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# A Novel Method for High Current Vacuum Arc Interruption Using Externally Applied Ultra High Axial Pulsed Magnetic Field

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Axial Magnetic Field (AMF) is widely used in vacuum interrupters to keep the arc in the diffused mode. With increasing axial magnetic field, the multiple arc mode extends to higher arc currents. In this mode of arc, the fault current can be easily interrupted due to fast recovery of the diffused vacuum arc. The magnetic field amplitudes considered in the preceding studies are all less than hundreds of mT. In this paper, the interaction of the vacuum arcs with much more intense magnetic fields of several T are considered. For this purpose, the MHD equations describing the behavior of the high current vacuum arc are simulated in presence of a very intense pulsed magnetic field that is generated by a high current pulsed power source (Cascaded Flux Compression Generators), and imposed to the interruption chamber externally. It can be possible by using a current carrying inductor, which firmly surrounds the chamber. This helical inductor is placed as FCG load. The results indicate that FCG can multiply the seed current, i.e., fault current (150-kA) up to 1-MA and consequently generate magnetic flux density in order of 10 T interior of the chamber. According to the simulation results, in such a magnetic flux density, the high current vacuum arc (150-kA) can remain in diffused mode; this method can be applied to improve the interruption capability of vacuum interrupters.

Keywords: Axial magnetic field, magnetic flux compression, pulsed power, current interruption in vacuum.

## 1. Introduction

Main engineering applications of high-current vacuum arcs (VA) are linked to their use in the vacuum switchgear. Therefore, the most studies on high current VA are in the parameter range specified by the tasks to be accomplished by switching apparatus. The most promising for vacuum interrupters (VIs) seems to be the use of arcs, stabilized by an axial magnetic field (AMF) [1,2]. The studies of high current VA in AMF are far advanced and underlie the creation of VI with high performance [1-3]. In recent years there has been an increased interest in the use of VIs for high voltages [3, 4], and also for high currents [1, 5]. For instance, a 168 kV two break porcelain type and a100 kA one break vacuum switchgear have already appeared in the Japanese market and they are currently being exported to world-wide markets [4].

For the quantitative prediction of the plasma status in high current VA, a multiphysics approach has been applied in this paper. Three qualifications have been checked for high current VA interruption using a finite element simulation: the electron and ion concentration in the VA, electron temperature and the arc voltage. This model assumes that an external ultra high AMF –in order of several Teslas- has been applied to the interruption chamber in a pulsed regime.

The magnetic field amplitudes which have been considered in the preceding studies are all less than hundreds of mT. The strongest AMF which is considered for high current VA control has been reported by Chaly *et al.* [1] is about 1.2 T which has studies only the dependence of arc voltage on the applied $B_{\mathrm{AMF}}$ strength. The main inhibitor to the application of the higher AMF to the VI is the huge dimension of the capacitor sets which produce AMF. This paper deals with up to 17-T strong AMFs. Such an intense magnetic field can be produced using huge capacitor-inductor sets which are not appropriate for current interruption purposes. This paper has proposed a novel approach in which a cascaded Flux Compression Generators (FCG) [6] has been applied to produce AMF inside the chamber with lower price, weight and volume [7]. For this purpose, the ultra high magnetic filed in a pulsed regime (generated by the FCG [6]) has been entered to the model in a time-dependent procedure.

Descriptions and results of the proposed method and detailed numerical simulations have been presented in sections 2, and 3 respectively. Major conclusion follows the results is that the method of high current VA control by pulsed axial magnetic fields is applicable and effective, which keeps high current VAs up to 200 kA in diffused mode.

## 2. Proposed System

Figure 1 illustrates the mechanism of generating ultra high magnetic flux density interior of the interruption chamber. One of the most advantages of the

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method is that no seed sources like, charged capacitors is needed. The fault current which passes the VA is adequate for flowing primary current through the FCG. For separating the circuit of FCG from power circuit, two high current transformers have been used. An example of a readily available tightly coupled transformers is current transformers (CT) used by utilities to measure large AC currents [8]. Such a transformer is normally operated with a short circuit in place with a large turns-ratio for utility applications. In the circuit of Fig.1, current multiplication of CTs is not required and turns-ratio can be chosen as 1. The main duty of these CTs is segregation of circuits. Also for preventing CT cores from saturation, segmented core transformers can be used instead of ordinary CT cores without any air gaps. The output current of CTs, is multiplied by a cascaded helical FCG [7] and applied to the surrounding winding of interruption chamber. Investigation of FCG behavior with such a highly inductive load has been performed by a finite element solution in which the action of FCG is modeled in a simultaneous 3-D thermodynamic and electromagnetic method [6,9]. For the cascaded FCG of [7] and winding with3-turns, 14-cm cross-section diameter and 4-cm altitude as the FCG load, the current reaches 8-T for more than 15-milli seconds. Further, numerical simulations are performed for physical behavior and heat flux to the anode of high-current diffuse of arcs as found in vacuum interrupters. The magnetohydrodynamic (MHD) approach is applied. Heat flux densities to the anode are predicted in the right order of magnitude and essential physical details of the high-current vacuum arc (in order of 100-kA) are disclosed in the presence of strong pulsed AMF which is created by surrounding winding of interruption chamber.

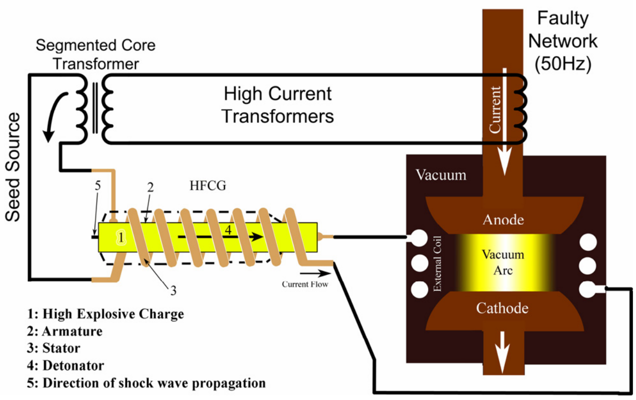


Fig.1 The mechanism of generation of the AMF: Seed current of the cascaded helical FCG is provided from power distribution system by means of high current segmented core current transformer. This FCG multiplies this current and injects it into the external coil to generate the intense pulsed AMF interior the interruption process.

## 3. Plasma model description

In this section, the mathematical formulation of the plasma expansion phenomena and current flow in the individual jets and the common current channel has been presented. In the inter-electrode plasma region, where the jets from the individual cathode spots in the case of the multi-cathode-spot VA are averaged and therefore all plasma parameters will be assumed to be uniform [5]. The high-current diffuse arc mode is imbedded by the multiple arcs at lower currents, by diffuse columnar arcs at higher currents and by columnar arcs at high current and low or no AMF [5, 9]. The arc plasma can be regarded as a fluid that flows from cathode to anode [9-11]. A 2-D cylindrical hybrid model has been developed in order to better predict the VI behavior in the presence of intense AMF. This hybrid model consists of (1): mass and (2): momentum conservation equations for electron, ion, (3): The heat balance equations that determine the temperatures of ions and electrons, and (4) detailed Maxwell equation

Plasma behavior and heat flux density to the anode are predicted for steady-state conditions, which approximate well those during arcing with sinusoidal 50-Hz currents (ac). This is because the time scales of relaxation are much faster than parameter variations (e.g., variations of current or contact distance).

$$\frac{\partial n_i}{\partial t} + \vec{\nabla} \cdot (\vec{u}_i \cdot n_i) = 0 \tag{1}$$

$$m_\alpha n_\alpha \left[ \frac{\partial \vec{u}_\alpha}{\partial t} + (\vec{u}_\alpha . \vec{\nabla}) \vec{u}_\alpha \right] = q_\alpha n_\alpha (\vec{E} + \vec{u}_\alpha \times \vec{B}) - \vec{\nabla} P - m_\alpha n_\alpha \gamma_m \vec{u}_\alpha \tag{2}$$

$$\frac{3}{2} n_\alpha \left[ \frac{\partial T_\alpha}{\partial t} + \vec{v}_{\alpha.z} \frac{\partial T_\alpha}{\partial z} + \vec{v}_{\alpha.r} \frac{T_\alpha}{\partial r} \right] + n_\alpha T_\alpha (\vec{\nabla} \cdot \vec{v}_\alpha) + \vec{\nabla} \cdot Q = \frac{m_e}{m} \frac{n_e}{\tau_{ei}} (T_e - T_i) \tag{3}$$

$$\vec{\nabla} \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}, \quad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \quad \vec{\nabla} \cdot \vec{D} = \rho, \quad \vec{\nabla} \times \vec{E} = 0 \tag{4}$$

where, symbol $\alpha$ represents electron, ions and non-charged particles indexes separately ($e$, $i$ indicate electron and ions indexes respectively). Other parameters can be defined as follows:

| | |
|---|---|
| $n$ | particle density; |
| $u$ | particle drift velocity; |
| $T$ | particle temperature; |
| $j$ | arc current density; |
| $Q$ | particle thermal flux; |
| $\sigma$ | conductivity; |
| $P$ | pressure; |
| $\Delta T$ | temperature differences between particle types |
| $\gamma$ | Braginskii coefficients; |
| B | magnetic field; |
| E | electric field, |
| $\rho$ | volume charge density; |
| $m$ | particle mass; |

As boundary conditions, the model assumes no further function of cathode and anode other than to host the cathode spots and to be a perfect sink, respectively [5]. Figure 2 shows simply the sketch of the VI geometry and model of the VA plasma expansion.

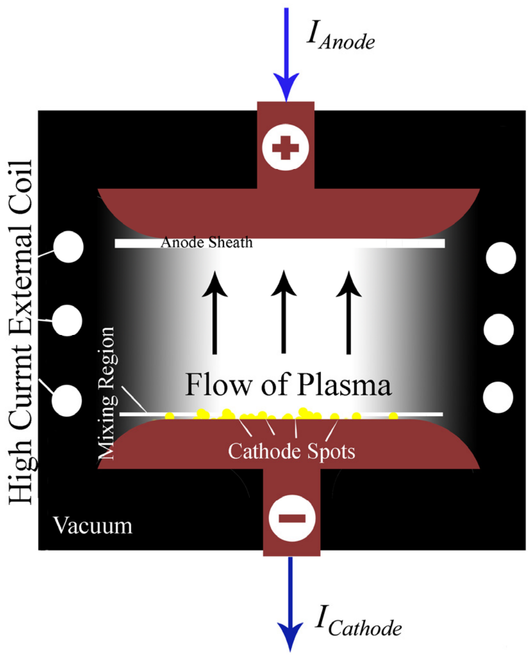


Fig.2: Sketch of the vacuum arc geometry and model of the vacuum arc plasma expansion.

## 4. Numerical simulations results

Figures 3, 4, 5 and 6 show simulation results for a 150-kA current which is to be interrupted. The effect of pulsed AMF has been investigated by applying the wave form of Fig.3 which is calculated in a separate simulation of FCG [6]. Fig.3 shows the time variations of pulsed AMF at the center of the interruption chamber. It can be seen in this figure that AFM remains higher than 8-T for more than 8-ms after detonation of the FCG. The distribution of $B_{AMF}$ has been calculated in the interruption chamber considering effect of induced current in electrodes and in plasma. Figure 4 demonstrates the distribution of magnetic field inside the chamber and in both electrodes in different time steps. After several micro seconds after detonation of FCG, the induction currents in the contacts prevent from rising of the magnetic flux density inside the inter-electrode area [Fig. 4, part (a)], however after elapsing several milliseconds, when the initial induction currents have diminished, intense magnetic flux density comes into the inter-electrode space where high current vacuum arc has been appeared at this period [Fig. 4, part (b)]. Inevitable resistive characteristics of the AMF coil (load of the FCG) results in an exponential decrease in its current and the generated AMF consequently. There is a bilateral relationship between plasma simulations (Eq. (1-3)) and electromagnet field calculations (Eq. 4). It can be inferred from Fig. 4 that the conductivity of plasma has a minor effect on the $B_{AMF}$ distribution. It is because of the electrical conductivity of VA is approximately one order of magnitude lower than copper (substance of the electrodes). The time varying distribution of $B_{AMF}$ has been entered to the plasma simulations in each time step of solution. Figure 5 lets the simulation results for proposed system and a conventional VI to be compared. According to distribution of electron and ion density in these figures, which have been expressed as mol/m$^3$, it is reasonable to think that the applied $B_{AMF}$ in the proposed system could diffuse the vacuum arc. Another result of the simulation, i.e., electron temperature in these cases, supports this idea. Based on Fig. 6, which shows the distribution of electron temperature in cases of conventional and proposed VI, at the time when each of them each of them reaches the peak of the electron temperature. As it can be seen from this figure, in the conventional VI, for a 150-kA arc, the electron reaches 8.41-eV, which is higher than the threshold [12] of diffused arc. This parameter for the proposed system, about 6.3-eV, is lower than critical range. The shape of this weak AMF distribution has been entered from an "AMF contact" generated field [12].

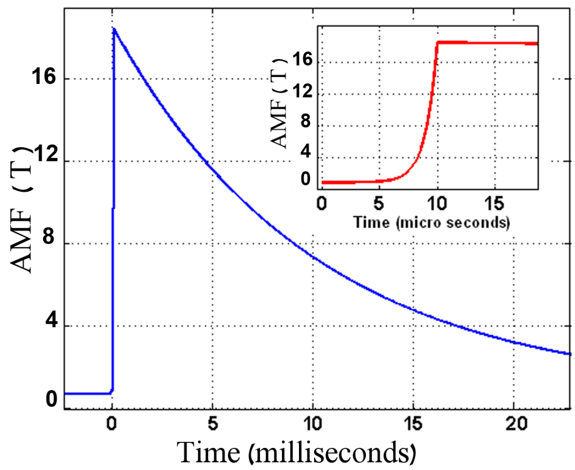


Fig.3: Variation of the pulsed AMF at the center of the interruption chamber in terms of time.

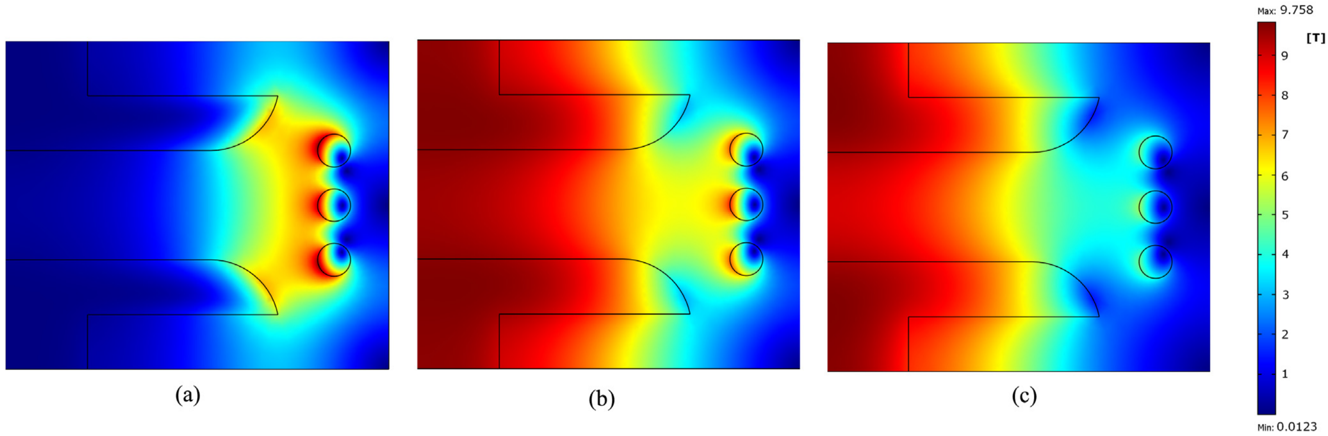


Fig. 4: Time variations of magnetic flux density interior of the vacuum interruption chamber, (a): 5μs, (b): 5ms, (c): 10ms after detonation of the HFCG.

It can be deduced from reduction of electron and ion concentration from 4, and 3 mol/m$^3$ into 1.2 and 1 mol/m$^3$ respectively that in the proposed system, the VA remain diffused. Also the comparison of the VA voltage indicates the transition of VA state from diffused into columnar VA [3].

Figure 7 shows the variations of arc voltage in terms of $B_{AMF}$ strength. It should be noted this figure demonstrates the peak value of the voltage. In the range $B_{AMF}$ is lower than 5-T at highest value in the pulsed shape (Fig. 3), the arc voltage shows some sporadic oscillations (one of the constricted arc signs), however, these fluctuations have been removed by increasing the $B_{AMF}$ peak. Furthermore, for $B_{AMF}$ peaks higher than 10-T, arc voltage shows negligible ripple which is another sign of diffused mode of the arc. In this study, all the applied $B_{AMF}$s assumed to be similar in the shape with Fig. 3 and only differ in magnetic flux density amplitude.

The qualitative reasons of voltage and concentration lowering of the vacuum plasma by increasing of $B_{AMF}$ can be explained by the concept of expanding cathode spot plasma jets. The inter-electrode plasma is generated by a number of cathode spots at the cathode surface, as shown qualitatively in Fig.8. In this figure, upper electrode is cathode, and the other one is anode. Each individual cathode spot produces an individual current channel. Due to its internal pressure gradient, each plasma jet expands radially [11]. Because of the radial expansion, the jets mix at some axial distance and form a common current channel in which concentration of particles are increases [2]. This common channel can lead to diffuse-columnar arc and even columnar VA in some extreme cases at low $B_{AMF}$. Two parameters control the state of the overlapped plasma jets. First is the gap distance, and the second is the strength of $B_{AMF}$. Longer gap distance let the jets have more room to overlap and produce columnar arc. The stronger AMF pinches plasma jets and prevent them from mixing together and produce columnar VA consequently (Fig. 8).

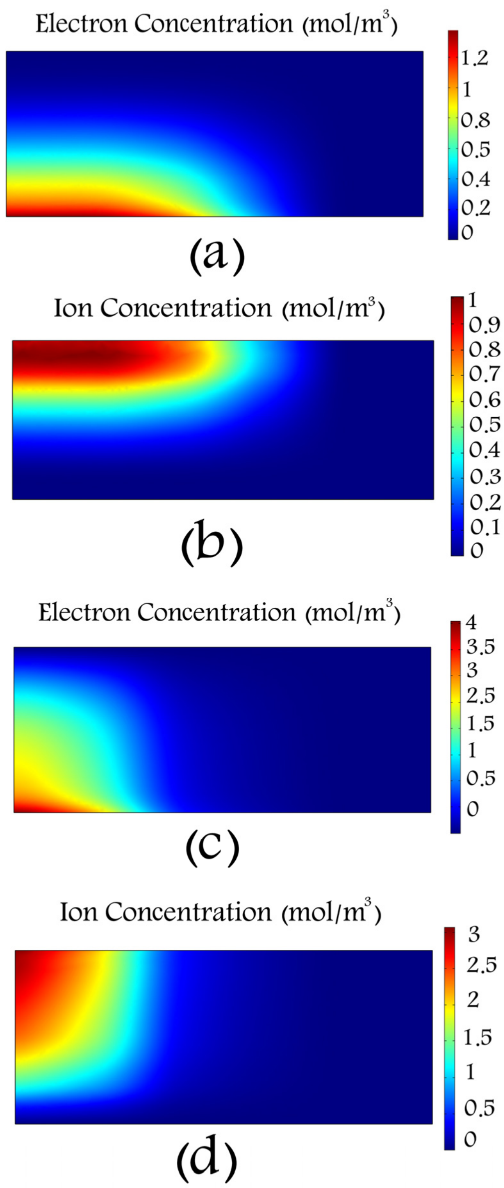


Fig.5: Simulation results for VA in the presence of AMF, (a): electron concentration for pulsed AMF: 12 T, (b) Ion concentration for pulsed AMF: 12 T, (c): electron concentration for AMF: 0.35 T, (d) Ion concentration for AMF: 0.35 T.

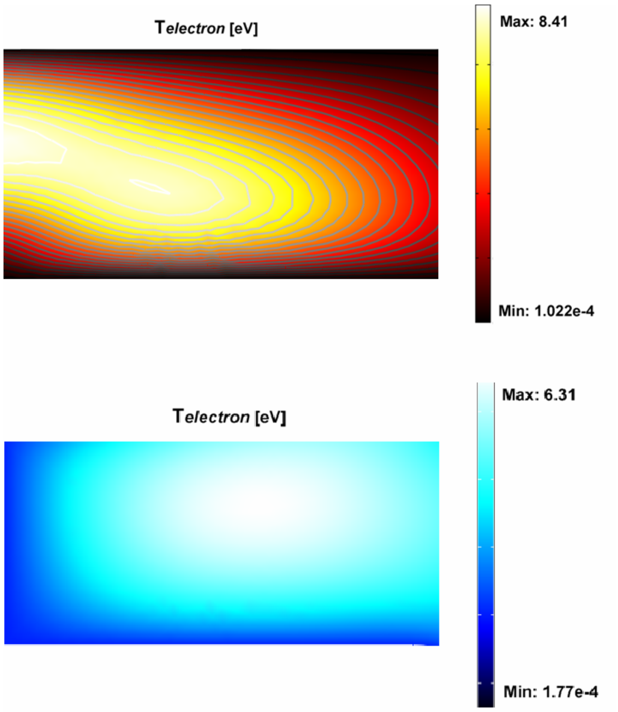


Fig.6: Temperature of the electron in (Top): for conventional AMF: (bottom): for the proposed system.

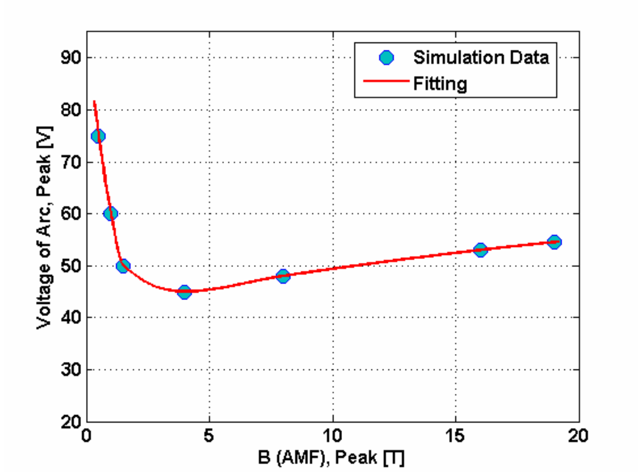


Fig.7: Dependence of voltage amplitude of the arc voltage (peak) on the strength of $B_{AMF}$

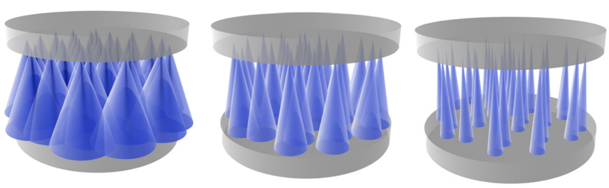

Fig.8: Schematic view of expanding plasma jets in terms of AMF strength. (Left): Weak or no AMF: constricted arc. (Middle): Strong AMF: diffused arc, (Right): Very strong AMF: multiple vacuum arc.

## 5. Conclusion

The study of high current vacuum arc, stabilized by the intense pulsed AMF, have revealed the capability of controlling vacuum arc efficiently and allowed developing the principles of construction of optimal AMF. The effectiveness of using pulsed ultra high AMF has been investigated in this paper by modeling MHD equations of vacuum arc. The results indicate that the application of FCG for producing intense magnetic field inside the interruption chamber can be a promising tool for high current interruption. The simulation results strongly need future experimental validation.

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