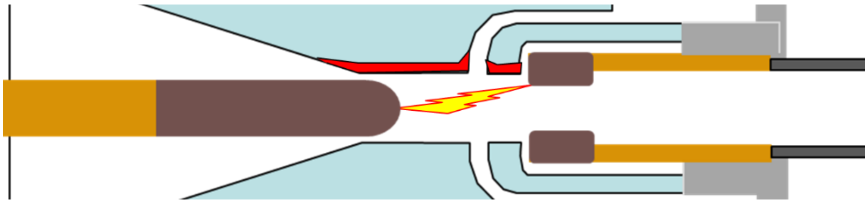

Figure 6. The arc between contacts radiates energy on the nozzle surface facing it. The red area represents the ablated material. It is shown only on one side for comparison with the original profile.

From one interruption to the next one, the nozzle throat becomes wider. The consequent higher distance from the arc to the nozzle wall results in lower energy absorption which means less PTFE vapours.

The lower injected energy together with the bigger gas flow cross section reduces the pressure build up in the chamber and by this the arc blow. The result is a reduced clearing capability primarily effecting switching cases, like the short line fault, where the maximum cooling power is required to turn the quenching medium from plasma status into dielectric one at zero current.

Although this degradation mechanism is understandable and easy to be followed in principle, quantitative information is required to provide a reliable ablation prediction. But having a reliable ablated material information is still not enough. The degradation of switching capability depends from the effect of geometry change to fluid dynamic efficiency of the specific interrupter design. A reliable degradation law as function of switched current, arcing time and contact travel can either be provided by the circuit breaker manufacturer or extracted from a dedicated power tests.

A principle “complex” function defining the circuit breaker wear could be the following:

$$Wear \sim k(I) \cdot d \int_0^{t_{arc}} F(I^x, {t_{arc}}^y)\, dt \qquad (4)$$

The wearing coefficient is the function of current *k(I)*, as well as the exponents *x, y* of current and time needs to be calibrated for every specific interrupter design.

Once the wear function is outlined, the limit not to be exceeded to guarantee the circuit breaker performance, must be also defined.

A first conservative approach could consider the limit value to ensure the full switching capability as required by IEC-62271-100 type testing [6].

A second approach could take as reference the equivalent wear as defined by IEC 62271-310 [7] for electrical endurance test.

A third level of critical wear could be estimated considering the actual circuit breaker installation conditions: A circuit breaker not feeding a line, and as such not facing any short line fault conditions, could accept a heavier nozzle ablation and still being able to clear a terminal fault current.

A more accurate information of the specific interrupter, would allow to set a wear limit closer and closer to the real needs of the specific circuit breaker avoiding useless maintenance costs.

6 Contact erosion

The contact erosion is the other main wear mechanism happening during current interruption. As known, every high voltage circuit breaker is equipped with a double contact system:

- The main contacts, out of silver plated copper, are designed to carry the nominal current in fully close position, ensuring the lower possible resistance minimizing the joule losses and the consequent temperature rise of the circuit breaker.
- The arcing contacts are made of tungsten copper to carry the current during the interruption process providing resistance against high temperature of the arc roots.

The two contact systems are electrically in parallel. The mechanical design is such that they are engaged and separated in different times to ensure the interrupter functionality.

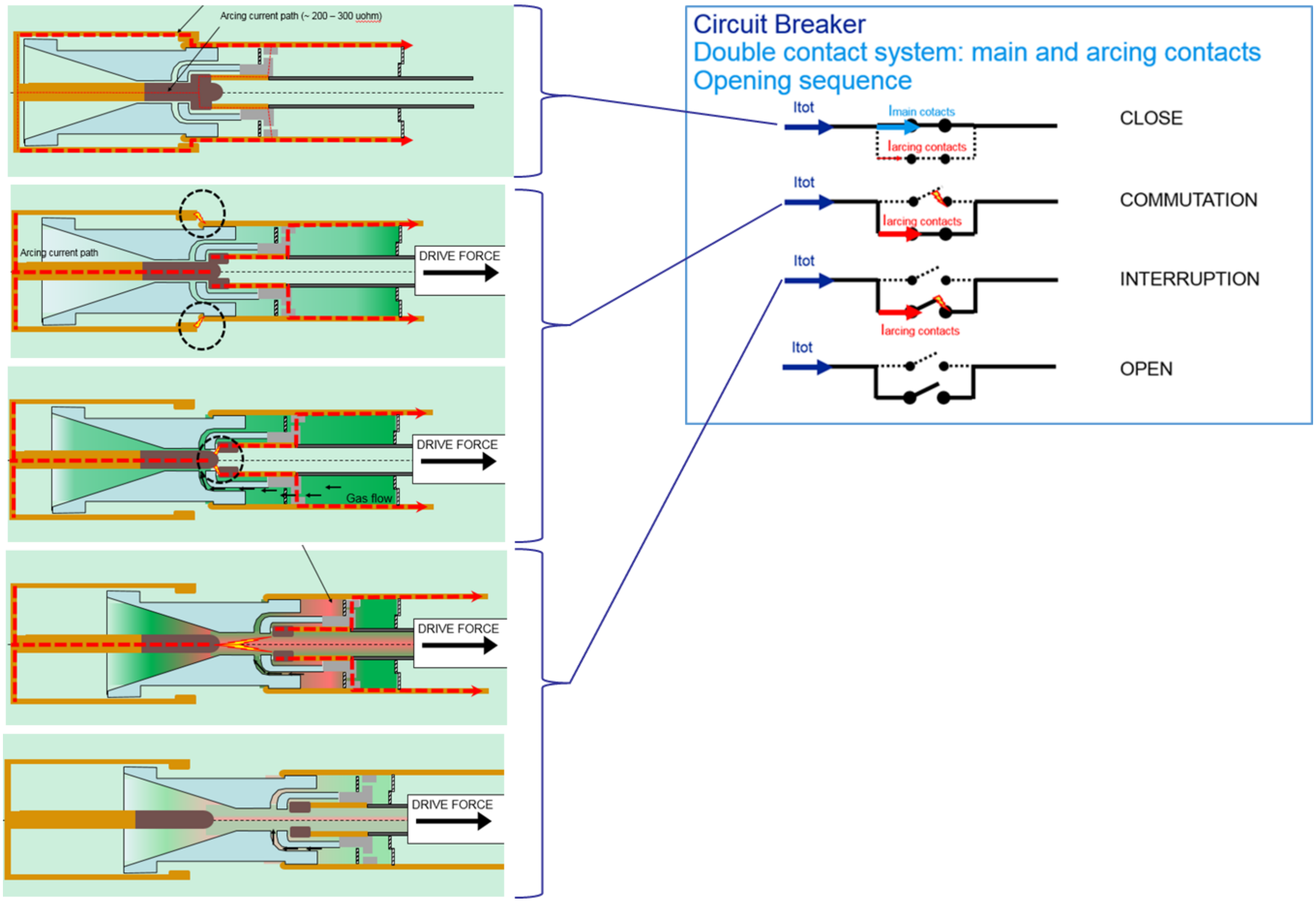

Figure 7 Principle scheme of main and arcing contact system: opening operation.

- In fully close position the two contact systems are close in parallel. The current flows primarily in the main contacts due to their lower resistance (5-10% of the arcing contact one)
- While opening, the main contacts separate first. The (very low) arc voltage pushes the current to arcing contacts while they are still engaged.
- After the commutation is over, the arcing contacts separate as well, defining the beginning of the interruption process.
- The overlap of arcing contacts is such to ensure a wide enough commutation window.

In Figure 7 the opening sequence is described. During the clearing process, the arc power sublimates WCu material from the contacts

As done for nozzle ablation, the amount of ablated contact material can also be put in relation with the injected arc energy of every switching operation using the similar equation typology as in (4).

The erosion happens not only by clearing but also by current making.

During a closing operation the contacts come together, before the contact touch, when the dielectric stress reaches the breakdown level, an arc starts burning between plug and tulip.

The time between current start and contact touch is called pre-arcing time.

Depending of the making instant, which is a stochastic parameter, the per-arcing time can typically vary from 0 to 5ms. Although it is much shorter than the typical arcing time (8-22ms), the profile change of arc and tulip cannot be neglected. In addition to material sublimation, there is also the effect of mechanical impact of contacts coming together having a quite high temperature caused by the pre-arcing energy. This effect is particular evident in circuit breaker facing high inrush current values like it is for back to back capacitor bank switching.

Still to consider is contact "Fretting" that is caused by repeated open/close contact movement creating an accelerated form of contact parts erosion. This activity dramatically increases the opportunity for arcing plug and tulip to momentarily seize. The material at the exact point of seizure may quickly break off causing an accelerated profile erosion. The fretting effect will complicate attempts to determine exact contact erosion based on cumulated injected arc energy

The contact erosion affects mainly plug and tulip tips. The removed material makes the plug shorter and the tulip wider causing a shift of contact separation earlier and earlier on the time axes. (see Figure 8).

If the arcing contacts start parting before the current commutation is over, an arc will burn between the main contacts resulting in a catastrophic failure.

The commutation time depends on the current amplitude on the resistance of main and arcing contact paths. The grid conditions and fault typology do not play any role here. A sound reference for commutation time for a high voltage circuit breaker is between 1 and 2 ms.

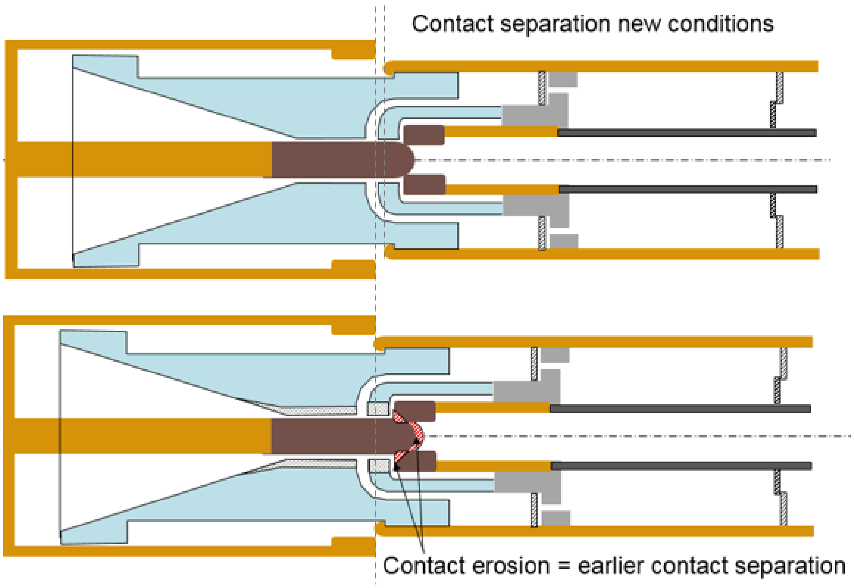

Figure 8 Earlier separation of arcing contact due to contact erosion

Unlike for nozzle ablation, a direct evaluation of the interval between separation of main and arcing contacts is possible by mean of the dynamic resistance measurement. This is an offline test where a DC current of in the range of 200-1000A is injected passing through the main contacts of the circuit breaker. The circuit breaker is then operated and the voltage drop across the interrupting chamber is recorded and the resistance is calculated. The difference resistance value of the main current path (10-30 µohm) in comparison to the arcing one (200-300 µohm), is enough to detect both parting times.

In Figure 9 a dynamic resistance measurement diagram is shown for a Close – Open operation.

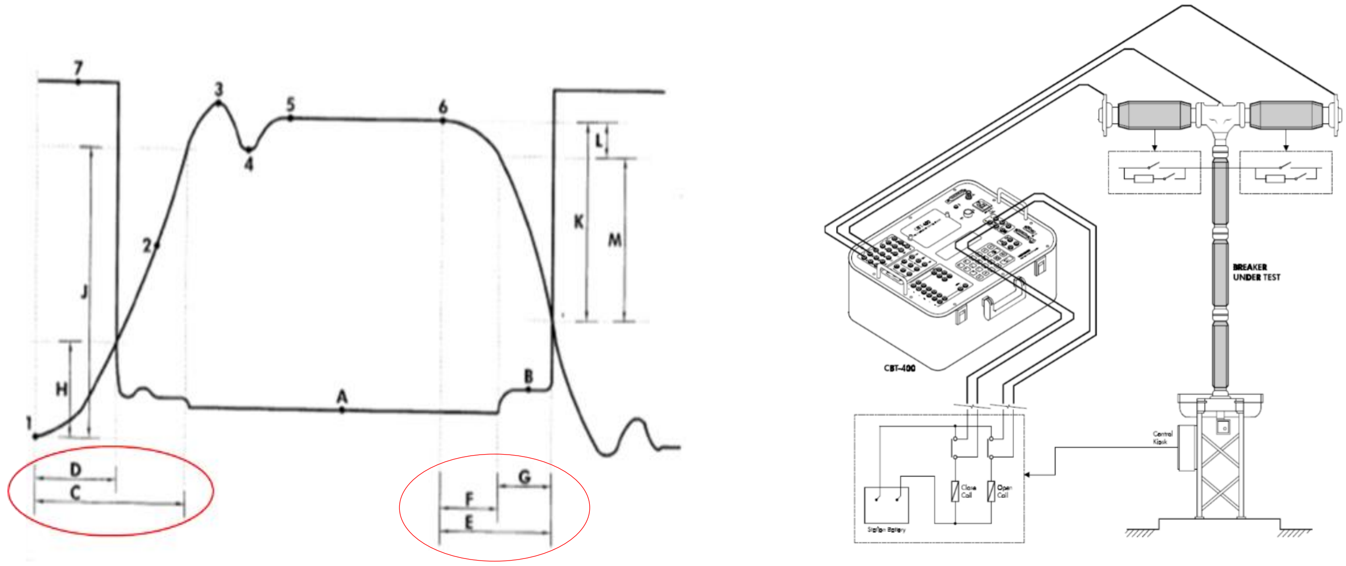

Figure 9 Dynamic resistance measurement Close – Open operation.
On the left the travel curve is shown together with the resistance diagram.

- Closing operation
    - D touch of arcing contacts
    - C touch of main contacts
    - C – D: time interval available for current commutation
- Opening operation
    - F separation of main contacts
    - E Separation of arcing contacts
    - G time interval available for current commutation

The minimum interval between main and arcing contact parting time to ensure a successful commutation is again design specific and is usually provided by the circuit breaker manufacturer.

For a specific circuit breaker, the actual commutation time increases with the current, but does not depend by the fault typology.

7 Conclusions

The electrical wear of a circuit breaker is still estimated by means of the cumulated “let-through energy”. The wear is more complex to assess. Starting from current and travel measurement, a finer and more precise evaluation could be possible, but it would require a deeper knowledge of the interrupter design and availability of development data.

The mechanism of performance degradation caused by nozzle ablation is easy to follow in principle, but difficult to quantify without a deep knowledge of the specific interrupter. Since the needed cooling power is subjected to fault typology, a wear limit tailored on the specific installation conditions would be possible.

The contact erosion mechanism is different by clearing and making and it can be accelerated by the “Fretting” effect. It impacts primarily on the available interval for commutation. The commutation time depends on the current but not on the fault typology. By means of the dynamic resistance measurement, a direct condition assessment of the contact is possible.

A finer, more reliable electrical wear estimation and limit definition are achievable with an evaluation process adjusted on the specific circuit breaker. The availability of information regarding interrupting chambers, specific erosion mechanisms and acceptable limits is the next challenge of the modern maintenance concept.

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