# Managing Wildfire Risks

UTILITIES AROUND THE WORLD ARE FACING UNprecedented levels of fire risk from routine electrical faults and failures in transmission and distribution lines and equipment. The risk is elevated by changing weather patterns that produce extreme drought conditions and violent storms. These utilities are confronting aging power apparatus and difficult-to-detect failure and arcing fault scenarios. Major fires in recent years have increased public awareness of the risk.

San Diego Gas & Electric Company (SDG&E) is among California utilities facing this hazard, dealing with its causes, and engaging in major efforts to reduce it. The program of risk reduction is based largely on innovative solutions—experimenting with and implementing a variety of new technologies and strategies. There is no single approach to fire risk reduction; SDG&E pursues a variety of apparatus upgrading programs and operational and event responses, as it develops new protection and control equipment and methods.

This article presents SDG&E's range of strategies for reducing fire risk, including grid-hardening replacements, weather monitoring, adaptive operating procedures, adaptive distribution fault detection and tripping designs, and faster and more sensitive new transmission line protection schemes. In addition, SDG&E has been the industry leader in the development of distribution falling conductor protection (FCP) based on phasor measurement units (PMUs) and synchrophasor data streams gathered across distribution circuits.

As we explain, detecting a conductor break and de-energizing a circuit while the conductor is still falling avoids an arcing ground fault that can ignite dry vegetation—the broken conductor has no power when it lands. SDG&E is preparing to deploy new transmission line FCP schemes based on PMU measurements, which can trip a line and avoid fire ignition risk in the same way that it does for distribution circuits. We summarize companywide strategies and give technical specifics for each protection and control strategy in the following sections.

## Grid Hardening and Operation Adaptations to Reduce Risk

SDG&E has developed a broad fire safety enhancement program combining fundamental, commonsense upgrade efforts to reduce root causes of risk through new technologies to detect hazardous events at specific locations on the grid. The company has invested billions of dollars for more than a decade in the risk assessment and mitigation phase of its wildfire risk control plan. In this section, we summarize highlights of that implementation plan.


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Planning begins with an assessment of cross-functional business and operational activities that impact wildfire risk reduction. These include the following:

- climate change adaptation, including bolstering system resilience and reducing greenhouse gas emissions
- an asset management program, including inspection and fleet assessment to identify and repair apparatus and facilities
- emergency preparedness and response, including proactive reactions to potential risk situations and post-event effectiveness analysis
- safety management systems, including communication networks and comprehensive team training about safety issues and procedures
- workforce training, qualification, and planning for all risk mitigation and response activities
- records management for internal and regulatory tracking.

# Protection System Technical Developments Combined With Operational Advances to Improve Public Safety

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### *Risk Bowtie*

The first step in developing a comprehensive risk reduction program is to identify the drivers and triggers of wildfires. A high-level list of drivers and triggers appears at the left in Figure 1, and any one of them can ignite a wildfire. This is illustrated by the central red disk. Should a fire occur, the consequences shown on the right are independent of the triggering event. With many choices of where and how to invest in new facilities, systems, and procedures, SDG&E has developed an ongoing prioritization process. Considering the Figure 1 bowtie diagram, there are opportunities to reduce the risk of fire ignition from the causes and the impact of each consequence.

Accordingly, SDG&E process managers and team members determine "likelihood of risk event" scores for every cause and "consequence of risk event" scores for the impacts, leading to the calculation of a total wildfire risk score. Tracking through time shows how specific programs may reduce risk, and it records improvements as programs are carried out. The total wildfire risk score includes the reduction of wildfire risks from the mitigation of triggers and the hazard reduction when SDG&E operations trigger a public safety power shutdown (PSPS) of selected facilities based on information processing systems described in the following sections.

### *Driver and Consequence Mitigation Programs*

Based on the risk–benefit analysis described previously, SDG&E has been carrying out major programs to reduce the likelihood of triggers.

#### Situational Awareness and Forecasting Programs

These programs include the following:

1) *Operational wildfire risk modeling*: SDG&E has developed an advanced operational model for wildfire risk based on weather and fuel moisture information, mountaintop camera network integration, weather station

data, wind deviations based on measurements across the service territory, and fire simulation analytics for all reported triggering events. This system gives operators the ability to invoke many of the hazard reduction strategies in areas where they are needed while minimizing customer service impacts where the risk is lower.

2) *Advanced weather station integration*: SDG&E has one of the most advanced weather station networks in the industry, monitoring temperature, wind, and fuel moisture. In 2020, the program added 30 stations and upgraded 50 others in a fleet of more than 200, with additional modernization taking place in 2021. New installations are validating novel sensors that more accurately assess fuel moisture conditions to correlate impacts on the spread of wildfires.
3) *Wireless circuit fault indicators*: Along with sensitive and expansive fault protection system responses, which are explained in the following sections, wireless fault indicators indicate a circuit section where a fault has occurred to focus the search for the exact location. This greatly speeds responses to faults and the location of sites where there is a risk of ignition.
4) *Creation of a fire science and climate adaptation department*: This organization was established in 2018 to strategize SDG&E's fire preparedness activities and programs. Among these are an ignition management program for root cause analysis and mitigation, a Fire Science and Innovation Lab that brings together experts and community stakeholders to create solutions and build regional fire resiliency, and university and institutional partnerships.
5) *High-performance computing infrastructure*: In partnership with the San Diego Supercomputer Center, SDG&E has developed and continues to advance big data tools that process high-resolution weather information into forecasts that generate real-time guidance for operators. These data are shared with the U.S. Forest Service and National Weather Service; the former publishes the guidance on its public website.

### Grid Design and System Hardening Programs

These initiatives include the following:

1) *Distribution supervisory control and data acquisition capacitor replacement*: New supervisory control and data acquisition (SCADA) capacitors with lower failure risks are replacing older fixed capacitors. SCADA introduces situational awareness of issues in capacitor banks as well as balance issues on circuits that can limit sensitivity to high-resistance faults and lead to undesired customer tripping.
2) *Covered conductor (tree wire) deployment*: SDG&E's analysis of the risk reduction benefit of new insulated

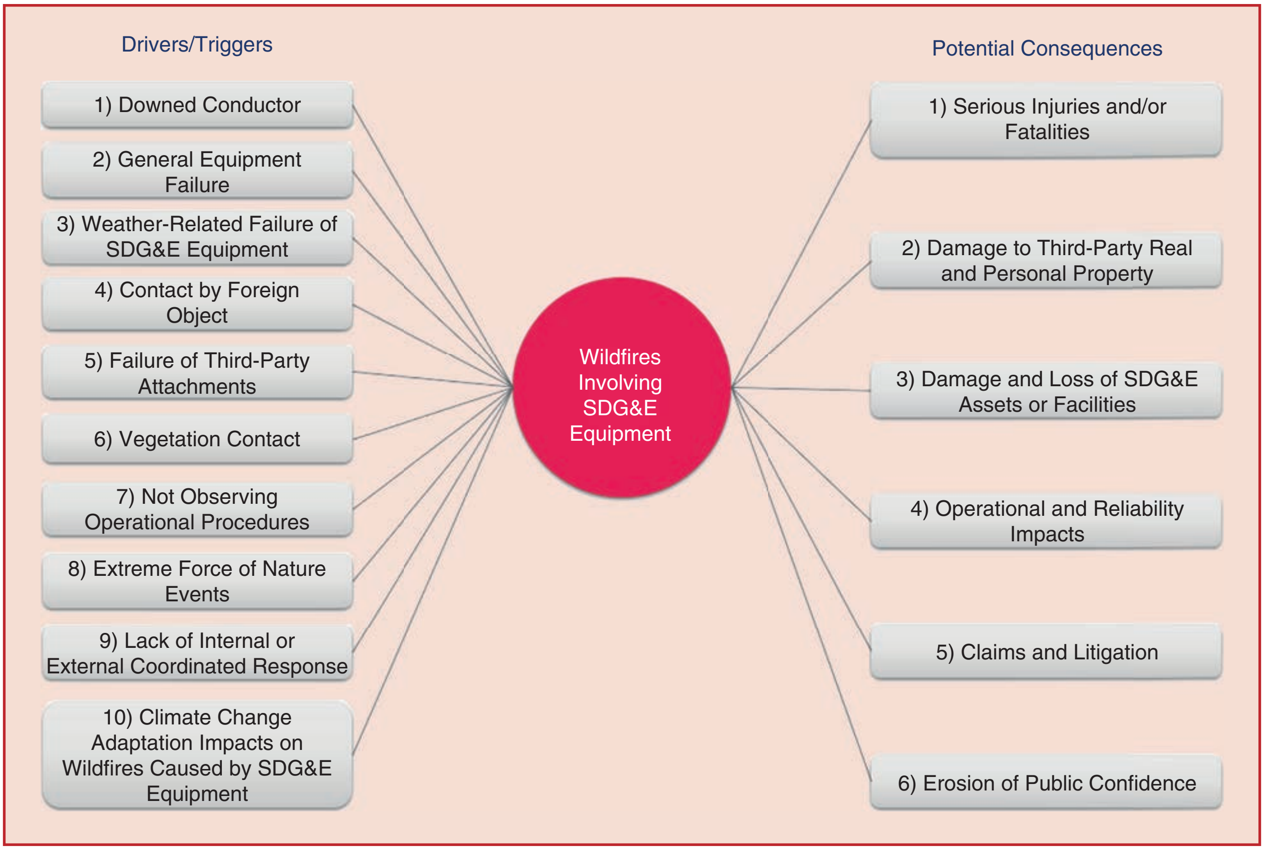


**figure 1.** The SDG&E risk bow tie.

conductors in consideration of root fault causes, along with a favorable pilot installation experience, is leading to the ongoing replacement of old, bare conductors with contact insulation conductors in the highest-fire-hazard zones. Insulated conductors raise the threshold for wind and fire risks for which a PSPS must be carried out. The deployment of thousands of miles of covered conductors is based on risk prioritization.

3) *Expulsion fuse replacement*: SDG&E is installing fuses with reduced discharge and fire risks that are approved by the California Department of Forestry and Fire Protection. About half of the old expulsion fuses were replaced in 2020, with work continuing in 2021.
4) *PSPS sectionalizing and switching enhancement*: SDG&E uses PSPSs as a last resort when the probability of ignition is higher than normal and the risk of spreading wildfire is extreme. Since PSPSs have such a negative impact on the community, a sectionalizing enhancement program has installed new isolating switches—more than 300 and counting—to limit shutoffs to the smallest practical areas.
5) *Microgrid deployment*: Microgrids can mitigate PSPS impacts where other solutions are difficult to implement. SDG&E is aggressively establishing microgrid areas, some initially configured with emergency generation connections for customer support in extreme fire risk conditions.
6) *Advanced protection program*: Advanced protection systems, including FCP, sensitive ground fault (SGF) protection, sensitive relay profile (SRP) settings, accurate fault location, remote event data gathering and reporting, SCADA communication with field devices, and increased sensitivity and transmission line protection, are focus topics of this article described in the following sections.
7) *Hotline clamp replacement*: Thousands of conductor hotline clamps are being replaced with compression connectors to reduce the risk of energized conductor separation and falling.
8) *Resiliency grants, assistance programs, and standby power programs*: These support the deployment of renewable and emergency generation for customers facing the risk of PSPSs.
9) *Strategic circuit undergrounding*: Burying circuits nearly eliminates the wildfire risk, but it is the most expensive mitigation approach. Land and environmental constraints further limit it. SDG&E is undergrounding circuits where wildfire risk is extreme and where PSPSs can be minimized by burying limited sections of larger circuits.
10) *Overhead distribution and transmission circuit fire hardening*: Coordinated and risk-prioritized, long-term construction programs are replacing wood poles with steel, installing high-strength conductors, and increasing conductor spacing where needed.
11) *Cellular LTE communication network*: This expands the coverage of reliable systemwide communication, including support for new protection technologies for distribution circuits, as we explain in the following sections.
12) *Surge arrester replacement*: SDG&E is deploying new California Department of Forestry and Fire Protection-approved arresters employing technology that adds arrester overload detection and isolation.

### Asset Management Technologies and Inspections: Vegetation Management

The following programs are included:

1) *Inspection programs*: These include annual circuit patrol inspections, five-year detailed transmission and distribution system inspections, 10-year intrusive inspections of wood poles, prioritized and more frequent inspections in high-fire-risk areas, and responsibility for individual circuits by designated personnel who monitor and report issues.
2) *Analysis of maintenance findings*: These involve the categorization and ranking of detailed maintenance findings, with root cause determinations for planning and prioritizing mitigation programs.
3) *Enhanced vegetation management*: This includes vegetation inspection, tree trimming, tree risk ranking, the analysis and management of fire fuel potential, and the removal of fuel near poles in high-risk areas.
4) *Lidar inspections*: 3D aerial surveys of complete electric transmission and distribution circuit rights-of-way determine clearances and validate engineering designs.
5) *Drone inspections*: SDG&E is developing drone camera image automated processing since the number of photos is beyond practical human analysis. So far, image analysis is demonstrating a higher rate of circuit issue detection than human inspection.

### Grid Operations and Procedures

SDG&E classifies operating conditions as normal, elevated risk, and extreme risk. The latter two result in system work being restricted and extra mitigation steps for work that cannot be delayed. The programs include the following:

1) *Firefighting aviation*: SDG&E operates helicopters and coordinates with other agency resources to ensure availability and coverage.
2) *Fire protection teams*: These teams have specialized utility infrastructure expertise.
3) *PSPS management*: This involves determination, initiation, and restoration management processes and criteria.
4) *Enterprise asset management platform*: This serves as a data repository for all historized and predictive fire, weather, and resource allocation information.
5) *Emergency operations center*: The center provides event management coordinated with other agencies and government activities.

## System Fault Detection Strategies

Short-circuit faults on distribution feeders and transmission lines often produce arcing, which can ignite combustible materials at or near fault locations. Arcs that can ignite fires may be visibly dramatic at the fault location yet may cause minimal electrical disturbance of feeder currents and voltages. This is especially true for ground faults with high electrical resistance, such as when a circuit conductor contacts earth with dry brush nearby.

### *Typical Distribution Fault Protection*

Distribution circuits in the SDG&E system are radially fed from a single source at a substation. For fault protection, overcurrent relays are used at the substation breaker and field reclosers downstream. These relays sense fault current above a set point for phase and ground current and are time coordinated to minimize impacts by tripping only the recloser closest to a fault. In recent years, the company has installed hundreds of new reclosers in high-risk circuits, which are sectioned into smaller segments, reducing patrol times when one reports an operation.

The major drawback of time–overcurrent coordination with added reclosers is the additional delay for upstream protection equipment to coordinate multiple devices in series. This increases the time that some faults persist before a recloser or protective relay trips. To improve sensitivity and reduce fault durations in comparison to traditional time–overcurrent protection, SDG&E employs two unique protection setting profiles on its overhead reclosers. These profiles, or configurations, invoked via SCADA commands to circuit reclosers, significantly limit fault energy and trip durations during high-risk periods when wildfire ignition and spreading are most likely to occur.

### *SRP Settings*

SDG&E developed its SRP profile strategy in 2010. A special group or profile of relay and recloser protection sensitivity and tripping time settings can be engaged by distribution operations at times of high fire risk. The set points are chosen as sensitively as possible without tripping for normal load conditions and will clear a fault in fewer than four power cycles or 70 ms. With conventional time–overcurrent protection settings, it may take seconds to clear a fault. When elevated and extreme fire weather conditions are forecast, SDG&E distribution operations enable SRP settings across the system.

To achieve optimum speed and sensitivity, historical five-year loading profiles for individual devices and circuits are gathered via SCADA data communications from every recloser. SDG&E has developed an automated data processing tool that analyzes the loading history of every device in high-fire-risk districts to flag SRP set points that need reverification. As a result, decision logic used by operators for SRP engagement is updated.

When elevated and extreme fire risk weather conditions are forecast by SDG&E's meteorologists, operators remotely switch a predefined list of reclosers to an SRP profile the prior night. These SRP settings do not coordinate with other protective devices, such as fuses and reclosers farther down a circuit. If there is a fault, the settings will trigger the uncoordinated tripping of multiple devices and de-energize larger sections of the feeder, impacting more loads and requiring more extensive patrols to locate the problem and ensure that the circuit is clear for re-energization.

SDG&E performed a benefit analysis from a sample set of SRP trips to determine the reduction of wildfire ignition risk. In total, from 40 trips that occurred when the SRP was enabled, there have been no fire ignitions. In comparison, when reclosers had normal protection settings in effect, 2% of trips caused fire ignitions found by field patrols. This shows how the fire mitigation benefits of using the SRP settings during high-wildfire-risk conditions outweigh the loss of protection coordination that causes larger outages.

### *SGF Protection*

Another layer of risk reduction is SGF protection. In many cases, distribution ground faults that could cause a fire, such as energized conductors on the ground (wires down), have a high ground path impedance and yield very little fault current. They cannot be detected by relays and reclosers using standard ground overcurrent protection settings. Standard settings are typically high enough to avoid tripping for normal phase load imbalances, which look to the relays and reclosers like low-current ground faults of the same magnitude as the imbalance. SGF protection replaces standard ground current magnitude trip settings with values that are customized for every device, set just above the normal unbalance seen by each piece of equipment.

As with the SRP, setting SGF protection requires constant reviews and adjustments of individual settings compared to field load data history to avoid trips for load imbalance. SDG&E implemented specially developed analytic tools to study the actual range of load-induced circuit current imbalance for every relay and recloser reporting load profiles, using systemwide, continuous operating measurements collected by the control center-based SCADA system. These are the same loading data and tool systems employed to determine annual baselines for SRP settings before every fire season. With this device-customized load imbalance profile, every device can be set just above its worst normal imbalance level, with a minimized risk of false tripping for normal loading. On well-balanced circuits, the setting can be far lower and more sensitive than a standardized one.

SDG&E applies SGF settings year-round as opposed to engaging them as part of an operating profile. This lowers the risk of wildfires and reduces public safety hazards from energized downed conductors. As with conventional time–overcurrent protection, SGF is time coordinated by setting a 0.5-s delay interval between the tripping times of reclosers along a circuit. This time delay minimizes the reliability impact by isolating a smaller section of the circuit when a fault occurs and thus enables the full-time use of SGF protection.

## Falling Conductor Protection

The purpose of FCP is to detect a broken energized conductor and de-energize it before it strikes the ground, eliminating the risk of fire ignition and public exposure to live equipment. SDG&E and other utilities experience conductor breaks even with vigorous circuit hardening programs. An SDG&E project team invented and patented the concept and scheme of FCP while developing new synchrophasor-based distribution circuit monitoring and protection system technology.

Figure 2 shows the time sequence for a broken overhead distribution conductor falling from 30 ft (9 m). Accelerating from the moment of the break, one or both ends reach the ground 1.37 s later. The FCP scheme can detect the break from circuit voltage signatures and issue trip commands so that the broken circuit section is de-energized 200–500 ms after the event—when a conductor has fallen only a few feet.

### *Scheme Components*

The system utilizes PMU-enabled protection and controls intelligent electronic devices (IEDs) along a distribution circuit; an Ethernet circuit-area, high-speed data communication system; and a substation-based phasor data concentrator (PDC) that sends collected synchrophasor streams to an adjacent real-time automation controller. The controller holistically processes all the circuit measurements with algorithms developed by the SDG&E project team to detect a break between two measurement locations. The controller can send trip commands to the circuit protection IEDs on circuit switching devices that can isolate the break, typically within 100 ms. Figure 3 illustrates two typical distribution circuits radiating from a substation, with arrays of circuit IEDs communicating with the substation scheme controller. Normally open tie switch connections can be included in the FCP scheme if the switch control IED is also streaming PMU measurements.

#### Substation and Circuit IEDs

IEDs participating in circuit FCP include protective relays at substation circuit breakers and recloser controllers and voltage monitors distributed along a circuit. The scheme

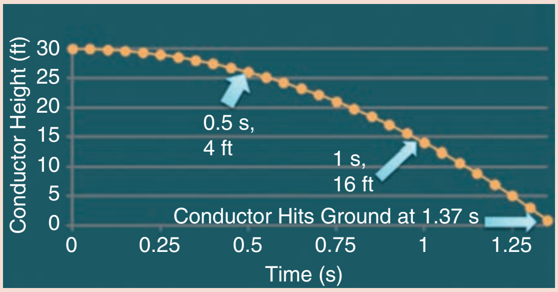


**figure 2.** The falling conductor timeline.

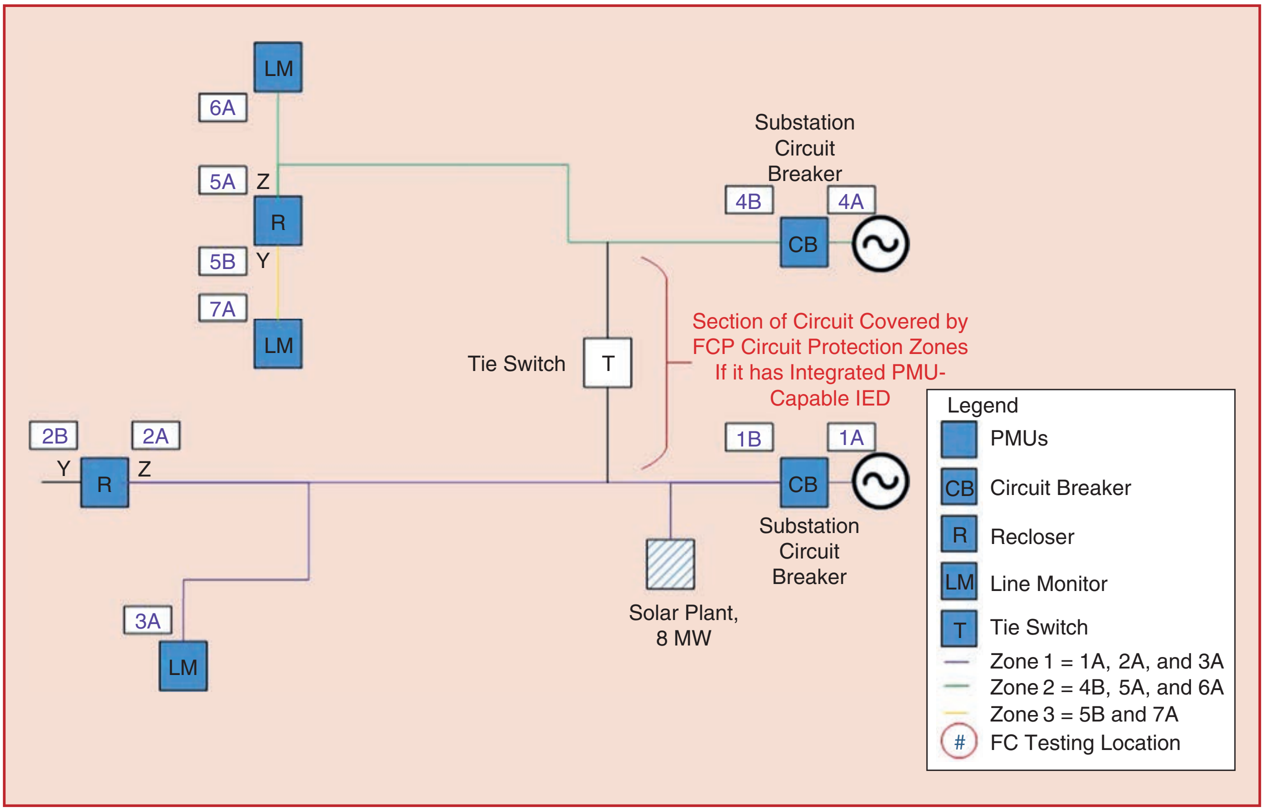


**figure 3.** The FCP two-circuit design.

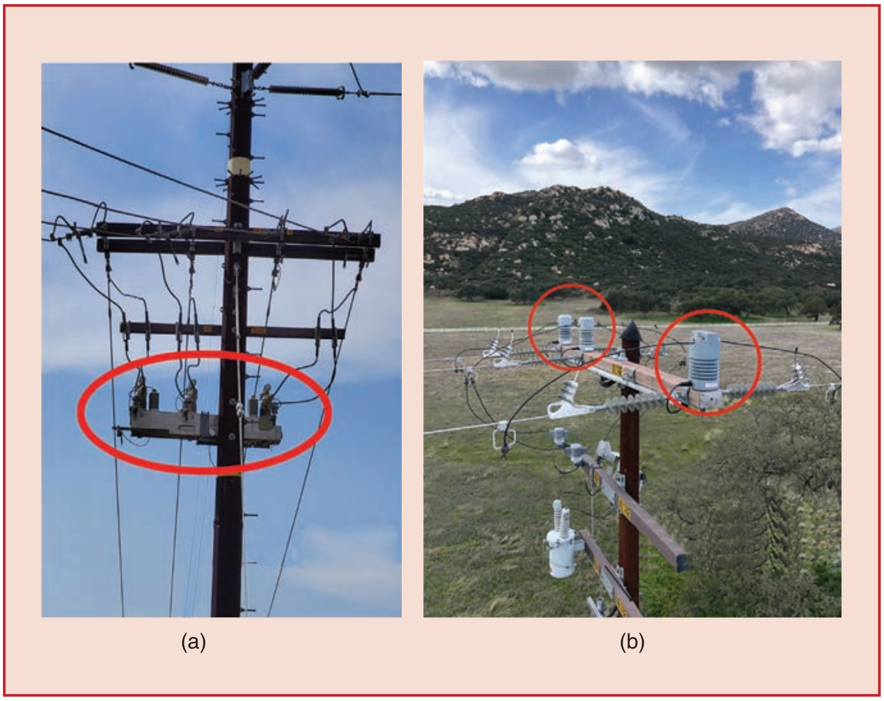


**figure 4.** The FCP circuit IED locations. (a) The distribution recloser. (b) The line monitor sensors. (Source: SDG&E.)

uses commercially available IEDs that are, in addition to their conventional protection and control and SCADA functions, capable of streaming synchrophasor voltage and current measurements via high-speed communication at a rate of 30 or 60 synchrophasor sets per second. Figure 4 displays typical circuit IED installations. If a substation controller detects a conductor break, it sends high-speed tripping commands to circuit switching devices (reclosers, circuit breakers, and high-speed transfer switches) over the same communication network that collects the synchrophasor measurements used by the algorithms.

## High-Speed Data Communication

Figure 5 details how circuit IEDs are coupled to an Ethernet radio

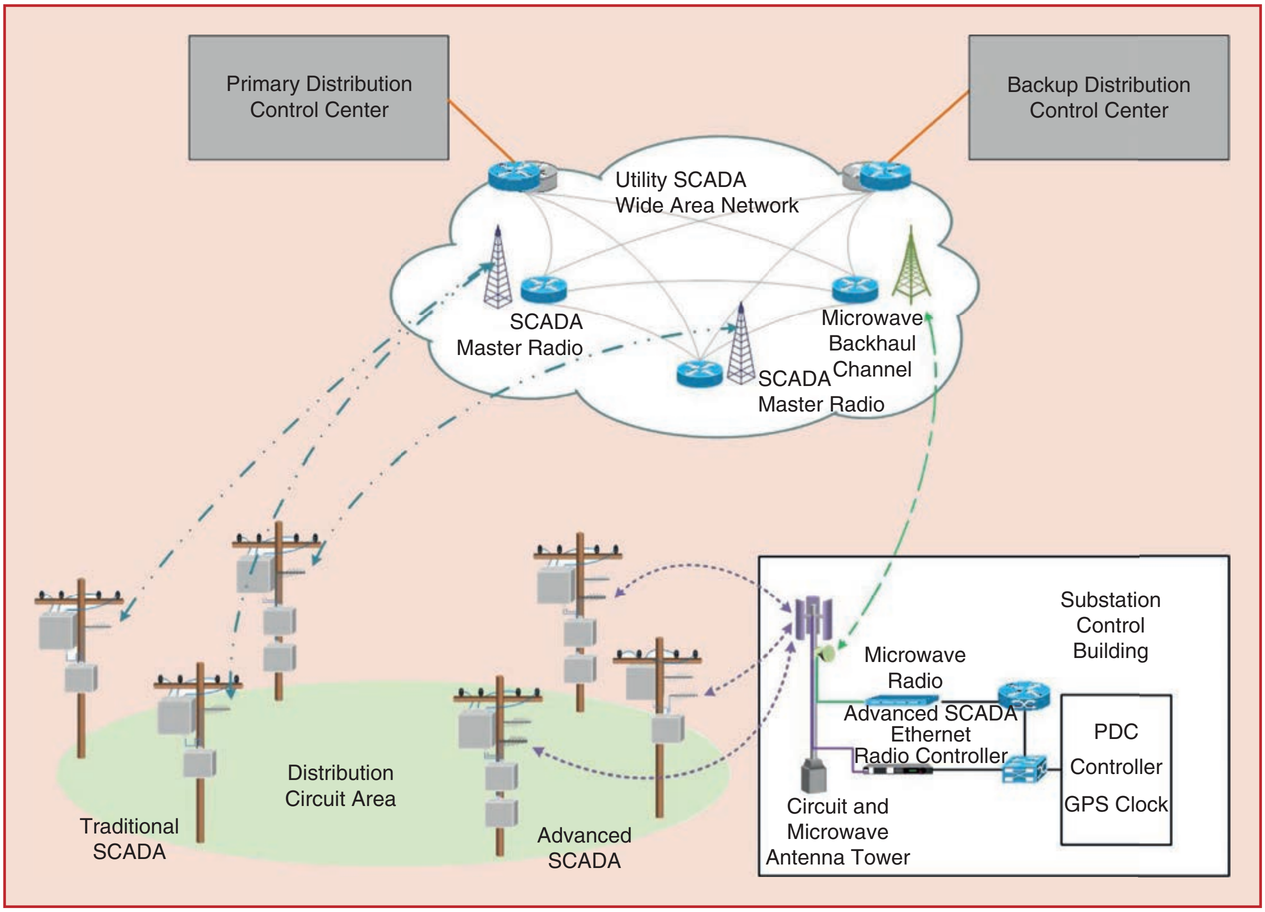


**figure 5.** The FCP radio communication architecture.

network to transport the PMU data stream of 30 to 60 frames/s back to a substation for processing. For returned FCP tripping commands, the controller publishes high-speed tripping commands using the International Electrotechnical Commission 61850 Generic Object-Oriented Substation Event (GOOSE) message packet specification. Fiber-optic connections are installed in the substation to connect PMU-enabled feeder relays to the PDC. Fibers along distribution circuit paths may be available in place of radio paths in selected service areas with high load densities.

FCP requires robust communication links that provide consistently high data rates and low packet loss rates. Recent FCP deployments use wideband Ethernet mesh, point-to-point, and point-to-multipoint radio systems with repeaters. These radio networks operate in the U.S. Federal Communication Commission-allocated 2.4- and 5.8-GHz unlicensed bands and can transport synchrophasor streams with a latency, or time delay, shorter than 50 ms. High-gain directional antennas boost the signal strength and signal-to-noise ratio for penetrating foliage and other environmental obstacles. Omnidirectional antennas are employed where directionality is not required, due to their ease of installation and use.

Figure 5 also shows how the high-speed radio communication for PMU data and tripping is overlaid on SDG&E's legacy wide-area and lower-speed distribution SCADA radio system so that both networks can simultaneously operate as advanced high-speed data collection and communication are being deployed across the company's distribution system. The lower-right portion shows a substation-based communication hub tied to FCP controller system components, as explained in the following. The substation hub communicates with circuit control devices over high-speed Ethernet radio, shown as the advanced communication system. Circuit synchrophasor measurements and FCP system data are transferred to control centers via a backhaul connection from a substation through the wide area network to control centers. The traditional SCADA communication system at the lower right includes a lower-speed, wide-area radio system exchanging data with circuit devices across the service area every few seconds. The traditional and advanced communication paths can be overlaid, even on a single circuit.

We have pointed out that SDG&E is deploying privately owned LTE cellular radio systems for a variety of grid monitoring and control applications. New FCP deployments operate over this expanding communication network. This commercial off-the-shelf solution features flexible network routing and the ability to integrate overlapping zones of coverage between geographical areas for improved reliability. The LTE solution decreases the cost of FCP deployment and improves cybersecurity management.

### Substation Processing Array

At the substation terminating each FCP-equipped circuit, the high-speed data radio system host transceiver node is combined on a rack with a PDC, FCP-programmed automation controller, Ethernet switch, and GPS receiver for precise system measurement and event timing (Figure 6). In newer deployments, PDC and FCP functions are combined in a next-generation automation controller.

Figure 7 displays the overall interconnection of components for the FCP system. Every circuit IED installation communicates with a host radio transceiver node in a substation, as in Figure 5. The radio node exchanges Ethernet data packets with the PDC and Ethernet network with a real-time scheme automation controller, substation relay PMU, and SCADA communication interface. In some installations, the scheme controller directly communicates with the distribution SCADA system, performing its own SCADA remote terminal unit function. In some FCP installations, the PDC concentrates and streams the entire circuit PMU data array from across the circuit over a wideband backhaul channel to a wide area network data center server (Figure 5). These full PMU measurement records are available to engineers for near-real-time circuit observation, event analysis, and archiving as well as the development of other distribution PMU applications, such as circuit voltage and current profile monitoring.

## *Scheme Operation*

The controller receives a new set of phasor frames from across a monitored circuit 30 or 60 times/s. With each new


**figure 6.** The FCP substation IEDs. (Source: SDG&E.)

frame, the controller executes a sequence of five algorithms that analyze three-phase voltage relationships across a series of frame times. A conductor break produces a unique shift in relationships among phase voltage magnitudes and angles. For example, Figure 8 shows how a composite extraction of angles from the three-phase voltages (negative- and zero-sequence voltage angles) across the circuit bracket the location of a break.

At the moment of a break, the extracted angles shift position, presenting a characteristic difference between angles on either side of the break. A comparison of these extracted angles across the circuit and several synchrophasor frame intervals gives a reliable indication of the section with the broken conductor and triggers a GOOSE trip command to the nearest switching devices on either side of the break. The controller delivers a SCADA alarm to the control center to alert an operator to specifics of the FCP isolation of a broken wire. This prompts an immediate field response to investigate the open circuit section, repair the break, and restore service. FCP experts perform postmortem analysis on historized synchrophasor and event records to ensure that the system operated correctly and guide algorithm improvements.

Five algorithms have been developed in extensive laboratory testing on a real-time digital simulation of a real feeder with varying loads, imbalances, and connected inverter-based energy sources, such as photovoltaic residential and commercial generation that is ubiquitous in the SDG&E distribution system. Each algorithm has the strongest detection capability for certain operating conditions. For the full range of circuit loading, load unbalance, and photovoltaic generation at high and low levels, multiple algorithms can detect a conductor break. The testing regimen also demonstrated security, or resistance to undesired operation, for normal switching events and unbalances from single-phase load switching and misalignments of voltage regulator taps.

For faults, relay and recloser control pickup blocks FCP so that the relays and fault protective devices on a circuit can execute properly located and timed trip decisions. Early field trial experience with FCP led to the inclusion of an algorithm that detects current arcing from failing apparatus insulation, blocking FCP operation from the voltage disturbance as it alarms for apparatus problems needing repair. These arcing signatures had been hidden from SCADA and relay measurements and bring additional value to the FCP scheme.

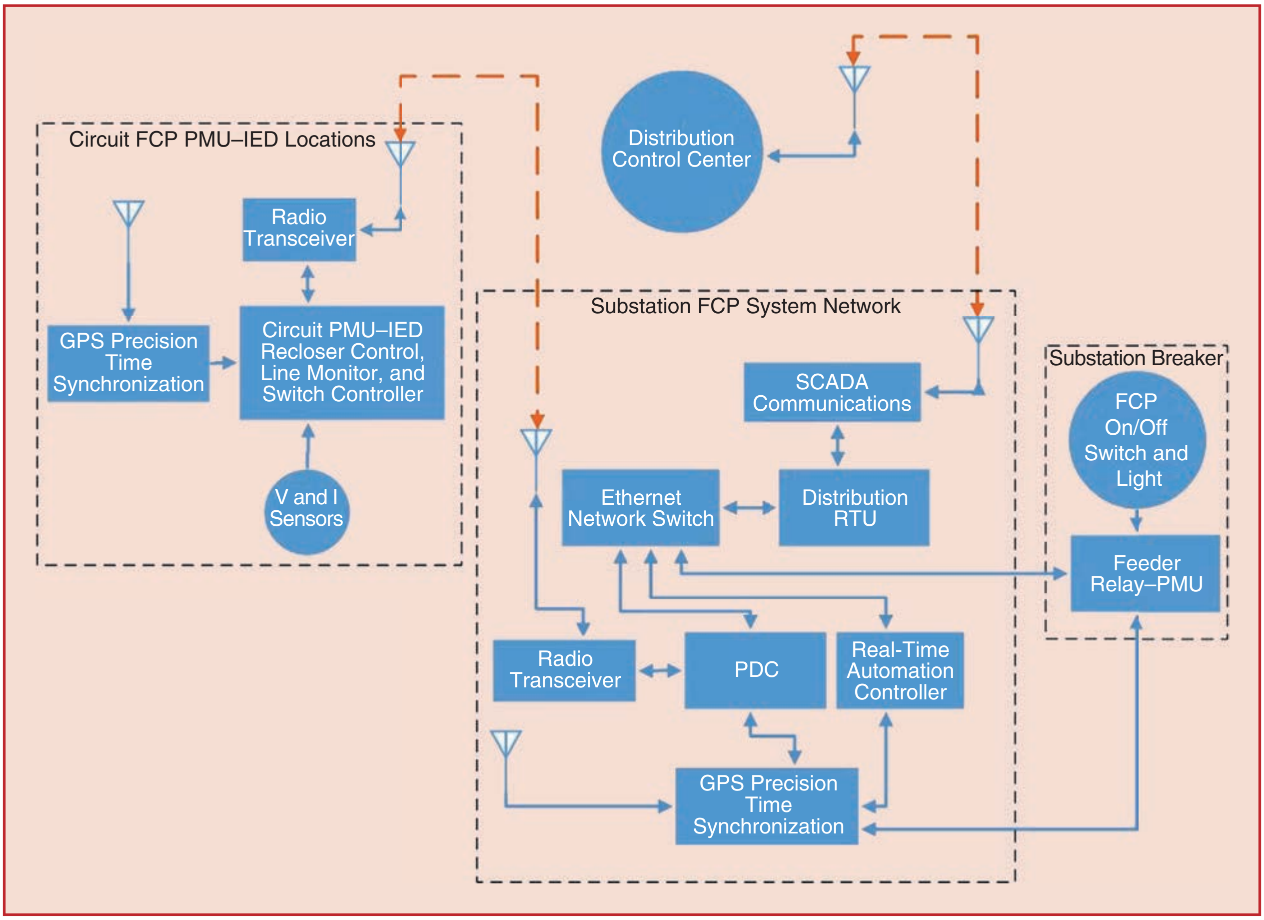


**figure 7.** The FCP system configuration.

### *Experience and Deployment Plans*

Experience gained from FCP deployment to date has shown how well-coordinated design, engineering, construction, and resource commissioning can achieve an efficient rollout across a service territory. FCP is currently operating on seven distribution circuits, with dozens more in development. Ultimately, SDG&E is planning FCP deployment on more than 150 distribution circuits. Thousands of PMU-enabled IEDs will be placed in service to gather measurements from across those circuits.

FCP applies to all circuits within tiers 2 and 3 of California utilities' high-fire-threat districts. Each installation is engineered for maximum circuit coverage, wildfire ignition risk reduction for the community, and circuit device installation service accessibility. Locations for circuit reclosers, which are the boundaries of the protective zone sections, are based on practical segmentation that minimizes the number of customers out of service after a falling conductor event. Line voltage monitors with PMU streaming are deployed to cover the ends and midpoints of lines and at fused circuit borders since fuses create the appearance of a broken wire when they operate.

High-speed radio networks are provisioned for streaming to substation FCP radio nodes and equipment racks. The selection and placement of reclosers, line monitors, and radio repeater poles must ensure that devices are accessible to trucks and crews, avoiding colocation on a pole with a service transformer. Equipment locations must not require helicopter access and must comply with environmentally sensitive area requirements. Due to the age of many distribution poles, replacement is typical for every installation location where an FCP device is added, and loading studies are thus avoided.

### Other Drivers for FCP System Deployment

SDG&E has seen a massive penetration of customer photovoltaic and distributed energy resources (DERs) into its transmission and distribution systems for more than a decade, fundamentally altering the power flows and electrical behavior of the grid as well as the business of coordinating energy supplies across the region. The company began researching the deployment of PMU measurements and data gathering to serve a long list of new applications and use cases for the operation of the emerging grid. As we stated, this work was underway in 2012, when project team members conceived, patented, and developed FCP to address fire risk issues and experiences.

Although FCP has drawn attention as wildfires become a chronic threat, drivers for other applications of PMU data collection are also growing to critical importance. The movement toward high DER penetrations and carbon-free energy resources brings new visibility and operating requirements for the distribution grid and adds huge value to the synchronized data gathering system that serves FCP. Among the new use cases for the FCP gathering and processing infrastructure are the following:

- ✔ high-accuracy fault detection and location
- ✔ wide-area visualization and advanced monitoring of the distribution grid
- ✔ real-time distribution system operation beyond today's SCADA capabilities

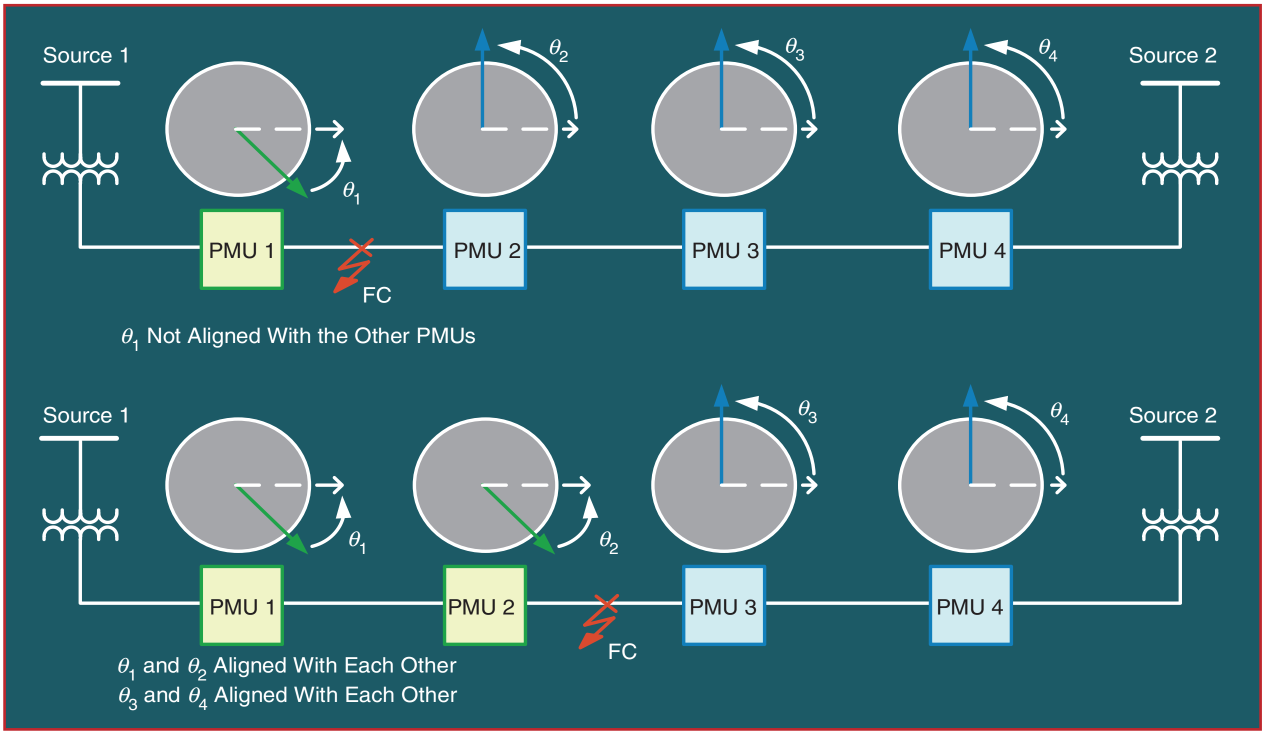


**figure 8.** A conductor break located using relationships of voltage phase angles along a circuit.

Quickly and accurately locating faults is key for long transmission lines traversing difficult-to-patrol terrain, and this becomes critical during fire season.

- ✔ advanced distribution system planning
- ✔ DER integration and operation
- ✔ distribution load, DER production, and electric vehicle demand forecasting
- ✔ monitoring and control of electric transportation infrastructure
- ✔ power apparatus monitoring and diagnosis
- ✔ asset management of critical infrastructure
- ✔ advanced microgrid applications and operation.

PMU data streams that are already being collected from the first FCP installations assist with the development of these use cases.

## Other Initiatives for Fast Fault Clearing and Fire Risk Reduction

### *Transmission Line Fault Protection and Teleprotection*

Quickly and accurately locating faults is key for long transmission lines traversing difficult-to-patrol terrain, and this becomes critical during fire season. Traditional methods of fault location based on impedance calculations introduce multiple sources of error when determining locations. SDG&E is deploying the latest generation of relays with traveling wave fault location on 500-, 230-, and 69-kV transmission lines. With traveling wave fault location, a simple calculation is based on a ratio of the times it takes for high-frequency traveling waves to propagate from a fault to the terminals of a line. Using this method, the location can potentially be determined within one tower span and reported to operations from the relay the instant the fault occurs.

SDG&E is also using an overlayed geographic information system (GIS) map to help field crews pinpoint a location reported by a relay. An additional benefit is traveling wave line monitoring—the ability to detect temporary disturbances from equipment, such as specific insulators that could cause permanent faults in the future. This functionality is being configured to notify field crews to inspect line sections where traveling waves indicate a potential precursor to failure. This technology could further reduce the risk of fire ignition from a transmission line.

### *PMU-Based, Wide-Area Situational Awareness and Transmission Visualization System*

SDG&E is among the utilities deploying wide-area situational awareness (WASA) systems in which PMUs distributed across the grid stream data to system operators at control centers to monitor network behavior. WASA deployment has evolved from a grid observation system built on PMU deployment during the past decade, now extending to most transmission lines and other system elements. It presently covers all 230- and 500-kV buses and transmission lines and is spreading to the 138- and 69-kV systems. The PMUs stream data at 30 or 60 frames/s providing exact time and angle relationships of measurements from across the grid. This is vastly superior to today's SCADA and energy management system (EMS) databases that depend on legacy SCADA remote terminal units transmitting unsynchronized values every 4–5 s. PMUs gather phase and sequence values of voltages and currents, power flows, frequency, and rate of change of frequency. Binary and analog point values are also being included in the PMU data streams to provide breaker statuses, fault distances, and fault type indications.

Today's system serves as a tool for engineers and operators to observe system behavior and perform postmortem analysis of disturbances and events. It has been installed in the transmission system operator console as a nonoperational tool for the past decade. This enables operators to become familiar with the technology, understand system events and data in real time, and review events and information that are not observable via the EMS. Streamed grid measurements and system status displays are available, as Figure 9 shows. A new WASA architecture with advanced cybersecurity and regulatory security compliance is being deployed for real-time operations to complement the EMS. This will enable transmission system operators to make real-time operating decisions based on information from the WASA system and EMS.

Several wildfire management applications are being developed for the WASA system, including a multilayered GIS map-based visualization software system that will show accurate fault locations plus point-on-wave event and weather (wind, fire, and lightning) data, helping the company quickly dispatch personnel, conduct event analyses and restoration, and manage PSPS events.

### *Transmission FCP Systems*

We have explained how SDG&E pioneered the development of a distribution FCP system to collect streaming synchrophasor measurements from distribution circuits and rapidly trip a circuit section with a broken conductor so that the device lands dead. FCP is now the subject of a widespread installation program. In 2019–2020, SDG&E built on this experience to develop transmission FCP (TFCP) systems. One scheme is based on real-time processing of the PMU data streams already being collected from ubiquitous transmission substation PMUs serving the WASA system. Figure 10 displays a typical TFCP system configuration for a two-terminal transmission line. TFCP schemes are being deployed for trial on 69-kV transmission circuits in 2022.

Figure 2 included a timeline for a falling distribution conductor from 30 ft (9 m). A broken overhead transmission conductor 60 ft (18 m) in the air takes even longer—almost 2 s—to reach the ground. With PMU measurements and detection algorithms, substation controllers and relays can trip line terminal breakers and clear a line by the time a failed conductor has fallen only a few feet. It lands on the ground or underbuilt infrastructure, de-energized, and the fire ignition risk is avoided.

The TFCP measurement system and algorithms are fundamentally different from those developed for distribution protection and depend more heavily on line current measurements. One TFCP method uses synchronized current comparisons from the line terminal PMU data streams to

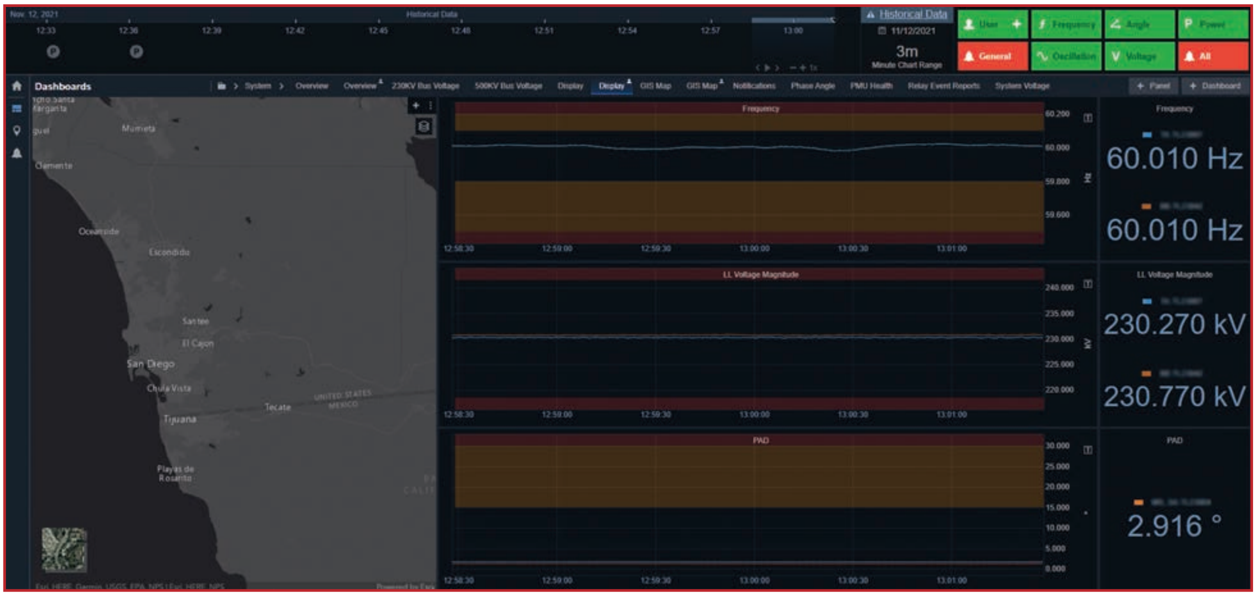


**figure 9.** A typical WASA display for a system operator.

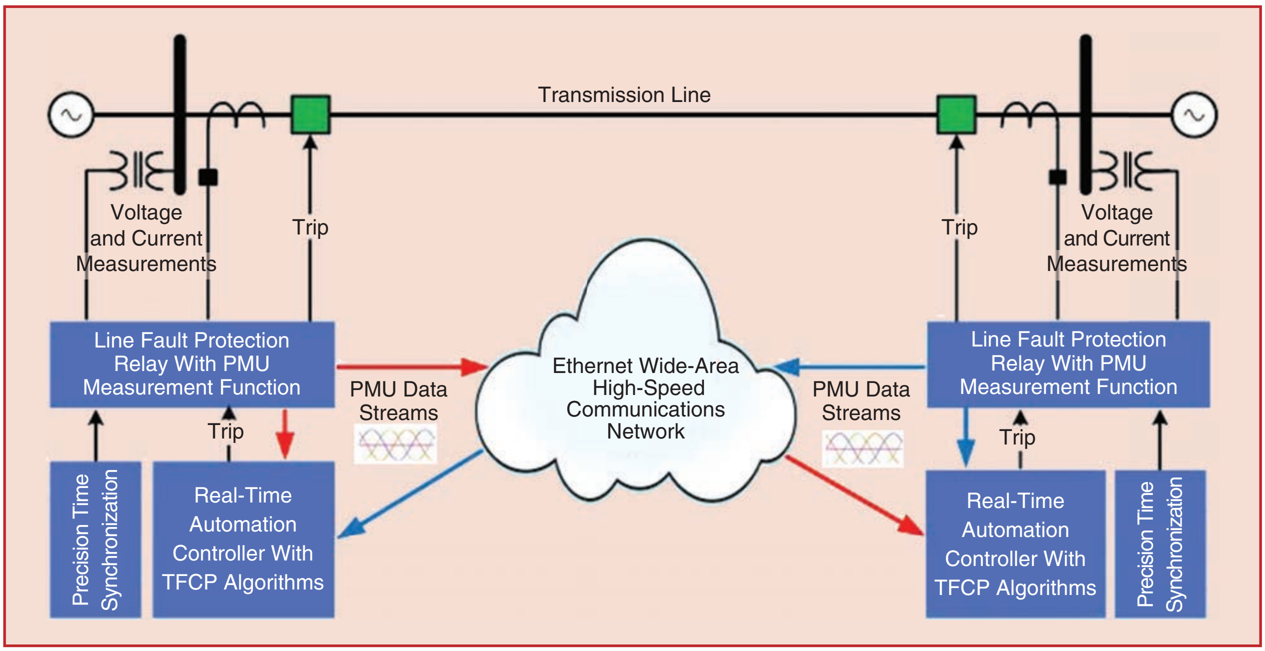


**figure 10.** The components of a TFCP system.

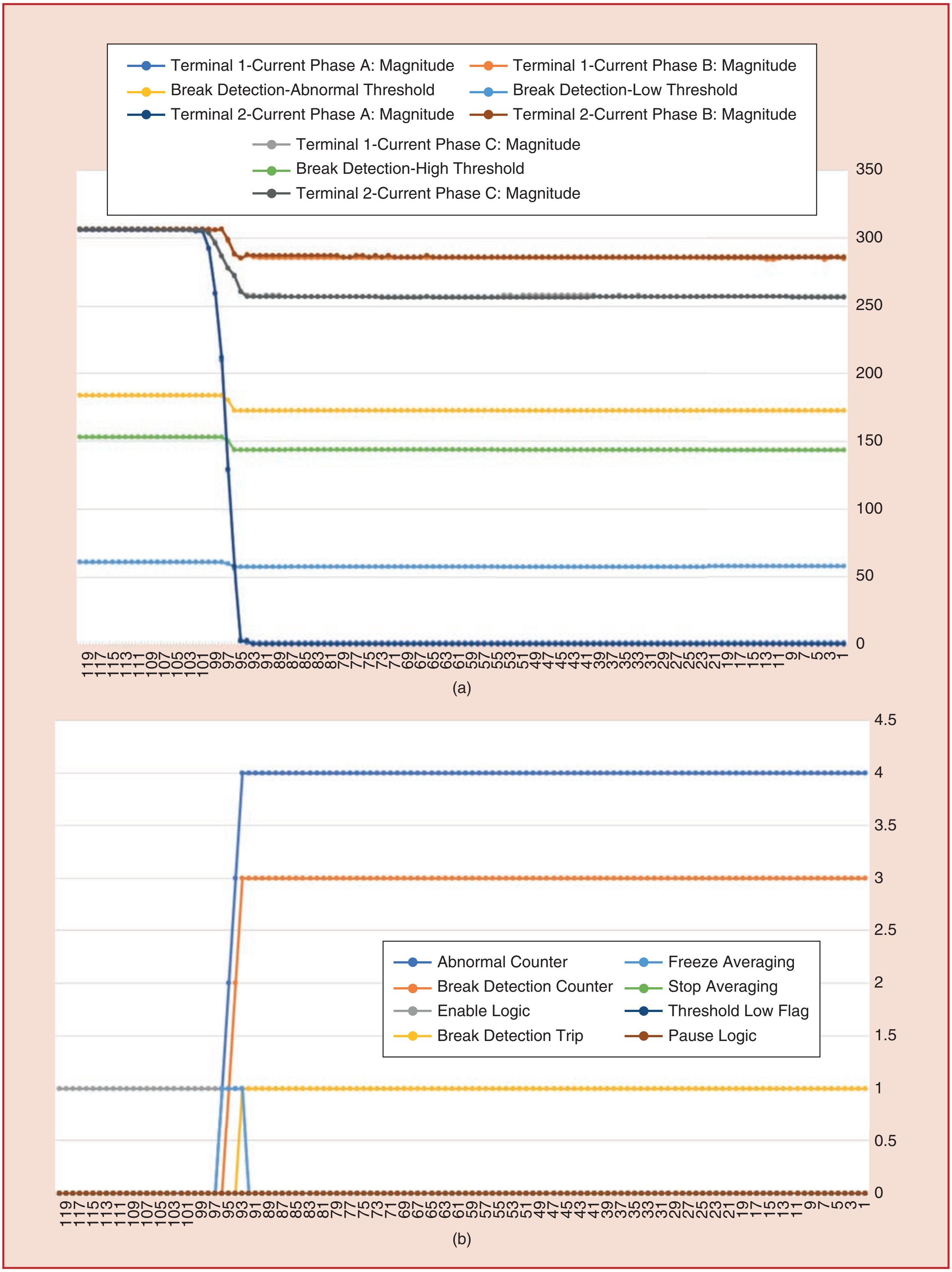


**figure 11.** (a): Break detection in phase A: phase currents and thresholds. (b) Break detection in phase A: counters and flags.

observe pre-event load flows and rapidly detect conductor breaks, even on multiterminal lines. Charging currents into broken conductor sections from each end helps to locate a break for rapid field crew deployment. Along with the FCP algorithms, the TFCP scheme includes high-sensitivity ground fault detection to trip within a few power cycles for nonbreak fire risk events, such as tree branches falling on and blowing into lines from outside the vegetation management right-of-way.

The TFCP system can detect and de-energize a line in fewer than 400 ms for falling conductor events and arcing ground faults of thousands of ohms whether accompanied by a break or not. The design is based on automation controllers installed in substations adjacent to protective relays. PMU data streams from local relays and remote line terminals—the same data streams supplied to the WASA system at the control center—provide the controller with complete, real-time current and voltage measurements. Programmed algorithms detect evidence of a conductor break or low-current ground fault and issue trip commands through local relay outputs to line circuit breakers. Some relays are also programmed with an internal logic that can detect conductor breaks in parallel with the scheme based on PMUs and automation controllers.

TFCP equipment and programming have been extensively tested on a model of a section of the SDG&E 69-kV transmission system, programmed on real-time digital simulator arrays in the company's integrated technology facility and at developer sites. In laboratory hardware-in-the-loop tests, the TFCP solution has demonstrated its tripping speed, dependability, and avoidance of undesired behavior for a host of break simulations, faults, and operating events on protected line and adjacent power system elements. TFCP controllers capture records of PMU data surrounding an apparent break or ground fault for postmortem plotting of algorithm performance and event replay using PC tools.

Figure 11(a) and (b) presents example plots of TFCP operation for a simulated break of a 69-kV line carrying a load. Every time increment (trace dot) is a synchronized measurement frame time of 16.7 ms (60 PMU data frames/s). The real-time digital simulator model of the break event includes a simulation of the series arc that may occur as broken load-carrying conductor ends separate. Automation controller logic checks for normal line operation before the event as well as a variety of conditions to distinguish a conductor break from other problems. Break detection is confirmed within two to three data frames or fewer than 50 ms. Separate current differential algorithms detect ground faults, even with thousands of ohms of resistance, and issue trip commands within a similar time frame.

## Summary

SDG&E is among electric utilities in the western United States and other regions around the world facing an alarming increase in wildfire risks due to changing weather patterns and drought. Fires can be triggered by faults, failures, and dry vegetation contacting operating power apparatus. SDG&E has confronted this risk for more than a decade with a combination of operating and situational awareness innovations, organizational preparedness, hardening of system infrastructure, and sustained technical innovation.

On the innovation front, the company's initiatives include the following:

- ✔ advanced weather data gathering and processing
- ✔ operational monitoring, event preparedness, sectionalizing ability, and safety shutdowns
- ✔ big data processing platforms and tools for fire risk-related analysis
- ✔ grid hardening programs based on asset data analysis
- ✔ advanced circuit apparatus to reduce fire risk
- ✔ new circuit monitoring equipment
- ✔ new fault protection methods and schemes
- ✔ WASA development, including a system for the transmission grid
- ✔ new fault protection strategies that improve the sensitivity and speed of existing relays to reduce the arcing ignition risk from failures and faults
- ✔ pioneering transmission and distribution circuit FCP schemes that can anticipate, minimize, and avoid arcing ground faults from conductor and hardware failures.

Distribution FCP is being aggressively deployed across the system, with priority for service areas with elevated fire risks. TFCP has been proved in the laboratory and is being installed for testing on the 69-kV transmission system at the time of writing. With PMUs already installed across the transmission system for WASA, TFCP can be expanded for the protection of the transmission grid in high-fire-risk areas.

## For Further Reading

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