21, rue d'Artois, F-75008 PARIS
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Fault Location using Distributed Sensors on Distribution Feeders

V. DONDE *, D. PARTRIDGE, N. ANJUM
Pacific Gas and Electric
USA

SUMMARY

Reliability and safety of power distribution systems is largely dependent on how quickly a fault is detected, located and service is restored. The process for fault location has traditionally been relied heavily on customer calls, Outage Management System and significant human involvement, thus making it inefficient and error-prone. Recent advancement in the monitoring and sensing technologies has made it possible to detect and locate fault events more reliably and quickly than before. This paper summarizes the field pilot activities that PG&E has been involved in during last couple years by installing line sensors and voltage sag monitors for experimental studies. Fault current data provided by line sensors installed at various locations on a feeder helps to estimate possible fault locations. Voltage sag data along the feeder provides additional information to further narrow down the estimates. When the different kind of data acquired from current and voltage sensors is analysed together, one gets a complete picture of the fault event. These efforts by PG&E are part of a larger activity from a three year smart grid project and this paper discusses the key elements such as sensors and monitors used for pilot deployment, modelling studies and field results.

KEYWORDS

Calculated Fault Location (CFL), Line Sensor, Voltage Sag Monitor, Distribution System, Smart Grid

vaibhav.donde@pge.com

1. Introduction

As part of a pilot research and demonstration project, PG&E has installed several line sensors and voltage sag monitors on its distribution feeders. These devices monitor the distribution feeder and detect anomalous conditions such as a fault event. Data captured during fault events provides invaluable information about the fault and its location.

Traditionally, the process of fault location on distribution network has relied heavily on customer calls. Utilities use an Outage Management System to estimate the fault location based on the customers calling to report the outage [1]. Understandably this is a time consuming process and affects reliability and safety directly. Several utilities have employed fault location algorithms to improve the effectiveness of the process; however, in many cases it relies on the fault current recorded at the substation. This results in a number of possible fault locations due to feeder branching. Fault data from other parts of the feeder could improve the estimation; however, historically a variety of issues including equipment and integration costs and communications have played against widespread success. Recent advancement in the monitoring and sensing technologies has led to new sensing devices that are low cost and easy to install on primary distribution lines and secondary circuits. Data from these distributed devices makes it possible for a utility to see the entire picture of the feeder during a fault event.

This paper discusses the use of the data obtained from line sensors and voltage sag monitors installed at various locations on PG&E's feeders for fault location. Section 2 briefly describes the sensors and monitors used for the pilot research study. Section 3 discusses analytical approaches used for data processing, algorithmic estimation and visualization of results. Sections 4 and 5 touch upon the field experience and practical challenges, followed by conclusions in Section 6.

2. Sensors and Monitors to capture Fault Data

Line sensors are devices mounted on primary distribution lines. They monitor the line current waveform and detect anomalies such as a fault event. Some sensors are also capable of inferring line voltage by sensing the electric field generated by the line. Voltage sag monitors are devices mounted on secondary side of distribution transformers. These are small portable devices that are easy to move around on the secondary network and provide a cost effective option to monitor voltage sag during a fault event by capturing a voltage waveform.

Figure 1 shows a typical line sensor and voltage sag monitor available from vendors installed on overheard lines and on the secondary of a distribution transformer respectively. After validating their performance in a laboratory, PG&E has installed selected sensors and monitors on its feeders for pilot studies during 2015-2016. Data acquired from the devices is processed and analyzed to distil information about underlying fault events, particularly the fault location.

Figure 1: Sensors and monitors to capture fault data. (Left) line sensor, (right) voltage sag monitor

Figure 2 shows typical waveforms captured by line sensors and voltage sag monitors during fault events. The waveforms are sampled at a rate 16 to 130 samples per cycle. They are used to extract the current magnitude at fundamental frequency and percentage volatge sag from the nominal, which are then used for estimating the fault location as described in the following sections.

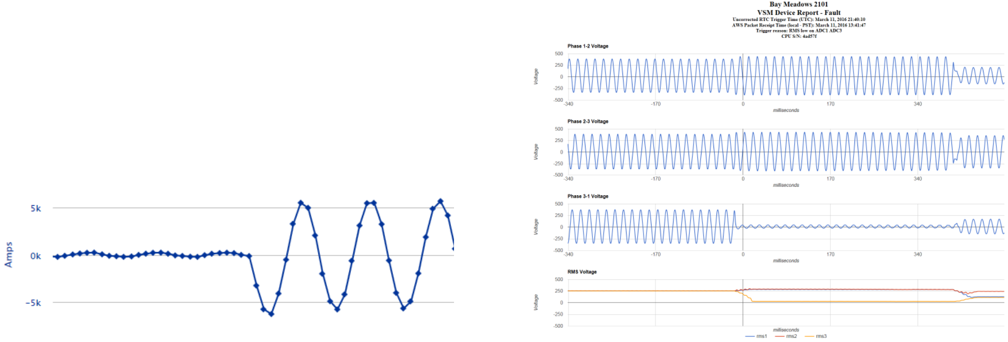

Figure 2: Waveform capture from a (left) line sensor and (right) voltage sag monitor

3. Analytics for Calculated Fault Location

Fault location estimation or Calculated Fault Location (CFL) is conventionally performed using the fault current measured at a substation and the feeder model [1, 2]. While it is popular due to the simplicity of its algorithm, it generally leads to multiple CFL results due to branching in the feeder circuit. Data obtained from line sensors and voltage sag monitors is helpful in improving the calculation. Following sections discuss the concepts using examples drawn from PG&E's experience during the pilot.

3.1. Estimation of CFL using Fault Current Data

Conventionally the CFL method uses a Short Circuit Analysis to obtain fault duties at all the nodes in the feeder for the given configuration and connectivity. Nodes where the recorded fault current best matches with the calculated fault duties are declared as calculated fault locations. This method requires only the fault current RMS value from the field, the fault type and the feeder impedance model while avoiding any need to have waveform data communicated to the fault location engine. However it generally results in a number of possible CFL results due to feeder branching.

If the feeder has multiple line sensors installed, they help in reducing the number of CFL results. They provide reduction of fault locations to a bracketed fault zone which is useful in narrowing down to the final CFL result. Locations that overlap with the fault zone provide the most likely fault location.

Figure 3 provides an example using a Single Line Diagram. The corresponding feeder is shown in Figure 4. Line sensor 60 is the most downstream sensor that has detected the fault and thus it defines a fault zone as the circuit downstream of its location. This is highlighted in yellow in Figure 3 and thick black in Figure 4. When Calculated Fault Location algorithm is run from the substation location, it results in three clusters as encircled in red. Note that only one CFL location overlaps with the fault zone as expected. This becomes the most likely location and is emphasized in thick red. The figure also shows the Actual Fault Location (AFL) for comparison which agrees with the CFL fairly well.

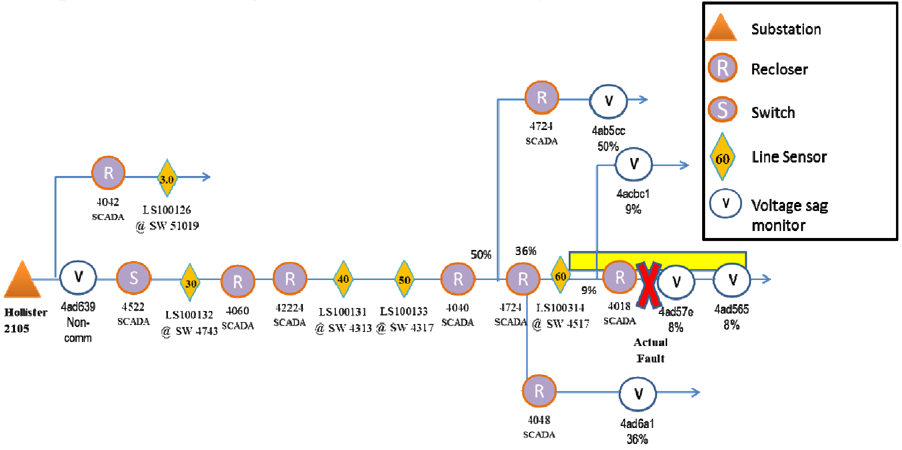

Figure 3: One line diagram of a feeder with sensors having a fault event

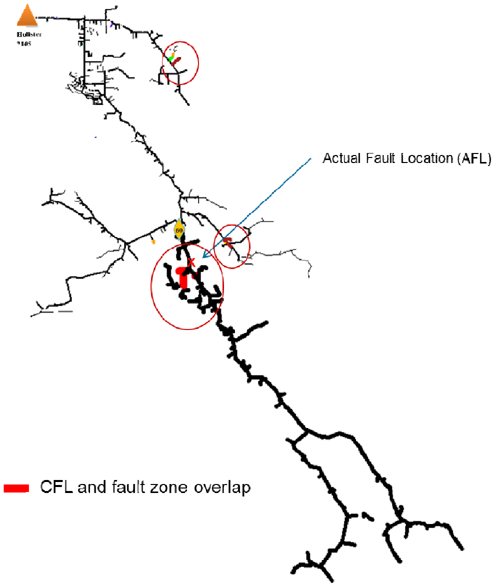

Figure 4: Fault location calculation using current data from line sensors

3.2. CFL Augmented by Voltage Sag Data

When the feeder is radial and distributed generation is insignificant, voltages would sag monotonically along the mainline during fault from the substation to the fault location. Beyond the fault location downstream on the feeder, the voltage would stay about the same as the voltage at the fault location. If it is a bolted ground fault, this voltage is close to zero. Otherwise the fault voltage would be determined by the fault impedance and the fault current.

Voltage sag monitors record the sag during a fault event. Referring to the single line diagram in Figure 3, the monitors are installed on the feeder at locations shown (as "V"). This is also shown in Figure 5 where the monitors are shown in green circles and a darker monitor indicates more significant sag (lower voltage percentages). The sagged voltages measured by the monitors help determine the fault zone on the feeder. Referring to the figure, the three monitors that are most downstream on the feeder have identical voltages about 8%. This indicates that the fault location is likely upstream of the monitor that has measured 9% voltage, but downstream of a tie point that connects to a lateral having the monitor measuring 36% sagged voltage. The estimated fault zone is highlighted in the figure in thick blue.

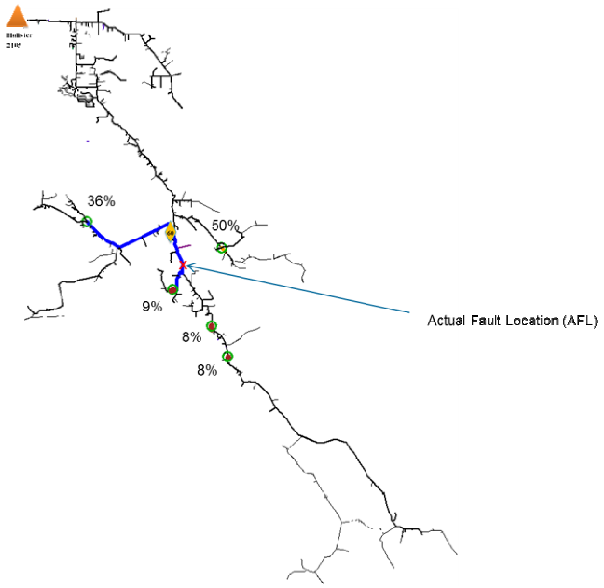

Figure 5: Fault segment estimation using voltage sag data

Just like the fault current by line sensor estimates a bracketed fault zone, voltage sag monitors are able to estimate the fault zone as illustrated by the above example. This latter fault zone also narrows down CFL results by eliminating the two CFL results in Figure 4, namely top-right and center-right, while keeping the one in the center as the most likely Calculated Fault Location.

3.3. Estimation of CFL using Voltage Sag Data Only

If the sagged voltages in percentages are plotted against the distance of tap points of the laterals having the sag monitors measured from the substation, a plot such as in Figure 6 is obtained. It highlights a characteristic that the voltages have sagged monotonously from the substation up to a certain point on the feeder mainline [3]. This point is presumably a tap connection of a lateral on which the fault is located. Beyond this point downstream on the feeder, the sagged voltages remain almost the same. This characteristic curve can be approximated by piecewise linear regression using a sloping line and a horizontal line, and the intersection point would then provide an estimate of the location of the faulty tap on the x-axis and the fault voltage on the y-axis. Electrical distance from the substation can be used instead of a physical distance for better accuracy.

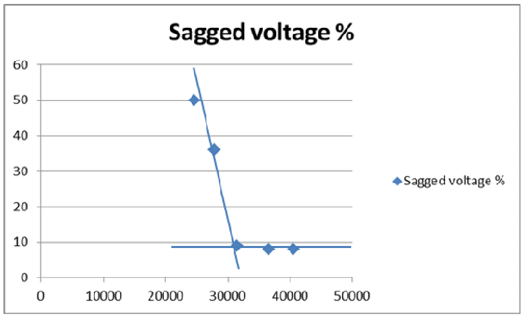

Figure 6: voltage profile during fault

Figure 7 illustrates an estimation of a faulty tap using voltage sag data. Thick blue segment highlights the estimated segments. Note that the estimated fault locations by voltage sag data in the left figure agrees with Figure 4 and Figure 5. Figure to the right shows another example and will be referred to again in the following section.

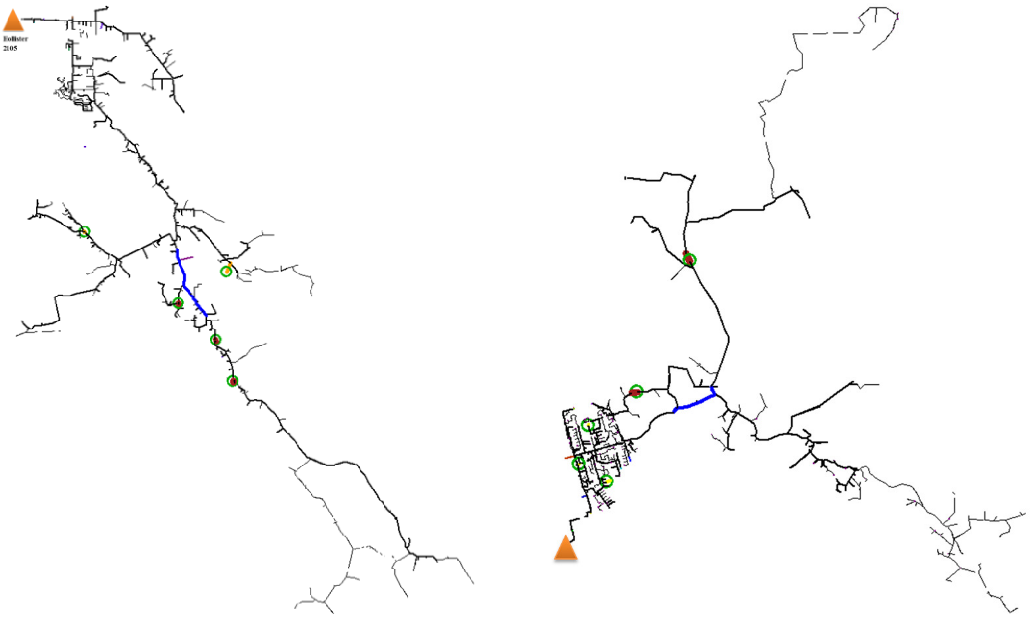

Figure 7: CFL estimation using voltage sag data only: (left) example feeder 1, (right) example feeder 2

3.4. Correcting the CFL by Voltage Sag Data

When arcing is involved in a fault, the fault impedance is not zero, and the CFL estimation must account for it. As the voltage sag data allows us to estimate the fault voltage, it also in turn provides an estimation of the fault impedance, or enables calculation of a correction factor for the fault current to account for fault impedance.

This process is described in Figure 8. A bolted-fault equivalent of a non-bolted-fault can be derived using an appropriate correction in the fault current. Value of the correction is a function of the voltage sag recorded by the monitor most downstream of the feeder at or downstream of fault location. In other words, the corrected fault current would let the CFL estimation still use an assumption of a bolted fault, but the correction would account for the fault impedance.

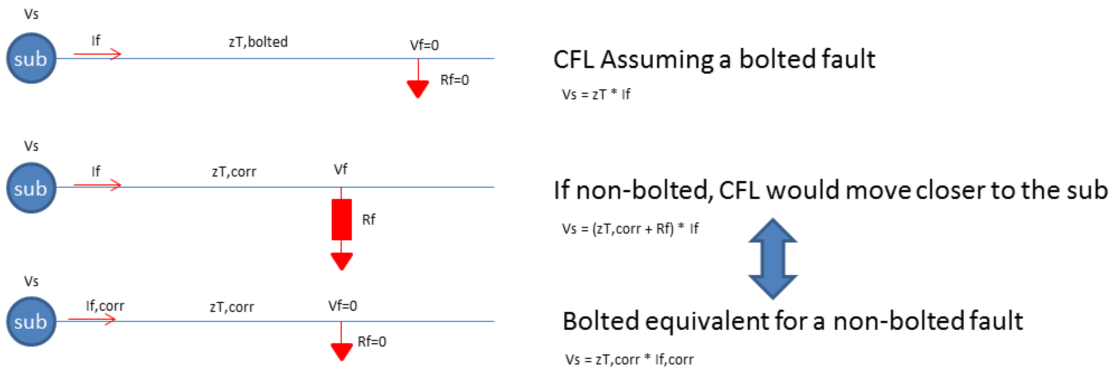

Figure 8: Fault current correction by incorporating voltage sag data

The corrected value of the fault current is

$$I_{f,corr} = \frac{1}{(1 - \text{FaultVoltagePU})} I_f ,$$

where “FaultVoltagePU” stands for the voltage sag in per unit recorded by a sag monitor downstream of the fault location.

Figure 9 shows the CFL result with and without the fault voltage based correction in left and right figures respectively. The colored segments on the feeder denote CFL results. Note that without correction, there is a cluster of CFL results located far away from Actual Fault Location (AFL). With correction, another CFL result results, which is close to AFL. This is also in agreement with the voltage sag based fault location in Figure 7 (right).

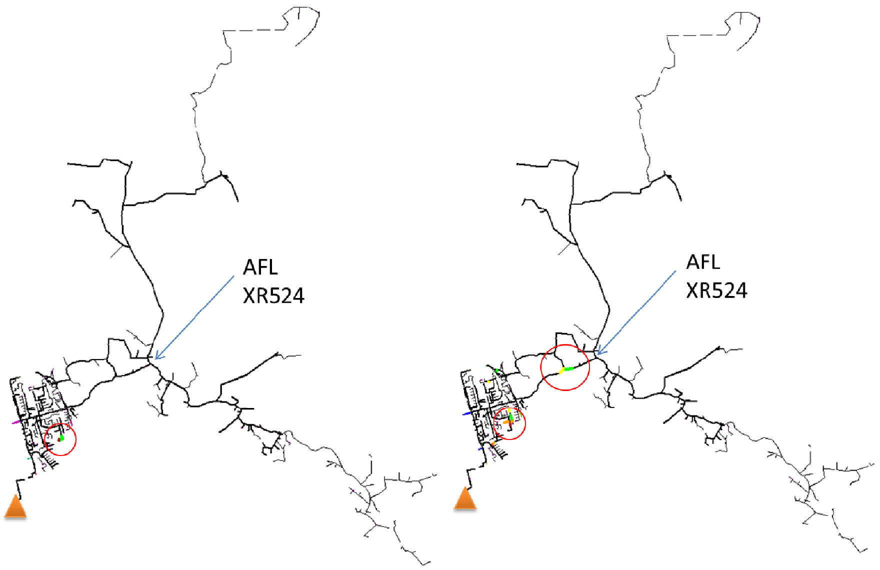

Figure 9: (Left) CFL using uncorrected fault current, (right) CFL corrected by incorporating voltage sag data

4. Field Experience during Pilot Project

Close to thousand line sensors and more than seventy voltage sag monitors have been installed on selected feeders in PG&E territory for experimental pilot in 2015-2016. Several fault events were recorded and fault currents and voltage sags were captured along the feeder. More than 700 voltage sag waveforms were collected, along with the corresponding fault current data from line sensors and actual fault location from PG&E's information historian for analysis. Overall the voltage sag data was found to be in agreement with line sensor fault current data. Analytics as illustrated by examples in earlier sections were used to validate the data and identify fault locations along the feeder.

5. Practical Challenges

Several practical challenges were faced during the study. Large volumes of data from the sensors pose difficulties in parsing and analysis. The voltage sag database acquires the raw voltage waveform data. Several sag monitoring devices report multiple waveform snapshots during a single fault event and in some cases managing and processing of the data manually becomes tremendously challenging. Automating the processes and integrating data into a single platform would prove to be beneficial. Separate head-ends for voltage sag and line current data poses another challenge. During the project, several prototypical automation tools have been developed for automating the data processing, execution of fault location algorithms and visualization of various results on a single map. Continued R&D in exploring visualization tools and techniques would lead to further enhancement and usefulness to distribution operators and engineers.

6. Conclusions

PG&E has installed many line sensors and voltage sag monitors on its distribution feeders for a pilot research activity to gather and analyze data during faults. Multiple sensors on selected feeders, have been shown to provide effective bracketing of the fault location. Also, numerous voltage sag waveforms and fault current have been obtained from the monitoring devices which also demonstrated the ability to converge on a fault location area. Overall, both the line sensors and sag monitors show promise to be beneficial and effective for distribution network fault location, particularly when their data is overlaid onto a single feeder map and is used by analytic algorithms to provide a single coherent picture of the fault event.

7. Acknowledgments

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BIBLIOGRAPHY

[1] T.A. Short, "Electrical Power Distribution Handbook," CRC Press, 2004
[2] A. Bergen and V. Vittal, "Power Systems Analysis," Prentice Hall, 2000
[3] M. Tremblay, R. Pater, F. Zavoda, M. Germain, "Electrical Network Fault Location by Distributed Voltage Measurements," US Patent 8269503 B2