A generic model for fuses to calculate the transients in low-voltage power networks

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Introduction

In low-voltage power networks fuses are mainly used to protect the equipment e.g. lines or transformers in case of short-circuits. Up to now only methods to calculate the steady-state of power networks have been used to select the right type of fuses. This selection is normally based on the calculation of the minimum initial short-circuit current I''_{SCmin} according the international standard IEC 60909 either processed by a software tool or calculated by hand [VDE0102, 2002]. The short-circuit calculation according IEC 60909 does not take into account neither transients nor harmonics. Based on the nominal current of the fuse I_n and the calculated minimum initial short-circuit current I''_{SCmin} the virtual pre-arcing time t_v can be easily determined using the fuse characteristics. The virtual pre-arcing time t_v is defined as the time between the occurrence of the short-circuit up to the melting of the fuse including the extinction of the arc. After elapsing the virtual pre-arcing time t_v the short-circuit current is interrupted by the fuse. The virtual pre-arcing time t_v considers neither the transients of voltages and currents after short-circuit occurrence nor harmonics. There are also software models for power network fuses available for time-domain network calculations. These models are mostly based on the calculation of the thermal energy of the fuse, which is compared to the I^2t-value of the fuse in combination with an ideal switch. The voltage drop across the fuse due to the increase in resistance during the melting process and the following arc-resistance is usually not considered. The latter can have a potential influence on the synchronization-methods of grid connected inverters, as increasingly found in the distribution grid. Therefore two extended fuse models for the use in time-domain power network calculations have been implemented and will be described in the following.

Distributed systems in low-voltage power networks

Typically NH fuses are used as a primary line protection in radial low-voltage grids. An additional backup is provided by a fuse at the low voltage side of the transformer (Figure 1). In case of a short-circuit within the grid a short-circuit current is fed by the overlaying grid, leading to a disconnection of fuse Fu2.

Nevertheless the further growing number of inverter based distributed resources in low-voltage power networks has a critical influence on the behavior of the phase currents after the occurrence of a short-circuit. In the following the exemplary situation shown in Figure 2 is regarded. The infeed of an inverter, connected in between Fu2 and the fault can lead to a reduction of the short circuit current level at Fu2. This can cause an increase of the tripping times of both fuses Fu1 and Fu2 up to a non-tripping, the so called blinding. Additionally the output current of inverter based distributed resources in case of grid faults potentially contains harmonics due to their topology mostly based on switched semiconductors with an overlaying control structure. Therefore the consideration of a full frequency range is necessary when analyzing potential influences onto the behavior of protection systems. Furthermore the melting and arcing process within the fuse has an influence onto the current shape within the grid. Due to the usage of synchronization methods within grid connected inverters for the determination of the amplitudes and phase angles of the injected current, inverters react to variations in the current and voltage at their point of common coupling. Therefore the impact of the arcing within the fuse needs to be investigated.

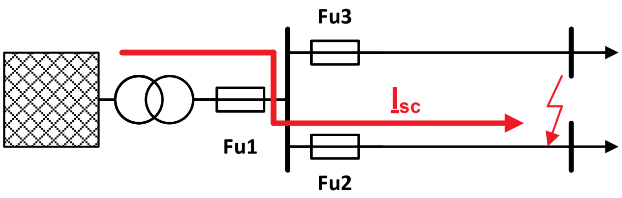


Figure 1: Short-circuit current in a low-voltage power network with radial network topology

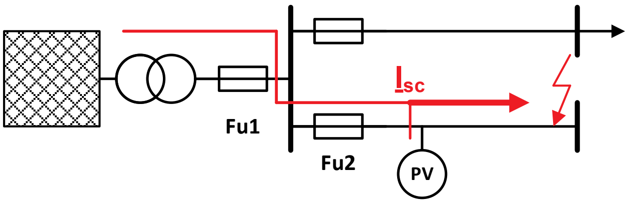


Figure 2: Reduction of the short-circuit current in fuse Fu1 caused by the photovoltaic system PV

Software based model of a fuse implemented in ATPDesigner/ATP

During the research project “Protection for Future Distribution Systems” (ProFuDiS) a generic software based model of a fuse has been developed and implemented in the network calculation program ATPDesigner/ATP (www.atpdesigner.de). The ATP (Alternative Transients Program, www.emtp.org, www.eeug.org) is the world-wide mostly used universal program system for digital simulation of transient phenomena of electromagnetic as well as electromechanical nature in electrical power systems. The network calculation program ATPDesigner uses the ATP to process power network simulations based on the ATP models but also based on own developed models and algorithms. The ATP provides an own programming language called MODELS to implement new software based models and algorithms e.g. of protection elements. The **Fuse Model** presented below has been developed using the MODELS programming language of the ATP and implemented in ATPDesigner.

„Black Box“-fuse model from the power network point of view

The structure of the **Fuse Model** is shown in Figure 3. The **Fuse Model** has been developed to simulate the electrical behavior of the fuse from the power network point of view. The model consists of a system to measure the phase currents $i_A(t)$, $i_B(t)$ and $i_C(t)$, a software based model of the melting of the fuse as well as a software based model to realize the arc using the arc resistance $\mathbf{R_{Arc}(t)}$ and a switch to interrupt the short-circuit current after the extinction of the arc. The behavior of all these components is controlled by the **Fuse Model** software. Analyzing the three phase currents the thermal energy is continuously calculated. If the thermal energy exceeds the virtual pre-arcing energy the software model uses a differential equation to simulate the time-depended behavior of the arc. In case of the extinction of the arc the switch will be opened phase selectively to interrupt the short-circuit current. The internal structure of the **Fuse Model** is shown in Figure 4.

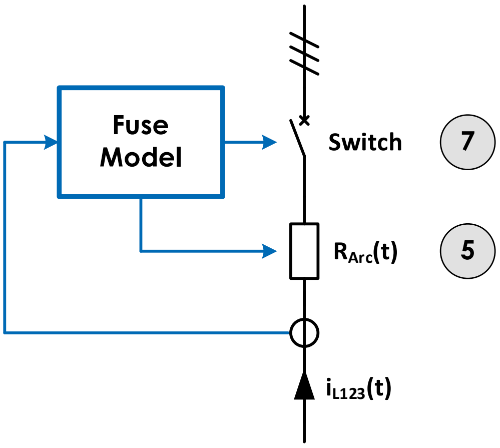


Figure 3: „Black Box“ Fuse Model

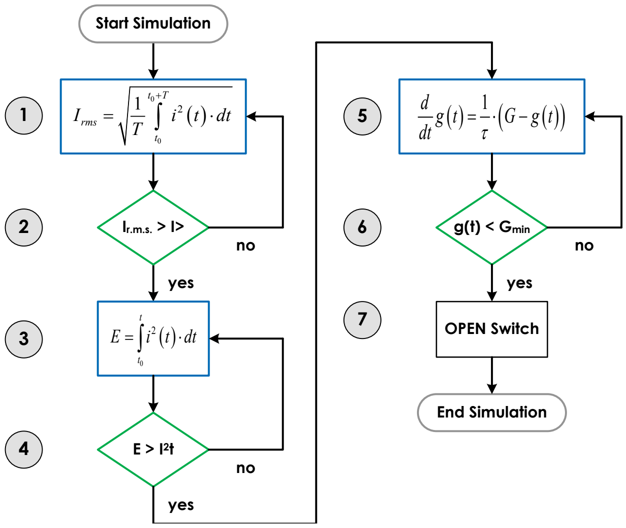
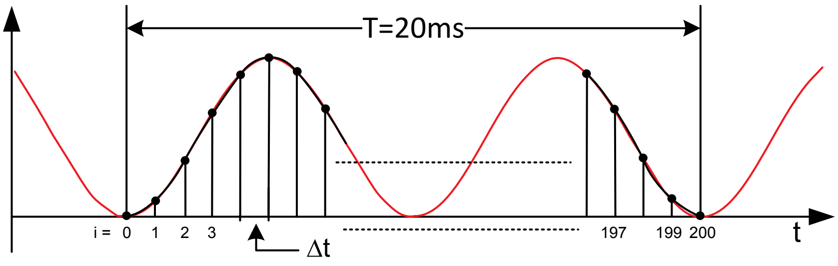


Figure 4: Internal structure of the Fuse Model software

After starting the simulation the r.m.s. values of the phase currents are continuously calculated ①. The r.m.s. calculation is processed by an integration algorithm using the Simpson-Rule (Figure 5). This integration algorithm also takes harmonics or other frequencies and transients into consideration which may be caused by the inverter of a photovoltaic system.



$$I_{r.m.s.}=\sqrt{\frac{1}{T}\cdot\frac{\Delta t}{3}\cdot\left(i^2[0]+\left(2\cdot\sum_{i=1}^{(N/2)-1} i^2[2\cdot i]\right)+\left(4\cdot\sum_{i=1}^{N/2} i^2[(2\cdot i)-1]\right)+i^2[N]\right)}$$

Figure 5: Calculation of r.m.s. values of the phase currents

If the r.m.s. value $I_{r.m.s.}$ exceeds the threshold I> ②, the calculation of the thermal energy is started ③. Depending on the sampling time ΔT and the sampled values of the phase currents $i_L(k \cdot \Delta T)$ the thermal energy E is continuously calculated (Figure 6).

The calculated value of the thermal energy E is continuously compared with the I^2t-characteristic of the fuse, which can be determined based on the virtual pre-arcing time t_v and the short-circuit current. If the current value of the thermal energy E is equal or greater than the I^2t-value of the fuse characteristic ④, the calculation of the thermal energy E is stopped and the arc-model based on the differential equation shown in Figure 7 is started.

$$E = \int_{t_0}^{t} i^2(t) \cdot dt \rightarrow E = E + \left[i^2(k \cdot \Delta T) \cdot \Delta T \right]$$

Figure 6: Calculation of the thermal energy caused by the phase currents

$$\frac{d}{dt} g(t) = \frac{1}{\tau} \cdot \left(G - g(t) \right)$$

Figure 7: Differential equation to simulate the time dependent behavior of the arc

If the resistance of the arc-model $\mathbf{R_{Arc}(t)}$ is less than a predefined value ⑥, the **Fuse Model** opens the switch to interrupt the short-circuit current ⑦.

Testing the „Black Box“-fuse model using ATPDesigner/ATP

The LV-power network shown in Figure 8 has been used to test the behavior of the **Fuse Model**. The network element **Z(x)** realizes the resistance $\mathbf{R_{Arc}(t)}$ of the model. A 3-phase-to-ground fault has been set at 25% of the line length. It can be seen, that the switch is opened to interrupt the short-circuit current.

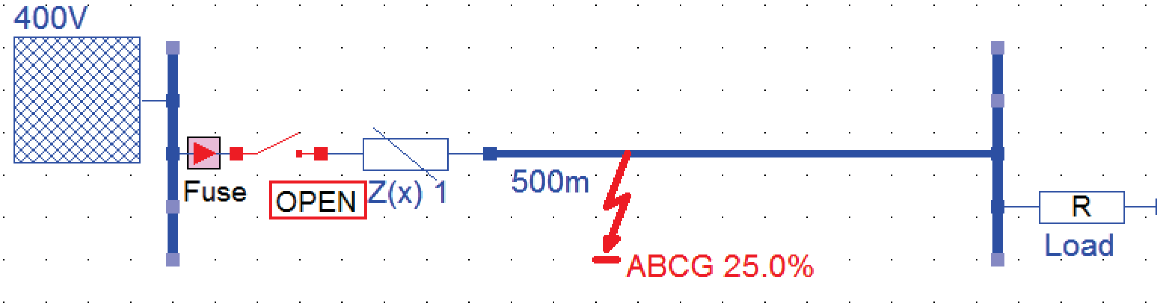
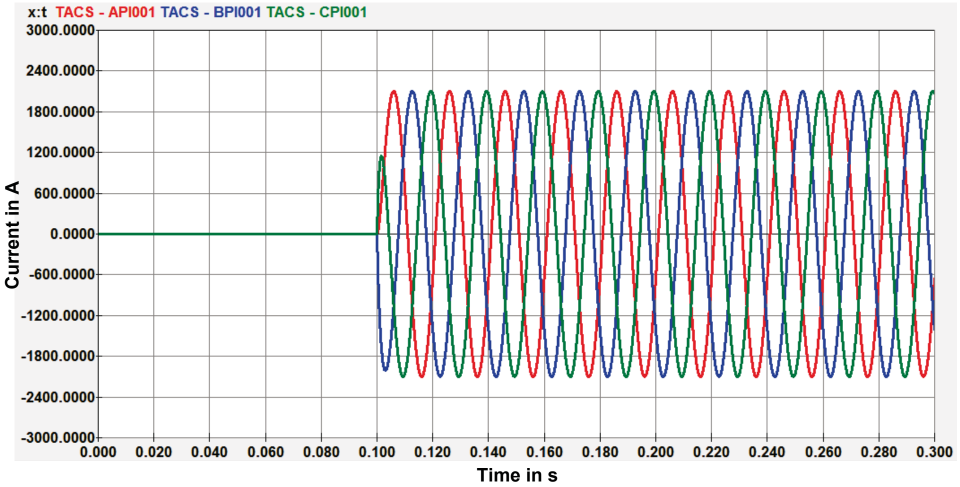


Figure 8: LV-network to test the behavior of the Fuse Model

The diagrams in Figure 9 and Figure 10 show the behavior of the **Fuse Model**. After the occurrence of the short-circuit at t = 100ms the phase currents $i_A(t)$ (**API001**) as well as the phase currents $i_B(t)$ (**BPI001**) and $i_C(t)$ (**CPI001**) takes about 1,5kA.



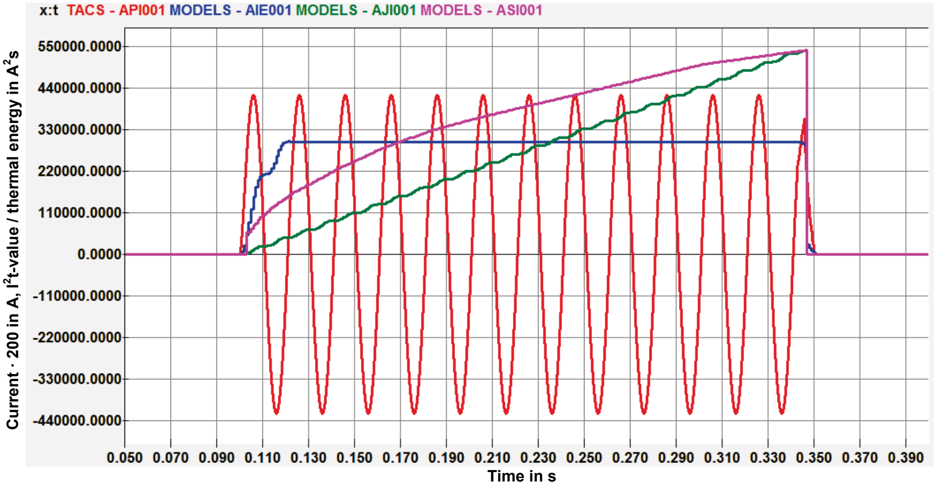
API001: Phase current $i_A(t)$

BPI001: Phase current $i_B(t)$

CPI001: Phase current $i_C(t)$

Figure 9: Phase currents in case of a 3-phase-to-ground short-circuit in the LV-power network

The diagram in Figure 10 only shows the phase current $i_A(t)$ and internal signals calculated by the **Fuse Model**. After the occurrence of the short-circuit at t = 100ms the r.m.s. value of the phase current **AIE001** rises and keeps constant after one cycle. The thermal energy E **AJI001** increases continuously. About 340ms after the occurrence of the short-circuit the thermal energy E is equal to the I^2t-value of the tripping characteristic of the fuse **ASI001**. At this moment the arc-model will be started. The switch will be opened at about t = 350ms to interrupt the short-circuit current.



API001: Phase current $i_A(t)$

AIE001: R.M.S. value $I_{r.m.s.}$ of the phase current $i_A(t)$ ①

AJI001: Thermal energy E ③

ASI001: I^2t-value of the tripping characteristic of the fuse

Figure 10: Fuse Model – Phase current $i_A(t)$ and other internal signals of the model

Both diagrams in Figure 11 show the impact of the arc-model as part of the **Fuse Model**. The left hand diagram shows the phase current calculated without, the right hand diagram with arc-model.

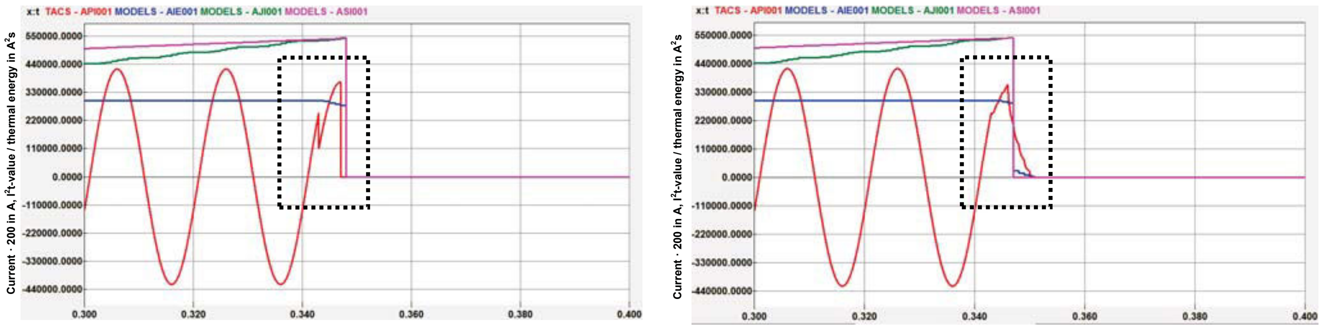


Figure 11: Phase current $i_A(t)$ calculated by the Fuse Model with and without the arc-model

Software based model of a fuse implemented in DIgSILENT PowerFactory

A second implementation of a fuse is conducted within DIgSILENT PowerFactory. Based on the theory of the implementation of a black box model using a parallel capacitance and controlled arc resistance [Petit et al, 1989] the model structure shown in Figure 13 is implemented. At the beginning of the simulation breaker S is closed and R_S represents the ohmic losses R_i in normal state. If the current exceeds an overcurrent-threshold, the model changes to the melting range and the joule integral I²t is calculated, similar to Figure 10. The result is compared to the I^2t characteristic of the fuse, triggering the arcing process. When the arcing process is initiated, R_S changes to a $R_L(i)$ characteristic, resembling the resistance during the arcing process.

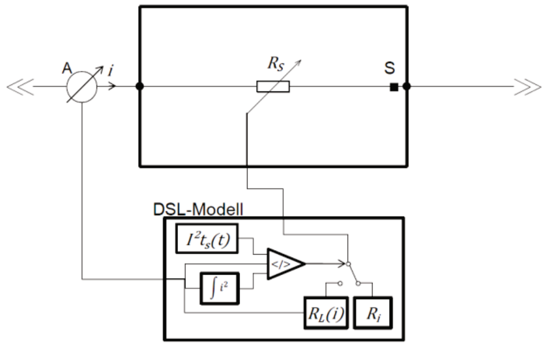


Figure 13: Simplified PowerFactory DSL Model of a NH-Fuse

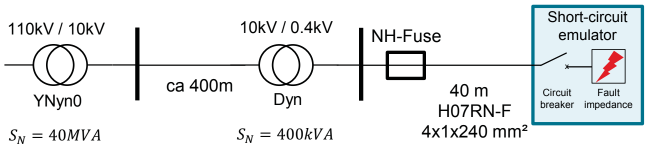


Figure 12: Schematic test setup at the IFHT testing center

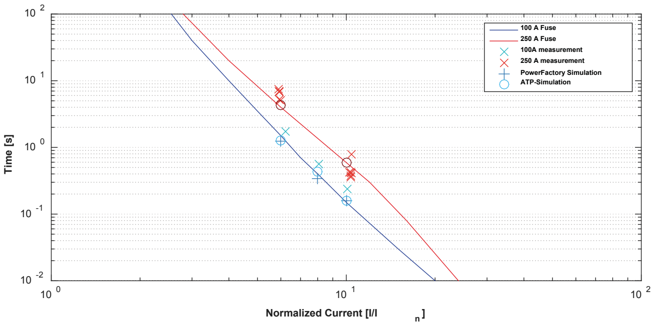


Figure 14: Measuring results NH2 gG fuses, 100A, 250A

Comparison with laboratory results

In order to test the behavior of the models, experiments in the testing center at the Institute for High Voltage Technology, RWTH Aachen were conducted. The testing center offers the capabilities to conduct short-circuit experiments in realistic grid topologies for low voltage grids. A 400kVA Dyn5 transformer, supplied by an overlaying 10kV MS grid is used for the test setup (Figure 13).

On the low voltage side the device under test is connected within a distribution box, followed by 40m H07RN-F 4x1x240mm² cable. With the help of a short circuit emulator, developed at the IFHT, it is possible to insert faults (symmetric, asymmetric, with / without fault impedance) into the low voltage grid [Glinka et al. 2014].

Exemplary results of the measurement of NH2 gG fuses with a rating of 100A and 250A NH2 are shown in Figure 14. The melting times of the investigated 250A fuses show a variance of up to 15% for ${}^{I}/_{I_N} = 10$ and up to 30% for ${}^{I}/_{I_N} = 6$. Also the arcing time as well as the maximum arcing voltage vary within the experiments. Possible explanations are different ages, preloading and manufacturers of the fuses, a slight difference in the testing current by up to 1,5% as well as a variation in the point on wave regarding the fault initiation. Apart from that it can be observed, that the simulation times of the ATPDesigner/ATP and PowerFactory models match the current-time-characteristic of the fuses quite exact, with a maximum deviation of 10%. This can be explained by slight differences in the chosen current-time characteristic. For the use in network calculation the deviation of both, the timing and the arcing characteristic are important. Since the information regarding the manufacturer, the age and preloading of the fuses is rarely available in the field, different scenarios need to be regarded, varying the time as well as the arcing behavior. The shown models provide the capabilities for these parameter studies.

Conclusion

Two models for NH fuses for time domain grid calculations with the help of the ATPDesigner/ATP and DIgSILENT PowerFactory are presented. Both models can be parameterized using the current-time-characteristics of the used fuse. They provide a representation of the arcing process and the resulting voltage drop across the fuse. Therefore they can be used for the investigation of possible influence on the synchronization-methods of grid connected inverters. Exemplary results from the testing center of the Institute for High Voltage Technology, RWTH Aachen show a variance in the time as well as the resistance of the fuse during the melting and arcing process for identical testing parameters. Therefore parameter variations are necessary to cover all possible situations. Both models shown provide the capability for these parameter variations.

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