Smart Fuses for Smart Grids

Considerations about the need, potential product features and feasibility

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Abstract

Fuses have been used for more than a century to protect low voltage (l.v.) distribution grids. Paramount features fostering this application were their high breaking capacity and long-term reliability at reasonable costs. Traditional radial networks, having unidirectional energy flow and gradually reduced conductor cross sections from supply transformer to customers can ideally be protected by means of electric fuses. Selectivity of protection can easily be achieved by means of standardized gG fuses having stepped down current ratings at each distribution point. Because of rapidly growing amounts of renewable energy being fed into the l.v. distribution grid (in Germany, more than 90 % of renewable energy is fed into the l.v. grid) the network structure needs to be adapted to energy flow in both directions. Overcurrent sensing and selective disconnection is expected to be more sophisticated in the future and to require smart devices such as active fuses that are able to disconnect currents upon a signal provided by intelligent fault sensing devices. Some operating principles of active fuses are listed as a base for smart fuse development and a way for fuses to survive in future smart grids.

Introduction

Electric fuses are designed to breaking a current when this exceeds a given value for a sufficient time. So, they can be considered current sensing protective devices, able to interrupt overcurrents in a circuit independent on its direction. General purpose (gG) fuses are widely used in l.v. distribution grids to protect electric conductors from overheating and mechanical damage in case of overloads and short-circuits. These fuses exhibit operating characteristics designed to match the current carrying capacity of adjacent conductors. In conventional radial distribution grids having unidirectional energy flow from transformer to customers, fuse ratings follow the stepped down conductor sizes at each distribu-

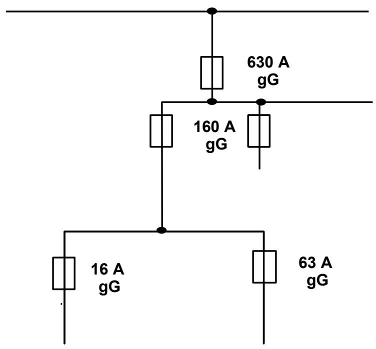


Fig.1 - Selectivity in a radial l.v. grid

tion point (fig.1). The intensities of prospective short-circuit and load currents are gradually reduced at each distribution level but their ratio stays sufficiently high to ensure reliable fuse operation. In this grid configuration, selective disconnection of faulted circuits can easily be achieved by proper co-ordination of rated currents of the fuses in series selected according to conductor sizes. Selective fault current interruption ensures continuity in supply of those customers not connected to the faulted circuit. However, in case of distributed generators and loads connected to an extended line, selectivity and short-circuit current interruption may be impaired and not be ensured by simple fuses as shown in the scenarios below.

Definition of a smart fuse

A smart fuse (or actor fuse) in this context means a fuse able to act on the command of a fault detecting device and to interrupt currents below its intrinsic time-current characteristic. Fault detecting devices may either be integral function of the fuse or external sophisticated grid control units as required for smart grids and are not subject of this paper.

Impact of distributed generation on low voltage grid protection

Within the research project “Protection for Future Distribution Systems” (ProFuDiS) the impact of distributed generation (DG) on the protection systems of distribution grids is being investigated. The effectiveness and applicability of today’s protection concepts and systems in distribution grids with high DG penetration is in focus. Within the consortium of universities (HTW Saar, RWTH Aachen), research facilities (FGH e.V.) and industrial partners (RWE Deutschland, SMA, NH-HH Recycling, OMICRON, ABB, Schneider Electric, Siemens) the necessity for adjustments regarding the protection systems is being explored and possible approaches for a reliable, secure and cost-effective protection for future distribution grids is being developed [1].

Within the project several cases have been identified that have a potentially negative effect on the correct operation of protective devices, specifically for low voltage distribution grids [1]. The increasing number of DG may lead to a higher loading of the grids. In some cases even short periods of overload will be tolerated. This will lead to increasing temperatures of the equipment. Furthermore, the gap between the maximum operating current and the minimum short-circuit current decreases, which makes a reliable fault detection more complicated. Apart from that, the contribution of DG to short-circuit currents within the distribution grids may lead to an unwanted operation of protective devices, e.g. in case of sympathetic tripping. This phenomenon has been discussed for the medium voltage and higher voltage levels especially for directly connected asynchronous and synchronous generators [2]. Due to their significant contribution to initial short-circuit currents (factor 6 and 8 respectively) they may cause tripping of protective devices in adjacent lines in case of faults with DG participation. Systematic investigations for low voltage grids have not been conducted yet. Apart from the unwanted reaction of protective systems, in some cases DG may cause delayed operation or failure of protective devices to operate. This effect of “blinding of protection” is shown in the following.

To quantify the possible impacts of DG on the protection systems with regard to network topologies, DG parameterization, location of the DG, etc. large parameter studies are performed using a steady-state short-circuit calculation method with a low computational time. Apart from that the simulation results are complemented by laboratory experiments. The testing center ("Zentrum für Netzintegration und Speichertechnologien") at the Institute for High Voltage Technology (IFHT), RWTH Aachen offers the capabilities to conduct short-circuit experiments in realistic grid topologies for l.v. grids based on commercially available components.

Blinding of protection

The contribution of DG to fault currents may lead to a variation of the short-circuit current from the overlaying grid in positive, negative and zero-sequence as well as in the phasing. In the following an exemplary l.v. line is used to visualize the effect. The line is fed one-sided by the overlaying m.v. grid. A fault at the end of the line leads to a short-circuit current fed by the overlaying grid flowing across the transformer. The fault current amplitude and phasing depends on the grid parameters, the fault type as well as the fault impedance. When introducing a DG between the transformer and the fault an additional contribution to the fault current needs to be considered (fig. 2). A similar effect is achieved when introducing a large DG towards the end of the line, while considering a fault in between of the transformer and the DG infeed (fig. 3). Both situations lead to a rise of the potential at the point of common coupling (PCC) of the DG, resulting in a decreasing fault current from the overlaying grid. As a result, the tripping time of the fuse may increase significantly up to non-tripping. At the same time, the fault current level may drop from short-circuit level down to overload-level, which needs to be handled by the fuse. This effect is referred to in literature as "blinding of protection". Prior investigations focus mainly on the medium voltage and higher voltage levels [2], [3]. Inverter based DG have rarely been addressed yet regarding their impact on l.v. grid protection. Therefore they are in focus of the present investigation.

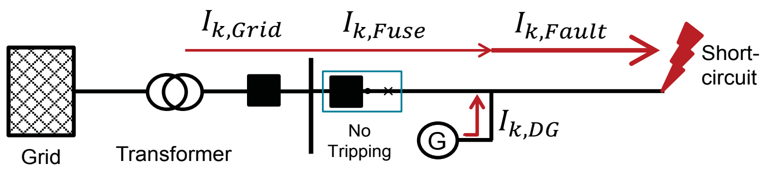


Fig. 2 - Blinding by intermediate DG infeed

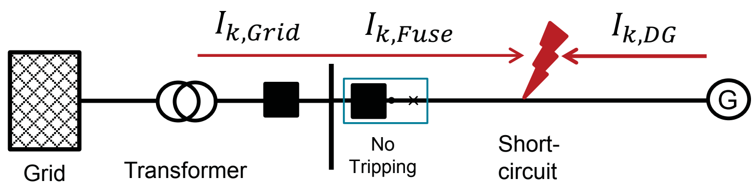


Fig. 3 - Blinding by backward DG infeed

Parameter-studies show that potential protection problems may specifically result from single line-to-ground faults, also with inverter based DG. To verify the results, the single line setup shown in (fig. 4) was built in the testing center of the IFHT. The line consists of a 762 m NAYY 4x150 mm² cable. The system is fed by a 10 / 0,4 kV Dyn5 transformer with a rating of 400 kVA. Within the first 150 m of the line photovoltaic converters with a total power of 109,5 kW (p.f. = 1) are connected. The connection is made via 4x35 mm² NAYY cable with a maximum length of 19 m, being typical for residential service lines. The photovoltaic inverters are parameterized with an undervoltage protection threshold of 0,8 p.u. according to the German application guide [4]. Consequently, the inverters do not provide a low voltage ride through mode. A single line-to-ground fault having a fault impedance of 105 mΩ is considered at the end of the line in phase L1. The fault is initiated with the help of a short circuit emulator, developed at the IFHT, which allows the insertion of different fault types (symmetric, asymmetric, with or without fault impedance) into the low voltage grid [5].

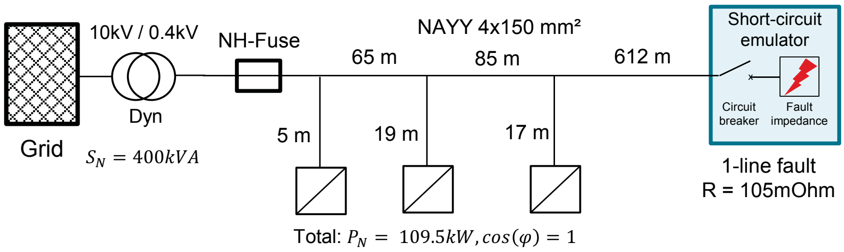


Fig. 4 - Blinding –Laboratory set-up at IFHT test center

Relevant for the investigation of blinding effects is the fault current at the position of the NH-fuse at the beginning of the line. A 250 A NH2 gG fuse is considered as the protective device. For the evaluation of the fuse operation the conventional fusing current of 1,6 I_N = 400 A is taken as the limit. Below that value the tripping behavior and time of the fuse are not clearly defined. Two separate short-circuit experiments are conducted. In the first case the photovoltaic inverters are not considered. Within this "classical" grid structure the short circuit current is fed by the overlaying grid. In the second run the DG feed their full nominal currents into the grid. It can be seen, that the current through the fuse at the beginning of the faulty line L1 is reduced by 27 % down to 359 A (fig. 5). Therefore, the minimum fusing current of 400 A is not reached any more. The currents in L2 and L3 can be explained by the three phase infeed of the inverters. The voltage at the PCC of the inverters does not drop below 0,8 p.u., therefore the short-circuit is not detected with the present manners, and the inverters are not disconnected from the grid. It can be concluded, that in the shown case the short-circuit current is reduced significantly and could lead to an uncertain behavior of the fuse. Therefore, measures to cope with blinding in low voltage grids need to be developed.

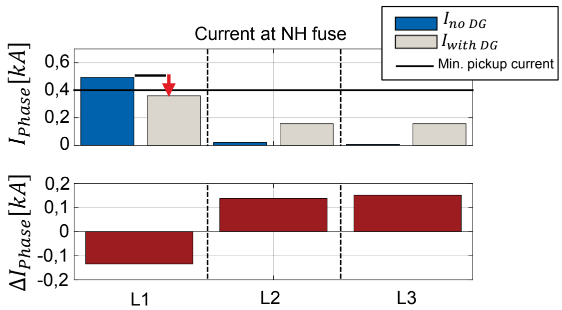


Fig. 5 - Blinding –test results

top: I_{fuse} without/with DG,
bottom: $\Delta I_{fuse} = I_{without\ DG} - I_{with\ DG}$

Justification for smart fuses in future l.v. grids

Even in the future, fuses will be able to reliably protect cables and lines from overheating and mechanical damage caused by sustained overloads and high fault currents respectively. However, in future l.v. grids, the number of operating and fault conditions that cannot easily be dealt with by means of conventional fuses is expected to grow.

As explained above, the current flowing through a fuse at the conventional feeder terminal of a main distribution line (mains fuse) usually located in the transformer substation, may be reduced by DG contributing to the fault current and stabilizing the line voltage. Such blinding effects may impair the ability of a mains fuse adjacent to the transformer to interrupt fault currents as expected. The fuse may operate delayed or may not operate at all. Other means of fault detection and protective devices that are able to operate on command of such fault detectors will be necessary to reliably protect l.v. grids of the future.

There are, of course, other protective devices available to meet the requirements of future distribution systems but replacing conventional fuses by actor fuses can be considered to be an easy and most economic solution.

Technical requirements to be met by fuses in future distribution grids

A major additional requirement for fuses in future l.v. distribution grids will therefore be the ability to operate on the command of a sophisticated fault recognition device. Such device, as described above, will have to unambiguously detect a faulty situation and decide on the appropriate protective device to clear that fault and trigger the selected device. In order to ensure selective protection under all fault conditions, a triggered fuse must operate faster than all other devices subjected to he fault current i.e., below its original time-current characteristic. The dimensions of such "active" fuse shall of course enable to replace a standard fuse in existing distribution boards. The latter has to be seen as a major justification for the development of active fuses.

Operating principles of actor fuses in future distribution grids

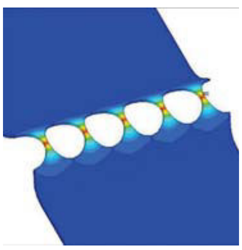


Fig. 6 - Fuse-element

Electric fuses operate based on heat generated by the current flowing through and melting conductor restrictions of the fuse-elements (fig. 6). The operating time is therefore depending on the intensity of the current. Fuse operation follows time-current characteristics specifically designed to protect associated equipment. At very high currents, all the thermal energy is stored in the restrictions until melting point is reached (adiabatic range). Below the minimum fusing current, all the power generated in

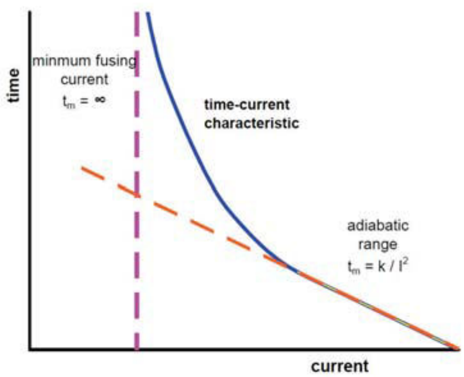
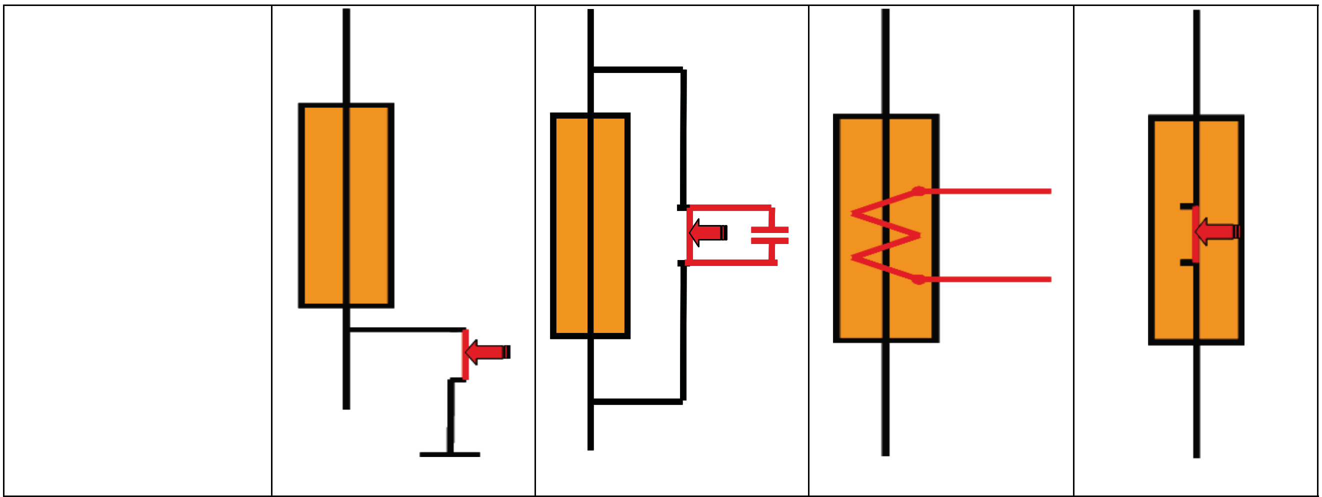


Fig. 7 -Time-current characteristic (schematic)

the fuse-element is dissipated to the surroundings and the fuse-element temperature stabilizes the below melting point of the fuse-element material (fig. 7).

Standard fuse-links exhibit time-current characteristics expected to stay unchanged for service life and fuse operation shall only be initiated by the current passing through the fuse-element. Actor fuses in the contrary, shall be able to safely interrupt operating currents below the minimum fusing current or enable faster operation than given by the time-current characteristic. Most of the operating principles of actor fuses as described below and illustrated in fig. 8 have been known for long but never been realized on l.v. fuses. They are either based on boosting the current through the fuse until it meets the time-current characteristic (figs. 8a,b,c) or to shift the time-current characteristic to lower current levels by addition of thermal power (fig. 8d). Mechanical interruption of the fuse-elements has also been realized (fig. 8e) for special applications.-



8a) Bypass	8b) Solid grounding	8c) Electric pulse	8d) Additional heat	8e) Mechanical break

Fig. 8 - Operating principles of actor fuses

- Bypass solution (fig. 8a)
  This technique has been invented and realized in the 1950th [6] and is still in use for short-circuit current limitation in m.v. installations. The bulk of the load current is carried by the by-pass conductor and a fraction only by the associated fuse having a correspondingly low rating. The fuse-link will be charged with the total current after the bypass is opened and operate fast corresponding to its time current characteristic. Opening of the bypass conductor associated to the fuse-link does not need be initiated by an explosive charge as described in the patent [6] but a mechanical switching device will be suitable. A major challenge will be to provide defined current distribution between fuse-link and bypass on a resistance level below one mΩ. Also, no protection is given without external activation of the bypass switch.

- Solid grounding (fig 8b)
  This method, quite common for arc fault protection as described in [7] and [8], can also be used for the interruption of any low fault currents that would not melt the fuse-element or after undue

delay only. Generally, the make-proof earthing switch does not need to be integral part of the fuse but installed close to it. Impedance may be added to the earth link to protect the switch and adjacent conductors from excessive stresses. The fuse will perform as normal unless the earthing switch is activated.

- Surge current injected (fig. 8c)
  A surge current may be added to a fault current of insufficient intensity to melt the fuse. This current in addition to the fault current must be high enough to reach the fusing current. The surge current may be supplied e.g., by an l.v. high power capacitor or by an h.v. capacitor or any other source separated by a current transformer from grid potential. The addition of surge currents enables very short fault clearing time independent on the fault level. However the triggering energy required will be substantial.

- Additional thermal power added (fig. 8d)
  On general purpose fuse-links a low melting point material (solder) is usually applied to the center restrictions (spots of highest temperature) to enable fuse operation at low overcurrents. An additional heater element attached adjacent to the solder spot (fig. 9) allows initiating fuse operation below its given time-current characteristic by an external signal while without such signal the fuse will operate according to its characteristic. Surface mount (SM) devices e.g., resistors or PPTC elements may be used as electric heaters [8]. The use of exothermal materials in place of solder has been mentioned as being more efficient and suitable for remote control of fuse operation [10]. More recently developed extremely reactive multi layer foils [11] consisting of nanolayers of different metals e.g., Ni/Al can be ignited with a low energy electric spark and generate temperatures above 1.000 °C within milliseconds.

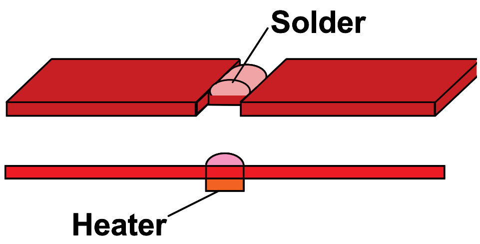


Fig. 9 - Heater element

- Mechanical breaking (fig. 8e)
  Mechanical breaking of fuse-element restrictions has been used to initiate low current interruption in h.v. fuses [12]. More commonly, this method is used for safety disconnection of batteries in case of car crashes [13]. Depending on the nature of the fuse-elements, multiple breaks of the fuse-element or one larger section cut out by means of insulating knives. The energy driving the actuator is commonly supplied by a propelling charge.

Conclusion

Protection of future l.v. distribution grids can be predicted to become a major task for network operators and suppliers of protective devices alike. A growing number of all sorts of renewable energy generators feeding into the existing distribution system turn the clearly structured distribution grid into a very complex and all but easy to handle l.v. grid of the future. There is common sense that future grids will require more “intelligent” components rather than mountains of copper to meet future requirements. Operation and protection of future grids will have to be “smarter” and require “smarter” grid components to interact with. It has been shown that extensive DG may impair conventional fuse protection in future l.v. grids as fault conditions may occur that require the replacement of standard fuses by active protective devices, e.g. actor fuses.

A major additional requirement for fuses in future l.v. distribution grids will therefore be the ability to operate on command of a sophisticated fault recognition device. Such device, as described above, will have to decide on the optimum location for fault current interruption and trigger the corresponding fuse. In order to ensure selectivity, the triggered fuse must operate below its original time-current characteristic and, of course faster than any other fuses subjected to the fault current but not supposed to operate. The dimensions of such actor fuses shall of course enable to replace a standard fuse in existing distribution boards. The latter has to be seen as a major justification for the development of actor fuses.

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