An Arcless Current Interruption Technique via Application of Resistive and Liquid Metal Contacts

P. Pourmohamadiyan, K. Niayesh, H. Mohseni

Abstract – In this paper, theoretical and experimental studies of an arcless current interruption technique are presented. The introduced method eliminates the switching arc and its consequences through application of liquid metal and resistive contacts. First, the solid-liquid contact system is analyzed and the basic phenomena related to arcless switching are elaborated. Then the design requirements are recognized and are converted to a set of mathematical expressions and accordingly the design parameters are determined. The major electromagnetic quantities like current density distribution, magnetic flux density and the force are obtained by a FEM solver and the calculated force is used in numerical calculations of motion simulation. Finally, the designed structure is evaluated through a set of experiments which test the performance of the switch especially in the arcless current interruption. Copyright © 2010 Praise Worthy Prize S.r.l. - All rights reserved.

Keywords: Arcless Current Interruption, Liquid Metal Contact, Inherently Controlled Switch

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$u_{LM}$</td>
<td>Voltage drop on the LM tail</td>
</tr>
<tr>
<td>$I_{LM}$</td>
<td>LM tail current</td>
</tr>
<tr>
<td>$R_{LM}$</td>
<td>LM tail equivalent resistance</td>
</tr>
<tr>
<td>$R_{\Delta}$</td>
<td>Incremental resistance element from the resistance profile which is bridged over by the LM tail</td>
</tr>
<tr>
<td>$I_{tot}$</td>
<td>Total current of resistance profile</td>
</tr>
<tr>
<td>$u_{contacts}$</td>
<td>Voltage of contacts after separation</td>
</tr>
<tr>
<td>$L_{sc}$</td>
<td>Equivalent inductance of the test circuit</td>
</tr>
<tr>
<td>$R_{sc}$</td>
<td>Equivalent resistance of the circuit</td>
</tr>
<tr>
<td>$R_{tot}$</td>
<td>Total resistance of the moving contact when the resistance profile is completely pulled out from the LM</td>
</tr>
<tr>
<td>$u_{Source}$</td>
<td>Source voltage</td>
</tr>
<tr>
<td>$i(t)$</td>
<td>Switch current</td>
</tr>
<tr>
<td>$R_{LM}(t)$</td>
<td>Variable resistance of LM bridge during commutation</td>
</tr>
<tr>
<td>$I_{LM}(t)$</td>
<td>Variable current of the LM bridge</td>
</tr>
<tr>
<td>$T_0$</td>
<td>The duration of current interruption</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Final temperature of the LM tail</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Initial temperature of the LM tail</td>
</tr>
<tr>
<td>$m_{LM}$</td>
<td>LM specific heat</td>
</tr>
<tr>
<td>$Q_{Resistiveheatloss}$</td>
<td>Heat loss dissipated by the resistance profile</td>
</tr>
<tr>
<td>$R_{ResistanceProfile}(t)$</td>
<td>Time / position depended part of the resistance profile lying above LM level</td>
</tr>
<tr>
<td>$m_{LM}$</td>
<td>LM mass</td>
</tr>
<tr>
<td>$C_{IF}$</td>
<td>Insulating Fluid mass</td>
</tr>
<tr>
<td>$m_{IF}$</td>
<td>Insulating Fluid (air) specific heat</td>
</tr>
<tr>
<td>$l_1$ and $l_2$</td>
<td>Radiiuses of the two axial coils</td>
</tr>
<tr>
<td>$F_{12}$</td>
<td>Force exerted on coil number 2 (the moving coil) by coil number 1 (fixed coil)</td>
</tr>
<tr>
<td>$I_1$ and $I_2$</td>
<td>Currents flowing through coils (in our case $I_1 = I_2$)</td>
</tr>
<tr>
<td>$N_1$ and $N_2$</td>
<td>Number of turns for fixed and moving coil respectively</td>
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<td>$d$</td>
<td>Distances between coils</td>
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</table>

I. Introduction

Switching arc has been known as a limiting factor in the circuit breaker design and fabrication [1]. Many efforts have been made to develop arc quenching techniques. Some of these techniques introduce relatively large size interruption chamber or operation mechanism to the circuit breakers. Moreover due to the nature of the arc, post-arc phenomena impose some special limitation on the insulation material and the structure of the interruption chamber. To reduce the arc consequences...
II. Working Principle

A special resistance profile is implemented on the moving contact of the switch. This resistance profile converts the interruption energy into heat and eliminates the arc by imposing a resistive voltage drop instead of arcing voltage. Figure 1 shows a scheme of the switch operation. As it can be seen the resistance profile is immersed in a LM contained vessel. During nominal current, the resistance profile is fully immersed in the LM and the conductive contact (copper part of the moving contact which is placed above the resistance profile) is in contact with LM bulk. Therefore as the liquid metal wets the surface of the conductive part, no transition resistance occurs and the equivalent contact resistance is less than that of conventional low voltage air insulated switches which its contact resistance is mainly depended on contact force.

To have a uniform symmetrical current distribution in the LM vessel, the fixed coil is connected to the bottom center of the vessel. It is also possible to design a more functional structure in which the nominal current can also flow through another separate path which doesn’t heat up the LM bulk in normal condition. This optional path may consist of the conductive contact shown in Fig. 1 and a flexible circular plate touching the metallic vessel edge. But for the present study the simple structure shown in figure 1 is applied. Upon external trigger or inherently during predetermined short circuit condition, this resistance profile is pulled out by a high speed electromagnetic repulsion drive mechanism. The driving electromagnetic force relates quadratically with the flowing current. It is generated via interaction of two magnetic fields originated from the coils located on the fixed and moving contacts. To achieve inherent control on the current, the coils are placed in series with the

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switch and the geometry are designed in such a way that
flowing of the predetermined threshold current through
the coils provide an electromagnetic force enough to
overcome the opponent forces (e.g. gravitation force,
friction, etc.). Once the electromagnetic force overcomes
the opponent forces, the resistance profile moves upward
from the LM bulk. This in turn causes actuation of PMS
which retains the resistance profile above the LM level.

Fig. 1. Scheme of the switch operation: Once the switch current exceeds
the threshold amount, the electromagnetic force between the moving
and fixed coils moves the moving contact upward

III. Liquid Metal Intermediate Contact Medium

A real solid surface can not be ideally burnished
because of asperities appearing during machining and
subsequent use. The solid surface experiences the effects
of various factors that can be classified into
manufacturing, operational, and structural. These errors
in form, waviness, roughness and subroughness [10]
become much more important especially when two solid
contacts have to slide on each other while carrying
electrical current. In contacts between liquid and solid
metals, the deformation of the solid member is
negligible. Here the load bearing and the apparent area
are equal. Therefore, the utilization of a liquid metal as
an intermediate medium separating solid contact
members significantly increases the contact area
encompassing almost the whole apparent area of the
solid electrode surface. If a liquid metal wets the virgin
surface of the solid electrode, no transition resistance
occurs provided that the metals do not produce chemical
compounds. When a liquid metal moistens the oxidized
surface of the solid electrode surface, the contact
resistance is controlled by the resistance of the oxide
film, which is in the order of $10^{-9} - 10^{-7} \Omega \text{m}^2$ for thick
metal oxide films [10]. In the proposed switch, liquid
metal intermediate contact medium does not only reduce
the contact resistance and friction coefficient but also it
rather maintains them in a firm contact during motion of
the resistance profile. This is a vital feature for the
arcless motion of the resistance profile. In [11], it was
concluded that interruption of metal bridges between
contacts at the highest temperature point causes a metal
transfer from the electrode closer to the maximum
temperature of the bridge toward the other one. In such
cases the remaining stubs, usually are reintegrated into
the electrodes by surface tension. This is usually
observed in “arcless” switching contacts. Therefore, such
“bridge transfer” or “fine transfer” is considered as a
major reason of “arcless” switching instead of the “arc
transfer” in currents strong enough to cause obvious
arching. The LM intermediate contact medium
considerably facilitates the prescribed material transfer
during switching and therefore the arcless switching
would be convenient. To have a desirable form of
material transfer, LM material should have low surface
tension with the resistance profile. Therefore,
machinists and chemical countermeasures have to be
considered in material selection for each component. In
our study the intermediate liquid metal is Mercury of
99% purity. Mercury has a relatively high boiling point
of about 357 °C and high density which results in less
evaporation and less drop scattering. These properties
make this liquid metal a proper choice for intermediate
contact medium though its toxicity and environmental
effects should be considered for further development.
Mercury also does not wet the surface of the material
selected for resistance profile. A composition of 80%
Nickel and 20% Chrome is used as resistive material.
The selected resistive material has resistive temperature
coefficient of about $5 \times 10^{-5} \text{K}^{-1}$ from 20 to 1000 °C
and thermal conductivity of about 15 W/mK at 120 °C.
Its coefficient of linear expansion which has great
importance in resistance profile design is $12.5 \times 10^{-6} / \text{K}
from 20 to 1000 °C$. Its melting temperature is 1400°C
which is much larger than maximum working
temperature of the contacts.

IV. Resistance Profile of the Contacts

The resistance profile should convert the interruption
energy into heat. From the circuit point of view, the
resulted resistive voltage drop should be large enough to
limit the separating contacts voltage to an amount less
than the minimum voltage needed for arc initiation.
Meanwhile, the resistance profile should reduce the
A detailed explanation is needed here.
current (i.e. $I_{tot}$) is calculated in each small time steps and inequality 2 is established based on the exact value of the total current as a function of time. Accordingly, the small increments of $R_\Delta$ per unit length of LM tail are obtained.

IV.2. Arcless Current Commutation

A. Steady State Arcs

Separation of two current carrying contacts results in initiation of switching arcs, if the voltage difference of the separating contacts exceeds a minimum level $u_{min}$ dependent on the contact material [13]. That is:

$$\Delta u < u_{min}^{arc} \quad (3)$$

Considering the equivalent circuit of Fig. 2, the arcless commutation constraint can be expressed as:

$$I_{tot} \left( R_X \frac{R_\Delta R_{LM}}{R_\Delta - R_{LM}} \right) < u_{min}^{arc} \quad (4)$$

Therefore the maximum allowable resistance profile gradient for given values of $R_{LM}$, $I_{tot}$ and $u_{min}$ is calculated as:

$$R_\Delta < \frac{u_{min}^{arc}}{I_{tot}} \left( 1 - \frac{4R_{LM}I_{tot}}{u_{min}^{arc}} \right) \quad (5)$$

To check the switch performance in the transient recovery voltages (TRV), equivalent circuit shown in Fig. 3 should be analyzed. In normal condition all switches of Fig. 3 are closed except the load bypass switch, $K_1$. The current mainly flows through the nominal contact, $K_2$ (i.e., the conductive contact in Fig. 1). As the resistance profile is fully immersed in the LM, the resistive contact may carry a very small portion of the switch current depending on the resistance of nominal current contacts. The abnormal condition starts when the load bypass switch, $K_1$, is closed. The current suddenly increases and the moving contact starts to move in upward direction and the nominal current contact is separated (that means the switch $K_2$ is opened). Then, the current flows through the resistive contact and the contact resistance rapidly increases. Accordingly, the circuit current is reduced to a small amount which is proper for arcless discharge. Bridge transfer is known as a way to prevent the apparent arc and facilitate “arcless switching” [15]. Once the resistance profile is separating from the LM, the LM bridge diameter decreases continuously while the constriction resistance and consequently the contact voltage/temperature in the contact constriction area

![Fig. 3. Equivalent circuit of the system for TRV calculation](image-url)

Essentially the waveform of the TRV is closely depended on the system parameters but it should be considered that due to the resistance profile of the contact, the X/R ratio of the circuit would be small before the contact separation. The resistance profile is designed in such a way that the circuit current just before contacts separation is below the minimum current needed for steady arc discharge. Therefore, having no thermo-field emission, insulation of the interruption medium should just be designed considering TRV waveform. The equivalent circuit of Fig. 3 can be described by equation (6):

$$u_{Source} = L_{sc} \frac{di(t)}{dt} + (R_\Delta - R_{tot})i(t) - u_{contacts} \quad (6)$$

The resulted contacts voltage should not exceed a minimum level $u_{min}^{arc}$:

$$u_{contacts} < u_{min}^{arc} \quad (7)$$

In other words, the voltage drop across the short contact gap should be less than minimum breakdown voltage of the insulating material. This voltage is also closely depended on the contact geometry. In the present study, the geometry and insulation material are not optimized from insulation point of view. Therefore, the selected test voltage is less than the minimum breakdown strength of air according to Paschen’s law [14].

B. Arc Modes of Short Length and Duration and Thermal Considerations

There are also a number of further arc modes which appear in extremely short gaps which are not stable [15]. These arc modes require minimum current and voltage values much lower than those of the steady arc discharge. Low current break arcs may pass some of these transient modes and they may lead to the steady arc. Bridge transfer is known as a way to prevent the apparent arc and facilitate “arcless switching” [15]. Once the resistance profile is separating from the LM, the LM bridge diameter decreases continuously while the constriction resistance and consequently the contact voltage/temperature in the contact constriction area
increase. The LM bridge prevents contact separation due to the surface tension. As the temperature inside the LM bridge increases, both viscosity and surface tension of the LM decrease. The bridge forms a catenoid. Before breakup, some small droplets may be separated from the LM bridge. Then it becomes weak and breaks at a contact distance of about 0.1mm. In the conventional switch contacts, directly after contact separation, evaporation of contact material is the main source of charged particles. Cathodes made from nonrefractory materials with a low boiling point, such as copper and mercury, experience significant material evaporation. These materials emit electrons at temperatures too low for thermionic emission and the emission of electrons is due to electric field emission [16]. In the proposed structure, the metal transfer in the switching contacts is not significantly affected by temperature (unlike to what happens in the molten metal bridge in normal solid contacts). However, the temperature of the LM bridge in the proposed structure indirectly influences the contingent arc phenomena following contact separation. Hence, the LM bridge temperature is of great importance. The temperature rise of the LM bridge can be overestimated. The heat loss energy in the LM bridge can be expressed as:

$$Q_{\text{Bridge heat loss}} = \int_{0}^{T_f} R_{\text{LM}} \left( I' \right)^2 \left( \dot{I} \right) dt$$

The time interval $T_0$ is selected from the moment which resistance profile is pulled out from the LM bulk and the LM bridge is formed till the breakup moment of the bridge which is depended on the motion velocity. To overestimate the LM bridge temperature rise, it is assumed that maximum switching current flows through the LM bridge when the formed catenoid has the minimum possible inner diameter considering the LM properties. In [17] the relationship between radius and length of dark contact bridge (in contrast with luminous bridge) is well elaborated. A similar approach is used to estimate the length and diameter of the bridge born from the specific a-spot which survived as a last one among multiple a-spots. The geometry is modeled in the FEM solver and the maximum LM bridge resistance just before breakup ($R_{\text{LM,\text{breakup}}}$) is calculated. Accordingly the maximum heat loss energy is calculated. Then, assuming adiabatic condition, the final temperature of the LM bridge is estimated with the following equation [18]:

$$T_f = \frac{Q_{\text{Bridge heat loss}}}{m_{\text{LM,\text{in}}} C_{\text{LM}}}$$

$T_i$ is in fact the temperature of the LM just before LM bridge formation which should be adopted considering the fact that before LM bridge formation and break up, the LM and its surrounding coolant medium (i.e. insulating fluid) have been heated up due to the heat losses in the resistance profile. Neglecting the heat losses in the metallic vessel, the total heat dissipated in the interruption chamber can be expressed as:

$$Q_{\text{Resistive heat loss}} = \int_{0}^{T_f} R_{\text{Resistance Profile}} \left( I' \right)^2 \left( \dot{I} \right) dt$$

$T$ is the total current commutation time interval. It starts from the moment that current is transferred to the resistance profile and ends when the current reaches zero. The left side integral of equation 10 is easily calculated considering the resistance profile increments and motion velocity. Assuming interruption chamber as an adiabatic system, the temperature change in the two phase mixture of LM and insulating fluid (IF) can be expressed as:

$$Q_{\text{Resistive heat loss}} = m_{\text{IF}} C_{\text{IF}} \Delta T + m_{\text{LM}} C_{\text{LM}} \Delta T$$

where $\Delta T$ is the maximum temperature rise of the interruption chamber during resistance profile motion and before LM bridge formation (e.g., with respect to ambient temperature). It should be noted that in the present study, it is not intended to optimize the resistance profile and LM vessel dimension. In the experimental results, it will be explained that there is a considerable margin in the thermal design of the switch. However, more precise thermal analysis may be needed to optimize the switch dimension.

V. Drive Mechanism

If an externally triggered operation is intended, the proposed contact system can be developed to an arceless switch by any fast and powerful drive mechanism which fulfills the minimum required speed (in our case it is about 2m/s). As the moving contact is heated up during current interruption, the speed of drive mechanism plays a critical role in the switch operation. For a system with current limiter, the limiting action should be taken before actuation of other protective devices. In the present study, the current limiting action is a subsidiary goal which is needed in the proposed structure for arceless switching. For inherently triggered operation, the critical aspect is to pull out the resistance profile and transfer the current to the resistive path by means of built in energy of the system during abnormal condition. The resistance profile is implemented in an aerodynamic geometry to reduce the opponent shear force. To demonstrate the proposed principle, high speed electromagnetic repulsion and permanent magnet spring (PMS) structure [9] are used for switch operation. But the method has to be modified in respect of the driving force and speed due to the different requirements. In inherently operated switch, the repulsion coils are fed by the switch current and are
design in such a way that once the current exceeds its threshold value, the resistance profile starts to move upward. Accordingly the normal contacts are separated and the current is transferred to the current limiting/interrupting system including the LM vessel and the resistance profile. Hence, while the resistance profile is in upward motion, the current flowing in the repulsion coils and the driving force are decreased. Meanwhile, the opponent force is also decreased as the resistance profile is pulled out from the LM bulk. In comparison with PMS used for the vacuum circuit breakers [9], less retaining force is needed for close status of the switch as the LM contact resistance is small enough needless to considerable pressure load on the contacts. Actually, the contact weight is adequate force to keep contacts closed despite the electromagnetic repulsion that occurs between the contacts at relatively high current. In contrast, due to the decreasing current and driving force, the PMS should provide more force during contacts separation. This is provided through a fixed U shaped permanent magnet and a cubic armature at the end of moving contact. Based on the specified threshold current, the resistance profile geometry, moving contact weight and motion profile the repulsion coils are designed in such a way that the resulted repulsion force prevails over the opponent forces and would throw the moving contact into the affected area of PMS. The repulsion force between two coaxial coils can be expressed as [19]:

\[
F_{12} = a_{11} I_1 I_2 \frac{3 \mu_0 N_1 N_2 b_1 b_2 d}{2 \left(d^2 - b_2^2 \right)^{3/2}}
\]  

(12)

Equation (12) is only used as a preliminary estimation. Once the main structure is designed, the motion time interval is broken to small time steps and in each step the geometry is modeled in the FEM solver. The model includes the coils of the electromagnetic repulsion mechanism and neglects eddy currents in the conductive parts. It calculates the force based on the current obtained from the analysis of the circuit in corresponding time step (i.e., depended on the position of the resistance profile). In each step, the force calculated in the electromagnetic transient FEM solver is assumed as an external body force for the moving contact. The calculated force is used in the simplified form of motion equation.

The procedure is similar to the method used in [20] for motion analysis but as the resistance profile is partly immersed in the LM and partly in the insulating fluid, the friction coefficient introduced in [20] and [8] may have an error in the velocity dependent opponent force [8] which essentially has a minor effect in the speed and the force profile. The possible error can easily be compensated by adjusting \( N_1 \).

VI. Experimental Study

To demonstrate the proposed principle for arcless switching, a switch is designed and made according to the described method. The prototype is designed to automatically interrupt 90A DC current without arc. From the preliminary experiments it was revealed that the LM tail in the geometry shown in Fig. 2 has a length of about 1.5mm when the moving contact speed lies between 1.6-2.3m/s. The contact resistance between copper part of the moving contact and the LM bulk in steady condition was not measurable. While the copper part of the moving contact is being pulled out from the LM bulk the measured resistance is of about 11 mΩ. This resistance is calculated through loss calculation where the losses of the various parts were not separable. The resistance profile is designed based on the constraints described in (2) to (7). Based on the results of [8], the LM tail resistance is about 6 mΩ. The maximum voltage \( u_{\text{max}} \) over the LM tail, at which no thermal overstress occurs, is in the range of 2 to 3V and \( u_{\text{min}} \) for the LM contact is of about 13V. Among these ranges, the most stringent assumptions are taken to design the resistance profile. The total resistance of the moving contact is 10.3 Ω at room temperature which fulfills the gradient imposed by equations (2) and (5). One important aspect in the design of resistance profile is the length of the profile which should not be larger than some centimeters due to the limitations of drive speed. This resistance is implemented in 5 centimeter length spiral structure and is pulled out by an average speed of 2m/s. Care should be taken regarding the permitted surface loading (W/cm²) of the resistive materials and their possible chemical reactions. The contact materials have been tested from wetability point of view. The contact angle of 1mm diameter LM droplets on the resistor material is greater than 150 degree. Possible chemical reactions, especially in high temperatures, have also been studied. It was observed that no chemical reaction occurs between the LM and resistance profile when the average temperature of the interruption chamber is 175 °C. The resistance profile carries current only in abnormal condition when the switch current exceeds the predetermined threshold value. The nominal switch DC current is 21.5 A. The test circuit used in the experiments is same as Fig. 3. A 15 V DC voltage source (i.e., greater than \( u_{\text{min}} \)) and its parallel capacitor bank provide currents with amplitudes up to about 100A peak. The total circuit series inductance is of about 1mH to 5mH, which results in current waveforms with different rise-times. Fig. 4 shows the switch current and voltage for a short circuit test performed by closure of load bypass switch across the load in Fig. 3. As it can be seen at \( t = 12 \) ms the load is bypassed by switch \( K_1 \) and the current suddenly jumps from 12A to 89A. Due to low circuit resistance, the parallel capacitor bank of the voltage source starts to discharge much faster. At \( t = 25 \) ms, while the switch current is of about 30A, the conductive contact is
completely separated from the LM bulk ($K_2$ is opened), at this time a step-like increase of the resistance occurs, it must be noted that the voltage step has to be kept under $u_{\text{max}}$. The current commutates to the resistance profile and continuously decreases. This current commutation results in a considerable current reduction and switch voltage increase. Figure 5 shows the quantities of Fig. 4 with smaller Time/Div. In this figure, it is illustrated that at $t = 32\text{ms}$, the current reaches below the amount allowable for arcless current interruption. At this moment the resistance profile separates from the LM bulk and the last formed LM bridge is broken ($K_3$ is opened).

It must be noted that this experiment is done just to investigate the proposed principle. Therefore to make it applicable in a real power circuits, the interaction of other system equipment and circuit parameters on the current waveform and resistance profile should be considered.

VII. Thermal Conditions and Hot Spot Motion

Equation (11) is used to overestimate the temperature rise of the contacts, it is assumed that the dissipated resistive heat loss is only expended to heat up the LM mass ($m_{\text{LM}}$). This would result in a temperature rise greater than real situation. It is revealed that even with the most pessimistic assumptions, i.e. the minimum drive speed and LM mass, the temperature rise of the interruption chamber would not be more than 23 °C. Furthermore, the specific heat of the LM, $C_{\text{LM}}$, is estimated through the method given in [21]. With most stringent assumptions for equation (9), the temperature rise of the LM bridge within the acceptable range of switch currents would not exceed 17.5 °C. It is notable that the contribution of the thermal conduction would result in even less temperature rises. Therefore, if the initial temperature of the interruption chamber is less than some 160 °C the LM bridge temperature would not reach the boiling point of the LM at atmospheric pressure. Hence, no metal vapor would be presented after contact separation. Therefore thermal-field emission of electrons would not be initiated.

To have an exact estimation of $R_{\text{LM}}$ and its dissipated heat power, the current density distribution in the last LM bridge formed between LM bulk and resistance profile is simulated in the FEM solver (i.e., the most difficult condition for thermal overstressing). Considering the method described in [17], the worst possible LM bridge geometry is determined and the excitations are extracted from circuit analysis. The LM tail geometry is meshed with elements with length smaller than 0.03mm. The analysis is performed with 20 passes and the error is limited to 1%. Figure 6 shows current density distribution at the endmost moment of current interruption.

![Fig. 5. Time zoom in the recorded switch current and voltage](image)

Fig. 5. Time zoom in the recorded switch current and voltage
The resistance is calculated considering the total heat loss power evaluated in the concerned part and the excitations currents given as input to the solver. In the sample switch the total heat loss power calculated for the last LM bridge is less than 2.6 mW for 1A of the flowing current.

Due to the magnetic field of repulsion coils which is perpendicular to the current density vectors in the LM, a tangential circular force is exerted on the LM bulk surrounding the immersed contact. Figure 7 shows the force directions obtained from the interaction of the magnetic field and current density vectors in the FEM solver in magnetostatic simulation.

This spiral motion of LM around the immersed contact causes hot spots motion and reduces the LM temperature rise around the hot resistive contact during normal operation of the switch. It is notable that as it was intended to operate the switch at relatively high current, the turn number of the fixed repulsion coil has been reduced to prevent unwanted actuation at low nominal currents. The tangential force could be stronger if more magneto motive force would be provided.

A. Stability in Transient Conditions

The designed structure is modeled in the FEM solver in 2ms time steps. In each position the force is calculated and used in the motion equation [20] to obtain the next position. From the stability point of view the steady state position of the moving contact including the resistance profile and moving repulsion coil is of utmost importance as any transient current would cause a force which may lead to a small vertical motion of the immersed part.

In the sample switch the immersed contact has 8mm free conductive part between the resistance profile (which is located under the LM level) and the moving repulsion coil (which is located above the LM level). This free conductive area stabilizes the switch in the system transients. To evaluate the switch behavior in the system transient, the ratio of the Lorentz force to the quadratic of current amplitude is calculated in first 3 time steps of the motion. The average of the mentioned ratios is used as a proportionality coefficient \( K_{Device} \) between the Lorentz force \( F_{Lorentz} \) and square of the current:

\[
F_{Lorentz} = K_{Device} I^2
\]  

This formula along with the motion equation is used to obtain the moving contact vibration amplitude versus the normalized transient current amplitude. Maximum vertical displacement of the immersed contact with respect to the equilibrium position is shown in Fig. 9. Time duration of the current transient is used as a parameter.
The effect of buoyancy force of the LM on the immersed contact has not been taken into account in this stability analysis. It should be noted that vibration amplitude larger than 8mm (free conductive length) would cause a current limiting effect since such amount of vertical motion would bring a portion of the resistance profile above the LM level. Study of these types of vibrations should take the effect of the system interaction and parameters into account.

VIII. Replacement of the Anode and Cathode

As the experiments performed with DC current, in a quite similar test the assignment of the LM vessel (the fixed contact) and the resistance profile (moving contact) to the cathode was replaced and no significant difference was observed in the results. Since the current amplitude was the main concern of arcless switching in this study, this is not far from the expectation as there was no arc and its subsequent free ions in the interruption medium. But the matter should be studied when higher voltage level is required.

IX. Conclusion

This paper presents a method for controlled arcless current interruption. The working principle of the proposed switch is based on the motion of a resistance profile inside the liquid metal medium under the influence of Lorentz force. The phenomena relating to the arcless current interruption have been investigated and the relevant theoretical constraints have been derived and the thermal considerations of the contact separation have been studied. A high speed inherently operated drive system has been designed for the switch and the driving force was simply regulated through correction of coils turn numbers. Then a switch has been made to study the proposed method. The experimental results indicate that no arc occurs during current interruptions. The switch takes the advantage of the controllable arcless operation without external triggering. Moreover due to the liquid metal intermediate medium between the contacts, some usual problems of conventional switches like surface degradation of contacts can be avoided. At the end some features of the switch like stability in the transients and hot spot motion have been discussed. As the drive mechanism of the sample prototype is not fast enough, the switch did not show a perfect independent current limiting characteristic for practical application. Due to the motion of heated resistance profile in the LM vessel, there is always the risk of LM vaporization though in our experiments it was not detectable. For higher voltage applications, a profound study should be performed to optimize the contact and LM vessel geometry to prevent insulation breakdown after separation.

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References

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