
Traveling Wave Fault Location in Power Transmission Systems

Application Note 1285



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Introduction

Accurate location of faults on power transmission systems can save time and resources for the electric utility industry. Line searches for faults are costly and can be inconclusive. Accurate information needs to be acquired quickly in a form most useful to the power system operator communicating to field personnel.

To achieve this accuracy, a complete system of fault location technology, hardware, communications, and software systems can be designed. Technology is available which can help determine fault location to within a transmission span of 300 meters. Reliable self-monitoring hardware can be configured for installation sites with varying geographic and environmental conditions. Communications systems can retrieve fault location information from substations and quickly provide that information to system operators. Other communications systems, such as Supervisory Control and Data Acquisition (SCADA), operate fault sectionalizing circuit breakers and switches remotely and provide a means of fast restoration. Data from SCADA, such as sequence of events, relays, and oscillographs, can be used for fault location selection and verification. Software in a central computer can collect fault information and reduce operator response time by providing only the concise information required for field personnel communications.

Fault location systems usually determine “distance to fault” from a transmission line end. Field personnel can use this data to find fault locations from transmission line maps and drawings. Some utilities have automated this process by placing the information in a fault location Geographical Information System (GIS) computer. Since adding transmission line data to the computer can be a large effort, some utilities have further shortened the process by utilizing a transmission structures location database. Several utilities have recently created these databases for transmission inventory using GPS location technology and handheld computers.

The inventory database probably contains more information than needed for a fault location system, and a reduced version would save the large data-collection effort. Using this data, the power system operator could provide field personnel direct location information. Field personnel could use online information to help them avoid spending valuable time looking for maps and drawings and possibly even reduce their travel time. With precise information available, crews can prepare for the geography, climatic conditions, and means of transport to the faulted location. Repair time and resources would be optimized by the collected data before departure.

Accurate fault location can also aid in fast restoration of power, particularly on transmission lines with distributed loads. Power system operators can identify and isolate faulted sections on tap-loaded lines and remove them by opening circuit breakers or switches remotely along the line, restoring power to the tap loads serviced by the unfaulted transmission sections.

Accurate and timely fault locating and reporting on important bulk transmission lines can be expensive. Because of their length and size, search efforts take longer to complete. Power generation and load are separated by larger distances and load becomes less economic to serve. The remaining power system may be operating inefficiently from a system security standpoint in order to meet power delivery requirements.

What is Traveling Wave Fault Location?

Faults on the power transmission system cause transients that propagate along the transmission line as waves. Each wave is a composite of frequencies, ranging from a few kilohertz to several megahertz, having a fast rising front and a slower decaying tail. Composite waves have a propagation velocity and characteristic impedance and travel near the speed of light away from the fault location toward line ends. They continue to travel throughout the power system until they diminish due to impedance and reflection waves and a new power system equilibrium is reached.

The location of faults is accomplished by precisely time-tagging wave fronts as they cross a known point typically in substations at line ends. With waves time tagged to submicrosecond resolution of 30 ns, fault location accuracy of 300 m can be obtained. Fault location can then be obtained by multiplying the wave velocity by the time difference in line ends. This collection and calculation of time data is usually done at a master station. Master station information polling time should be fast enough for system operator needs.

Benefits of Traveling Wave Fault Location

Early fault locators used pulsed radar. This technique uses reflected radar energy to determine the fault location. Radar equipment is typically mobile or located at substations and requires manual operation. This technique is popular for location of permanent faults on cable sections when the cable is de-energized.

Impedance-based fault locators are a popular means of transmission line fault locating. They provide algorithm advances that correct for fault resistance and load current inaccuracies. Line length accuracies of $\pm 5\%$ are typical for single-ended locators and 1-2% for two-ended locator systems.

ends. Transmission line ends represent a discontinuity or impedance change where some of the wave's energy will reflect back to the disturbance. The remaining energy will travel to other power system elements or transmission lines. Figure 2, a Bewley lattice diagram, illustrates the multiple waves (represented by subscripts 2 and 3) generated at line ends. Wave amplitudes are represented by reflection coefficients k_a and k_b which are determined by characteristic impedance ratios at the discontinuities. τ_a and τ_b represent the travel time from the fault to the discontinuity.

With GPS technology, τ_a and τ_b can be determined very precisely. By knowing the length (l) of the line and the time of arrival difference ($\tau_a - \tau_b$), one can calculate the distance (x) to the fault from substation A by:

$$x = \frac{l - c(\tau_a - \tau_b)}{2}$$

where c = the wave propagation of $299.79 \mu\text{m}/\mu\text{sec}$ ($\cong 1\text{ft}/\text{ns}$).

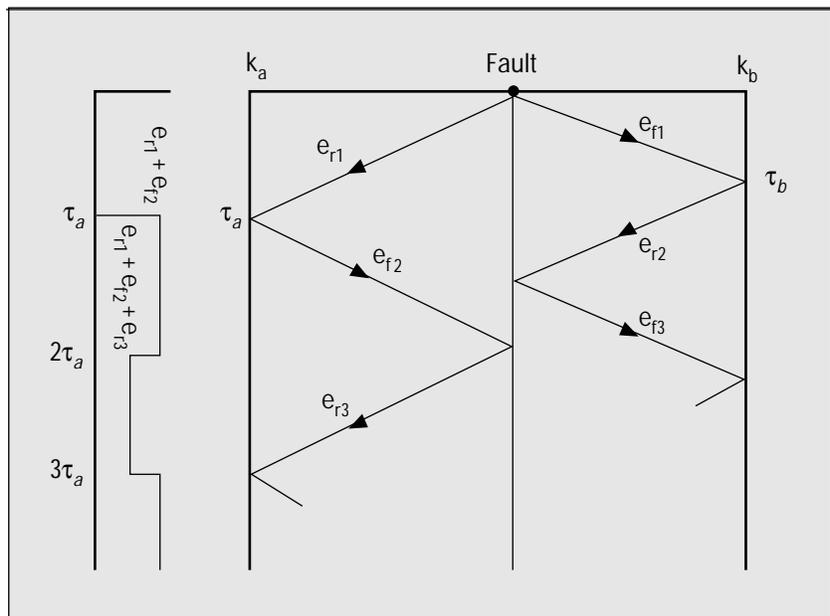


Figure 2. Bewley Lattice Diagram

Traveling Wave Detection System

The traveling wave detection system consists of capacitive coupling voltage transformer (CCVT) with drain coil, fault transient interface unit (FTIU), GPS receiver with event storage, communication system, and master station with software. The CCVT, FTIU, and GPS receiver are located at transmission line ends in substations. The master station is typically located at a dispatch or operations center near other fault recorder masters and supervisory control.

The CCVT provides a coupling for the transient traveling wave from high voltage to the electronic equipment voltage, and it filters out the power frequency by means of a drain coil. Three CCVTs, one from each phase, are connected via carrier lead-in cable to the FTIU located in the substation control house.

Upon receipt of sufficient transient magnitude, the FTIU's front end filters 35 to 350 kHz transients and triggers TTL logic. The FTIU is then locked out for 780 milliseconds to prevent multiple triggers due to succeeding waves.

The FTIU output is sent to the HP GPS receiver which time-tags the front of the wave to 0.1 microsecond resolution. It stores the event until polled by the communications system which is constantly communicating with the traveling wave equipment sites, fault or no fault. Event data can be transported to the master station in seconds, depending upon communication system configuration, communication channel speed, and scan rates.

The master station receives data from the faulted line as well as other lines in the area. The faulted line generally will have the earliest time tags. Other information systems, such as relays and fault recorders, will confirm the fault. Once the faulted line is identified, the fault location calculation occurs. The use of conductor length instead of line length during the calculation can improve the accuracy. Further conductor length accuracy can be obtained by considering conductor sag due to loading and temperature and wind conditions at the time of the fault.

With sufficient detail line information, the system operator will be able to locate the transmission tower or towers to investigate and their location and number can be given to the field crews. The system operator may also be able to isolate the fault via supervisory-controlled switches or circuit breakers to quickly restore service to customers.

Timing Requirements

Utility time information is ultimately received from radio or satellite timing sources. Those are the high frequency radio WWV broadcast, low frequency radio WWVB broadcast, and GOES (Geostationary Operational Environmental Satellite) and GPS (Global Positioning System) satellites. Both signal availability and timing accuracy have improved through this evolution. Substation masters then distribute this time to substation equipment by a one-pulse-per-second signal (1 PPS), IRIG (Inter Range Instrumentation Group) serial time code signal, or a private communications system. Radio reception produces accuracy of one millisecond at best, and it is not available at all locations. GOES satellite reception is widely available in the western hemisphere and produces one millisecond accuracy; however, GPS is available worldwide and is specified at microsecond accuracy.

GPS (Global Positioning System)

The NAVSTAR Global Positioning System (GPS) is currently deployed by the U.S. Department of Defense as a navigation system. The GPS system is the most accurate radio navigation system and precise time and time interval (time and frequency) ever deployed. The 24 satellite constellation enables worldwide users to determine the correct time with a higher degree of accuracy than ever before available.

Each of the 24 satellites carries an ensemble of onboard atomic clocks which are tracked and maintained traceable to Universal Time Coordinated/U.S. Naval Observatory (UTC/USNO) to better than 100 nanoseconds. The completed system contains six orbits with four satellites, each at a height of ~10,900 miles, thus ensuring that any unobstructed spot on the earth will be able to “see” a minimum of four satellites at any moment. Once exact position of the receiving antenna is known, only one satellite is required to determine and maintain timing accuracy to the system’s accuracy limits.

HP 59551A GPS Measurements Synchronization Module

The HP 59551A GPS Measurements Synchronization Module is an excellent timing source for the utility substation and power plant. Its $<1\mu\text{s}$ precision exceeds current requirements and make it well-suited for future timing requirements for wide area synchronous measurements, adaptive protection, and real time control.

The HP 59551A provides a low-cost, stable, worldwide timing source using the HP10811D Quartz Oscillator. It is a highly reliable crystal component which experiences low sensitivity to temperature variation and has low phase noise and well understood aging characteristics.

Integrated with HP SmartClock algorithm, the HP 59551A “learns” the quartz oscillator’s aging behavior and environmental conditions over time and adjusts the oscillator’s output frequency accordingly to improve accuracy. When locked to GPS, the HP 59551A is good for 110 nanoseconds.

A holdover mode ensures accurate synchronization in the unlikely event of satellite signal loss or interruption. HP SmartClock will continue to maintain time and frequency with less than an 8.6-microsecond loss in accuracy for up to 24 hours of GPS signal loss. See Figure 3. The light line shows the oscillator steering commands over time. During the 3-day time period, it learns while locked to GPS signal. The heavy line starting on day 4 shows *predicted* performance if the GPS signal has been lost. The *actual* performance is shown by the light lines after Day 3. The difference between actual and predicted is shown in the table in Figure 3. The dominant correction factor was due to external temperature changes. If the GPS signal had actually been lost, HP SmartClock would have steered the oscillator into holdover mode, making determined corrections.



The low cost of the HP 59551A makes monitoring wide-area transmission systems affordable.

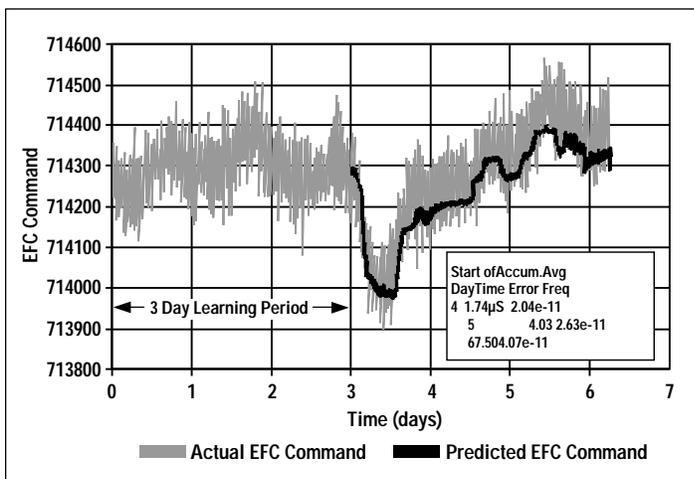


Figure 3. HP SmartClock holdover.

Integrating HP 59551A into Power System Environment

The HP 59551A system can be configured to meet customer requirements. It includes a rack-mountable surge-tested receiver that is ac/dc volt powered. The HP 59551A Measurements Synchronization Module is designed to operate in 0 to 50°C. The HP 58504A Antenna is designed to operate in -30 to +80°C. The HP 59551A module meets surge-withstand tests ANSI C37.90 and C37.90.1. The HP 58504A active antenna is designed to operate with up to 53 meters of RG-213 cable without line amplification. The cable is terminated in type N and TNC connectors at each cable end. If required by customer installation, longer cable lengths can be provided using lower loss cable and antenna line amplifiers for up to 425 meters. A lightning arrester assembly is also available to protect the HP 59551A (not the antenna). See an HP representative for a copy of HP 59551A Price List, which includes additional options and ordering information.

The HP 59551A system provides One Pulse Per Second (1 PPS) output for existing system compatibility. An IRIG-B123 output port with BNC connector is also provided. An additional alarm BITE output is provided for indication of loss of satellite lock or system fault. A normally open solid state relay is used with a 200 volt, 0.5 amp rating using a twin BNC connector.

Hewlett-Packard can also supply a fiber optic distribution system (HP 59552A Fiber Optic Distribution Amplifier and HP 59553A Fiber Optic Receiver) that transmits signals and timecodes through noise-immune filters for maximum noise immunity.

The HP 59551A can be monitored locally from the front panel LED indicators: Power, GPS Lock, Holdover, and Alarm. It can also be monitored through a supplied HP SatStat (HP Part Number 59551-13401) program. This Microsoft Windows® 3.1 computer program continually polls the HP 59551A via an RS-232 serial interface to obtain receiver information: tracked satellites elevation and azimuth, HP SmartClock state (such as locked and holdover), antenna coordinates, time and frequency figures of merit, and other data. A real-time clock window is also provided. HP SatStat allows the user to change receiver parameters like antenna delay without developing software. With HP SatStat remotely installed, the HP 59551A can be remotely accessed via a modem from the serial port to provide quick troubleshooting capability to an alarm.

The HP 59551A can also serve the function of a sequence-of-events recorder by recording up to 256 events to 100 nanosecond resolution. Events can be downloaded locally or remotely via a modem, remote terminal unit, or a SCADA system. Other than communications software no additional software is required.

For more detail information contact your local HP representative and ask for HP Specification GPS Synchronization for Power Transmission Systems.

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