Numerical Simulation of an Explosively Driven HVDC Circuit Breaker

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(Received: 2 September 2008 / Accepted: 9 February 2009)

High Voltage Direct Current (HVDC) circuit breakers have to suppress high values of currents at high voltages in absence of current-zero points. This makes the arc interruption more severe than the case of conventional AC networks. For circuit breaking in HVDC networks, a capacitor-inductor set has been inserted in parallel with the circuit breaker to inject reverse current to the interruption chamber and create the artificial current-zero points. In this paper, a novel method for reverse current injection has been proposed in which a high current pulsed power source (Helical Flux Compression Generator) has been employed to generate the opposing current. Numerical simulation of high-current arc in case of HVDC circuit breakers has been presented. For this purpose, the MHD equations describing the behavior of the DC arcs are jointed to the circuit equations of Flux Compression Generator which is coupled to a simple HVDC network. The results indicate that the explosively driven current injection set can make the current-zero point properly and lead to successful interruption of DC current consequently. This method needs much less volume and cost in comparison with the parallel capacitor-inductor sets.

Keywords: High Voltage Direct Current, magnetic flux compression, current interruption in vacuum.

1. Introduction

The Vacuum Interrupter (VI) without external support is really an AC current switching device. Where there is cyclically occurring current zeros at which interruption of current can be effected, the VI has a well-proven capability to reliably interrupt that current and to withstand the resulting Transient Recovery Voltage (TRV) [1]. In saying this, VIs have been used for many years to switch low dc currents (~10 A) in circuits with a system voltage of a few kV [1,2]. These VIs use the instability phenomenon of low-current vacuum arcs (VAs). Here it can be seen that a 10 A arc between W contacts would self-extinguish in about 1 ms. Once this arc goes out, the contact gap will be able to withstand recovery voltages up to tens of kilovolts [1,2].

In order to switch high currents in High Voltage DC circuits (HVDC), it is necessary to create an artificial current zero to allow the VI to extinguish the VA and to withstand the TRV. Greenwood *et al.* [3,4] demonstrated the first successful use of a VI to switch these DC currents. They created a current zero in the VI by injecting an opposing current from a parallel pre-charged capacitor (series capacitor-inductor set). When the DC current has to be interrupted, the VI opens and the VA is established. Once the contacts reach their fully open position, a switch in series with capacitor is closed, which initiates a high-frequency counter current through the inductor and VI [4,5].

Yet another application for DC current interruption has emerged since 70s; this is for a switching device to interrupt the current in the Ohmic-heating coils of Tokomaks and similar fusion machines. This is an exacting application, since it requires frequent switching operations of high DC current and the circuit is highly inductive. VI is a proper choice for these two requirements [1,2]. The current counter-pulse scheme [3,4] has been successfully employed for switching the DC current in the Ohmic-heating (OH) coil for fusion experiments in the United States, Europe and Japan [1].

In this paper, a method for high current interruption in HVDC networks, OH coil circuits or any other highly inductive circuit is proposed. In this method, two separate high current explosively driven pulsed power source Flux Compression Generator (FCG) [6-7] has been applied to generate the opposing current and intense Axial Magnetic Field interior of the Vacuum Interrupter (VI) which is necessary to keep the Vacuum Arc (VA) in diffused mode. The simulation results (Section 4) indicate that the explosively driven current injection set can make the current-zero point and intense Axial Magnetic Field (AMF) properly. Such current-zero points and intense AMF are essential to a successful interruption process of DC current. Application of this approach firstly needs much less volume and cost in comparison with the parallel capacitor-inductor current injection sets. Secondly, the conventional capacitor sets requires a huge capacitor bank to be kept standby charged all the time. This calls for an auxiliary energy source which increases the cost of the system and complicates the maintenance of the breaker as well. As it will be elucidated in Section.2 the proposed method uses a portion of the energy of the HVDC, or OH system as seed energy which transferred to the FCG. On the other hand, the AMF which is generated by the second FCG in this method is about one order of magnitude larger than conventional VIs. In the DC circuit breakers which are limited by the numbers of

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the current-zero points it is absolutely helpful [1,8]. Description of the system structure have been presented and discussed as well as numerical multiphysic simulation of high-current vacuum arcs and circuit equations in Sections 2, 3 respectively.

2. Proposed System

2.1. Flux Compression Generator Design

The current or energy gain of single stage helical flux compression generator (HFCG) [6] is strongly dependent on essence of the generator's load. The performance of single stage HFCGs in order to high impedance loads is poor [5,6]. Adding a transformer between generator and load seems to be the solution for the problem that single-stage HFCGs are quite inefficient if fired into a large inductive load [9]. However, an additional standard transformer will increase the system size considerably. Also such an intermediate transformer usually causes a large loss in the HFCG performance. The more successful approach is to combine two HFCG stages, the first one having a small load inductance (thus a large energy gain) and the second stage having a large final load inductance [10-12]. This second stage efficiently steps up the voltage level of the first stage. The key point in this approach is that the load of the first stage is used as the field coil for the second stage [11]. An implementation of such a system driving a high inductance load has been shown in Fig. 1.

The initial current in the field coil L_1 is established by a Primary Energy Source (PES), e.g., with discharging a pre-charged capacitor bank by closing the switch S_0.In the proposed method, the PES is supplied by the energy of flowing current of HVDC circuit itself (Section 2.2). Just before that the current of L_1 reaches its maximum, the detonator has to be fired and moving armature traps the flux established by L_1 in the space between armature and L_2. It should be noted that no direct electrical connection between L_1 and L_2 is necessary. L_3 has a small inductance (a few hundreds of nanohenries) and serves as the load for L_2 and as field coil for the second stage.

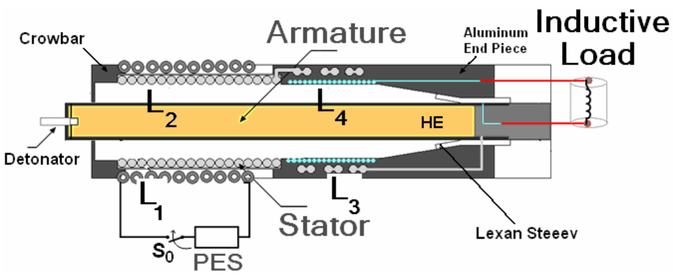

Fig.1: Cascaded HFCG connected to an inductive load; PES: Primary Energy Source; S0: Closing switch; L1: Field coil for first stage; L2: First-stage coil; L3: Primary of dynamic transformer (second stage); L4: second-stage coil (Secondary of dynamic transformer).

Again, L_4 is not directly connected to L_3 and carries no current before the armature has made contact with the first turn of L_4. The step-up ratio of the second stage between L3 and L_4 is of the order of ten. Thus, the second stage is designed to produce a voltage gain (little energy gain, e.g., 1), whereas the first stage amplifies current and energy. As a consequence, current derivative and current of the second stage of a cascaded HFCG fired into a high impedance load both of them would be high enough.

2.2. Current Interruption System

The initial DC circuit breaker designs used VIs with Transverse Magnetic Field (TMF) contacts. The variability of the VA voltage with this contact design gives a somewhat erratic performance [2,8]. The development of VIs with AMF contacts or with external AMF coils and the resulting stable VA voltage has greatly improved the reliability and performance of high-current DC interruption [1,5]. There are, however, essential criteria to take into account when using a conventional VI with an AMF. First of all, there is a time lag, which is a function of the current to be interrupted, before the fully diffused VA is established [1]. Secondly, the strength of the AMF to develop a fully diffused VA depends on the current to be interrupted [2,8]. Thirdly, too small a contact diameter for a given current will result in a constricted diffuse column, which can affect the recovery performance of the vacuum gap between the open contacts [8]. The use of AMF has insured uniform and acceptable contact erosion for as many as 1500 operations for currents of 55 kA [1]. It has also been used for high DC currents (>90 kA) where parallel VIs are used [1,8].

Figure 2 illustrates the structure of the proposed system. By multiplying the flowing current of DC circuit, an intense AMF appears interior of the interruption chamber. Such a multiplication can be performed exclusively by a cascaded helical FCG [9-11]. This method has three main advantages: firstly, instant times of applying AMF and opposing current are controllable; the HFCG can be detonated when the contacts reach their full distance from each other, and VA enters the steady state. Secondly, the strength of AMF is no longer dependent on interrupting current; it only depends on FCG properties, e.g., number of FCG helix turns, FCG volume and weight of High Explosive (HE) has been used. Thirdly, in the proposed method, the fault current which passes the VA is used to provide primary current of FCG. In other words no auxiliary seed source is required in the proposed method. Based on Fig.2, right HFCG provide the opposing current into the interruption chamber by multiplying the initial current of HVDC circuit. Keeping DC circuit breaker standby all the time is expensive in conventional approaches since the large capacitor of the system should remain charged.

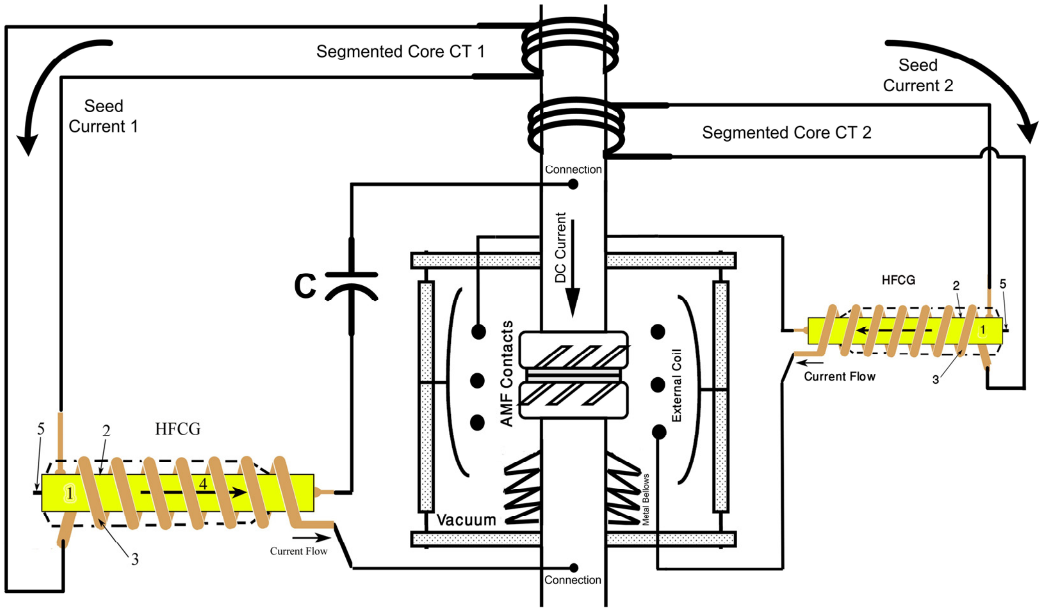

Fig.2: Schematic view of the proposed DC circuit breaker system, 1: High Explosive Charge, 2: Armature, 3: Stator, 4: Direction of shock wave propagation, 5: Detonator.

A capacitor is placed in series with FCG to limit the current of parallel branch after interruption of VI (current commutation). Here is not any obligation for capacitor to be pre-charged.

For separating the FCG circuit 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.2, 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. For preventing CT cores from saturation, segmented core transformers can be used instead of ordinary CT cores which are without any air gaps.On the other hand, the output current of CT 2, is multiplied by another cascaded helical FCG [9,10] and applied to the surrounding winding of interruption chamber (Fig. 2). External AMF is applied immediately after the VA is formed. In fact the vacuum arc formation instant and the detonation time of the FCG are simultaneous. Due to conservation of magnetic flux, the AMF sustains higher than 8-T for several milliseconds after arc formation. This time depends on the dimension of the surrounding inductor. In essence this time is related to the rime constant of inductor ($T \approx L_{ind}/R_{ind}$).

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 study [9-13]. For the cascaded FCG of [10] and 3-turns winding inductor with 14-cm cross-section diameter and 4-cm altitude, the average AMF inside the interruption chamber reaches 5-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 VIs. The magnetohydrodynamic (MHD) approach is applied.

3. Plasma model description

In this section, the mathematical formulation of the plasma expansion phenomena and current flow in 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 [1,8]. The high-current diffused 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 [1]. The arc plasma can be regarded as a fluid that flows from cathode to anode [1,8]. A 2-D cylindrical hybrid model has been developed in order to better predict the VI behavior in the presence of intense pulsed 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 dynamic state (changes in order of microseconds have taken into consideration).

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

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

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

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

where, symbol α represents electron, ions and non-charged particles indexes separately (e, i shows 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;
σ	conductivity;
P	pressure;
ΔT	temperature differences between particle types
γ	Braginskii coefficients;
B	magnetic field;
E	electric field,
ρ	volume charge density;
m	particle mass;

Figure 3 shows simply the sketch of the VI geometry and model of the VA plasma expansion.

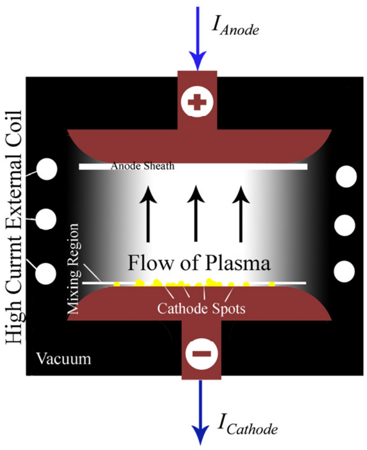

Fig.2: Sketch of the vacuum interrupter geometry and model of the vacuum arc plasma expansion.

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.

4. Simulation results and discussion

The MHD equations of vacuum plasma have been solved simultaneously with circuit equations of a simple circuit (Fig. 4).

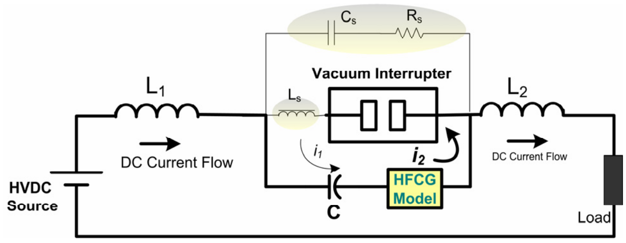

Fig.3: Schematic view of a simple DC circuit.

Simulation of the circuit of Fig. 4 has been performed a time-dependent code in MATLAB. The models of the HFCG and VA have been converted to some "black box" models to be able to import the data of finite element model of them into the circuit simulation. These black box models are, in fact, some time dependent look-up tables which construct the relationship between voltage and current of the device at any time-steps. Results have been shown in Figs. 5 and 6 as interrupting current and TRV. For this typical circuit, voltage of the source has been chosen as 250 kV DC.

One of the disadvantages of FCG driven reverse current injection is that the artificially created current zero is single, and if VI is not successful in the first current zero interruption, it will not have another chance, and another FCGs should be detonate to make other current zeros. Because of this issue, the capacitor in series with FCG should be chosen larger (order of 100 μF) to be able to generate more current zeros in oscillation with circuit and arc inductor. The capacitor C determined as 120μF for the case study which has mentioned in Fig. 4. It is obvious that a capacitor in order of 100μF which has to work in 250-kV is very large, however it should be compared with those capacitors are used in the conventional DC breakers which are at least similar to this value of capacitance [3,4], further they should be kept charged to exactly in 250-kV all the time. For such DC capacitors, the loss factor (RC) is not too high and is about several hundreds of seconds and it is the severe job to maintain them standby in comparison with manufacturing them.

Another solution is recommended in the HVDC circuit is that the contacts of VI should be of AMF contact type [1], so that after detonation of FCG which is responsible for AMF generation (right FCG in Fig.2), self arc current generated AMF could be able to keep AMF high enough for next current zeros. If the VI has no success in the first or second current zero, this modification could be vital to the current interruption process. The other point is when the current of a highly inductive circuit is changed rapidly, very high overvoltages would appear. Computer simulation results show that dI/dt before current zero and dV/dt after current zero are both very high. These results are in a good accordance with experimental records [2]. Even a VI may have difficulties in these circumstances. To overcome this issue, one can propose two solutions: 1) a saturable reactor can be placed in series with VI and 2) snubber circuit can be placed in parallel with VI to lessen the duty of the VI. Figures 5 and 6 illustrate simulation results that are modified by the presence of these components. As it can be seen from these waveforms, the effectiveness of saturable reactor is not overwhelming. Nevertheless, the role of snubber circuit is remarkable. There is a good accordance between these results and some experimental measurements [2-4] about effectiveness of the saturable reactor on one hand and capacitive snubbers on the other hand. Saturable reactors are inserted in the circuit mainly to prevent re-strikes (high frequency currents) in vacuum interrupters [1]. However in the proposed method of generating reverse current by HFCG here, these equipments will turn into saturated status and can not perform in optimal working point. For more reliable limiting of overvoltages in HVDC networks it is recommended to use some forms of surge arrestors. When switching Ohmic-heating coils in fusion machines, a portion of the overvoltages' energy finds its way into the plasma, but much more goes into a shunting resistor which is introduced to limit the voltage [1,2].

5. Conclusion

It has been proven that AMF leaves much more reliable effect on DC current interruption in vacuum interrupters. However, it has some weak points yet. Some theoretical suggestions have been proposed in this paper to use high DC current itself to generate high pulsed AMF and even to produce injecting current in reverse for creating artificial current zeros which is inevitable for DC current interruption. The method has been analyzed by solving some combined MHD and circuit equations. The simulation results were in a good agreement with previous experimental records and indicate the feasibility of applying high explosive driven pulsed power to switch high DC currents.

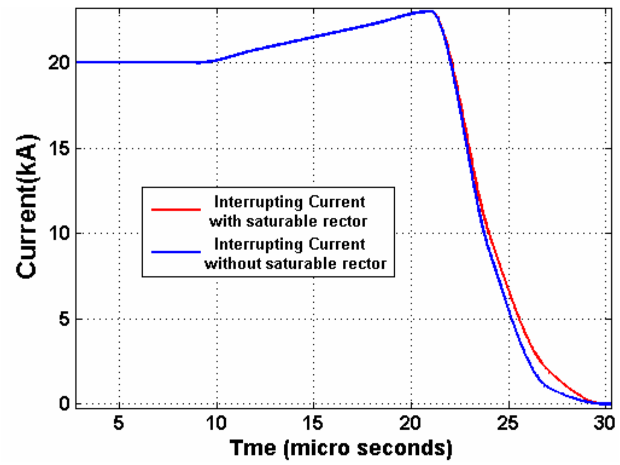

Fig.4: Interrupting current waveform for two cases: Red line: Circuit has saturable reactor, and Blue line: Circuit does not have any saturable reactor.

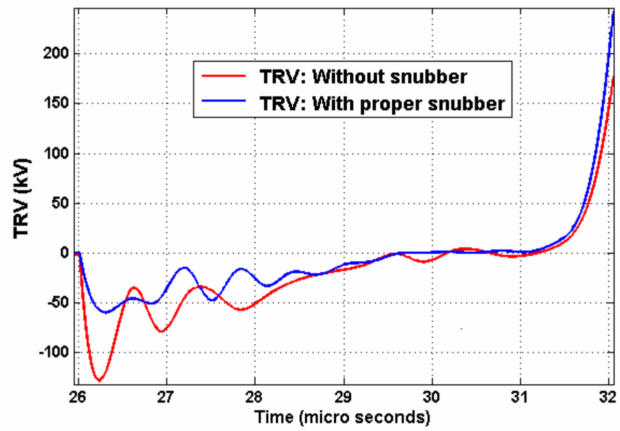

Fig.5: TRV waveform for two cases: Red line: Circuit does not have any snubber, and Blue line: Circuit has shunt snubber.

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