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Self-Extinguishing Faults in MV Cable Networks - Feasibility Study of Fault Prediction

F. Koehler[1], S. Cobben[1,2] and F. Provoost[1]

[1] Alliander N.V.
Utrechtseweg 68, 6812 AH, Arnhem (The Netherlands)
e-mail: **fabiankoehler@web.de**, **Frans.Provoost@Alliander.com**

[2] Eindhoven, University of Technology
j.f.g.cobben@tue.nl

Abstract. The Dutch grid operator Alliander started an ongoing substation refurbishment in 2006 with SASensor, a measurement, protection and control system, including fault localization of persistent faults. Around 20 percent of the recorded measurements comprise the phenomena of 1-phase self-extinguishing faults. In order to assess the usability of these events to predict faults, the phenomena and their behaviour in time are described in MV networks with isolated neutral and low-impedance earthing. Furthermore the feasibility of fault localization using the information included in those events is discussed.

Key words

self-extinguishing faults, transient faults, single-phase faults, MV cable networks, fault prediction

1. Introduction

In present and future the high quality of electricity supply is a key feature for the distribution system in the 10 kV grid of Alliander. Furthermore governmental and regulatory framework requirements lead to changes in grid operation. In present, intelligent network concepts, as the measurement system SASensor, help to assure a high quality of supply and to evolve the distribution network into a smart grid. The reduction of outages and customer minutes lost is a goal when improving the grid. In practice, it is the reduction of time for manual fault localization, which offers most improvements. Also the amount of voltage dips in the network can be decreased by searching possible coming fault in the network, and repair cables even before there is a short circuit which leads to voltage dips.

After four years of SASensor data collection and more than 4000 events recorded, these data contain great chances for the development of new software-based systems, like fault localisation of persistent faults [1, 2]. These developments are based on the stored data files, which are comprised of substation and trigger information and phase currents and voltages measurements. Already being detected in the SASensor measurements in 2007, the phenomena of self-extinguishing single phase faults could practically not be used for fault localisation [1, 4]. The fact that most faults in MV cable networks start as 1-phase faults, a relation between the phenomena of self-extinguishing single phase faults and a persistent single phase fault could help to predict cable faults and improve the reliability of supply. Therefore an automatic software-based system filtering self-extinguishing single-phase faults and using them as an indication on future persistent faults is designed. The idea behind fault prediction is illustrated in Fig. 1, based on the recorded data of SASensor as a starting point. With characteristics of self-extinguishing single phase faults, those events can be filtered out and the information included stored in a data-base. The most important information, fault location and the number of past occurrences can be sent as message to the control centre to take precautions, like switching actions at Normal Open Points (NOP) to reduce the number of customers affected at a later outage.

This paper describes the feasibility of this idea, beginning with the phenomena of self-extinguishing faults and their evolution into persistent faults. With their characteristics, fault recognition is explained. Furthermore, the possibility of using the transient of a self-extinguishing fault for fault localization is researched using simulations, as well as SASensor measured data.

2. THE PHENOMENA OF SELF-EXTINGUISHING FAULTS

Self-extinguishing single phase fault events are characterized clearly by zero-sequence current and voltage. Therefore the description of those events for sorting is based on symmetrical components with definitions in (1) and (2).

$$I_0 = \frac{1}{3}(I_A + I_B + I_C) \quad (1)$$

$$V_0 = \frac{1}{3}(V_A + V_B + V_C) \quad (2)$$

In the grid of Alliander, various substation configurations, regarding earthing policy exist. It was decided to equip substations with low-impedance earthing during their refurbishment. However a great number is still operated as networks with isolated neutral.

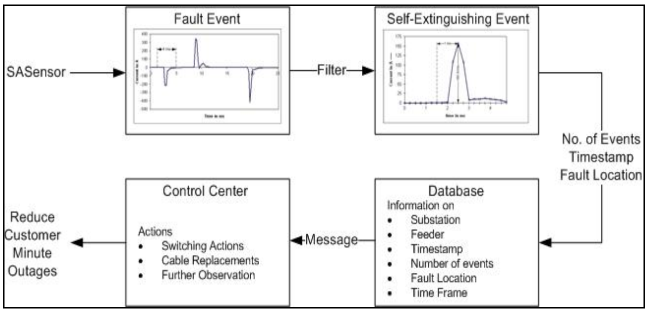

Fig. 1. Idea behind fault prediction in 10 kV MV cable networks

A. Networks with Isolated Neutral

In networks with isolated neutral a self-extinguishing single phase fault is just comprised of a transient, which features a high frequency, shown in Fig. 2. This transient is mainly the result of the discharging of the faulty capacitances and the charging of the healthy phase capacitances. Due to the displacement of the system's neutral and the zero-sequence voltage remaining in the system, restriking is very likely [3]. The corresponding phase voltages, seen in Fig. 3, face a much higher voltage than at normal operations. Ideally, each restrike occurs in half-period steps with periodic changing of polarity and add-up of zero-sequence voltage. As a result, each restriking transient's current is increased due to the higher charging of capacitances (Fig. 4).

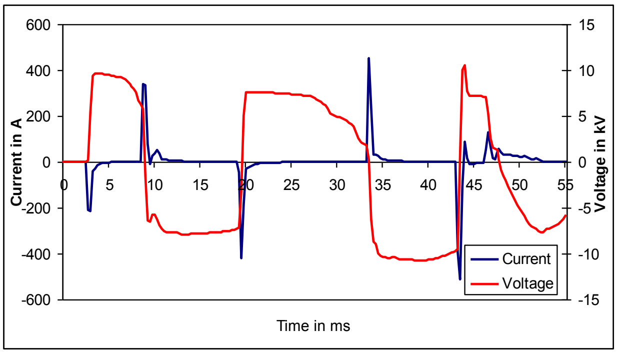

Fig. 4. Zero-sequence current and voltage of a restriking self-extinguishing single phase fault in a network with isolated neutral

SASensor measurements of self-extinguishing faults show that this zero-sequence voltage is decreased to zero in a period of time shorter than 1 second, depending on the number of restrikes.

B. Networks with low-impedance earthing

Self-extinguishing single phase faults in a network with low-impedance earthing, are comprised of a transient, a steady short-circuit fault and an Eigenfrequency oscillation after the self-extinguishing, shown in Fig. 7. A single event lasts not longer than half a period. The discharging transient follows the same conditions as in a network with isolated neutral. But from the moment, where the transient current reaches its maximum the earthing impedance has to be taken into account to.

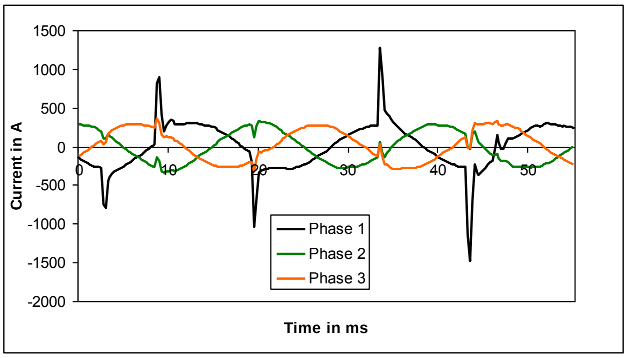

Fig. 2. Measured phase currents during a self-extinguishing single phase fault in a network with isolated neutral

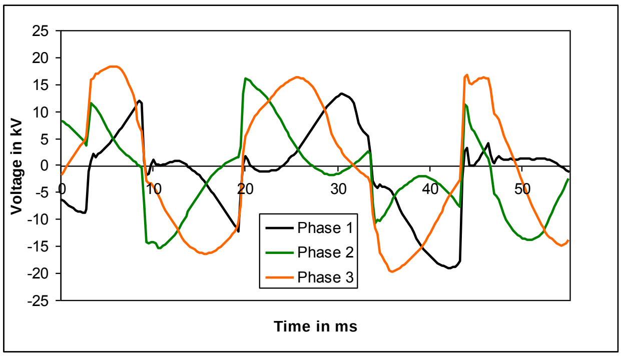

Fig. 3. Measured phase voltages during a self-extinguishing single phase fault in a network with isolated neutral

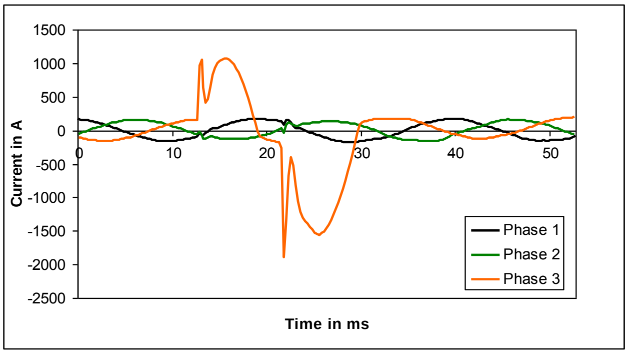

Fig. 5. Measured phase currents during a self-extinguishing single phase fault in a network with low-impedance earthing

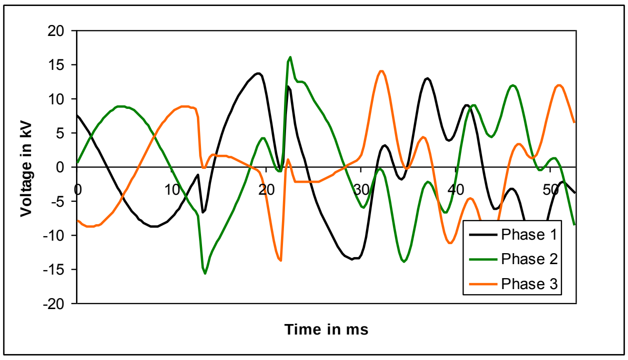

Fig. 6. Measured phase voltages during a self-extinguishing single phase fault in a network with low-impedance earthing

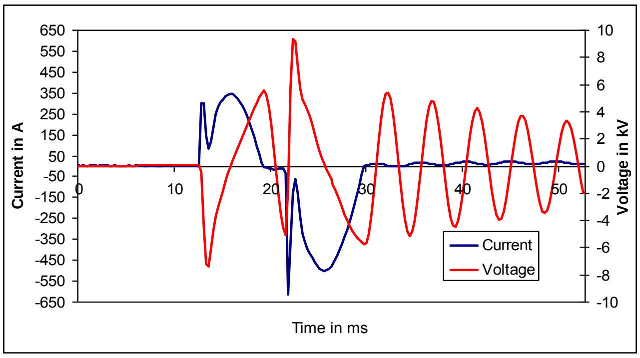

Fig. 7. Zero-sequence current and voltage of a restriking self-extinguishing single phase fault in a network with low-impedance earthing

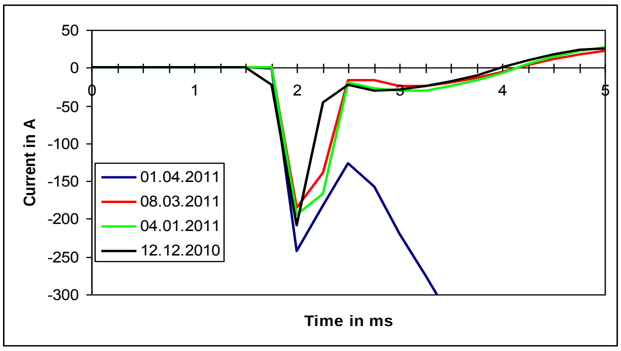

Fig. 8. Different self-extinguishing single phase fault current events at a substation with low-impedance earthing at the same location

The earth-circuit path formed by Z_E is the main path for the steady short-circuit fault current starting at the charging of healthy phases until the self-extinguishing at zero-crossing of the fault current, shown in Fig. 5 and Fig. 6. The charged capacitances are then discharging over the earthing impedance. The small damped oscillation, seen in Fig. 7 after the self-extinguishing is unique for each substation, as it is the Eigenfrequency of the cable network and earthing impedance. It ranges from 150 Hz to 350 Hz. The SASensor measurements show, that the zero-sequence voltage is decreased in a time shorter than 250 ms after the self-extinguishing fault. Therefore restriking is not as likely as in a system with isolated neutral.

3. Feasibility Study on Fault Localisation

With experience from the recorded self-extinguishing events and the description of them in symmetrical components, it is discovered, that the information about the self-extinguishing fault's location is included in the transient event. In Fig. 8 an overlay of several events at the same location with the same characteristics of the transient's current are observed in a time span in a feeder until it turned into a persistent fault. The transient's dI/dt as well as the transient's amplitude features approximately equivalent values. These circumstances are discovered for a large number of connected self-extinguishing fault events in the SASensor measured data.
Because no data of different self-extinguishing faults in the same feeder were discovered, a simulation study is performed to determine the self-extinguishing fault dependencies on fault location. The aim of the study is to obtain a rough indication on a faults location based on a typical 10 kV MV network. Therefore only the main rings are taken into account. Normally these networks also contain sub rings (with NOP) and some lateral branches. It is investigated whether there is a difference in shape for faults nearby or far away from the substation. Therefore a fault was made at 10, 50 and 90% of the feeder. The presence of branches (sub-rings or laterals) does not influence this result. The simulation model is based on the network of Fig. 9, where an earthing impedance of 7 Ω is connected for low-impedance earthing and disconnected for network with isolated neutral. The self-extinguishing single phase fault is modeled as a direct single phase to earth fault with occurrence at maximum phase voltage and clearing after 0.5 ms.

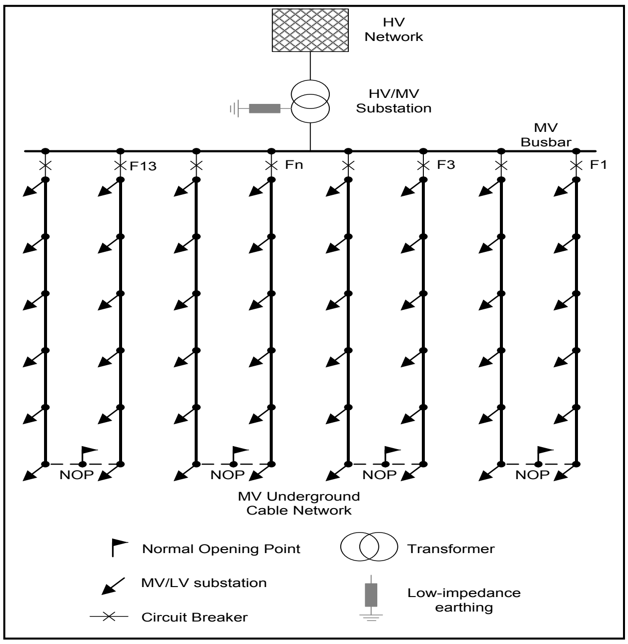

Fig. 9. Typical Alliander 10 kV cable network configuration

The time of occurrence is derived from SASensor measurements, where the stress to the insulation is maximal. The 10 km cables in Power Factory are built of π-models without conductance. Also parasitic effects are not taken into account, which smoothens the transient's waveform. The fault locations are at 1 km, 5 km and 9 km of the radial cable network of one feeder. Furthermore simulations with half of the load are performed to gain knowledge about the impact of load.

A. Simulation Results for a Network with Isolated Neutral

The results of the simulation in a network with isolated neutral are shown in Fig. 10 to 12. Due to the higher cable impedance and capacitance for a fault further away from the infeed the transient's amplitude of the self-extinguishing single phase fault as well as the transient's frequency is decreased. Furthermore, the load has only a minor impact on the transient's shape. Therefore, the in-formation about fault location is found in the transient's frequency. Then these results are compared with the transient waveforms in Fig. 8. The transient frequencies match, because earthing has minor influence on the transient.

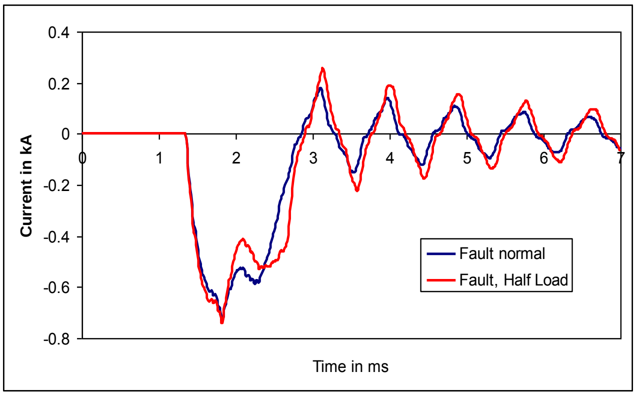

Fig. 10. Simulation of self-extinguishing single phase fault in a network with isolated neutral, fault location 1 km

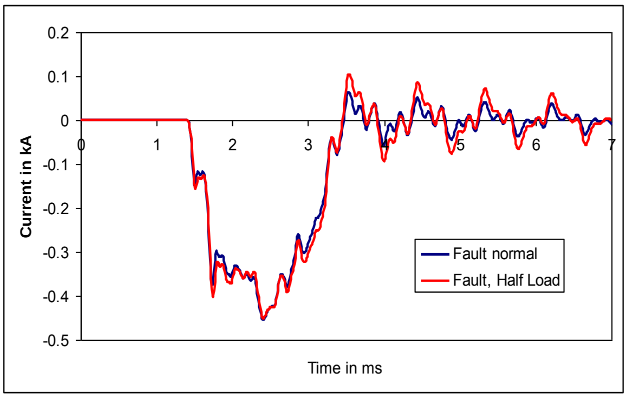

Fig. 11. Simulation of self-extinguishing single phase fault in a network with isolated neutral, fault location 5 km

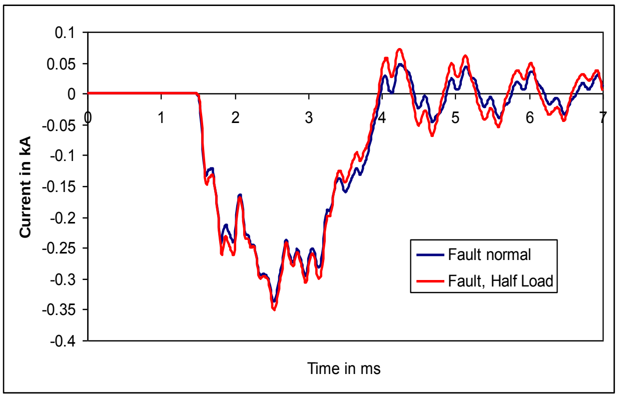

Fig. 12. Simulation of self-extinguishing single phase fault in a network with isolated neutral, fault location 9 km

B. Simulation Results for a Network with Low-Impedance Earthing

The simulation results in a network with low-impedance earthing in Fig. 13 to Fig. 15 show the same results as for a network with isolated neutral referring to the transient. But because of the steady short-circuit current the transient's frequency cannot always be determined. With an ongoing evolution process of self-extinguishing faults into persistent faults, as seen in Fig. 8, also the transient's waveform is changing with time. The steady short-circuit current includes information about the fault location as well, because the fault at location 1 km does not show the steady short-circuit current.

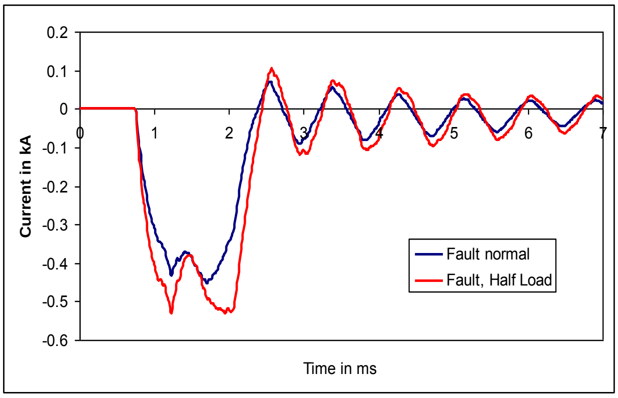

Fig. 13. Simulation of self-extinguishing single phase fault in a network with low-impedance earthing, fault location 1 km

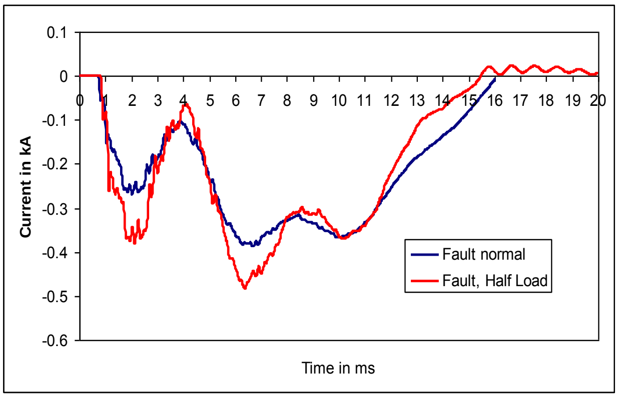

Fig. 14. Simulation of self-extinguishing single phase fault in a network with low-impedance earthing, fault location 5 km

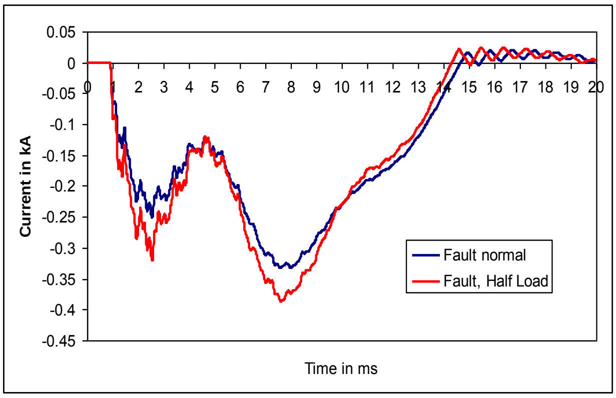

Fig. 15. Simulation of self-extinguishing single phase fault in a network with low-impedance earthing, fault location 9 km

4. FILTERING OF SELF-EXTINGUISHING EVENTS

The starting point for the automatic software-based system is the ASCII files, which consist of substation and trigger information alongside with the event recorded phase currents and voltages. These files are read into the system and trigger information is queried. If zero-sequence current trigger information is detected, the zero-sequence components of current and voltage are calculated. Two different methods of self-extinguishing fault filters, a maxima frame comparison and a d/dt filter are used, each for a specific purpose, to search for self-extinguishing fault waveforms.

If a waveform triggers the values set for self-extinguishing faults, a collector function saves the substation and feeder information, as well as the number of events. At the moment this function is only used to show this information on the screen, but later on, the function should start the fault localization program and store all information in a database. The processing scheme of the present filtering can be seen in Fig. 16.

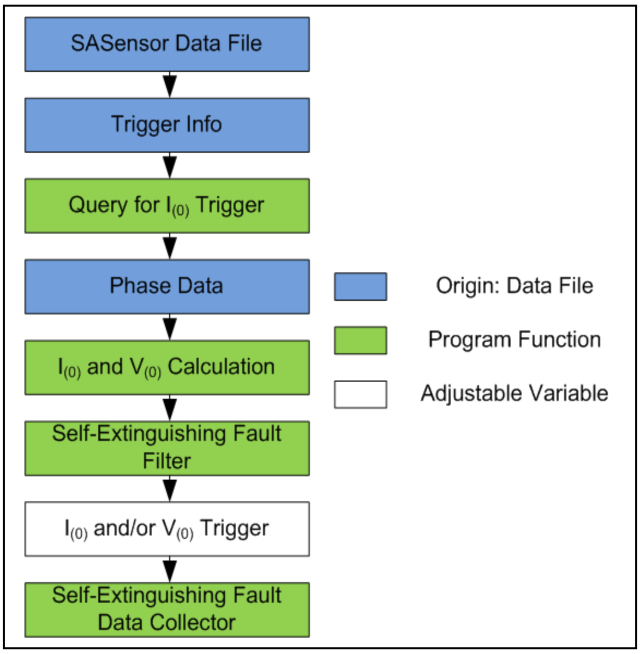

Fig. 16. Processing Scheme of Filtering

A. *Maxima Frame Comparison Filter*

This filter uses the well-known principle of comparing two frames combined with an absolute maxima-determination function as shown in Fig. 17 and is designed for counting events. If the first frame's maximum exceeds the first frame maximum value set and the second frames maximum is lower than the second frame value set the waveform is recognized as a self-extinguishing fault. The frame size has a great influence on the recognition rate and is dependent on the networks earthing. For networks with isolated neutral a frame size of quarter or half of a period and for networks with low-impedance earthing a full period can be used to achieve a high recognition rate. A balanced filter for the SASensor data performs with a recognition rate of 90 to 99% using zero-sequence current as data source in both networks and additionally zero-sequence voltage for networks with low-impedance earthing. The corresponding parameter values for a filter used in low-impedance earthed and isolated networks are summarized in Table I.

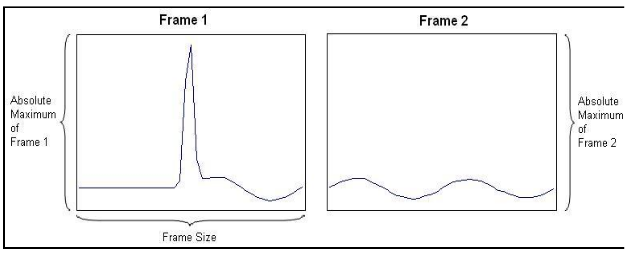

Fig. 17. Maxima frame comparison filter design

Table I. Parameter values for maxima frame comparison filter

Frame Size 20/ 10 ms	$I_{(0)}$	$V_{(0)}$
Frame 1	>125 A	>4.33 kV/-
Frame 2	<50 A	<4.33 kV/-

B. *d/dt Filter*

The d/dt filter's purpose is to find the first transient of a series of self-extinguishing single-phase faults, which is used for fault localization. Zero-sequence current and/or voltage are searched for a high d/dt with a pre-existing very low value of the zero-sequence component. If these conditions can be applied on the zero-sequence waveform, it is recognized as a first self-extinguishing event. A summary of tested parameter sets on reference data in a network with low-impedance earthing is shown in Table II. The recognition rate is lower than it is for the maxima frame comparison filter and the problem remains, that every persistent single-phase fault is recognized as a self-extinguishing event. Therefore the information of a protection operation has to be queried from the SASensor data file to determine persistent faults.

Table II. Parameter sets for d/dt filter in network with low-impedance earthing

Frame 1 Max. dI/dt	Frame 2 Max. dI/dt	Single events	Restrik-ing events	Persist-ent Events (>4 periods)	Oth-er
Ref.	Ref.	12	1		
>75 A	<30 A	11	1	1	2
>100 A	<50 A	10	1	1	3
>150 A	<75 A	8	1	0	0
>150 A	<100 A	9	1	0	0
>150 A	<125 A	9	1	1	0
>175 A	<125 A	9	1	1	0

In networks with isolated neutral the waveform is only comprised of the transient. Therefore the d/dt Filter is not combined with a frame comparison, but uses the following succeeding parameters for zero-sequence current:

- $I_{(0)} < 20$ A / 20 ms
- $I_{(0)} > 125$ A / 1 ms
- $I_{(0)} < 75$ A / 1 ms

With this filter the same recognition rate as for the maxima frame comparison filter is achieved. The major advantage of the d/dt criterion in networks with low-impedance earthing and isolated neutral is that all transients are recognized depending on the filters parameter set.

5. Feasibility Study on Fault Prediction

The recognition of self-extinguishing faults is accomplished, but takes very long to be processed. Improvements in the code, as well as the connection between the programs have to be made. The fact that the amplitude of the transients of a timeline of events is consistent with a minor deviation for the same fault location leads to the conclusion, that the information needed for fault location is comprised in these transients. Because of the high frequency of the transients, the sampling rate is not always sufficient for measuring the exact waveform. Therefore the real amplitude of the transient is not always represented. With the results of the simulations and experience from the SASensor measurements a rough fault location, weather the fault is in the beginning or the end of the network is possible. The database storing event data is still under development and timelines of self-extinguishing events had to be sorted out by hand. Derived from experience with SASensor data, the time span for self-extinguishing faults in systems with low-impedance earthing ranges from minutes to months and in systems with isolated neutral from days to years. As the risk for a fault in a cable network is low, the risk of two faults occurring at the same time can almost be neglected. However, it is possible that the high transient voltages in the healthy phases will weaken the insulation. This might result in a break-through of the insulation in the same or another feeder. This event has been noticed only one time in the past 4 years. Therefore no relation between the number of self-extinguishing faults until the evolution into a persistent fault and time span could be found so far. Up to now, there exists no automatic message system for self-extinguishing faults in the control centre, but switching actions in one case due to self-extinguishing faults were already performed before the persistent fault occurred. The number of customers lost during this outage was reduced due to these switching actions.

6. Conclusion

The idea of using self-extinguishing single phase faults as an indication for future persistent faults is quite promising. Self-extinguishing faults do not interrupt the electricity supply and will not cause harmful voltage dips. However, without measures, they will sooner or later develop into a persistent single- or multi-phase fault, causing interruption of power supply and voltage dips. The time between the first occurrence of a self-extinguishing fault and the actual persistent fault is often several weeks or months. Therefore the grid operator has time to take measures to limit the area which will be affected when the persistent fault occurs. These measures mainly consist of switching actions relocating the normal open point (NOP). It might even be possible to prevent the persistent fault. The grid operator can be helped when more information is obtained about the location of the self-extinguishing fault. This information must give a rough indication (beginning, middle or end of the feeder). But as long as no database and automatic filtering for event recorded data exist, only few timelines of events can be researched. The increasing amount of data due to on-going substation refurbishment has to be handled to give an overview of all timelines of self-extinguishing faults needed for finding relations to the time span until a persistent fault occurs. Further research on the fault location has to be performed to improve the very rough fault location, but the promising outcome of the study have resulted in a further investigation which finally will lead into a practical tool to support the grid operator.

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