Effect of contactless hybrid current limiter on voltage dips in power system

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Abstract: The paper presents the operation of a hybrid contactless short-circuit current limiter on the basis of computer simulation. Special attention was paid to the possibility of the quality improvement of the delivered electrical energy, through the limitation of the duration of voltage dips in the power grid owing to the application of a hybrid circuit breaker. The calculations were performed using the PSPICE and MATLAB software.

Keywords: electric fuse, contactless hybrid current limiter, simulations, current limitation, voltage dips

1. Introduction

In power distribution systems the power quality is of increasing importance as the low voltage consumers use microelectronic components for control and operation, which are sensitive to voltage dips and power supply interruptions. Voltage dips can be defined as follows: a voltage dip is a sudden voltage reduction ranging from 10% to 90% of the nominal voltage and with a short circuit duration from 10 ms up to one minute [1]. In the US a short-duration reduction (up to a few seconds) in the voltage amplitude is termed a voltage sag [2].

Typically, voltage dips are due to short circuit faults in the power system. The time of disturbance elimination by classical contact circuit breakers is of several dozens milliseconds. It is too long to limit fault currents, and to reduce the duration of the voltage dip. Effective limitation of voltage dips can be achieved, among other means, by the application of hybrid circuit breakers [2,3], whose idea consists in the compensation of flaws of the contact circuit breaker with a semiconductor switch in parallel intercepting the current during the process of interruption. Such limiters may be characterized by high speed of operation (below 1 ms) and the ability to conduct considerable currents during normal operation, if special drives are applied.

One of the first hybrid circuit breakers put in the practice was that designed by Collard and Pellichero [4]. Later on Żyborski [5] and Bartosik [6] significantly developed their idea. A modified approach was presented by Wolny [7,8] who applied a special ultra short fuse in the place of the contact switch. This way the need for a fast electrodynamic drive was eliminated, which allowed to considerably reducing dimensions and costs of the hybrid current limiter. The new device is called the contactless hybrid current limiter (CHCL).

The paper presents the possibility of elimination of voltage dips in power distribution systems, using a contactless hybrid current limiter. The analysis was performed using computer simulation for the operation of assumed models of current limiters.

Below, an analysis of effects of the arc ignition model applied on the calculation results is presented. Ultra-short fuse arc models based on a modified black-box arc model, as well as models offered by commercial software packages were used. Results of the simulation carried out with the application of the PSPICE and MATLAB were compared with experiments on a real contactless hybrid current limiter

2. Design of the analyzed CHCL

In Fig. 1 the structure of the analyzed CHCL is presented. It consists of the following basic elements: the ultra short fuse (USF) shunted by the semiconductor device (SD), controlled by a special control system (CS), and the metal oxide varistor (MOV) absorbing the magnetic field energy of the switched-off circuit. The triggering impulses are controlled by the voltage across the USF.

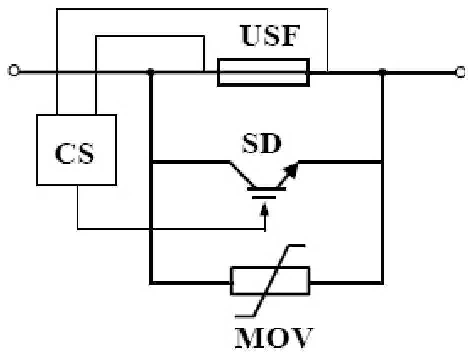

Fig. 1: The model of a DC CHCL [7]

An ultra short fuse as a part of the CHCL assembly is characterised by the following properties:

- short fuse element: a few millimetres in length;
- very fast t – I characteristic;
- very high current density in working conditions;
- marginal power losses in normal conditions.

In Fig. 2 the voltage and current traces of the CHCL operation are shown. The experiments were carried out in the oscillatory LC circuit at the frequency of 480 Hz and the prospective short-circuit current of 1.2 kA. The used frequency higher then 50 Hz increased the rate of current rise, important for the operation of current limitation devices.

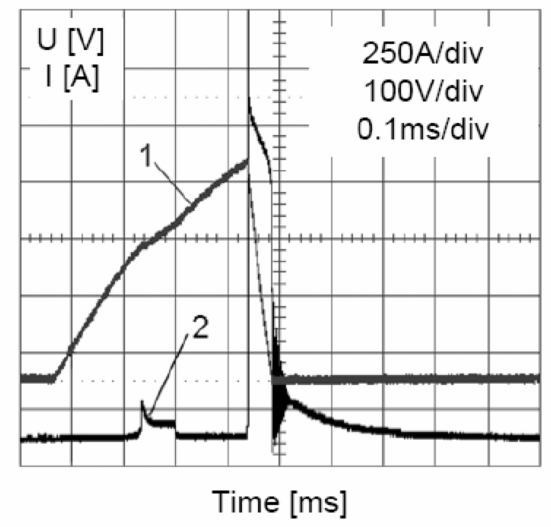

Fig. 2: Current and voltage records of the CHCL operation
1 - the current, 2 - the voltage

3. The hybrid switch calculation model

Mathematical modelling is a powerful tool in the analysis of operation of hybrid switches, allowing for a better identification of requirements concerning the switch components and the effect of circuit parameters, as well as the switch behaviour in critical conditions. However, it is important to properly select the simulation models. Since it is impossible to create a model taking under account all the possible phenomena playing a role in the current limitation process, certain simplifications are very often introduced, or commercial software packages offering simplified models are used. In simulations of the operation of a CHCL, the selection of the ultra short fuse arc model is a difficult and important issue, since due to the prevailing axial cooling no existing arc model can be directly applied.

The calculations were performed using the PSPICE and MATLAB software. The process of current commutation between the fuse and the IGBT was modelled with the MATLAB, while the process of current transfer from the IGBT to the varistor was modelled with the PSPICE software.

In Fig. 3 a diagram of the CHCL used for simulations is shown. 30-nH inductance of current commutation loop was assumed, as well as 50-μΩ resistance. The mutual inductance was neglected.

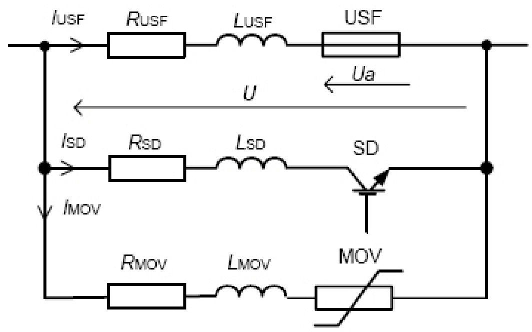

Fig. 3: The modelled circuit of current commutation loop

3.1 The ultra-short fuse model

In hybrid circuit breaker the arc voltage is the driving force of the arc-to-SD current transfer. Therefore the arc model must be carefully selected.

In regard to the PSPICE simulations, the arc model was founded on a voltage-controlled switch modified by the application of a nonlinear resistance connected in parallel to the opening contacts. A varistor with the threshold voltage of 20 V was used, as the nonlinear element.

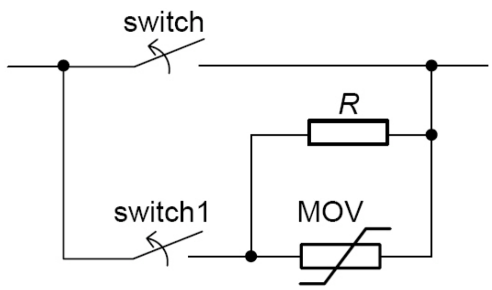

Fig. 4: The USF model (PSPICE)

The simulation results for the assumed model are presented in Fig. 5.

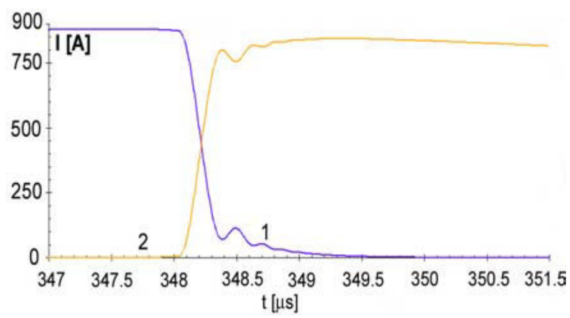

Fig. 5: The simulated IGBT – MOV current transfer
1 – the IGBT current, 2 – the MOV current

With regard to the MATLAB a ready-to-use model based on the Cassie's concept is offered [9]. This model is described by the following relationship:

$$\frac{1}{g}\frac{dg}{dt} = \frac{d\ln g}{dt} = \frac{1}{\tau}\left(\frac{u^2}{U^2_c - 1}\right) \qquad (1)$$

where: g – the conductance of arc, u – the voltage across the arc, i – the current through the arc, τ – the arc time constant, U_c – the constant arc voltage.

The independent parameters (τ, U_c, g(0), a_t (s)) have to be selected and set manually.

In order to model the process of disintegration of the fuse element and the fuse arc ignition, initially the following fuse model was applied:

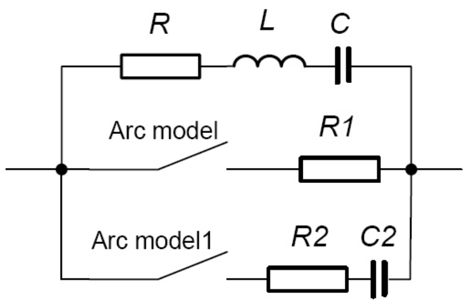

Fig. 6: The USF model (MATLAB)

However such a rough model did not work properly. Hence modification had to be introduced consisted in the addition of energy-absorbing elements connected in parallel to the arc. The resistance and capacitance were used. Dozens of experiments have proven, that such a model operates in a satisfactory manner providing reliable results for the current transfer between elements of the CHCL. The simulation results are presented in Fig. 7.

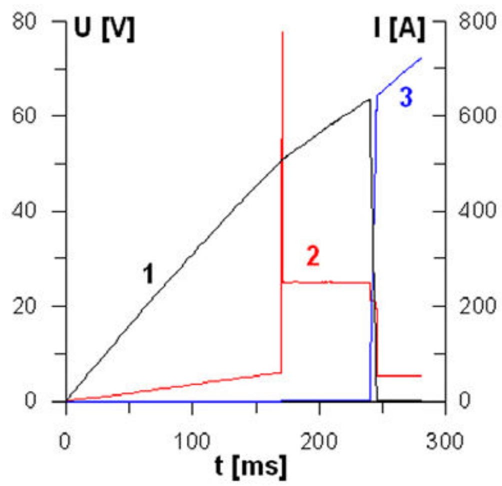

Fig.7: The simulated USF – IGBT current transfer
1 – the USF current, 2 – the USF voltage, 3 – the IGBT current

The results of simulations are presented in Fig. 8. The calculations were carried out in the oscillatory LC circuit at the frequency of 480 Hz and the prospective short-circuit current of 1.2 kA

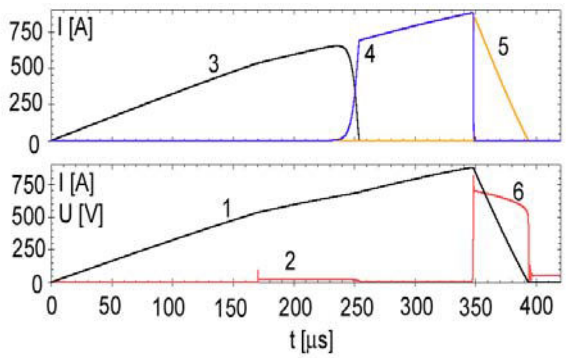

Fig. 8 : The simulation of CHCL operation (PSPICE)
1 – the short-circuit current, 2 – the USF voltage, 3 – the USF current, 4 – the IGBT current, 5 - the MOV current, 6 – the MOV voltage

Satisfactory agreement between the results obtained with the simulation (Fig. 8) and measurements (Fig. 2) allows for an extension of the application of the model used e.g. for the analysis of the CHCL operation in circuits and conditions, say, in an AC circuit at the frequency of 50 Hz.

3.2. Models of semiconductor devices

Commercial programs offer a large selection of models of the semiconductor devices available on the market. The list is amended every time when a new device is developed. Different approaches of model selection are adopted in the MATLAB and the PSPICE. In the former case, parameters of a generic model of the device are modified in accordance to the actual catalogue data. In the case of the PSPICE ready-to-use models are only available.

4. Effect of CHCL on quality of energy

Today voltage dips are the most important power quality problems. Each year they disturb production, resulting in large economical losses, especially in the case of electronic devices (computer equipment, PLC programmable controllers) which are very sensitive to voltage changes. The voltage dips are characterised by two parameters:

- duration Δt and
- depth ΔU.

Voltage dips are due to short circuit faults in power distribution systems and other high overcurrents producing significant voltage drops across impedances of the system's elements. The magnitude of a voltage dip is mainly determined by the faulted line impedance and the connection method of the transformer windings [10]. The short-circuit fault reduces the voltage almost to zero exclusively at the fault position. Both Δt and ΔU depend on the speed of CB operation. The CHCL being fast reduces the extend of voltage dips.

To eliminate short circuits contact switches are commonly used. Their operation time is of the order of tens of milliseconds. A long duration voltage dips can not be tolerated in the power grid due to the susceptibility of the electronic devices used. The regulations proposed by the CBMA (Computer Business Manufacturer Association) [11], define a band characteristic presenting the acceptable limits of the voltage changes in both directions, i.e. the dips ΔU and overvoltages as a function of , the disturbance duration Δt. With regard to the voltage dips the acceptable Δt is of several ms. This characteristic was modified in 1996 and now it is known as the ITIC (Information Technology Industry Council) characteristic [11]. A classical switch cannot ensure such a short time of elimination of a short circuit fault.

On the substitution of fast semiconductor or hybrid switches for contact circuit breakers the duration of voltage dips can be significantly reduced [2,3]. In LV networks CHCL can be applied. However, in the latter case features of IGBT define current limitation capacity of the whole assembly. Due to the relatively low current switching ability of the transistor, at present, the CHCL can be applied in circuits with rated currents of maximum several hundreds amperes.

In Fig. 9 the modelled power system has been presented, in which the simulations of a short-circuit fault interruption by means of a classical contact CB vs. CHCL were performed. Line – erth short circuit at A was assumed. The values of parameters used in the simulations are given in Table 1.

Table 1. The parameters of the modelled network used in simulations

Element	Symol	Value
System impedance	Z_{sc}	54Ω
Step-down transformer	MV/LV	630kVA 16.75kV/400V D1/Yg
Step-down transformer	HV/MV	6.3MVA 115kV/16.5kV Yg/D11
Cable line impedance	Z_c, Z_{c1}	Length: 10km 0.74Ω
Load impedance	Z_l	0.58Ω power factor: cosφ = 0.86

The numerical experiment was performed with the MATLAB software.

When the voltage on the faulted line goes to zero at the fault location, the voltage at the substation and on the parallel feeders depend on the distance of the fault from the substation.

In Fig. 10, 11, 12 clearing of a short circuit fault in the power system by contact CB is presented. The assumed fault clearing time corresponding to the voltage dip is Δt =51ms.

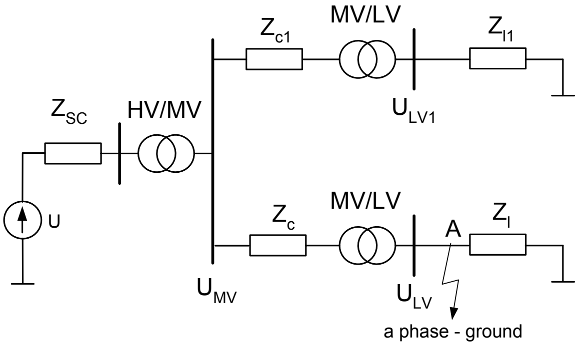

Fig. 9 : The modelled power-system grid
U – the voltage source, Z_{SC} – the system impedance, HV/WV, MV/LV –the transformer, Z_l, Z_{l1} – the load impedance, Z_c, Z_{C1} – the cable line impedance

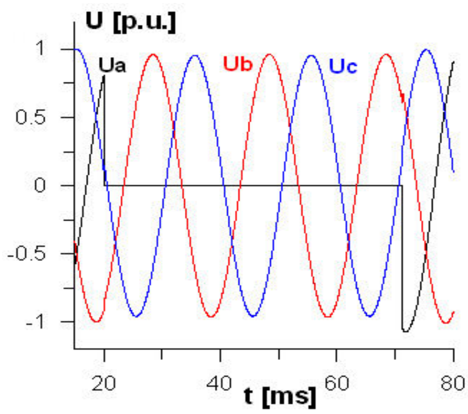

Fig. 10: The simulated U_{LV} voltage traces at the fault location when the short-circuit fault is cleared with a contact CB
Ua, Ub, Uc – the voltages on the busbars U_{LV}

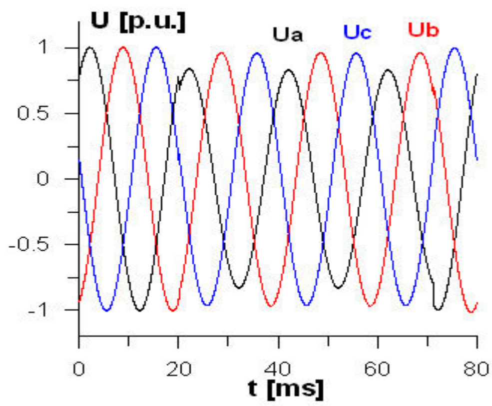

Fig. 11: The simulated U_{LV1} voltage traces of the nearest switchgear, when the short circuit is cleared with a contact CB
Ua, Ub, Uc – the voltages on the busbars U_{LV1}

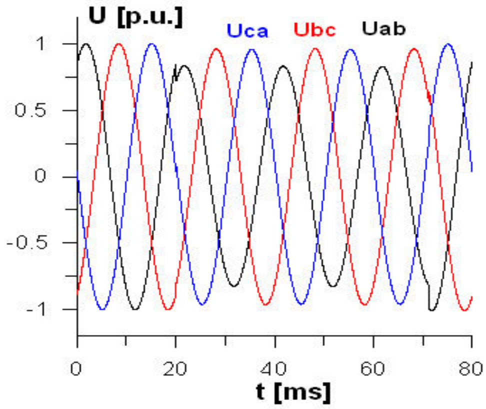

Fig. 12: The simulated U_{MV} voltage traces when the fault is cleared with a contact CB
Uab, Ubc, Uca – the voltages on the busbars U_{MV}

In Fig. 13,14,15 similar simulated voltage traces of the interruption of the short circuit current are presented when a hybrid circuit breaker with the switching off time $\Delta t = 2$ ms was used.

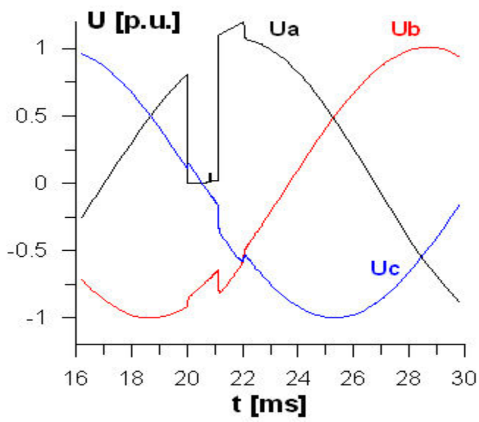

Fig. 13: The simulated U_{LV} voltage traces when the fault was cleared with the CHCL
Ua, Ub, Uc – the voltages on the busbars U_{LV}

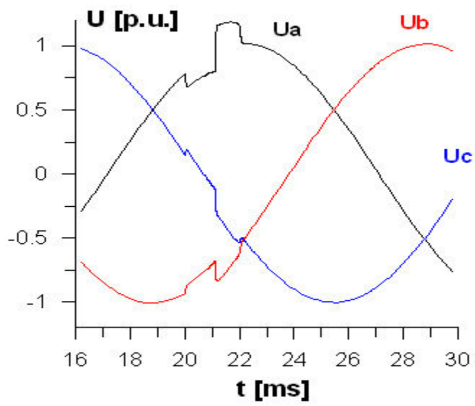

Fig. 14: The simulated U_{LV1} voltage traces when the fault was cleared with the CHCL.
Ua, Ub, Uc – the voltages on the busbars U_{LV1}

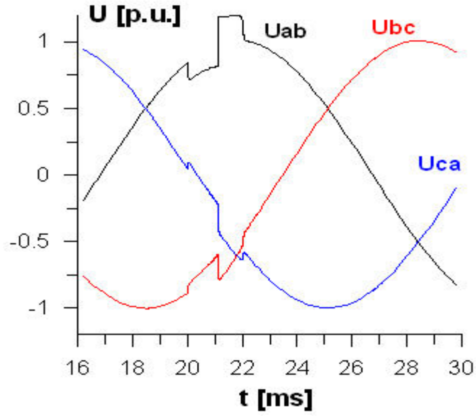

Fig. 15: The simulated U_{MV} voltage traces when the fault was cleared with the CHCL
Uab, Ubc, Uca – the voltages on the busbars U_{MV}

Owing to the application of the hybrid CB the time of power supply disturbance was significantly reduced. Since this time does not exceed several ms, the disturbance cannot be called „voltage dip" any more, if the definition by [1] is taken under consideration.

5. Effect of the IGBT control on the operation of a hybrid circuit breaker

In the operation of a hybrid circuit breaker an important problem is the proper control of the semiconductor device [13]. Delayed turn-off causes an increase in the cut-off current, while in the case of an early turn-off, there is the possibility that the gap in the molten fuse element will be too short and will not withstand the recovery voltage. Durations of the fuse element melting and the increase in the recovery dielectric strength are associated with the cut-off current, while the recovery voltage, which must be withstood by the limiter, depends on the actual state of the power system. Any delay in the cut-off process is detrimental, as it increases the limited current, fault clearing time and the energy allowed through by the hybrid circuit breaker.

Selection of the optimal making and cut-off moment of the semiconductor device is of great significance for the quality of the power supply. The shorter the duration of the short circuit fault, the sorter the duration of the voltage disturbance in the power system will be. However, selection of very short turn-on and let-through times of the IGBT will cause the arc reignition, and this way an increase in the duration of disturbance in the power delivery and the possibility of current limiter damage.

A considerable limitation of the disturbance duration is achieved using a hybrid circuit breaker. In this case, the time necessary to eliminate a disturbance depends, to a great degree, on the IGBT control delay.

However, the selection of the optimum current let-through time of the semiconductor device is a very complex issue. It should be as short as possible from the point of view of the quality of the supplied power. On the other hand, taking into consideration the current transfer requirements it must be long enough to allow for the disintegration of the fuse element and the recovery of dielectric strength of the fuse, in order to prevent the reignition.

6. Summary

The proposed model of CHCL enables simulation of the short circuit current interruption. The difference between calculation results and measurements are quite modest.

The CHCL model used for simulation of a short-circuit current interruption in an example network confirms the expected effect of voltage dips reduction by the hybrid current limiter.

Since CHCL operation depends on current in a similar manner as a classic fuse, the level of voltage dips changes as short circuit conditions in contradiction to other hybrid current limiters.

Pre-arcing time depends of the fuse element dimensions. However the arcing and SD operation times are linked to the fuse element decomposition and the recovery of voltage strength. In advantageous conditions the time needed to eliminate the short circuit by this switch is in the order of several hundred μs.

Appropriate control of the semiconductor device plays an important role in the CHCL operation. The fuse-element burn-back time and the gap deionisation have to be taken under consideration.

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