WEB-BASED AUTOMATIC ARC CLASSIFICATION FOR SINGLE-PHASE FAULTS BASED ON SYSTEMATIC FAULT RECORD ANALYSIS

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Abstract

Clearance of short-circuit faults on extra high voltage (EHV) transmission lines is critical for power system stability. Therefore, most system operators use single-pole tripping and auto-reclosing in order to give single-phase arcing faults a chance of extinguishing while keeping the two healthy phases of the line in operation.

The dead time of the auto-recloser should be long enough for the so-called "secondary arc" to stop burning, and yet as short as possible in order to reduce the power system disturbance. Since a fixed time setting is used, the scheme sometimes fails and the sequence ends up with final three-pole tripping of the line. In this case, the operators have to decide whether it is appropriate to manually reclose the line after a couple of minutes, by assessing the risk of fault restrike.

This paper shows the efforts and experience of Vattenfall Europe Transmission (VE-T) in implementing an automatic arc fault classification system which can, in case of unsuccessful autoreclosures, automatically differentiate between “secondary arc faults” and other faults, and eventually determine the fault extinction time. Depending upon the signal analysis, the system advises the operators to reclose the line or not. It also provides statistics of the arc burning time in order to help to optimize the autoreclose dead time.

Introduction

Short circuits in EHV transmission systems can cause two major problems. They can stress the equipment, such as cables, insulators and generators. They can also cause severe power outages, due to a loss of stability of the generating system. The second risk is to be taken very seriously, and a set of countermeasures are commonly used. In particular, modern protection systems are designed to minimize the fault clearance time, they are able to trip a single phase of the line, and autoreclosing relays [2] are used to try put the line back into operation as soon as possible.

In case of unsuccessful auto-reclosing, the control center operators have to decide whether to reclose or not in a matter of a few minutes. Reclosing is advisable if it appears that the fault had an arcing, self-extinguishing behavior, and the auto-reclosing actually took place too soon. But the operational time frame is too short for carrying out any manual expert analysis of the sequence of events. The paper shows how this task has been automated by automatically analyzing transients recordings from digital protection relays. Automatic event analysis based on transients recordings [7][9] has several other uses, including fault location, fault analysis for reporting, and equipment (e.g. circuit breaker) monitoring.

Single-pole tripping and autoreclosing

In VE-T's transmission system, lightning-induced single-phase to ground faults with self-extinguishing behavior are very common. Let's consider the evolution of such a fault on a two-terminal EHV transmission line (Figure 1).

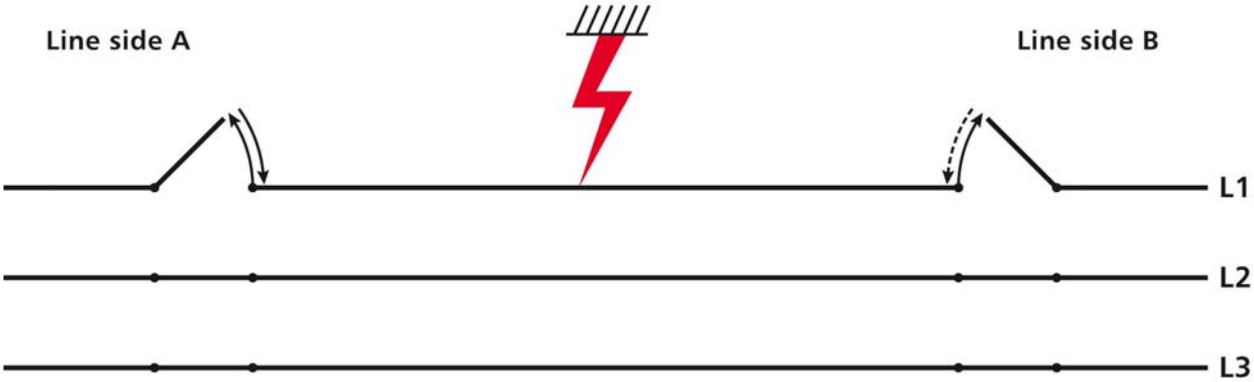

Figure 1: Two-terminal line during autoreclosing dead time.

VE-T uses high-speed distance and line differential protection for clearing the faulted phase [5]. After that, an autorecloser waits for a constant dead time of about 1s before reclosing the first line end (called side A). In case a fault is still present, the line will be immediately tripped 3-pole. In case no fault is present, the autorecloser on side B operates too, after a slightly longer dead time and a check that the measured line voltage is within operational limits.

Secondary arcing

After the opening of the circuit breakers, the primary fault arc extinguishes, but a low-current "secondary arc" may continue to burn, due to capacitive coupling of the faulted conductor with neighboring energized conductors and, to a lesser extent, to inductive coupling which may be caused by earth return currents. Let us focus on the main effect which is caused by the voltages on the healthy phases of the same circuit (Figure 2).

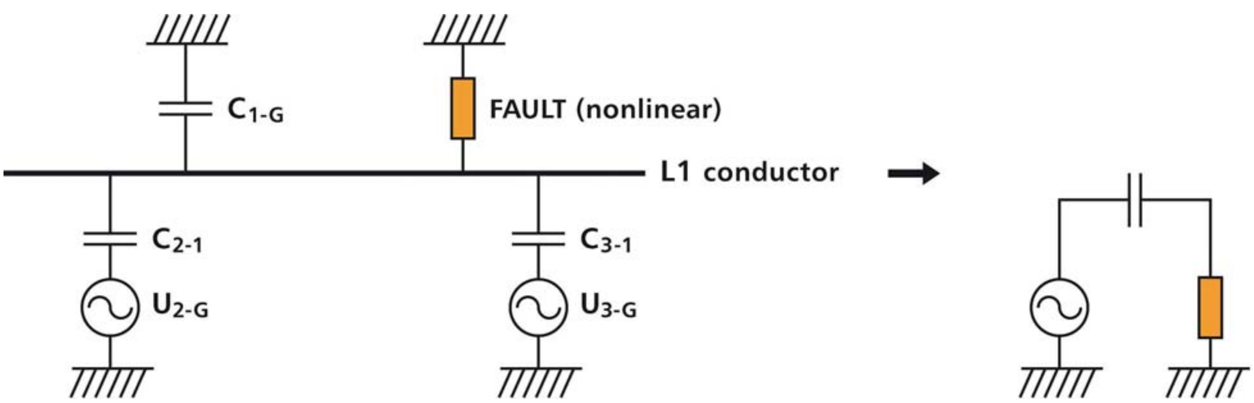

Figure 2: Equivalent circuit of a secondary arc fed by capacitive coupling with the two healthy phases.

For a given arcing path, the amplitude of the secondary arc increases with system voltage and line length. At the highest voltage levels, secondary arcs may not self-extinguish [1] and it is necessary to provide a shunt path for the fault current (reactors are used) in order to force the extinction of the arc. However, up to 500 kV, the natural cooling of the arc path may be sufficient. The secondary arc typically restrikes several times until the ionized air recovers sufficient voltage withstand capability. Then, after about 60 to 400 ms, depending on many factors such as the line geometry, the past short-circuit current and the local weather conditions, reclosure of the circuit breaker may be successful. If auto-reclosure takes place during secondary arcing, or a short time after true fault extinction, auto-reclosing typically fails.

New operational requirement for increased system stability

Vattenfall Europe Transmission system operation showed increased interest in novel schemes that could improve the manual reclosing decision, i.e. reduce the probability of stressing the equipment one more time due to a permanent fault while reducing the total time the line remains out of operation.
For this purpose, VE-T has studied the rate of success of automatic and manual reclosing after single-phase arcing faults and designed an optimization scheme together with the Technical University of Dresden.
According to this scheme, an automatic function should analyze the transients recordings produced by digital line protection and compute a suggestion to the operator within a couple of minutes, in case of unsuccessful single-pole auto-reclosing.
If a secondary arc is detected that lasts during the complete duration of the dead time, or if the secondary arc extinguishes "too late" i.e. within less than 200 ms or so before the auto-reclosing order, then the fault is likely to extinguish during the few minutes that follow, and the operators should be suggested to reclose the line.
In other cases, including dubious situations where the sequence of events cannot be completely analyzed, the operators should be prompted not to reclose. The line will remain out of operation until an inspection is made.

Detection of secondary arc and measurement of its extinction time

Research on secondary arcs has focused on designing an optimal autoreclosing relay, which would offer the best operational compromise between the risk of fault restrike after reclosing and the risk of a loss of synchronism because reclosing is being delayed.
The project described here runs in a slightly different context, since the complete sequence of events is being analyzed afterwards by an expert software.

By collecting transients recordings of a sufficient length – covering the complete fault sequence at both ends of the line - it is possible to detect pre-fault, fault, line tripping, auto-reclosing and post-fault conditions, and to recognize unsuccessful auto-reclosing sequences and their exact timing.
After the opening of the circuit breakers, the primary fault arc extinguishes, but a low-current "secondary arc" may continue to burn, due to capacitive coupling of the faulted conductor with neighboring energized conductors and, to a lesser extent, to inductive coupling which may be caused by earth return currents. The analysis of the voltages of the faulted phase during the dead time reveals the secondary arc behavior, as shown in Figure 3.

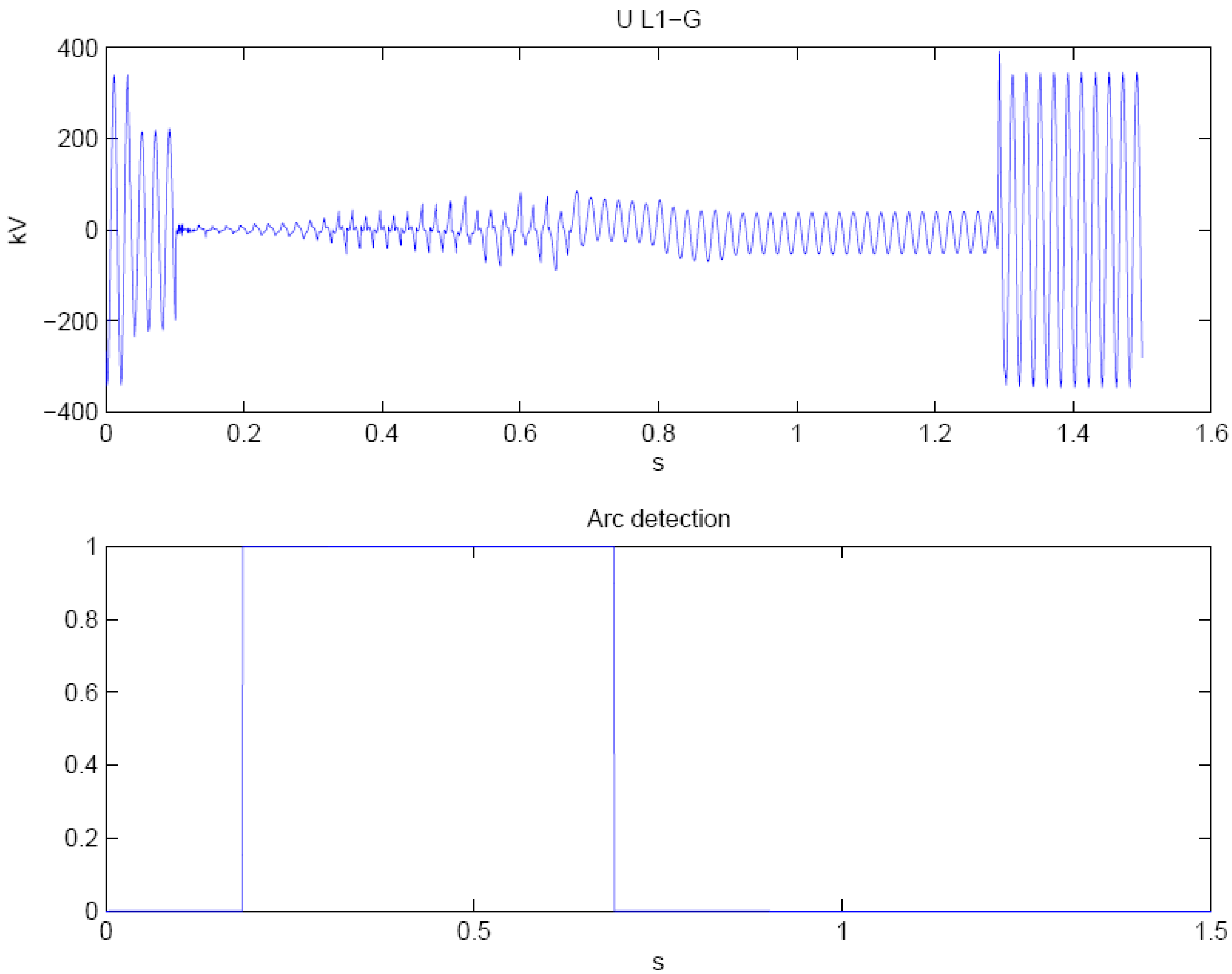

Figure 3: Line voltage during the extinction of an arcing fault, and arc detection by the algorithms.

The “secondary arc” voltage exhibits a characteristic pattern of high harmonic distortion, significant amplitude (not higher than 40% of the normal voltage, though) and changing waveform. These criteria [8], which are comparable to other voltage waveforms classifiers [3][4], are used to build a "secondary arc detection" signal. It wad found that the secondary arc must last 60 ms or more for reliable detection.

In case of secondary arcing, a transition to quasi-sinusoidal voltage that is characteristic of capacitive coupling of a floating, fault-free conductor, can be expected towards the end of the dead time. The exact amplitude and phase of this voltage can be estimated using an analytical model of the system [6]; however, for the present purpose it was found that it is sufficient to recognize a steady, quasi-sinusoidal waveform of low amplitude. These criteria are used to build a "normal steady voltage" signal.

The duration of the secondary arc, of the recovery voltage (if any) and of the auto-reclosing dead time are measured for building the manual reclosing decision and for statistical analysis.

Software platform

After a testing phase was complete using a software prototype, the algorithms used were incorporated into commercially available software. These algorithms include the classification of auto-reclosing sequences, secondary arc detection and measurement of the duration of the secondary arc and the capacitive coupling voltage.

The commercial software platform collects automatically all available recordings from protective relays and digital fault recorders (DFR), after they are exported in COMTRADE format by different substation automation systems (SAS) or manufacturer-specific software, and processes them in a homogeneous way regardless of their origin.

This platform has existing modules for fault detection, classification, storage, automatic reporting and accurate fault location as well. Therefore, the introduction of this technology has several benefits besides the optimization of line reclosing.

System architecture

The software implementation is based on a server application engine written in Java. This engine is a middleware which is also used for other monitoring applications. The application is deployed on several computers.

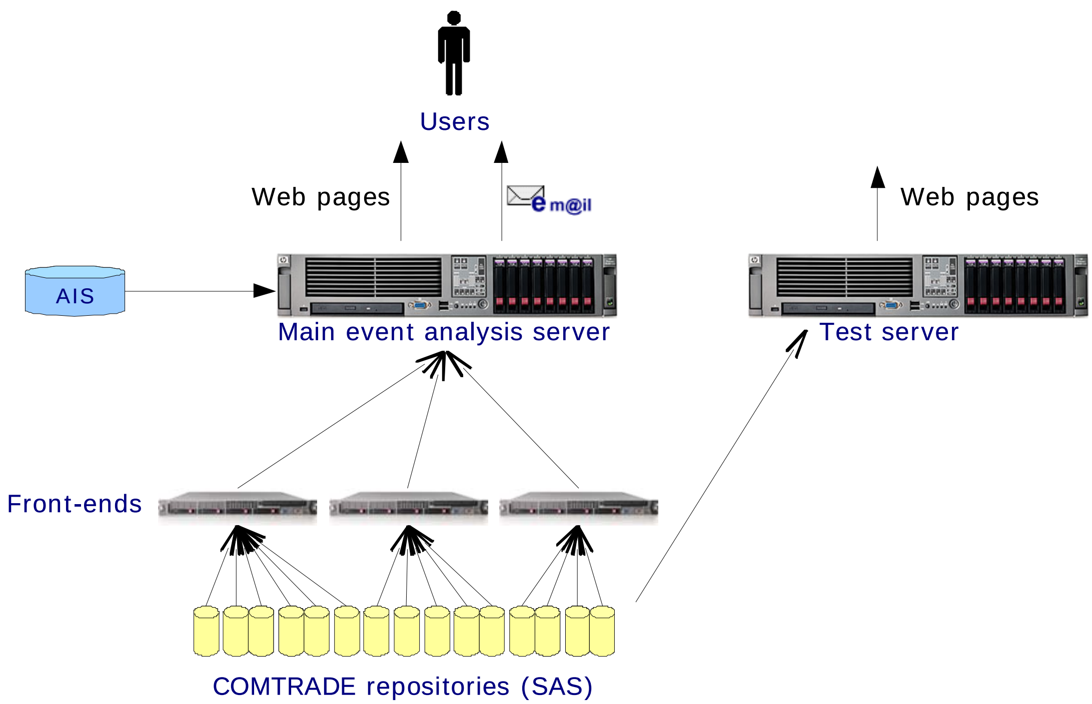

Figure 4: System architecture.

In the final setup (Figure 4), the server application runs on three front-ends that collect COMTRADE transients recordings from the SAS computers, using FTP as the transfer protocol. The front-ends pre-process the recordings. Test recordings are produced into some dedicated subdirectories, not considered when importing.
A main server collects, archives and analyses the pre-processed recordings. Every time a new recording comes in, it is associated to a power system event and the computations for that event are repeated.

The application is configured using some dedicated web pages. The description of the recording channels and the information regarding the monitored lines are grouped into a power system description (PSD) file in Excel format. A part of the PSD information is imported from the corporate asset management data base for EHV stations, called AIS, which is connected to a

SAP information management system. The configuration process is supervised by the administrators of the application, who can also set up the users' access rights and monitor the operation of the software components.

A test server is used in parallel with the main system in order to experiment some variants of settings or algorithms, or to process some particular data sets.

Automatic generation of a suggestion to the system operators

The application generates a dynamical web page that lists all recent auto-reclosing events – successful or not (Figure 5). This page is displayed on a monitor in the control room. In case of unsuccessful auto-reclosing, the suggestion whether to reclose the line or not is displayed. The operator can browse to additional details on the event (including fault location) if needed.

Fault analysis

Events | Records | Auto-reclosings

Auto-reclosings

Begin 2000/02/15 10:59:28 End 2008/09/02 10:59:28 OK

152 auto-reclosing from 2000/02/15 10:59:28 to 2008/09/02 10:59:28

Date and time	Equipment	Fault type	Autoreclosing type	Secondary arc detection	Suggestion to operator
2008/09/02 05:24:25	Nhg-Vie 304 (Line)	Single-phase (L3-Ground)	Successful	Yes	
2008/08/30 08:01:43	Gue-Sow-Wol 513-512 (Line)	Single-phase (L3-Ground)	Unsuccessful	No	No manual reclosing advised
2008/08/30 06:08:19	Lau-Wol 535 (Line)	Single-phase (L1-Ground)	Successful	No	
2008/08/23 05:42:34	Be-Nhg 303 (Line)	Single-phase (L3-Ground)	Successful	Yes	
2008/08/19 19:53:58	Bae-Str 558 (Line)	Single-phase (L3-Ground)	Unsuccessful	Yes	Manual reclosing advised
2008/08/18 06:14:38	Pe-Wol 516 (Line)	Single-phase (L1-Ground)	Successful	No	
2008/08/08 14:06:22	Gue-Pz-Pe 514 (Line)	Single-phase (L2-Ground)	Successful	No	
2008/08/08 05:32:32	Nhg-Vie 304 (Line)	Single-phase (L1-Ground)	Successful	No	
2008/08/07 05:31:42	Gue-Iv-Pas 316 (Line)	Single-phase (L3-Ground)	Successful	No	
2008/07/29 12:59:13	Roe-Hr 446 (Line)	Single-phase (L1-Ground)	Unsuccessful	No	No manual reclosing advised

Figure 5: List of recent auto-reclosing events for display in the control room.

Web-based analysis of the event

Operators and experts can obtain a lot of pre-processed information about any fault event, well beyond a simple verification of the related transients recordings.

As shown in the example of Figure 6, the web application provides a synopsis about the fault characteristics (type, duration, position on the line), the auto-reclosing sequence and direct access to the details regarding protection starting and tripping, circuit breaker operation, pre-fault and fault phasors or RMS values, power flow, loop impedances etc.

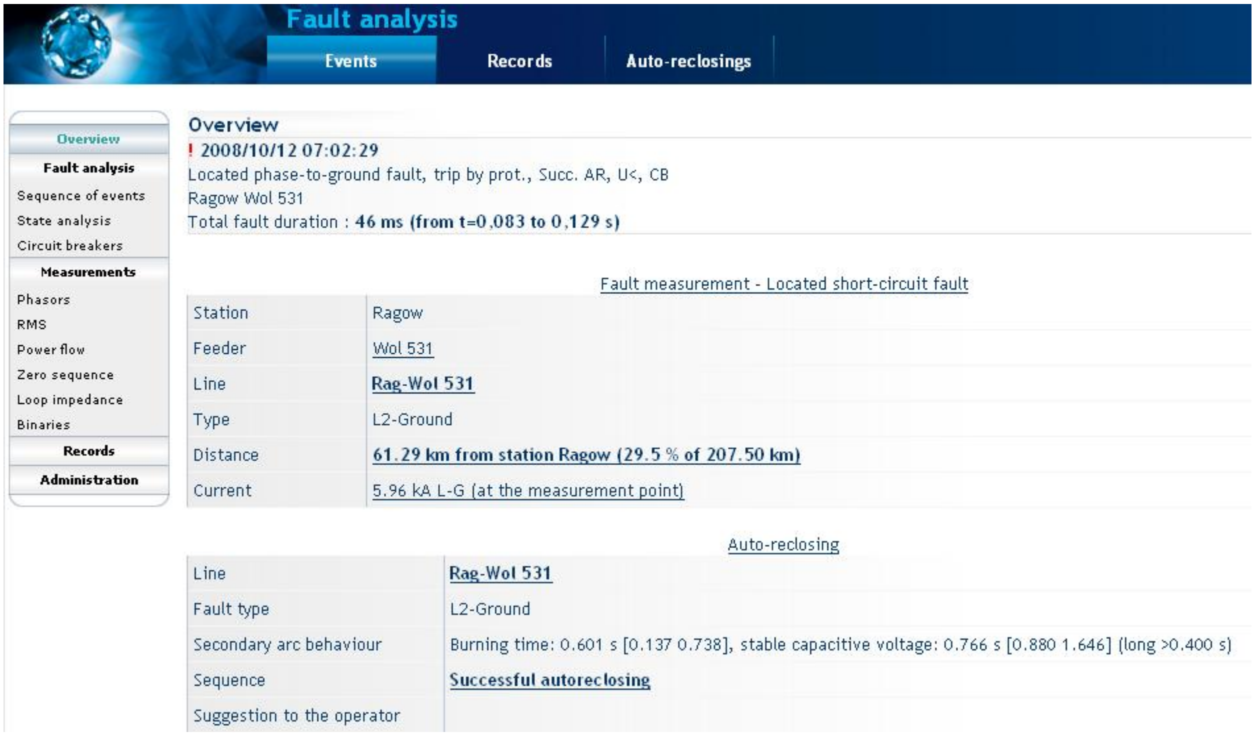

Figure 6: Overview of an auto-reclosing event.

Current state of the project

At the time of writing, the new solution is in the deployment stage. The 400 kV stations are integrated one after the other, which includes the standardization of all recordings (device and channel naming) and a verification of the analog and binary signals produced.
It is expected that the complete transmission network of VE-T will be monitored by July 2009. Data from more than 2000 digital protection relays will then be collected.

Possible further developments

The following extensions are envisaged by VE-T after the completion of the current project:

- Statistical analysis of the likelihood of fault restrike depending on the duration of voltage recovery at the end of the dead time, either as a way of optimizing the settings of the autoreclosers or for assessing the possible benefits of adaptive auto-reclosing.
- Application to three-terminal lines, which requires some minor logical adaptations.

Theoretically, the principles developed in this project are also applicable to other configurations:

- Three-pole auto-reclosing, if parallel circuits provide enough coupling for a secondary arc to be observed (an alternative being the detailed monitoring of the line discharge through the voltage transformers)
- Single-pole tripping for two-phase faults.

Conclusion

The improvement in the substation communication infrastructure allows quick export of data from devices at bay level to a central location. Modern software platforms can convert this data quickly into valuable information to determine fault location and support a manual close decision after unsuccessful auto-reclosure.

The reclose (or not) recommendations from the events in the substations already connected to the system, as of December 2008, have a 100% hit rate. It is now necessary to gather additional experience from other substations being connected to the system and future events.

In the future the "secondary arc detection" could be incorporated into the protective relay autoreclose functionality to increase autoreclose success by adapting the dead time to the fault.

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Biographies

Luc Philippot was born in Rome, Italy, on December 25th, 1965.
He studied electrical engineering and received his M.Sc. and Ph.D. degrees from Brussels University (ULB), Belgium, in 1988 and 1996, respectively.
His academical experience includes 5 years of research work at ULB on phasor estimation, line fault location, sensitive earth fault detection and power system event classification. He also taught power systems protection and computer science at the University of Rwanda in Butare. He joined the power automation department of Siemens in 1996 and designed a two-ended fault locator and a line differential protection relay, working as a project leader and product manager in Stuttgart, Berlin and Nuremberg, Germany. He has been working for NetCeler, a software company in Veynes, France, since 2002, designing web-based applications for power system fault analysis, equipment monitoring and power quality monitoring.

Silvio Roesler was born in Sao Paulo, Brazil on March 20th, 1962.
He studied electrical engineering and received his M.Sc. degree from Mackenzie University in 1985. He joined Siemens in 1986 in the power division, worked several years in low and medium voltage projects and was head of the protection group in Brazil from 1997 to 2003, working on multiple large turn key projects up to 750KV .
He worked in Siemens Germany from 2003 to 2006 as regional business manager in the Energy Automation Group and since 2006 he is now located in Wendell, NC, where he manages the Customer Service Department for Energy Automation Products.

Jens Hauschild was born in Oschatz, Germany, on January 3rd, 1962.
He studied electrical energy systems at the Technical University of Dresden from 1983 to 1988 and finished his study as graduate engineer.
After that he joined the process automation department of the transmission grid of the GDR in Berlin, the today’s company Vattenfall Europe Transmission.
He is currently responsible for the protection systems in the department operational system operation, especially for the settings of protection devices and for the clearing of disturbances.
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