Arc Extinguishing in the DC and Photovoltaic Networks

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In this contribution the various behaviors of arc voltage created with extinguishing system and the influence on current and energy released behavior in the extinction system are theoretically and experimentally analyzed. In the area of photovoltaic it represents the increase of working voltages up to 1500 V. In the experimental part the oscilogrammes of DC current interruption with various extinction systems are presented. For the reliability of current interruption mainly in the photovoltaic (PV) networks it is necessary to dedicate increased attention to development and design of switch and protection gears.

Keywords: DC current, extinguishing chamber, PV source, switchgear

1 INTRODUCTION

Current interruption in circuits with DC voltage is a specific problem. In the distribution systems with conventional sources (rectifier, etc.) with linear VA characteristics and voltage up to 220 V (440 V) are used for current switching conventional DC contactors or circuit breakers. Devices have extinction systems using self or external (permanent magnets) magnetic field and ceramic or deion chambers. Rotary switches are using different extinction system, based on the effects of slot arcing chamber, without the use of a magnetic field. In circuits with currents of 100s to 1000s amps and voltages to 3 kV are used for switching dimensional high-speed circuit breakers.

Current interruption in circuits with photovoltaic voltage sources is specific in that the PV sources are of nonlinear VA characteristic and voltage 600-1500 V. Furthermore, it is desirable that the switching and protective devices have been designed in European size module. Preferred are closed systems during which activity no outflow of ionized gases into the environment occurs.

This paper deals with theoretical and experimental examination of the effect of changing the arc voltage of switchgear on the behavior of interrupted current and arc energy. The phenomenon will be studied in a circuit with rectifier source and PV source. Experimentally will be evaluated the advantages and disadvantages of the various devices arcing extinction systems designs for PV distribution systems.

2 THEORETICAL ANALYSIS AND SIMULATION

Let us examine the circuit on fig. 1, in which operates unspecified source with voltage U, the switch S, which forms voltage U_a during interruption, and current I=U/R. The time constant of the circuit is τ=L/R. From 2nd Kirchhoff's law and requirement that the current during the switch interruption must decrease follows that

$$L\frac{di}{dt} < 0 \tag{1}$$

and arc voltage must be during current decrease

$$U_a > U - Ri \tag{2}$$

This condition is fundamental and depends not on the type of source.

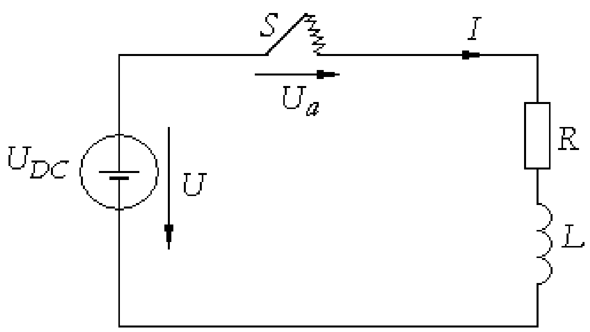

Fig. 1: Wiring diagram for investigation of DC current interruption. U_{DC} – conventional or PV source, S – DC switch

In the following, we will investigate how the source parameters (VA characteristic) and switch (ability to generate the arc voltage of variable value and time behavior) will affect the parameters of current interruption: arcing time and arc energy. Suppose, in the circuit on fig. 1, source with VA characteristic according to fig 2, line a (conventional source).

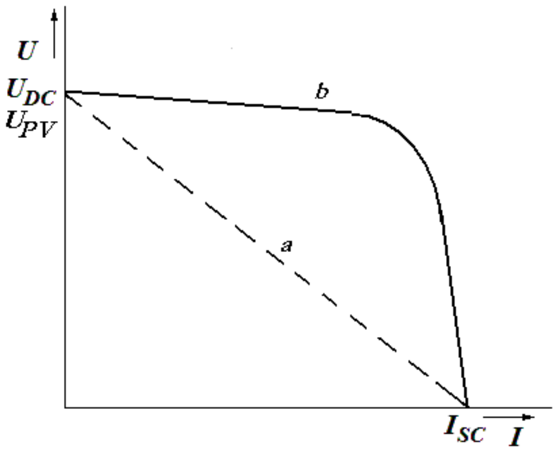

Fig. 2: Voltage-current characteristic of conventional DC source (a) and PV source (b)

Let the voltage on the switch S during the interruption grow steeply to U_a. Then, the time behavior of the current in circuit will be

$$i(t) = \frac{U_{DC}}{R} - \frac{U_a}{R}(1 - e^{-\frac{t}{\tau}}) \qquad (3)$$

This behavior will not be analyzed further, it has little practical significance.
In a circuit with the same source may switch create arc voltage according to the equation

$$u_a(t) = C_1 t \qquad (4)$$

Arc voltage during the current interruption will linearly increase with time. The time behavior of current will be given by

$$i(t) = \frac{U_{DC}}{R} - \frac{C_1}{R}\left[t - \tau(1 - e^{-\frac{t}{\tau}})\right] \qquad (5)$$

The simulated behavior of interrupted current i, the voltage on the switch u and arc energy w_a is on the fig. 3. For the simulation, we used the program SADYS [1] and the following values: U_{DC} = 600 V, I = 100 A, τ = 1 ms.

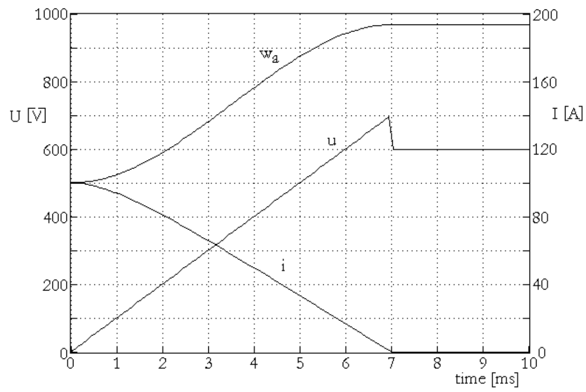

Fig. 3: Time behavior of current and voltage in the circuit with conventional source and linear arc voltage rise, W_a = 93 J

In the following, we assumed that the switch in function of time creates a quadratically increasing arc voltage.

$$u_a(t) = C_2 t^2 \qquad (6)$$

Then the current time behavior will be described

$$i(t) = \frac{U_{DC}}{R} - \frac{2C_2}{L}(\tau^3 + \frac{\tau}{2}t^2 - \tau^2 t - \tau^3 e^{-\frac{t}{\tau}}) \qquad (7)$$

Waveform is simulated in fig. 4. It can be seen that the voltage on the switch before the current interruption increased to $U_a >> U_{DC}$. The circuit parameters are the same as in the previous case.

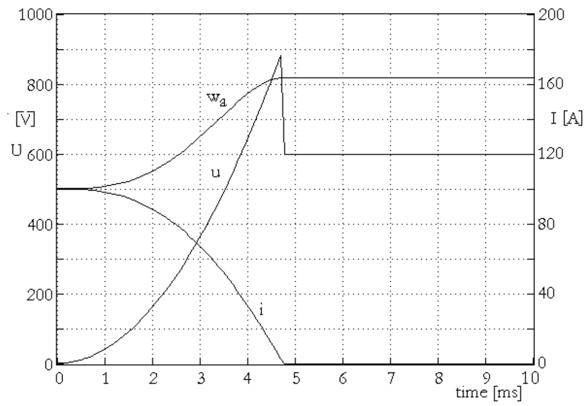

Fig. 4: Time behavior of current and voltage in the circuit with conventional source and quadratic arc voltage rise, W_a = 35 J

Let us replace in the examined circuit conventional source by PV source. These sources have VA characteristic according to fig. 2, line b. From the comparison of the characteristics it is evident that to comply with the condition (2) must the switch create a much higher arc voltage as in previous cases. To perform experiment with PV source recommends standard [2] to use an equivalent PV source, which VA characteristic must be located within the hatched area (fig. 5). For the simulation we used the VA characteristic indicated by the solid line. For a voltage at the switch according to (4) is a simulation of the fig. 6, for the behavior (6) is the simulation of the fig. 7. The steep decrease in current to zero value after reaching $U_a \geq U_{PV}$ is due VA characteristic of source and change in the parameters of the circuit.

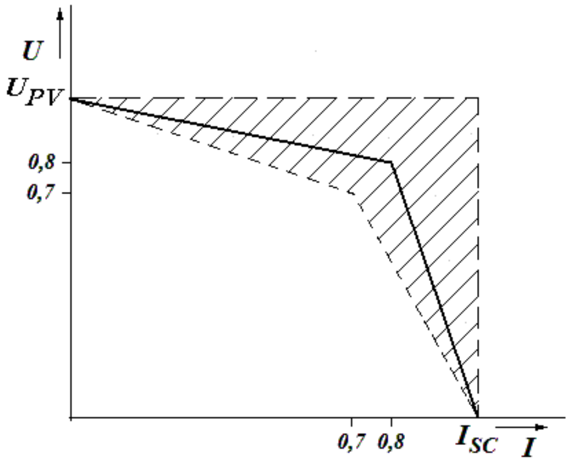

Fig. 5: Voltage-current characteristic of simulated PV source (cross-hatching) according to [2] and characteristic used for simulation (full line)

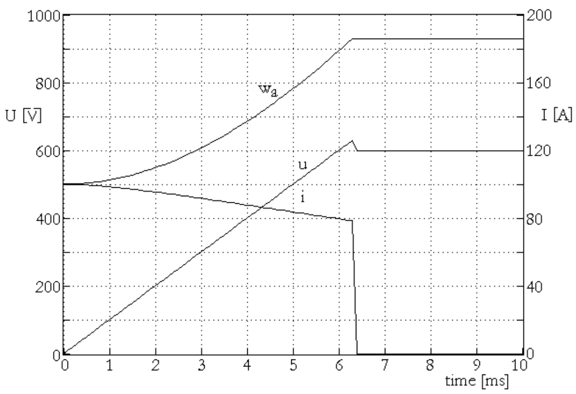

Fig. 6: Time behavior of current and voltage in the circuit with PV source and linear arc voltage rise, W_a = 172 J

From the comparison of energy W_a can be stated that the highest value is reached for the circuit with PV source and linear increase of arc voltage.

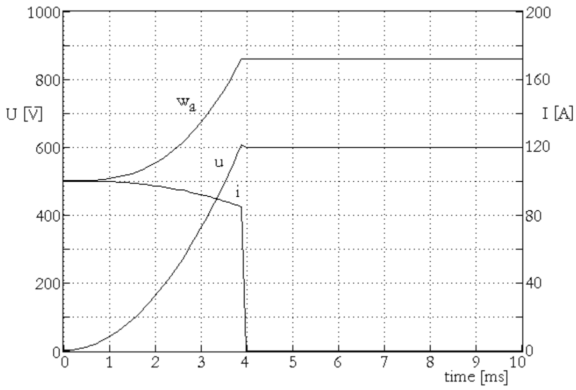

Fig. 7: Time behavior of current and voltage in the circuit with PV source and quadratic arc voltage rise, W_a =72 J

In other cases, the energy W_a comparable. It follows the part conclusion, that for the circuits with PV sources are not suitable the extinction systems with slow increase of U_a, because they have to accumulate higher amounts of arc energy. This may cause increased wear of extinction systems materials and reduce its durability.

3 EXPERIMENTAL INVESTIGATION OF EXTINCTION SYSTEMS

The aim of this part of the solution of the problem was to find out how the extinction systems of commercially produced switches interrupt the current and assess their advantages and disadvantages. On the base of knowledge's construct a model of the switch with progressive action of extinction system.

Experiments were carried out by the rectifier circuit with capacitor current source, whose characteristics are close to the source of constant current [2]. During the experiments, we varied the voltage of source, current through the switch and the time constant of the circuit. We explored virtually all types of switches and extinction systems. Here we will comment only the most important of them.

Fig. 8 is a recording of DC current interruption with circuit breaker with deion chamber. The movement of the arc from the contacts was driven by permanent magnet without pole pieces. Extinction system created constant but low U_a. For use in PV circuit is to advise to connect those systems in series (up to 8). This increases disproportionately the width of the switch (6-8 TE) and price.

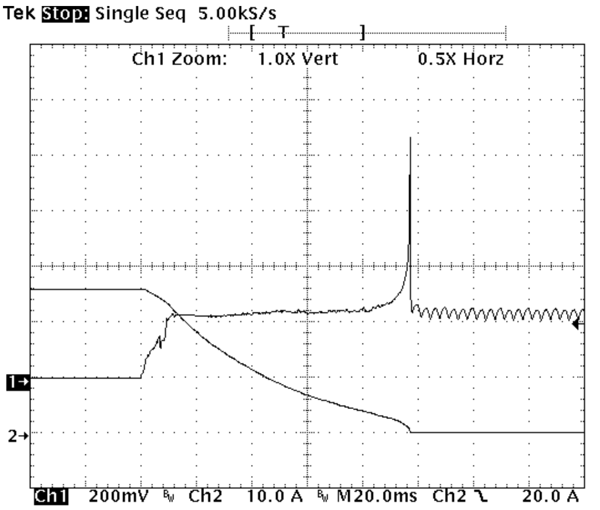

Fig. 8: DC current interruption with MCB with deion chamber. U_{DC} = 200 V, I = 26 A, t_a = 96 ms

Fig. 9 shows the current interruption by rotary switch with a slot chamber. This record also proves that for higher U_{PV} must be connected several switching (arcing) units in series.

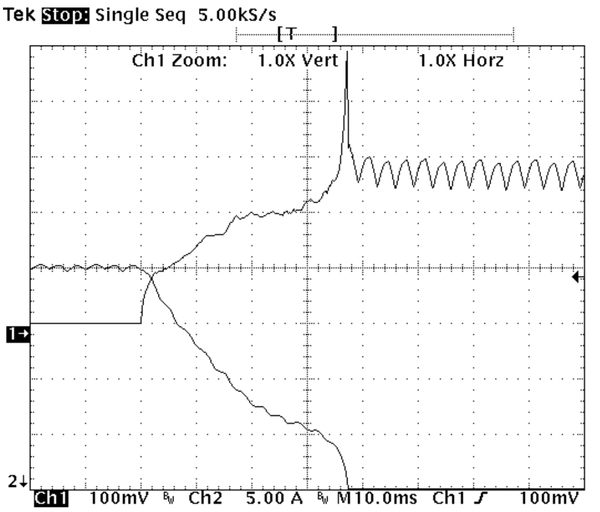

Fig. 9: DC current interruption with switch with slot arcing chamber. U_{DC} = 250 V, I = 20 A, t_a = 37 ms

The disadvantages of this solution are limited to:

a) with increasing voltage of switching unit decreases its switching ability

b) switches have low durability because the arc burns the slot material.

Detailed results can be found in [4]. Approve changes of the switch characteristics with the number of disconnections. It extends the particular arcing time and increases the arc energy, etc. These switches tend to have problems during the tests of operational capability even for the use in category DC-21B [3]. For comparison, we present the results for the model switch with a width 1TE (Fig. 10) and model DC spark gap with a width of 1.5 TE (Fig. 11), which were equipped with a new extinction system.

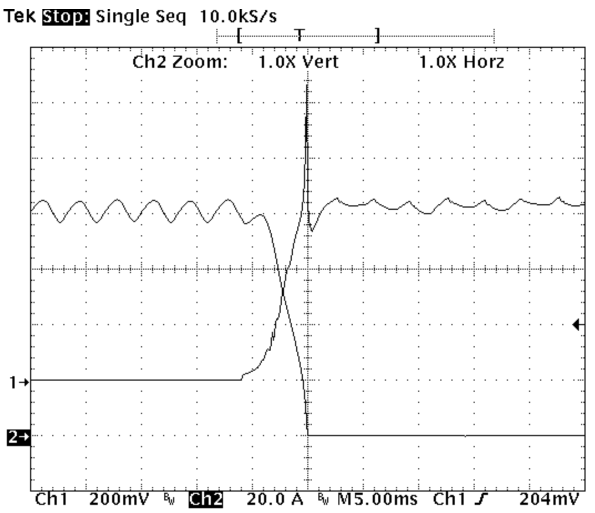

Fig. 10: DC current interruption with experimental switch. U_{DC} = 600 V, I = 80 A, t_a= 6 ms

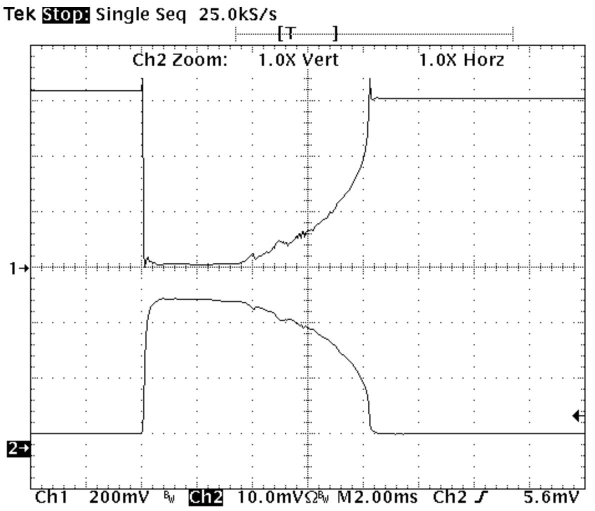

Fig. 11: Follow DC current interruption with experimental spark gap with DC extinguishing system in the circuit with condenser current source. U_{DC} = 600 V, I = 50 A, t_a = 8 ms

Switch interrupted the currents up to 100 A at U_{DC} = 600 V and τ = 1 ms. Extinction system of spark gap interrupted the follow currents up to 300 A at U_{DC} = 600-700 V (circuit with a capacitor current source).

4 RESULTS AND DISCUSION

In this work we have shown that simulation methods are significantly helpful in determining the characteristics of switches needed for reliable power interruptions and in circuits with conventional DC sources, as well as PV sources.

The best results were obtained with quadratic increase time behavior of switch arc voltage.

Experiments demonstrated that the in commercially available switches the manufacturers failed to resolve the present state of knowledge of current interruption in PV distribution systems. So far it is not known whether any spark gap SPD for PV distribution systems. The results obtained with the model switch show the way, which the development of these devices for PV distributions may take in the future.

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