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SIMULATION OF A MEMRISTOR-SPARK-GAP MODEL FOR LIGHTNING PROTECTION PURPOSES

Ildikó Horváth

Original scientific paper

Memristors will surely have application in secondary lightning protection as well. This paper proposes a combined over-voltage protecting device consisting of a memristor connected in series with a spark gap. Operation of this combined device has been simulated with circuit simulation software on a model proposed in this paper. The memristor is applied for dissipating lightning surge energy and for breaking the short circuit current.

Keywords: *lightning protection, memristor, modelling, simulation, spark gap*

Simulacija modela memristor-iskra-razmak u zaštiti od munja

Izvorni znanstveni članak

Memristori će svakako naći primjenu i u sekundarnoj zaštiti od munja. U radu se predlaže kombinirani uređaj za zaštitu od prevelikog napona koji se sastoji od memristora serijski spojenog s odvodnikom. Rad toga kombiniranog uređaja simuliran je računalnim programom simulacije strujnog kruga na modelu predloženom u ovome radu. Memristor je primijenjen za disipaciju energije prenapona od munje i prekidanje struje kratkog spoja.

Ključne riječi: *memristor, oblikovanje, odvodnik, simulacija, zaštita od munje*

1 Introduction

A memristor (MR) is an electric circuit element with two connections, the characteristic memristance M which can be determined by the dependence between the electric charge q and magnetic flux φ postulated by Leon Chua in 1971 [1]. The characteristic of the MR as the dependence between q and φ is

$$M(q)=\frac{\mathrm{d}\varphi}{\mathrm{d}q}, \tag{1}$$

in unit ohm (Ω). Memory-like behaviour of an MR means that resistance, i.e. memristance value of MR depends on the electric charge $q = q(t)$ driven through the device by the current $i = i(t)$ flown through it in the past, i.e.

$$q(t)=\int_{-\infty}^{T} i(t)\mathrm{d}t=q(t_0)+\int_{t_0}^{T} i(t)\mathrm{d}t. \tag{2}$$

Resistance of the MR increases if the current flows through it in one direction and decreases if the current flows through it in the opposite direction. When connecting an MR in series with a spark gap the above feature of MR can be utilised to break the short circuit current flowing through the spark gap after the surge.

2 Expected function of the memristor-spark-gap unit

One of the most simple and cheapest devices in lightning protection is the spark gap, which is however not able to dissipate the energy of the lightning as heat and is not able to break the short circuit current on its own. Connecting a memristor in series with a spark gap, the dissipative behaviour of the MR and that, its resistance increases in certain conditions can be used to solve the problem of the spark gap.

In its idle state this combined device consists of a memristor switched on, i.e. having a low resistance $M = R_{\mathrm{ON}}$ and a spark gap switched off with its very high insulation resistance. In the case of a lightning surge the spark gap switches on at a certain voltage amplitude to its nearly short circuit state, actually to its arcing voltage.

After a certain amount of charges passing through the memristor it switches off to its high resistance $M = R_{\mathrm{OFF}}$ (Fig. 1).

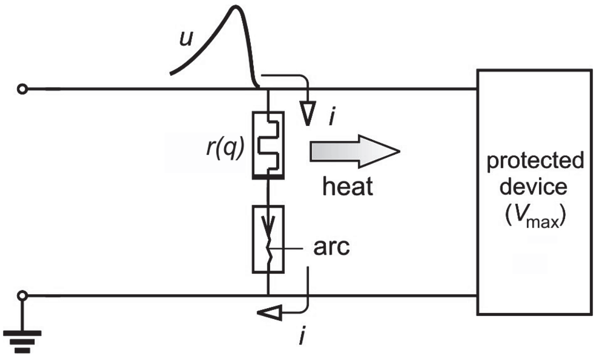

Figure 1 Draining lighting current to the earth

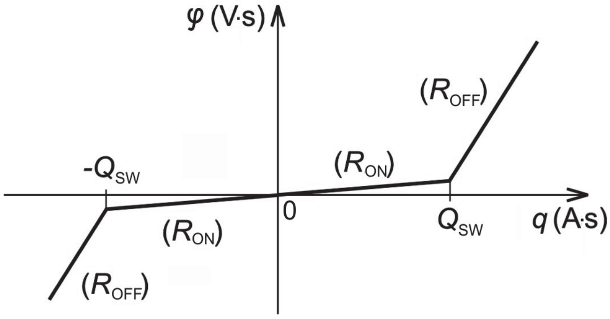

Figure 2 $\varphi(q)$ characteristics of an ideal two-state memristor

While current flows through the MR it dissipates a part of the energy of lightning current by its varying memristane $M = r(q)$ and after the current surge it switches off the short circuit current ding several hundreds of microseconds, i.e. much earlier than the fuse built into the protected circuit [2].

Fig. 2 shows the $\varphi(q)$ characteristics of a two-state MR, while Fig. 3 shows the dependence of memristance M on charge q. This function changes its slope at the Q_{SW} switching charge.

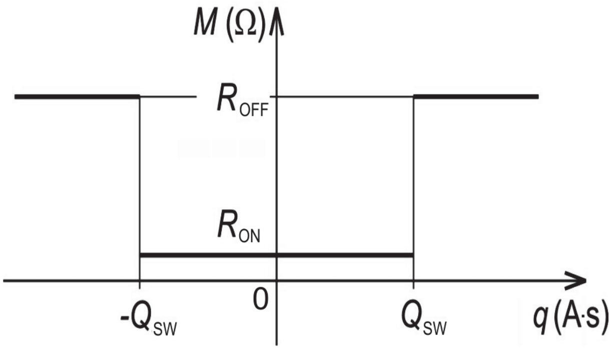

Figure 3 $M(q)$ characteristics of an ideal two-state MR

Voltage of the MR equals with the product of its current and actual resistance in the workpoint. In a general form

$$u_{\mathrm{MR}} = i \cdot r(q). \tag{3}$$

At the moment of the peak current the resistance of the MR has to be at the low $M = R_{ON}$ value, when the voltage of MR is

$$U_{\mathrm{MRmax}} = R_{\mathrm{ON}} \cdot I_{\mathrm{peak}}, \tag{4}$$

however the voltage must not supersede the allowed value either on the decreasing period of lightning current. As a consequence, MR should switch to its R_{OFF} value when its voltage is lower than the allowed one by an amount enough for not to supersede the allowed voltage value after switching off, as well. In general charge forced through the MR by the current surge must not supersede the switching over charge Q_{SW}

$$\int_0^{t_{\mathrm{SW}}} i(t)\mathrm{d}t \le Q_{\mathrm{SW}}. \tag{5}$$

where t_{SW} is the time instant after the beginning of the current surge when the voltage of the MR is lower than the allowed value in case of R_{OFF}.

Fig. 4 shows the characteristics of the surge current taken into account during simulation. U_{p} is the peak value of the voltage, I_{p} is that of the current on a normalised vertical axis, t_{r} is the rise time and t_{d} is the half value time.

In the disturbance voltage source time dependence of the surge is modelled with a curve consisting of two exponential functions as the simplest solution [3]

$$U(t) = \frac{U_{\mathrm{p}}}{\eta}\left(-\mathrm{e}^{-\frac{t}{\tau_1}} + \mathrm{e}^{-\frac{t}{\tau_2}}\right), \tag{6}$$

where η is the correction coefficient of the peak value, τ_1 is the time constant of the rise time and τ_2 is the time constant of the decreasing part.

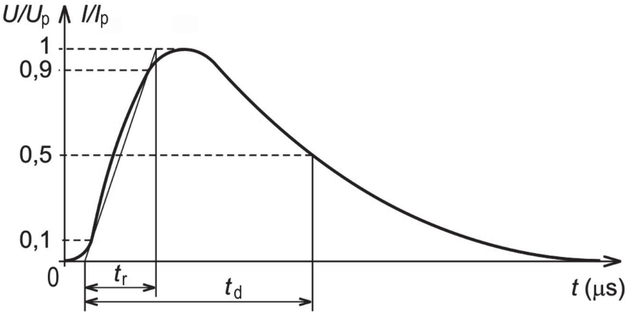

Figure 4 Characteristics of the surge

Function of the charge Q, i.e. the current surge function integrated by the time from 0 to t [3]

$$Q(t) = \int_0^T i(t)\mathrm{d}t = \frac{I_{\mathrm{p}}}{\eta}\left(-\tau_1(1-\mathrm{e}^{-\frac{T}{\tau_1}}) + \tau_2(1-\mathrm{e}^{-\frac{T}{\tau_2}})\right) \tag{7}$$

and the total charge supplied by the surge is [3]

$$Q_{\mathrm{Surge}} = \int_0^\infty i(t)\mathrm{d}t = I_{\mathrm{p}}\tau_1\left(\frac{\tau_2}{\tau_1}\right)\frac{1}{\frac{\tau_2}{\tau_1}-1}. \tag{8}$$

When dimensioning the over-voltage protection at the LPZ 0-1 zone border the current surge time function 10/350 µs shown in Fig. 5 has to be taken into account. However voltage values were tested during the simulation sessions as a first attempt, currents were determined by the embedding circuit.

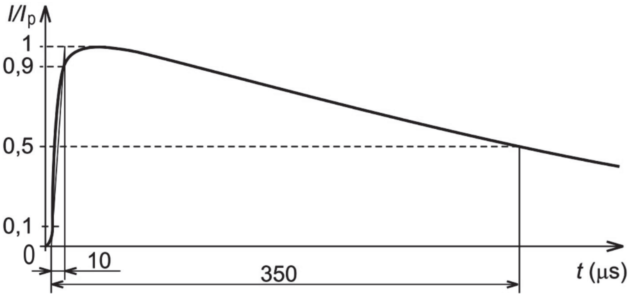

Figure 5 Surge current 10/350 µs versus time

Surge current 10/350 µs versus time

$$i(t) = \frac{I_{\mathrm{p}}}{\eta}\left(-\mathrm{e}^{-\frac{t}{\tau_1}} + \mathrm{e}^{-\frac{t}{\tau_2}}\right), \tag{9}$$

where $I_{\mathrm{p}} = 100\,000$ A were during simulation and $\eta \approx 1$, $\tau_1 = 4{,}1$ µs and $\tau_2 = 470$ µs were the time constants [3]

$$i(t) = 100000 \cdot \left(-\mathrm{e}^{-\frac{t}{4{,}1\times10^{-6}}} + \mathrm{e}^{-\frac{t}{470\times10^{-6}}}\right), \mathrm{A}. \tag{10}$$

At the zone border LPZ 1-2 the induced time function 8/20 µs shown in Fig. 6 has to be taken into account.

During the simulation sessions current peak value I_p was supposed to be 100 000 A in this case as well.

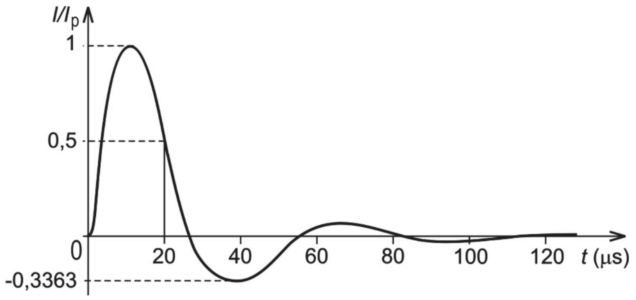

Figure 6 Surge current 8/30 μs versus time

Surge current 8/20 μs versus time

$$i(t)=\frac{I_\mathrm{p}}{\eta}\mathrm{e}^{-\frac{t}{\tau}}\sin\omega t, \tag{11}$$

where $I_\mathrm{p} = 100\,000$ A, $\eta \approx 0{,}615$, $\tau = 24$ μs and $\omega = 120023\ \mathrm{s}^{-1}$ [3].

Time functions of voltage and current of a two-state MR during conducting lightning surge are shown in Fig. 7. Current is shown with thin line and the voltage with the thick line. Fig. 7 shows the time functions for a current surge of 10/350 μs.

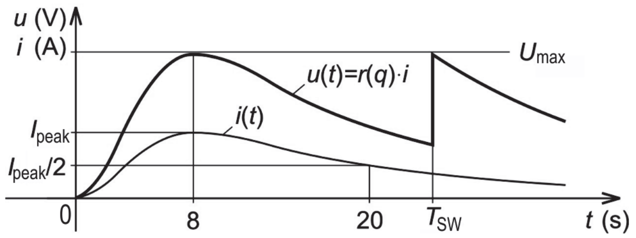

Figure 7 Time functions of voltage and current of a two-state MR during lightning surge

3 Simulation

The general circuit for simulation can be seen in Fig. 8. This model is simpler than that proposed by Strukov et. al., because the two-state version of MR has been used here [4]. Resistor R_L models the load, R_mains is the resistance of the supply network and U_mains the single phase mains voltage of 50 Hz and 230 V RMS value with the time function

$$U_\mathrm{mains} = 312\cdot\sin(2\pi\cdot 50t + 90°),\ \mathrm{V}, \tag{12}$$

where the phase angle 90° ensures that the disturbance voltage appears always at the maximum of the mains voltage.

Both the spark gap (SPD) and the memristor (MR) have a voltage-controlled switch, the V_SPD and the V_MR respectively. The former switches the spark gap to a parallel branch of $L_\mathrm{SPD} - R_\mathrm{SPD\text{-}ON}$ at a certain voltage (750 V). The later switches the MR to its high resistance value ($R_\mathrm{MRD\text{-}OFF}$) at a certain charge having been flown through it.

For the sake of a simpler handling of the integrator unit the spark gap is connected to a higher potential, thus one of the connections of the MR is at earth potential. Resistance of 10 μΩ converting the current signal to a voltage signal does not exist in reality, it belongs only to the model of the MR. Similarly the integrator and the inverting operational amplifier do not exist either, they model only the behaviour of the MR. Capacitance $C_2 = 10{,}5$ nF at the integrator is the parameter for setting the switching moment of the MR.

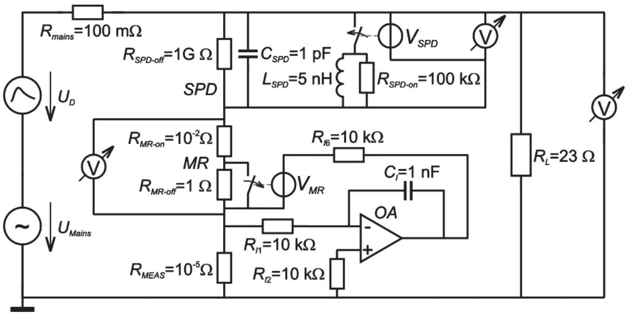

Figure 8 General simulation circuit

Simulation circuit for surges of 10/350 μs can be seen in Fig. 9. Simulation sessions have been performed on the software package TINA version 5.11.

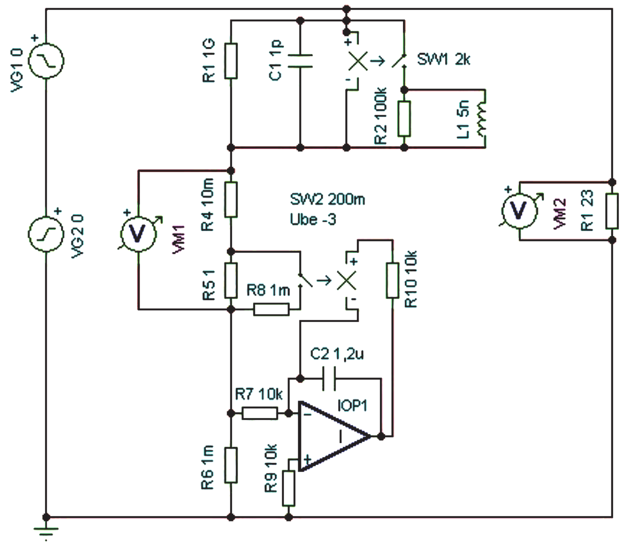

Figure 9 Simulation circuit for surges of 10/350 μs

In this case the disturbance voltage is defined by the following user function of the voltage source VG1:

```
Function Signal (t);
Begin
Signal := 6000 * (1-exp(-t/4,1e-6) – (1-exp(-t/4,7e-4)));
End;
```

Voltage of both sources, i.e. of the AC voltage source and of the disturbance voltage source for surges 10/350 μs, voltage along the MR and the load are shown in Fig. 10 beginning at the appearance of the surge for a 2 ms period.

In Fig. 10, the curve plotted with thin dashed line belongs to the supply voltage beginning at its peak value. Thick solid line shows the disturbance voltage, the dashed line is the voltage along the load and the dotted line is the voltage along the memristor. After the MR has been switched over the negligible voltage on it increases to a significant value. This voltage adds up to the voltage along load, however not causing voltages higher than the peak after the beginning.

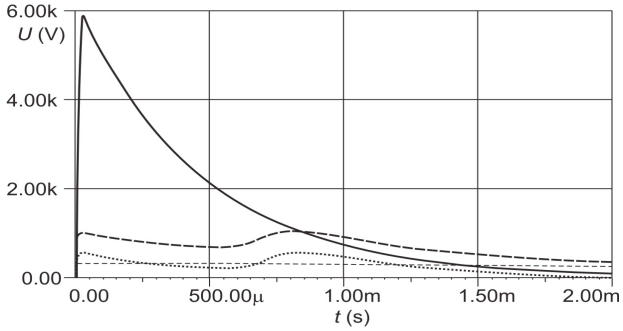

Figure 10 Simulated voltage signals surge of 10/350 μs

The switching on of the spark gap is controlled by the voltage-controlled switch SW1 at its voltage of 750 (V). The switching over of the MR can be controlled by the integration parameters $R7-C2$ or with the voltage UBE of the voltage-controlled switch SW2.

Simulation circuit for surges of 8/20 μs can be seen in Fig. 11 and the results of simulation are shown in Fig. 12. In this circuit two voltage-controlled switches are connected in parallel to the spark gap model, since in this case alternating current flows through it. Control voltage of the second switch equals the one of the first but it has a minus sign, i.e. −750 V. For maintaining the circuit regular two resistances have to be connected in series to the pins of the second switch.

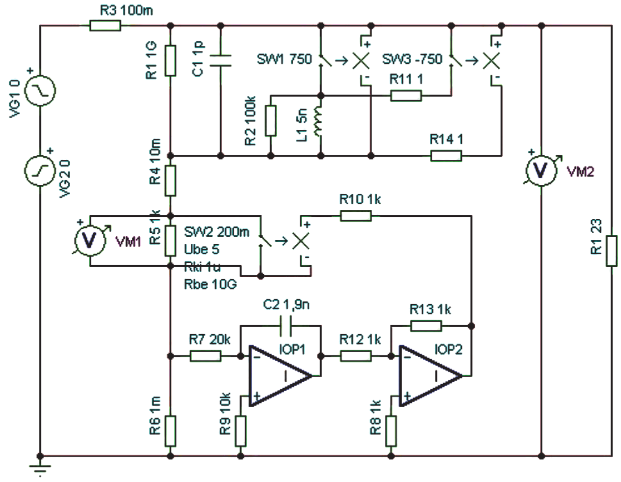

Figure 11 Simulation circuit for surges of 8/20 μs

In this case the disturbance voltage is defined by the following user function of the voltage source VG1:

```
Function Signal (t);
Begin
Signal := (2500/0,615) * (exp(-t/24e-6))*
(sin(120023+t));
End;
```

Voltage of both sources, i.e. of the AC voltage source and of the disturbance voltage source for surges 8/20 μs, voltages along the MR and the load is shown in Fig. 12 beginning at the appearance of the surge for a 200 μs period.

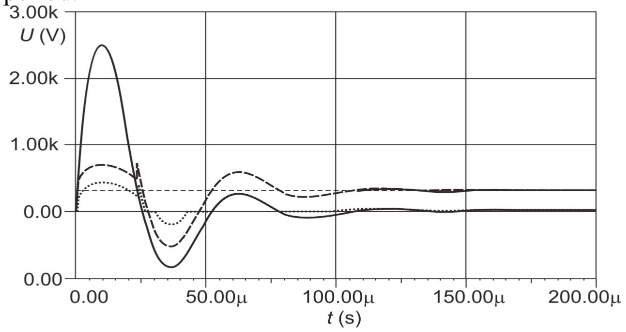

Figure 12 Simulated voltage signals a surge of 8/20 μs

In Fig. 12 the curve plotted with thin dashed line is the supply voltage again, the thick solid is the disturbance voltage, the dashed line is the voltage along the load and the dotted line is the voltage along the memristor. In this the time of about 25 μs of the switching over of the MR can be seen well.

4 Conclusions

Simulation results show good correspondence with the function expected from this combination of spark-gap-memristor unit. The switching over of MR at the right time is well shown by the simulation results.

It is obvious that the same MR cannot be applied in both cases. In case of current surges of 8/20 μs less charges pass through the MR by a magnitude of order until the required time of switching over. This disturbance is alternating at the same time, thus a more precise pre-setting of the MR is required for not switching on the MR again. It can be advantageous to switch off the MR after the second or third peak of disturbance voltage.

5 References

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Authors' address

Ildikó Horváth
Eötvös Lóránt University, Faculty of Natural Sciences
Pázmány Péter sétány 1/C
H-1117 Budapest, Hungary
E-mail: ildikovh@gmail.com