An Improved Circuit-Breaker Model in MODELS Language for ATP-EMTP Code

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Abstract: **In this paper an improved circuit-breaker simulation tool written in MODELS language for ATP-EMTP is presented. The arc dynamic is based on the combination of Mayr's and Cassie's differential equations. The usage of MODELS in the ATP-EMTP is underlined by stressing the differences in approach and use as compared to TACS. The tool has been verified by carrying out a comparison with measured results reported in technical literature; its use in simulating the opening of a SF6 circuit-breaker in a realistic power system MV network, is illustrated.**

Keywords: Circuit-breaker model, ATP-EMTP, Mayr's arc equation, Cassie's arc equation.

I. INTRODUCTION

The increasing use of electronic equipment in electric power substations imposes to deepen the electromagnetic compatibility (EMC) studies related to transient phenomena generated by faults and switching events. Electromagnetic interference (EMI) can arise from any operation that interrupts or changes currents in electric circuits; thus circuit-breakers operations are among the most important causes of EMI in power systems.

The simulation of transients due to switching operations in power systems is very helpful in designing the electronic components of control and protective devices in substations. It is costly, both in time and money, to perform an experimental EMC study. The objective is to avoid equipment failures and misoperations during the common real operations in the electromagnetic environment in which the devices must operate.

An advantage of a numerical simulation is that electrical voltages and currents profiles can be obtained also where it is very difficult to perform test measurements.

In order to simulate power systems transient phenomena, the ATP-EMTP is widely used and, in the last years, the development of MODELS facility [1] has made it possible to control component characteristics in an external program having voltages and currents from the circuit as input. Recent further developments have increased the capabilities of MODELS and also an user-friendly interface called ATP-DRAW [2] has been developed.

In this paper, an improved circuit-breaker simulation tool written in the MODELS language for ATP-EMTP is presented.

Simulations of circuit-breakers involve a sophisticated arc-model inserted into a simple equivalent network. Two mathematical models were developed in the middle of this century: Mayr's and Cassie's differential models [3,4]. More precise measurements in recent years have shown that the arc behaviour can not be accurately described by such equations. This led to the introduction of modified models based on a combination of Mayr's and Cassie's equations. The composition of the two models has been recognized as having great practical application in circuit-breakers development also showing a very good agreement with measured data related to SF_6 circuit-breakers [5].

The authors have developed a model of circuit-breakers written in the MODELS language. Based on the combination of the Mayr's and Cassie's equations, the model consists of two series-connected resistors. One of them represents the arc resistance obtained from Mayr's equation, the other is related to the arc resistance obtained from Cassie's differential model. In this case at high currents, practically all the arc voltage is supplied by Cassie's portion. Mayr's portion increases just before current zero and takes over all the transient recovery voltage after the current interruption, while Cassie's portion goes to zero.

The model has been verified by means of measured and calculated results described in literature.

The most important advantages of this tool written in MODELS language can be summarized as follows: no transition conditions are needed and all aspects of the representation, solution and initialization of the circuit-breaker are completely under user control.

The use of the tool in simulating the opening of a SF_6 circuit-breaker during different short-circuit conditions in a simple MV radial network, is illustrated.

II. SIMULATION MODEL OF CIRCUIT-BREAKER

Cassie [3] and Mayr [4] developed two differential equations based on rather different approaches to the physical nature of the arc. Particularly, the following differential equation is related to the Mayr's model of the arc conductance:

$$\frac{dg_m}{dt} = \frac{1}{\tau_m} \cdot \left(\frac{i_a^2}{P_0} - g_m \right) \qquad (1)$$

while the Cassie's differential model is described by the following equation:

$$\frac{dg_c}{dt} = \frac{1}{\tau_c} \cdot \left(\frac{i_a^2}{u_s^2 \cdot g_c} - g_c \right) \qquad (2)$$

In (1) and (2), i_a is the current in the circuit-breaker, g_m or g_c is the arc conductance, τ_m or τ_c is the time constant of the arc; in (1) P_0 is the steady-state power loss of the arc and in (2) u_S is the steady state arc voltage [6].

As it can be seen, the differential models of the arc conductance are those with constant parameters but, a combination of Mayr's and Cassie's equations is considered. The possibility of using the combination of the two models derives from the following considerations. At high currents Cassie's portion of the arc voltage is the main part of the total arc voltage; when current is close to zero May's model describes the arc behavior more closely and the related portion of the arc voltage increases just before current zero and takes over the transient recovery voltage after the current interruption, while Cassie's portion goes to zero [7]. So, it seems correct to simulate the arc conductance with the two differential models working simultaneously and constituted of two resistors series connected.

The total arc-resistance $r_{arc}=1/g_{arc}$ is given by:

$$r_{arc} = \frac{1}{g_{arc}} = \frac{1}{g_c} + \frac{1}{g_m} \qquad (3)$$

Each phase of a circuit-breaker is simulated by means of two series-connected resistors whose conductance is represented by the variable arc-conductance g_{arc}.

The circuit diagram of the circuit-breaker is shown in fig. 1. Each phase of the circuit-breaker is represented by a MODELS-controlled type-13 switch (SW2) in series with the arc-resistance represented by a MODELS-controlled type-91 variable resistance $r_{arc}=1/g_{arc}$. In addition $u=i_a/g_{arc}$ is the total arc-voltage between nodes 1 and 2 of fig. 1.

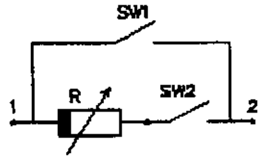

Fig. 1. Circuit diagram of the circuit-breaker.

The circuit-breaker is initially in a closed position, and its resistance is constant and very small. For both parts, the value of 10^{-7} Ω is used. Another closed switch (SW1) is placed in parallel with the two series elements of the circuit-breaker, in order to represent the condition of the circuit-breaker during the steady-state initialization of the network where it is placed. This parallel switch is opened when the circuit-breaker starts to open.

The arc-conductance is calculated according to (3), until the arc resistance reaches a predefined high value. In the simulation a threshold of 10^7 Ω is considered for a successful arc interruption. In this case, the MODELS-controlled type-13 switch in series with the arc-resistance opens and the resistance of both parts of the model is set to the threshold value, thus representing the opening of the circuit-breaker.

As already underlined, the most important advantages of this simulation model are that no transition conditions are needed and all aspects of the representation, solution and initialization of the circuit-breaker are completely under user control.

III. VERIFICATION OF THE TOOL

Before using the tool in realistic simulations, it has been verified by comparing the computed results with measured and calculated ones described in literature [6, 8]. The use of the model in simulating the opening of a SF_6 circuit-breaker in the test circuit of fig. 2, reported in [6], is illustrated. The parameters of the test circuit are: U=51 kV, L_0=3 mH, R_0=450 Ω, C_0=9.6 nF and C=1.1 nF. The used parameters for the SF_6 circuit-breaker arc model are: τ_m=0.22 μ s, τ_c=0.8 μ s, P_0=8.8 kW and u_S=2.35 kV. In fig. 3 the waveform of the calculated arc current is reported.

In fig. 4 the waveforms of the calculated arc voltage u, Mayr's portion voltage u_{ma} and Cassie's portion voltage u_{ca}, are reported. As it can be noticed, for high values currents, practically all the arc voltage is supplied by Cassie's portion; Mayr's portion increases just before current zero and takes over the transient recovery voltage after the current interruption, while Cassie's portion goes to zero.

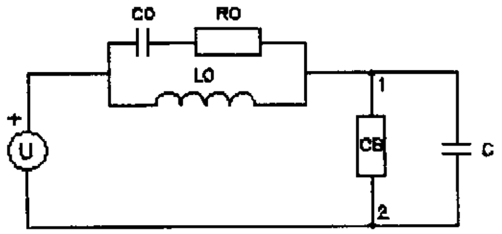

Fig. 2. Test circuit for verification of the tool. Nodes 1 and 2 are those referred in fig. 1. CB as circuit-breaker.

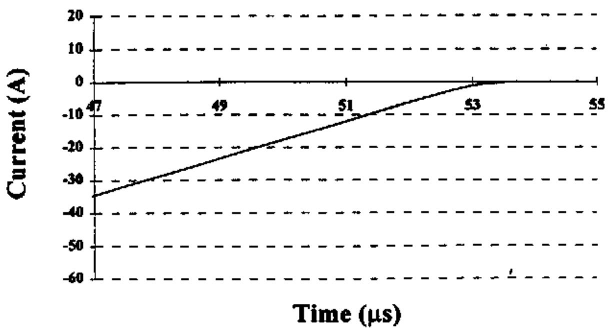

Fig. 3. Arc current time profile for test circuit of fig. 2.

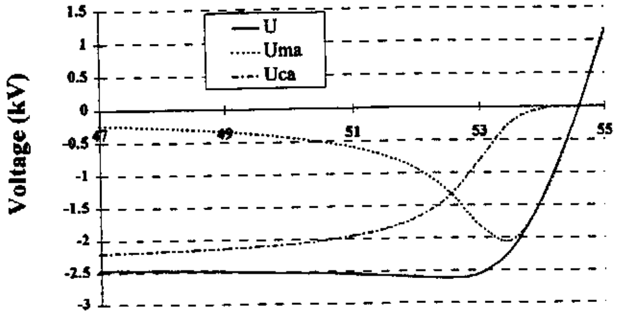

Fig. 4. Arc voltage time profile for test circuit of fig. 2. Note that u is the total voltage, u_{ma} is the Mayr's portion and u_{ca} is the Cassie's portion.

In fig. 5 the calculated total arc voltage is compared with the experimental results related to the test circuit of fig. 2, found in [6]. As it can be noticed, a very good agreement has been found.

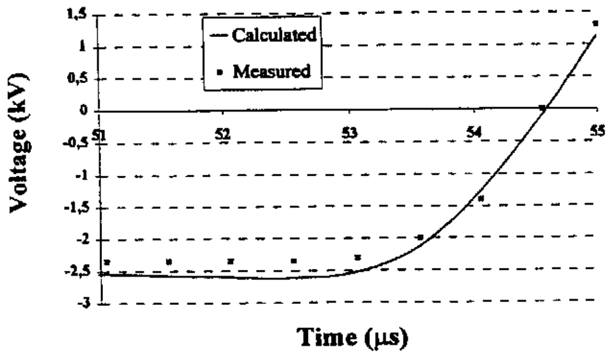

Fig. 5. Arc voltage time profile for test circuit of fig. 2. Comparison between calculated and measured total voltage u [6].

IV. APPLICATION EXAMPLE

A simple radial MV network with ring structure is used to show the performances of the circuit breaker model in simulating a realistic opening operation during a fault condition. The network consists of two MV outgoing overhead lines from the same HV/MV substation (150/20 kV/kV); the busbars of the two MV/LV substations are connected each other through another MV overhead line. The MV lines are with insulated neutral.

In particular the network is composed by (fig. 6):

1. a 150 kV equivalent voltage source, having short circuit power equal to 1500 MVA;
2. an HV/MV substation with a transformer of 25 MVA and having the HV windings star connected and the MV windings triangle connected;
3. three MV overhead lines 20 km length and with conductors placed in triangle configuration; the lines are simulated by employing a distributed parameters model available in ATP-EMTP code (K.C.Lee line model); two of such lines feed two MV/LV transformers of 250 kVA with MV winding triangle connected and LV winding star connected with grounded neutral; the other one connects the busbars of the two MV/LV substations.
4. two SF_6 circuit-breakers (CB1 and CB3) located inside the HV/MV substation at the two outgoing MV lines;
5. two SF_6 circuit-breakers (CB2 and CB4) located at the MV busbars of the MV/LV substations.
6. two loads of 200 kW and a power factor equal to 0.8.

The SF_6 circuit-breakers are simulated by means of the previously described differential model with the parameters values already described in section III. The used network is a typical example of a MV line of the Italian electric power distribution system, with insulated neutral. Three kinds of faults have been considered: a three phase to ground fault at the beginning of line L2, a three phase to ground fault and a single phase to ground fault on MV busbars of transformer TR2 (fig. 5).

Fault impedance is set equal to zero.

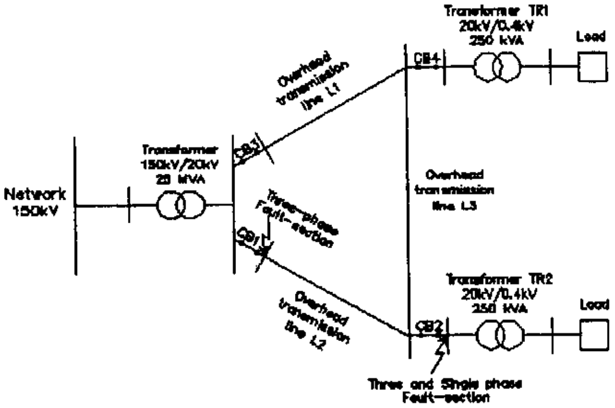

Fig. 6 – MV network used for the application example.

In fig. 7 the waveform of the calculated arc current during the three phase to ground fault at the beginning of line L2 is reported. In fig. 8 the waveforms of the calculated arc voltage u, of Mayr's portion u_{ma} and of Cassie's portion u_{ca}, are reported.

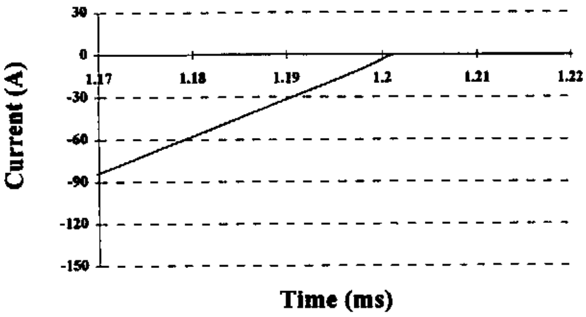

Fig. 7. Three phase to ground fault at the beginning of line L2 of fig. 6. - Phase-R arc-current.

The circuit-breaker CB1 begins its opening at t=0 s and the complete extinction of the subsequent arc is reached in about 1.2 ms, as it can be seen in fig. 9 where the time profile of the phase-R calculated arc-resistance is shown.

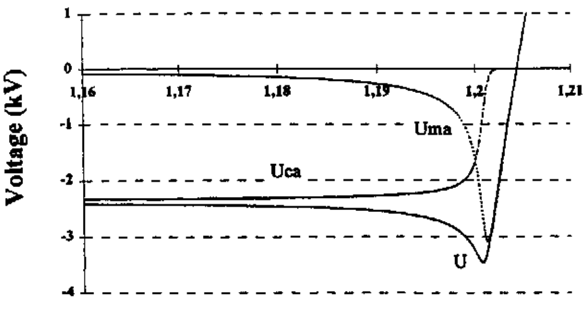

Fig. 8. Three phase to ground fault at the beginning of line L2 of fig. 6. - Phase-R arc voltage time profile. Note that u is the total voltage, u_{ma} is the Mayr's portion and u_{ca} is the Cassie's portion.

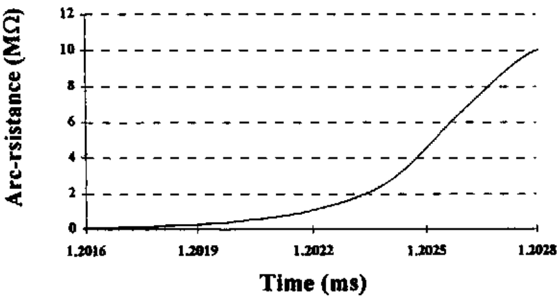

Fig. 9. Three phase to ground fault at the beginning of line L2 of fig. 6. - Phase R-arc-resistance.

In order to illustrate the importance of using the accurate model of the arc dynamics in the circuit breaker, in fig. 10 the time profile of the MV busbar voltage in the HV/MV substation obtained by using the arc model in the circuit breaker, is compared with that calculated by using an ideal switch, during a three phase to ground fault condition interrupted by CB1 (fig. 6).

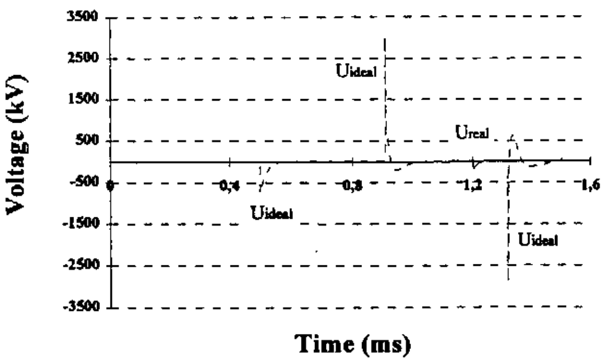

Fig. 10. Three phase to ground fault at the beginning of line L2 of fig. 6. – Comparison between MV busbar voltage time profile with the arc-model (u_{real}) and with an ideal switch (u_{ideal}).

As it can be seen, the accurate simulation of the circuit breaker enables to avoid the computation of unrealistic value of the voltage to ground.

As mentioned above, a three phase to ground fault and a single phase to ground fault on MV busbars of transformer TR2 have been also considered. The circuit-breaker CB2 is that which operates during these fault conditions.

In fig. 11 the waveform of the calculated arc current during the three phase to ground fault on MV busbars of transformer TR2, is reported. In fig. 12 the waveforms of the calculated arc voltage u, of Mayr's portion u_{ma} and of Cassie's portion u_{ca}, are reported.

A comparison between fig. 7 with fig. 11 shows that the time necessary to a circuit-breaker for its opening depends on the fault location. In fact, the MV busbars of transformer TR2 are more far from the generator respect to beginning of line L2, thus the complete extinction of the subsequent arc in the circuit-breaker CB2 is reached in about 0.9 ms while the complete extinction of the subsequent arc in the circuit-breaker CB1 is reached in about 1.2 ms.

In fig. 13 the waveform of the calculated arc current during the single phase to ground fault on MV busbars of transformer TR2 is reported. In fig. 14 the same arc current time profile is reported in an expanded scale. In fig. 15 the waveforms of the calculated arc voltage u, of Mayr's portion u_{ma} and of Cassie's portion u_{ca}, are reported.

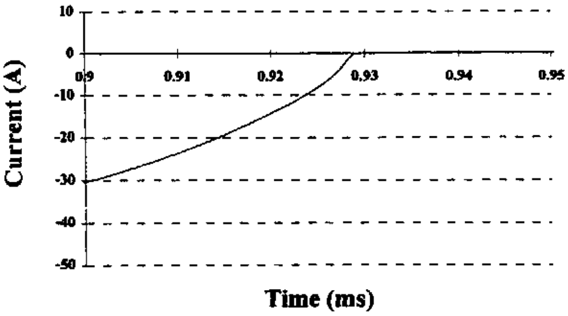

Fig. 11. Three phase to ground fault on MV busbars of transformer TR2 of fig. 6. - Phase-R arc-current.

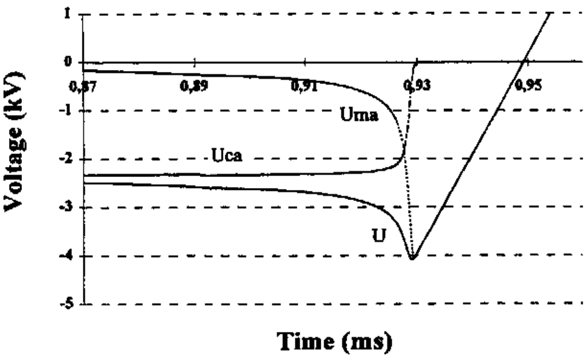

Fig. 12. Three phase to ground fault on MV busbars of transformer TR2 of fig. 6. - Phase-R arc voltage time profile. Note that u is the total voltage, u_{ma} is the Mayr's portion and u_{ca} is the Cassie's portion.

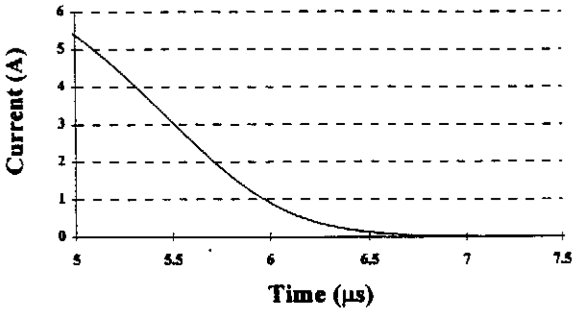

Fig. 13. Single phase to ground fault on MV busbars of transformer TR2 of fig. 6. - Phase-R arc-current.

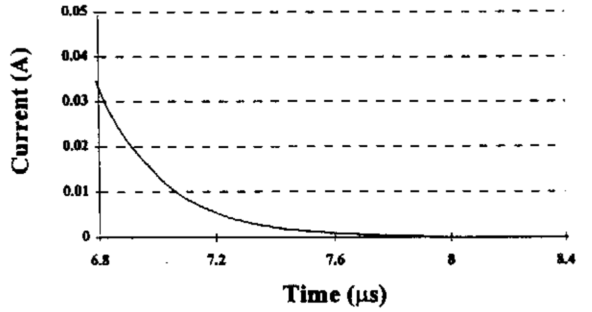

Fig. 14. Single phase to ground fault on MV busbars of transformer TR2 of fig. 6. - Phase-R arc-current near current-zero.

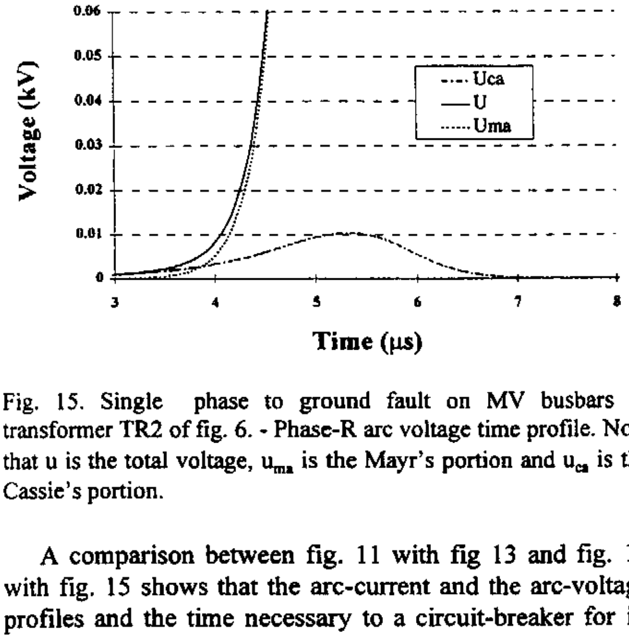

Fig. 15. Single phase to ground fault on MV busbars of transformer TR2 of fig. 6. - Phase-R arc voltage time profile. Note that u is the total voltage, u_{ma} is the Mayr's portion and u_{ca} is the Cassie's portion.

A comparison between fig. 11 with fig 13 and fig. 12 with fig. 15 shows that the arc-current and the arc-voltage profiles and the time necessary to a circuit-breaker for its opening depends on the fault type.

As already pointed out, from the simulations carried out it is possible to underline that the arc-current and arc-voltage profiles depend on the type of fault and location, while its duration is influenced from the operating time of the circuit-breaker.

V. CONCLUSIONS

Based on a complex differential model of arc dynamics, the simulations of opening operations of a power system circuit-breaker was carried out by using a tool developed in MODELS language which can be used in the ATP-EMTP. It is based on the combination of the well known Mayr's and Cassie's equations. The most important advantages of this tool are that no transition conditions are needed and all aspects of the representation, solution and initialization of the circuit-breaker are completely under user control. The results obtained by using the tool are in agreement with the measured ones found in technical literature. The model has been used in simulating the opening of a SF_6 circuit-breaker during different short-circuit conditions in a simple power system MV network.

VII. REFERENCES

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APPENDIX

In the following, the listing of the routine of the model of the circuit breaker written in MODELS language is reported.

```
MODEL arcresistance
CONST
 minconduc  {VAL [illegible] E-7}
DATA
 power   {DFLT:8[illegible]}
 taum    {DFLT:2.[illegible]-7}
 vc      {DFLT:2350}
 tauc    {DFLT:8.E-7}
INPUT
 current
 status
 closecommand  {DFLT:false}
 opencommand  {DFLT:false}
VAR
 conductance
 arcresis
 conductancema
 arcresisma
 voltma
 conductanceca
 conducta
 arcresisca
 voltca
 drivingma
 drivingca
 openclose
 isopening
OUTPUT
 arcresis
 openclose
TIMESTEP MAX: tauc/11
INIT
 IF status=open THEN openclose:=open;
    conductancema:=minconduc;
    conductanceca:=minconduc; conductance:=minconduc
 ELSE openclose:=closed; conductancema:=1/minconduc;
    conductanceca:=1/minconduc;
    conductance:=conductancema*conductanceca/(conductancem
    a+conductanceca)
ENDIF
 arcresis:=recip(conductance);
  arcresisma:=recip(conductancema);
 arcresisca:=recip(conductanceca); voltma:=current*arcresisma;
 voltca:=current*arcresisca; isopening:=false
ENDINITEXEC
 IF status=open AND closecommand THEN
   openclose:=closed; conductancema:=1/minconduc;
   conductanceca:=1/minconduc;
    conductance:=conductancema*conductanceca/(conductancem
    a+conductanceca);
   arcresisma:=recip(conductancema);
   arcresisca:=recip(conductanceca);
   arcresis:=recip(conductance);
   voltma:=current*arcresisma;
   voltca:=current*arcresisca
 ELSIF status=closed AND opencommand THEN
  isopening:=true
 ENDIF
 IF isopening THEN
   drivingma:=current**2/power
   DIFFEQ( 1.0|D0 + taum|D1 )|conductancema:=drivingma
   drivingca:=current**2/vc**2
   DIFFEQ( 1.0|D0 + (tauc/2)|D1 )|conducta:=drivingca
   conductanceca:=sqrt(conducta)
    conductance:=conductancema*conductanceca/(conductancem
    a+conductanceca)
   IF conductance<=minconduc THEN
      openclose:=open; conductance:=minconduc;
      conductancema:=minconduc;
      conductanceca:=minconduc; isopening:=false
   ENDIF
   arcresis:=recip(conductance);
   arcresisma:=recip(conductancema);
   arcresisca:=recip(conductanceca);
   voltma:=current*arcresisma;
   voltca:=current*arcresisca
 ENDIF
ENDEXEC
```