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ПАРАМЕТРИЧЕСКОЕ ИССЛЕДОВАНИЕ МОЩНОГО ВЫКЛЮЧАТЕЛЯ ПОСТОЯННОГО ТОКА, ОСНОВАННОГО НА ВАКУУМНЫХ ДУГОГАСИТЕЛЬНЫХ КАМЕРАХ И ПОЛУПРОВОДНИКАХ

Проведено параметрическое исследование мощного выключателя постоянного тока, выполняющего функцию токограничения за счет своего быстродействия. В состав выключателя входят две вакуумные дугогасительные камеры, соединенные последовательно, причем одна из них шунтирована сборкой полупроводников. Принцип действия выключателя основан на том, что при размыкании контактов вакуумной камеры создается альтернативный путь протекания тока через параллельно включенные диоды, что существенно облегчает условия погасания дуги в вакуумной камере. Эти диоды также облегчают условия восстановления электрической прочности второй вакуумной камеры, конденсаторная батарея противотока переключает ток из цепи диодов и второй вакуумной камеры в батарею и варистор. Быстродействующий выключатель позволяет существенно ограничить амплитуду тока короткого замыкания, что особенно важно для цепей с малыми значениями индуктивностей, где большие производные нарастания тока.

ВЫКЛЮЧАТЕЛЬ ПОСТОЯННОГО ТОКА; ВАКУУМНАЯ ДУГОГАСИТЕЛЬНАЯ КАМЕРА; ПОЛУПРОВОДНИК; КОНДЕНСАТОР; ВАРИСТОР.

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PARAMETRIC STUDY OF A HIGH POWER DC CIRCUIT BREAKER BASED ON VACUUM INTERRUPTERS (VI) AND SEMICONDUCTORS

Parametric study of a two-stage high-power DC circuit breaker is carried out. It is a current-limiting breaker which is characterized by a fast opening time. The circuit breaker under consideration consists of two vacuum interrupters in series and one of them has the semiconductors in parallel. The principle of operation of this vacuum interrupter is mainly based on providing an alternate path for the load current to flow through parallel-connected diodes so that the contacts of the vacuum interrupter can be opened under minimal arc conditions. The diodes help restore the dielectric strength of the second vacuum interrupter when the counter pulse capacitor switches the current from the diodes and the second vacuum interrupter to the capacitance and varistor. A fast circuit breaker substantially reduces the short circuit current. This is especially important for the circuits with small inductances and therefore high current derivatives.

DC BREAKER; VACUUM INTERRUPTER; SEMICONDUCTOR; CAPACITANCE; VARISTOR.

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Introduction

The process of commutation in DC circuits differs from AC circuits in the sense that in AC circuits, the breaker can be opened at the instant when the current is close to zero. But in the case of DC circuits, since this phenomenon is absent alternate methods of opening the circuit breaker need to be devised. Also, the presence of energy storage elements (inductances) complicates the process of commutation as the energy stored in these elements can further fuel the arc between the contacts of the circuit breaker. Therefore, all of these constraints are taken into account while designing a DC circuit breaker.

DC breakers

In DC circuits, during the short circuit mode, the current increases monotonically up to the steady state level which can be rather higher than a nominal value.

A very important feature of the breaker is the possibility to limit the maximum value of the short circuit current. To execute such a function, the breaker has to be as fast as possible. The current limiting breakers are characterized by a minimal value of opening time usually up to 5 ms.

Fig. 1 illustrates the difference between current limiting and non-current limiting breakers.

The current diagrams for current limiting breaker (i') and for the breaker without current limiting function (i'') are shown in Fig. 1. The first interval, t_0 is the time which is needed for the current to reach the limiting level, this depends on the circuit parameters and not on the breaker; $t_{1'}$ — is the breaker opening time and it is an important breaker parameter. The current tends to increase for a short period of time until $t_{2'}$ since the voltage appearing on the arc is still less than the source voltage. Time interval $t = t_0 + t_1 + t_2$ is the time for current limiting. During this time interval, the di/dt (current derivative) is very high and prolongation of it leads to a high increase in current. The values of the $t_1 + t_2$ time interval strongly depends on the breaker design. Therefore, by limiting it, the short circuit current can be limited.

Time interval $t_{3'}$ is the time duration for arc shut down during which the current monotonically decreases.

Two stage vacuum valve breaker

The DC circuit breaker considered herewith is a two stage breaker. The first stage is one (or several) mechanical vacuum interrupters (*VI*) which under normal operating conditions carries the current. The second stage is a controlled semiconductor assemblage is connected in parallel to the mechanical valve and this carries the short circuit current for a short period, this is done for the current to bypass the mechanical valve through the semiconductor assemblage. A counter pulse capacitor (*CC*) is used to mitigate the current through the semiconductor which is eventually transferred to and damped by a varistor [1–3].

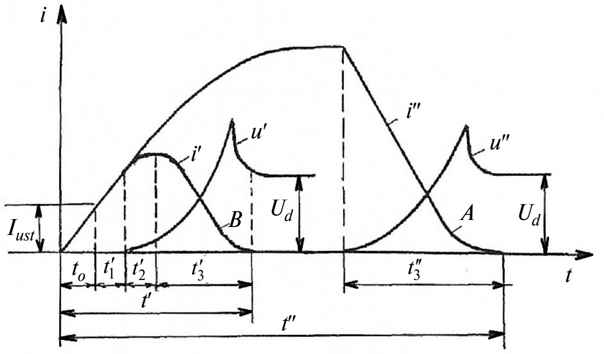

Fig. 1. Breaker current and voltage behavior:
i' and u' — for current limiting breaker;
i'' and u'' — for non-current limiting breakers

Fig. 2 represents the circuit scheme with two vacuum interrupters *QS*1 and *QS*2 which are connected in series. A diode set *VD*2 is connected in parallel to *QS*2. The counter pulse capacitance along with the discharger *FV*1 and diode *VD*1 together are connected in parallel to both the vacuum interrupters and a varistor *RU*1 is connected across the branch of the counter pulse capacitance.

The vacuum valves *QS*1 and *QS*2 can be connected in parallel or in series. The reason for having the vacuum valves in series as opposed to them being in parallel is to reduce the total switching time by opening the contacts of both the vacuum valves simultaneously instead of one after another.

The command to open the contacts of both the vacuum valves, *QS*1 and *QS*2 are given simultaneously. Under the influence of the arc voltage drop on *QS*2 and voltage drop on its inductance, the current from *QS*2 switches into *VD*2.

After the current through *QS*2 reduces to zero and after *QS*2 regains its dielectric strength, the counter pulse capacitance (*C*1) is introduced into the circuit by means of igniting the discharger *FV*1. A choke, L connected in series with *C*1 is used to limit the value of the current derivative through the semiconductors. As the capacitance discharges, the current through *VD*2 and *QS*1 is mitigated and now the current begins to flow through the counter pulse capacitance thereby recharging it. When the current through *QS*1 reduces to zero, the voltage remaining on the *C*1 is applied to *VD*2 to keep it in the off state, so that it is ensured that *QS*1 regains its dielectric

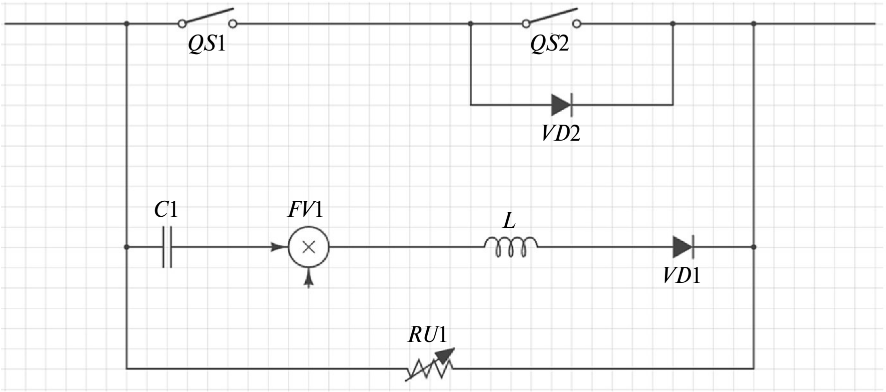

Fig. 2. Scheme of the with two vacuum interrupter: *QS*1, *QS*2 — vacuum interrupter; *VD*1, *VD*2 — diode sets; *C*1 — counter pulse capacitor; *L* — choke; *FV*1 — discharger; *RU*1 — varistor

strength. The diode, *VD*2 serves two purposes, one to provide a path for the current to bypass *QS*2 so that its contacts can be opened and another to ensure that a high voltage does not appear across *QS*1 until the moment the voltage across *C*1 changes polarity. When the voltage of the counter pulse capacitance *C*1changes polarity and reaches the operating level of the varistor, the current now flows through the varistor. The operating voltage level of the varistor is approximately two times the initial voltage on the *C*1 which is close to the voltage of the main DC source. Due to the varistor voltage, the current in the circuit subsequently damps to zero.

Switching virtual test

Main technical parameters of the circuit components:

1. Circuit inductance and resistance are calculated from the nominal values of source voltage and maximum prospective short circuit current. Tests are done for two values of source voltages, 5 kV and 10 kV, while the maximum value short circuit current in both the cases is taken to be 200 kA. The time constant in the short circuit mode is 6ms. From the aforementioned values, the values of circuit resistances are 0,05 Ω and 0,025 Ω for 10 kV and 5 kV respectively and the values of circuit inductances are 0,3 mH and 0,15 mH for 10 kV and 5 kV respectively.

2. The inductance of the vacuum interrupter is fixed as 0,4 μH. The dynamic resistance of the arc in the vacuum interrupter is 1,5 mΩ. The cathode arc voltage drop is 15 V. The vacuum interrupter voltage recovery time is taken to be 0,1 ms and the vacuum interrupter opening time is 0,5 ms. It can be reached by help of the special electro dynamic drive system.

3. The parameters of the diode set (*VD*2) in parallel to the vacuum interrupter are:

The inductance is 0,1 μH, *VD*2 threshold voltage — 4 V, *VD*2 slope resistance — 0,15 mΩ. Permissible value of the current derivative in the *VD*2 — 1 kA/ μs.

4. The counter pulse capacitor (C1) which is initially charged is provided to supply a current in the opposite direction to the fault current so as to mitigate it.

*C*1 parameters are as follows:

Initial voltage — 10 kV (for the source of 10 kV) and 5 kV (for the source of 5kV).

The initial value of the *C*1 capacitance was taken as 0,4 mF, but it may be changed to obtain the required time interval to recover the interrupter voltage strength (0,1 ms). Permissible overvoltage of the *C*1 = = 20 kV (for the source of 10 kV) and 10 kV (for the source of 5 kV).

The dynamic resistance of the *FV*1 switch is 0,1 mΩ.

Results and observations

Switching test was carried out for two values of source voltages 10 kV and 5 kV.

The following are the results obtained for a source of 10 kV.

The behavior of the load current can be seen in Fig. 3.

Fig. 4 represents the voltage across the counter pulse capacitor.

I(*QS*2) is the current through the VI connected in parallel across the *VD*2. *I*(*VD*2) is the current through the diode set. *I*(*C*1) is the current through the counter pulse capacitance.

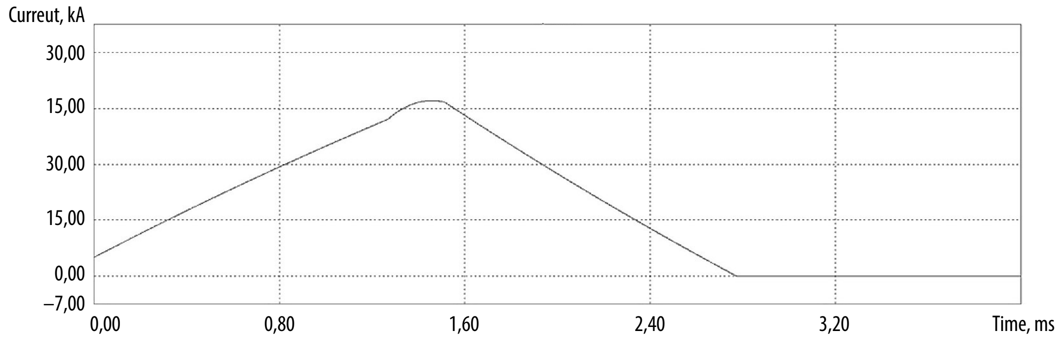

Fig. 3. Load current vs. time

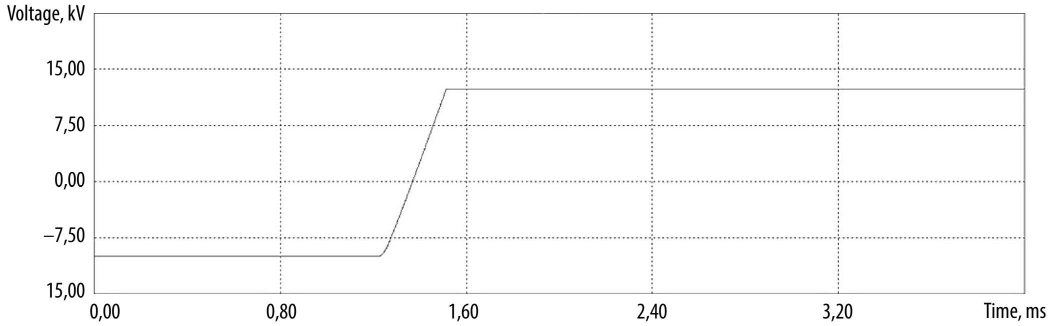

Fig. 4. Current pulse capacitor voltage vs. time

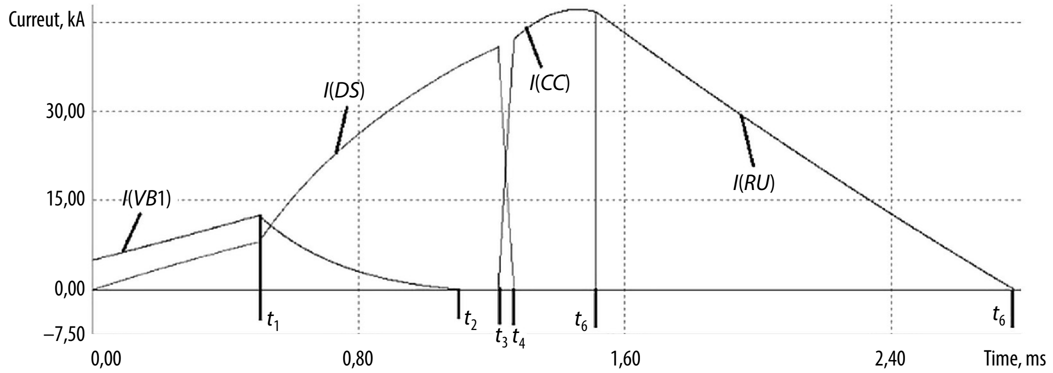

Fig. 5. Breaker current vs. time: *I*(*VB*1) — vacuum interrupter *QS*1 current; *I*(*DS*) — diode set *VD*2 current; *I*(*CC*) — current pulse capacitor current; *I*(*RU*) — varistor *RU*1 current

The typical operation of the DC breaker under consideration can be divided into three stages. The first stage begins when the command to open the contacts of both the vacuum interrupters (*QS*1 and *QS*2) is given. As the breaker opening time is specified to be 0,5 ms, the contacts are opened after this duration and an arc appears between the contacts. Under the influence of the arc voltage drop, the current in *QS*2 start to reduce and switches to the diode set (*VD*2). The current through *QS*2 completely drops to zero at t_2 this is the end of the first stage and after a period of 0,1 ms which is the time necessary for the vacuum interrupter to regain its dielectric strength, the discharger (*FV*1) is ignited so as to introduce the counter pulse capacitor (*C*1) into the circuit which is the beginning of the second stage at t_3. The *C*1 is initially charged and when connected, it discharges by supplying a current in the direction opposite to the load current through *VD*2 and *QS*1. When this current completely drops to zero at t_4, the remaining voltage on the *C*1 kept applied to *VD*2 in order to keep it in the switch off state and to ensure that there is no voltage applied to *QS*1 in order to enable it to regain its dielectric strength. It is necessary that the back voltage is kept applied across the *VD*2 for not less than for 0,1 ms.

Thus, for a period from t_0 to t_4, the load current is completely transferred from the branch of the vacuum interrupters *QS*1 and *QS*2 to the counter-pulse capacitance branch. Now the current entirely flows through the C1 branch and thus forming a series *RLC* circuit. The end of the second stage is attained when the voltage on the *C*1 changes its polarity and increases up to the level of the DC source voltage and even further. So the load current reaches its maximum value and begins to decrease thereafter.

The third and final stage begins immediately after the completion of the second stage when the load current is decreasing. When the capacitor voltage exceeds the operating voltage of the varistor, it leads to a rapid decrement of the varistor resistance and, as a result, a complete shunting of the capacitor bank by the varistor takes place. Full transition of the load current from the capacitor branch to the varistor occurs at the instant t_6. Varistor parameters are selected such that the voltage across the capacitor does not exceed 20 kV for a source voltage of 10 kV (and 10 kV for a source voltage of 5 kV). Thus provides both a sufficient level of the load voltage which is necessary for a rapid decrease of the load current, and protection of the capacitor bank against overvoltages. The varistor subsequently damps the load current to zero which terminates the switching process at t_6. The results obtained for a source of 5 kV have similar characteristics to that of 10 kV.

For successful switching, the value of the counter pulse capacitance should be such that a minimum of 100 μs is ensured between the instants when the current through the *VD*2-*QS*1 branch drops to zero and the instant of changing polarity of the *C*1 voltage. It is found to be 0,55 mF for a source voltage of 10kV and 1.1 mF for a source voltage of 5 kV. Therefore, it is observed that as the source voltage is halved (10 kV to 5 kV), the minimum capacitance value is doubled (0.55mF to 1,1 mF), but the capacitance energy will be halved too. The maximum stored energy in the C1 was found to be 27,5 kJ (for 10 kV) and 13,75 kJ (for 5 kV).The maximum load current was found to be 47,08 kA (for 10 kV) and 45,875 kA (for 5 kV).

Summary and conclusion

The switching off process in the two stage breaker was studied. It was shown that by using vacuum interrupters with a small opening time (0,5 ms), one can significantly reduce the maximum values of the short circuit current from 200 kA up to 48 kA. The diode assemblage connected in parallel to one of the two vacuum interrupters, which are connected in series, allows not to pay attention to the value of the current derivative near the zero point during the current switching off as it is usually important to the vacuum interrupters.

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