GETTING REAL-TIME FAULT LOCATION INFORMATION FROM MULTI-VENDOR LEGACY PROTECTION SYSTEMS

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ABSTRACT

Fault locations systems have gained an increasingly higher importance in everyday operation. However, it requires that the substation's protection system is able to provide that data. The protection unit's asset base of EDP comprises relays ranging back 20 years to those installed last month. There is a significant number of relays which cannot supply fault location data, due to various reasons, but have disturbance recordings. If the data already present in these legacy relays could be used to determine fault locations it would be of great importance to EDP.

EDP then teamed up with QEnergia to tackle this issue. The solution was to install an off-the-shelf communications gateway with special software for fault location calculation from disturbance recordings.

The proposed algorithm, developed by QEnergia, was then tested against the outputs of vendor's protection unit's. It was deemed that the algorithm exhibited similar outputs. The system was then installed in five substations and the behaviour of the fault location system in the presence of real network faults was assessed. It was determined that the system's output provides reliable fault location information.

This system can be installed at 1/30th of the cost of a new protection system due to its ease of installation and making use of the existing infrastructure. It is, therefore, a highly competitive solution for obtaining fault location data from legacy systems.

INTRODUCTION

Impedance based fault location systems have become an important tool for system operation. However, obtaining this information can be expensive as it is usually associated to installing a new protection system.

The EDP protection asset base comprises a significant number of legacy protection units which can record disturbances but do not have a fault location calculation or the fault location it provides does not fulfil EDP's requirements on this subject.

If the information present in those legacy protection units could be used for fault location at a small cost it would be very beneficial for EDP. EDP and QEnergia teamed up to tackle this problem. The solution was a system based on an off-the-self Communication Gateway with some software adaptations. Namely being able to support an algorithm to determine fault location data base on disturbance recordings.

SYSTEM DESCRIPTION

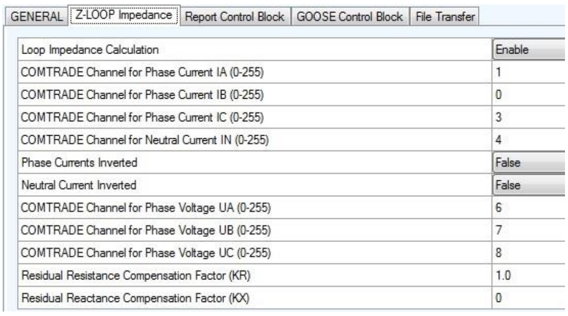
The system's architecture is built around an off-the-shelf communication gateway (CG), capable of implementing multiple protocols and interfacing with different kinds of physical networks, example RS232, RS485 and Ethernet. This flexibility ensures support not only for modern communication protocols like IEC 61850 but also for legacy serial protocols, proprietary and standard ones. The following protection units and communication protocols were chosen to be included in Pilot Systems due to representing in a large scale EDP's installed base of MV protection systems in non numerical Substations (without a Substation Automation System):

- ABB REF 615 protection units / IEC 61850 Protocol / Ethernet
- GE F650 protection units / MODBUS Protocol / RS485
- Alstom P143 protection units / Courier Protocol / RS485
- ABB REF541 protection units / SPA Bus Protocol / Fiber Optic

One of the biggest challenges in deploying such systems corresponds to ensuring that existing functionalities like Remote Access to protection units for configuration / parameterization purposes is kept functional, something critical in the case of "Master / Slave" serial protocols. The answer to this challenge comes in the form of a clever protocol management, in the sense that only one Master can be active at a time, either a Remote or a Local one.

By default it is the Local Master that takes control of the communication bus, cyclically polling protection units for the existence of new disturbance records and performing time synchronization related tasks, critical when there is no dedicated time synchronization system in the Substation. Local Master will be immediately interrupted in case there is an attempt from a Remote

Master to communicate with the protection units, resuming communication after a configurable time without any activity from the later. This mechanism, called "Priority Transparent Channel", plays a critical role in ensuring already existing functionalities are kept working, even with the addition of the CG.
While acquisition of disturbance records from protection units that rely on legacy serial protocols is typically a scheduler based activity (example, every minute CG checks for the existence of new records), for modern protocols like IEC 61850 it is possible to configure an event based acquisition, as long as protection units make available RDRE Logical Node that informs the CG about the existence of new records, which triggers an immediate upload process.
Disturbance records acquisition performance is affected, in the case of legacy serial protocols, by the protocol itself and the way information is transmitted, as it is very common to find communication speeds of 9600 bps, which typically leads to the use of complex data compression mechanisms in order to speed up transmission. Since disturbance records are not transmitted as files but as serial streams, a decoding process must be carried out on the CG side, along with the creation of valid COMTRADE records, in the form of "*.cfg" and "*.dat" files.
Performance-wise, disturbance records acquisition time ranges from 5 seconds in the case of IEC 61850 enabled protection units (event based) up to three minutes in the case of protection units that rely on legacy serial protocols (scheduler based).
Whenever CG retrieves a new disturbance record from a protection unit, conversion from proprietary to COMTRADE format is performed, with files being stored in a user configurable folder structure of CG's flash based file system, adopting an IEEE naming convention (1). This file system is used as a temporary repository and has a capacity of 200 MB through a flash card. In parallel, a scheduler runs at predefined intervals, ensuring new disturbance records are transmitted to a Remote SFTP Server, courtesy of CG's internal SFTP Client, and stored in a configurable folder structure.
In spite the COMTRADE format being an IEEE [2] and IEC [3] standard it does not define rules for the naming of variables. Therefore, it was necessary to find a way of linking COMTRADE analog channels with phase and neutral currents and phase voltages, which led to building a specific user interface in CG's configuration tool. It is possible to invert current direction and to handle cases of 2phase+1neutral CT arrangements for the feeders.



Loop Impedance Calculation	Enable
COMTRADE Channel for Phase Current IA (0-255)	1
COMTRADE Channel for Phase Current IB (0-255)	0
COMTRADE Channel for Phase Current IC (0-255)	3
COMTRADE Channel for Neutral Current IN (0-255)	4
Phase Currents Inverted	False
Neutral Current Inverted	False
COMTRADE Channel for Phase Voltage UA (0-255)	6
COMTRADE Channel for Phase Voltage UB (0-255)	7
COMTRADE Channel for Phase Voltage UC (0-255)	8
Residual Resistance Compensation Factor (KR)	1.0
Residual Reactance Compensation Factor (KX)	0

Figure 1 – User interface for the disturbance recording configurations in the system

As soon as a new disturbance record in COMTRADE format is stored in CG's file system, running application automatically calls a special library (ZLoop) that uses this information to identify the "best" fault instant and the corresponding fault type in order to calculate the fault loop impedance (FLI). The algorithm uses a merit mechanism to determine a reliability value that is taken into consideration when deciding if FLI calculation is valid or not. An "*.out" file is always generated by Zloop, which provides detailed information about performed calculation and respective results, being also transmitted to the Remote SFTP Server along with the associated COMTRADE files.

ZLoop algorithm tries to identify which part of the COMTRADE record can be considered as corresponding to line in service in order to calculate pre-fault load current, and segment the voltage in transient and stable segments using a fast and slow voltage variation detection mechanism. The algorithm then calculates, during the stable voltage segments, fault type and corresponding impedance for all the instants that are triggered by the following elements, blocked by second harmonic of currents:

- Current is over last trigger value
- Polarized negative current unbalance is over last trigger value
- Polarized zero current unbalance is over last trigger value
- Polarized wattmetric zero directional value is over last trigger value

Impedance values considered as outliers are eliminated, with fault instant being selected from the remaining values corresponding to the instant with minimum impedance. Final value is corrected taking into consideration pre-fault load current.

The merit mechanism used to estimate calculation reliability takes into consideration if the pre-fault load current could be estimated or not, eventual fault type changes for evolving faults, fault impedance variation and the number of fault time instants used by the algorithm.

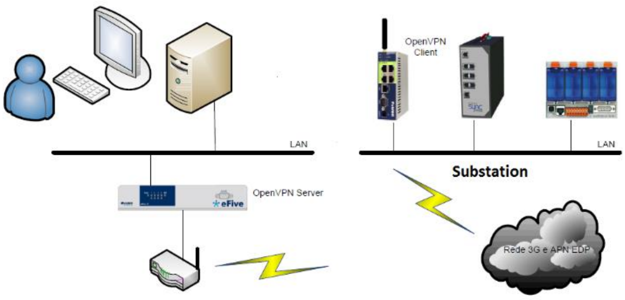


Figure 2 – System topology at the central engineering station

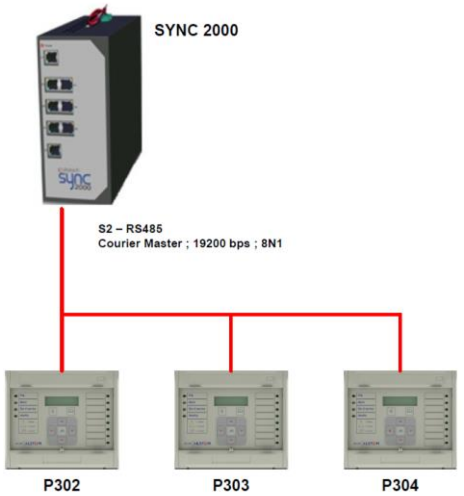


Figure 3 – System topology at the substation level

There is a decision mechanism that controls whether a new calculated FLI (RLoop ; XLoop) is updated on CG's database or not. It takes into consideration not only the validity flag returned by ZLoop algorithm but also a 2 hour time window between CG's local time and fault instant local time to enable update. If updated on CG's database, new FLI related to a fault is transmitted to Network Control Center in one of two forms:

- CG sends FLI (RLoop ; XLoop) to Substation RTU via IEC 60870-5-104 Protocol

- CG sends FLI (RLoop ; XLoop) to Substation RTU via hard-wire (0 … 5mA)

Upon reception at Network Control Center, SCADA / DMS system locates all possible MV line segments for which X has values between (XLoop – error x Zloop) and (XLoop + error x Zloop).

IMPLEMENTATION

One of the major advantages of this system is that it requires minimum changes to the existing infrastructure at the substation, namely to the local communication network(s) and IEDs. Therefore, the cost of installing and configuring the fault location system is small and falls under the overall substation costs. An example of the equipment installed at substations is shown in Figure 4.
Additionally, due to the fact that both protection units and local communication network(s) were previously tested, it is relatively easy to install this system.
In some substations, older RTU's are still being used, which dictates that exchange of information with CG has to be made via hardwired analog signals . However, if modern RTU's are used instead, then exchange of information relies on IEC 104 communication protocol, leading to less wiring, less equipment and easier maintenance and expansion.
The installation of the fault location system is performed with the substation in service, requiring just 1 - 2 days to install and test the whole system, including communication to SCADA, in a cost-effective way.

Figure 4 – System installed in a Substation

RESULTS

The described system was implemented in five substations of the Portuguese Distribution Network, each one equipped with protection units from different vendors, models and communication protocols.
Depending on the legacy relay model and manufacturer, the disturbance record internal data storage can be very limited and fail in meeting EDP's needs. For legal purposes, storage of all disturbance records for a minimum period of five years may prove advantageous, although challenging. With the described system, this difficulty can be easily overcome since all disturbance records are automatically retrieved from protection units and uploaded to a central system where information is immediately available to users.
However, the main purpose of the system is to provide fault location for legacy protection units.

Fault location algorithm comparison with Vendor's proprietary algorithms

EDP has been installing protection units with fault location since 2010. Presently about 15% of EDP's MV feeders are reporting impedance-based fault location data using different vendor proprietary algorithms, depending on protection unit manufacturer and model. Such value is largely comprised by modern integrated Protection and Control Systems. Therefore there is a significant amount of information regarding fault location and fault disturbances.
As a way to access the reliability of the developed impedance-based fault location algorithm, oscillographic fault records data from other EDP's substations were used as an input to the referred algorithm. The generated results were compared to the fault impedance values computed by three different vendors' protection units' proprietary algorithms.
Table I shows three examples of the referred comparison. All fault impedance values take into account pre-fault load current.

Table I – Comparison between developed algorithm and different vendors' proprietary algorithms.

Vendor	Developed algorithm fault impedance		Vendor's algorithm fault impedance		R Error (%)	X Error (%)
	R (Ω)	X (Ω)	R (Ω)	X (Ω)		
A	1.350	1.955	1.324	2.029	1.93	3.65
B	2.527	2.331	2.713	2.340	6.86	0.39
C	1.159	1.300	1.120	1.360	3.36	4.41

All tests resulted in a considerably low error, none being higher than 5-10%, which proved the reliability of the developed algorithm. The cases of a relatively high error (such as Table I - Vendor B), were mainly due to a non-static fault behavior and the fact that time instant used to perform the fault impedance calculation is different from case to case. However, in some cases, this fact turned out to be an advantage since the algorithm results were more accurate than those of the proprietary algorithm. The developed algorithm automatically chooses the best instant of time to compute fault impedances, in contrast to vendors' algorithms which typically set a predefined instant of the fault (ex.: beginning) as an input for the fault impedance calculation.

Real Fault Locations Comparison

For further assessment of the performance of the fault location algorithm, the actual faults that occurred in the network after the system was installed were assessed. The output of the fault location system was compared to the network impedances by using the network analysis software (DPlan). With this software it is possible to compare the algorithm output value with the impedance of the actual fault locations and compute the error.

Table II – Fault Locator Performance

Substation	Average apparent impedance error	Faults analysed
A	6%	9
B	4%	6
C	3%	5
D	5%	6
E	4%	19

From the table above one can notice that for the five substations – where this approach was initially implemented – the average margin of error needed to successfully determine fault location is lower than 10%, which is a common value for the impedance calculation error.
The results also prove that the proposed system offers a simple solution with a very competitive accuracy.

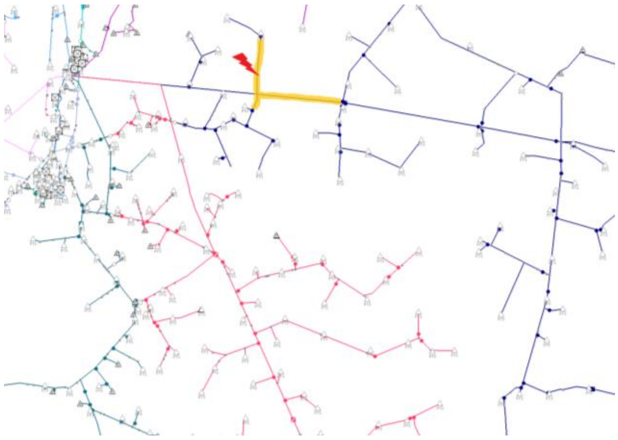


Figure 5 – Successful fault location from substation B

Figure 5 illustrates one example of a successful fault location using the described system. The fault location algorithm output is highlighted in yellow. The red symbol marks the zone where a damaged insulator was found by the maintenance team.
For the five substations where the described system was first implemented, a 10% margin of error was considered for fault location purposes in the Dispatch Center systems. With this consideration, network maintenance departments have given a very positive feedback, denoting significant improvements to the fault location identification process.

CONCLUSION

The described system can retrieve disturbance data from legacy protection units and run an algorithm to determine fault location data. It can also send this data to the Dispatch SCADA system. The availability is very high.
Fault location data calculated by the system has proven to be similar to the output of protection vendor's proprietary algorithms. The system was installed in 5 substations and since then 45 permanent faults have been observed in their MV network. Fault location data provided by the system for these real events has also proven to be reliable.
By using the existing infrastructure, and being easy to install, this system costs about 1/30th of a new protection and automation system for the substation. Therefore it is very competitive to obtain fault location data from legacy systems.

REFERENCES

[1] C37.232-2011 - IEEE Standard for Common Format for Naming Time Sequence Data Files (COMNAME)

[2] C37.111-1999 - IEEE Standard for Common Format for Transient Data Exchange (COMTRADE) for Power Systems

[3] IEC 60255-24 (2013) - Common Format for Transient Data Exchange (COMTRADE) for Power Systems