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2017 J. Phys.: Conf. Ser. 803 012123

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Arcless opening of direct current circuits in technical systems

S.V. Pustynnikov, S.A. Novikov, S.S. Zhidov

Tomsk Polytechnic University, 30, Lenina ave., Tomsk, 634050, Russia

E-mail: pustynnikov@list.ru

Abstract. Operation of the proposed DC circuit breaker consists in the fact that the closing of the thyristor in the DC power circuit with an inductive load results from opening the auxiliary circuit with a current value several fold less than the load current. The power and auxiliary circuits are connected by means of a current transformer having counter switch windings. After switching, the load is shunted by a diode and does not affect the transition process. Simulations and experimental tests of the DC circuit breaker model showed its performance capability, and the breaker can be used for switching in existing DC high current circuits with inductive loads.

1. Introduction

In order to increase efficiency and electrical safety of energy consumption, the projects of DC microgrids are developed for one or more objects in a local area. A highly efficient AC–DC converter is installed at the input port of a microgrid. These local networks have advantages when non-conventional DC energy sources are effectively used. Those are wind turbines, solar cells, fuel cells, and they do not require mutual coordination of their operation.

The projects of DC power supply are also known. For example, Lappeenranta University of Technology (Finland) developed the project of the power supply and communication LVDC (Low voltage direct current) systems [1]. The project involves the replacement of expensive conventional three-phase AC power distribution networks 20/0.4 kV for underground cable DC lines LVDC (± 0.75 kV). Each building and construction will be connected to the network via the DC converters matching LVDC voltage and the voltage required by a consumer. This solution significantly reduces the cost of the network, effects of weather conditions and increases efficiency by eliminating conversion of AC / DC [2]. The change-over to DC power consumption requires significant upgrades of the equipment, technical standards and energy usage conditions. Consequently, the proper selection and development of new switching equipment for DC circuits are necessary [3].

An electrical circuit comprising an inductive load and having an internal inductance stores the magnetic field energy. Therefore, the electric arc occurs at contact separation of DC circuit switches due to ionization of the contact area. Another problem is the overvoltage that may be several times higher than the voltage of the DC source. The overvoltage is hazardous to DC power lines and can damage the insulation of windings in electric motors, generators, switching equipment.

The opening in DC circuits with the inductive load can proceed with arc switching or without arc between the disconnected contacts [4]. For arcless DC switching, thyristors are widely used due to their fast operation. Opening of a common thyristor is initiated by applying a current pulse of positive polarity, relatively the cathode and the control electrode. The transient time after the turn-on of the thyristor is determined by a type of the load (active, active-inductive, capacitive), the amplitude and



the rate of the control current pulse rise, the temperature of the thyristor semiconductor structure, the applied voltage and load current.

The thyristor turn-off may be normal or forced (external triggering). Normal turn-off occurs at the moment the current value passes zero when the thyristor operates in AC circuits. The turn-off time is from 2 ms to 20 ms depending on the operational power. There is no polarity changing in DC circuits so special blanker circuits, forming reverse current or voltage, are used [5,6].

In the reverse voltage circuit, the precharged capacitor is discharged into the thyristor so the reverse voltage is applied to the thyristor and it gets closed. The main condition is the stored charge in the capacitor should be enough to maintain a sufficient value of the reverse voltage throughout the transient of thyristor closing. The scheme is simple. The disadvantage of the scheme is that at the time of switching the voltage surge of the charged capacitor voltage value occurs across the load, and the value can be several times higher than the operating voltage of the source.

In the reverse current circuit, the capacitor discharges into the primary winding of the current transformer, which secondary winding is connected to the thyristor anode circuit. The current formed in the second winding is directed opposite to the current of the thyristor anode circuit. As a result, the thyristor current becomes smaller than the retaining current and the thyristor becomes closed. The main condition is the capacitor stored charge should be sufficient to maintain adequate largest reverse current during the transient process of closing the thyristor. The advantage of the scheme is at the moment of switching no overvoltage occurs at the load. The disadvantage is similar to the reverse voltage circuit, that is the value of the capacitor voltage is several times greater than the source voltage. Furthermore, the current transformer windings should have a high Q- value for producing the control turn-off pulse.

2. Setting the problem

The equivalent circuit of the DC breaker maintaining arcless opening of high power circuits with the inductive load was proposed in [7]. Figure 1 shows the equivalent circuit of the DC circuit breaker which allows opening the circuit with high current i_2 generated by voltage source (VC) E_2 by opening the circuit with low current i_1 generated by VC E_1 .

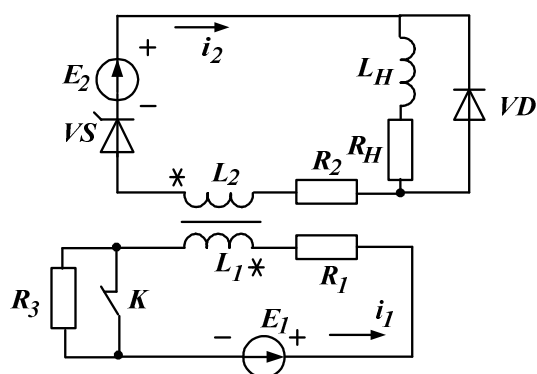


Figure 1. The equivalent circuit of the DC circuit breaker. R_1, R_2, R_3, R_H – resistors; VS- thyristor; VD- diode; L_1, L_2, L_H - inductances; E_1, E_2 – voltage sources.

First, switch K gets opened and current i_1 in the primary winding falls down to zero. As the current transformer windings have a subtractive polarity and the inductive coupling factor of the windings is $M = K_c \sqrt{L_1 L_2}$, where K_c is the coupling coefficient, the current negative pulse is generated in secondary winding R_2, L_2 . It causes current i_2 to pass the zero value, close thyristor VS and cut the load off VC E_2 . Diode VD is connected in parallel with the load to shunt it when the thyristor is getting closed.

The objective of the study is application of the DC circuit breaker for opening the DC circuit with an inductive load on the basis of the laboratory model.

3. Theory

Thyristor VS had the nonlinear volt-ampere characteristic, therefore the operation of the circuit was analyzed, excluding the thyristor, as it simplified calculations and did not affect operational principles. Also, it could be assumed, once switch K operates, the load is shunted by diode VD and the R_H, L_H load parameters do not affect the transient in the circuit. Opening switch K at moment $t=0_+$ means connecting additional resistor R3 of the value much higher than R1 to the circuit with current i_1 so the conditions of the incorrect switching are not valid. Starting at moment $t=0_+$, the transient is determined by the set of equations derived for momentary values according to Kirchhoff laws [8].

$$\left. \begin{aligned} i_1(R_1 + R_3) + L_1 \frac{di_1}{dt} - M \frac{di_2}{dt} &= E_1 \\ i_2 R_2 + L_2 \frac{di_2}{dt} - M \frac{di_1}{dt} &= E_2 \end{aligned} \right\} \quad (1)$$

Because of the conception of the total magnetic flux linkage continuity, the initial condition can be written as:

$$\psi(0_-) = \psi(0_+) \quad (2)$$

According to the generalized switching laws:

$$L_2 \cdot i_2(0_-) - M \cdot i_1(0_-) = L_2 \cdot i_2(0_+) - M \cdot i_1(0_+) \quad (3)$$

Here M is mutual inductance, $t=0_-$ is the moment just before the switching, $t=0_+$ is the moment just after switching. If switch K is opened the current in the primary circuit is $i_1(0_+)=0$ and the current step in the high current circuit is

$$i_2(0_+) = \frac{L_2 \cdot i_2(0_-) - M \cdot i_1(0_-)}{L_2} = \frac{E_2}{R_2} - K_{c\theta} \sqrt{\frac{L_1}{L_2}} \cdot \frac{E_1}{R_1} \quad (4)$$

So the following condition should be fulfilled to make current $i_2(0_+)$ pass through zero:

$$K_{c\theta} \sqrt{\frac{L_1}{L_2}} \cdot \frac{E_1}{R_1} \geq \frac{E_2}{R_2} \quad (5)$$

Operation of the DC breaker model was calculated for particular values of the circuit parameters

$$E_1 = E_2 = 10V, R_1 = 66.5 \text{ Ohms}, L_1 = 0.857 \text{ H}, R_2 = 1.07 \text{ Ohms}, L_2 = 1.87 \text{ mH},$$

$$R_3 = 100000 \text{ Ohms}, R_H = 4.2 \text{ Ohms}, L_H = 68.8 \text{ mH}, K_C = 0.8, M = 32 \text{ mH}.$$

Resistance R_H includes load resistance $R_H^l=3.2$ Ohms and the resistance of current-measuring shunt $R_s = 1$ Ohm. Resistance R_2 includes second winding resistance $R_2^l=0.07$ Ohms and the resistance of current-measuring shunt $R_s = 1$ Ohm. The steady state values of the currents before switching are $i_2(0_-)=1.9$ A and $i_1(0_-)=0.15$ A, the high current step in the secondary winding after switching is about 2.3 A.

Current i_2 as a function of time during the transient is presented in Figure 2. The minimum negative value is $i_{2min} = -0.64$ A, the width of negative part Δt is about 0.12 ms and it is sufficient for reliable closing of thyristor VS. The minor variation from the calculated value of i_2 is attributed to R_3 in the equivalent circuit which shunts switch K at the opening for eliminating conditions of the incorrect switching.

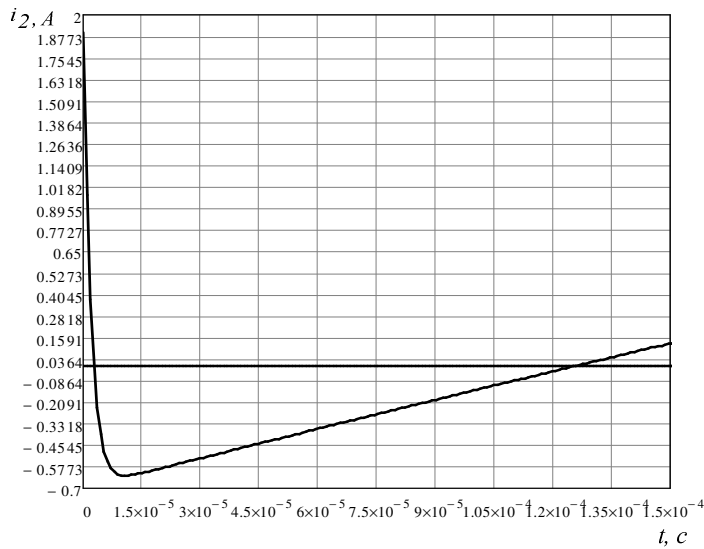


Figure 2. The time dependance of the current in the secondary winding after opening switch K

4. Experimental results

The DC circuit breaker model with the parameters given above was used in laboratory tests. Schottky diode 1N58222 was taken as diode VD shunting the load. The current in the load before switching was $i_2 = 1.9$ A, the current in the primary winding was $i_1 = 0.15$ A. The oscillogram for i_2 is shown in Figure 3. The minimum negative value is $i_2 \approx -0.5$ A, the width of the negative part of the pulse is $\Delta t \approx 0.3$ ms. Figure 4 presents the oscillogram for i_2 when thyristor TYN1225 was connected into the circuit in Figure 1 as element VS. As the oscillograms proves, the thyristor is closed practically instantly after opening switch K in the primary winding of the current transformer.

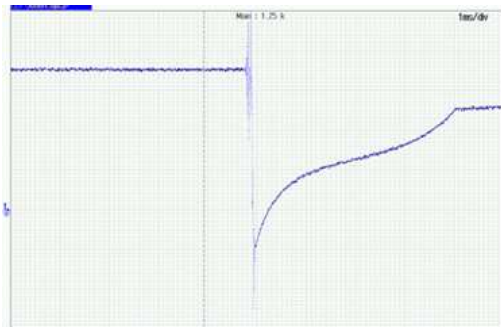


Figure 3. The oscillogram of the high power circuit current after opening switch K .

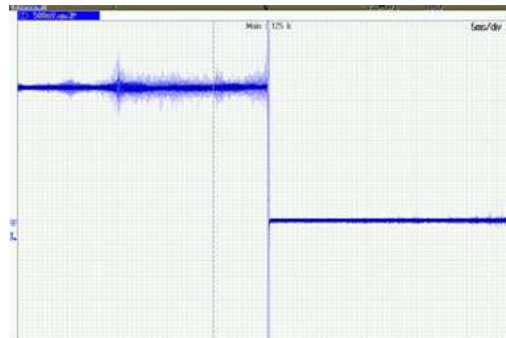


Figure 4. The oscillogram of the current through the thyristor after opening switch K .

Figure 5 shows the current in the inductive load through the bypass diode. The duration of the transient when the load current decreases to zero is $t_l \approx 60$ ms.

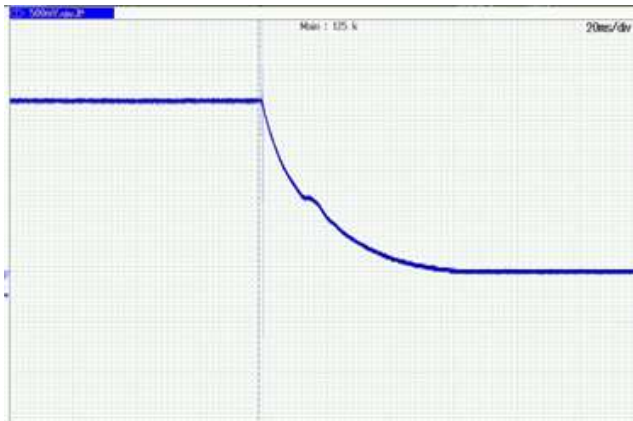


Figure 5. The oscillogram of the current in the load at closing thyristor VS.

Calculation of the DC circuit breaker model showed that the thyristor carrying the current of 1.9 A is reliably cut off by opening the low-current circuit with a current that is 12.6 times less than that of the thyristor. The experimental tests of the laboratory DC circuit breaker model showed that the thyristor, opening the high power circuit, is cut off practically instantly after the K switch breaks in the primary winding of the pulse transformer.

5. Conclusion

The proposed DC circuit breaker provides arcless opening of the high power DC circuit with inductive load by opening the low-current DC circuit. The value of the current primarily switched is several times less than that of the load current.

The mathematical model for the calculation of the transient allows estimation of the high current value at given parameters of the DC circuit breaker.

The experimental tests showed fast cut-off of the thyristor in the breaker after opening the low current circuit by the control switch. That suggests an advantage in using such a device for switching high-power high-current DC circuits with inductive loads.

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