Investigation on DC interruption based on artificial current zero of vacuum switch

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Abstract—Direct current interruption utilizing vacuum switch based on artificial current zero is investigated. A high-speed vacuum switch, which is driven by electromagnetic repulsion force, is adopted as the main switch. The injection of high-frequency countercurrent is controlled by a triggered vacuum switch. The main experimental current is supplied by a LC circuit. The overvoltage generated during interruption is suppressed by metal oxide arrester. The interruption process is also simulated via a circuit model, with which the two important current commutation processes are analyzed, i.e., the current commutation from main switch to countercurrent branch, and the current commutation from countercurrent branch to arrester branch. Simulation results are compared with measured waveforms of voltage and current.

1. INTRODUCTION

Vacuum circuit breakers (VCBs) have been being widely used in AC power system, particularly, at medium voltage level due to distinct performance of vacuum interrupters (VIs), e.g., high breakdown voltage, fast dielectric recovery speed after current zero, low arc energy, fire safety, maintenance free, etc.

The excellent performance of VCB has also prompted substantial researches on its application in DC power system, e.g., in nuclear fusion experiments, in high-voltage DC transmission lines, and in railway DC system with relatively low voltage \cite{1-5}. The most commonly used approach of vacuum DC interruption is based on artificial current zero (ACZ) method shown in Fig. 1 schematically, in which a VCB is used as the main circuit breaker (CB\textsubscript{m}).

The basic interruption process starts from the separation of CB\textsubscript{m} followed by the formation of vacuum arc in CB\textsubscript{m} conducting the line current (i\textsubscript{l}), i.e., the main current (i\textsubscript{m}). As the electrodes gap of CB\textsubscript{m} reaches certain safe stroke to withstand the recovery voltage, the commutation circuit breaker (CB\textsubscript{c}) is made to inject high-frequency oscillating commutation current (i\textsubscript{c}), which is generated by discharging a pre-charged commutation capacitor (C\textsubscript{c}) through commutation inductance (L\textsubscript{c}). Then the superimposition of i\textsubscript{c} will force i\textsubscript{m} to drop to zero. Consequently, CB\textsubscript{m} can be interrupted with the extinguishment of vacuum arc.

Some important points should also be noted for practical application of vacuum DC interruption based on ACZ. Firstly, to interrupt short circuit current with high current rise rate, the CB\textsubscript{m} should have short inherent opening time as well as high opening speed to interrupt the short circuit current as early as possible during its rising stage. In this way, the damage on protected circuit caused by electrodynamic force can be lessened. On the other hand, lower i\textsubscript{m} implies that we can use i\textsubscript{c} with lower amplitude. It will lead to lower di/dt at current zero crossing, which has been shown to be very important for successful interruption \cite{1, 4}. A high-speed and short-delay operation mechanism driven by electromagnetic repulsion force has been applied to meet above requirement \cite{3-6}.

Secondly, we have same requirement for CB\textsubscript{c} to ensure precise and quick injection of countercurrent. It can be easily satisfied by using a triggered vacuum gap (TVG) \cite{3}, which has very short switch-on time on the order of several microseconds. Further more, the TVG can be switched off at zero crossing of i\textsubscript{c}. It means that the commutation branch can be interrupted “automatically.” Obviously, it is more controllable than the fast close and fast open switch adopted in \cite{5}.

Thirdly, a large over voltage can be exerted across CB\textsubscript{m} after its current zero crossing. Therefore, the over voltage should be suppressed. A metal oxide arrester is commonly used for this purpose \cite{3-5}. In the presence of arrester, there will be an additional current commutation process from countercurrent branch to arrester branch.

In this paper, recent experimental investigation on DC interruption based on ACZ is presented. With the aid of a circuit model, the current commutation process is analyzed and discussed.
II. EXPERIMENTAL TECHNIQUE

A. Main circuit breaker

The main circuit breaker is shown in Fig. 2 schematically. The operation mechanism of CB consists of an electromagnetic repulsion (EMR) system, and a permanent-magnet (PM) system. The PM system is used in the case of interrupting rated current to avoid frequent large impact caused by the operation of EMR system. In present work, only the EMR system is used for experimental investigation. The working principle in different operations and states are as follows.

1) Close state: the electrodes are hold with certain pressure by PM.

2) Breaking short circuit current: a pre-charged capacitor (Cem) is discharged through the coil of EMR system generating a high-frequency oscillating current in the coil, which interacts with eddy current induced in the metal plate made of aluminium to repulse the plate downwardly. Then the movable electrode of VI can be opened with a high speed. The discharge circuit of the coil is shown in Fig. 3 [6].

3) Breaking rated current: a countercurrent is conducted in the coil of PM system to counteract the holding force of PM. As the holding force decreases to certain value, the movable electrode of VI can be drawn by the pre-elongated spring with a relatively low speed.

4) Making operation: an excitation current is conducted in the coil of PM system. As the magnetic force is strong enough to overcome the counterforce of the spring, the movable electrode of VI can be attracted upwardly.

5) Open state: the movable electrode of VI is hold in open position by the elastic force of the spring.

A commercial AC VI, which has rated voltage and rated short circuit breaking current of 12kV, and 31.5kA, respectively, was used for experiments. CuCr25 electrodes with axial magnetic field configuration are adopted in the VI.

B. Experimental circuit

Experimental circuit is shown in Fig. 4. A sinusoidal current generated by a LC circuit (C_s=33.6mF, and L_s=0.3mH) with frequency of 50Hz was used to imitate the rising stage of short circuit current in DC system.

The commutation current with frequency of about 3kHz was injected by a TVG. The value of C_c and L_c is 600μF and 4.5μH, respectively.

Three capacitors used in experiments, C_p, C_c, and C_emr, were charged one by one to different values controlled by main charging switch (K), and relevant charging switch, K_c, and K_emr, respectively. The charging circuit was then isolated from the main experimental circuit.

A metal oxide arrester (ZnO) was used to suppress the over voltage across CB_m. The critical operating voltage and residual voltage of the arrester is 6kV, and 10kV, respectively.

The voltage across CB_m and the current in CB_m branch was acquired by a high-voltage probe and a noninductive shunt, respectively, and recorded by an oscillograph (Tektronix DPO4034) with bandwidth of 350MHz.

The experiment was triggered by making the source circuit breaker (CB_s). As the output voltage of current shunt, which was also inputted to the detecting and controlling circuit, reached certain preset value corresponding to a critical current (1.2kA in present experiments), the detecting and controlling circuit sent a triggering signal to the thyristor of EMR system. After a preset time delay, the TVG was triggered to inject commutation current.

The amplitude of source current was adjusted by charging C_s to different values. Due to the limitation of the capacity of C_s, its charging voltage did not exceed 2.8kV in present experiments.
II. SIMULATION ON INTERRUPTION PROCESS

For better understanding of the interrupting process, we modeled the experimental circuit by Matlab/Simulink.

A. Simulation model

The circuit model used for simulation is shown in Fig. 5. The reference direction of source/load current (i_s), countercurrent (i_c), main current (i_m), arrester current (i_a), voltage across electrodes gap of CBm (u_m), and voltage across commutation capacitor (u_e) is also shown. Besides the main parameters described above, a parasitic capacitor (C_prn and C_pe) with capacitance of 20pF is assumed across the electrodes of CBm and TVG.

B. Simulation results of low-current interruption

A series of experiments have been conducted. Two typical simulation results with same circuit parameters used in experiments are as follows.

Fig. 6 shows the simulation results of low current interruption with prospective peak source current (I_p) of about 4.1kA. The charging voltage of C_s and C_c was about 390V and 350V, respectively. For clarity, Fig. 6 only shows the time span near current commutation process. The abscissa is based on the onset of the sinusoidal source current.

We can see from Fig. 6 that the countercurrent is injected at t_1=3ms with i_c=3.3kA. The current commutation process between CBm and countercurrent branch ended at t_2=3.05ms along with the current zero crossing of i_m. At t_3=3.79ms, the source current was interrupted completely at current zero of i_e. The commutation capacitor began to discharge at t_1. Then u_e was less negative, and then positively charged gradually until t_3, from which it was isolated from the circuit with a residual voltage of about 2.6kV. After each experiment, the commutation capacitor was discharged to prepare for next experiment.

We can also see from Fig. 6 that u_e is nearly identical to u_c in t_2-t_3. It’s caused by the fact that the CBm was connected in parallel with the commutation branch, in which the voltage drop across very small commutation inductance (4.5μH) and vacuum arc in TVG was negligible compared with u_c.

It should be noted that there was a transient recovery voltage (TRV) with high oscillating frequency across the electrodes gap of CBm at zero crossing of i_m at t_1 and of i_c at t_3. The first TRV with frequency of about 17MHz was caused by the LC oscillation between C_pm and L_c. The second TRV with frequency of about 15MHz was mainly caused by the LC oscillation between C_pm, C_pe, and L_c. After the second TRV, u_m transited to the residual voltage of source capacitor (C_s). In practical DC system, u_m should transit to the rated system voltage in stead.

From Fig. 6 and above analysis, we can see that the over voltage on CBm is lower than the critical operation voltage of the arrester. Consequently, there was only one current commutation process during interruption. However, the maximum over voltage at t_3 was about 2.6kV, which was much higher than the charging voltage of source capacitor (390V). It can be expected that the arrester should take effect as the source current is further increased.

C. Simulation results of high-current interruption

Fig. 7 shows the simulation results with I_p of about 29kA. The charging voltage of C_s and C_c was about 2.7kV and 2.8kV, respectively.

In principle, the first current commutation process was same to that in low-current interruption discussed above except with t_1=3.1ms and t_3=3.14ms.

The second current commutation process started at t_3=3.38ms as the arrester is fully conducted. It should be noted that, in fact, the arrester was conducted before t_3 with very low current. It was caused by the transition stage between the critical operation voltage and residual voltage of the arrester, in which the resistance of the arrester was still relatively high.

At t_4=3.49ms, the current in commutation branch decreased to zero, and source current was fully transited to the arrester branch, which declined to current zero at
\( t_s = 4.22 \text{ms} \).

It can be seen that the over voltage is limited to below 10kV by the arrester. In addition, energy absorbed by the arrester was about 87kJ according to simulation results.

**IV. EXPERIMENTAL RESULTS**

Measured 41 and 3 in the experiment with \( I_p \) of 4.1kA and 29kA is shown in Fig. 8 and Fig. 9, respectively. Simulation results presented above are also shown for comparison. Basically, simulation results are in good agreement with experimental results except in TRV process.

In experiment with \( I_p = 4.1 \text{kA} \), the sampling rate of oscillograph (100k/s) was too low to recognize the high-frequency oscillation of TRV. Only the envelope of TRV was recorded. Much higher sampling rate of 50M/s was used in the experiment with \( I_p = 29 \text{kA} \). In this way, the TRV waveform was well resolved. The measured TRV frequency was about 1MHz and 0.1MHz at zero crossing of CBm branch and arrester branch, respectively, which are about one order lower than simulation results. Further more, we can see that the magnitude of TRV in experiments is also lower than simulation results.

The divergence of TRV between simulation and experimental results should be partly caused by the underestimation of parasitic capacitor used in circuit model, to which the TRV process is significantly sensitive. Another possible reason might be related with the fact that resistance of electrodes gap after current zero is not infinite in practice, which is not yet well considered in present model. Obviously, the residual resistance of an electrodes gap favors the damp of TRV across the gap.

The charging of commutation capacitor by high-frequency transient recovery voltage can appear across electrodes gap of main circuit breaker. In present experimental configuration, the oscillation frequency is on the order of 1MHz at zero crossing of main circuit breaker branch and arrester branch, respectively.

3) It seems that the DC interruption process based on ACZ can be well simulated by proposed circuit model. It should be a helpful tool for designing and optimizing practical vacuum DC switchgear, e.g., the configuration of commutation branch and the protecting characteristics of arrester.

![Fig. 8. Comparison between experimental (sampling rate: 100k/s) and simulation results (\( I_p = 4.1 \text{kA} \)).](image)

**REFERENCES**


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