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Experience with automated protection performance evaluation based on disturbance recordings

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- Novel Applications of Transient Recordings
- Experiences with Web-based Technology for IED Transient Recordings
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Abstract

A Protection Performance Monitoring (PPM) software has been designed on top of an Automated Fault Analysis (AFA) kernel, in order to partially automate the inspection of protective relay behavior following each fault in a transmission or sub-transmission network.

The advantages and limits of this technology have been assessed through several projects for transmission system operators during the last years.

PPM has been found to effectively unveil some deviations with respect to ideal protection behavior, such as inappropriate or missing response of back-up protection, late tripping, carrier failure etc.

Protection experts can verify, validate and complement the statements and alerts produced by automated analysis. By doing so, high-quality data can be produced in a short time for the reports but also for further statistical use or higher-level applications like conditional maintenance of protection relays and circuit breakers. This situates AFA

and PPM software solutions as central contributions to the monitoring ecosystem in the modern, digitized grids.
The paper concludes by reviewing the challenges to roll-out semi-automated protection behavior analysis in large-scale projects by retrieving the required input data and producing results through a variety of standard interfaces and formats, including COMTRADE of course, but also 61850, CIM, ICCP and COMFEDE.

Introduction

The widespread use of digital protection and recording devices and the possibility to efficiently connect the substations to a data center have paved the way for a number of computer-based applications designed for better operation and maintenance of the power system.
Among these, Automatic Fault Analysis (AFA) technology (/1/, /2/) is able to process disturbance records and event logs and provide precise indications about a fault in the power system. It also reports about the sequence of protection tripping, circuit breaker opening, auto-reclosing etc. .
An AFA system, which gathers and organizes the event-related data automatically and presents comprehensive view about a disturbance, is of particular interest to follow up numerous faults, or to monitor critical assets and their protection scheme. It has appeared that a part of the routine verifications of the protection behaviour can be automated.
This paper reports about practical experience with the design and implementation of Protection Performance Monitoring (PPM) solutions, using two complementary approaches, as applied in three TSO projects where the technology is used country-wide.

The ladder of power system disturbance analysis

The foundation of automatic event analysis is made of either digital fault recorders or digital protection relays with an enabled disturbance recording function, capturing records of voltages, currents and binaries upon pick-up of any protective function. The quality of the foundation determines what can be built on top. For the sake of the discussion, it is assumed here that a sufficient number of these devices is available, effectively monitoring at least half of the line feeders and most transformer feeders as well (the better the coverage, the better the monitoring reports); that these intelligent electronic devices are time synchronized with a local or central clock and that the maximum time error is less than one second; that triggered records are produced in, or converted to, the COMTRADE file standard /4/ and that they can be automatically transferred to a data center in a short time for automatic analysis. When the binary

signals in the COMTRADE records are scarce, it is useful to collect event logs from substation automation systems, RTUs or the SCADA as well.
Of course, these prerequisites for AFA and PPM are strong assumptions. In practice, many utilities do not dispose of a suitable infrastructure yet and may need almost a decade to re-design and modernize their infrastructure to meet such expectations. The monitoring requirements may simply have been forgotten or downsized in the specifications, driven by the sole need for control and protection. Cyber-security may also be a hurdle, particularly if it is considered last - when trying to implement data collection from an existing station - instead of being an integral part of the original design.
Additionally, the analytics will need to dispose of a model of the stations, lines and recording equipment. This usually implies to import data from existing reference systems, merge it and complement it with some additional configuration.

The AFA technology, which may be considered as mature /3/, can determine the faulted asset, provide accurate and reliable fault location (even in near real time, for use by the operators) and reconstruct the sequence of events (SoE) from fault appearance until final reclosing. This saves considerable time and hassle to fault analysis experts.
Essential contributions of AFA are to correctly correlate the analog and binary signals to the power system elements (because the source data usually only refers to them with human-readable texts), to group the data pertaining to the same disturbance and to perform a precise time alignment of the signals.

Building upon this well-structured disturbance analysis pattern provided by AFA, the goal of the next stage of the analytics is oriented towards blackout prevention and asset management. It is proposed to use a set of rules to determine whether the protection equipment and the circuit breakers operated as expected.

Considerations for a robust design of monitoring rules

Given the heterogeneous infrastructure and the fact that some information may simply be missing, AFA and PPM need to be flexible and robust.
Rules can be designed in a modular way, each rule considering a particular problem with few inputs and outputs, and carefully checking the available data. The goal is to produce a reliable output; when this is not possible, confidence indices or weighting can be used, not unlike a fuzzy logic design, and rules can be combined to produce an assertion in the chain of reasoning.
Adapting to the available data may raise a variety of challenges, including : using busbar voltages when line-side voltages would have been preferred; selecting among redundant data from, say, main 1 and main 2 protection relays; evaluating tripping

action without any phase-segregated signals; determining the state of a circuit breaker knowing only the phase currents.
Robustness of the monitoring rules with respect to uncommon situations such as busbar faults, double faults, breaker failure etc. is critical as well. Since few real examples are available, power system simulation can significantly help testing a ruleset.
The authors have favoured a deterministic approach, proceeding with successive layers of rules or calculations, which successively build up facts or statements with an increasing level of abstraction and an increasing likelihood. This approach does not exclude the use of artificial intelligence techniques to solve partial problems in the process but, in essence, the multi-layer design aims to separate the different steps and the types of problems and allow to maintain and improve the ruleset more easily.
The design also aims to robustness with respect to engineering errors or incomplete configuration /5/. Most problems will be caught at the entry by a configuration processor.

System-level verification of protection schemes

In a first project, a PPM solution has been developed using essentially high-level verifications, derived from the overall protection concepts, and refraining to consider particular behaviours which are dependent on relay settings. Such a **system verification** analyzes whether, facing a given disturbance pattern observed by AFA, the installed protection schemes have operated as expected. Typical verifications include the following ones.

- A fault in the transmission system should not last more than 100 ms
- In a main 1 / main 2 scheme, both relays are expected to operate similarly
- In case of a single-phase fault, a single-pole opening of the breaker must be observed if single-pole tripping and auto-reclosing is implemented
- In case of a fault at a certain voltage level, no protection at another voltage level should pick up, except on transformer feeders
- No sympathy trips of healthy assets
- In case of a line fault, distance protection of adjacent feeders should pick up.

System verifications come with an intrinsic robustness and simplicity. They are suitable when one disposes of numerous observations and they do not require a lot of specific engineering, which reduces implementation costs.
A positive verification indicates that everything has been working, including hardware, communication, adequate settings… but of course, without knowing the details and just for a single, particular disturbance.
System verifications are good for usual fault scenarios but not robust with respect to a number of complex situations, including multiple faults, evolving faults, high-resistance faults, disconnected lines. Therefore, specific detectors must be used to detect these

and avoid to produce incorrect statements.

Functional, parametric verification of protection behaviour

For the protection engineer, the concept of protection testing is immediately associated to the periodical functional (or parametric) testing to which every protection relay is traditionally submitted. During such tests, the protection observes a variety of simulated scenarios and its reaction is typically compared to a tripping characteristic.
In the same line of thought, if the implemented protection functions and their most relevant settings are known, a PPM solution can figure out the expected behaviour for a realistic fault scenario and compare it with the observed behaviour of the protection relays during the actual fault.
This approach particularly makes sense to monitor the behaviour of distance and instantaneous overcurrent protection functions, for which the expected behaviour can be determined with some confidence.
Of course, functional verification requires to accurately model the protection functions /6/. The authors decided to focus on a steady-state model, like in most dedicated simulation, engineering and testing packages, but the behaviour may eventually be further refined using transient models if enough information about the protection algorithms is available.

Advantages of the parametric approach include the ability to pinpoint a problem quite precisely, to detect a mismatch with respect to the known (or assumed) settings and to handle situations such as: double, evolving or resistive faults; back-up operation; and situations where the fault position is actually unknown.
Therefore, it can be considered that functional verifications allow to “dig deeper” than the system verification and complement it nicely. This benefit comes at the price of additional engineering effort. In practice, a PPM solution will greatly benefit to be coupled with a relay database from where the key data - the implemented devices, functions and their settings - can be extracted easily.

Application to distance relaying for transmission lines

Let’s assume a power transmission system where most lines are protected by differential (main 1) and distance (main 2) protection.

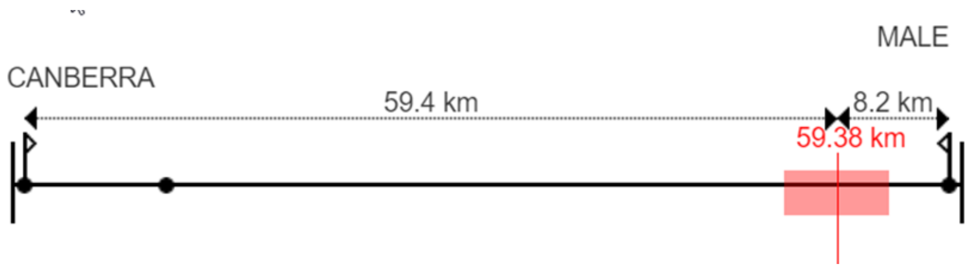

Figure 1: Indication of the estimated position of a fault on a transmission line, with a confidence interval.

Following a fault on any line and the transfer of disturbance records to a data center where an AFA+PPM monitoring software is operated, the AFA will typically pinpoint the fault location (Figure 1) and structure all the observations related to the event.

Then, the following system verifications can typically be carried out.

- The fault doesn't last too long
- Correct fault phase identification by the protection relays
- Main 1 trips at both ends
- Main 2 trips at both ends
- Teleprotection signals are sent and received
- Back-up distance relays pick up
- Phase-segregated tripping (if applicable)
- Auto-reclosing (if applicable)

Additionally, the following functional verifications can be performed.

- Correct zone, depending on the observed loop impedances
- Pick-up and tripping times of all observable functions
- Forward/backward sensing

Finally, it is possible to consider distance protection control by teleprotection or by the companion differential protection scheme, and exceptions such as missing reaction from the bays which are out of operation.

The following screenshot (Figure 2) illustrates the verification of pick-up and tripping by distance protection relays at various locations of a power system.

	0 ms	CANBERRA : B208 : P437 08	Start	
	0 ms	JAKARTA : JAKAR 220 MALE 207 : 7SA513 5	Start and trip	
	0 ms	CANBERRA : B208 : 7SA612 08	Start and trip	
	0 ms	CANBERRA : CANBE 220 JAKAR 203 : 7SA612 09 D	Start	
	0 ms	CANBERRA : CANBE 220 T 401 : 7SA611 14	Start	
	0 ms	JAKARTA : JAKAR 220 CANBE 203 : 7SA513 4	Start	
	0 ms	JAKARTA : JAKAR 220 CANBE 203 : PD551 4	Start	
	0 ms	JAKARTA : JAKAR 220 MALE 207 : PD551 5	Start	
	0 ms	MALE : B208 : 7SA513 6	Start and trip	
	0 ms	MALE : B208 : PD551 6	Start and trip	
	0 ms	BANJUL : BANJU 220 MALE 231/T 201 : BANJU 7SA513 1	Start	

Figure 2: Sample report showing various evaluations (ok, doubtful operation, misoperation) for protection relays at different locations. The faulted line is CANBERRA-MALE (220kV).

Each statement in the list above results from the aggregation of the underlying rules which have provided an output. For instance, while pick-up and tripping of the relay in JAKARTA station may seem timely, this was actually a false (sympathy) trip.

	0 ms	JAKARTA : JAKAR 220 MALE 207 : 7SA513 5	Start and trip	

Result per rule

	Trip delay	Real delay 55ms <= 80ms
	Start delay	Real delay 40ms <= 50ms
	Distance backup start	
	False tripping detection	Unexpected trip

Figure 3: Example of a more detailed view showing the individual results of several rules.

In station Jakarta, another distance relay (Figure 4) was found to correctly pick up, ensuring back-up distance protection. However, the pick-up took a long time, well above the allowed limit of 50 ms.

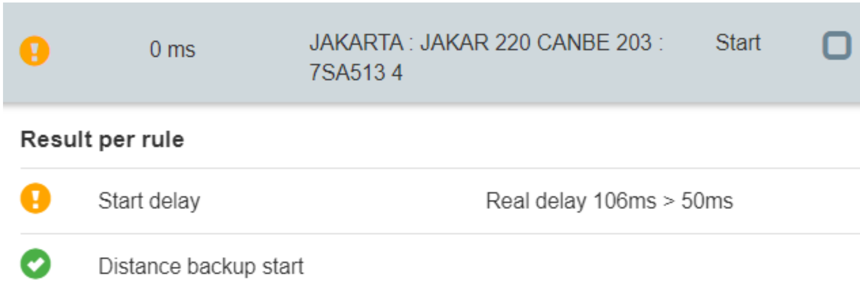

Figure 4: Short report on back-up distance protection.

Integration and further use

The information produced by the rulesets presented above is intended for the following workflow:

- Verification by fault analysis expert as a part of the post mortem disturbance analysis, whereas the expert can typically edit, complement and validate the results from the automatic analysis.
- Export to a system capable of implementing a maintenance policy and managing work orders, such as: specific system for protection relay maintenance, outage management system, or generic asset management tool.

Therefore, remembering that an AFA system is fed by different sources of data and needs to import a model of the monitored power system from existing information systems, the presented data analytics solution will naturally find a dedicated position within the ecosystem of software applications (Figure 5), at a level which is similar to a SCADA system.

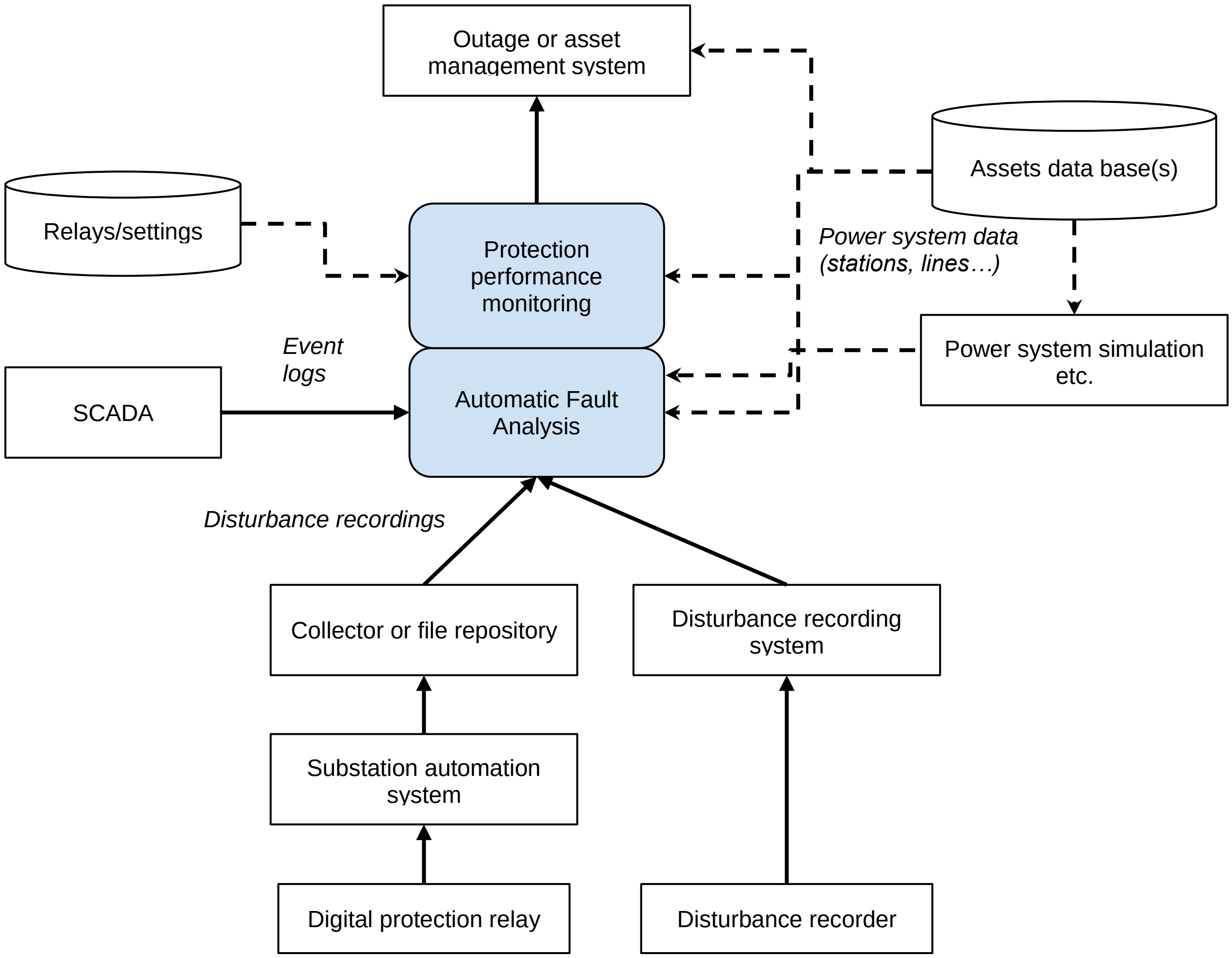

Figure 5: Ecosystem of information systems around an AFA+PPM solution.

From an asset management perspective, PPM technology helps the disturbance analysis team to deliver a comprehensive behavioral evaluation of all protection relays and to do this systematically. This allows to transform periodical protection testing into a conditional-based maintenance program according to the following guidelines:

- Postpone the inspection of a protection relay - e.g. by one year - if it operated recently and did it well;
- Advance a planned inspection if a protection relay was found to operate in a doubtful manner;
- Hasten it in case of a critical misoperation, even if it had no severe consequence so far.

Station	Bay	Device	Model	Qualified statements	% OK	Last correct operation	Last misoperation
RABAT	220 T 22	7UT63 04	7UT63	127	95 %	2019/03/30 Start	2019/03/10 Start
APIA	50 VILNI 01	REL316_4 01	REL 316*4	43	78 %	2018/12/26 Start	2019/02/06 Start
LIMA	20 SCH. 07	7SJ64 07	7SJ64	128	72 %	2019/02/11 Start	2019/01/30 Start
NASSAU	NASSA 110 SF 12	NASSA PD552 12	PD552	99	82 %	2019/03/22 Start	2019/01/30 Start
NASSAU	NASSA 110 T 204	NASSA PD552 14	PD552	42	81 %	2019/01/01 Start	2019/02/10 Start

Figure 6: Example of a statistical view of protection operation for a given time period.

Main obstacles to automating the event analysis

Experience with the automatic fault analysis and protection performance monitoring projects - which are still not widespread - has shown that the following issues deserve particular attention.

- The key input data (event logs, COMTRADE files) have originally been intended for manual interpretation and limited use. Therefore, significant engineering effort is needed to make them machine-readable and systematically available. By contrast, when connecting to high-level information systems (lightning strike monitors, asset management systems), the interconnection is quite easy.
- The delay to collect records from the IEDs to substation automation equipment, and from there to a data center, represents the bottleneck and can jeopardize near-real-time use until the infrastructure is upgraded.
- Collected power system data often exhibit inconsistencies, possibly starting with a substation appearing with different names in the SCADA, in assets database and in simulation software. Previous experience of the utility with similar IT projects helps a lot, proving that the implementation of data analytics forces to care more about data quality and that the effort pays off when additional applications are introduced.
- Correct evaluation of complex fault cases simultaneously hits different barriers: few test cases to develop and check the rules, complex and less-robust algorithms, difficulty to correctly present the results to the user. Therefore, it is important that the fault analysis experts know the tool well, understand its limits

and perform the final steps of complementing and validating the analysis.

New technological enablers

Among the promising technologies and approaches related to grid digitization, the following ones are definitely good enablers for streamlining future implementations of AFA and PPM:

- GPS-synched IEDs;
- IEC 61850, mainly for speed with respect to older communication buses;
- COMTRADE records carrying sufficient semantic information for machine processing, building upon COMTRADE Ed. 2 extensions;
- Development of interfaces between applications in the asset management ecosystem: open interfaces to lists of assets, relay database, exchange of event-related data;
- IEC 61970-301 (CIM), assuming that the software manufacturers work together to make a real use of the standard to distribute the power system model efficiently to all applications.

Conclusions and future trends

While an AFA system in its simplest form can provide critical event reports to power system operators and streamline the work of event analysis teams, it is possible to generate additional benefits by partially automating the verification of protection behaviour. These include the possibility to alert the operator about critical misbehaviour, such as breaker failure or main protection failure; time optimization of manual event analysis by attracting the attention on potential problems; and a way to support conditional maintenance in particular when scheduling protection tests.

In order to make protection monitoring software usable with moderate engineering effort, the solutions are progressing but actions are actually required by different parties:

- Recognition that data analytics apps, which can take advantage of the wealth of digital data, are much dependent on data quality: a utility can “close the loop” and organize data maintenance in shorter cycles and with stronger verifications, for the benefit of all.
- The technical requirements of protection monitoring and maintenance deserve more attention in the design of modern digital substations, because neglecting them causes significant costs if the designs and substations have to be adapted afterwards.
- Further standardization of the protection evaluation methodology will help standard software solutions to come to market and reduce implementation costs.

- Cooperation between suppliers of different applications (like power system simulators, SCADA and asset management software) is expected to reinforce common data models (like CIM) and increase interoperability of the applications.

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About the authors

Luc Philippot obtained an Electrical Engineering degree and a Ph.D. from the Ecole polytechnique of Brussels University (ULB) in 1989 and 1996, respectively. After research works on line protection, fault location and power quality, he has worked for Siemens in Germany from 1996 to 2002, designing a novel line differential protection and developing automated disturbance analysis technology. Then he joined NetCeler, where he is currently General Manager and leading the department of power system monitoring applications.

Andrea Fortunato received his Degree in Electronic Engineering with specialization in Microelectronics from University of Bologna, Italy in 1985.
He held several positions in the domain of micro-electronics, ranging from design and implementation of integrated circuits to Customer support and Business development.
He joined NetCeler in 2015 as Key Account Manager, position still held for several European and International Utilities. He is also an IEEE member since 2016.

Frédéric Mariton received his degree in Electrotechnical Engineering and Computational Mathematics from the Ecole Polytechnique of Grenoble in 2012 and has worked at NetCeler since 2014.
He has technical expertise in fault location, fault analysis and power system protection/control.
He is currently responsible for the R&D team with an active participation in the product management of IVPower and is an IEEE and CIGRE member.

Marc Koulisher received his Engineering degree in Electrical Networks from the Ecole Polytechnique of Université Libre de Bruxelles in 1985.
He initially devoted himself to research, and participated in the development of the first digital protections for generators, with Siemens. He then briefly worked at Solvay on the design and installation of industrial

networks and finally founded NetCeler company in 1997. He is now involved in NetCeler's research and development, in the field of automatic assessment of the behavior of protections.