HYBRID SWITCHING IN A DIRECT CURRENT CIRCUIT

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The hereby study describes the benefits delivered by hybrid switching in a direct current (DC) circuit in comparison with electromechanical and static switching. In order to highlight the benefits, we analyse herein three types of switching: electromechanical switching, static switching and hybrid switching. With respect to these, certain simulations were conducted using PSpice, for a low-voltage DC circuit, low voltage, $U_n = 750V$ *. The load of the circuit is resistive-inductive. The results show the performance achieved in the case of the hybrid circuit breaker, the flow of the short-circuit current through 0 was achieved in 0,4 ms, and the amplitude of maximum short circuit current which is 0,6 kA is much lower than current in the case of electromechanical breaker. In the same circuit, the static circuit breaker ensured the shortest switching off time for short-circuit current, of about 150 μs, but, in this case, a proper protection to switching overvoltage must be ensured, as it has a value of 2,1 kV.*

Keywords: electrical switching, electrical circuits, simulation

1. Introduction

Because in the DC circuits is no natural flow of current through value zero, as in alternating current (AC) circuits, current switching in electromechanical circuit breakers occurs by means of external conditions, which force the flow through zero [1]. Due to the presence of the arc, these circuit breakers need constant maintenance and have limited endurance. An alternative solution to mechanical circuit breakers is represented by static and hybrid circuit breakers. The development of semiconductor power devices like IGCT *(Integrated Gate-Commutated Thyristor)* [2] allowed them to be used in different types of static [3] and hybrid circuit breakers [4], [5].

The combination between a static device and an electromechanical circuit breaker, in a certain configuration, is represented by a hybrid circuit breaker. Therefore, the hybrid circuit breaker uses the advantages provided by electromechanical circuit breakers, the low resistance of mechanical contacts and the lack of arcing of static circuit breakers. The main producers of electrical switching devices have designed hybrid switching circuit breakers, deployed for various industrial applications.

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Static circuit breakers supply several advantages in comparison to mechanical circuit breakers, starting with the fact that it takes a few μs [6] to switch current off, while conduction loss remains the main fault.
Static circuit breakers are arc-free, while hybrid circuit breakers produce arcing at very low intensity.

In this paper we analyze the process of switching for three types of switches at the appearance moment of a short-circuit current in a traction network with nominal voltage. The load of the circuit is resistive-inductive. In the simulations realized with PSpice program, we observe the performances of three types of circuit breakers and we can choose the optimal variant for the traction network.

2. Theoretical considerations

In a DC circuit, current may be switched off by electromechanical, static or hybrid circuit breakers. In order to analyse the switching process for all three types of circuit breakers, we begin by providing a theoretical description of these.

2.1 Electromechanical circuit breaker

The breaking of short – circuit currents can cause the damage of mechanical contacts or other device components due to electro-dynamic stress. At the closing sequence of the electromechanical circuit breakers, the electrical arc can occur between the mechanical contacts but its effect is negligible. Electromechanical circuit breakers need constant maintenance [1].

2.1.1 Breaking the nominal current

While breaking nominal current between the electromechanical circuit breaker contacts, an arc is generated but its breaking doesn't endanger the device, as it can switch this current off really quickly and the arc has little energy. Below, we provide a circuit diagram equivalent to a DC circuit, where nominal current is broken [1].

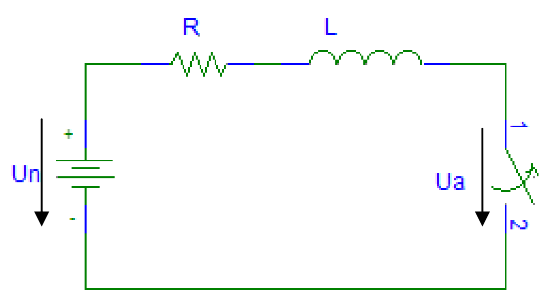

Fig.1. Circuit diagram of the DC circuit at nominal current breaking

Un – stands for the nominal value of the power-supply voltage

R – stands for the equivalent circuit resistance
L – stands for the equivalent feeder and receiver inductance
Ua – stands for the arc voltage

When the circuit breaker switches on, the arcing produces between its contacts. The arc voltage *Ua*, is higher than the power-supply voltage *Un*.

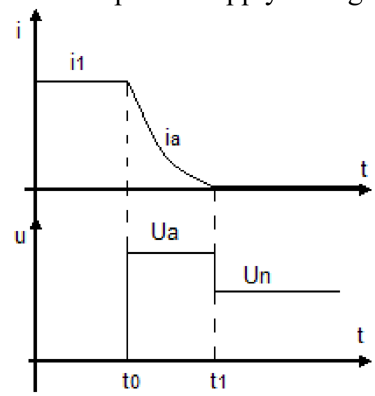

Fig.2. Wave forms at nominal current breaking

Where:
i_1 – stands for the instantaneous value of the nominal current in stationary regime,$i_1 = I_n$
i_a – stands for the instantaneous value of the broken current
t_0 – stands for the time when separation of the circuit breaker contacts begins
t_1 – stands for the time of arc breaking
t_a – stands for the arc duration, $t_a = t_1 - t_a$

The circuit equation at arcing is:

$$U_n = Ri_a + L\frac{di_a}{dt} + U_a, \quad (1)$$

$$U_n - Ri_a - L\frac{di_a}{dt} - U_a = 0, \quad (2)$$

This equation shows that current i_a can be forced to become zero only if the arc voltage U_a is higher than the power-supply voltage. The expression for this current is [1]:

$$i_a = I_n - \frac{U_a}{R}\left(1 - e^{\frac{-t}{T}}\right). \quad (3)$$

Where:
T - stands for the time constant, $T = L/R$.

2.1.2 Breaking the short-circuit current

The electromechanical circuit breaker is subjected to thermal and electro-dynamic stress during breaking of the short-circuit current. Below, we provide a circuit diagram equivalent to a DC circuit where a short-circuit current is broken.

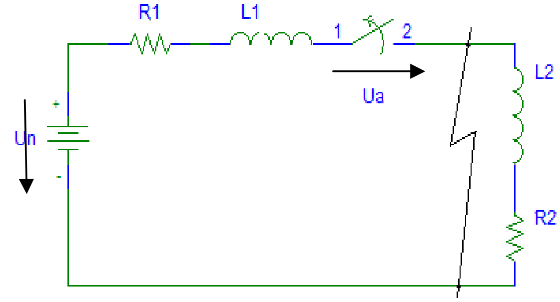

Fig.3. The circuit diagram of the DC circuit for breaking of the short-circuit current

– stands for the equivalent circuit resistance

– stands for the equivalent feeder inductance

– stands for the charge resistance

– stands for the charge inductance

The short-circuit current appears in moment , thus the current starts increasing through the circuit breaker. The electromechanical circuit breaker receives an opening command, starts separating contacts at moment and the arc is generated [1].

During the entire period of arc breaking, the arc voltage is higher than the power-supply voltage and this can be observed. To break the arc, the circuit breaker must create certain cooling conditions in the extinction chamber and at the time it is produced the interruption of short-circuit current. Depending on the type of electric circuit, the circuit breakers can be disposed in series [7] for a better protection to short-circuit currents.

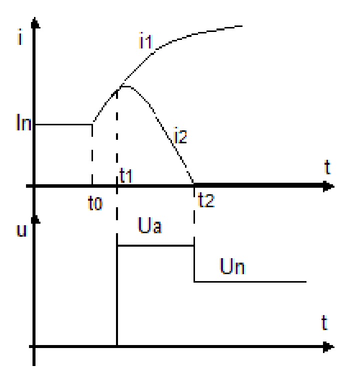

Fig.4. Wave forms at short-circuit current breaking

i_1 – stands for the prospective short-circuit current
I_n– stands for the nominal current
t_0 – stands for the moment of short-circuit current
t_a – stands for the arc duration, $t_a = t_2 - t_1$
t_p– stands for the pre-arcing duration, $t_p = t_1 - t_0$

The circuit equation at arcing is:

$$U_n = R_1 i_2 + L_1 \frac{di_2}{dt} + U_a\,, \tag{4}$$

$$L_1 \frac{di_2}{dt} = U_n - R_1 i_2 - U_a, \tag{5}$$

The successful arc-breaking occurs if:

$$L_1 \frac{di_2}{dt} < 0, \tag{6}$$

The determination ratio for the prospective short-circuit current is:

$$i_1 = I_{sc}\left(1 - e^{-\frac{t+(t_1-t_0)}{T}}\right) + I_n e^{-\frac{t+(t_1-t_0)}{T}}, \tag{7}$$

If we know the arc and pre-arcing duration, the values of the stabilized short-circuit currents and, respectively, the nominal current value are known, the ratio of the arc voltage can be calculated [1] :

$$U_a = R_1 \frac{I_{sc}(1-e^{-\frac{t_p+t_a}{T}} + I_n e^{-\frac{t_p+t_a}{T}})}{(1-e^{-\frac{t_p+t_a}{T}})}. \tag{8}$$

2.2 Static circuit breakers

Static switching electrical devices more frequently used in DC circuits are contactors and relays. In the last years, due to progress in the development of power semiconductor devices such as IGBT, GTO and IGCT, they have become more and more frequently used for the development of static circuit breakers [8]. Power semiconductors are used in switching processes in the electric circuits due to their quick reaction, safe functioning and also because they do not need maintenance. Unlike mechanical circuit breakers, they do not have any mobile contacts, therefore no arc is generated. IGCT (Integrated Gate-Commutated Thyristor) is a semiconductor device combining the advantages delivered by two power semiconductor devices: the IGBT transistor and the thyristor. Therefore, IGCT acts like an IGBT in the blocking process and like a thyristor in the conduction process [2]. Now, there are such devices that are capable of breaking currents of up to *4 kA* and block voltages of up to *4,5 kA*. Their switching frequency is up to *1 kHz*. Current breaking can occur in 1ms. The main advantage of IGCT is that it can be cooled at both ends. Static circuit breakers for medium voltage were also produced and documented; the study [6] presents a static circuit breaker that uses IGCT. The circuit breaker can break current in maximum *100 µs*. As concerns static circuit breakers, the closing sequence is produced through a resonance circuit in series with the main semiconductor device, by placing over it, at the same time, a capacitor with semiconductor-operated discharge, positive closing. As for forced commutation, the parallel circuit acts only on the closing sequence, unlike the series capacitor. There are also other closing methods [9], but these are the main ones.

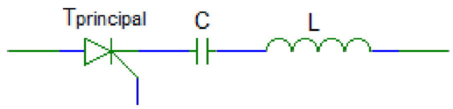

Fig.5. The switching of the main static circuit breaker through a serial resonance circuit

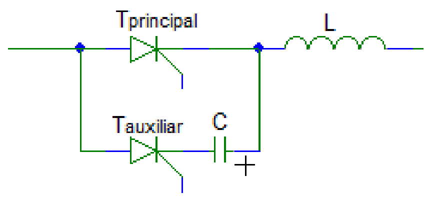

Fig.6. The switching of the main static circuit breaker through simultaneous use of a capacitor and an operated, semiconductor device

2.3 Hybrid circuit breakers

The hybrid switching technique is used in circuit breakers and also in contactors. From a constructional perspective, the hybrid circuit breaker is a mechanical circuit breaker that has a parallel commutation circuit installed. The commutation circuit is represented by static circuit breakers in series with a *LC* circuit [8]. The main mechanical circuit breaker ensures the path of current for normal functioning. The parallel part acts only in the phase of current switching. The figure below shows the basic diagram of a hybrid circuit breaker, where capacitor *C* is preloaded. Tyristor *T* triggers its discharge *T*. Varistor *V* supplies overcharge protection.

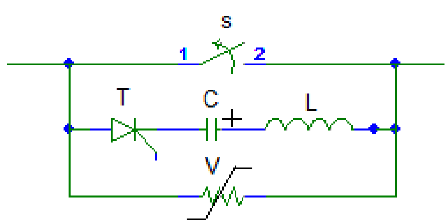

Fig.7. Basic diagram of a hybrid circuit breaker

There are many researches on hybrid circuit breakers for both direct and alternating current. Studies [8] and [4] show and focus on the types of hybrid DC circuit breakers, while study [5] describes an AC circuit breaker.

The hybrid circuit breaker breaks interrupts currents quicker than a mechanical circuit breaker. Still, an arc appears between the mechanical contacts of the hybrid circuit breaker, but its intensity is much lower than that of a classical mechanical circuit breaker. Compared to a static circuit breaker, this doesn't suffer much conduction loss as the nominal current flows through the contacts of the mechanical circuit breaker.

3. Analysis of the switching process

3.1 Hybrid switching simulation

Fig. 8 shows the PSpice simulation diagram of a circuit using a hybrid circuit breaker [10]. The figure doesn't illustrate the preloading circuit of the capacitor. The components have the following values: power-supply $V1 = 750\ V$, feeder resistance $L1 = 40\ \mu H$, charge resistance $R2 = 3\ \Omega$, charge inductance $L2 = 150\ \mu H$, commutation capacitor $C1 = 1100 \mu F$ and initial charge $Vco = -1000\ V$, commutation inductance $L3 = 150\ \mu H$. Assembly *S3– D1*, stands for the one-way operated static circuit breaker. This assembly, along with inductance *L3* and the commutation capacitor *C1* stands for the commutation circuit of the hybrid circuit breaker and *S1* stands for its electromechanical part.

The commutation circuit shall create an current which is opposite to the current through the electromechanical circuit breaker. The commutation capacitor shall discharge and in this way is created the flow of current through value zero. In our case the oscillation frequency of current is

$f = 392Hz$. Maximum current provided by the commutation capacitor *C1* is $Ic = 2700A$. The dimensioning of commutation circuit was done in a previous paper realized by the authors of this article.

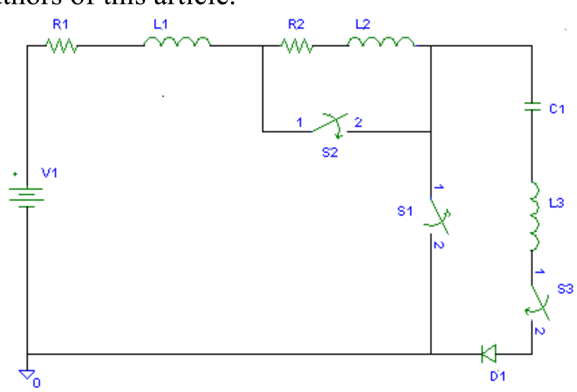

Fig. 8. Circuit diagram for hybrid switching

Switching control: the load is short-circuited by means of the *S2* circuit breaker closing at moment $t = 2\ ms$. The electromechanical circuit breaker *S1* receives an opening command at $t=2,1\ ms$ and the opening of the static circuit breaker (assembly *S3–D1)* occurs at $t = 2\ ms$. Transition time of electromechanical circuit breaker *S1,* from closed to open position is *1,8 ms*. Transition time of static circuit breaker (assembly *S3-D1*), from open to close position is $60 \mu s$. The value of the contact resistance for the circuit breaker *S1* is $r = 0{,}01\Omega$. The value of the resistance for static circuit breaker is $r = 1\ \Omega$.

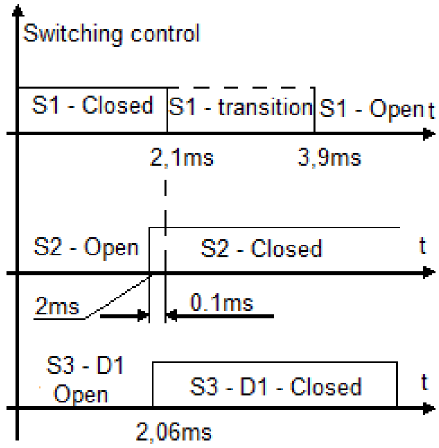

Fig.9. Diagram for the switching control

The switching times of the circuit breakers have been set in PSpice program. The value of these times was chosen according to technical characteristics of an electromechanical DC circuit breaker for low voltage, respectively an thyristor. Using the simulations in PSpice we obtain the figure below that shows the wave forms of the current and voltage for the opening sequence of mechanical contacts of the hybrid circuit breaker.

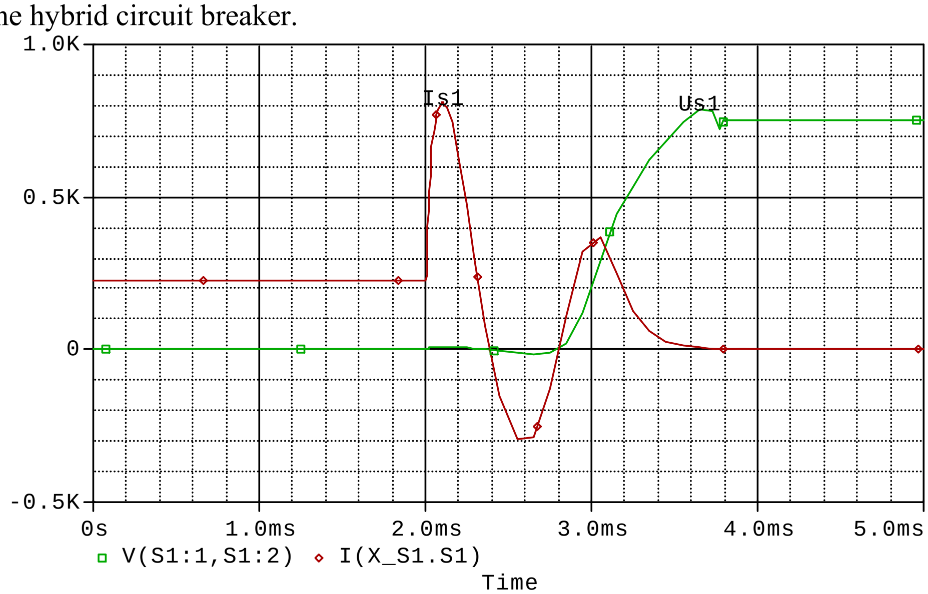

Fig. 10 . Current and voltage wave form on S1, hybrid switching

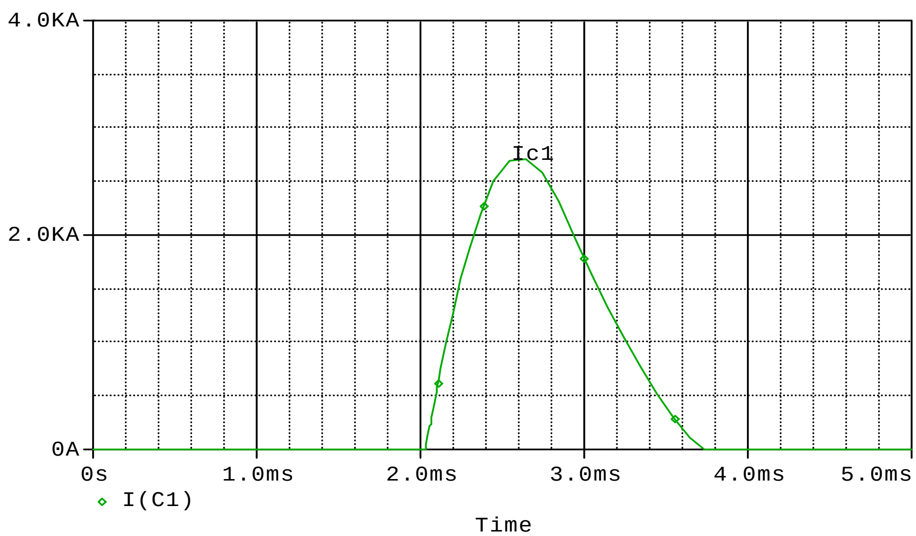

Fig. 11 . Discharge current of the capacitor, hybrid switching

In the above wave forms we can see that the discharge current is injected when the breaker *S3* is closed. This fast current limits the short-circuit current through *S1* (electromechanical circuit breaker) and forces the current to pass through zero value. The first flow of current through value zero occurs at the time of *0,4ms*.

3.2 Static switching simulation

The simulation diagram keeps the same value for the power-supply network components and the same charge value.

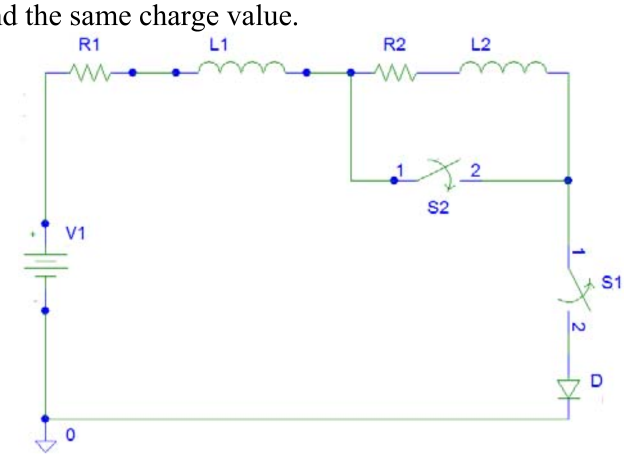

Fig. 12. Circuit diagram for static switching

Assembly *S1-D* stands represent a controlled static circuit breaker and its closing time (closed - open position) is *60 μs*. The short-circuiting time and the opening

command time for the circuit breaker coincide with the time of the hybrid switching simulation, at moment *t = 2 ms*.
Below is represented the diagram for the switching control.

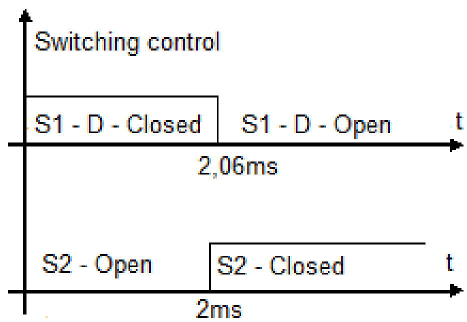

Fig.13. Diagram for the switching control

Using the simulations in PSpice we obtain the figure below that shows the wave forms of the current and voltage for the static circuit breaker.

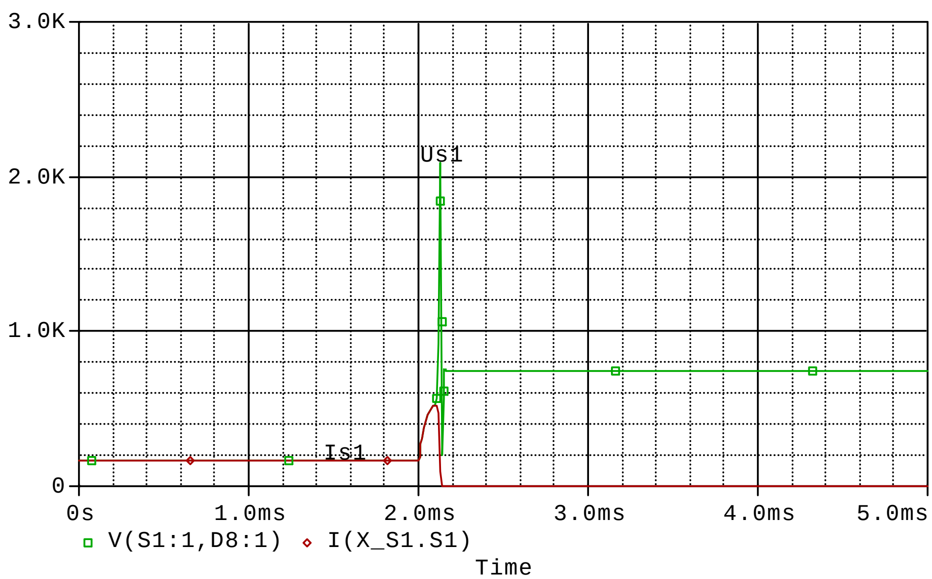

Fig. 14. Current and voltage wave form, static switching

In the above wave forms we can see that the time of interruption of the short-circuit current is *0.15 ms*, a very short time, but in the process of switching occurs an overvoltage of *2,5 kV*.

3.3 Simulation of electromechanical switching

The simulation diagram keeps the same value for the power-supply network components and the same charge value. The elctromechanical circuit breaker *S1* receives the opening command at *t=2,1 ms*. Transition time from closed to open position is *1,8 ms*. The contact resistance of the electromechanical circuit breaker *S1* is $r = 0,01\Omega$.

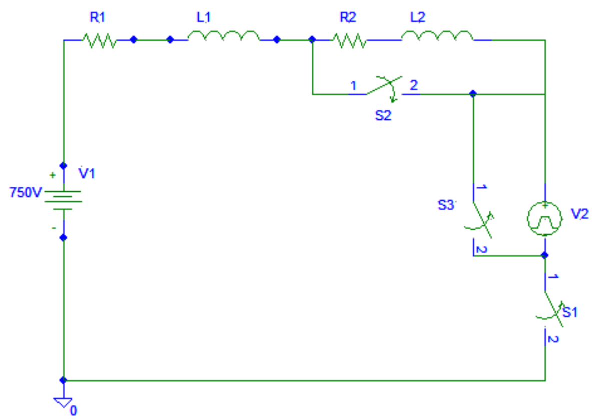

Fig. 15. Circuit diagram for mechanical switching

The electromechanical circuit breaker must generate a reverse arc voltage, opposed, as sense, to the power-supply voltage, producing a flow of current through value zero. The reverse arc voltage must be about 1,3-1,8 times higher than the power-supply voltage, in order to ensure arc extinction.
To simulate the arc voltage which appears at the opening sequence, we introduced in circuit the power supply *V2*. The power supply provides a pulse voltage with value of *975V*. The shorting of the load is realized through the breaker *S2* which closes at $t = 2ms$. At the time of the short circuit, the breaker *S3* is closed and introduces in circuit the power supply *V2* so that is simulated the arc voltage.
Practically, the interruption of the short-circuit current in electromechanical circuit breakers is realized by a lengthening and cooling of the arc in the extinction chamber. The time of electric arc in the extinction chamber is directly proportional with the circuit time constant *T* and a parameter λ, which is a property of switchgear [1]. So that, for reducing the duration of the arc is necessary to decrease the time constant of the circuit and also the parameter λ. The decreasing of the parameter λ is achieved by increasing the arc voltage.
In normal regime, *S3* and *S1* are closed, so the nominal current passes through the following components: *V1-R1-R2-L1-L2-S1-S3*. Transition time from the closed

to open is *2μs* for the breaker *S3* and its resistance is *100μΩ*. These parameters were set to not influence significantly the interruption process.
Below is represented the diagram for the switching control.

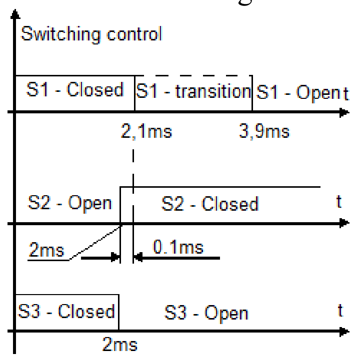

Fig.16. Diagram for the switches control

Using the simulations in PSpice we obtain the figure below that shows the wave forms of the current and voltage for the electromechanical circuit breaker.

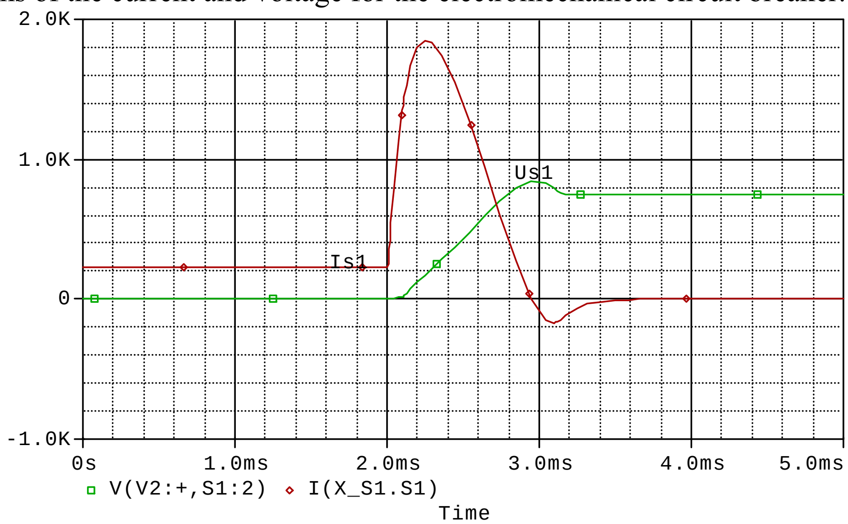

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Fig.17. Current and voltage wave form, electromechanical switching

In the above waveforms we can see that the short-circuit current reaches the maximum value of *1,9 kA* and its interruption is realized in a time of *1,6 ms*. The first passing through value zero occurs after *0,9 ms*. The pre-arc time has a duration of *0,1 ms.*

4. Conclusions

The simulations realized on the traction circuit have highlighted the behaviour of three types of circuit breakers on the base of simulations with a specialized program. As a result of simulation and analysis we can choose the optimal type of breaker that can be used in such a circuit.

In the case of the hybrid circuit breaker, the values of its components were dimensioned and optimized according to parameters of electrical circuit where it was installed. In the simulation performed, the hybrid circuit breaker has reduced quickly the amplitude of the short-circuit current and produced the first flowing through zero in *0,4 ms*. The maximum amplitude of the short-circuit current trough the hybrid circuit breaker is *0,6 kA*. The total switching off time is *1,6 ms*, value equal with that obtained in the case of the electromechanical circuit breaker.

The amplitude of the short-circuit current has reached a maximum value of *1,9 kA* in the electromechanical circuit breaker. The lowest switching off time for the short-circuit current was achieved by the static circuit breaker, in *0,15ms*. In this case, also, the highest device overvoltage switching was reached, at *2,1 kV* and the conduction loss is not insignificant.

Comparing the simulations performed and analysing the efficiency of short-circuit current switching off in the described circuit we find that the hybrid circuit breaker represents the optimal solution for the described circuit.

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