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Contact Behavior of Electrical Vehicle-Battery Junction Box under High Shorting and Breaking Current

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Abstract—The motor of an electric vehicle and its equipment are connected to the battery via a junction box that contains power relays that ensure current flow when closed but can break the current in abnormal situations. The contacts of such relays have to ensure and maintain a low contact resistance and support a shorting current of a few kA and an acceptable breaking capacity under a normal load of a few hundred amps.

We have developed a test involving a shorting current of 4000A passing during 50ms through closed contacts in which we study welding and arcing phenomena. The origin of arcing has been attributed to the shorted contact produced by the electromagnetic repulsion force that is able to counterbalance the contact force and separate the contact. The power arcing burns during the short circuit and a irreversible damage is observed when the accumulated arc energy exceeds a certain critical value.

In this paper, the main cause of the repulsion phenomena and minimum arc energy criteria inducing substantial damage and cap sule breaking is studied. By varying conditions of current for two relays equipped with different materials, filled with a specific gas and employing a magnetic field we found that shorting damage was not avoided below 2KJ. Fortunately breaking capacity is achieved without damage and relay function is ensured.

Keywords—component; formatting; style; styling; insert

I. INTRODUCTION

Electrical contact in power relay should ensure breaking and current handling with minimum arc damage to the contact materials and the surrounding equipment. This defines the well known breaking capacity depending upon to the load, current and voltage during an operation number without fault (low contact resistance, no welding etc). This normal breaking at nominal current <100A is ensured by de energizing a coil, but an abnormal contact separation due to repulsion force under short circuit conditions, because this force may counterbalance the contact force. In fact with the growth of electric power in electrical vehicles battery this phenomenon is becoming crucial in shorting conditions and it is recognized as the main cause of power arcing with collateral damage. This repulsion force exerted on contact can counterbalanced partially or totally the spring force applied to keep close the contact and ensure nominal contact resistance. This repulsion force is comprised by various contributions such as F_l (electromagnetic looping), F_r (constriction region) and assisted by F_a (arc plasma pressure etc.) after arc ignition. Neglecting F_l and F_a , the main force F_r called electrostatics force is described in Ref. [1] and rarely investigated in Ref. [2] and experiment [3-4] for AC current mainly.

In this paper we present a calculation of the repulsion force and we describe a test at a DC current of 4 000A for 50ms duration to closed contacts. In fact we test one type of relay where the spring force F_s is counterbalanced by the repulsion force F_r and arcing appear. There was also a second type of relay where the spring force is higher than repulsion force and where there is no separation but in fact welding take place. The calculation takes into account the minimum repulsion and spring forces and the minimum arc energy criteria inducing reversible relay damage.

Furthermore the normal break arc blowing by external field is investigated in terms of arc duration, energy and subsequent erosion.

II. EXPERIMENTAL TEST AND PROCEDURE

In an electric vehicle the motor and equipment are connected to the battery via a junction box. This box includes power relays (in closed situation) that ensure current flow via fuse in order to supply the motor with electrical power. This closure and opening are made under zero current prior to motor starting and after motor stop. To simulate the shorting condition (Test number 0 in TABLE I) and as shown in the circuit test of Fig.1, the relay was connected to a very low inductive load of 100 m Ω supplied by $U_b=400$ VDC. The pulse of current 4kA with fast rise time was applied during 50ms by closing the relay service after closing relay test. In addition, breaking by switching off the relay coil at a current of less than 1 kA presenting emergency situation is investigated in test 1, 2, 3. These conditions are summarized in the TABLE I. The tested relays type A and B are quite similar and were encapsulated in a ceramic chamber filled with hydrogen gas for arc cooling and contact oxidation and pollution protection.

TABLE I TEST CONDITIONS

Test	Breaking by Repulsion test	Breaking by coil de energizing		
Current (A)	4 000	200	100	750
Voltage V	400	240	240	50
Operation	1	100	100	5
Test number	0	1	2	3

Contacts are equipped with pure copper for relay A and copper chromium materials for relay B and using double breaking contacts by a mobile bridge see Fig.1. In addition magnetic field B of approximately 30 mT is applied by an

external magnet. This allows of undesirable arcing to be blown in the narrow gap of 1mm as described in earlier works [5]. Contact force values at each side of the bridge of 10N and 5N are measured for relay A and B respectively.

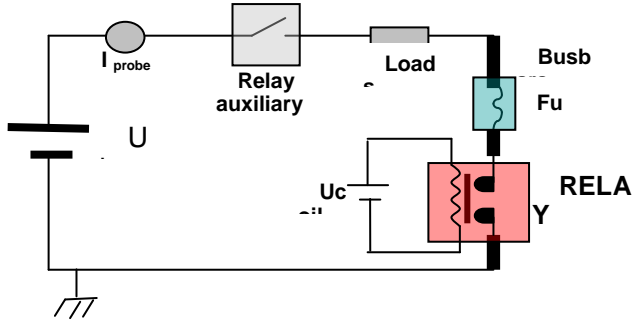


Fig.1 Test circuit

III. THEORETICAL CALCULATION OF REPULSION FORCE

The main cause of repulsion is the constriction current line in the contact zone. These current deviations produce an electromagnetic force F_r (Laplace) component in the direction of current flow I . As it shown in Fig.2 in ideal situation of contact zone of radius a between two hemispherical cylinder of radius R crossed by current I induce a current density $J = I/2\pi R^2$. The current fraction in the direction θ in constriction volume is :

$$I_\theta = J \int_0^\theta R d\theta \int_0^{2\pi} R \sin\theta d\varphi = I(1 - \cos\theta) \quad (1)$$

This current creates an orthogonal radial magnetic field which tangent to the circular contour:

$$B_\theta = \mu I / 2\pi R ((1 - \cos\theta)) / \sin\theta = \mu_0 I / 2\pi R \tan(\theta/2) \quad (2)$$

A current element $dI = I \sin\theta d\theta$ with a length dr undergoes the elementary Laplace force df

$$df = dI dr \times B = dI dr \frac{\mu_0 I (1 - \cos\theta)}{2\pi r \sin\theta} \sin\theta d\theta \quad (3)$$

In addition this force has an axial component in the Oz direction which produces the repulsion force df_r

$$df_r = df \sin\theta = dI dr \times B \sin\theta = dI dr \frac{\mu_0 I (1 - \cos\theta)}{2\pi r \sin\theta} \sin\theta \sin\theta d\theta$$

The total repulsion force F_r is given by integrating r from a to R and θ from 0 to $\pi/2$

$$F_r = \frac{\mu_0}{2\pi} \int I dI \int_a^R \frac{dr}{r} \int_0^{\pi/2} (1 - \cos\theta) \sin\theta d\theta = \frac{\mu_0}{4\pi} \log\left(\frac{R}{a}\right) \quad (4)$$

As we can see the repulsion force F_r depends on the square of the current intensity, the quotient of the conductor radius R , and contact area radius a . In practice this contact area A_c is achieved by action of the contact force imposed by spring F_s and partially compensated by repulsion F_r . It can be expressed in the high force corresponding to elastic domain by $A_c = \pi a^2 = \frac{F_c}{\xi H}$

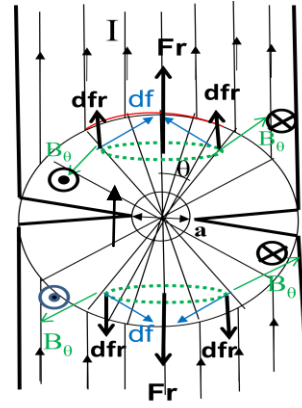


Fig.2 Repulsion forces F_r between two conductors in contact under contact force F_s

Here $\xi=0.38$ and H is the hardness of the contact materials and $F_c = F_s - F_r$ becomes the contact force. Substituting these expressions into the main Eq. (4) for the repulsion force, we obtain :

$$F_r = \frac{\mu_0 I^2}{8\pi} \log\left(\frac{\xi H \pi R^2}{F_s - F_r}\right) \quad (5)$$

We note that F_r depends on F_s but also F_r itself. So the analytic solution for this transcendental equation is not available except for the case of a high spring force $F_s \gg F_r$ as in the Snowden work [3]. However a numerical solution can be found by deducing the expression F_s as in the Barkan work [2].

$$e^{-\frac{8\pi F_r}{\mu_0 I^2}} = \left(\frac{F_s - F_r}{\xi H \pi R^2}\right)$$

$$(F_s - F_r) = \xi H \pi R^2 e^{-\frac{8\pi F_r}{\mu_0 I^2}}$$

$$F_s = F_r + \xi H \pi R^2 e^{-\frac{8\pi F_r}{\mu_0 I^2}} \quad (6)$$

The plotted curves for different current values from 1kA to 6kA and for the two materials in relay A and B are given in the Fig.3 and Fig.4.

As we expected this repulsion force remains stable and lower when the applied spring force is higher. This means that large constriction radius value a avoids repulsion and contact separation. However when this force F_s is reduced and approaches the repulsion force values, a minimum values F_{sm} at F_{rm} are observed and indicated by square label in the Fig.3 and 4. It announces the instability of the contact and beyond these critical values the contact separation is expected.

This phenomenon is accentuated by the current. Furthermore due to the higher material hardness $H=1.3$ GPa equipping the relay B (copper silver chromium alloy) than material of relay A $H=0.7$ GPa (pure copper) the repulsion force is higher of approximately 1N. This confirms that repulsion force depend on contact materials as reported in Ref. [4].

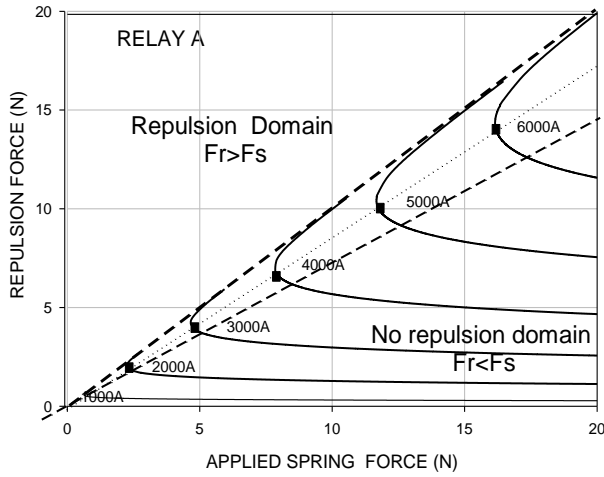


Fig.3 Repulsion force versus spring force at different current intensity for copper materials of relay A. Bold dashed curves indicate the limit of high probability of separation zone

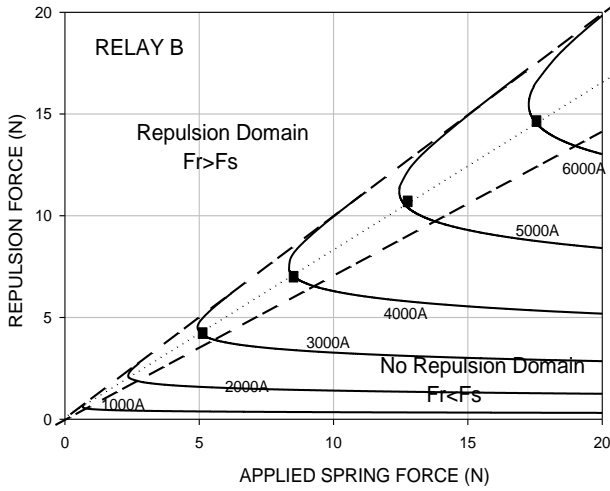


Fig.4 Repulsion force versus spring force at different current intensity and copper chromium material

These important critical values F_{rm} and F_{sm} can be expressed by derivation the Eq. (6):

$$\dot{F}_s = 1 - \xi H \pi R^2 * \frac{8\pi}{\mu_0 I^2} e^{-\frac{8\pi F_r}{\mu_0 I^2}} = 0$$

By solving this equation we find the expression of minimum repulsion force F_{rm} in Eq. (7). Then reporting this expression in the Eq. 6 we get the expression of minimum spring force needed to ensure stability

$$F_{rm} = \frac{\mu_0 I^2}{8\pi} \ln \left(\frac{8\pi \xi H \pi R^2}{\mu_0 I^2} \right) \quad (7)$$

$$F_{sm} = \frac{\mu_0 I^2}{8\pi} \left(\ln \left(\frac{8\pi \xi H \pi R^2}{\mu_0 I^2} \right) + 1 \right) \quad (8)$$

$$F_{sm} = F_{rm} + \frac{\mu_0 I^2}{8\pi} \quad (9)$$

These two expressions between current and the critical value of the forces specifies the minimum forces external forces such as springs which must be applied at the contact surface in order to maintain stability when carrying current I . Drawn in Fig.5 for two relays material A and B, it shows that the differences in the two forces are increased at high hard material used in relay B. Furthermore large cross section πR^2 of the conductor were an accelerating factor for the repulsion.

IV. EXPERIMENTAL RESULTS OF REPULSION

When the contact of the closed relay B are made to undergo a square current pulse of 4KA during 65ms their separation to, takes place after 15 ms and arc ignition.

This separation occurs because the spring force of 5N is quite lower than the calculated repulsion force of 8N Fig.5. Shown in Fig.6, this self opening is accompanied by an electrical arc ignition at 20 volts which is equal to the minimum arc voltage in the case of hydrogen Surprisingly the arc voltage value of 20V tends to prove that only one side of double breaking is separated. This means that the mobile bridge is not perfectly equilibrated and additional plasma pressure exerted on this side accentuated this bridge inclination.

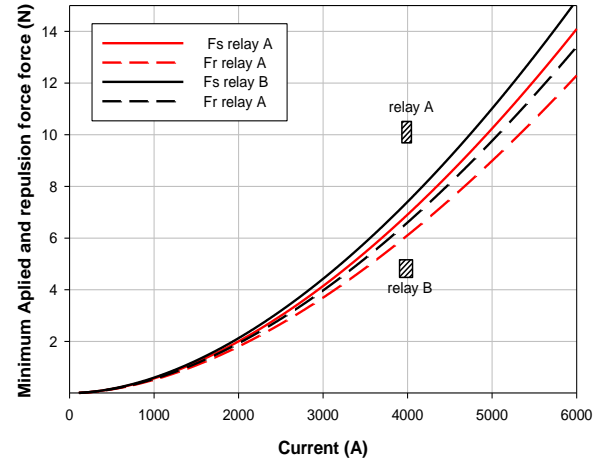


Fig.5 Critical Repulsion force F_{rm} (dashed lines) versus current and applied spring forces F_{sm} (solid lines) for copper and copper chromium materials

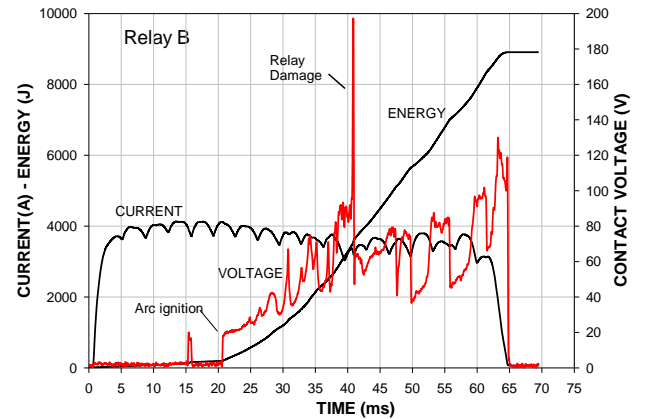


Fig.6 Contact current, arc voltage and arc energy ignited by separation due to repulsion force in relay B.

Then the arc voltage is increased and supply energy which is accumulated in the sealed capsule of the relay. It was found when accumulated energy reaches 4KJ the relay structure is damaged and the ceramic chamber is broken as was observed by high speed camera imaging.

For relay A the spring force is higher than the calculated repulsion force (see Fig.5), no arcing takes place with current pulse. But the high current causes the well known welding. In fact joule heating of the contact zone which is enough to induce melting of the contact constriction zone S and subsequent welding at the current cession could occur. In this melting contact zone the contact voltage stays low close to melting the 1.6V required for melting which is the sum of the two voltage drop measured on each side (see Fig.7). One can note that this voltage level is close to melting voltage of copper.

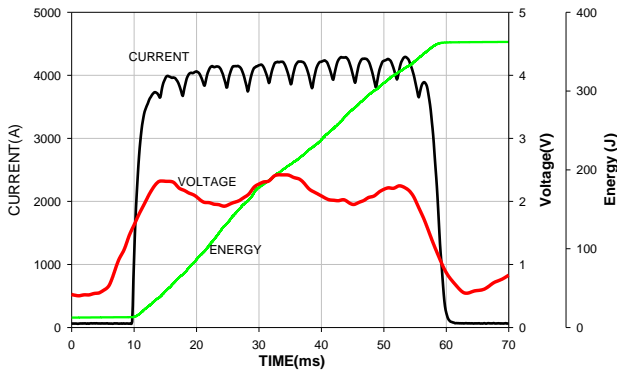


Fig.7 Contact current, voltage and energy without arcing in relayA (no separation due to repulsion force but welding).

Let remark that repulsion force reduce contact force and make constant cross section S smaller and facilitate the melting phenomena. As in the fuse domain we can evaluate The melting time t_f by Mayer's law $t_f I^2 = K S^2$ where K is Mayer constant $K=8.10^{16} \text{ A}^2 \text{ s m}^4$ and $S=(F_s-F_r)/\xi H$.

$$S = \pi a^2 = \frac{F_s - F_r}{\xi H} = \pi R^2 e^{-\frac{8\pi F_r}{\mu_0 I^2}} \quad (10)$$

$$t_f = K \left(\frac{\pi R^2}{I} e^{-\frac{8\pi F_r}{\mu_0 I^2}} \right)^2 \quad (11)$$

In the minimum condition using F_{rm} Eq. (7) we get the expression of melting time depending on the current and material hardness

$$t_f = K \frac{\mu_0^2 I^2}{64 \pi^2 \xi^2 H^2} \quad (12)$$

A rough calculation of melting time called pre arcing shows that this time is less than $1 \mu\text{s}$ and demonstrates that the contact may be melting during the applied high current pulse of few ten of milliseconds. This melting could leads do welding. Indeed, as demonstrated by Slade [5], we can define a welding current I_{weld}

$$I_{weld} = \frac{1}{9\rho} \sqrt{\frac{F}{H}} [10^{-7} (T_m^2 - T_b^2)] \quad (13)$$

where T_m is the molten temperature of the material and T_b the bulk temperature. By applying this formula with data provided

by Slade, we found a welding force of 20N, which is too high to be broken by the spring force.

V. EXPERIMENTAL RESULTS OF BREAK ARC

In emergency situations during vehicle use, these relays must break and open the circuit to isolate the battery from the motor and other equipment. This separation is ensured by switching off the coil driving under 12 v. Three current levels are tested with corresponding operation numbers up to 100 as mentioned in TABLE I.

It is well known that breaking at such high current and voltage levels will generate very long and sustained arcing regarding the narrow contact gap as low as 1mm [6]. Fortunately some arc mitigation solutions are included in those relays. For this aim, a magnet blows the arcs under a magnetic field of 30 mT as we have demonstrated in our previous work [6]. In addition the capsule (arc chamber) is filled with hydrogen which allows more efficient arc extinction than air.

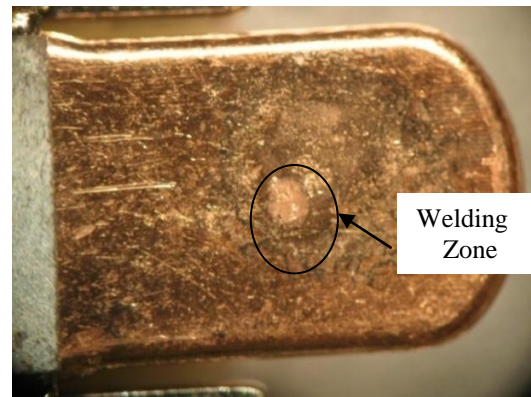


Fig.8 Contact welding without arcing (no separation due to high repulsion force in relay A)

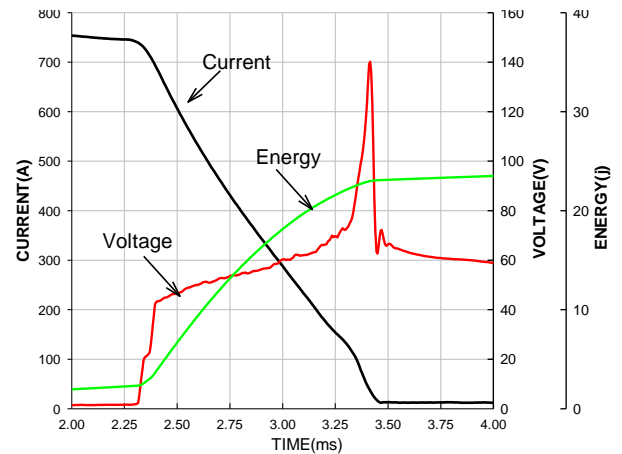


Fig.9 Arc voltage and current characteristics on break

A typical example of an arc voltage and current and energy characteristic are shown in Fig.9 for test 1 and relay A.

On arc we distinguish the step voltage from 20 to 40v due to the second serial arc in this double breaking design. As summarized in TABLE II, we see short and similar arc duration close to 1ms. This means that extreme and rapid arc

extinction takes place. Similar arc duration with various conditions of current and voltage means that magnetic field is the main parameter and cuts the arc at this time whatever the current. Arc duration is reduced by several orders of magnitude compared to the natural free arc in the absence of mitigation.

TABLE II BREAK ARC DURATION FOR THREE TESTS

Test number	T1	T2	T3
Relay A: Duration (ms)	1.23	1.23	.91
Relay B: Duration (ms)	0.98	1.10	1.03

Finally we remark if the hydrogen gas is removed by simulating a leak in the arc chamber, the arc duration is increased by a factor of two. However when we remove the magnet, the overheating caused by the sustained arc destroys the relay.

As is shown in Fig.10 the surface damage by arc arcing is very great due to erosion of the contact material. In fact the arc energy of about 25Joule was considered to produce such a fault.

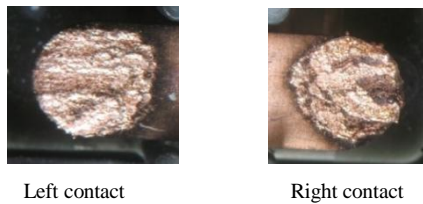


Fig.10 Contact surface erosion after normal arcing at 200VDC and 200A and 100 operations

VII. CONCLUSIONS

Theoretical calculation of repulsion force exerted on contact on close situation was confirmed by experimental test on two

commercial relays. In some cases, the repulsion force counterbalanced the spring force, leading to contact separation and irreversible degradation. On the other hand, in other cases the spring force (contact force) was higher than repulsion force no separation occurred but contacts welding took place. To avoid abnormal separation an effort should be made by increasing the spring force over the calculate F_{sm} value. In addition materials other than pure copper can be a key factor to avoid welding and may contribute to arcing damage limitation.

In normal use, arc on break is efficiently blown by the external field combined with hydrogen surrounding atmosphere in a sophisticated tight ceramic capsule.

In the aim to simplify and reduce the cost of the relay, some work is in progress in our laboratory. We are examining self blowing material [6] which can ensure arc mitigation and provide benefits action against welding.

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