FIELD VALIDATION OF A NOVEL PMU-BASED FAULT DISTANCE ESTIMATION SOLUTION FOR DISTRIBUTION NETWORKS

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Keywords: PMU, SYNCHROPHASOR, FAULT LOCATION, DISTRIBUTION

Abstract

This paper presents the field validation of a novel fault distance estimation method in a real medium-voltage grid. The novelty is that this approach is a centralized fault locator which combines multiple synchronized measurements from Distribution Phasor Measurement Units (D-PMUs) installed at different grid locations, thus enabling the achievement of higher accuracy compared to typical distance relays that use local measurements only. The fault locator first identifies the faulted grid area delimited by one or more D-PMUs and secondly computes the precise location within the identified faulted area. This allows network operators to further decrease the fault search time and thus improve grid reliability indices.

1. Introduction

Distribution System Operators (DSOs) are asked to improve reliability indices to comply with regulations (e.g., [1], [2]). Indeed, the operation of distribution grids is becoming more complex due to the increasing penetration of Distributed Energy Resources (DER) and to the customers demand for a higher continuity of supply. In this respect, DSOs are looking for Fault Location, Isolation and Service Restoration (FLISR) systems that can handle the bidirectional power flows and automate the fault location process.

The first step in FLISR is to obtain an accurate fault location. There are several fault location algorithms which are specific to medium-voltage (MV) grids [3]. The use of Distribution-Phasor Measurement Units (D-PMUs) deployed in MV grids for fault location has been identified as an important step in modernizing distribution grids [4]. Compared to distance relays which only use local measurements typically at the primary substation, D-PMUs enable a centralized approach that leverages synchronized measurements from multiple grid locations. Impedance-based approaches [5], [6] have been proposed to take advantage of the availability of multiple synchronized measurements to improve the accuracy as well as limit the number of possible solutions. However, there are few results from the field which quantify the performance of these techniques when deployed in real-world conditions.

This paper presents real field results of a novel centralized fault location solution using synchronized measurements from D-PMUs installed in a real distribution grid operated by Services Industriels de Genève (SIG). SIG operates the distribution grid of Geneva and the surrounding communities, covering an area of about 249 km^2. With the aim of reducing the power outage time for its customers, SIG deployed the D-PMUs at strategic grid nodes and the automated fault location solution of Zaphiro Technologies in a portion of the MV grid of Geneva composed of multiple feeders. The main objective is to correctly and quickly identify the faulted line between two secondary substations. The automation of the fault location process would allow control-room operators to immediately coordinate the network reconfiguration to restore the power supply to the healthy parts of the grid as fast as possible and without repeated switching manoeuvres.

The paper is divided into 4 sections. Section 2 discusses the distribution network and the monitoring infrastructure. Section 3 explains the proposed fault location method. Section 4 presents the successful field results during two real faults.

2. Project Description

This section presents the SIG's MV grid which was selected to deploy the D-PMU-based fault location solution and provides an overview of the D-PMU monitoring infrastructure.

2.1. Grid characteristics

Figure 1 shows the single line diagram of the selected MV grid portion. The area, which is located in the countryside of Geneva, Switzerland, includes one primary substation, 5 MV feeders, 83 secondary substations and over 82 km of lines (a mix of overhead and underground lines). The grid is operated at a rated voltage of 18.2 kV, with the neutral of the HV/MV transformer resonant grounded, i.e. compensated with a Petersen coil on the MV side [7]. Table 1 provides more details about the monitored feeders.

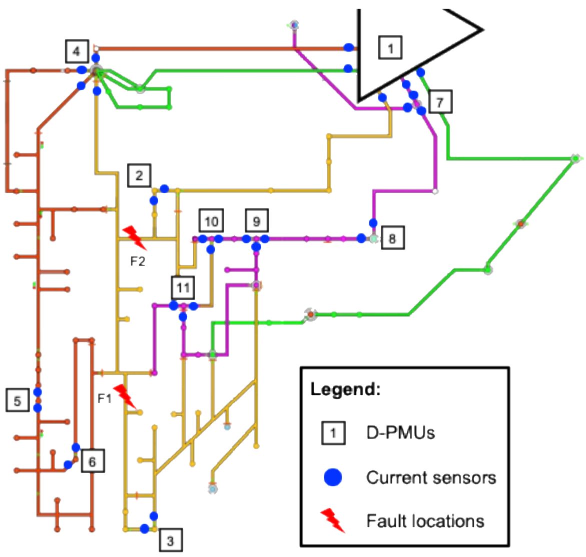

Figure 1 – The monitored grid topology, D-PMU positions, and the locations of the two faults described in Section 4.

Table 1 - Details of the monitored feeders

Feeder	Length	MV-LV substat.	Max load	Average load
Green	11.2 km	8	2 MVA	0.8 MVA
Yellow	28.8 km	22	5.5 MVA	1.7 MVA
Red	21.5 km	27	4.4 MVA	2.2 MVA
Green	4.5 km	5	7.7 MVA	4.4 MVA
Magenta	16.4 km	21	5 MVA	2.7 MVA

2.2. D-PMU monitoring infrastructure

The deployed monitoring infrastructure consists of a total of 11 D-PMU devices (SynchroSense) from Zaphiro Technologies, installed in the primary substation and 10 strategic secondary substations. The D-PMU devices were provided in dedicated wall-mount cabinets including: (i) a D-PMU device, (ii) a power supply unit, (iii) a 4G router, and (iv) a supercap-based Uninterrupted Power Supply (UPS) to guarantee a stable power supply also during disturbances such as blackout.

All D-PMUs measure current synchrophasors via class 0.5 clamp-on current sensors based on Rogowski coil technology, installed in every line departure and, where possible, on every MV-LV substation transformer. Voltage is measured at the primary substation by D-PMU 1, via already installed Class 1 Voltage Transformers (VTs). It is also measured by 5 additional D-PMUs (2, 3, 9, 10 and 11) via retrofit-type non-conventional VTs based on resistive divider principle. Every D-PMU is connected to a dedicated combined GNSS-LTE antenna for both time synchronization and communication purposes. Data communication is done via a secured VPN tunnel over a public 4G/5G LTE network.

D-PMU data are collected by Zaphiro Technologies' central SynchroGuard software platform hosted on an AWS cloud. This platform leverages a micro-service and event-driven architecture running on a Kubernetes cluster. The software platform main modules (services) are highlighted in Figure 2. The Phasor Data Concentrator module collects and time-aligns D-PMU data from the field. The Topology processor module updates the grid model based on the field measurements and other information (e.g., switches status). The Fault location module detects, classify and locates faults in the monitored grid. The PQ monitoring module calculates PQ indicators as well as detects and classifies PQ events with the possibility to identify the root cause. Data are shared between the various modules using a high-speed data bus. A time-series database guarantees long-term storage of D-PMU measurements and derived quantities.

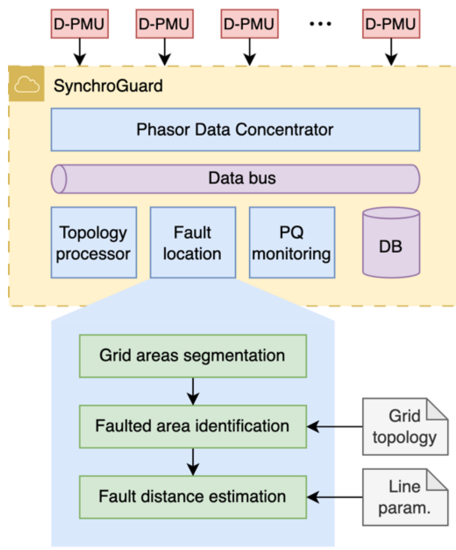

Figure 2 – System architecture, including the modules of the software platform and the main fault location steps

3. Fault Location Method

This section explains the current fault location process at SIG and how the proposed D-PMU based solution can assist in improving their fault location process.

3.1. Existing fault location process at SIG

In the MV grid, today SIG performs fault location by using information from already deployed protection relays and Fault Passage Indicators (FPIs), where available. In particular, in case of multi-phase faults, non-directional overcurrent protections at the primary substation allow to identify the faulted feeder. If available, overcurrent-based FPIs installed along the MV feeder can narrow down the faulted area. Finally, the exact component identification is performed by sequential switching operations (either performed remotely from the control centre and/or on site by field crews) which may stress the grid components. For ground faults, the faulted feeder is identified using directional earth-fault protection at the primary substations. As no directional-based FPIs are available, the faulted component can only be identified via sequential switching operations as described above.

3.2. D-PMU-based fault distance estimation

In order to improve the current fault location process, SIG rolled out D-PMUs that enable Zaphiro's innovative fault location solution. The proposed solution relies on a centralized fault location technique that uses only synchronized measurements from D-PMU devices installed along the feeder. It can accurately locate many fault types (such as 3-phase, 2-phase, earth faults) in all the grid topologies and grounding systems (such as radial or meshed as well as solidly grounded or isolated or compensated). A major advantage is the easy installation and deployment since the algorithm needs only a single voltage measurement at the primary substation and it is not required to install voltage sensors inside distribution feeders. D-PMUs at MV/LV nodes inside the feeder need only to measure currents. However, the availability of multiple voltage measurements can enhance the reliability and accuracy of the solution.

Figure 2 shows the details of the fault location process integrated with SynchroGuard's architecture. The fault location solution can be divided into two phases. The first phase has been described in [8] along with the field results achieved. In this phase, the network is segmented into areas which are delimited by D-PMUs. The fault locator identifies the faulted area using different algorithms based on the type of fault and type of neutral treatment. In the case of multi-phase faults or single-phase-to-ground faults in solidly grounded or impedance-grounded networks, an algorithm similar to the differential approach is used to identify the faulted area. In case of single-phase faults in isolated or resonant-grounded networks, the algorithm used is based on a directional approach.

Once the faulted area is identified, the second phase of the fault location process is the fault distance estimation, namely the estimation of the position of the fault inside the faulted area. The distance calculation is performed only for multi-phase faults and single-phase-to-ground faults in solidly and impedance grounded. The proposed novel method allows to achieve an accuracy of few hundred meters in most cases. The algorithm of fault distance estimation is an advanced impedance-based algorithm that uses multiple synchronized voltage and current measurements from D-PMUs at different locations to pinpoint the location of a fault within the faulted area. This approach allows to reduce the impact of loads and distributed generation, thus significantly improving the accuracy of fault distance estimation compared to a typical fault distance relay at the primary substation. Indeed, a relay at the root of the feeder cannot isolate the fault current from the feeder current since it does not have any information about the power flows along the feeder, thus introducing a relevant error in the distance estimation. Indeed, most fault distance estimation methods for distribution grids which are based on a single measurement at the primary substation exhibit high estimation errors that make them unpractical.

If there are multiple laterals in the faulted area, there could be multiple location estimates as the same impedance could lie in multiple paths. The multiplicity of solutions can be limited by optimally placing D-PMUs at the main bifurcations. For a given grid topology, it is possible to optimally place D-PMUs so that multiple distance estimates can be minimized.

4. Field results

This paper presents two fault cases (F1 and F2 shown in Figure 1) recorded during the project. The faults were recorded using the D-PMUs deployed in the feeder and the fault distance estimates were validated using the information provided by SIG's maintenance crew.

4.1. Fault F1 recorded on 2023-05-17

In this section we describe a fault that occurred in May 2023, referred to as F1 in Figure 1, which was a 2-phase fault characterized by a fault current of 2.6 kA, as shown in Table 2. As confirmed by SIG's maintenance crews, the fault locator was able to pinpoint the fault location with an accuracy of 30 meters, thus allowing the correct identification of the faulted section.

Table 2 - Fault F1 - Fault characteristics and location error

Fault type	Fault current	Location error
2-ph	2.6 kA	30 m

The sequence of events recorded during the fault event at F1 is presented in Table 3. The fault was interrupted by opening a breaker at the primary substation in about 140 ms. After the feeder was reconfigured, a reclosure was attempted unsuccessfully, since the breaker reclosed on the fault due to the fact that the faulted section was not isolated during the first reconfiguration. The tripping time of the breaker is again 140 ms. The total time taken to isolate the faulted section and resupply the feeder was about 54 minutes after the breakers tripped for the first time.

The currents and voltages recorded by all 3 D-PMUs during the fault are shown in Figure 3, Figure 4 and Figure 5. The pre-fault voltages were around 1 pu at all the D-PMUs and the pre-fault load current at the feeder root by D-PMU 1 was around 100 A. During the fault, the voltages on the two faulted phases B and C recorded by D-PMU 1 show a small dip and return to normal once the fault is cleared by the feeder protection, since the voltage is taken at the primary substation busbar. It is worth to notice some post-fault voltage oscillations due to the presence of the Petersen coil. The voltages at D-PMUs 2 and 3 drop to zero after the fault is cleared, showing the power outage of the feeder. The fault current was around 2.6 kA during the fault, as measured by D-PMUs 1 and 2. D-PMU 3 observes only some perturbations on the load current during the fault, since it is placed after the fault.

By integrating the fault location solution in the FLISR process, the prompt availability of the precise fault location information after the first fault would have helped to reduce the fault search time and would have avoided any breaker reclosure on the fault that stresses the various grid components.

Table 3 – Fault F1: Sequence of events

Time	Event
08:50:50.920	2-phase fault inception
08:50:51.060	Breaker opening and feeder blackout
09:03:12.100	Feeder reconfigured
09:03:27.240	Reclosure attempt 1 unsuccessful and 2-phase fault reappears
09:03:27.380	Breaker opening and feeder blackout
09:44:58.680	Reclosure attempt 2 successful and power supply restored

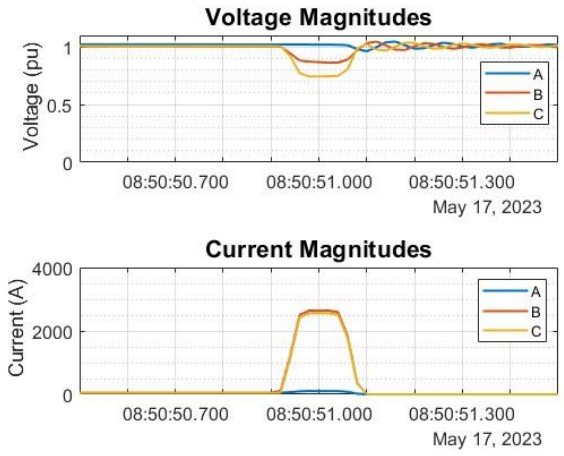

Figure 3 – Fault F1: phasors recorded by D-PMU 1

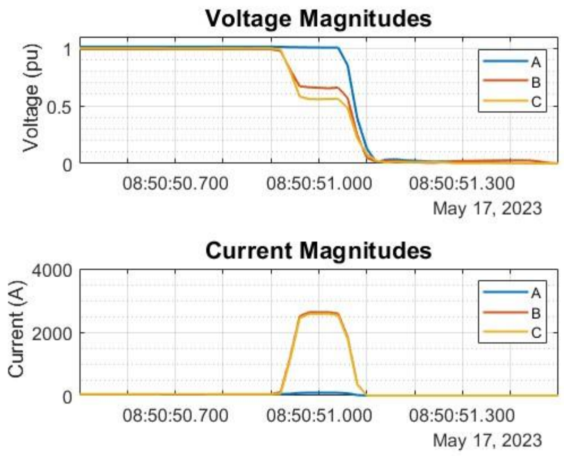

Figure 4 - Fault F1: phasors recorded by D-PMU 2

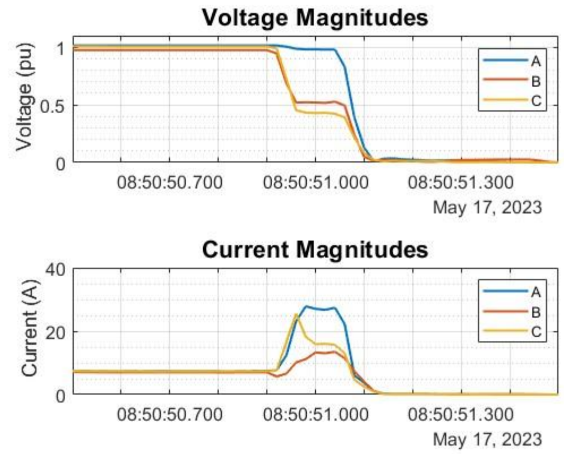

Figure 5 - Fault F1: phasors recorded by D-PMU 3

4.2. Fault F2 recorded on 2023-11-10

In this section we describe the fault occurred in November 2023, denoted as F2 in Figure 1. As it can be seen in Table 4, it was a 2-phase fault characterized by a fault current of 3.6 kA. Table 4 shows 3 faults because, in addition to the initial fault, there were 2 unsuccessful reclosure attempts, which allowed the fault locator to generate 3 fault locations. The fault locator located the fault with an accuracy of about 120-170 meters, thus allowing the correct identification of the faulted section. It is worth noticing that the fault locations provided by the system for the 3 subsequent fault recordings are consistent with each other, being in the range of only 50 meters.

The sequence of events observed during the fault event F2 are listed in Table 5, which shows the unsuccessful reclosure attempts. The power supply is finally restored successfully after 92 minutes. Figure 6 shows voltages and currents measured at the root of the feeder for one of the 2-phase faults. The other faults exhibit similar behaviour.

Table 4 - Fault F2: Fault characteristics and location error

Fault type	Fault current	Location error
2-ph	3.6 kA	170 m
2-ph	3.7 kA	121 m
2-ph	3.7 kA	153 m

Table 5 - Fault F2: Sequence of events

Time	Event
02:35:09.300	2-phase fault inception
02:35:09.420	Breaker opening and feeder blackout
03:02:06.100	Reclosure attempt 1 unsuccessful and 2-phase fault reappears
03:02:06.220	Breaker opening and feeder blackout
03:02:57.320	Reclosure attempt 2 unsuccessful and 2-phase fault reappears
03:02:57.440	Breaker opening and feeder blackout
03:46:48.400	Feeder is reconfigured
04:07:37.500	Reclosure attempt 3 successful and power supply restored

5. Conclusions

This paper presents a novel fault distance solution for distribution networks based on synchronized measurements from D-PMUs, which enhances the fault location accuracy. The goal is to reduce the outage time by identifying the faulted line in a quick and automated way, and thus restore as soon as possible the power to the feeder customers. The paper also illustrates the implementation of the solution in a real distribution network operated by SIG in Geneva. The results from two real faults were presented and discussed. In both cases, the faulted section was correctly identified with an error of around 30 m and 150 m, respectively. The actual fault location was validated by the DSO's maintenance crews, demonstrating the effectiveness of the proposed method.

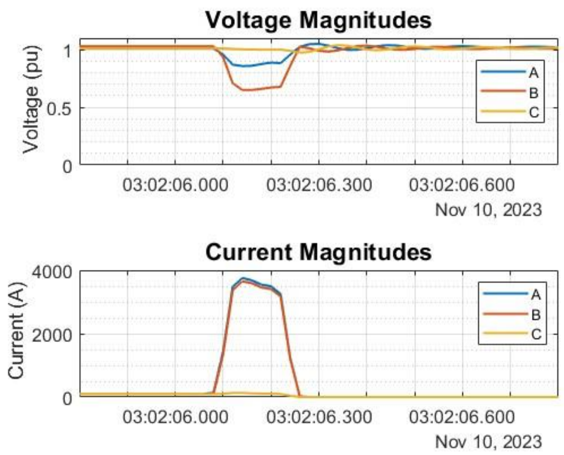

Figure 6 – Fault F2: phasors recorded by D-PMU 1

6. References

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