

Apply a Wireless Line Sensor System to Enhance Distribution Protection Schemes

Kei Hao, Shankar V. Achanta, Jakob Fowler, and David Keckalo
Schweitzer Engineering Laboratories, Inc.

© 2017 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

This paper was presented at the 70th Annual Conference for Protective Relay Engineers and can be accessed at: <https://doi.org/10.1109/CPRE.2017.8090006>.

For the complete history of this paper, refer to the next page.

Presented at
CIDEL Argentina 2018
Buenos Aires, Argentina
September 24–26, 2018

Previously presented at the
IEEE ROC&C 2017, November 2017,
53rd Annual Minnesota Power Systems Conference, November 2017,
70th Annual Conference for Protective Relay Engineers, April 2017,
and XIII Simposio Iberoamericano Sobre Proteccion de Sistemas
Electricos de Potencia, February 2017

Previously published in the
proceedings of the 71st Annual Georgia Tech
Protective Relaying Conference as an alternate, May 2017

Originally presented at the
43rd Annual Western Protective Relay Conference, October 2016

Apply a Wireless Line Sensor System to Enhance Distribution Protection Schemes

Kei Hao, Shankar V. Achanta, Jakob Fowler, and David Keckalo, *Schweitzer Engineering Laboratories, Inc.*

Abstract—Traditionally, utility crews have used faulted circuit indicators (FCIs) to locate faulted line sections. FCIs monitor current and provide a local visual indication of recent fault activity. When a fault occurs, the FCIs operate, triggering a visual indication that is either a mechanical target (flag) or LED. There are also enhanced FCIs with communications capability, providing fault status to the outage management system (OMS) or supervisory control and data acquisition (SCADA) system. Such quickly communicated information results in faster service restoration and reduced outage times.

For distribution system protection, protection devices (such as recloser controls) must coordinate with downstream devices (such as fuses or other recloser controls) to clear faults. Furthermore, if there are laterals on a feeder that are protected by a recloser control, it is desirable to communicate to the recloser control which lateral had the fault in order to enhance tripping schemes. Because line sensors are typically placed along distribution feeders, they are capable of sensing fault status and characteristics closer to the fault. If such information can be communicated quickly to upstream protection devices, at protection speeds, the protection devices can use this information to securely speed up distribution protection scheme operation.

With recent advances in low-power electronics, wireless communications, and small-footprint sensor transducers, wireless line sensors can now provide fault information to the protection devices with low latencies that support protection speeds. This paper describes the components of a wireless protection sensor (WPS) system, its integration with protection devices, and how the fault information can be transmitted to such devices. Additionally, this paper discusses how the protection devices use this received fault information to securely speed up the operation speed of and improve the selectivity of distribution protection schemes, in addition to locating faulted line sections.

I. INTRODUCTION

The main objectives of distribution system protection are to minimize the duration of faults and reduce the number of customers affected by them [1]. Today's distribution protection systems use selectivity to achieve a reasonable service continuity and limit the number of affected customers. This tradeoff uses time delays to establish selectivity when many protection devices (such as protective relays and recloser controls) in series see the same fault current. Fig. 1 shows a radial system with two inverse-time overcurrent devices. To ensure selectivity, the upstream device (backup) must add an intentional delay for the downstream device to clear a fault. The time-overcurrent curve of the upstream device is set above (slower than) the downstream protection devices, with some margin, as shown in Fig. 1. This type of scheme sacrifices speed to achieve selectivity. Fault-clearing times can increase when a fault is located closer to the source because the upstream device has a slower response due the

forementioned coordination with downstream devices [2], such as I_{F3} in Fig. 1. Furthermore, fault currents are usually higher for this type of fault, which results in undesirably longer clearing times and more stress on the system.

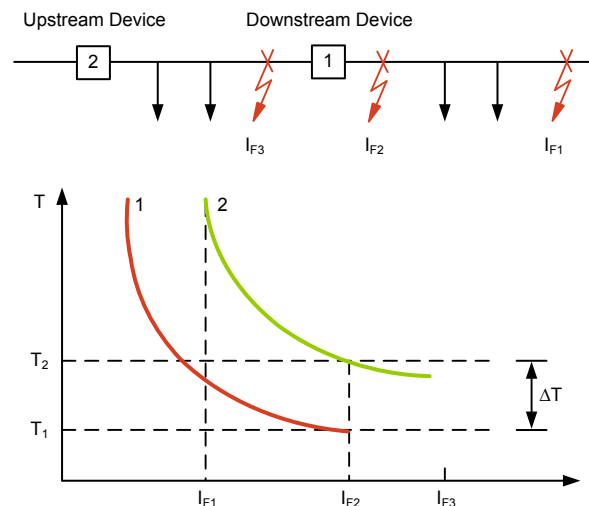


Fig. 1. Time-Overcurrent Protection Is Time-Delayed to Provide Coordination

In recloser-fuse coordination, the recloser cannot differentiate fused sections from unfused sections. If a fault occurs on the unfused line section, the recloser still has to wait for the fuse coordination time margin before tripping. Because the recloser cannot determine which section has a fault, the system delays protection action due to selectivity.

Traditional faulted circuit indicators (FCIs) and communication-capable FCIs (wireless FCIs) have helped utilities quickly locate faulted line sections to decrease system restoration times. In addition to fault location, wireless FCI systems with data concentration capabilities allow utility systems to process the FCI data and provide useful information for system planning. The latest generation of sensors, which are wireless multifunction line sensors, provide much more information than FCIs. These wireless line sensors provide valuable data that fill the information gap between protection devices and customer meters. The new data allow utilities to monitor load across a wide area, locate faults, and improve automation and control. While all data from the sensors are useful, they are usually not transmitted quickly enough for protection applications. The next generation of FCIs discussed in this paper are wireless protection sensors (WPSs). These WPSs are capable of providing fault information to protection devices at protection speeds to influence protection decisions. For example, if WPSs can

indicate a fault that is on an unfused line section rather than a fused line section, the recloser control can trip faster because there are no fuses with which to coordinate. In this case, the WPS help increase the speed of protection.

II. DISTRIBUTION PROTECTION SCHEMES

A typical radial distribution circuit is shown in Fig. 2. A feeder starts at the feeder circuit breaker located inside the distribution substation. Multiple feeders leave the substation. The feeder breaker protective relay generally includes overcurrent elements to operate for downstream faults. This protects the conductors from damage due to through-fault current by isolating the faulted portion from the rest of the distribution bus. Utilities often install pole-mounted reclosers (with accompanying controls) along the distribution feeder to interrupt faults on downstream segments of the feeder in order to achieve reasonable service continuity and reduce the number of affected customers. Numerous laterals tap off of the feeder. It is common practice to use fuses on the laterals to isolate faulted branches of the feeder.

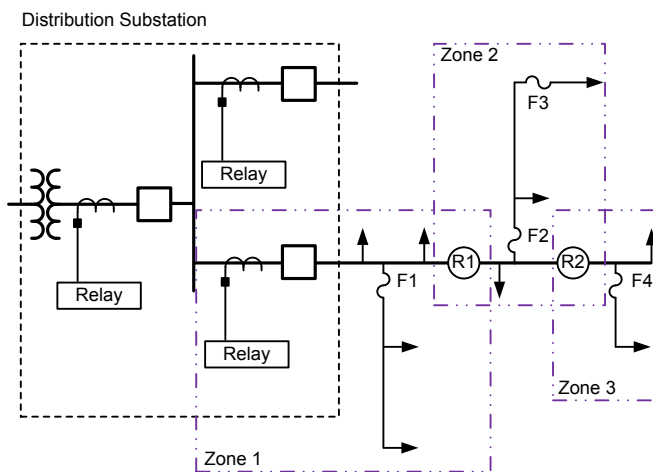


Fig. 2. Typical Overhead Distribution System

Many utilities are progressively installing automated tie points between feeders to facilitate outage restoration when an adjacent feeder is available to pick up de-energized line sections. The tie points are often mid-line reclosers or smart switches. While these looped systems appear to form a network, they are usually operated in a radial mode, except for brief intervals during switching. When the looped systems operate in this mode, the radial line schemes discussed in this paper are applicable to them.

Ideally, for a radial system, the feeder breaker relay, recloser controls, and fuses are fully coordinated. Coordinating all of these elements is difficult because the available fault current varies over the length of the feeder, and there are multiple protection devices in series. For example, Fig. 2 shows a feeder that is protected by one breaker relay, two reclosers, and four fuses on laterals. To achieve coordination, it is necessary to divide the feeder into various protective zones. For safety, the protective zones must overlap so that no part of the feeder is left unprotected.

Each protective zone has a protection device that is responsible for clearing faults within it. Faults beyond a protective zone must be cleared by the downstream protection devices in the zone. If a protection device fails to clear a fault inside its protective zone, the upstream device, also known as the backup device, clears the fault. In order for this principle to work, the upstream device (backup) must add an intentional delay to wait for the downstream device to clear the fault. The selected time-overcurrent curve of the upstream device must be above the downstream device curve, with a time margin. Fig. 3 shows the time-overcurrent curves for the Fig. 2 example.

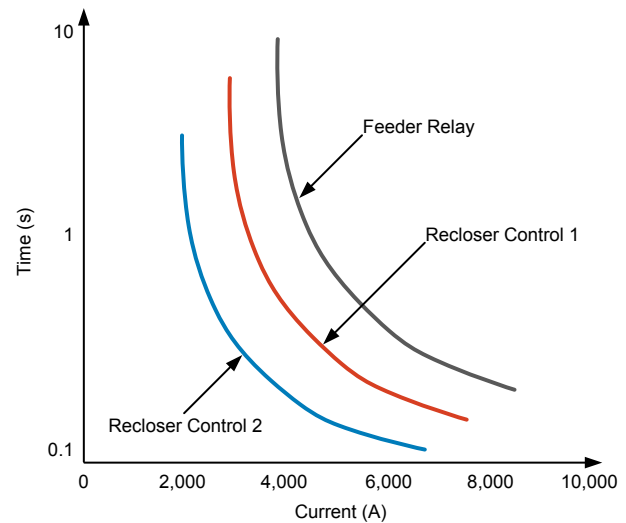


Fig. 3. Time-Overcurrent Coordination Among the Feeder Relay and Two Recloser Controls

Protection coordination may consider several device combinations, such as relay-to-recloser, recloser-to-recloser, or recloser-to-fuse coordination. This paper focuses on the recloser-to-fuse coordination, which is widely used to interrupt faults on a feeder and its laterals. The principles are the same for feeder-relay-to-fuse coordination.

On an overhead distribution system, a fault instance may be permanent, such as a tree across the line that requires repair. However, an estimated 80 to 90 percent of overhead faults are temporary in nature [3], such as an animal contact event, where repair is not needed when the fault is interrupted quickly as the animal falls away from the equipment. In contrast, practically all faults are permanent on an underground distribution system.

Utilities generally apply one of two fuse-coordination philosophies on a feeder with recloser-to-fuse coordination: either the fuse-saving scheme or the fuse-blowing (trip saving) scheme. Below is a summary of the advantages, disadvantages, and limitations of each scheme.

A. Fuse-Saving Scheme

Utilities employ fuse-saving schemes to overcome the extended outages caused by temporary faults on fused line sections. When any fault is detected, the goal is for the recloser to interrupt the fault current before a fuse begins to melt. This is achieved via a fast-curve operation. If the

recloser was able to interrupt the fault and the fault is not present upon reclosure, then power is restored to the circuit beyond the recloser and the fuse remains unblown (saved).

If, however, the fault is permanent, then fault current resumes upon reclosing. The recloser then reverts to operate on a delayed time-overcurrent element (also known as the slow curve) that is coordinated with the downstream fuses. Such coordination allows the fuse to clear (blow), isolating the faulted line section. When the fuse clears the fault, the recloser will cease timing and refrain from tripping, and the rest of the feeder will remain in service. Fig. 4 shows recloser-to-fuse coordination for a fuse-saving scheme.

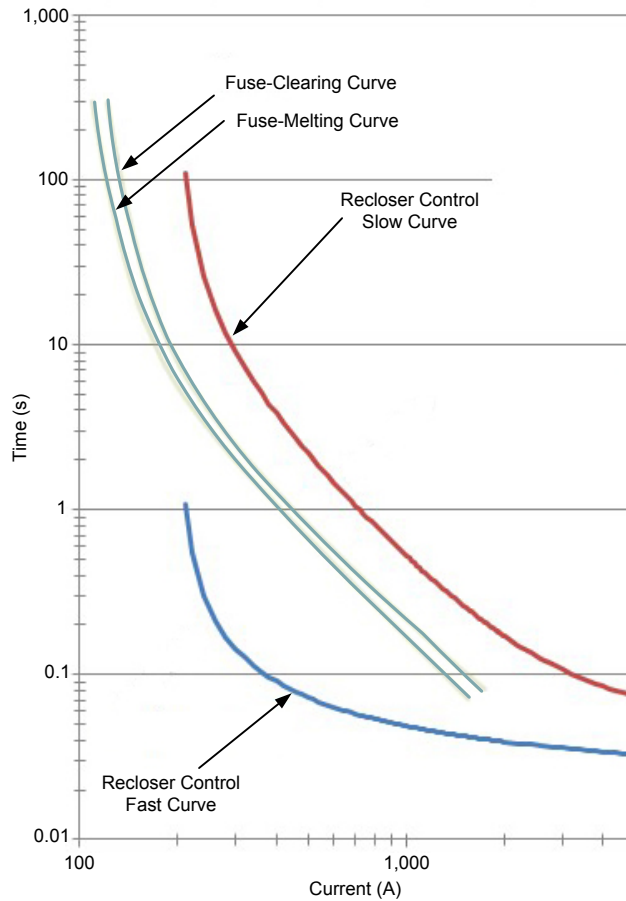


Fig. 4. Example of Fuse-Saving Time-Overcurrent Coordination

If the fuse does not clear the fault, then the fault is located on a line section not protected by any fuse and the recloser must clear the fault. In this example, the recloser permanently opens (locks out) after the second reclose attempt. Some applications use more than one fast- or slow-curve operation, but the goal is the same.

As Fig. 4 shows, the recloser fast curve is selected to coordinate with the minimum melting time characteristic of downstream fuses. The recloser slow curve is selected to coordinate with the maximum clearing time-current characteristic of a downstream fuse. Fuse-saving schemes clear any temporary fault located on the line without blowing a fuse but interrupt service to the entire circuit downstream of the recloser for at least one reclose attempt. Permanent faults

downstream of a fuse are cleared by the fuse operation, and the rest of the feeder remains in service. Permanent faults on line sections not protected by fuses are cleared by the recloser.

Proper coordination of fast and slow curves with multiple downstream fuses is not easy because the fuses often have different ratings and will be subjected to different maximum fault current levels. Fuse-saving schemes are difficult to coordinate with different fuse sizes, especially for fuses close to the recloser, and for faults located near the recloser control where the fault levels are the highest. Faults located further downstream of fuses may have low enough current to coordinate with the recloser fast curve clearing time.

To determine the performance of a fuse-saving scheme, the designer should consult the fuse minimum melting curve and find the intersection with the sum of the recloser control processing time and the interrupting time (clearing time). This exercise provides the maximum coordination current, I_{Fmax} , valid for the selected fuse size. Other fuse sizes have their own I_{Fmax} values.

Another limitation of the fuse-saving scheme is that coordination is only possible for faults below I_{Fmax} for a given fuse. For fault currents above I_{Fmax} , the recloser may begin the tripping operation for the fast curve, but the fuse may operate faster than the recloser contacts can open and extinguish the arc. This results in an unnecessary recloser trip and reclose operation. If the fuse does not operate, it may have partially melted, effectively lowering its rating for future events.

If fuses are only installed in locations where the I_{Fmax} value is below the available fault current, the fuse-saving scheme will successfully coordinate with that fuse. Practically speaking, on any moderately developed feeder, there will always be some fuses that will not coordinate.

The fuse-saving scheme has the capability to automatically restore service to all customers after temporary faults, eliminating the need for a utility crew to replace a blown fuse. The main disadvantage to this scheme is that customers downstream of the recloser always experience temporary interruptions for faults. The fuse-saving scheme is primarily directed at reducing sustained interruptions.

Fuse-saving schemes are popular in rural areas with a high system exposure to faults, a low customer count, and a long and costly crew response.

B. Fuse-Blowing Scheme

The fuse-blowing scheme may also be referred to as the trip-saving scheme. The goal of this scheme is to minimize the number of customers exposed to an interruption by allowing a fuse to clear a given fault. The recloser only trips for faults that are on either the main line section (with no fuses in line) or unfused line sections.

In the fuse-blowing scheme, the recloser is configured with a slow curve that has been selected to coordinate with the maximum clearing time-current characteristic of all downstream fuses. When a fault occurs, the fuse-blowing scheme allows enough time for any downstream fuse to operate and clear the fault. If no downstream fault-clearing

action occurs before the slow curve element times out, the recloser will trip.

If the recloser trips, the fault must not be on a fused line segment. The recloser waits (remaining open) a short time for the fault to clear on its own. If the recloser recloses back in and the fault is not present, then no further action is required. If the fault persists after the first reclose operation, the fault current resumes and the recloser control trips and remains permanently open (locked out). If reclosing is not enabled, every fault on the main line or unfused sections results in a permanent outage. This action may have value for installations where power quality is a critical requirement, for instance, when two heavy voltage dips in a row will adversely affect customers on other parallel feeder sections or on feeders with large portions of underground conductors, where continued exposure to through-fault currents could damage the conductor.

The fuse-blowing scheme with reclosing clears temporary faults that occur on unfused feeder sections. Permanent faults on the feeder are cleared by opening the recloser and interrupting power to downstream feeder portions. Any other faults, whether caused by permanent or temporary events, are cleared by a fuse. In the latter case, the rest of the feeder remains in service.

Except for in the case of self-clearing faults (which are assumed to be rare), one of the main drawbacks of the fuse-blowing scheme is that all faults on fused laterals become permanent outages, even those that have a temporary cause.

Another drawback of the fuse-blowing scheme is that faults on unfused sections persist for a longer period of time because the recloser control coordination is designed to wait for a tap fuse to blow. This causes longer voltage sags, impacting power quality for customers on the same feeder and on adjacent feeders supplied by the same substation bus.

The fuse-blowing scheme is primarily applied to reduce the number of temporary interruptions. This scheme is often preferred in urban areas with a low system exposure to faults, a high customer count, a rapid crew dispatch, and where a fuse-saving scheme is difficult to implement.

III. IMPROVING THE SPEED OF PROTECTION SCHEMES

A. *Traditional Selectivity and Speed*

In radial distribution protection, time delays are used to establish selectivity because many protection devices in series may see the same fault current on a feeder with multiple reclosers and numerous laterals. Selectivity is achieved using inverse-time overcurrent curves, which offer a means of assigning unique time delays to each device for any given fault current. As discussed in the introduction of this paper, this type of scheme sacrifices speed.

Because today's distribution protection systems do not have visibility of downstream line sections, the protection schemes cannot determine which line section has the fault. If a fault occurs on the unfused line section, the recloser waits for a downstream fuse to clear the fault due to selectivity. When no fuse clears the fault, the recloser trips. Because the recloser cannot determine which section has a fault, the overcurrent protection is time-delayed to provide coordination.

It is clear that selectivity has been chosen over speed in traditional distribution protection. One of the reasons for this is that the devices—feeder relays, reclosers, and fuses—provide selectivity under most circumstances at a reasonable cost.

B. *The Need for Speed in Distribution Systems*

Reducing fault-clearing time is important in distribution systems because of the amount of energy released during a fault. The energy released is proportional to the amount of time the fault persists and the square of the fault current. The energy released can cause severe consequences if the protection system does not clear the fault quickly. Speeding up protection schemes in distribution is important for the following reasons:

1. **Public safety.** A fault or downed line poses a hazard through direct or indirect electrical contact and as an ignition source for fires. The potential for injury and property damage increases when faulted conductors are not quickly de-energized.
2. **Stress on the distribution system and damage to equipment.** One of the consequences of a fault is conductor burndown, where the heat from the fault current or an arc can burn and break conductor connections. Equipment damage includes reduced service life for substation transformer banks.
3. **Power quality.** Industrial, commercial, and residential customers on distribution systems have different power quality requirements and expectations. While a fault is in progress, customers on both the faulted feeder and adjacent feeders fed from the same substation may experience partial or complete voltage collapse. The longer the system must supply energy to a fault, the more onerous the low-voltage effects. Some equipment cannot tolerate even short voltage sags lasting 10 cycles, such as in industrial processes that completely restart if motors stall. Fig. 5 shows the Computer and Business Equipment Manufacturers Association (CBEMA) curve, which was established by the Information Technology Industry Council [4]. The CBEMA curve, shown in Fig. 5, indicates a generally acceptable voltage range for power delivery.

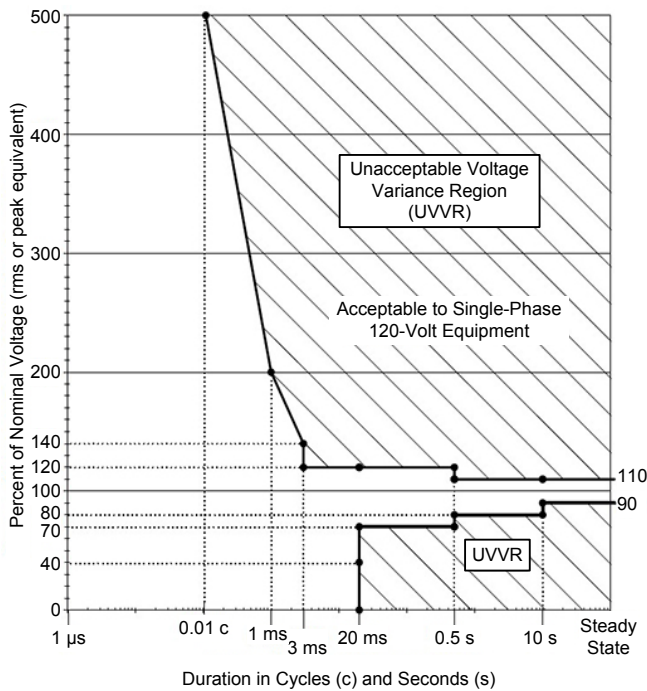


Fig. 5. CBEMA Curve

C. Improving the Speed of Distribution Protection

As discussed previously in Subsection A, the protection devices found in traditional distribution systems are unable to discriminate between fused and unfused downstream faulted line sections, thus fast clearing time is sacrificed for many fault occurrences. The WPS system discussed in Sections IV and V is an innovative approach to speeding up and improving distribution protection schemes.

When WPSs are placed strategically on feeders, whether on the main line or lateral sections, a fault occurring downstream triggers the sensor to transmit a message wirelessly to the receiver while the fault is present. The information is immediately shared with the upstream recloser control or protective relay. The recloser control or relay can use the faulted sensor status, along with local overcurrent elements, to identify the faulted line segment and modify the protection response accordingly.

When WPSs are installed at branch points, the recloser control can use predetermined rules to choose the appropriate response for a given fault. For example, if the WPS system indicates that a fault is on an unfused line section rather than on a fused line section, the recloser control can allow a faster trip because there are no fuses in line with the fault. In this case, the WPSs increased the speed of protection.

IV. WIRELESS PROTECTION SENSOR SYSTEM

The WPS system has high-speed wireless communications capabilities to send fault information at protection speeds. The WPS system consists of WPSs, a collector, and a protection

device (such as a recloser control or relay), as show in Fig. 6. When a fault occurs, the WPSs that sense the fault immediately send fault status to the collector. The collector sends the received fault status at a high speed to the recloser control.

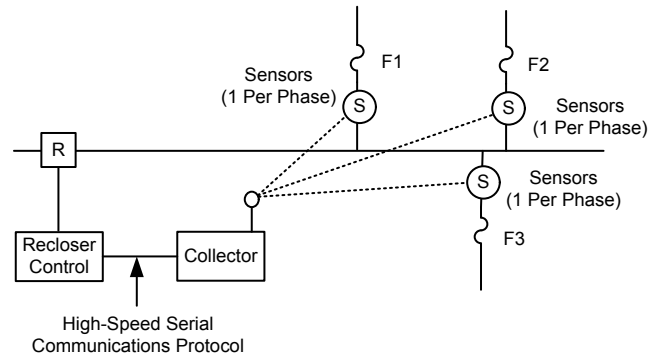


Fig. 6. WPS System

A WPS system typically includes multiple sensors. The recloser control or relay can receive the fault information from a sensor in less than a cycle. The communication between the collector and the recloser control uses a high-speed serial communications protocol. To monitor the WPS system health status, the WPS periodically sends a heartbeat signal to the collector.

V. APPLYING WPSs TO IMPROVE PROTECTION SCHEMES

A. Principles for Applying WPSs in Distribution Protection

The following principles must be considered when applying a WPS system in a distribution protection scheme.

1. The protection devices shall not make protection decisions based *solely* on fault data from the WPS system. The protective relay must never trip a circuit breaker (nor a recloser control a recloser) based solely on sensor information. To follow this principle, the protection device must itself sense a fault using overcurrent elements before acting on the additional sensor information.
2. Protection devices should fallback to a backup scheme in the absence of sensor data. This fail-safe principle covers cases when the WPSs are unable to provide fault information to the protection devices. In other words, a lack of sensor data must never block protection device functionality.
3. The protection device should only use the sensor fault information to augment existing schemes when fully designed, commissioned, and enabled. Because the WPS system gives more visibility into the distribution power system, the protection device can use the sensor fault data to improve protection decisions.

B. WPS System Latencies

In order for the WPS system to work properly in distribution protection systems, the latency of the sensor system must be carefully considered. Fig. 7 shows a timing diagram of the WPS system.

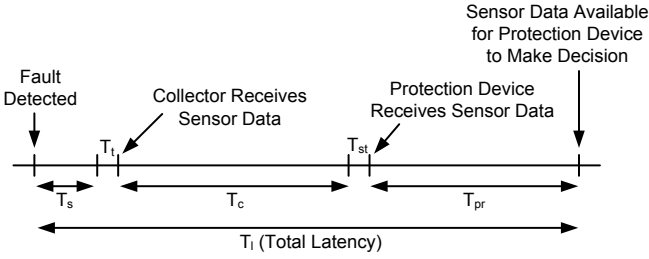


Fig. 7. WPS System Timing Diagram (not to scale)

The total latency (T_1) of the WPS system is the sum of the sensor time (T_s), transmission time (T_t), collector processing time (T_c), serial cable transmission time (T_{st}), and protection device processing time (T_{pr}). T_s is the sensor processing and data transmission times after detecting a fault. T_c includes decoding the received messages from the sensors, processing the sensor data, and encoding the information to transmit over the serial cable. T_{pr} is the time required to decode information from the serial cable, process it, and make it available to use. T_1 is given by (1).

$$T_1 = T_s + T_t + T_c + T_{st} + T_{pr} \quad (1)$$

The sum of all of the times should be less than one cycle.

C. Latency Requirements for the Fuse-Saving and Fuse-Blowing Schemes

In order for WPS information to be useful in protection decisions, the latency should be less than the protection scheme time requirements. For example, switching over “on the fly” from the fuse-saving to fuse-blowing scheme (described in detail in Section VI) requires that the WPS data be processed before the fast curve times out and has enough time to suspend the fast curve tripping. A similar requirement applies to switching over on the fly in reverse, from the fuse-blowing scheme to the fuse-saving scheme. The WPS data need to be processed in order for the protection device to enable the fast curve of the fuse-saving scheme and trip the recloser before the fuse starts to melt. All of these schemes have stringent latency requirements.

The estimated WPS system latency is less than one cycle, that is 16.67 ms from the recognition of fault current at the sensor to the status change in the recloser control. Once the status change is available, the recloser control uses the data as part of its decision, as shown in Fig. 8.

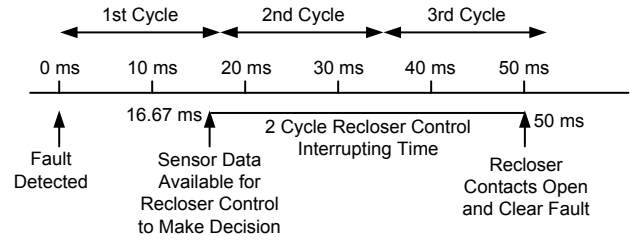


Fig. 8. Example Timing Diagram

Some applications need to account for the maximum expected breaker or recloser interrupting time. The interrupting time for a typical breaker or recloser is between 1 and 5 cycles. For a 2-cycle interrupting time at 60 Hz, the total time becomes 16.67 ms + 33.33 ms = 50 ms (or 3 cycles). At 3 cycles, the WPS system is fast enough to coordinate with Type T-Tin fuses with the following current limits. Table I shows the maximum current limits that coordinate well with different fuse sizes.

TABLE I
MAXIMUM COORDINATION CURRENT FOR TYPE T-TIN FUSES

Type T-Tin Fuse Size	Maximum Coordination Current (minimum melting time of 3 cycles)
15T	570 A
40T	1,500 A
65T	2,500 A
100T	3,800 A
140T	5,850 A

VI. APPLICATIONS

This section discusses distribution protection applications that use the WPS system. Its implementation speeds up fault-clearing times or narrows the area of outage impact, thus improving reliability.

A. Switchover On the Fly From a Fuse-Blowing Scheme to a Fuse-Saving Scheme

This switchover scheme gives utilities the option to tailor protection for specific line segments with different characteristics. If the sensor declares that a fault is present on a candidate line section, the scheme enables fuse saving (fast curve operation) while the fault is in progress. For other faulted line segments, the fuse-blowing scheme works as usual. This application allows a single protective zone to have both fuse-saving and fuse-blowing schemes in service.

This switchover scheme is permissive. The fuse-blowing portion of the scheme is always active, and the fuse-saving portion is only enabled under certain conditions. In order to make switching over from fuse blowing to fuse saving successful, the fuse rating and the fault current have to meet the following two conditions:

- The fuse must be able to coordinate with the recloser in the fuse-saving scheme. The fuse size must be large enough so that the fast curve element of the recloser is faster than the slow curve of the fuse-saving scheme.
- The fault current must be smaller than the I_{Fmax} value discussed in Section II, Subsection A. The fault current must be low enough so that the recloser operates before the fuse starts to melt.

When the recloser detects a fault, the slow time-overcurrent element picks up and starts timing for the conventional fuse-blowing behavior. At the same time, a parallel fast time-overcurrent curve starts timing for fuse-saving behavior. The slow time-overcurrent element time-out output is unconditionally routed to the recloser control trip logic. Regardless of the WPS output, the slow curve element timeout results in a trip, satisfying Principle 2 from Section V. Conversely, the fast time-overcurrent element time-out signal is not directly tied to the trip logic. Instead, the signal is combined with the permissive logic. Fig. 9 shows one possible implementation of this logic

If the sensor on the candidate lateral sends a fault indication that is received while the fast curve element is timing but has not yet timed out, the fast curve fuse-saving element output is allowed to influence the trip logic. However, if the sensor fault signal is received after the fast curve

element times out, it is too late to successfully switch to fuse saving. In this situation, the fast curve output is not routed to the trip logic.

Because the fuse-blowing logic remains in service in all cases, this switchover scheme logic follows the three principles described in Section V.

To overcome the overtripping difficulties often found in fuse-saving schemes, the switchover is only allowed when the recloser control determines that fuse saving can be successful, typically for fault positions further out on a tap. Optional overcurrent element supervision can be included, as shown in Fig. 9.

B. Switchover On the Fly From a Fuse-Saving Scheme to a Fuse-Blowing Scheme.

Similar to the previous application, this switchover scheme uses the WPS system to indicate which line section contains a fault. However, in this version, the fuse-saving scheme is the default operating mode. If the sensor declares that a fault is present on a candidate line section, the scheme can enable fuse blowing (slow curve operation) while the fault is in progress. For other faulted line segments, the fuse-saving scheme works as usual. This switchover scheme also allows a single protective zone to have both fuse-saving and fuse-blowing schemes in service.

This switchover scheme is a blocking scheme. The fuse-blowing portion of the scheme is always active, and the fuse-saving portion is blocked under certain conditions.

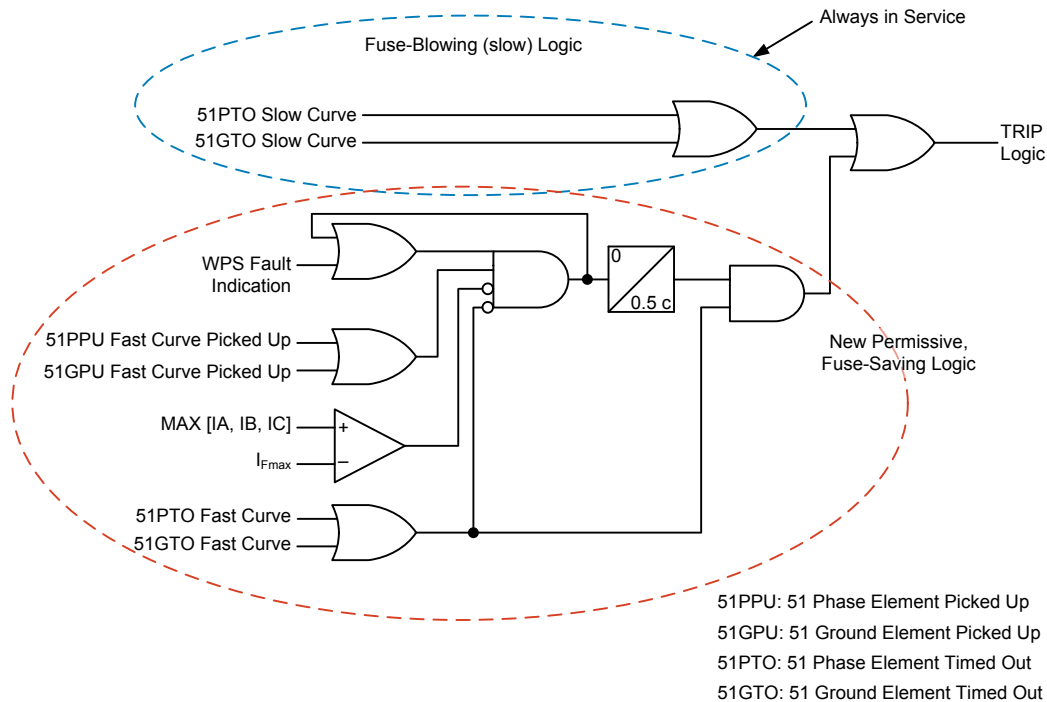


Fig. 9. Fuse-Blowing to Fuse-Saving Switchover Logic

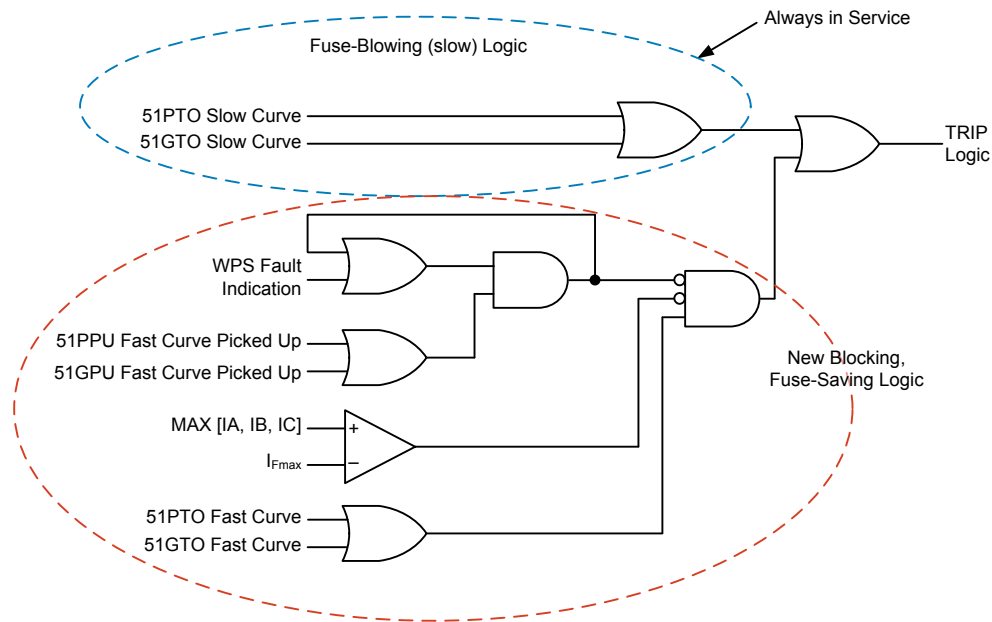


Fig. 10. Fuse-Saving to Fuse-Blowing Switchover Logic

When the recloser detects a fault, the slow time-overcurrent element picks up and starts timing for the conventional fuse-blowing behavior. At the same time, a parallel fast time-overcurrent curve starts timing for fuse-saving behavior.

The slow time-overcurrent element time-out output is unconditionally routed to the recloser control trip logic. Regardless of the WPS output, the slow element timeout results in a trip, satisfying Principle 2.

Conversely, the fast time-overcurrent element time-out signal is not directly tied to the trip logic. Instead, the signal is combined with the blocking logic. Fig. 10 shows one possible implementation of this logic.

If the sensor on the candidate tap sends a fault indication that is received while the fast curve element is timing but has not yet timed out, the blocking signal is asserted, preventing the fast curve fuse-saving element output from activating the trip logic. The logic has selected the fuse-blowing scheme by blocking the fuse-saving scheme for this particular fault.

However, if the sensor fault signal is received after the fast curve element times out, it is too late to perform the blocking because the trip logic has already been activated. In this situation, the fuse-saving fast curve output is allowed through to the trip logic because there is no block signal.

Because the fuse-blowing logic remains in service in all cases, this application logic follows the three principles described in Section V.

C. Switchover On the Fly Between Feeder Cable Protection and First-Span Protection

This scheme helps increase system availability by reducing the number of sustained outages that are caused by overhead faults being mistaken for feeder cable faults.

Often a feeder starts with an underground line section (feeder cable) that spans a distance to a terminal pole or riser pole where the overhead line section begins, as shown in Fig. 11. To protect feeder cable substation egress, some

utilities use instantaneous overcurrent elements with pickup levels set to cover the entire cable length, plus some margin that overreaches onto a portion of the overhead line. In these applications, a high-current fault causes an instantaneous trip with no reclosing permitted.

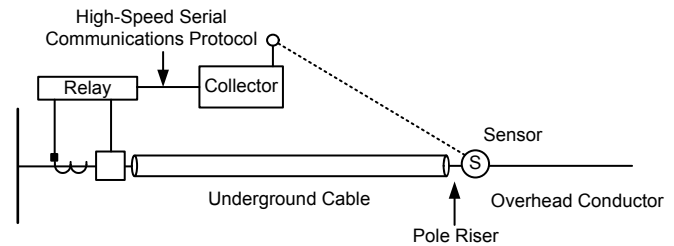


Fig. 11. Underground and Overhead Combined Feeder

While this approach protects equipment, most of the time it causes an unnecessary permanent outage. Recall that the majority of overhead faults are caused by temporary events and that overhead faults are far more likely than underground faults. By not reclosing for close-in overhead faults, the entire feeder suffers a permanent outage that may have been avoided.

This switchover scheme can be improved with information from a strategically placed WPS. The WPS can be used to allow reclosing when a fault is on the overhead line but not for cable faults. The instantaneous overcurrent trip function is not altered. This simple modification of an existing scheme improves system availability.

WPSs installed at the terminal pole or after one span of overhead lines are only exposed to faults on the overhead line section. The feeder relay uses the WPS system fault information in the decision to allow or block reclosing after an instantaneous trip operation. This decision result is available within a few cycles of the initial trip decision.

Fig. 12 shows simplified sensor logic for this switchover scheme. If the fault is in the cable section, the WPSs do not detect the fault or send a message and reclosing is blocked.

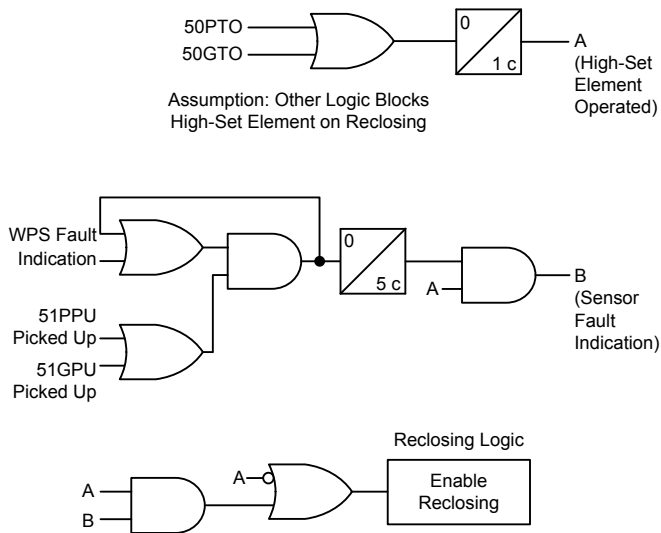


Fig. 12. Sensor Logic for Reclosing

If the fault is on the overhead line section and the high-set instantaneous overcurrent element operates, the WPS system fault indication allows a reclose operation. On this, and any subsequent reclosing attempt, the instantaneous element is blocked to allow for inrush current. This leaves a fast curve (or slow curve) element in service to provide fuse-saving (or fuse-blowing) protection as desired. Further reclosing can be configured as needed.

If the fault is on the overhead line but below the high-set cable protection threshold, the relay does not immediately trip and follows the usual fuse-saving or fuse-blowing scheme. The instantaneous overcurrent element is generally blocked on any reclose attempt to allow for inrush current. In this scenario, the WPS data do not influence the logic. Table II summarizes the logic for reclosing operations.

TABLE II
RECLOSING OPERATION

High-Set Element	Sensor Fault Indication	Action
Not operated	No fault	Enable reclosing
Not operated	Fault	Enable reclosing
Operated	No fault	Block reclosing
Operated	Fault	Enable reclosing

D. Speeding Up Tripping for Faults on Known Line Sections

1) Unfused Line Sections

This switchover scheme eliminates the delay for a fuse to blow when there is no fuse to blow. It is not always practical to install fuses on every lateral or line section of a distribution system. If a fuse-blowing scheme is implemented, any fault on an unfused lateral or line section will stress the system needlessly.

Reducing the time to trip also improves power quality upstream of the tripped breaker, and on feeders that are fed by the same substation bus, by shortening the voltage dip duration.

By installing WPSs on the unfused line section, the breaker relay or recloser control can be configured to speed up the trip response for such faults. Fig. 13 illustrates this scenario.

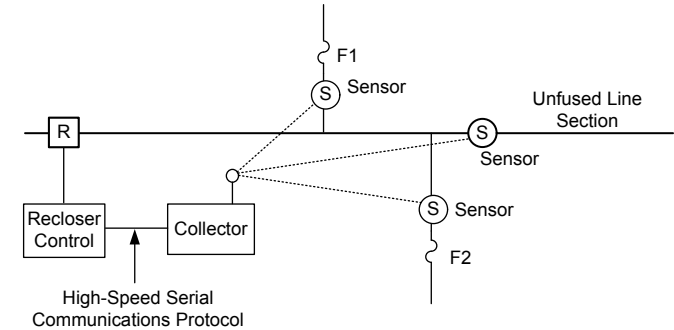


Fig. 13. Example of Unfused Section

Upon detecting a fault using local overcurrent elements, the recloser control operates the fuse-blowing scheme as usual when no fault indication is received from the WPS on the unfused line section.

If the WPS on the unfused line section indicates a fault while the local overcurrent elements are picked up, the recloser control enables a faster characteristic. The fuse-blowing overcurrent element is left in service as a backup.

In most cases, at least one reclose is attempted to allow service restoration if the fault is temporary.

2) Discriminate Between Taps for Fuse-Blowing Schemes

This scheme minimizes fault duration when there is a permanent fault on an unfused line section and there are fuses further down the same line section. Fig. 14 illustrates this concept. The example feeder has close-in taps protected by 100T fuses and a long line section that is not protected by a fuse but has taps farther down with 40T maximum fuse ratings.

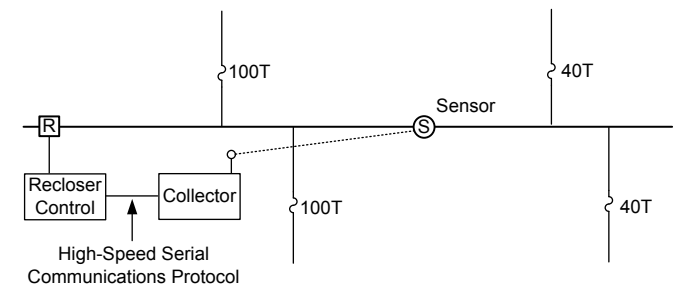


Fig. 14. Feeder With Different Fuse Sizes

The timing requirement for a traditional fuse-blowing scheme on this feeder must coordinate with the 100T fuse maximum clearing time-current characteristic. This strategy results in proper coordination, but in some cases, a fault may persist longer than necessary.

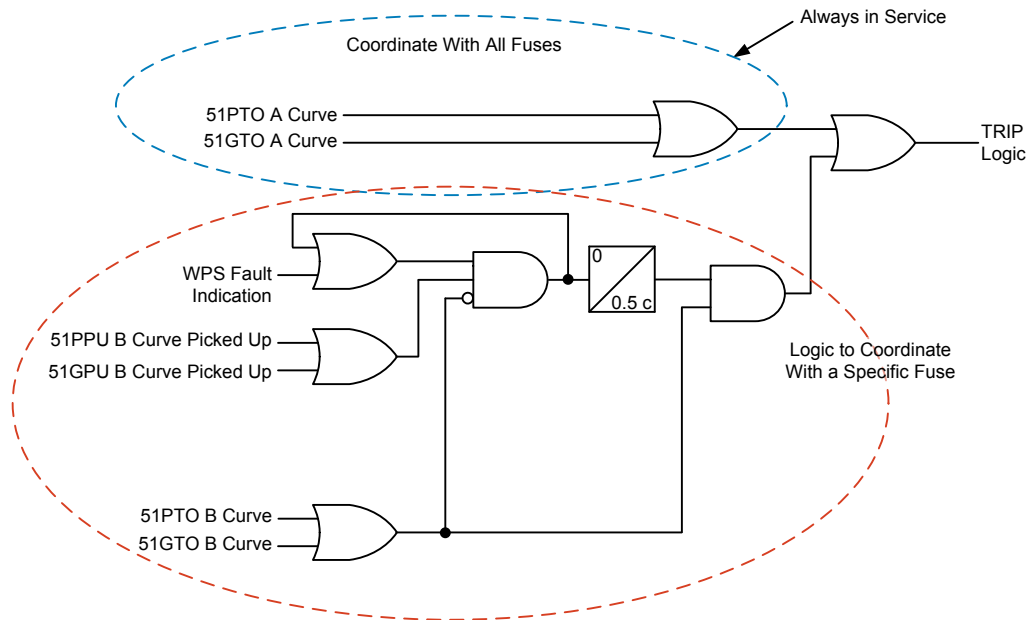


Fig. 15. Coordination With a Specific Fuse

For example, if there is a fault beyond one of the 40T fuses, the fuse will blow quickly and the breaker relay or recloser control will not operate. If, however, the fault is on an unfused line section that is not beyond a fuse, the recloser control must wait for the entire 100T-coordination delay before tripping. This adds stress to the system and affects power quality the same as in the previous example in Fig. 13.

In this situation, tripping could occur after a 40T coordination delay, which for a 2 kA fault is 3.3 cycles. This is much faster than the 100T coordination delay of 18 cycles.

By installing WPSs before the start of the line section with the 40T laterals, the recloser control can be configured to speed up the trip response for such faults.

Upon detecting a fault using local overcurrent elements, if no fault indication is received from the WPS, the relay operates the fuse-blowing scheme. This coordinates with 100T fuses.

If instead, the WPS fault indication is received while the local overcurrent elements are picked up, the relay enables a characteristic that coordinates with a 40T fuse. The slower 100T-coordinated, fuse-blowing overcurrent element is left in service as a backup. Fig. 15 illustrates this logic. For faults beyond any fuse in Fig. 14, the fuse-blowing scheme simply allows a fuse to blow. For faults on the unfused line section, the recloser trips on the faster characteristic, reducing stress on the system.

In most cases, at least one reclose is attempted to allow service restoration if the fault is temporary.

With additional sensors, this customized coordination can be applied to other unfused taps or line sections that have only 40T taps.

VII. TEST RESULTS

Bench tests are valuable to characterize the performance of any new technology. The WPS system test setup block

diagram is shown in Fig. 16. The test setup includes a current loop, a WPS, a collector, an emulated protection device, and an oscilloscope.

The current loop generates a 10 A, 60 Hz power system signal that simulates a power line. The loop is also capable of generating a 1,000 A fault current. The WPS contains fault detection logic, a transmitter, and an antenna. The collector contains radio receivers, a human-machine interface, and a serial interface that allows communication with the protection device.

The oscilloscope is connected to the test equipment via three probes. One probe measures the current in the sensor. The second probe measures a signal in the collector that is ready to be sent out. The third probe measures the output contact of the protection device. The probe connections are shown in Fig. 16.

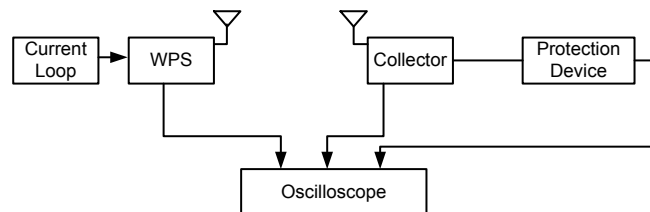


Fig. 16. Test Setup

The test characterizes the time required for the system to assert the protection device's output contact from the instant a fault is detected. This provides the latency of the entire system. Fig. 17 shows the measurements taken from all three probes. Point A indicates the instant when the fault is detected by the WPS, and Point B indicates when the protection device's output contact is asserted. In this test, the overall latency from fault detection to output contact assertion is 8.24 ms. The test shows that the WPS system can have a latency between 0.5 and 1 cycle. This is the latency that a

protection device, such as recloser control, requires in order to receive the fault status and make protection decisions.

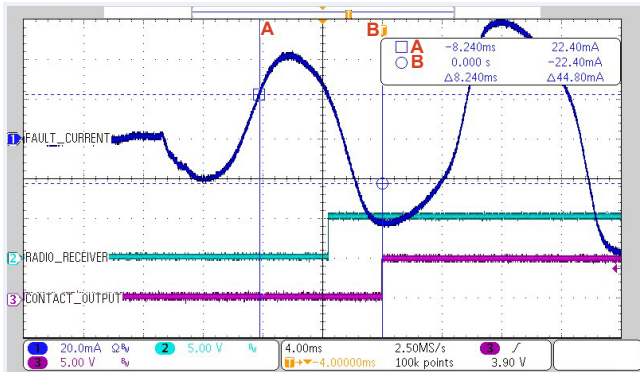


Fig. 17. Example of the Test Result

VIII. CONCLUSION

The WPS system gives more visibility into the distribution power system. WPSs indicate which lateral(s) has a fault and send the fault status to a protection device (like a protective relay in the substation or a recloser control out on a pole) at protection speeds. With this information, the protection devices have additional information to make decisions, altering (for the better) the traditional tradeoff between selectivity and speed. The WPS information allows protection devices to speed up protection actions without sacrificing selectivity. This reduces the duration of faults and therefore reduces the risk to public safety, reduces stress on the power system, and increases power quality.

The WPS system improves the operation of several distribution protection schemes. The improvements are in either speed or system reliability. Switching over on the fly from fuse saving to fuse blowing, or vice versa, gives flexibility to utilities dealing with different weather conditions or different line sections. For example, in severe weather conditions, switching over from a fuse-blowing scheme to fuse-saving scheme is perfectly acceptable because customers expect brief interruptions during such conditions, and utilities may want to try to save the fuses instead of blowing them. By switching over on the fly between feeder cable protection and first-span protection, the WPS system improves system reliability when the feeder transitions from underground to overhead or vice versa.

The WPS system helps improve the speed of protection actions by knowing that a fault is on an unfused section. The system also helps to speed up protection actions when using different fuse sizes. The protection devices do not have to wait for the largest (or slowest) fuse to blow when faults are on taps with smaller fuse ratings.

This paper provides three principles for deploying WPS systems in distribution protection schemes. The principles help ensure safe distribution protection scheme operation even when the WPS system is unable to provide fault indication data. The protection devices should not make protection decisions based solely on sensor data and should only use such data to augment existing schemes.

Test results prove that the WPS system can meet the stringent latency requirements of distribution protection schemes. The test shows that the protection devices can decode the received information and use it to make decisions within 1 cycle after fault detection. At this speed, it is fast enough to handle fault currents up to 7 kA for 100T Type T-Tin fuses, for example. As a result, a WPS system significantly improves a wide range of distribution protection schemes.

IX. REFERENCES

- [1] T. Gönen, *Electric Power Distribution Engineering*, 3rd ed. CRC Press, Boca Raton, FL, 2014.
- [2] J. Blair, G. Hataway, and T. Mattson, "Solutions to Common Distribution Protection Challenges", proceedings of the 69th Annual Conference for Protective Relay Engineers, April 2016.
- [3] J. L. Blackburn and T. J. Domin, *Protective Relaying: Principles and Applications*, 4th ed., CRC Press, Boca Raton, FL, 2014.
- [4] J. Roberts and K. Zimmerman, "Trip and Restore Distribution Circuits at Transmission Speeds," proceedings of the 1999 IEEE Rural Electric Power Conference, Indianapolis, IN, May 1999.

X. BIOGRAPHIES

Kei Hao, P.E., received his Ph.D. in electrical engineering from the University of Wisconsin–Madison, his M.S.E.E. from the University of Wisconsin–Milwaukee, and his B.S.E.E. from La Universidad de la República, Uruguay. He joined Schweitzer Engineering Laboratories, Inc. in 2010 as an automation and protection engineer. He is presently a lead product engineer in research and development. He has experience in control and automation systems, wireless communications systems, and power system automation and protection. He is a member of the IEEE and a registered professional engineer in the state of California.

Shankar V. Achanta received his M.S. in electrical engineering from Arizona State University in 2002. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2002 as a hardware engineer, developing electronics for communications devices, data acquisition circuits, and switch-mode power supplies. Shankar currently holds six SEL patents, and he is an inventor on several patents that are pending in the field of precise timing and wireless communications. He currently holds the position of engineering director for the precise time and faulted indicators and sensors group at SEL.

Jakob Fowler received his B.S. degree in electrical engineering from Northern Illinois University in 2011. He joined Schweitzer Engineering Laboratories, Inc. in 2011 as an associate field application engineer in the fault indicator and sensor division. He focused primarily on support for faulted circuit indicators used on distribution circuits. In 2014, Jakob transferred to the research and development division to work on the development of faulted circuit indicators and sensors.

David Keckalo received his B.S. degree from the University of British Columbia in 1987. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 1998 and is a lead power engineer in wireless systems. In previous positions, he worked on the design and development of many of SEL's protective relay products, including product literature. Prior to SEL, David held various positions at BC Hydro, concluding 10 years of service as a senior distribution engineer. He holds one U.S. patent, is a registered professional engineer in British Columbia, and is a member of the IEEE.