Journal of Energy Technology

JET Volume 14 (2021) p.p. 11-22
Issue 3, November 2021
Type of article 1.01
www.fe.um.si/en/jet.html

TRANSIENT CIRCUIT SIMULATION OF ARC-FREE CURRENT BREAKING BY RESISTANCE RISE

ČASOVNO ODVISNA SIMULACIJA TOKA ODKLOPNIKA BREZ OBLOKA IN NARAŠČAJOČO UPORNOSTJO

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Keywords: current breaking, ATP-EMTP, time-dependent resistance, optimisation, concave & convex functions.

Abstract

There has been intensive research and development in the field of Circuit breakers, whether DC and AC, or low voltage and high voltage. The result of this has led to the production of highly reliable circuit breakers that accompany a built-in arc extinguishing system. However, the purpose of this study is to give the basics for arc-free current breaking with fast interruption of fault currents, e.g., in surge protective devices (SPD) for AC and DC systems, by means of a time-dependent resistor with fast rising resistance. This investigation shall illustrate how the current can be driven almost to zero with a steadily time increasing resistance, and interrupted completely without an electric arc. The basic aim of the conducted transient circuit simulations is to determine suitable time functions for the current or resistance and necessary initial and final resistances. This paper will discuss the "optimisation conditions", a switching time as short as possible, small switch-off overvoltage, and possibly an energy conversion in the resistor as low as possible is set using ATP-EMTP and analytical calculations.

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Povzetek

Na področju odklopnikov, bodisi enosmernega ali izmeničnega toka, nizke ali visoke napetosti, poteka veliko raziskav, kar rezultira v proizvodnji zelo zanesljivih odklopnikov, ki spremljajo vgrajeni sistem za gašenje obloka. Namen tega članka je pokazati osnove za odklop električnega toka brez obloka s hitrimi prekinitvami okvarnih tokov, npr. v prenapetostnih zaščitnih napravah za izmenične in enosmerne sisteme s pomočjo časovno odvisnega upora s hitro naraščajočo upornostjo. Ta študija ponazarja, kako lahko električni tok prekinemo z enakomerno naraščajočo upornostjo in kako ga lahko popolnoma prekinemo brez električnega obloka. Glavni cilj izvedenih simulacij je določitev ustreznih časovnih funkcij za električni tok ali upor ter potrebne po začetnih in končnih upornostih. V članku so predstavljeni »optimizacijski pogoji«: čim krajši preklopni čas, majhna izklopna prenapetost, in morebitna čim nižja pretvorba energije v uporu, ki je določena z uporabo ATP-EMTP in analitičnih izračunov.

1 INTRODUCTION

In conventional switches (circuit-breakers), switching principles are applied based on electric arc interruption [1], [2]. The arc plasma, with its high temperature, intense radiation and stochastic behaviour, can lead to destruction, erosion and ageing. Arc-free switching, especially breaking of large currents with switching devices of equally small size is therefore desirable. Many considerations, especially in the DC sector, are given to power electronic switches or hybrid switches, which, however, usually require several "chop" switching operations [3]. Here, on the other hand, steady resistance increases $R(t)$ or $R(t,i(t))$ of a lumped solid resistor are to be investigated for switching off. Although this switching principle is supposed to be applicable for AC and DC as well as independent of the voltage level, the temporal resistance elevation corresponds to the so-called DC or low-voltage switching principle (current-limiting).

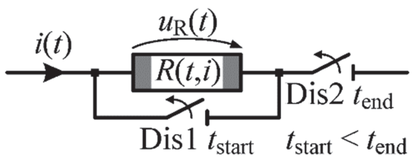

***Figure 1**: Schematic of switching device with time-dependent resistor*

For the defined start and end of the switching operation, the auxiliary switches in Fig.1 are recommended, exclusively, disconnectors (Dis1, Dis2) without breaking capacity. The conditions for these auxiliary switches are derived, and these are, in particular, the resistance values of the resistor at the start and at the end.

The basic question to be clarified is which continuous time function of resistance enables an ideal switch-off. This requires the solution of an optimisation task with regard to the switch-off overvoltage and the energy in the resistor.

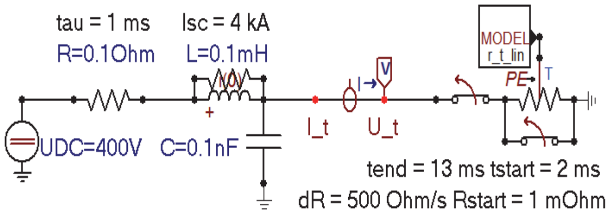

Figure 2: *Single-pole ohmic-inductive DC circuit for transient simulation in ATPDraw*

The study was carried out using analytical and numerical network analysis (Fig.2), using ATP-EMTP with ATPDraw interface [4] for circuit simulation.

2 PRINCIPLE OF OPERATION

The time-dependent resistance was simulated in ATP-EMTP with a TACS resistor, which is controlled by a time function programmed in MODELS [4]. Fig.3 shows a transient switch-off process with linearly increasing resistance in a DC circuit with a moderate time constant.

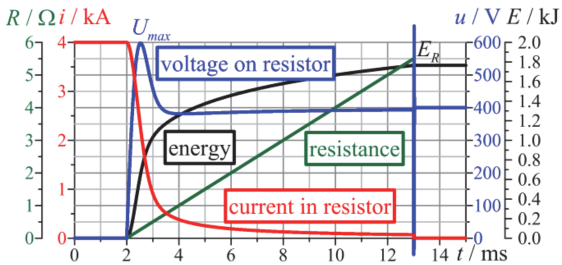

Figure 3: *Switching off with a linear rise of resistance in the ohmic-inductive DC circuit*

In order to allow a switch-off process to start from a steady-state operation and to be completed without numerical oscillations, the "switching conditions" must be considered in the numerical solution of the differential equation system (the trapezoidal rule used in ATP-EMTP).

2. 1 Conditions for opening of the first disconnector, Dis1

With reference to Fig.1, the closed disconnector Dis1 carries the current to be interrupted until the breaking process starts with the help of the resistor. This disconnector thus represents the low impedance bridging of the initial value R1 of the resistor.

Opening Dis1 at the instant start triggers the breaking process. To avoid ignition of an arc in the disconnector, the minimum arc voltage Uarc,min = 20 V to 40 V must be undercut when opening: $U_1 = R_1 \cdot I_1 < U_{arc,min}$. The limit value for the initial resistance R1 can be calculated with the instantaneous current I1 to be switched off: $R_1 \leq U_{arc,min}/I_1$. If the instantaneous current is not known, then the short-circuit current ISC in the circuit can be used for worst-case consideration: $R_1 \leq U_{arc,min}/I_{SC}$. Regardless of the voltage level, short-circuit currents are in the range ISC = 500 A ... 50 kA.

e.g. $U_{arc,min}$ = 40 V I_{SC} = 4 kA → $R_1 \leq 10$ mΩ

e.g. $U_{arc,min}$ = 20 V I_{SC} = 20 kA → $R_1 \leq 1$ mΩ

Because of the small voltage U1 = Uarc,min and the finite voltage rise across the resistor, re-ignition of disconnector Dis1 is unlikely.

2. 2 Conditions for opening the second disconnector, Dis2

The current i(t), decreasing due to the increasing resistance R(t), flows through the closed disconnector Dis2. Because the current cannot become exactly zero with a finite resistance R(t) and an isolating clearance is to be established, disconnector Dis2 is necessary.

Opening Dis2 at time end is the final completion of the breaking process. Opening the disconnector Dis2 without igniting an arc is possible if the current i(t) falls below the minimum arc current Iarc,min = 0.5 A to 1 A. Since the resistance R(t), which increases with time, becomes much larger than the line impedance or short-circuit impedance, the necessary resistance value R2 for the minimum arc current Iarc,min can be estimated with the open-circuit voltage UOC = 100 V – 100 kV of the system: $R_2 \geq U_{OC}/I_{arc,min}$.

e.g. $I_{arc,min}$ = 0.5 A U_{OC} = 250 V → $R_2 \geq 0.5$ kΩ

e.g. $I_{arc,min}$ = 1 A U_{OC} = 11.6 kV → $R_2 \geq 11.6$ kΩ

With the small current, the voltages across the disconnector Dis2 and voltage across the resistor R(t) = R2 should also be small enough to prevent re-ignition and flashover.

3 TEST SETUP AND SIMULATIONS

A brief introduction was given regarding the software ATPDraw and ATP-EMTP, which is being used here to simulate a circuit that represents a short circuit current of different magnitudes. As shown in the circuit diagram reported in Fig.2, we have a DC source, a series resistor and an inductor. This series resistor is used to change the short circuit current magnitude, whereas the inductor is used for changing the time constant, or it can actually realise how different voltage levels can affect our system. Then there is a variable resistor, which is controlled using programmable MODELS [4]. This can be programmed for a resistance rise using a linear function as well as non-linear, i.e., quadratic, or exponential, and also to calculate multiple characteristics during this rise of resistance taking place.

3. 1 Model and resistance rise functions

The model is programmed with different resistance rise functions in order to identify the optimal one.

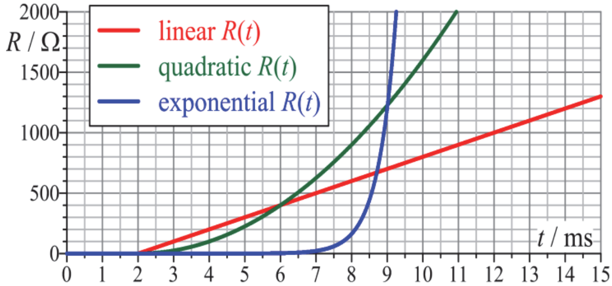

Figure 4: *Output of different resistance rise with respect to time*

With linear resistance rise, even after a very long time, the final resistance is not very high. This is not very suitable, because, if we want to decrease and limit the high short circuit current near to zero, we need the resistance to be high enough so that there is no arc. This can be achieved with a high rate of resistance rise, but it will also create a high Umax, i.e., voltage across the Dis1 which will cause arcing, as well as may cause it to reclose. Using a quadratic function, the resulting resistance rise can be seen (Fig.4). This solves the problem of high Umax, since the resistance rise is slow at the start. Moreover, the resistance rise also reaches the desired value for the current limiting. The only issue here is that it takes a large time to reach that value. The exponential rise function gives the best result in terms of the resistance at the beginning of the current breaking process, as well as at the end. Since at the start when Dis1 in parallel to resistance opens, we need a small resistance so that the product with a high short circuit current results in a smaller Umax, but then an exponential rise to a high enough value that can limit the current to a near zero value easily in a short time, so that the overall stress on the system is minimal.

4 MATHEMATICAL MODELLING

The main goal is to achieve a time-based function for the variable resistance which enables ideal switch-off in the DC circuit, and which we can implement for all cases and scenarios. This requires the solution of an optimisation task regarding the switch-off time and the switch-off overvoltage.

4. 1 Time function based on Current

The optimisation goal is to search for an optimal time function of resistance R(t) to break a short circuit current. Therefore, instead of trying to model resistance functions in search of an optimum solution from them, we can work with the current functions.

$$U_{DC} = R_n \cdot i(t) + L_n \cdot \frac{di(t)}{dt} + R(t) \cdot i(t) \quad i(0) = \frac{U_{DC}}{R_n}$$

$$i(t) = \left(\frac{U_{DC}}{L_n} \cdot \int_0^t e^{-\int_0^T \frac{R_n + R(\vartheta)}{L_n} d\vartheta} dT + \frac{U_{DC}}{R_n} \right) \cdot e^{-\int_0^t \frac{R_n + R(T)}{L_n} dT}$$

However, these formulas are difficult to use for finding an optimal time course for breaking. What we can do is to replace our planned current breaking mechanism with another modelling and a controlled current source. Therefore, the search for the solution can be done by a predefined goal-function for i(t), as shown in Fig.5 below.

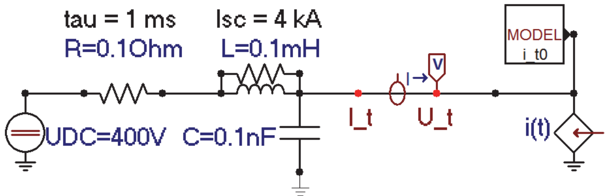

Figure 5: *ATPDraw circuit containing a current source controlled by a predefined current time function*

With the given time function of i(t) from tstart to the end above we can obtain tbreak. For the breaking voltage u(t) and its peak value on R(t) can be written:

$$u(t) = U_{DC} - R_n \cdot i(t) - L_n \cdot \frac{di(t)}{dt} \rightarrow U_{max}$$

The energy dissipated in resistance R(t) is:

$$E(t) = \int_0^t u(T) \cdot i(T)\, dT \rightarrow E_R = \int_0^{t_{break}} u(t) \cdot i(t)\, dt$$

There are many possible ways for the decrease of the short circuit current in a window from corner s to corner e according to Fig.6.

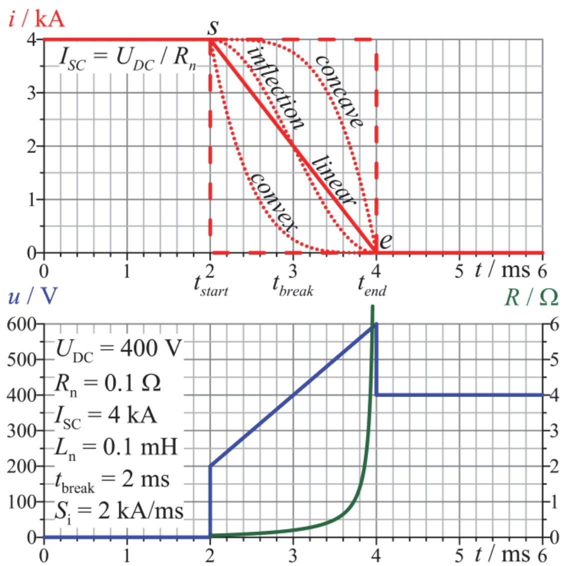

Figure 6: *Short circuit current decreasing in a time window and highlighted basic case linear decreasing current*

4. 2 Basic case

Analysing the linear decrease of i(t), where we have an initial high current, Rn·i(t) is high and constant current steepness over tbreak, Ln·di(t)/dt is not very high nor very low and the linear drop of current to zero (at s and e discontinuities) the function is:

$$i(t) = I_{SC} - S_i \cdot t \quad S_i = \frac{I_{SC}}{t_{break}} = \frac{U_{DC}}{R_n \cdot t_{break}} \quad I_{SC} = \frac{U_{DC}}{R_n}$$

$$i(t) = \frac{U_{DC}}{R_n} \cdot \left(1 - \frac{t}{t_{break}}\right) \quad u(t) = \frac{U_{DC}}{t_{break}} \cdot \left(t + \frac{L_n}{R_n}\right)$$

$$\Longrightarrow \quad u(0) = \frac{U_{DC}}{t_{break}} \cdot \frac{L_n}{R_n} \quad t(U_{max}) = t_{break}$$

$$U_{max} = U_{DC} \cdot \left(1 + \frac{L_n}{R_n} \cdot \frac{1}{t_{break}}\right)$$

$$R(t) = \frac{u(t)}{i(t)} = \frac{R_n \cdot t + L_n}{t_{break} - t}$$

$$R(0) = L_n / t_{break} \quad R(t_{break}) \to \infty$$

$$\boldsymbol{E(t) = \frac{U_{DC}^2}{R_n} \cdot \frac{t}{t_{break}} \cdot \left(\frac{t}{2} + \frac{L_n}{R_n} \cdot \left(1 - \frac{t}{2t_{break}}\right) - \frac{t^2}{3t_{break}}\right)}$$

$$E_R = \frac{U_{DC}^2}{R_n} \cdot \left(\frac{1}{6} \cdot t_{break} + \frac{1}{2} \cdot \frac{L_n}{R_n}\right)$$

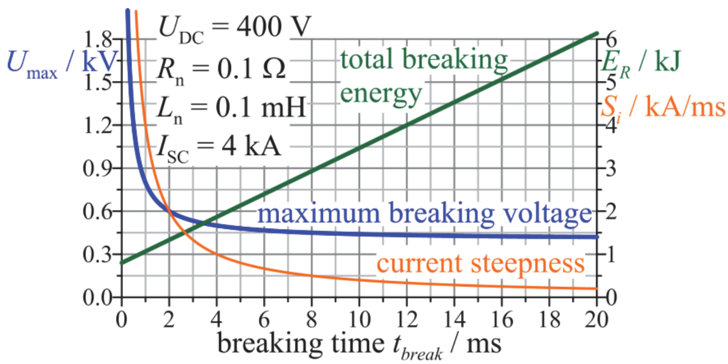

Figure 7: *Relation between maximum breaking voltage, total breaking energy, and breaking time for a linear decaying current*

Using fixed circuit parameters as shown in Fig.7, we obtained a relation between three important parameters for our study, Umax (on the y-axis left) and ER (on the y-axis right), with tbreak as the variable function. From this we can simply conclude that with increasing t_{break}, U_{max} tends to decrease, and ER increases, so we just have to find a common optimum solution.

4.3 Further cases

Using the same procedure as for the linearly decreasing current, many other current functions can be tested, and resistance functions can be calculated from them. Some selected suitable current functions are those listed below.

Concave quadratic function:

$$i(t) = \frac{U_{DC}}{R_n} \cdot \left(1 - \frac{t^2}{t_{break}^2}\right) \qquad R(t) = \frac{u(t)}{i(t)} = \frac{(R_n \cdot t + 2 \cdot L_n) \cdot t}{t_{break}^2 - t^2}$$

Convex quadratic function:

$$i(t) = \frac{U_{DC}}{R_n} \cdot \left(1 - \frac{t}{t_{break}}\right)^2$$

$$R(t) = \frac{R_n \cdot t \cdot (2 \cdot t_{break} - t) + 2 \cdot L_n \cdot (t_{break} - t)}{(t_{break} - t)^2}$$

Concave nth power function:

$$i(t) = \frac{U_{DC}}{R_n} \cdot \left(1 - \frac{t^n}{t_{break}^n}\right) \quad n = 1, 2, 3, \dots \quad R(t) = \frac{(R_n \cdot t + n \cdot L_n) \cdot t^{n-1}}{t_{break}^n - t^n}$$

Convex nth power function:

$$i(t) = \frac{U_{DC}}{R_n} \cdot \left(1 - \frac{t}{t_{break}}\right)^n \quad n = 1, 2, 3, \dots$$

$$R(t) = R_n \cdot \left(\frac{t_{break}}{t_{break} - t}\right)^n - R_n + \frac{n \cdot L_n}{t_{break} - t}$$

Concave exponential function:

$$i(t) = \frac{U_{DC}}{R_n} \cdot \left(e \cdot \left(1 - \frac{t}{t_{break}}\right) + 1 - e^{1 - \frac{t}{t_{break}}}\right)$$

$$R(t) = \frac{R_n \cdot e \cdot \left(t_{break} \cdot \left(e^{-\frac{t}{t_{break}}} - 1\right) + t\right) + L_n \cdot e \cdot \left(1 - e^{-\frac{t}{t_{break}}}\right)}{t_{break} + e \cdot t_{break} \cdot \left(1 - e^{-\frac{t}{t_{break}}}\right) - e \cdot t}$$

Convex exponential function:

$$i(t) = \frac{U_{DC}}{R_n} \cdot \left(e^{\frac{t}{t_{break}}} - e \cdot \frac{t}{t_{break}}\right)$$

$$R(t) = \frac{R_n \cdot e \cdot \left(t_{break} \cdot \left(1 - e^{\frac{t}{t_{break}}}\right) + t\right) + L_n \cdot \left(e - e^{\frac{t}{t_{break}}}\right)}{t_{break} \cdot e^{\frac{t}{t_{break}}} - e \cdot t}$$

Concave trigonometric function:

$$i(t) = \frac{U_{DC}}{R_n} \cdot cos\left(\frac{\pi}{2} \cdot \frac{t}{t_{break}}\right)$$

$$R(t) = \frac{R_n \cdot \left(1 - cos\left(\frac{\pi}{2} \cdot \frac{t}{t_{break}}\right)\right) + \frac{\pi}{2} \cdot \frac{L_n}{t_{break}} \cdot sin\left(\frac{\pi}{2} \cdot \frac{t}{t_{break}}\right)}{cos\left(\frac{\pi}{2} \cdot \frac{t}{t_{break}}\right)}$$

Convex trigonometric function:

$$i(t) = \frac{U_{DC}}{R_n} \cdot \left(1 - sin\left(\frac{\pi}{2} \cdot \frac{t}{t_{break}}\right)\right)$$

$$R(t) = \frac{R_n \cdot sin\left(\frac{\pi}{2} \cdot \frac{t}{t_{break}}\right) + \frac{\pi}{2} \cdot \frac{L_n}{t_{break}} \cdot cos\left(\frac{\pi}{2} \cdot \frac{t}{t_{break}}\right)}{1 - sin\left(\frac{\pi}{2} \cdot \frac{t}{t_{break}}\right)}$$

Trigonometric inflection point function:

$$i(t) = \frac{U_{DC}}{R_n} \cdot \frac{1}{2} \cdot \left(1 + cos\left(\pi \cdot \frac{t}{t_{break}}\right)\right)$$

$$R(t) = \frac{R_n \cdot \left(1 - cos\left(\pi \cdot \frac{t}{t_{break}}\right)\right) + \pi \cdot \frac{L_n}{t_{break}} \cdot sin\left(\pi \cdot \frac{t}{t_{break}}\right)}{1 + cos\left(\pi \cdot \frac{t}{t_{break}}\right)}$$

Using the current function and the voltage equation a formula of resistance was found, and also the formula for the energy dissipated in that resistance. After different trials and errors, we finalised the above-mentioned set of current functions, and then simulated them using our controlling factor this time i.e., the current breaking time, tbreak. With different values of tbreak we calculated for our functions the maximum overvoltage and the energy dissipated in the resistance.

4. 4 Results and Optimisation

In the Table below we have the ATP simulation results tabulated in terms of U_{max} and E_R at three different t_{breaks}.

Table 1: *ER and Umax for different functions at three different* t_{breaks}

U_{max} = 400 V, R_n = 0.1 Ω, L_n = 0.1 mH	t_{break} = 2 ms		t_{break} = 6 ms		t_{break} = 10 ms	
	U_{max} [V]	**E_R [J]**	**U_{max} [V]**	**E_R [J]**	**U_{max} [V]**	**E_R [J]**
quad convex	500	1226	411	2080	404	2933
exp convex	502	1241	413	2126	405	3010
trig convex	508	1237	413	2115	404	2985
trig inflection	572	938	425	1998	409	2798
cubic convex	600	1142	407	1828	401	2514
linear decrease	600	1334	466	2400	439	3466
trig concave	714	1237	504	2115	462	2985
exp concave	744	1241	514	2126	468	3010
quad concave	800	1226	533	2080	480	2933
cubic concave	1000	1142	600	1828	520	2514
pow10 convex	2000	938	666	1216	415	1493
pow10 concave	2399	938	1066	1216	800	1493

respect to maximum overvoltage, as this factor is very important for the resistance to become part of the main circuit. After this we chose three functions that had the least value for energy. These current decaying functions were cubic convex, quadratic convex and power 10 convex.

5 TESTING RESULTS

For our final trial we tested each one of our chosen functions one by one, by taking their evaluated equation for resistance and putting them into the ATP model circuit. Using the same circuit with controlled resistance MODELS, we implemented the functions obtained for the resistance as functions of time from the previous analysis.

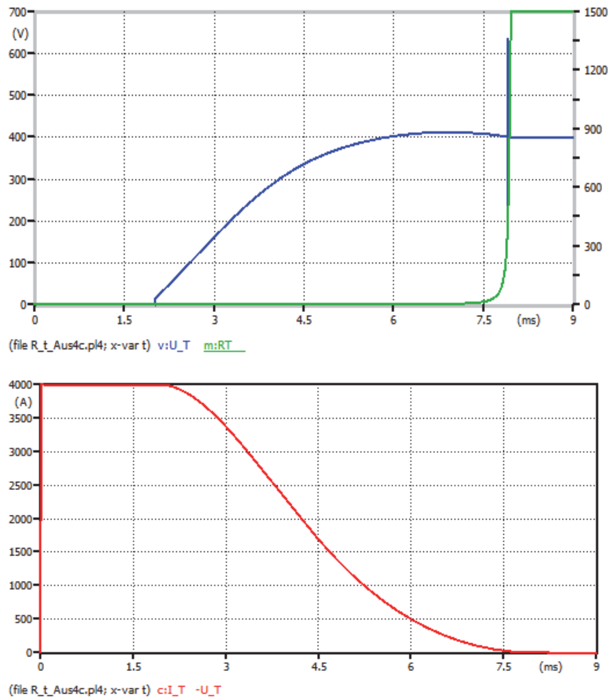

Figure 7: *Short circuit current (red) decreasing with increasing resistance (green) and behaviour of the voltage (blue)*

The results of one of our trials are given in Fig.7 where it can be seen that, with the increasing resistance the current is decreasing, but the time set here was for 6 ms, so itwas very smooth, and at t = 6 ms the resistance goes infinite, and the circuit opens.

So now these functions are dependent on t_{break}. Once the parallel switch, Dis1, will open at t_{start}, the second switch is programmed to open as soon as the current in the main circuit is less than or equal to 1 A, therefore fulfilling the condition of no arcing in the current breaking.

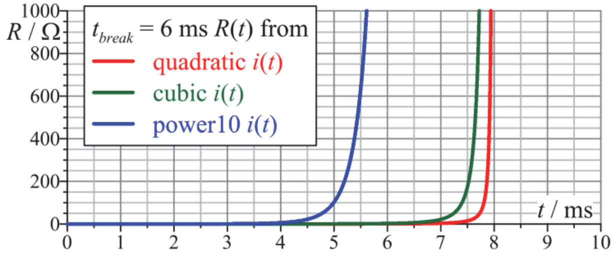

Figure 8: *Variable resistance rise using ATP with respect to time*

6 FUTURE SCOPE

To realise such resistances we need to perform further investigations and look into research related to different arrangements of controllable power-electronic switches, and the other being research related to the resistivity of different conducting, semi-conducting and superconducting materials.

Power Electronic devices, especially the controllable semiconductor switches with continuous voltage-current characteristic and switching characteristic, such as transistors, MOSFETs and IGBTs, can help us implement our resistance function. The parallel connection of several semiconductor switches serves to increase the current carrying capacity i.e., a short-circuit current.

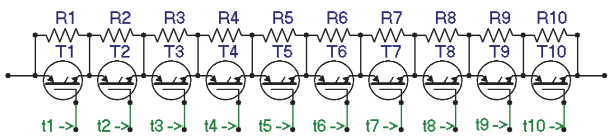

Figure 9: *Many power-semiconductor switches in switch-off mode, each with a parallel connected resistor in series*

With more stages in series the better the desired resistance-time or current-time function can be performed and the smaller the jumps, but the steady-state power dissipation or voltage drop at the operating current (and short-circuit current before the start of breaking)will be larger.

In terms of the resistivity of different materials, we can look into suitable conductors that exhibit a resistance time behaviour that is similar to the ones obtained in our results. Different alloys can also be shaped into forming a suitable resistance here for our case, depending upon their resistivity. The general rule is that resistivity increases with increasing temperature in conductors, and decreases with increasing temperature in insulators. It is also understood that when there is an increase in current, the temperature of the material it is flowing through will also increase, and therefore it is all related. Unfortunately, there is no simple mathematical function to describe these relationships displaying such behaviour of different metal alloys; the change in their resistivity with rise in temperature.

7 CONCLUSION

With the simulation of simple circuits in ATP-EMTP it can be shown that the interruption of small (open-circuit, operating) to large (short-circuit) electric currents can be realised arc-free. To do so we had to find a suitable variable resistance function and a schematic of operation. For the schematic part we just had to devise two switches with a coordination, and set some limiting conditions for current and voltage. However, an optimisation task had to be done for the part to find a suitable resistance function.

Thus, now, we have different resistance functions. But if we observe them closely, it can be said that all of these functions have similar shape, and, moreover, they are all analogous to the exponential resistance rise that we had found before. All three functions were shown to fulfil the aim of our study, and these resistances can be realised as shown in Figure 8.

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Nomenclature

(Symbols)	(Symbol meaning)
tbreak	Time taken to break open the circuit
ER	Energy dissipated by the resistor
Umax	Maximum voltage
Rn	Nominal resistance
Ln	Inductance