PERFORMANCE OF VACUUM CIRCUIT-BREAKERS WITH CONTACT BOUNCING DURING CLOSING

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ABSTRACT

Bouncing is a phenomenon often experienced during vacuum circuit-breaker (VCB) no-load operations. The effect occurs at the moment the interrupter contacts touch each other during closing. It is anticipated that the bouncing duration is somehow correlated with the oscillatory frequencies of the moving parts of the vacuum interrupter and of the kinematic chain of support and mechanical parts. The influence of bouncing on the capability for short-circuit making and capacitive switching is discussed. It is shown that the no-load bouncing time is not a relevant parameter to predict the performance of a VCB. Therefore it is not useful to set arbitrary limitations on the value of this parameter.

INTRODUCTION

Bouncing on closing is a phenomenon observed with all breakers [1] and in particular with vacuum circuit-breakers [2, 3]. Since the introduction of VCB technology, manufacturers have specified maximum bouncing times for their vacuum interrupters, though international standards do not pose any specific requirements [4, 5]. Generally speaking, different manufacturers provide different recommendations according to their best practice. In principle, when contacts are temporarily disengaging under the flow of current, arcing will occur, which melts the surfaces locally. This might result in some contact welding when the contacts engage again. The paper provides the technical background of bouncing for vacuum interrupters and deals with the consequences from the point of service life of a VCB. In particular, it discusses the impact of bouncing on short-circuit interruption and capacitor bank switching.

BASICS OF CONTACT BOUNCING

Impacting bodies

The impact of two or more bodies will in general create bouncing depending upon a number of parameters. For a VCB, the main parameters affecting the phenomenon can be identified as follows (Fig. 1):

- Closing speed v_c of interrupter measured at push-rod
- Bouncing speed assumed as fraction ß of v_c
- The mass M_a of the fixed interrupter contact (1) (incl. all fixed masses somehow involved in the impact)
- The mass M_s of the movable interrupter contact (2) and connected parts such as the stem and current lead
- The mass M_b of the push-rod (4) incl. contact springs (3), spring cup and parts connected rigidly to the push-rod
- Spring coefficient D_s of contact spring (3) and force F in pre-charged condition
- Spring coefficient D_a of interrupter support structure
- Spring coefficient D_b of push-rod kinematic chain

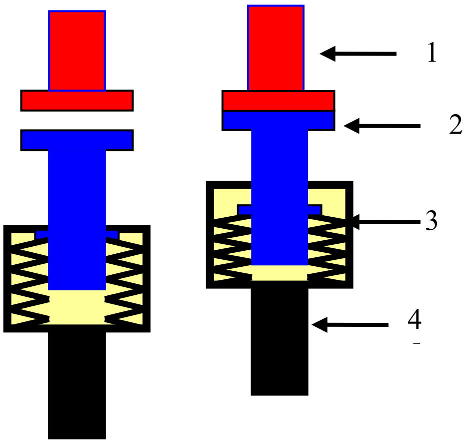

Fig. 1. Schematics of vacuum interrupter and associated parts: Left: Pre-charged spring before the contacts touch Right: Completely charged spring after contact closing Fixed interrupter parts (1), movable interrupter stem (2), contact spring (3), push-rod (4) with associated parts.

At the instant the movable contact plate touches the fixed interrupter contact during closing operation, the interrupter stem (2) rebounds into the contact spring (3). The “fixed” interrupter contact (1) and the push-rod (4) carrying the contact springs (3) and being driven by the breaker mechanism experience at this moment a mechanical shock. In both parts an oscillatory motion is generated with a frequency determined by the mass of the parts and their elasticity. In [6] a closing travel oscillogram with long bouncing times of up to 6 ms is shown. The bouncing period T_s is derived from the distance between two consecutive contact touches. The bouncing time T_B is the interval between the first contact touch and the final closing. The bouncing effect might occur differently in the three poles of a circuit breaker though all of them have the same design and approximately the same spring parameters. The motion of the fixed interrupter contact cannot be accessed from travel oscillograms.

Equations of motion and associated periods

The bouncing period T_s and depth of rebounding x_s of the interrupter stem into the contact spring are determined by the balance of kinetic energy of the rebounding stem and the elastic energy of the contact spring compressed by the rebound length x_s in addition to the pre-charge L. The stem has a total mass M_s and rebounds with fraction ß of the closing speed v_c [6]. The situation refers to the left side of Fig. 1, where the contact spring already has a pre-charge giving the minimum value of contact force F.

$$\frac{1}{2}M_s\cdot(\text{ß}v_c)^2=\frac{1}{2}D_s(L+x_s)^2-\frac{1}{2}D_sL^2 \qquad (1)$$

The balance of energy (1) yields the bounce length x_s:

$$x_s=\frac{M_s}{2F}(\text{ß}v_c)^2 \qquad (2)$$

The period of bouncing T_s results from the equation of motion of a harmonic oscillator [6]:

$$T_s=2\frac{\text{ß}v_c}{F}M_s \qquad (3)$$

The oscillation of the fixed contact or any other part is derived from a typical mass-spring system with the mass M_a and the elasticity D_a of its support. The speed transferred to M_a is some other fraction α of the closing speed v_c:

$$\frac{1}{2}M_a\cdot(\alpha v_c)^2=\frac{1}{2}D_a{x_a}^2 \qquad (4)$$

The period of motion is independent of v_c and given by:

$$T_a=2\pi\sqrt{M_a/D_a} \qquad (5)$$

Comparison of calculated and measured periods

Fig. 2 shows fair correlation of measured and calculated bouncing periods of the movable interrupter contact for a variety of vacuum circuit-breakers [6].

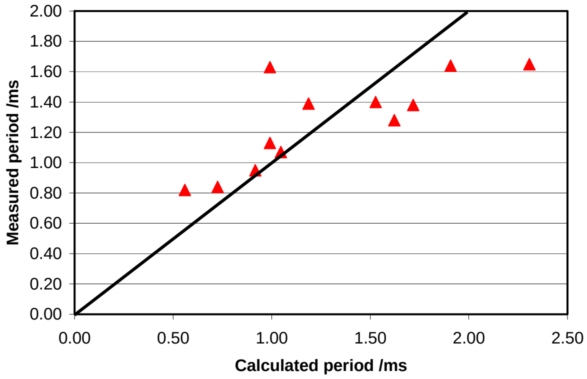

Fig. 2: Comparison of measured and calculated bouncing period of the movable interrupter contact; bold line is the 1:1 relation.

Here, the rebound fraction ß is assumed as constant fraction with a value of 0.65. The deviations from perfect fit come from the simplified formula (3), slightly different contact spring values, deviations of the factor ß from the assumed constant value,, and the non-uniformity of the bouncing motion. Due to the loss of speed at every bounce, the period is decreasing.

The rebounding depth x_s as calculated from (2) using actual contact forces between 2000 and 4000N, interrupter stem masses of 1.4 to 3 kg and closing speeds around 1m/s are between 0.1 and 0.5 mm. This is consistent with observations made by a fast video camera.

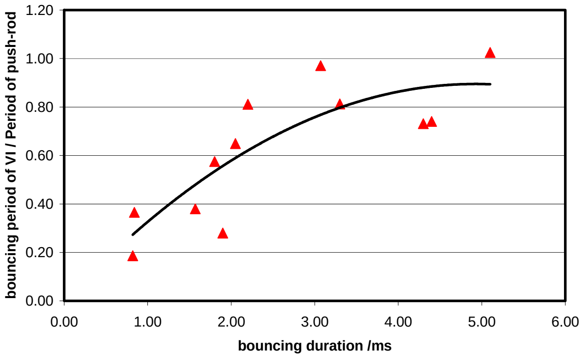

Fig. 3: Dependence of bouncing time of VCB on the ratio of bouncing period of moving interrupter stem and oscillatory period of push-rod.

In Fig. 3, the ratio of the two measured periods T_s of the movable interrupter stem and T_b of the push-rod is plotted against the bouncing duration. It seems that the longest bouncing durations occur when the two bouncing periods are in resonance, though the coupling between push-rod and interrupter stem is only via the contact spring. Numerical simulation of the elastic impact of two bodies seems to indicate also some resonance effect when the ratio of T_s and the oscillatory period T_a of the fixed contact is close to 2: this effect is under further investigation. Experiments show the vibrations of the fixed parts influence the bouncing time: for example addition of a heavy contact arm to the terminals of a breaker, as required for a removable VCB, can reduce the bouncing time from 4 ms to 1 or 2 ms.

The coefficient of restitution, characterizing the elastic properties of the impact, is of particular importance. It is related to the fraction ß above. On new circuit-breakers, the contacts are hardened by each successive no-load mechanical operation. Under these circumstances the bouncing time is observed to increase with the number of operations. Vice versa, in the service life of switchgear, a pre-arc will always strike between closing contacts thereby heating the contact surfaces. This will reduce significantly the coefficient of restitution and give shorter bouncing times as described below.

EFFECTS OF CONTACT BOUNCING

In order to evaluate the impact of contact bouncing on the vacuum circuit-breaker service life, the bouncing effect is separately discussed for different test duties [7]:

A. making and breaking of short-circuit currents

B. making and breaking of single capacitor bank charging currents

C. making and breaking of back-to-back capacitor bank charging currents

A. Making and breaking of short-circuit currents

When contacts approach during making, they will eventually reach a distance at which voltage breakdown occurs: this leads to pre-arcing with short-circuit current starting to flow before the contacts touch. As a consequence, the contact surface will be locally heated and possibly melted. When the contacts actually touch, the melted area solidifies and probably gets welded. The longer the arcing time, the larger the arc energy, the larger the melted area, and the stronger the resulting weld between contacts. If a bounce follows, the engaged melted material will be disrupted again: temporary short arcs occur across the gap, increase the temperature of the contact surfaces and produce larger areas of molten material. For a 12kV breaker, which exhibited a bouncing duration of more than 4 ms, the bouncing time was only 1.5 to 2 ms afterwards proving the restitution effect:

Operation	I / kA_{peak}	Bouncing times /ms
10 x CO	0	3.8 – 4.0 – 4.2
2 x C	68, 75	NA
1 x CO	0	0 – 2.0 – 0
After 10 x CO	0	0 – 3.5 – 1.5
1 x C	80	NA
1 x CO	0	0 – 1.5 – 0
After 10 x CO	0	0 – 3.5 – 2.0

Table 1: Bouncing times measured in all 3 poles during no-load and after short-circuit making operations for a 12kV / 25kA VCB.

The same was observed in [8]. After 10 no-load operations, the original bouncing duration was reproducibly established again. In conclusion, the main problem left is the possible inability of the circuit-breaker mechanism to break the contact weld during the subsequent opening operation. As long as the making and breaking type-tests prove that the opening energy is high enough to break the weld under any circumstances, bouncing is of no concern for the user.

Making and breaking of load currents is covered by the more demanding case of short-circuit currents [7]. Therefore it is not discussed in this paper.

B. Making and breaking of single capacitor bank charging currents

The making of a single capacitor bank involves an inrush current which can reach several kA, depending on the bank capacitance, the service voltage, the source impedance, and the instantaneous voltage value at the moment of closing.

In fact, the rather high current values on closing will cause some welding of the contacts. During the subsequent opening, the weld is broken but the arc current is too low (less than a few hundreds amperes) to smooth the contact surface. The damaged surface might produce increased electric field at the microscopic level. This reduces the dielectric strength between the contacts, which makes re-strikes more likely [9]. Bouncing is suspected to intensify this process, because it involves an arcing phase during closing which can lead to a stronger contact welding.

These arcs occasionally extinguish at a high-frequency current-zero so that the charging voltage of the capacitors appears again across the gap. However, even with the high breakdown field strength of a vacuum interrupter of 20 to 30 kV/mm, the recovery voltage is limited to 10 to 15 kV, since the contact gap due to rebounding is below 0.5 mm. Over-voltage generation is therefore not possible due to contact bouncing during closing.

Experiments [10] could not distinguish between the effects of welding due to the inevitable pre-ignitions and welding due to bouncing after contact touch. An enhanced bouncing duration (but improved capacitive switching performance) was observed with a fast closing speed and short pre-arc, and little bouncing with lower speed and longer arcing time. This can be explained by softening of the contact surface by arcing and an associated “damping” behavior as explained before.

In [7] the transients during closing of a cable are depicted. Most of the events take place during the pre-arcing period before contact touch, when the gap distance is still several millimeters. No interruption of current is visible after closing of contacts in all three phases, although the switchgear used in these tests exhibited a (no-load) bouncing time of about 4 ms.

C. Making and breaking of back-to-back capacitor bank charging currents

The phenomena are hardly different from those observed for a single capacitor bank, except that, the inrush current being higher, all the consequences already described are intensified [11]. Type tests [4] are prescribed with an inrush peak current of 20 kA at a frequency of 4 kHz and a damping factor of > 0.75 (ratio of two consecutive peaks in one polarity).

If bouncing of contacts actually occurs during the inrush current flow, the effects will be less severe than those related to pre-arcing. Since the inrush current is decreasing over time due to damping, the heating effect during bounces has less influence than the heating effect during the pre-arcing time (see Fig. 4). Taking the values from above, the integration of the inrush current during a 2ms pre-arc gives an integral of 11As, whereas the integration of the subsequent 2ms during bouncing adds up to only 1.5As. Even for a bouncing duration of 5ms, the integral is only increased by 2%, which is negligible. Bouncing under such conditions might be even beneficial, since the surface is hardened as under no-load operations. As obvious from Fig. 4, the current integral from the feeding source will rather dominate the effects during bouncing.

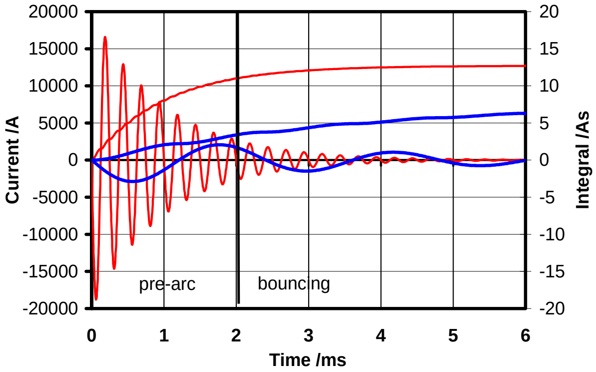

Fig. 4: Back-to-back inrush current of a capacitor bank and the associated source inrush current; steadily increasing traces give the integral of current.

REQUIREMENTS FOR CONTACT BOUNCING

Since the introduction of this technology manufacturers of vacuume interrupters have specified the maximum allowable bouncing time in their data sheets, together with other application data such as contact speeds, contact force, over-travel, etc. These parameters are to be understood as interface data in order to allow the circuit-breaker manufacturers to attain the expected performances during the type-tests, on the basis of the experience cumulated by the interrupter manufacturer. This explains the variety of values for the maximum allowable bouncing time stated in the data sheets of different manufacturers, ranging from 2 to 5 ms for the total duration of the bouncing phase: no general rule but a case by case application recommendation. The non relevance of bouncing time is confirmed by the situation found in the main circuit-breaker standards: neither IEC 62271-100 [4] nor the ANSI C37.09 [5] mention the bouncing time. The same is true in China for GB 1984, DL/T 402-403, and JB/T 3855. Only GB 50150-2006 [12], intended to provide criteria for the acceptance and maintenance of electrical equipment, gives limitations for the bouncing time.

CONCLUSION

This investigation shows that bouncing can be understood as rebound of the movable vacuum interrupter contact into the associated contact springs. The duration of bouncing and the involved frequencies depends on the masses of moving parts, on the closing speed, on the wipe of contact springs, the condition of contact surfaces, the elasticity of supporting elements, etc. A resonance effect between the movable interrupter parts and those parts associated with the support and kinematic chain might be active. However, since none of these elements determines the bouncing duration uniquely, it does not make sense to limit the bouncing time for all circuit-breakers.

On the other hand, it has been shown in making and breaking test duties with VCBs having bouncing times of 4 to 5 ms that the switching capability of the breaker is not degraded in any way, either for short-circuit interruption or for capacitive current switching.

A generalized requirement for an arbitrary maximum bouncing time in customer technical specifications for circuit-breaker procurement puts a burden on manufacturers that is not justified by any actual service advantage. Moreover, bouncing time is never mentioned in the basic circuit-breaker product standards as a parameter useful to characterize the circuit-breaker performance. A more rational approach would consist in performing type tests (short-circuit making and breaking, capacitive current switching, electrical endurance) on specimens characterized by the maximum bouncing time accepted in routine tests.

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