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Welding when contacts close electrical circuits

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The paper presents analysis of the welding due to pre-arcing contacts and due to bounce arcs. Welding happens following arcing at make or break where the arc roots generate over 10 times more heat than seen in the former constriction example and thus melt and soften the contact material, arc welding. The higher the value of velocity of contact closing, the shorter the arcing time. High velocity has a negative aspect since it causes bouncing of contacts finger from the butt. Welding caused by solidification of a molten metal bridge is an extreme case of resistance welding. The welding force increases during the early operation cycles.

Keywords: *contacts, arcing time, impact of contacts, welding.*

Introduction

When a interrupter's contacts close in a power circuit, there will be a period before they touch when the electric field across them will be high enough for breakdown to occur. This will give rise to a "prestrike" arc, which will form between the contacts and will carry the power circuit's current. If the current is high enough (e.g., in a fault current situation), it is possible that the contact surface will melt. Where they touch a small weld can form. Arcing also can continue is the contacts bounce once they have initially touched [1—4].

In a single-phase circuit and a three-phase grounded circuit, once a breakdown occurs in a single interrupter the circuit current will flow. The breakdown of the contact gap occurs at the moment of equalising of contact gap dielectric strength u_p (t_s, t) with the momentary value of the voltage $u(t)$ applied to the gap (fig. 1).

Assuming that the breakdown voltage is proportional to the distance between the contacts, and that it is not polarity-dependent, it is possible to determine the time t_p when the breakdown occurs during current switching on from the relation [5]:

$$U_m \left|\sin \omega t\right| = E_c v_s (t_s - t_p) = E_c v_s t_a , \tag{1}$$

where $E_c \equiv E_k$ — critical value of electric field strength; t_p — moment of breakdown of contact gap; t_s — moment of contact closing; v_s — closing velocity of the contact gap; t_a — the arcing time.

In the operation of switching on an alternating current circuit, the signal to make the electric switch usually is not correlated with the voltage phase, so breakdown may occur at various distances between contacts, and at various moments, i.e. at various voltage phase angles. Hence, the arc duration may be different for each current switching on. The arc duration $t_a = t_s - t_p$ depends on the velocity v_s of contact closing, and on the electric field strength value E_c [6, 7].

In a three-phase ungrounded system, under voltage between phases, the flashover takes place simultaneously in the contacts of two phases and then in the third pole of a switch (fig. 2).

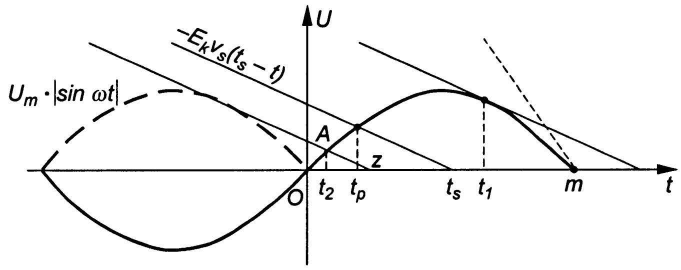

Fig. 1. Determination of the breakdown moment.

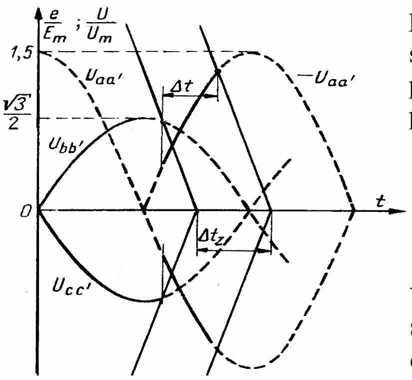

Fig. 2. Mechanism of non simultaneously switching on circuit current in circuit system; phase A lag Δt to the phases B, C, if the delay of pole A to the poles B, C is equal Δt_z.

It is shown that the individual phases of a three-phase circuit are switched on non simultaneously even if circuit breaker contacts are equalised.

Welding of closing contacts

The formation of the weld between the interrupter's contacts is a complex function of multiple variables. Some of these include the value of the circuit current, the steepness of a wave front of a pulse of a current, whether or not arcing occurs, whether or not the contacts are closed or are closing, the contact material, the structure of the contact' surfaces, and the design of the mechanism in which the interrupter operates [8—12]. In this section, I will develop the concepts of contact welding in a vacuum interrupters during closing contacts.

On closing the contacts, the prestrike breakdown might be expected to occur at a longer gap and result on a longer arcing time. This, in turn, may result in a larger molten pool and a stronger weld after the contacts have mated.

Assuming that the course of short-circuit current in pole of switch is defined by *i(t)*, the energy emitted in electrical arc W_a during of make-time t_a , can be determined from relationship

$$W_a = \int_0^{t_a} u_a i(t)dt \cong E_c \int_0^{t_a} l_a(t) i(t)dt = E_c \int_0^{t_a} i(t)(d_s - n\overline{V}_s t)dt \quad (2)$$

where u_a — electrical arc voltage drop, V; *i(t)* — short-circuit current, A; E_c — critical value of electrical field between contacts, V/m; n — number of the contact gaps in one pole of a switch; t_a — the switching-on arc duration, s; d_s — distance between contacts, m; $\overline{V}_s$ — average value of the velocity of contacts closing; l_a — length of arc, m; $l_a(t) = d_s - n\overline{V}_s t$.

On the base of expression (2) we can ascertain, that the switching-on energy:

a) decreases with increasing value of product $n\overline{V}_s$;

b) grows as a function of voltage;

c) is proportional to the value of electrical field E_c ;

d) can be accordingly small, if during the arc duration, the current i(t) doesn't reach its peak value, ie. if $t_a \leq \frac{1}{4f}$.

In general, the higher the value of velocity v_s of contact closing, the shorter the turn-on time. Resulting is a shorter time of arc duration that enhances the life of the electric switch. High velocity has a negative aspect since it causes bouncing of contacts finger from the butt.

Before the contacts finally touch a vacuum breakdown of the contact gap d_s, will occur when the electrical field between the contacts equals a critical value E_c given by

$$E_c = \frac{\beta \cdot U_\mathrm{B}}{d_S}, \tag{3}$$

where U_B — breakdown voltage; β — enhancement factor $(\beta = \beta_\mathrm{g} \cdot \beta_\mathrm{m})$; β_g — geometric enhancement factor; β_m — microscopic enhancement factor.

Once the vacuum breakdown occurs, a vacuum arc is formed, which continues to burn until contact is established between the two contacts [3, 13]. The first operation in the sequence for both contact materials always occurs at the shortest contact gap, has the shortest arcing time and contact touch occurs at the lowest current. Thus, the total energy into the arc roots is much less than it is for subsequent close and latch operation [12]. Because the new contact surfaces will have a more or less uniform β_m, we can assume that the first breakdown will be in the region of the maximum β_g; that is close to the contacts' edge.

It is possible to obtain an estimate of the maximum weld force F_W by making some simply assumptions. The volume of metal in the contact region that is melted is assume to be a sphere whose radius (a) is the radius of the weld in the area A_W. It is also assumed that almost all the energy from the welding current is used for adiabatic heating of this spherical melted region [3]. The energy W_C to melt the contact region is

$$W_C = m[c_V(T_m - T_0) + c_L], \tag{4}$$

where m — the mass of material melted; c_V — the specific head; T_m — the melting temperature; T_0 — the initial temperature; c_L — the latent heat of fusion.

If all the energy is used to melt the contact spot, then

$$W_C = \int U_C i(t) dt, \tag{5}$$

where U_C — the voltage measured across the contacts.

The maximum weld force that would be expected to occur for different materials are given below [3]:

$$\text{for silver: } F_W = 67 W_C^{2/3}; \tag{6}$$

$$\text{for copper: } F_W = 127 W_C^{2/3}; \tag{7}$$

The energy into the contact spot during contact closing is a complex function of: energy from the breakdown arc + energy from the bounce arc(s) + + energy from contact spot heating.

As the two contact surfaces make impact, the energy of impact is dissipated by a rebounding of the contact resulting in an arc with a subsequent closure of the surfaces. Such action can provide conditions for contact welding.

The maximum welding force as a function of the energy from the bounce arc (*s*) input into the contact spot for different contact forces *F* are presented at fig. 3.

In this figure, you can see that the higher value contact forces *F* the lower value of welding forces F_W [14].

The tendency of Cu to form strong welds when closing on high currents in vacuum prevented its use in practical vacuum interrupter designs. Thus, mixtures of materials that cannot be contemplated for application in gaseous environments such us air or SF_6 can be considered. For example, Cu-based material with other metals added to increase its weld resistance by reducing its mechanical strength from one side and reduce energy W_C to melt the contact region [3, 15].

The optimum ratio of Cu to Cr has not been universally accepted for all vacuum interrupter designs and for all vacuum interrupter applications. There have been studies that show a Cu—Cr (50% (wr.) works well. Indeed a high Cr content contact will have a good resistance to welding [3, 13]. On the other hand, increasing the Cr content and the decreasing Cu content will lower the contact's thermal and electrical conductivities.

Values of F_W less than those calculated by knowing W_C are frequently observed and can be explained by a combination of a number of possible physical effects [3]. For example, if the arc roots on the contacts move, the melted spot may not be exactly opposite to each other when the contacts finally come to rest, thus reducing A_W. If the arc duration *t* is great enough, the heating of the contact region will not be adiabatic and the effect of heat conduction into bulk of the contact has to be considered. If the arc is very long, not all the arc energy goes into heating the contact spots: for example, some is lost by radiation and some is lost by radial conduction of heat. The bounce time of the contacts can be complex with the contacts opening and closing a number of times during one closing operation. Also during the bouncing the contact spot may vary from bounce to bounce. Thus, the exact value of the energy into the final melt zone is not easy to determine. Finally, the contact surface itself can be different from the bulk metal.

In practical switching device that employs a vacuum interrupter in a well-designed mechanism, it can be seen from voltage or current records whether or

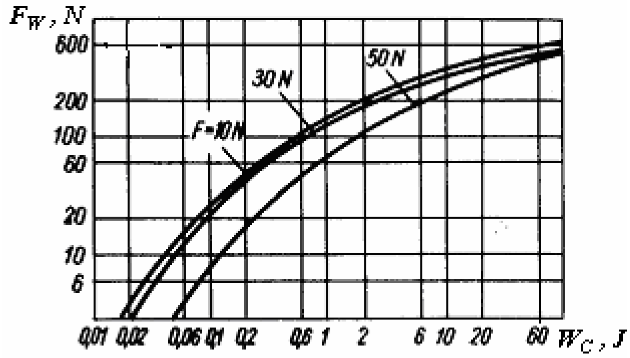

Fig. 3. The maximum welding forces F_W versus of the energy W_C from the bounce arc (*s*) for copper contact and for different contact forces *F*.

not the mechanism will provide enough force (energy) to break any welds that may form.

Conclusions

The welding contact closing is proportional to energy from the breakdown arc, energy from the bounce arc(s) and energy from contact spot, heating.

All these energies are proportional to the value of the current, the steepness of a wave front of a pulse of a current and arcing, bouncing times.

The contact materials ought to have satisfactory current interruption ability, reasonably high-voltage withstand capability and did not readily weld.

The contact force has positive influence at the lower value of welding forces.

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Зварювання контактів при замиканні електричного кола

Станіслав Кулас

Стаття являє собою аналіз умов зварювання контактів. Зварювання відбувається як наслідок виникнення і гасіння дуги, там де тепловиділення на порядок більше, де матеріал розм'якшується, плавиться і має місце зварювання контактів. Чим вище швидкість зближення контактів, тим коротше час дугового впливу. Висока швидкість має негативний вплив, оскільки це викликає відскок контактних пальців від з'єднання. Зварювання, викликане твердінням металу розплавленого містка, є граничним випадком опору зварювання. Сила зварювання збільшується на протязі ранніх циклів комутації.

***Ключові слова**: контакти, час горіння дуги, співударяння контактів, зварювання.*

Сваривание контактов при замыкании электрической цепи

Станислав Кулас

Статья представляет собой анализ условий сваривания. Сваривание происходит следом за возникновением и гашением дуги в основании дуги, где тепловыделение на порядок больше, при этом материал размягчается, плавится, имеет место дуговая сварка. Чем выше скорость сближения контактов, тем короче время дугового воздействия. Высокая скорость имеет негативное влияние, так как это вызывает отскок контактных пальцев из соединения. Сваривание, вызванное затвердеванием металла расплавленного мостика, является предельным случаем сопротивления свариванию. Сила сваривания увеличивается в течение ранних циклов коммутации.

***Ключевые слова:** контакты, время горения дуги, соударение контактов, сваривание.*