# Addressing the Challenges of Building a Fully Automated Fault Location System

**Monica Anderson, Robert James, Daniel Zhang, Abesh Mubaraki,**
**PG&E**

**Juergen Holbach, Eric Udren, Damir Novosel, Xinyang Dong**
**Quanta Technology**

**SUMMARY**

The timely and accurate fault location is essential for an efficient dispatch of a service crew and rapid restoration. Protection, automation, and communication technology has improved quite significantly during the last decade enabling advances in determining the fault locations. The paper reports on a PG&E project that envisions to take full advantage of the new technology by creating a fully automated fault location system. The fully automated system is triggered by a fault event and collects all available data needed for an accurate calculation of a fault location. The fault location calculation is done using methodologies that compensate for various errors caused by effects of load, non-homogenous line, resistive fault, multi-terminal and series compensated lines and mutual coupling effects. The results from various methodologies will be combined and weighed by an expert system that utilizes other data sources like ASPEN OneLiner, travelling wave fault calculation, lightning database, and SCADA information to report the most accurate results. The fault location report is to be generated and sent automatically. It will have a detailed description of the fault (e.g. type, location) and should name and show the actual tower location of the fault on a map. The challenges PG&E faces and how these challenges are addressed are reported.

**KEYWORDS**

Fault location, automation, expert system, protection, system reliability

**Introduction**

The project goal was to optimize the three main objectives of the fault location process:

- **Time:** The time needed to determine the fault location, inform operators, and dispatch the maintenance crew defines the outage time and should be minimized.
- **Accuracy:** The accuracy of the fault location has a direct impact on the time needed by the maintenance crew to find the fault location on the line or equipment and start their restoration work. The knowledge of an accurate fault location is particularly important for line sections not easily accessible. Crew awareness of the confidence level of a location report can also improve the field location process.

- **Resources:** The optimization of the resources needed for the determination of a fast and accurate fault location is important for the implementation of proposed changes. Any proposed improvement must be weighed by its expected economic benefit.

After the review of the existing processes and tools used by PG&E today, it was found that a full automated fault determination system would serve all objectives in an ideal manner.

**Review of existing PG&E process**

During the process review, it was found that there are four essential tasks that can be discussed and reviewed as sub-tasks in the overall fault location process as shown in Figure 1.


*Figure 1: Subtask for fault location determination process*

**Fault Notification**

Ideally, each unplanned protection operation would be analyzed for proper operation in response to electrical system disturbances, and for possible human errors or equipment failures. Most of these unplanned outages are precipitated by electrical short circuits or faults. The primary purpose of the analysis is to report the apparent physical location of the fault to the Grid Control Center (GCC) operators, who will convey the information to transmission line repair crews (T-line crews). For sustained line outages, accurate location reports speed restoration, minimizing customer outage time or operational risk. On momentary operations were line patrols are conducted, the accurate fault location supports the patrol crew. A major additional value of the analysis is that it can identify problems even before they create a severe customer outage. In addition, the results can be used to verify the fault simulation computer model used for the setting and coordination of transmission line protective relays.

System Protection Department engineers are responsible for analyzing fault data and reporting fault locations to GCC operators as soon as is practical after the fault. Faults occur at all hours; this responsibility takes priority during routine working hours or personal time of engineers. The notification to System Protection of a protection system operation and the GCC request to provide fault location information is typically initiated by the System Operator.

On permanent faults with customer outages, the on-call contact must determine if a protection engineer in the area of the fault was called directly or has become aware of the need for a fault location and is working on the analysis. If not, the on-call contact needs to find an appropriate protection engineer and assign the fault location task. For temporary faults, the on-call contact must ensure that the fault location is available no later than the next business day for use by the T-line patrol team.

The operator uses one or more of the following for notification of System Protection engineers and on-call contacts that a fault requires a location analysis and feedback:

- Pager

- Phone call
- e-mail (TransSub e-mail)

The operator uses the above-listed methods to inform the protection department about faults in the system and make requests for information on the fault location from the protection department. The only method defined by a process is the TransSub Update email distribution list. The operator must send a notification about all faults by issuing a TransSub Update-mail. All other methods are optional and may be used by experienced operators to accelerate the fault location determination process.

On permanent faults, protection engineers typically achieve a location reporting time between 30 minutes and 1 hour, if communications access to fault record data is available and they are called directly during working hours.

Response times, necessarily, increase substantially if the protection engineer is notified only after a delay, and/or must make special personal arrangements and travel to access a computer and communications to attempt data retrieval and analysis. Communication problems from the engineer to a relay in the substation may greatly increase reporting time or can inhibit access to adequate data for any calculation.

Often, the fault location calculated by the relay is communicated right away to the operator (in under 10 minutes) as a rough location. Even though this value can have a large error, it can be helpful for the operator and gives general guidance. The fast feedback is also a good indicator for the operator that the protection engineer is engaged in the process.

PG&E does not have a clear requirement for feedback times on temporary faults and performs the fault location calculation, typically, the next day or next business day. For permanent faults, the protection engineer will commonly communicate the fault location directly to the operators by phone and then send the Trans-Sub email out afterwards.

Accuracy of results could be improved if the operator would provide information in the call on primary equipment outages that would affect the fault location calculation, such as local generation being off-line, or transmission lines or transformer banks being off-line near the fault location area.

**Communications Infrastructure**

The protection engineer assigned the task of calculating the fault location will start to gather recorded fault data from protection relays and digital fault records if available around the location of the faulted line. In substations with electromechanical relays, DFRs are the only local source for fault locations.

Based on the generation of the substation or NERC categorization, PG&E has the following standard communication access available:

- **Dial-In connection:** The substation phone numbers and passwords are managed in an Excel table on a shared drive folder and are also recorded in a book in the relay laboratory.
- **Operational Data Network (ODN) connections:** Modern substations and NERC critical sites, are equipped with network connections. The Citrix secure access system provides an application interface for all user programs used to gather data from the relays (AcSELerator & EnerVista). Citrix communicates via the ODN to a Cisco switch in the substation.

Ideally, the protection engineer can access and download all fault records from all relays on all line terminals of the faulted line. This is, unfortunately, not always possible as not all substations have communication access or numerical relays available.

The last resort for the protection engineers to get access to fault record data from substation that has no working communicating, is to send out a technician to the substation who will download the records via a direct serial connection to the front of the relay and will e-mail the fault record to the protection engineer. In most cases, this works well, although, it introduces an additional time delay. It can take hours until the technician reaches the substation and finds, after downloading the fault record, another site with cellular access from where it is possible to e-mail back the fault record.

If remote access to relays is not unavailable, the engineer may be able to use data from remote stations and lines to provide the fault location. This process has some inherent inaccuracies but can be used if the situation is urgent. This can also be done if there are electromechanical relays on the line in question. This provides the timeliest information to support the electrical outage and customer restoration activities in these challenging circumstances. Outage status information on primary equipment in the area, from the operator to the protection engineer locating the fault, may be particularly important for the best practical accuracy using remote data.

An issue to resolve when gathering records from different substations is the unreliable time tagging of the fault and event data due to unavailability of reliable GPS clocks and associated facilities in many substations.

**Fault location calculation**

The accuracy of a calculated fault location depends on many factors like availability of fault records, availability of the system configuration data, and algorithms used during the calculation process. The spectrum used by PG&E goes from the very accurate doubled-ended travelling wave method to a less accurate manual calculation based on fault impedance calculations from one-line terminal.

Different engineers use different techniques, based on their own experience. Some are quite creative, and overall accuracy of results appear to be quite good despite data gathering challenges. The use of a variety of methods may be appropriate since different regions and jurisdictions may have to deal with different situations and applications. However, it is realized that standard fault location processes and tools would benefit significantly the protection engineers.

Two main approaches include:

- Simulate the fault in Aspen OneLiner and change the location of the fault until the fault voltages and currents at a specific location match with those recorded by relays (or DFRs). The identified location (with some percentage of accuracy) is the actual location of the fault.
- Use the recorded voltage and current values and feed those to the Aspen OneLiner model (newer software version). The software will then provide the approximate fault location, assuming the pre-fault operating conditions are accurate.

For 500 kV lines owned by PG&E on both ends, travelling wave information from dedicated fault locators is processed to determine the fault location. This gives very reliable and accurate information for all lines where information from both line terminals is available. Lines connecting to neighboring utilities are difficult as there is no access to their travelling wave devices, even if they are available.

For all faults on series compensated lines, the state of the series capacitor bypass switch is not always available from the bank control system (being added at all sides to comply with NERC PRC-002-2 requirments) – this can lead to confusion for some fault location determinations using fault records rather than traveling waves.

**Reporting**

After the fault location and the fault type is determined, the protection engineer must distribute this information and must log it in the Dispatching database entry created for each outage.

The calculated fault location data will be communicated back to the operator and other stakeholders via the e-mail (TransSub). The format is standardized by the protection group as shown below.

> **Revised System Protection Fault Location Estimate**
> **Line and time of outage:** XXX - YYY aaakV line at mm/dd/YY @hhmm
> **Phase Involved in Fault:** PG&E phase c-c. (B-G, B-C-G, A-B-C, etc.)
> **Fault Location (in miles):** X.Y from CCC terminal/bus/switch/junction
> **Fault Location details:** Structure xx/yy
> **Accuracy of Location:** +/- xx miles

Some protection engineers use a two-step notification process. In the first step, they publish the fault location; automatically determined by the protection relay. The value is provided directly via SCADA or can be read from the relay right away once connected. The accuracy of this fault location is, normally, not very high as it is mostly based on a single ended fault location calculation. However, feedback can be provided to the operator right away which is already helpful in most cases for the dispatching of the inspection crew.

In the second notification, which is delayed by the calculation process, the calculation results are distributed.

The information in this notification is clear and based on calculations and findings in the fault records. The knowledge of the tower structure location is useful for the inspection crew and can be determined by the protection engineer based on the fault distance.

The accuracy is the only value a protection engineer cannot clearly determine. Here, the engineer is asked to give a confidence estimate for the calculation results. This is helpful for the inspection crew as it helps them to know in which area they must inspect the line.

To close out the fault location process, all data needs to be stored in a directory on a common drive. In addition the review of the proper relay operation is also required.

**Fully automated fault location system**

The above described process works efficiently during working hours. The process relies on manually performed tasks and human interactions.  For permanent faults, protection engineers typically achieve a location reporting time between 30 minutes and 1 hour, if communications access to fault record data is available.

During weekends and night hours, the process can become delayed based on availability of supporting protection engineers. In some instances, the protection engineer must drive to the office to be able to access the substations.

An automated fault location system was proposed that should improve the fault location determination process by:

- Automatically generating a notification
- Automatically retrieving all available and needed fault record information
- Automatically calculating the fault location
- Automatically sending out a fault location report to the operator or T-line crew

In the final implementation, the system would automatically perform all tasks needed to determine the most accurate fault location and send the result out almost immediately without the need to involve a protection engineer. The protection engineer will still have to review the automatically generated results for quality assurance at the beginning of the implementation before the result will be distributed, but this may still be beneficial in the final system.

A protection engineer needs to review, in any case, when the automated system concludes that the calculation has a complexity that it should be reviewed by an expert. The system could raise such a flag when a different calculation algorithm used parallelly presents different results.

The components of the automatic fault location system are shown in Figure 2.

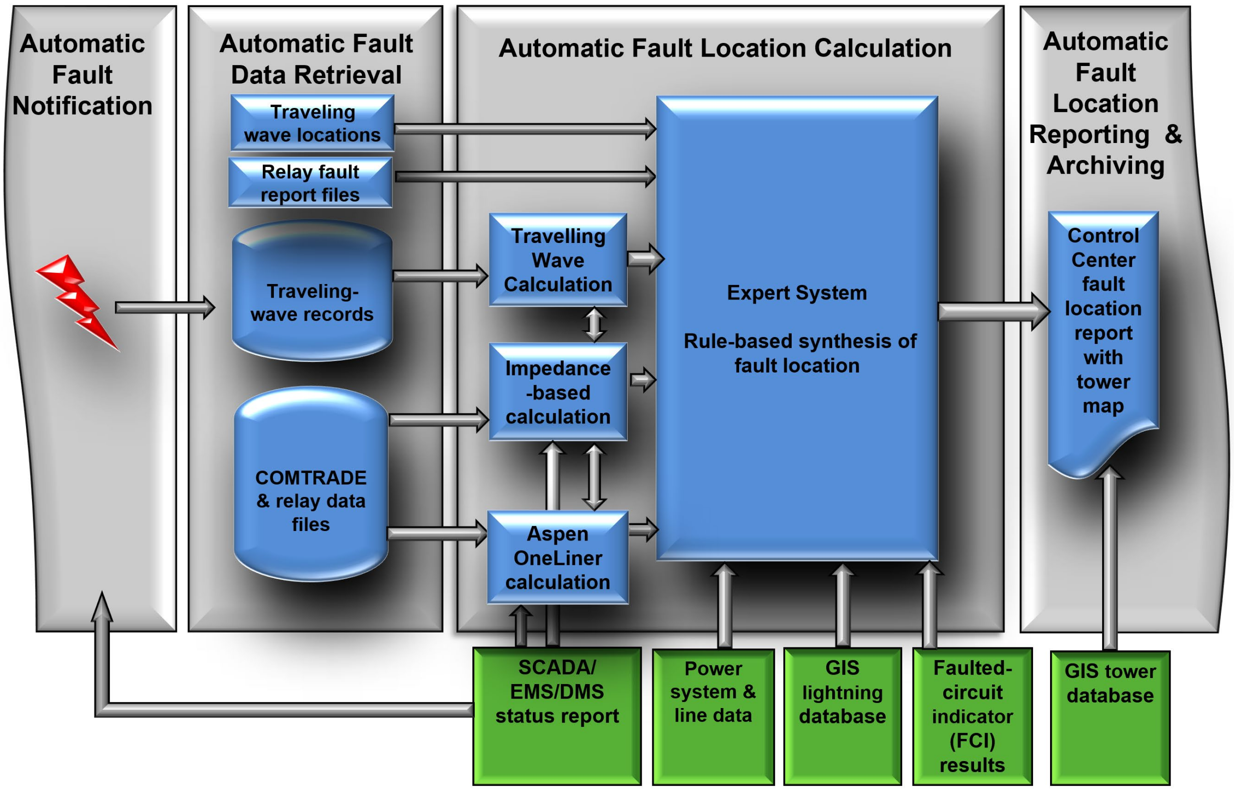


Figure 2: Components of the automatic fault location system

**Automatic fault notification**

The automatic fault notification system would handle the task of initiating the fault location determination process based on a protection operation. The trigger information can be directly generated from microprocessor relays in substations or via a SCADA/EMS system. The system should be able to inform the Fault Data Retrieval System and Fault Location Calculation module which line contains the fault and needs the fault location determination.

**Fault retrieval system**

The communication to the substations is essential for the automated fault location system to perform its task. Therefore, during normal operations (no fault) the fault retrieval system must monitor the communication links to the substation and send notification of any communication failure so that the communication can be restored.

There are two data collection approaches – pull and push:

- **Pull system, which may be based on an automatic fault notification system**

  *The data retrieval must be triggered by a fault notification system to the central server that will collect the records.*

  *Individual relays can alarm or indicate that they have responded to faults via SCADA, which, in turn, must report to the server. The data retrieval server looks up the list of relays expected to have data records and imports the records.*

*Otherwise, the data gathering system must ping each substation with a form of flag indicating the presence of fault data.*

*The server accesses relays in priority order: those most likely to capture data or the best data records, then other relays on the same line, finally followed by adjacent–circuit relays whose data will serve to assist in determining fault location via Aspen modeling if the preferred data is unavailable. The priority list is composed by System Protection and is static but is capable of human modification.*

- **Push system**

*If the data collection is based on servers in substations that push data through firewalls to an engineering access server, the substation collection server can poll relays for fault records and act right after the fault occurs and would inherently include a fault notification system.*

*A push architecture can monitor its data connections by periodically sending test messages, monitoring collection server response, and reconfirming receipt of that response. This can be implemented in the data collection system; eliminating the need for a separate communications test system.*

The choice of a pull versus push system may be different for substations with phone-line access versus those with ODN access.

**Automatic fault location calculation**

The calculation of an accurate fault location is an engineering challenge that requires the experience and knowledge of an expert. This is particularly true in complex fault scenarios where tapped load and generation, mutual coupling, complex grounding conditions, and other difficult conditions have an influence on the fault location calculation. The above makes automating the fault location calculation challenging. However, if the automated calculation system is designed as a practical expert system that implements the human expert knowledge needed to master the fault location calculations, including for complex fault scenarios, it will result in major improvements in speed, accuracy, and efficiency. This type of system, with initial implementation at PG&E, will be described next.

The calculation module was developed as a PG&E-customized piece of software, as it must interface with many PG&E systems and data sources. Some of the submodules are based on standard solutions that can be integrated into the automated system. During this project, a program was developed for demonstration purposes and as a proof of concept tool that automated some of the tasks. The goal of the program is to gather a sample of all the experience from the experts at PG&E and implement their knowledge inside this calculation module.

The calculation task consists of different submodules and has many interfaces to other data sources. In the following chapters, the different submodules and interfaces will be described in detail.

**Impedance-based calculation submodule**

The impedance-based calculation submodule processes data records from IED's or digital fault recorders provided by the automatic fault record retrieval system. For standardization of the input format, the IEEE standard COMTRADE file format is proposed; although, other manufacturer's proprietary formats (SEL-CEV, SEL-EVE) are supported as well.

The module calculates the fault impedance by using different algorithms. The program selects the algorithms automatically based on the available data and whether it should perform a single-ended, double-ended or multi-ended fault location calculation.

The module runs several algorithms in parallel, because there is no one algorithm that can always calculate the fault location 100% accurately and compensate for error sources such as the following:

- Resistive faults in combination with load
- Non-homogenous lines
- Accuracy of zero sequence compensation factor
- Mutual coupling
- Infeed and/or load on line tap

This is particularly true for single-ended fault location calculations where certain assumptions must be made. The results from the different algorithms are used to select a final fault location value to be reported; the results are also used to define a level of confidence for the provided fault location value.

One advantage of this tool is that it will serve as a knowledge base that can sample all the expertise and calculation approaches used by different groups and personnel within PG&E. The development of this submodule is planned as an ongoing project that will always improve the calculation methodology based on new findings.

The initial implementation uses the following algorithms for single-ended fault location calculation:

- Reactance [1]
- Re/RL and Xe/XL zero sequence compensation [13]
- Io based load compensation [13]
- Takagi [2]
- Novosel [11]

The results from this algorithm are combined and weighed by an expert system to provide the most accurate location. The project included sophisticated testing of different algorithms applied on different fault scenarios to determine how to weight the different results.

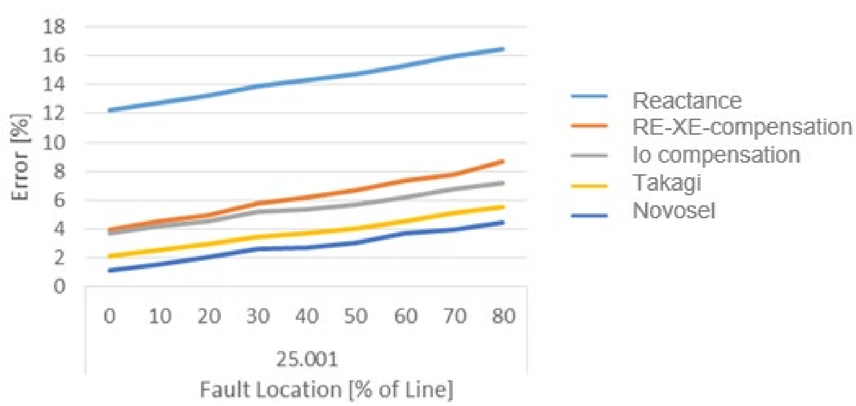


*Figure 3 : Test results for 25 Ohm restive fault with load*

The doubled ended fault location calculation is very accurate but requires that fault records from both line terminals are available. The voltage drop along the line toward the fault is calculated from both line terminals, and the fault location is determined to be where the line voltages are equal as calculated from both line terminals. The initial implementation uses the following algorithms for double-ended fault location calculation:

- Calculation based on negative sequence system (Novosel) [10]
- Calculation based on positive sequence system (Novosel) [10]

The use of negative sequence quantities has the advantage that it eliminates problems with zero sequence components, mutual coupling, and load related issues.

The positive sequence method is used for three-phase faults. Initially the double ended fault location calculation was also performed by using the zero-sequence system. However, the results were not accurate enough compared with the calculations of the positive and negative sequence system.

The double-ended method only works on clean two-terminal lines and does not work if there are infeed (tapped generators, three terminal lines) tapped to the line. Since the calculation simply provides a percentage of the line where the fault is located, it will not provide a location on any branching taps.

For faults on tapped lines, the result of a double ended fault location can be improved by using the ratio of the phase current or negative sequence current of the two ends:

Phase current ratio: $$\frac{I_{Ph\ local}}{I_{Ph\ locacl} + I_{Ph\ remote}}$$

Negative sequence current ratio: $$\frac{I_{2\ local}}{I_{2\ locacl} + I_{2\ remote}}$$

The ratio can either be used to correct the impedance drop along the tap portion of the line or by using Aspen OneLiner and simulating faults along the line to try finding where the ratio matches when simulating faults along the line in ASPEN OneLiner. The method eliminates fault resistance as a source of error, since the ratio of one end to the total current remains unchanged.

When using the values from two terminals for the fault location calculation, it is imperative that the records from both terminals are using the same scaling base for the analog values. It is possible to see different scaling bases when secondary values are reported, and different CT or PT ratios are used on both line terminals. Even if primary values are recorded, the records may use different scaling based on implementation by different manufacturers. For example; converting an SEL record from a native SEL format into COMTRADE format will introduce a square root of 2 factor to the values, which will cause problems when compared with a COMTRADE file recorded from another manufacturer. A review is performed by comparing the pre-fault voltages from both line terminals and a correction of the sqrt(2) issues can be performed.

The submodule, after being triggered by the notification system, scans the fault record file server for new fault records related to the reported line outage. The naming convention of the fault records files is composed so that each record can be clearly associated to the location of the record, the IED, and the time when the record was created. It is proposed to follow the IEEE Standard C37.232, “IEEE Standard for the Common Format for Naming Time Sequence Data files (COMNAME)”.

Before an impedance loop can be selected for the calculation, the submodule identifies the following:

- A data window to be used for the calculation
- The fault type

The calculation should be based on a data window that includes records from immediately prior to when the fault is cleared by the circuit breaker and where the fault values are stable. The data window of the 1$^{st}$ fault cycle can be impacted by transients or relay filtering and should not be used for the fault location calculation. Change of values based on evolving faults or operation of the remote terminal must be identified and must be outside of the selected data window. If the calculation is performed based on records from multiple terminals, the data windows must be synchronized and should include data from the same period of time.

The identification of the fault type is important, as it will provide the information for what fault loops are available for the impedance calculation. For a phase-phase-ground fault and three-phase fault, all faulty loops should be calculated and considered for the final reported fault impedance. Phase-to-phase loops would be preferred for the selection of the reported fault impedance, as they exclude many error sources based on zero sequence system phenomena (mutual coupling, zero sequence compensation factor, etc.). The results from the expert system tool will be presented to the protection engineer for a manual review (see Figure 4) at this time.

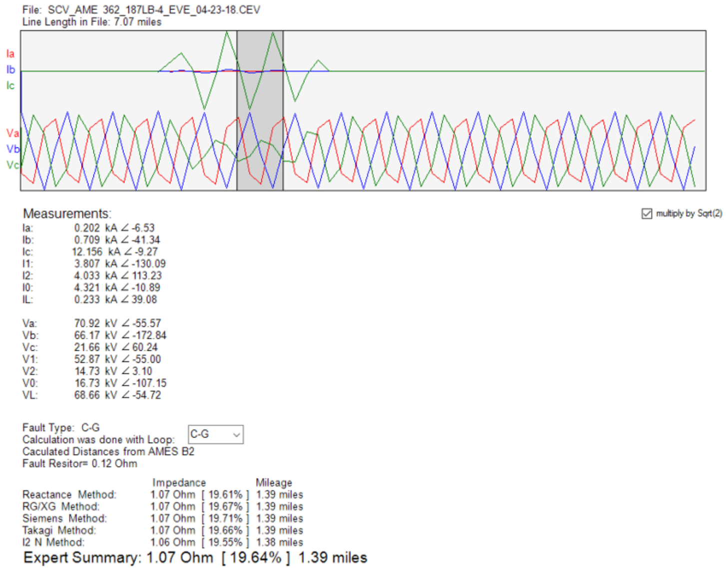


*Figure 4 Single Ended fault location result for review*

Additional information, such as the line impedances and topology information, are needed in the calculation module. The proof of concept program accesses the power system data that are modeled in the Aspen OneLiner® short circuit program used by PG&E.

On lines with multiple sections, where each section has different line parameters, the program will be able to use the provided information to convert the impedance to a correct distance to the fault. All taps on the line should be considered when a fault location is calculated. This will result in multiple possible fault locations that have to be reported.

A prerequisite for using the Aspen OneLiner data is that all data modeled in OneLiner follow certain naming conventions. All buses and lines must be named following an agreed upon naming convention. The bus names should be unique and identical to the names used to name the recorded COMTRADE files.

**Aspen OneLiner submodule**

Aspen OneLiner is currently used at PG&E to support fault location calculation. This is accomplished automatically by using the built-in capabilities of Aspen OneLiner to calculate the fault location based on the provided fault records, or manually by applying a fault on the faulted line. The automated system proposed here should perform the same task.

The proof of concept tool interacts with Aspen OneLiner via a provided Python API. This allows the tool to perform, automatically, the following tasks that were previously performed manually:

- Performing request fault simulation
- Outage and activation of power system elements
- Report parameters of power system element
- Update automatically line parameters in Aspen OneLiner
- Update automatically bus type in Aspen OneLiner

Part of the project is also to update the ASPEN OneLiner database by adding the mileage value of each line section. This value was not always entered by PG&E in the past but is needed for presenting the fault location in miles rather as in ohms.

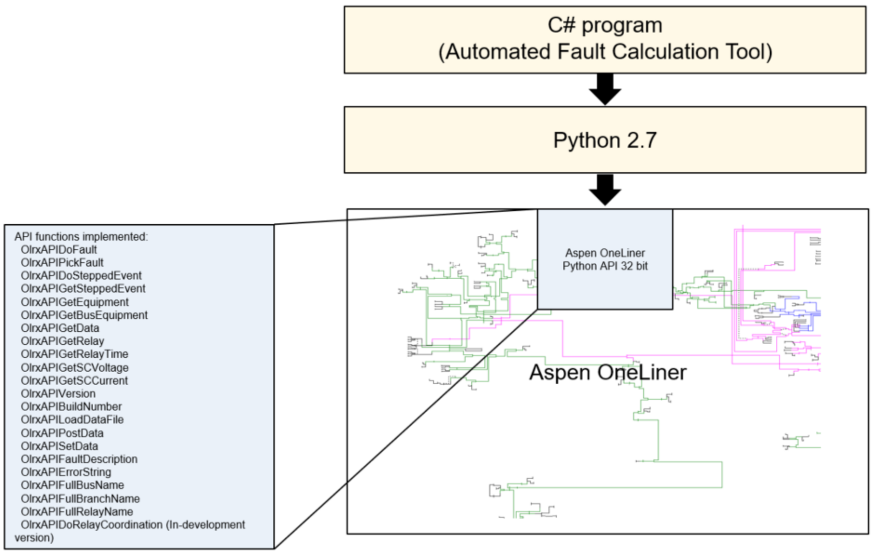


*Figure 5 Aspen OneLiner API*

**Interface to SCADA System, EMS, or DMS**

The information of the actual status of the power system is important when calculating the fault impedance and running simulations in Aspen OneLiner. Important information includes the following:

- Power system status
- Load values on feeder and tapped loads
- Generation capacity on tapped-in generators

The power system status and all outages and changes in the system should be updated in Aspen OneLiner before simulations are conducted that support the fault location determination task. The load and generation values on tapped feeders are always a source of error when a fault impedance calculation is conducted.

The above-mentioned information is available in different PG&E systems. This project envisioned, in the next step, must access other PG&E systems to make the information available for the fault location calculation module. The module should be able to automatically request the information or access the appropriate databases when needed.

**Travelling wave calculation submodule**

The Travelling Wave Calculation submodule is not addressing a new development, but, rather, it addresses the integration of the existing travelling wave system into the automated calculation module. Currently, the travelling wave information is provided by two different sources.

PG&E uses the IQ+ system, which supports the retrieval of travelling wave information from recording devices in the PG&E system and performs the calculation based on the information from records of all available line terminals. Another source of information on travelling wave fault locations is protection systems that are installed on line terminals and communicate with each other. The calculation is performed inside the relays themselves by evaluating local information from the remote line terminals.

The IQ+ system used today provides a user interface that allows the user to select the lines for which a calculation will be requested.

It is proposed to utilize the existing system inside of the automated calculation module. This will require the development of an application programming interface (API) that allows the automated calculation program to request information from the IQ+ system to automatically perform the tasks that are currently being performed manually. The API request would specify the line and time window for which a travelling wave record must be evaluated. The IQ+ system would return the calculated fault location.

Alternatively, the processing of the raw travelling wave data inside the calculation module can be considered. This will require that the raw data that records the reflection of the travelling wave be provided by the automatic fault data retrieval system.

The fault location calculated by the relay system, based on traveling wave information, can be accessed by the automatic fault data retrieval system and can be made available to the calculation module.

**Automatic fault location reporting**

The automated fault location system, when fully developed, will deliver the needed location results quickly, in most cases, but won't work perfectly in every case. Humans are better at spotting anomalies and applying corrections; experts typically possess a creative talent that, simply, cannot be fully programmed. Nonetheless, an automated system using multiple algorithms in an optimized tool, will give a fast and accurate result in most of the cases, along with indication of method and data quality that can inform operators and field crews on the likely accuracy of the result.

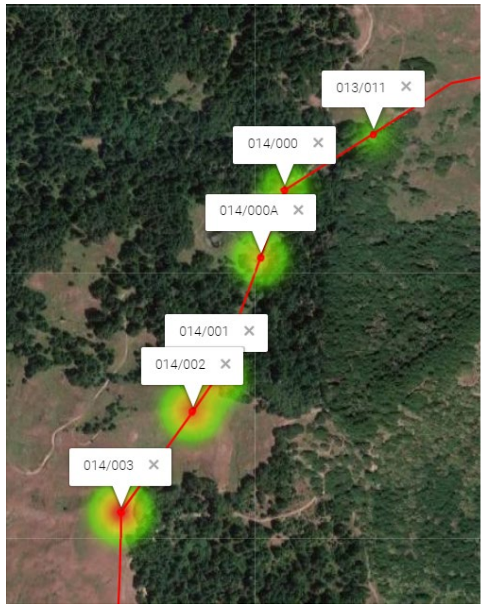


*Figure 6: Fault Location Report Information*

This would very significantly alleviate the time and workload pressures of the protection engineers, so they would have more time available to analyze the fault causes and review the proper relay operation of the entire protection system, as well as to address difficult cases that are beyond the capacity of the automated system.

**Conclusion**

Protection, automation, and communication technology has improved quite significantly during the last decade enabling advances in determining the fault locations. The automation of the fault location process helps to shorten the time it needs to process all steps needed for the fault location determination and reduces in the same time the resources involved in the process; this is particular true for fault events that occur not during working hours (i.e. Sunday morning 4 am). The accuracy of the fault location is improved by a fully automated process based on the ability of the tool to access and process all available information by an expert system. The expert system is a repository of expert knowledge based on algorithm and methods used by PG&E and known by the industry. The system selects automatically the most accurate algorithm and method based on the fault conditions.  The investment for the implementation of an automated fault location system are justified based on a better power system reliability, resilience, and better engineering staff productivity. Detecting faults faster and identifying root causes can help with minimizing fault impact and repeated occurrences, this making a system more resilient.

**BIBLIOGRAPHY**


[1] IEEE Guide C37.114 “Guide for Determining Fault Location on AC Transmission and Distribution Lines”.

[2] Takagi, et al.,”Development of a New Fault Locator Using the One-Terminal Voltage and Current Data” IEEE Transaction on PAS, Vol PAS 101,No8, August 1082,pp.2892-2898

[3] W. Peterson, D. Novosel, D. Hard, T.W. Cease, J. Schneider, “Tapping IED Data to find Transmission Faults”, IEEE Computer Applications in Power ,Volume: 12, Issue: 2, Apr 1999.

[4] J.B. Starling, “The Sixthman, Always on Duty”, Georgia Tech Fault and Disturbance Analysis Conference, April 27-28, 2015.

[5] C. Black, M. Behe, G Wilson, P Myrda, “Automated Fault Location Analysis”, EPRI 2016.

[6] S. Das, S. Santoso, A Gaikwad, M. Patel, “Impedance-Based Fault Location in Transmission Networks: Theory and Application”, IEEE 2014

[7] A. Saeed, T. Nguyen, “Fault Location Experience using Simulation Software”, Georgia Tech

[8] K. Zimmerman, D. Costello, “Impedance-Based Fault Location Experience”, Annual Georgia Tech Fault Protective Relay Conference, 2015

[9] Georgia Tech Fault and Disturbance Analysis Conference, 2005

[10] D. Novosel, D.G. Hart, E.A. Udren, and J. Garitty, “Unsynchronized Two-Terminal Fault Location Estimation,” IEEE Transaction on PWRD, Vol. 11, No. 1, pp. 130-138, Jan. 1996.

[11] D. Novosel, D.G. Hart, E.A. Udren, and M.M. Saha, “Fault Location Using Digital Relay Data,” IEEE Computer Applications in Power, Volume 8, Number 3, June 1995.

[12] G. Kiessling, S Schwabe, J. Holbach, “Power System Fault Analysis using Fault Reporting Data of Numerical Relays”, Annual Georgia Tech Fault Protective Relay Conference, 2005

[13] G. Ziegler, Numerical Distance Protection: Principles and Applications, John Wiley & Sons, 2011

**Biographical Sketch**

**Monica Anderson** received her BSEE in 1988 from the University of California, Davis. Monica is a registered professional engineer in California and has been with PG&E system protection since 2003. Her current PG&E position is a protection engineer supporting the 500 kV system. Previously she worked at Western Area Power Administration, First Energy Corp, and Puget Sound Energy.

**Robert James**, Senior Protection Engineer, PG&E, received his BS in Electrical Engineering and Computer Science from University of California, Berkeley in 2005, and graduated with distinction with an MS in Electrical Engineering from California State University, Fresno in 2009. He started his career with Pacific Gas and Electric Company in 2008 as an intern in Distribution Engineering and has held his current position as a Transmission System Protection Engineer since 2010. Robert has previously presented at the Western Protective Relay Conference and Georgia Tech. He is a registered Professional Engineer in the state of California.

**Daniel Zhang** is currently working with Pacific Gas and Electric as an Expert Protection Engineer. He has been working in the field of power system protection and control with utilities and engineering firms for about 20 years. He received his BSc and MSc degrees from Xi'an Jiaotong University, Xi'an, China in 1993 and 1996 respectively.

He is a registered professional engineer in New York State.

**Abesh Mubaraki Abesh Mubaraki** received his BSEE and MSEE degree from California State Polytechnic University, San Luis Obispo. Abesh is a System Protection Engineer at Pacific Gas and Electric Company, where he has been employed since 2013. He is a member of IEEE.

**Juergen Holbach, PhD**, *EXECUTIVE ADVISOR, Senior Director of Automation & Testing, P&C Solutions,* has more than 30 years of experience in the design and application of protective relaying. An IEEE member and chairman, he has published over a dozen papers and holds three patents. In 2009, Juergen received the Walter A. Elmore Best Paper Award from the Georgia Tech Relay Conference. Juergen's areas of expertise include Automation & Protection, Transmission Protection, RTDS Testing, and IEC 61850 Compliance.

**Damir Novosel, PhD,** *President, Quanta Technology,* has over 35 years of experience working with electric utilities and vendors and is one of the nation's leading technology and business experts on electrical power systems. He has developed and consulted on a number of concepts and methods to improve power system planning, operation, and maintenance, and has created and managed several reputable and successful organizations that developed innovative technology and industry best practices in various areas of power systems. Damir was elected into the National Academy of Engineers in 2014, and served as President for the IEEE Power & Energy Society (PES) in 2016

**Eric Udren**, *EXECUTIVE ADVISOR, Advisory Services,* has over 40 years of experience leading design and application of protective relaying systems, substation control, wide-area monitoring and control systems, PMU applications, and communications systems. Eric is an IEEE Life Fellow, holds 12 US patents, and is author of over 90 papers and book chapters including an IEEE Prize Paper, a Walter A. Elmore Best Paper Award, chapters in the 2012 PAC World Conference book, the Westinghouse Applied Protective Relaying book, and two papers in IEEE’s Press Book on Relaying. Eric is the Industry Guru of PACworld Magazine in September 2016.

**Xinyang Dong,** *Senior Engineer, P&C Solutions*, graduated with an MS degree from the Department of Electrical and Computer Engineering, North Carolina State University in 2015. She has been working at Quanta Technology since 2016. During her time at Quanta Technology, she has gained experience in wide-area coordination, line and transformer protection, feeder studies and relay coordination, fault location algorithms, and short circuit analysis using CAPE, ASPEN, and CYME. She also has experience with automating studies by writing CAPE CUPL macros, C# programs, and SQL queries.