Accurate Transmission Line Fault Location Using Synchronized Sampling

Application Note 1276-1

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Introduction

A continuous and reliable electrical energy supply is the objective of any power system operation. Nevertheless, faults do inevitably occur in power systems. A transmission line is the part of the power system where faults are most likely to happen.

Transmission line faults must be located accurately to allow maintenance crews to arrive at the scene and repair the faulted section as soon as possible. Rugged terrain and geographical layout make some sections of power transmission lines difficult to reach; therefore, the robustness of fault location determination under a variety of power system operating constraints and fault conditions is an important requirement.

In order for a fault location algorithm to be robust, it has to demonstrate high accuracy under a variety of operating and fault conditions such as:

- Long and short transmission lines
- Parallel lines
- Multi-terminal lines
- Transposed and untransposed lines
- High and low loading faults fed from both ends
- Faults with time-varying fault resistance
- Faults of any fault type and incidence (voltage angle)

An algorithm that can accurately locate a transmission line fault under these constraints may have multiple uses, but it may also require a particular implementation approach.

Uses of the Fault Location Algorithm

Besides being used to accurately locate a fault, such an algorithm can be used for automated fault analysis. Any occurrence of a fault should be detected and cleared by the protective relaying devices. An analysis of the protective relaying operation is required if an assessment of its performance is needed. In order to perform the analysis, one has to have a reference algorithm with which to compare the relay operation. The fault location algorithm that can provide both fault classification and location is an ideal reference for the correct protective relaying operation. The algorithm can be incorporated into an automated fault analysis by providing high speed indication of the fault type and fault location. This is sufficient information for determining if a protective relay has operated correctly since the relay is also supposed to determine fault type and location.

Location determined by the relay does not have to be too accurate since it only has to determine the zone of the fault occurrence. Exact location of the fault provided by the fault location algorithm is more accurate and is needed as a comparison reference point.

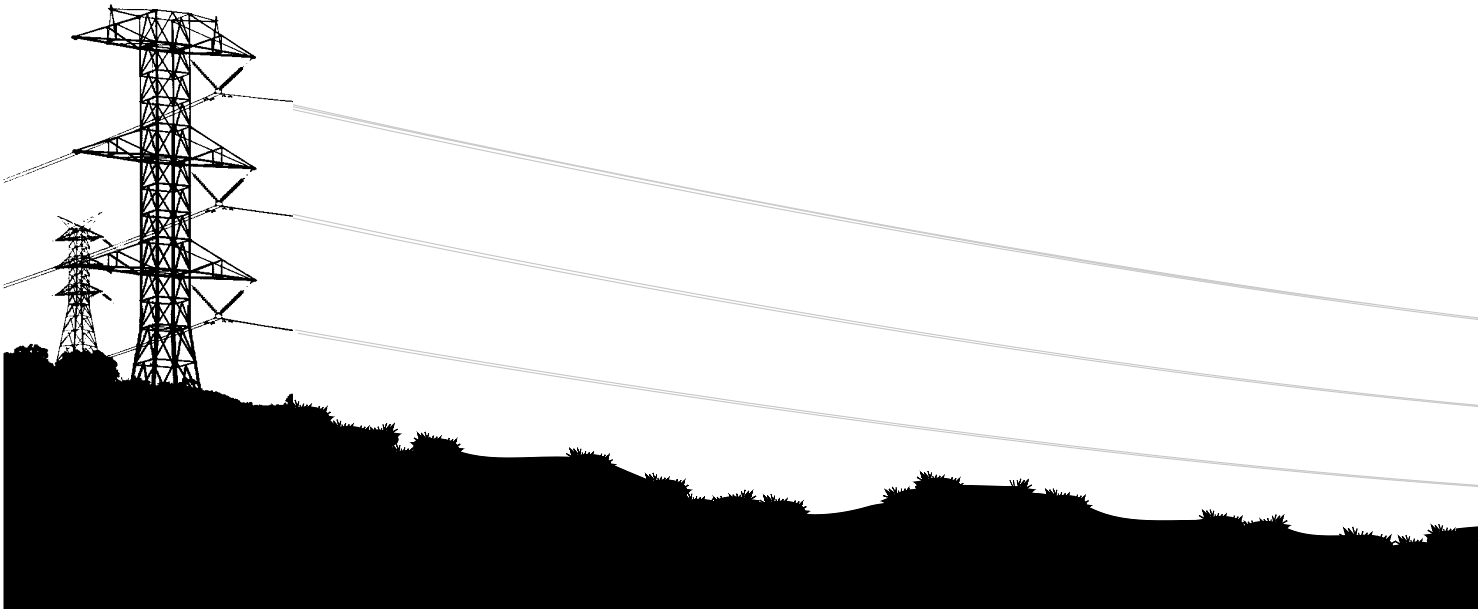
Implementation Requirements

Accuracy improvement can be achieved if the accuracy of data acquisition and related signal processing is improved. In the fault location case, this translates into the use of synchronized sampling at both ends of a transmission line. Synchronized sampling is an advanced data acquisition and processing technique made possible by advancements in precise time receivers. In particular, Global Positioning System (GPS) satellites have recently provided a source of precise time. The GPS receiver developed by Hewlett-Packard is a high-precision instrument capable of providing a sampling pulse with extreme accuracy. Information on the instrument is given on page 14.

Use of such a high-performance instrument has enabled implementation of an accurate synchronized sampling method. This in turn has facilitated the development of a high accuracy fault location algorithm that demonstrates major performance enhancements when compared to the other existing solutions.

Existing Fault Location Requirements

In the past, various fault location algorithms were introduced as either add-on features in protective relays or standalone implementations in fault locators. In both cases, the measurements of current and voltages were taken at one terminal of a transmission line only. Under such conditions it is difficult to determine the fault location accurately, since data from other transmission line ends are required for more precise computations. In the absence of that data, existing algorithms have accuracy problems under several circumstances, such as varying switching and loading conditions, fault infeed from the other end, and random value of fault resistance. In addition, most one-end algorithms were based on estimation of voltage and current phasors. The need to estimate phasors introduces additional difficulty in high-speed tripping situations where the algorithms may not be able to determine fault location accurately before the current signals disappear because of the relay operation and breaker opening.



In a review of existing fault location techniques, several implementation characteristics and approaches can be identified.

Data Acquisition Placement Choices

Data for the fault location function may be acquired either locally, and/or at remote sites. The obvious choices for placement of data acquisition equipment are:

- One transmission line end
- Both transmission line ends
- All transmission line ends (in the case of a multi-terminal line)
- All ends of the adjacent parallel lines (in addition to the data from the line of interest)

All cases, except the first one, require collecting and using data from different locations that may be dispersed over a large area. Synchronized sampling makes it possible to collect data with a very precise time reference.

Implementation Equipment Selection

Fault locating algorithms may be implemented in a variety of equipment such as:

- Standalone fault locators
- Protective relays
- Digital fault recorders (DFRs)
- Remote terminal units (RTUs) of a Supervisory Control and Data Acquisition (SCADA) system

In all of these approaches, except the first one, the equipment design already exists. Any new fault location algorithm that requires synchronized sampling can be implemented on an existing device if at least an external connection to a synchronization instrument is made available. In some instances, it may even be advantageous to have the synchronization signal receiver as a part of the equipment design.

Data Sampling Frequency Range

Fault location has been implemented using different data sampling frequencies. At least three ranges of sampling frequencies for data acquisition equipment can be recognized today:

- Below 1 kHz for protective relaying and RTU applications
- Between 1 kHz and 5 kHz for most DFR applications
- Over 5 kHz for high performance recording devices

Existing fault location algorithms are primarily based on phasor measurements; therefore, most of the existing implementations are based on the sampling rates below 1 kHz. The new algorithm that uses synchronized sampling may benefit from using the sampling frequencies over 5 kHz. A high performance DFR may be the most suitable environment for the algorithm's implementation.

Techniques for Synchronization

A variety of synchronization techniques for data acquisition have been used in the past including:

- Zero crossing determination
- Rotation of samples (for phasors)
- Accurate time reference (IRIG-B and GPS)

All of these techniques have been demonstrated in the field. The GPS approach provides the most accurate time reference source for synchronization. Availability of high-performance GPS receivers for accurate time reference makes the implementation of synchronized sampling much easier.

Signal Processing Approaches

Signal processing approaches have been selected based on signal components used for the algorithms. The following are the most common choices:

- Fundamental frequency (phasors)
- Transient waveforms (direct use)
- Traveling waves (reflection times)

The most commonly used approach in the past is the phasor-based approach. Increased accuracy has been achieved using the other approaches. In particular, direct use of synchronously sampled transient data has shown some definite performance improvements.

Performance Limitations

Most existing algorithms have some inherent performance limitations for a variety of reasons.

The new fault location algorithm discussed in this application note provides major improvements over existing algorithms as follows:

- It offers increased accuracy under a variety of operating and fault conditions
- It is very robust, since it is virtually transparent to any changing power conditions on the power system surrounding the transmission line of interest
- It is not affected by fault resistance and can even provide accurate fault location determination for a time-varying fault impedance
- It can easily be applied to three-terminal lines, as well as parallel lines with strong mutual coupling.

The algorithm uses a very short data window and enables fast fault detection and classification. This makes the algorithm a good candidate for future applications in protective relaying as well.

Fault Location Based On Synchronized Sampling

Implementation

To simplify introduction of the new concept, a two-terminal transmission line is considered using a lumped parameter model where line conductance and capacitance are neglected. The one line representation of the three-phase system is used. The fault location set-up is shown in Figure 1, where "*S*" and "*T*" are the sending and receiving ends, CT is the current transformer, CCVT is the capacitor coupling voltage transformer, CB is the circuit breaker, DFR is the digital fault recorder, F is the location of the fault, ∂ is the transmission line length and x is the distance to the fault. The proposed implementation is centered around the use of DFRs, but other substation equipment may be used as well as long as it can be interfaced to the GPS receiver.

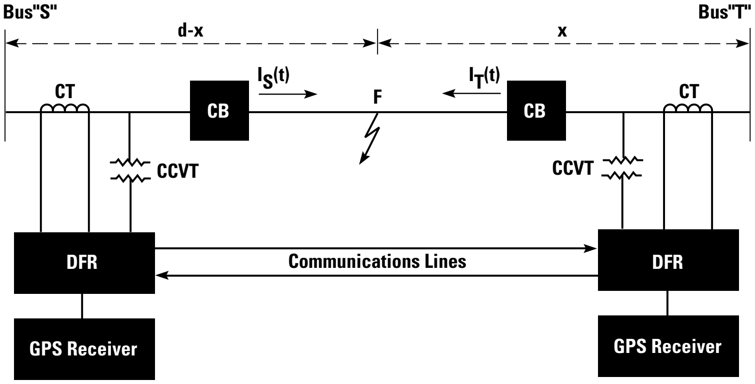


Figure 1. Fault Location System

For the transmission line given in Figure 1, the following two vectors can be defined, where $V_S(t)$ and $V_T(t)$ are the vectors of phase voltage samples; $I_S(t)$, $I_T(t)$, and $I_F(t)$ are the vectors of phase current samples; "*S*" and "*T*" are the transmission line ends; and R and L are the matrices of self and mutual line parameters:

$$\Delta I(t) = I_S(t) + I_T(t) \tag{1}$$

$$\Delta V(t) = V_S(t) - V_T(t) + d\left[RI_T(t) + L\frac{\partial I_R(t)}{\partial t}\right] \tag{2}$$

In normal operating conditions, the fault current $I_F(t)$ is zero. As a consequence of Kirchoff's current and voltage laws, the above vectors are equal to zero.

$$\Delta I(t) = 0 \tag{3}$$

$$\Delta V(t) = 0 \tag{4}$$

If the line is faulted, the values of these vectors are:

$$\Delta I(t) = I_F(t) \tag{5}$$

$$\Delta V(t) = x\left[RI_F(t) + L\frac{\partial I_F(t)}{\partial t}\right] \tag{6}$$

where $I_F(t)$ is the phase vector of samples of fault current. The fault current does not have to be measured since it may be eliminated from equations (5) and (6) leading to:

$$\Delta V(t) - x\left[R\Delta I(t) + L\frac{\partial}{\partial t}\Delta I(t)\right] = 0 \tag{7}$$

Equation (7) can be used to find the fault location x.

The values of the vectors $\Delta V(t)$ and $\Delta I(t)$ [equations (1) and (2)] at times n/f_s, where f_s is the sampling frequency, can be calculated from current and voltage samples:

$$\Delta I_n = I_{Sn} + I_{Tn} \tag{8}$$

$$\Delta V_n = V_{Sn} - V_{Tn} + d\left[Ri_{Tn} + f_s L\left(I_{Tn} - I_{Tn-1}\right)\right] \tag{9}$$

VS_n, VR_n, IS_n and IR_n denote vectors of samples taken synchronously at moments n/f_s. It should be noted that the expression for ΔV_n is an approximate one, since the current derivative can not be measured. The derivative is approximated with "backward" approximation.

Application

Short-Line Application: The short transmission line model used is presented in Figure 2.

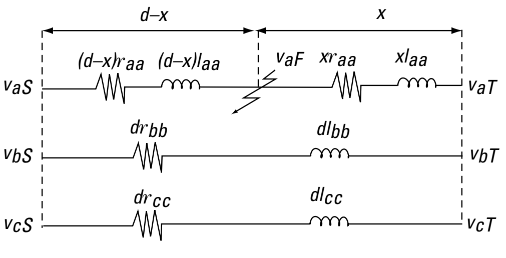


Figure 2. Faulted Short Three-Phase Transmission Line

- Self (phase) resistance: r_{aa}, r_{bb}, r_{cc}
- Mutual resistance: r_{ab}, r_{ac}, r_{bc}
- Self (phase) inductance: l_{aa}, l_{bb}, l_{cc}
- Mutual inductance: l_{ab}, l_{ac}, l_{bc}

No other assumptions about the transmission line are needed.

In the case of such a transmission line, the generic fault location equation becomes a system of three equations:

$$v_{mS}(t) - v_{mT}(t) - d \sum_{p=a,b,c} \left[\tau_{mp} i_{pS}(t) + 1_{mp} \frac{\partial i_{pS}(t)}{\partial t} \right] \tag{10}$$

$$+x \sum_{p=a,b,c} \left[\tau_{mp} i_{pT}(t) + \tau_{mp} i_{pS}(t) + l_{mp} \frac{\partial i_{pR}(t)}{\partial t} + l_{mp} \frac{\partial i_{pS}(t)}{\partial t} \right] = 0$$

$$m = a, b, c$$

Since the phase, voltage, and current at both ends of the line are available in the sampled form, the system of fault location equations (10) can be rewritten in the discrete form as:

$$\begin{aligned} A_m(k) + B_m(k)x &= 0 \\ m &= a,b,c \\ k &= 1,2,\dots,N \end{aligned} \tag{11}$$

where $A_m(k)$ and $B_m(k)$ for $m=a,b,c$, and $k=1, 2, \dots, N$ are defined as:

$$A_m(k) = v_{mS}(k) - v_{mT}(k) - d \sum_{p=a,b,c} \left[\left(\tau_{mp} + \frac{l_{mp}}{\Delta t} \right) i_{pS}(k) - \frac{l_{mp}}{\Delta t} i_{pS}(k-1) \right] \tag{12}$$

$$B_m(k) = \sum_{p=a,b,c} \left\{ \left(\tau_{mp} + \frac{l_{mp}}{\Delta t} \right) \left[i_{pT}(k) + i_{pS}(k) \right] - \frac{l_{mp}}{\Delta t} \left[i_{pT}(k-1) + i_{pS}(k-1) \right] \right\} \tag{13}$$

In equations (12) and (13), $v_{mS}(k)$ and $v_{mT}(k)$ are phase ($m=a, b, c$) voltage samples taken at the time instant $t=k\,\Delta t$ ($k=1,2, \dots, N$), at the line ends "*S*" and "*T*," respectively. Similarly, $i_{mS}(k)$ and $i_{mT}(k)$ are phase current samples taken at the time $t=k\Delta t$ at the line ends "*S*" and "*T*". Δt is the sampling step and N is the total number of samples considered.

The system of fault location equations given by expression (11) is over-specified since it has just one unknown variable, distance x to the fault point. Therefore, the unknown distance x is determined using the *least square estimate* for all three phases of the line together:

$$x = \frac{- \sum_{m=a,b,c} \sum_{k=1}^{N} A_m(k) B_m(k)}{\sum_{m=a,b,c} \sum_{k=1}^{N} B_m^2(k)} \tag{14}$$

Expression (14) is the equation that defines the fault location algorithm for the short three-phase transmission line.

Long Line Application: To simplify the presentation, only a lossless single-phase long transmission line is considered as described by the following equations:

$$\frac{\partial \underline{v}(x,t)}{\partial x} = -l\frac{\partial \underline{i}(x,t)}{\partial t} \tag{15}$$
$$\frac{\partial \underline{i}(x,t)}{\partial x} = -c\frac{\partial \underline{v}(x,t)}{\partial t}$$

Using the traveling wave approach, Bergeron's solution of equation (15) is:

$$v_T(t) = \frac{z}{2}\left[i_S(t-\tau) - i_S(t+\tau)\right] = \frac{1}{2}\left[v_S(t-\tau) + v_S(t+\tau)\right] \tag{16}$$
$$i_T(t) = -\frac{1}{2}\left[i_S(t-\tau) + i_S(t+\tau)\right] = \frac{1}{2z}\left[v_S(t-\tau) - v_S(t+\tau)\right]$$

where v_R and i_R correspond to the end "T" of the line, and $v_S(t)$ and $i_S(t)$ corresond to the end "S" of the line. z is the surge impedance of the line and τ is the surge traveling time, defined as:

$$x = \sqrt{\frac{l}{c}} \tag{17}$$

$$\tau = d\sqrt{lc} \tag{18}$$

In equation (16) it can be seen that, the distance does not appear explicitly; it is hidden in the surge traveling time τ. Furthermore, τ does not appear as the variable of equation (16), but as the value that the voltage and current depend on. Physically, equation (16) has the following meaning: to calculate voltage and current at any point of the line, "forward" and "backward" waveforms of current and voltage at the other end are needed, and they are a function of the distance. Therefore, an explicit fault location equation for the long transmission line can not be derived out of the generic equation. Instead, an indirect method is used for solving the fault location equation in this case. A procedure has been developed for finding the solution x by systematically changing the parameter τ.

Advantages

Accuracy and Performance: Fault location algorithms for short and long transmission lines were extensively tested using the Electromagnetic Transient Program (EMTP) models of sections of actual power systems. Table 1 shows typical test results for:

- Short, 161-kV line which has strong mutual coupling with several adjacent lines; the transmission line considered is fully transposed and 13.35 miles long.
- Long, 345-kV line which runs in parallel with another line; the transmission line considered is untransposed and 195 miles long.

Table 1 represents the percentage error of the algorithm for a phase-A-to-ground fault. The elements given in Table 1 indicate the remaining three parameters that can be changed for a trasmission line fault as follows:

R_f — designates fault reisitance.
Location of fault % — represents the line length from one end of a line.
Incidence angle — designates the angle of the voltage waveform at the time when the fault has occured.

All of these parameters are controlled through simulation.

Table 1. Fault Location Algorithm Error Percent for a Phase-A-to-Ground Fault

Location of fault %	0.1		0.5		0.8	
Incidence angle (deg)	0	90	0	90	0	90
Short Line						
$R_f = 3\Omega$	0.4344	0.4346	0.2901	0.2093	0.0388	0.0390
$R_f = 50\Omega$	0.4576	0.4549	0.2237	0.2229	0.0464	0.0472
Long Line						
$R_f = 3\Omega$	0.4283	0.4212	0.3912	0.3966	0.4783	0.4152
$R_f = 50\Omega$	0.4301	0.4832	0.3991	0.4003	0.4853	0.4765

The error of the fault location algorithm is calculated as follows:

$$\text{error}(\%) = \frac{\text{actual fault loc.} - \text{calculated fault loc.}}{\text{total line length}} \times 100 \qquad (19)$$

Worst case errors were close to 0.7% for line-to-line faults, but in most cases the errors did not exceed 0.5%. This accuracy is remarkable, considering the different models used as well as the range of operating and fault conditions considered.

Algorithm Robustness: The fact that a very small number of constraints is imposed on the algorithm derivation reveals that the synchronized sampling algorithm is very robust since it is not affected by conditions that would affect most of the other algorithms. For example:

- Fault location, type and incidence angle have very little effect on accuracy.
- Synchronized sampling at two ends of a line makes the algorithm transparent to the model characteristic and operating conditions of the rest of the power system.
- The algorithm can easily cope with any level of mutual coupling, and it is applicable to multi-terminal lines.
- Operating conditions on the line of interest can be highly unbalanced, including cases where some phases may be de-energized. The algorithm can operate accurately on both transposed and untransposed lines.
- Although fault impedance may contain an inductive component and the fault resistance may be variable in time, the algorithm will still preserve the high accuracy.

A last point about the time variable resistance is illustrated in Figure 3 (on the next page). This case is commonly found in applications in the arc resistance is established in bursts, where a foreign object such as a tree limb touches the line repeatedly at given time intervals.

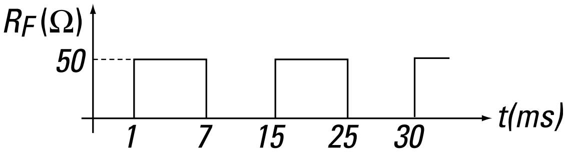


Figure 3. Variable Resistance R_F

For this difficult application, the algorithm requires a higher sampling rate than is otherwise needed, but the accuracy achieved is still comparable to the overall accuracy discussed earlier. Typical test results for time variable fault resistance are shown in Table 2.

The first column represents the phases of a three-phase system involved in a fault. For example, a-g is a fault between phase a and the ground; b-c is a fault between phases b and c, and so forth. In summary, we are dealing with a three-phase system with phases a, b and c, a fault making shorts between various phases, and sometimes a gound.

Table 2. Error (Percent) for the Fault Location 10% of the Line with Time Variable Resistance R_F as Shown in Figure 3

Type of Fault	Frequency (kHz)		
	24	12	6
a-g	0.1330	0.6969	2.2398
b-c	0.2736	0.4380	1.5619
b-c-g	0.2537	0.2880	0.1832
a-b-c-g	0.2719	0.2441	0.1615

Fault Location Improvements: Use of synchronized sampling in the fault location algorithm provides the following additional benefits not found in the previous solutions:

- The algorithm is based on the direct solution of a set of differential equations. Therefore, it provides accurate results for almost any type of transmission line as long as a model of this line is available.
- The algorithm is extremely robust, giving accurate results for a fault on a transmission line under a number of operating and fault conditions. These conditions include different loading, a change in the switching conditions in the rest of the system, time varying fault resistance, multi-terminal lines, and mutually coupled lines.

- The algorithm is extremely fast, with a data window of one cycle, and is capable of performing both fault detection and classification. This makes it a promising candidate for an ultimate protective relaying algorithm using an accurate fault location as the relaying principle.

Future Applications of Synchronized Sampling

The algorithm presented in this application note may be used for related applications in the future.

System Wide Monitoring and Control

As mentioned earlier, other uses of this algorithm are in automated fault analysis. This concept may be expanded in the future to include system-wide fault monitoring and restoration control that will be automated and based on synchronized sampling. The main advantage of synchronized sampling is an ability to provide consistent data for overall system analysis using a direct solution of the system equations.

This enables determination of fault location, sequence of events in the system switching caused by relay operation, and accurate load flows in the remaining system that have not been disconnected as a consequence of a fault. This information, if obtained on-line and in real-time, may be used by operators as a starting point for system restoration procedures. An accurate assessment of the system state is an essential condition for selection of correct restoration sequences. Therefore, synchronized data sampling, combined with accurate fault location, can be used to improve the quality of fault analysis and determination of a correct post-fault system state.

New Protective Relaying Scheme

The new fault locating algorithm can also be used for protective relaying in the future.

An ultimate goal in relaying selectivity is to be able to accurately determine if the fault is on a given transmission line. The fact that the new algorithm accurately determines the fault location is the most desirable feature for a relaying function. Hence, the new algorithm may be used as a relaying algorithm in the future. It also provides classification which is an important feature when single-pole autoreclosing is considered.

The main constraint in the use of the new algorithm in protective relaying is response time. Fault location is an off-line application, and as such, it does not have to meet the stringent time-response requirements placed on protective relaying algorithms. The new algorithm can be made to operate in real-time and with a time response of a relaying function, if the required data communication between various data acquisition sites is provided.

Hewlett-Packard GPS Synchronization Solutions
HP 59551A GPS Measurements Synchronization Module

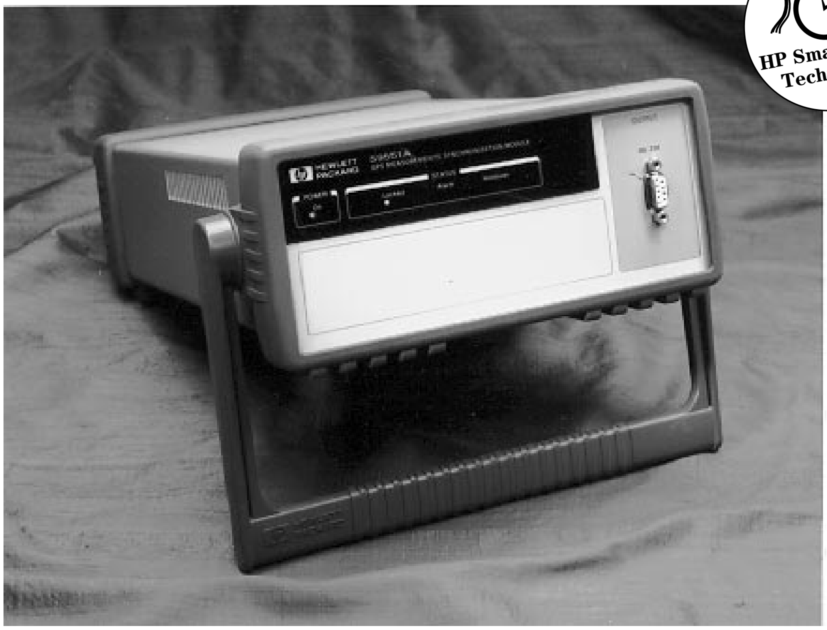
The HP 59551A GPS Measurements Synchronization Module, designed especially for power systems, is Hewlett-Packard's first precision timing product based on advanced GPS technology. It provides a low-cost synchronization foundation for monitoring wide-area transmission systems, or for real-time monitoring and control.

The time base for the HP 59551A is the HP 10811D Quartz Oscillator, a highly-reliable crystal component characterized by low sensitivity to temperature changes, low phase noise and well-understood aging characteristics. Integrated with the quartz oscillator, HP's SmartClock technology boosts the performance of the HP 59551A, making it approach the performance of a rubidium-based solution with accuracy of 110 nanoseconds at 95-percent probability.

HP SmartClock technology compares the oscillator frequency with the GPS reference signal. By "learning" the aging behavior and the environmental effects on the oscillator over time, HP SmartClock adjusts the oscillator output frequency accordingly and significantly improves accuracy.

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 8.6 microseconds loss in accuracy for up to 24 hours of GPS signal loss.

HP SmartClock Technology



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

HP 59552A Fiber Optic Distribution Amplifier and HP 59553A Fiber Optic Receiver

High-integrity distribution of a common clock is the backbone for power utility substation synchronization. The HP 59552A Fiber Optic Distribution Amplifier and HP 59553A Fiber Optic Receiver provide a simple, modular approach to signal routing. Immunity to electrical noise makes fiber optic cable a superior choice for the challenging environment of the power substation.

The HP 59552A Fiber Optic Distribution Amplifier receives a digital (TTL) signal and an analog signal via two BNC connectors. The HP 59552A combines the signals, and transmits the result on each of eight fiber optic outputs. Signal integrity is even maintained over customer-supplied, fiber optic cable lengths of up to a kilometer.

An HP 59553A Fiber Optic Receiver resides near each remote equipment installation. The HP 59553A receives the signal on fiber optic cable, separates analog and digital waveforms, and outputs each signal on a BNC connector.

HP fiber optic products are designed to provide clean timing-quality transmission signals to monitoring, analysis and control equipment. In a typical application calling for distribution of 1 pulse per second (1PPS) and IRIG-B time code, each substation instrument receives an identical, synchronous, high-quality clock signal and precise time of day.

High-quality timing signals (both 1PPS and IRIG-B) are available as standard back-panel outputs of the HP 59551A GPS Measurements Synchronization Module.

Coupled with the HP 59551A, the HP 59552A and HP 59553A form a complete master clock and distribution system for power substations. This system could be used for applications like fault location, adaptive relaying, and disturbance analysis.

The HP 59552A and HP 59553A can be coupled with the HP 59551A to form a complete master clock and distribution system for power substations.

For more information on Hewlett-Packard Test and Measurement products, application or services please call your local Hewlett-Packard sales ofices. A current listing is available via Web through AccessHP at http://www.hp.com. If you do not have access to the internet please contact one of the HP centers listed below and they will direct you to your nearest HP representative.

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