Adaptive Coordination Schemes to Reduce Fault Energy in Distribution Feeders Using Wireless Protection Sensors

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***Abstract*—Many utilities with overhead distribution lines make tradeoffs when designing protection schemes. Ideally, the system minimizes fault energy by limiting fault duration in high-risk environments, yet maximizes power quality and availability in urban areas.**

This paper describes how these contrasting goals are achieved using wireless protection sensors to identify the faulted line section and instantly transmit fault messages to a recloser control. With this real-time information, the protection logic adapts its response for the faulted section, dynamically applying fast overcurrent elements with a truncated reclosing sequence to reduce fault energy in high-risk sections, using standard schemes elsewhere.

I. Introduction

Today's distribution protection systems sacrifice speed for selectivity to provide reasonable service continuity and limit the number of affected customers. The tradeoff uses time delays to establish selectivity when many protection devices (such as protective relays, reclosers, and fuses) in series detect the same fault current. To ensure selectivity, the upstream device (backup) must include an intentional coordination delay to allow any downstream device enough time to clear a fault. The time-overcurrent curve of the backup device is set slower than the downstream protection devices, including some margin.

When faults occur in the immediate zone downstream of a device, that device becomes the primary protection. However, the coordination delay designed for the backup role is still in service, leading to long fault-clearing times.

When a fault occurs on a distribution feeder, the high current level can result in equipment damage and expose bystanders to an arc-flash burn hazard at the fault location. The energy released is proportional to the amount of time the fault persists and the square of the fault current. While fault magnitude generally cannot be controlled on a multi-grounded system, the fault duration can be managed. The energy released can cause severe consequences if the protection system does not clear the fault quickly, especially in high-risk environments. Therefore, reducing fault-clearing time on a distribution feeder is a critical path to reducing the energy released during a fault.

The main incentive for speeding up protection schemes in distribution feeders is public safety. A fault or downed conductor poses a hazard through direct or indirect electrical contact and is an ignition source for wildfires. The potential for injury and property damage increases when faulted conductors are not quickly de-energized. Other benefits include reducing stress on the distribution feeder and equipment, and improving power quality and reliability.

A solution to reduce fault duration, at least at specific areas, is to sacrifice selectivity to speed up tripping. Although this is a solution that is only acceptable under certain circumstances, this paper shows that it is possible to speed up tripping without sacrificing selectivity in other areas through the use of wireless protection sensors (WPSs). It describes how WPSs can reduce fault duration by identifying a faulted line segment in high-risk areas and communicating the information to a relay or recloser control with minimal latency. With real-time knowledge of where a fault is occurring, the relay logic can adaptively enable a fast time-overcurrent curve and/or change the reclosing sequence that coordinates with downstream devices. Therefore, by adaptively changing the tripping speed, the feeder protection reduces the fault energy released, reducing hazard levels and minimizing the negative impact of faults in high-risk areas.

II. Distribution Protection Schemes and Equipment

A typical radial distribution system is shown in Fig. 1. In this example, two distribution feeders emanate from circuit breakers attached to the substation bus (only one feeder is drawn in detail). Each feeder breaker is controlled by a protective relay that trips during overcurrent conditions caused by downstream faults, which protects the conductors and substation equipment from fault damage and isolates the faulted line from the rest of the distribution bus. Usually, the feeder main line is a three-phase circuit with lateral branches that tap off the main line. The branches can be one-, two-, or three-phase circuits. Utilities often install pole-mounted reclosers (with accompanying recloser controls), sectionalizers, and fuses along the distribution feeder to interrupt faults on downstream segments of the feeder and isolate the faulted segment. It is common practice to use fuses on the laterals to isolate faulted branches of the feeder.

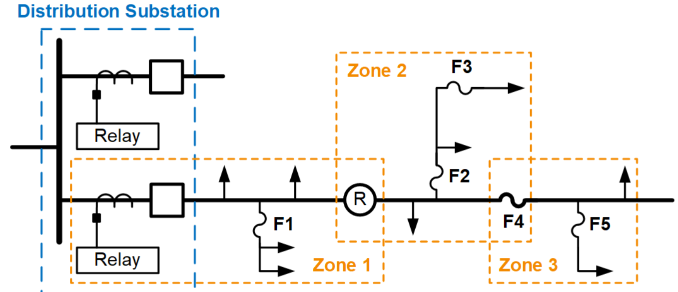

Fig. 1. Typical Overhead Distribution System

Ideally, for a radial system, the feeder breaker relay, recloser controls, sectionalizers, and fuses are fully coordinated to achieve reasonable service continuity and reduce the number of affected customers. 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. The example feeder in Fig. 1 is protected by one breaker relay, one recloser, and five fuses. 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 unprotected.

Each protective zone has a protection device responsible for clearing faults within it. Faults outside a protective zone must be cleared by downstream protection devices. If a protection device fails to clear a fault inside its protective zone, the backup (upstream zone) device clears the fault. For this principle to work, the backup device must have an intentional delay to allow the downstream device to clear the fault. The selected time-overcurrent curve of the upstream device must be above the downstream device curve, including a time margin. Fig. 2 shows the time-overcurrent curves for the Fig. 1 example.

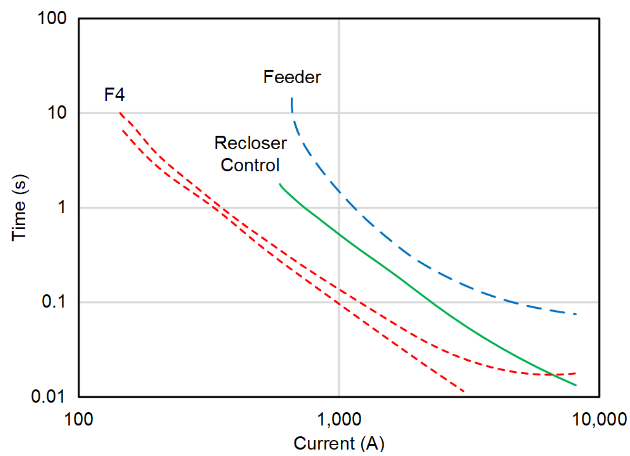

Fig. 2. Time-Overcurrent Coordination Among the Feeder Relay, Recloser Control, and Fuse F4

A. *Types of Faults*

1) Temporary Faults

Approximately 80 percent of the total number of overhead line faults are temporary. Temporary faults usually occur when phase conductors momentarily contact other phase conductors or ground due to trees, birds, rodents, high wind, lightning, flashover, and other causes.

2) Permanent Faults

Permanent faults require crews to repair them. Permanent faults on an overhead distribution system are usually sectionalized by fuses. While overhead faults are usually temporary, underground faults are usually permanent.

B. *Distribution Protection Equipment*

Distribution protection uses a variety of equipment. The type of equipment depends on the system element that is being protected and the system voltage level [1]. However, the most commonly used devices for distribution system protection outside the substation are reclosers, sectionalizers, and fuses.

1) Reclosers

A recloser is a type of circuit breaker, mated with a recloser control, that automatically trips and recloses a preset number of times to clear temporary faults or isolate permanent faults [2]. Two types of operations are typically available with recloser installations: nearly instantaneous (fast curve) and time-delay (delay curve) trip operations. Reclosers can be set for different trip operation sequences, such as

- Two fast curve trip operations, followed by two delay curve trip operations (shown in the Fig. 3 example).
- One fast curve trip operation, followed by three delay curve trip operations.
- Three fast curve trip operations, followed by one delay curve trip operation.

Fig. 3 shows a typical sequence of recloser operations.

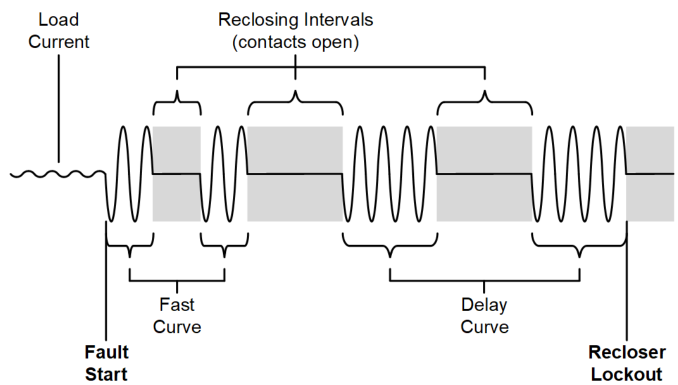

Fig. 3. Typical Recloser Operation Sequence (not to scale)

2) Sectionalizers

A sectionalizer is a device that automatically isolates a faulted line segment when an upstream breaker or recloser has interrupted the fault current. Sectionalizers have no capacity to interrupt fault current and must be used with a backup device [1]. The sectionalizer counts the number of interruptions caused by the backup automatic interrupting device and opens during the recloser-open interval after a preset number of tripping operations of the backup device [2].

The operation modes of a sectionalizer are as follows [2]:

- If a fault is cleared while the reclosing device is open, and the sectionalizer has not reached its preset count, the sectionalizer counter resets to its normal position when it detects load current after the circuit is successfully reclosed.
- If a fault persists (beyond the sectionalizer) when the circuit is reclosed, the fault current counter in the sectionalizer again prepares to count the next opening of the reclosing device.
- With the sectionalizer set to trip during the reclose interval following the second-to-last tripping operation of the reclosing device, the sectionalizer opens before the reclosing device closes the last time. Thus, the reclosing device recloses successfully because the sectionalizer is open, isolating the faulted line section and avoiding lockout.

3) Fuses

A fuse is an overcurrent device with a circuit-opening fusible member (i.e., fuse link) that is directly heated and destroyed by the passage of overcurrent through it when in an overload or short-circuit condition. Therefore, the purpose of a fuse is to clear a permanent fault by removing the defective segment of a line or equipment from the system [2].

A fuse is designed to blow within a specific time for a given value of fault current. The time-current characteristics of a fuse are represented by two curves:

- The minimum melting curve is a plot of the minimum time versus current required to start melting the fuse link.
- The total clearing curve is a plot of the maximum time versus current required to completely melt the fuse link and extinguish the arc.

C. Coordination of Distribution Protection Devices

Coordination is the process of selecting overcurrent protection devices with certain time-current settings and appropriately arranging them in series along a distribution circuit to clear faults from the lines and apparatus according to a preset sequence of operation. When two protection devices installed in series are designed to execute a specified operation sequence, they are considered coordinated or selective [2].

The following basic criteria typically apply when coordinating time-current devices in distribution systems [1]:

- The primary protection device clears a permanent or temporary fault before the backup protection operates.
- If the primary protection is a fuse and the backup protection is a recloser, in a fuse-saving scheme the fast curve of the recloser control operates for a fault beyond the fuse (with the recloser ideally clearing the fault before the fuse starts melting). The recloser then closes to test the fault. If the fault persists, this sequence can repeat if the recloser control is configured for additional fast curve operations.
- After any fuse-saving fast curve operation(s), the recloser reverts to its backup role and uses a delayed curve, which allows for a fuse to eventually operate if the fault is permanent. If no fuse blows, the recloser trips. If the recloser is configured with additional delay curves, it closes again and either trips again (if the fault persists) or remains closed if the fault has abated.
- An outage caused by a permanent fault is restricted to the smallest part of the system for the shortest time possible.

1) Recloser-to-Recloser Coordination

Coordination between reclosers depends on the type of reclosers. There are essentially two types of reclosers: hydraulic and electronically controlled.

a) Hydraulic Reclosers

In hydraulic reclosers, a current coil and its piston or mechanism opens the high-voltage contact. The operating speed of these devices is affected by ambient temperature. When determining curve coordination between devices, these additional criteria must be taken into account (example numbers may differ between recloser classes):

- Separation of the curves by less than 2 cycles always results in simultaneous operation.
- Separation of the curves by between 2 and 12 cycles could result in simultaneous operation.
- Separation of greater than 12 cycles ensures nonsimultaneous operation.

b) Electronically Controlled Reclosers

Two reclosers in series can be coordinated more closely. The downstream recloser must be faster than the upstream recloser. The clearance time of the downstream recloser, including its tolerance, should be lower than the upstream recloser response time, not including its tolerance.

2) Recloser-to-Sectionalizer Coordination

Since sectionalizers do not have time-current operating characteristics, their coordination does not require an analysis of time-current curves.

The coordination is based on the number of operations of the backup recloser. The operation can be any combination of fast or delay curve trip operations. The sectionalizer should be set for one trip operation less than the total number of trip operations for the recloser. If a permanent fault occurs beyond the sectionalizer, the sectionalizer opens and isolates the fault after the second-to-last operation of the recloser. For example, the sectionalizer opens on the third operation if the recloser is programmed for two fast and two delay curve trip operations.

If two sectionalizers are installed in series, the farthest sectionalizer should be adjusted for a smaller count. A fault beyond the last sectionalizer results in the operation of the recloser and the start of the counters in all the sectionalizers.

3) Recloser-to-Fuse Coordination

To protect against permanent faults, fuses are usually installed on overhead feeder taps and laterals. The use of reclosers as backup protection against temporary faults eliminates many unnecessary outages that occur when only using fuses. In a fuse-saving scheme, the recloser is set to trip for a temporary fault before any of the fuses can blow and then reclose the circuit. However, if the fault is permanent, it is cleared by the correct fuse before the recloser delay curve trip operation, following one or two fast curve trip operations [2].

The criteria for determining recloser-fuse coordination depends on the relative position of the devices, i.e., whether the fuse is on the source or load side of the recloser [1]. When considering source-side fuses, any substation primary-side transformer fuses should be included in the analysis.

a) Source-Side Fuse

When the fuse is on the source side, all recloser operations should be faster than the minimum melting curve of the fuse. The pre-fault thermal fuse loading should be included in the evaluation.

b) Load-Side Fuse

When the fuse is on the load side, the following procedure for coordination is used:

- To account for fuse heating from fault current and fuse cooling during a recloser-open interval, the minimum melting time of the fuse must be greater than the fast curve of the recloser scaled by a multiplying factor [1].
- The maximum clearing time of the fuse must be shorter than the delay curve of the recloser without any multiplying factor. The recloser should have at least two or more delay curve trip operations to prevent loss of service if the recloser trip overlaps a fuse operation.

On an overhead distribution system, a fault may be permanent, such as a tree lying across the line that requires repair. However, an estimated 80 to 90 percent of overhead faults are temporary [3], such as an animal contact event, where repair is not needed because the fault is interrupted quickly and 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 methods on a feeder with recloser-to-fuse coordination: a fuse-saving scheme or a fuse-blowing (trip-saving) scheme. Reference [4] provides a summary of the advantages, disadvantages, and limitations of each scheme.

4) Fuse-to-Fuse Coordination

The main criterion for fuse-to-fuse coordination is that the maximum clearing time for a primary fuse not exceed 75 percent of the minimum melting time of the backup fuse. This ensures that the primary fuse interrupts and clears the fault before the backup fuse is affected. The factor of 75 percent compensates for effects such as load current, ambient temperature, and fatigue in the fuse caused by the heating of fault currents [1].

III. Fault Energy

When a short circuit occurs in an electric distribution system, the resulting currents can be very high and introduce a significant amount of energy in the immediate vicinity of the fault. This paper focuses on overhead distribution systems, where faults generally occur between conductors and between a conductor and ground. Vegetation and structures may be involved in either fault type.

Some events start as one kind of fault and then evolve into another. For example, in a storm a tree may be blown onto an overhead feeder and initially cause a ground fault through the tree, and then a phase-to-phase fault can occur as the conductors are pressed together and make contact.

All components of the distribution power system that carry the short-circuit current are subject to both thermal and mechanical stresses due to the fault current flow. This paper focuses on the fault energy at the point near the fault itself. At the fault location, arcing and burning can occur, damaging equipment and creating a safety hazard.

Faults involving ground or vegetation provide a heating effect around the point of contact, potentially igniting combustible material. Arcing faults between conductors do not provide a direct heating source (as in a ground contact), but they can generate a fireball that damages the conductor by pitting the material, launching molten pieces of conductor into the air, and sending out sparks that can fall to the ground and act as an ignition source [5].

A. Math Review and Simplification

Equation (1) shows the Ohm's law derivation for power (P) produced when voltage (V) is applied across a resistance (R). When the current (I) through R can be directly measured, there is no need to separately consider V.

$$\begin{aligned} P &= VI \\ V &= IR \\ P &= I^2R \end{aligned} \tag{1}$$

Equation (2) defines energy as a function of I and time (T). This derivation is suitable when I is expressed as a root-mean-square (rms) magnitude.

$$E = PT = I^2RT \tag{2}$$

Using (2) for distribution system fault energy calculations is suitable when the modeled fault current is provided as an rms quantity and the fault duration is more than a few cycles.

To determine the energy for short duration faults, where T is less than 2 cycles, (3) factors in the time-varying nature of the instantaneous current (i). This detailed calculation includes the effect of transient dc offset that may be present in the first cycles of a fault.

$$E_T = R\int_{t=0}^{T} i^2 dt \tag{3}$$

Considering that a fuse is the only equipment capable of interrupting fault current in less than one cycle, the fastest relay or recloser control and associated interrupting mechanism requires more than one cycle to interrupt a fault; and considering that dc transients are short-lived at the fault levels on distribution systems, the simpler (2) is used in this paper for coordination and fault energy improvement examples.

B. Fault Resistance Treated as a Constant

The value of R is difficult to quantify. For ground faults, R can be affected by arc length, moisture, temperature, surface characteristics, and subterranean structures. The value of R can also change because of heating during a fault event. To maintain the focus of this paper, R = 1 is used, allowing the complexity of resistance to be ignored.

Removing R from consideration, current and time remain. Equation (4) expresses a unitless, normalized fault energy.

$$E_F = I^2T \tag{4}$$

Systems that use reclosing can cause more than one instance of fault energy. The heating effect of multiple fault current appearances during a reclose sequence must be considered.

Equation (5) expresses total fault energy (E_{FT}), including from an initial fault (T_{F1}) and two reclose attempts (T_{F2} and T_{F3}).

$$E_{FT} = I^2T_{F1} + I^2T_{F2} + I^2T_{F3} = I^2\left(T_{F1} + T_{F2} + T_{F3}\right) \quad (5)$$

The final summation term is the fault dwell time, which is the sum of each fault duration in the reclose sequence. If a fuse blows and interrupts fault current during any of the fault instances, the fault duration is cut short and there are no subsequent fault instances because the backup device does not trip. Fault dwell time is a convenient way to compare the performance of schemes with different reclosing strategies.

There is a cooling effect between faults in a reclose sequence, which depends on the reclosing relay open interval time settings. This cooling effect does not lower the total fault energy, but it can reduce the temperature level at the fault site. This paper ignores the cooling effect and uses (5) directly when reclosing is considered.

C. *Controlling Fault Energy*

According to (5), fault energy can be reduced by reducing fault current and/or fault dwell time.

1) *By Limiting the Fault Current*

The energy released in a fault depends mostly on the amount of arcing current, which is proportional to the square of current magnitude. Reducing the fault current is a good goal. Current-limiting (CL) devices and noncurrent-limiting breakers, along with protective relays, can reduce the energy released by reducing "let-through" fault current. CL techniques include using higher impedance transformers, high-resistance grounding, and devices such as reactors and CL fuses.

2) *By Limiting the Fault Dwell Time*

Often, the fault current magnitude cannot be economically controlled, so the fault dwell time is the controllable variable. This paper studies a solidly grounded system with noncurrent-limiting fuses, circuit breakers, and reclosers.

According to (5), fault energy is directly proportional to fault dwell time. The lowest possible duration for a single fault is determined by the interrupting device. Expulsion fuses can interrupt fault current as fast as 0.8 cycles (≈13 ms at 60 Hz). Reclosers are available with interruption times from 1 to 3 cycles (17 to 50 ms) and circuit breakers from 3 to 5 cycles (50 to 83 ms). Actual fault duration is usually longer, depending on fuse characteristics and coordination principles. In a coordinated scheme, both a fuse and an inverse-time overcurrent element in a relay provide a slower trip response at low fault current levels and a faster response at higher levels.

This paper explores changes that can minimize fault dwell time through changes in the protection scheme, recognizing that fault energy reduction can affect electric service availability.

IV. Speeding Up Feeder Protection for the Main Line

A. *Reference Case*

In this example, the feeder main line represents the conductor protected solely by the substation breaker and intentionally excludes line sections downstream of protection devices, such as midline reclosers and fuses. Although the main line can have branches, it is best represented as a straight line, as shown in Fig. 4. In this discussion, the main-line sections are called "in zone" and nonmain-line sections "out of zone."

This example uses a fuse-blowing scheme for the feeder main line, so the feeder breaker only trips for main-line faults. The feeder breaker must also trip as backup protection for out-of-zone faults not interrupted by a downstream device, usually in the case of miscoordination events.

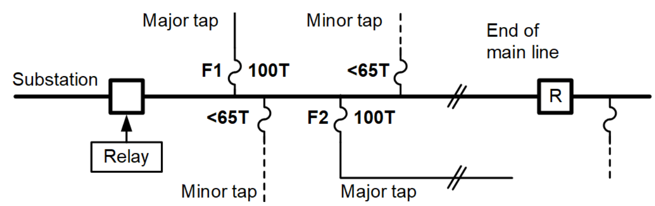

Fig. 4. Reference Feeder: In Zone (Main Line) and Taps

1) *Out-of-Zone Faults*

To provide security during out-of-zone faults, the standard protection element is a time-overcurrent (51) element. Fig. 5 shows the time-current characteristics for a typical substation relay, fuse, and field recloser. The feeder relay curve must be chosen to allow enough time for the slowest interruption of any possible out-of-zone fault, including a margin. The slowest device is usually the largest fuse tapped off the main line, which is the longest out-of-zone line section (i.e., a location with the lowest fault duty). The recloser (R) time-overcurrent element in Fig. 4 must also trip and interrupt fault current before the feeder relay can respond.

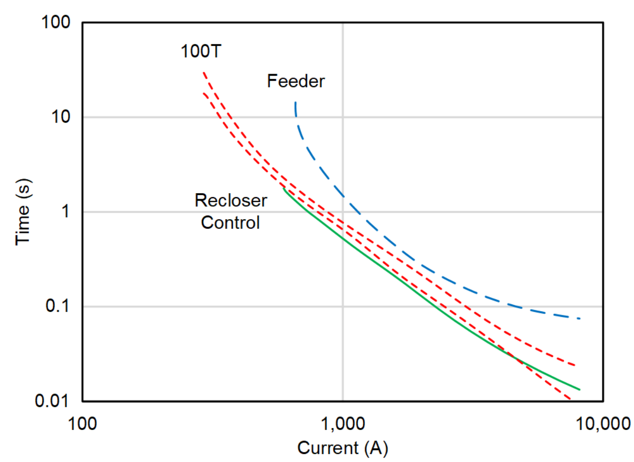

Fig. 5. Feeder Relay and Fuse Time-Overcurrent Coordination

Fig. 6 shows out-of-zone fault F1-1 protected by the 100T fuse (F1). A 6 kA fault will cause the fuse to blow in about 35 ms, long before the feeder protection times out at 88 ms. This timing is shown in Fig. 7a.

Once an out-of-zone fault causes the fuse to blow, the feeder relay time-overcurrent element drops out and then resets. Other than a voltage dip caused by the fault itself, customers outside the faulted zone do not experience an outage. The same coordination principle applies to faults beyond the field recloser, where the feeder breaker should not trip except as a backup.

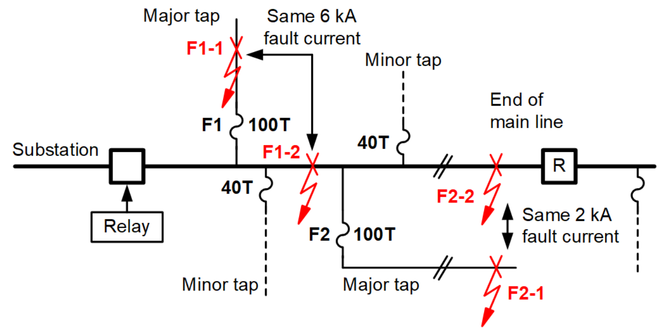

Fig. 6. In-Zone and Out-of-Zone Faults Reference Feeder Locations

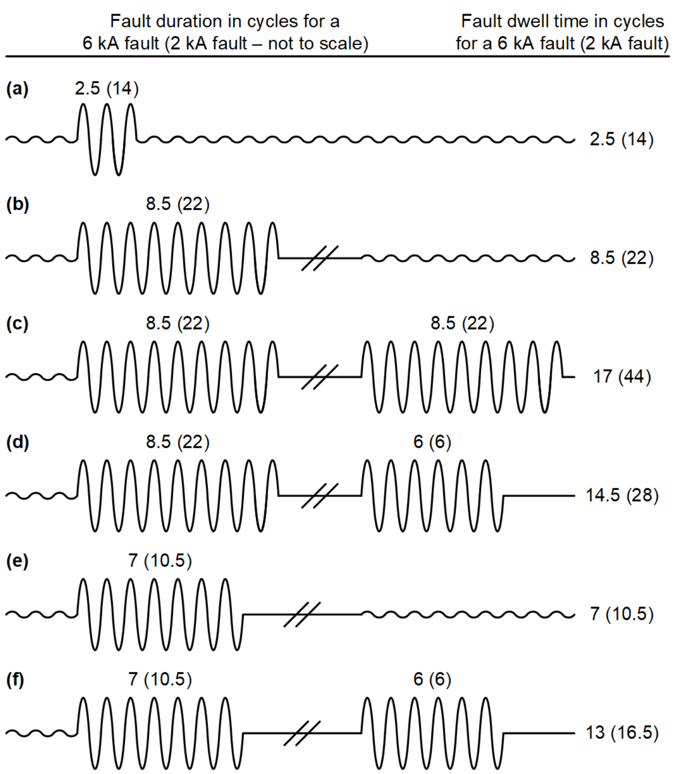

Fig. 7. Fault Dwell Time Comparison for Traditional Schemes (a) (b) (c) vs. Improved Schemes (d) (e) (f)

2) In-Zone Faults

For a main-line fault, the feeder relay operates on the same time-overcurrent curve, but in this case the element times out because no other device clears the fault.

Fig. 6 shows an in-zone fault (F1-2) not protected by a fuse. A 6 kA fault causes the feeder relay to trip after 88 ms, and the breaker interrupts the current 3 cycles later, for a total fault duration of 142 ms. Fig. 7b (first half) shows the timing.

The resulting feeder breaker trip causes a complete feeder outage. This is a successful operation. However, the cause of the fault may have abated, and the crew may find nothing to repair. In this case, the protection scheme effectively converted a temporary fault into a permanent outage.

Because main-line faults can be temporary, the feeder protection is frequently configured to perform one reclose attempt after an overcurrent trip event. If the fault does not reappear after reclosure, power returns for all customers (second half of Fig. 7b). This strategy reduces the number of permanent outages for the whole feeder.

In a traditional scheme, the relay arms the same time-overcurrent curve after breaker reclosure. If the fault is still present, the relay trips the breaker another time and locks out the reclosing relay. The whole feeder is de-energized until a crew can repair the line. Using the F1-2 example, the fault duration of the second fault is also 142 ms. The dwell time for a permanent fault as used in (5) is 17 cycles (283 ms at 60 Hz), which accounts for the initial fault and the reclose attempt. This timing is shown in Fig. 7c.

3) Problems With a Traditional Fuse-Blowing Scheme

The relay can only distinguish whether the faulted line segment is in zone after waiting for a fuse to isolate an out-of-zone fault. Fig. 6 shows two examples of in-zone faults: at positions F1-2 and F2-2. Once the feeder relay trips, useful information is gained about the fault: it must be in zone.

In a standard fuse-saving scheme, the relay uses the same time-overcurrent characteristic after the reclose attempt. If the fault is temporary, there will be no overcurrent pickup after reclosing, and the relay will reset. This timing is shown in Fig. 7b. However, if the fault is permanent, the relay applies the same curve as the initial fault and trips after the same delay. This is wasteful because there is no fuse present, and there is no reason to wait for one to blow. Fig. 7c shows the second fault with the same duration as the first fault. Table I shows the fault dwell time and normalized fault energy for the traditional scheme at the four fault points identified in Fig. 6.

Following the argument of this example, a second reclose attempt is ineffective for permanent faults. This extra line test causes unnecessary fault current exposure and no improvement to feeder availability [6].

B. Improvement 1: Shortening the Second Fault Duration

An easy improvement is to use a definite time-overcurrent element that trips quickly after a reclose attempt. The time delay could be set to a few cycles to test the line and provide immunity to short duration inrush current. Fig. 8 (top) shows a relay logic implementation.

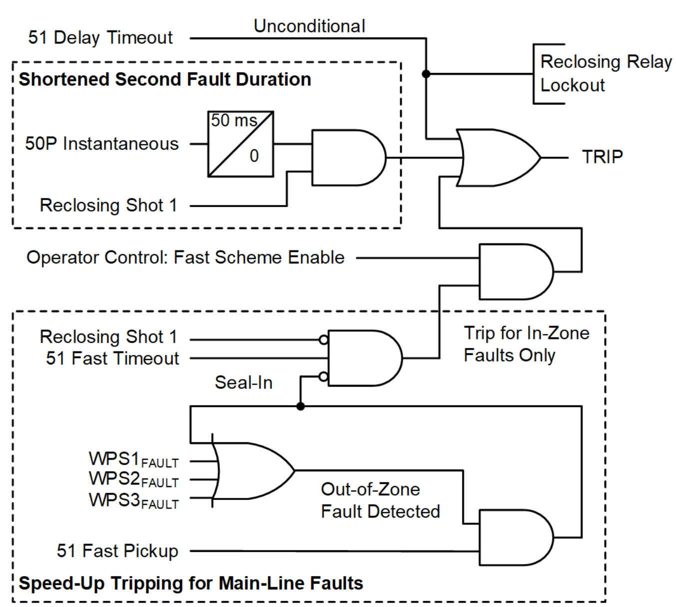

Fig. 8. Relay Logic Implementation for Improvements 1 and 2

By arming a 50 ms definite-time overcurrent element (horizontal line in Fig. 9) for the breaker reclosure, the duration of the second fault is shortened, thus reducing fault energy for in-zone faults such as F1-2. Fig. 7d shows the faster tripping response using Improvement 1. The traditional scheme response is shown in Fig. 7c.

Using this definite-time overcurrent element during the reclose attempt reduces fault dwell time (and fault energy exposure) for permanent in-zone faults. Table II shows the fault dwell time and normalized fault energy for the fuse-blowing scheme with Improvement 1 at the four faults at points identified in Fig. 6.

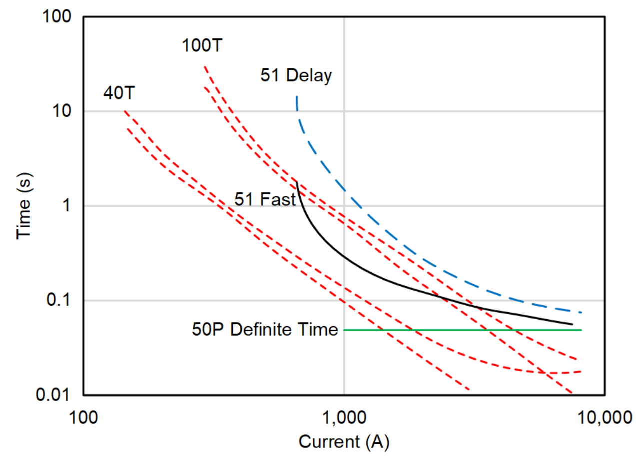

Fig. 9. Improvements 1 and 2 for In-Zone Faults

TABLE I
TRADITIONAL FUSE-BLOWING SCHEME

Fault Position (Fig. 6)	Description	Fuse Action	Relay Action (first fault detection)	Relay Action (second fault detection)	Total Fault Dwell Time (cycles)*	Total Fault Dwell Time (ms)†	Proportional Fault Energy‡
F1-1	Out-of-zone fault with high current (6 kA)	F1 blows in 35 ms	None	NA	2.5	42	1.50
F1-2	Temporary in-zone fault with high current (6 kA)	None	Trips after 88 ms	NA	8.5	142	5.10
F1-2	Permanent in-zone fault with high current (6 kA)	None	Trips after 88 ms	Trips after 88 ms	17	283	10.20
F2-1	Out-of-zone fault with low current (2 kA)	F2 blows in 230 ms	None	NA	14	233	0.93
F2-2	Temporary in-zone fault with low current (2 kA)	None	Trips after 312 ms	NA	22	367	1.47
F2-2	Permanent in-zone fault with low current (2 kA)	None	Trips after 312 ms	Trips after 312 ms	44	733	2.93

* Fault dwell times are rounded to the next half cycle.

† Calculated for a 60 Hz system.

‡ A smaller value is better.

TABLE II
IMPROVEMENT 1: SPEED-UP TRIP AFTER A RECLOSE OPERATION

Fault Position (Fig. 6)	Description	Fuse Action	Relay Action (first fault detection)	Relay Action (second fault detection)	Total Fault Dwell Time (cycles)*	Total Fault Dwell Time (ms)†	Proportional Fault Energy‡
F1-1	Out-of-zone fault with high current (6 kA)	F1 blows in 35 ms	None	NA	2.5	42	1.50
F1-2	Temporary in-zone fault with high current (6 kA)	None	Trips after 88 ms	NA	8.5	142	5.10
F1-2	Permanent in-zone fault with high current (6 kA)	None	Trips after 88 ms	Trips after 50 ms	14.5	242	8.70
F2-1	Out-of-zone fault with low current (2 kA)	F2 blows in 230 ms	None	NA	14	233	0.93
F2-2	Temporary in-zone fault with low current (2 kA)	None	Trips after 312 ms	NA	22	367	1.47
F2-2	Permanent in-zone fault with low current (2 kA)	None	Trips after 312 ms	Trips after 50 ms	28	467	1.87

* Fault dwell times are rounded to the next half cycle.

† Calculated for a 60 Hz system.

‡ A smaller value is better.

C. Improvement 2: Using WPSs to Speed Up Tripping for Main-Line Faults

If the faulted segment can be determined in real time, the feeder relay can accelerate tripping for all main-line faults. WPSs can provide this real-time faulted segment indication.

The improvement requires installing a WPS just before the fuses at the start of the major out-of-zone line sections (with the largest fuse ratings), installing a companion wireless fault receiver and antenna at the substation and connecting it to the feeder relay via high-speed serial communications, as shown in Fig. 10. Additionally, all other tap or service fuses connected to the main-line section should be specified with a lower rating than the major fuses (≤40T).

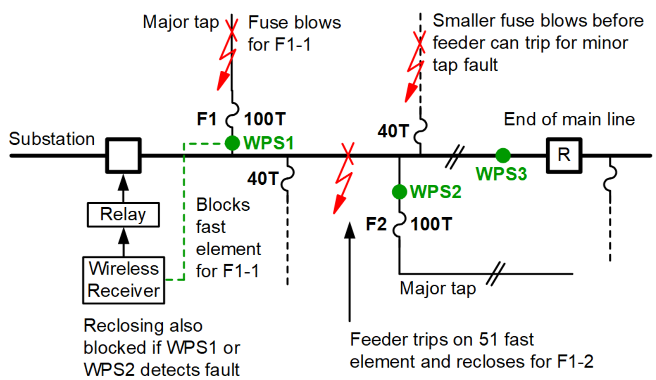

Fig. 10. WPS1 Detects Out-of-Zone Faults

The relay settings are modified to include a fast curve (51 fast) that coordinates with the smaller tap 40T fuses. This fast element is blocked only when a fault is determined to be out of zone, which includes the two major taps and the line past the field recloser (R). The delay curve is unconditionally in service. Fig. 9 shows the resulting time-current coordination graph.

With modest logic programming, the feeder relay can detect out-of-zone faults as they occur and block the fast curve. The Improvement 2 relay logic is shown at the bottom of Fig. 8.

The WPS identification from each of the locations shown in Fig. 10, Fig. 11, and Fig. 12 can alter the protection response, as outlined in the following:

- When a fault is identified as out of zone, one of the WPS1 or WPS2 installations sends a fault-detected signal back to the wireless receiver, as shown in Fig. 10 and Fig. 11. When the feeder relay receives this fault-detected signal, it blocks the fast element and uses its standard time-overcurrent element.
  - The expectation is that the identified out-of-zone section fuse will blow (Fig. 7a) and the breaker will remain closed.
  - If the fuse does not blow (due to miscoordination or equipment failure), the feeder relay standard time-overcurrent element times out, commands a trip, and blocks reclosing (left part of Fig. 7b), as indicated at the top of Fig. 8.
- The field recloser (R) is also considered out of zone. When the WPS3 installation detects a fault, it sends the status signal to the wireless receiver, as shown in Fig. 12. The feeder breaker blocks the fast curve to allow the recloser to operate without tripping the entire feeder. Backup protection is still available via the standard time-overcurrent element. Feeder breaker reclosing is blocked in this case.
- When a fault is *not* identified as out of zone, the feeder relay does not receive a WPS fault indication and does not block the fast time-overcurrent element that is coordinated with all minor tap fuses and service fuses.
  - If any fuse blows before the relay overcurrent element time out, the breaker remains closed.
  - If a fuse blows after the relay overcurrent element times out, the breaker trips too. In this case, the fuse likely miscoordinated and operated before the feeder breaker could interrupt fault current.
  - In any case, if the feeder breaker trips, the relay arms a definite-time overcurrent element (added in Improvement 1) and issues a reclose after the open interval time.
  - If no fault current appears after reclosing, service is restored for all customers, except those beyond any open fuses (Fig. 7e).
  - If the fault current reappears, the relay trips the breaker after the short delay (50 ms in the earlier example) and locks out reclosing (Fig. 7f).
- The trip speed-up logic can be disabled by operator control, as shown in the middle part of Fig. 8.
- Additional logic (not shown) automatically disables the trip speed-up scheme (Improvement 2) by monitoring the link quality of the WPS. This mitigates a situation where an out-of-zone fault occurs without WPS fault indication and the feeder breaker trips before the faulted tap fuse (100T) blows.

The performance of the fuse-blowing scheme with both Improvement 1 and 2 is shown in Table III.

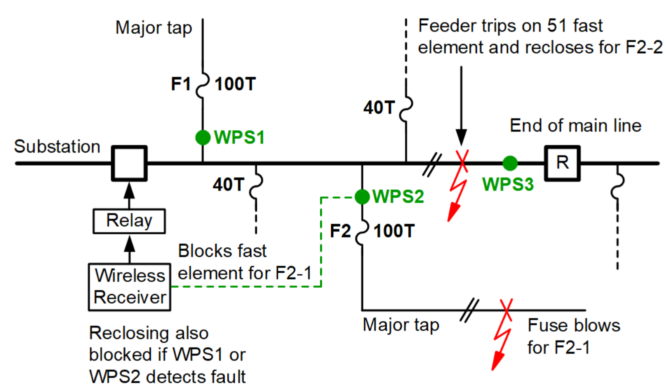

Fig. 11. WPS2 Detects Out-of-Zone Faults

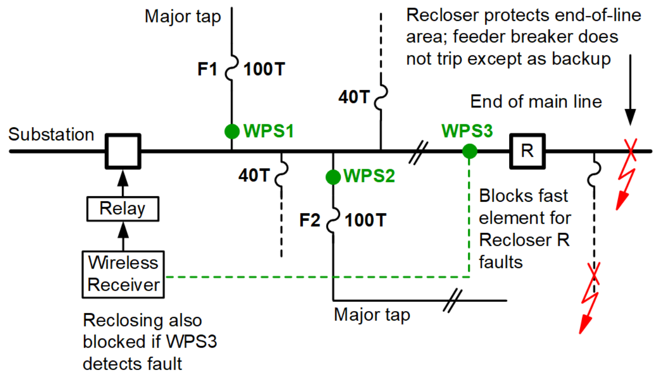

Fig. 12. WPS3 Detects Out-of-Zone Faults Beyond Recloser R

The WPS fault indication (for an out-of-zone determination) must be received quickly enough to successfully block a fast-responding element. The signal must be received and processed by the relay logic before the fast time-overcurrent curve can time out. Using 6 kA as the highest fault level, the Table III first fault detection value for 6 kA is 62 ms, which is approximately 3.75 cycles. The system described in Section VI operates in approximately one cycle, which is an adequate separation in this example.

This analysis should be performed on any system adopting Improvement 2 (speeding up tripping for main-line faults). If there is a tight margin between the WPS indication and fast curve timeout, a minimum response time can be added to the fast time-overcurrent element to increase the margin.

D. *Performance Comparison of the Traditional Scheme With Improvement 1, and Improvements 1 and 2 Together*

The original scheme and the two improvements are compared at two high-current fault locations (6 kA) and two low-current fault locations (2 kA).

Total fault dwell time for each scheme is listed in Table I, Table II, and Table III. Table IV provides a comparison of the fault dwell time and fault energy results from Table I, Table II, and Table III and includes a percentage reduction of proportional fault energy.

The total fault dwell time entries for relay operations in Table I through Table IV include a breaker clearing time of 3 cycles (50 ms at 60 Hz). The fuse-blowing times do not require any additional factors.

Overcurrent element settings and assumptions used in the example calculations are as follows:

- The standard feeder time-overcurrent curve is a U.S. very inverse curve (U3) with 600 A pickup and a time dial setting of 0.65. The curve coordinates with a 100T fuse-clearing characteristic and field recloser curves.
- The definite-time overcurrent element has a 1,000 A pickup and a delay setting of 50 ms.
- The fast feeder time-overcurrent curve is an International Electrotechnical Commission (IEC) short-time inverse curve (C5) with 600 A pickup and a time dial setting of 0.12. This curve coordinates with a 40T fuse-clearing characteristic.
- The circuit breaker interrupting time is 3 cycles.

Proportional fault energy is for comparison purposes, as described in Section III and (5).

Fault energy is reduced by up to 36 percent with Improvement 1 (speed-up trip after a reclose operation) and up to 63 percent with both Improvements 1 and 2 (speed-up tripping for main-line faults).

TABLE III
BOTH IMPROVEMENTS 1 AND 2 (SPEED-UP TRIP AFTER RECLOSING AND SPEED-UP TRIP FOR MAIN-LINE FAULTS)

Fault Position (Fig. 6)	Description	WPS	Fuse Action	Relay Action (first fault detection)	Relay Action (second fault detection)	Total Fault Dwell Time (cycles)*	Total Fault Dwell Time (ms)†	Proportional Fault Energy‡
F1-1	Out-of-zone fault with high current (6 kA)	1 (fault)	F1 blows in 35 ms	None	NA	2.5	42	1.50
F1-2	Temporary in-zone fault with high current (6 kA)	None	None	Trips after 62 ms	NA	7	117	4.20
F1-2	Permanent in-zone fault with high current (6 kA)	None	None	Trips after 62 ms	Trips after 50 ms	13	217	7.80
F2-1	Out-of-zone fault with low current (2 kA)	2 (fault)	F2 blows in 230 ms	None	NA	14	233	0.93
F2-2	Temporary in-zone fault with low current (2 kA)	None	None	Trips after 122 ms	NA	10.5	175	0.70
F2-2	Permanent in-zone fault with low current (2 kA)	None	None	Trips after 122 ms	Trips after 50 ms	16.5	275	1.10

* Fault dwell times are rounded to the next half cycle.

† Calculated for a 60 Hz system.

‡ A smaller value is better.

TABLE IV
COMPARISON OF TOTAL FAULT DWELL TIME AND PROPORTIONAL FAULT ENERGY RESULTS

Fault Position (Fig. 6)	**Table I Traditional Scheme**		**Table II Improvement 1**		**Fault Energy Reduction Compared to Table I**‡	**Table III Improvements 1 and 2**		**Fault Energy Reduction Compared to Table I**‡
	Total Fault Dwell Time (ms)*	**Normalized Fault Energy**†	**Total Fault Dwell Time (ms)***	**Normalized Fault Energy**†		**Total Fault Dwell Time (ms)***	**Normalized Fault Energy**†	
F1-1	42	1.50	42	1.50	0%	42	1.50	0%
F1-2 temporary	142	5.10	142	5.10	0%	117	4.20	18%
F1-2 permanent	283	10.20	242	8.70	15%	217	7.80	24%
F2-1	233	0.93	233	0.93	0%	233	0.93	0%
F2-2 temporary	367	1.47	367	1.47	0%	175	0.70	52%
F2-2 permanent	733	2.93	467	1.87	36%	275	1.10	63%

* Calculated for a 60 Hz system.

† A smaller value is better.

‡ A larger value is better.

V. MITIGATING FAULT ENERGY IN HIGH-RISK ZONES

A. High-Risk Zone Applications

A high-risk zone is a zone that requires specific protection schemes to mitigate the impact of the zone hazards. For example, a utility operating a feeder in a high-risk wildfire zone may require the feeder relay or recloser(s) to trip quickly for any detected fault and suspend reclosing in the dry seasons to reduce the risk of wildfire.

As shown in Section III, disabling reclosing reduces fault dwell time, as do the additional trip speed-up improvements explored in Section IV.B. The trip speed-up and reclose blocking schemes can be applied to high-risk zones, either seasonally or permanently.

However, there are drawbacks to operating a feeder with hair-trigger protection and no reclosing; almost every fault event causes a permanent feeder outage. These outages require time-consuming line patrols to find and correct the cause of the fault. After a temporary fault that does not blow a fuse, there may be nothing for the repair crew to find. Reducing the outage zone and patrol area footprint reduces the outage duration.

B. Fail-Safe Requirement

One requirement for any new scheme using WPSs is to "do no harm" to the original scheme [4]. The imperfect nature of radio communications must be acknowledged. The chances of a false positive (incorrect fault declaration) are very small, while a false negative (missing fault declaration) is greater and depends on factors mostly related to the radio signal path, interfering signals, and environmental conditions. For the example system, these uncertainties are summarized as follows:

- For conditional actions that would increase risk, using the WPS signals in a permissive role is a safe approach. For example, if using the WPS fault declaration signal to enable reclosing, reclosing would remain in the disabled state in case of a missing WPS signal.
- For conditional actions that would decrease risk, using the WPS signals in a blocking role is a safe approach. For example, if using the WPS fault declaration as a blocking signal for a fast time-overcurrent element, the fast element would remain enabled in case of a missed WPS signal, which is a safe outcome.
- With careful evaluation and scheme design, it may be possible to use WPSs in a blocking or permissive scheme in contrast to the previous two bullets.

The last examples in this section are applications of a blocking function for a reclosing scheme and its rationale.

C. High-Risk Zone Application Examples

1) Reducing Dwell Time When an Entire Distribution Feeder Is Inside a High-Risk Zone

The feeder in Fig. 13 is protected by a substation feeder relay that uses a fuse-blowing scheme covering the entire feeder (as discussed in Section IV.B). The relay is equipped with both fast and delay time-overcurrent elements (51). When the feeder relay detects a fault, both relay elements (51 fast and 51 delay) are picked up. The 51 delay curve is always enabled in the trip logic.

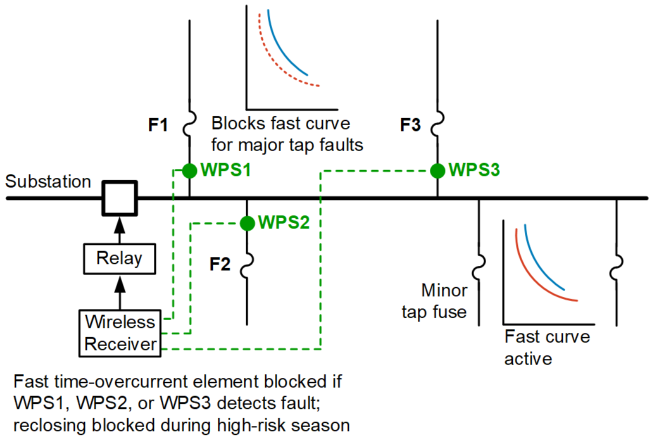

Fig. 13. Entire Distribution Feeder Is Inside a High-Risk Zone

In this example, every major feeder tap uses a fuse (F1, F2, or F3) for protection, and each tap also has a WPS (1, 2, and 3) to indicate if a fault has occurred on the tap. These major tap fuses must be coordinated with the feeder relay delay curve so the fuse blows before the feeder relay trips. Fuses downstream (not shown) of the major tap fuses coordinate with the tap fuse.

Minor taps and services do not have WPSs installed and are equipped with fuses with lower ratings that coordinate with the relay fast curve. By default, the relay fast curve is enabled, allowing a minor tap fuse or service fuse to blow without tripping the breaker. If the fault is on the main line and not protected by a fuse, the breaker trips on the fast curve (and does not reclose).

A fault on a major tap activates the associated WPS and wirelessly sends the fault-detected signal to the feeder relay via the wireless receiver. The relay protection logic uses the WPS fault signal to block the fast element from asserting the trip logic. With the fast curve disabled, the relay continues timing on the delay curve until the fault is cleared by a fuse (F1, F2, F3, or a downstream fuse along the tap). If no fuse interrupts the fault, the relay trips on its delay curve (and does not reclose). This latter case is an unexpected miscoordination; most likely, the tap fuse is incorrectly sized. Fig. 14 shows the simplified logic implementation.

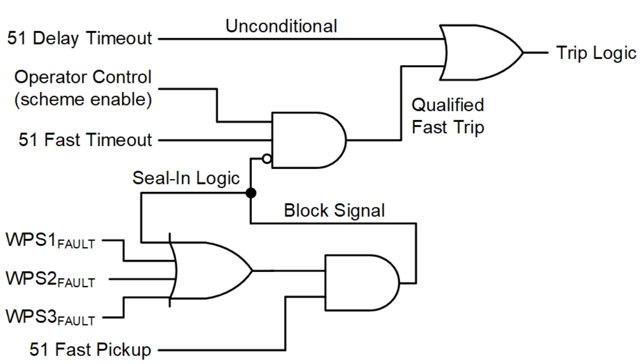

Fig. 14. Trip Speed-Up Logic for an Entire Feeder High-Risk Zone

2) *Allowing Reclosing Only in the Normal-Risk Zone of a Feeder*

The feeder is divided into two zones, with the high-risk zone on the source side and a normal-risk remote zone.

The previous example operates an entire feeder as a high-risk zone. While maximizing safety, this strategy exposes all customers on the feeder to outages because reclosing is not allowed. If the remote line is not in a high-risk area, a more conventional protection approach is preferred.

This approach is performed by installing WPSs at the boundary of the high-risk and remote zones, as shown in Fig. 15. By default, the feeder operates with reclosing disabled and a 51 delay characteristic that coordinates with 100T fuses.

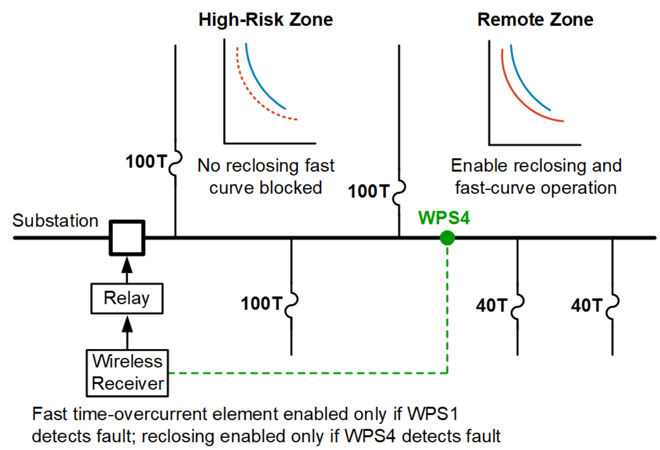

Fig. 15. Distribution Feeder With Two Risk Level Zones

The relay is also equipped with a 51 fast time-overcurrent element, which allows time for a smaller tap (e.g., 40T) or service fuse to blow in the remote line section, similar to Fig. 9.

The wireless receiver sends the relay a WPS4 fault indication when a remote zone fault occurs. The protection logic uses this information to enable reclosing and enable the 51 fast element. The resulting behavior allows for faster trip responses for remote zone faults (not cleared by a fuse) and reclosing after a remote zone trip.

If the relay does not receive a remote fault indication from the WPS, the 51 delay element is still in service and reclosing is inactive. This behavior is no worse than before the change, satisfying the three principles [4]. Fig. 16 shows a simplified logic implementation.

The speed-up function of Fig. 14, with a WPS installation on each major tap, could be combined with Fig. 16, but it is omitted for clarity.

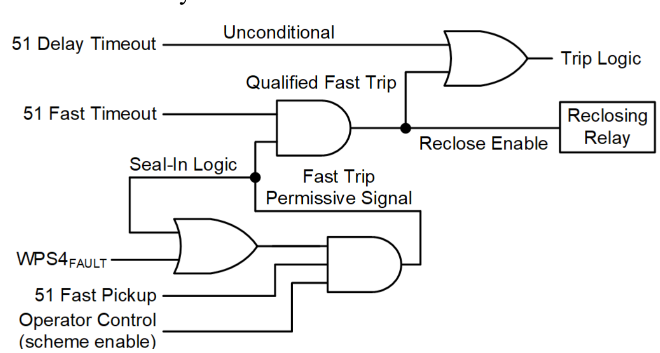

Fig. 16. Conditional Fast Trip and Reclosing Logic for Feeder With Two Risk Level Zones

3) *High-Risk Zone With Sectionalizers*

a) *Layout*

The distribution feeder depicted in Fig. 17 is separated into three segments. The source zone (left) is protected by a substation recloser (R1), and this zone extends to R2. A high-risk zone is bounded by R2 on the source side and Fuse E on the remote (right) side.

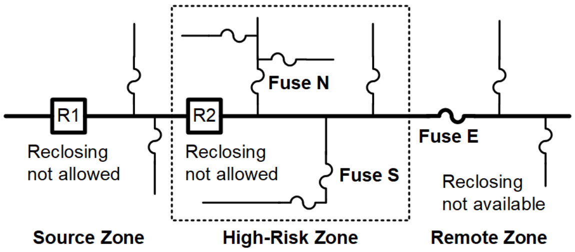

Fig. 17. Feeder With a High-Risk Zone Protected by R2

If the feeder protection has already been configured to minimize fault energy (Section IV.B), during critical environmental conditions, the utility selects a fast-tripping scheme with no reclosing to minimize fault energy in the high-risk zone (logic not shown). Thus, R2 trips for any fault, even if a fuse is melting. The simultaneous fuse and recloser operations successfully reduce fault energy, but all customers beyond R2 unnecessarily suffer an outage after the fault.

During standard environmental conditions, the utility could enable a fuse-blowing scheme at R2, allowing larger fuses to blow before R2 can trip. However, managing a seasonal change is inconvenient for systems that do not have remote configuration capability.

If R1 is properly coordinated with R2, customers in the source zone will not experience a service interruption for faults beyond R2 because R1 will not trip. However, R1 must not be permitted to reclose because it provides backup protection for R2 and the high-risk zone. The result is that all customers on the feeder will suffer an outage for any fault that trips R1, including source-zone faults.

The probability of R2 failure is low, but the nonreclose requirement at R1 degrades service availability by converting any unfused main-line fault in the source zone into a permanent feeder outage, but this tradeoff is necessary in extreme conditions. Rethinking the scheme and using sectionalizers alongside WPSs can reduce the scheme impact on system availability without increasing fault energy.

b) *Improvement 1: Allowing R1 Reclosing in the Source Zone While Providing Backup to the High-Risk Zone*

The additional equipment in Fig. 18 allows conditional reclosing of R1. By installing WPS W at the start of the high-risk zone and a wireless receiver connected to R1, the reclosing function of R1 can be enabled by default and blocked when WPS W indicates a fault.

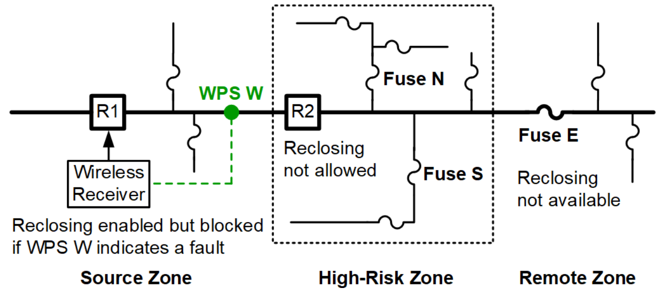

Fig. 18. Using WPSs to Provide a Reclose Block Signal to R1

Fig. 19 shows a logic implementation that blocks R1 reclosing for faults beyond R2 (WPS W fault indication received) or when the WPS W link status is down. The 30-minute dropout delay provides extended R1 reclose blocking while performing R2 backup protection, even if R2 seasonal reclosing is unintentionally left enabled. In this example, the WPS W fault pickup setting should be set between the R2 and R1 51 pickup levels to ensure reclose blocking is initiated only for faults that R1 can detect to avoid nuisance blocking for distant, lower current faults.

This reclose blocking scheme is secure for a single contingency failure. Protection system designers should follow best practices and evaluate the suitability of the scheme. A double contingency R2 failure coincident with a missed WPS W fault indication could cause undesirable R1 reclosure.

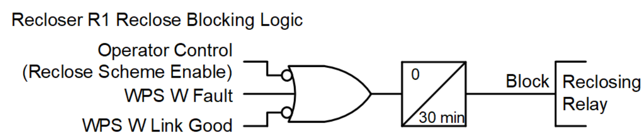

Fig. 19. Protection Logic for R1 Reclose Blocking Logic in Source Zone

c) *Improvement 2: Allowing Low-Risk Reclosing for Major Taps in High-Risk and Remote Zones*

Minimizing fault energy in the high-risk zone by using a nonreclose policy compromises system availability when a main-line fault is temporary. In Fig. 18, any fault that causes R2 to trip results in a permanent outage. During the high-risk season, the fast time-overcurrent elements may not allow time for a major tap fuse to blow (e.g., Fuse N and Fuse S) or remote zone Fuse E. The responding crew may need to patrol the entire R2 outage zone if the original fault was beyond one of the intact fuses.

The improved system shown in Fig. 20 replaces Fuse N, Fuse S, and Fuse E with electronic sectionalizers Sect N, Sect S, and Sect E in series with WPS N, WPS S, and WPS E. All sectionalizers three-phase trip. Both Sect N and Sect S are configured for one count to operate, and Sect E is configured for two counts. Finally, a wireless receiver is connected to R2 and the control logic modified to block reclosing by default, only unblocking in specific conditions.

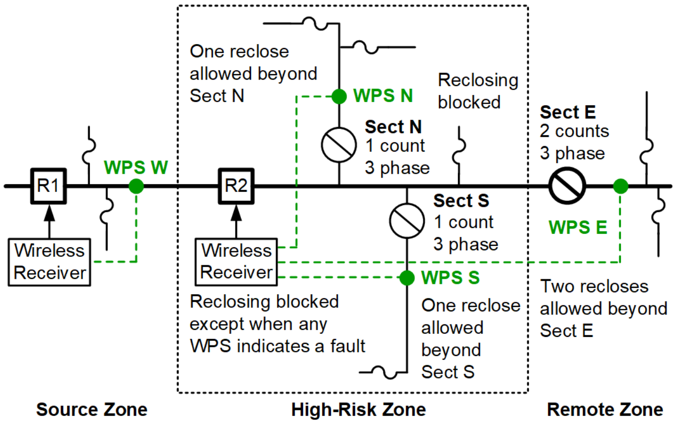

Fig. 20. Installing WPSs to Enable R2 Safe Reclosing for Certain Tap Faults

The extra equipment allows the following two major protection improvements and fail-safe case:

- The faults on the N or S taps that cause R2 to trip will also cause Sect N or Sect S to open. The companion WPS N or WPS S will send a fault-detected signal to the wireless receiver. With this available faulted segment information, R2 may execute one reclose operation without risk of energizing a second fault because a sectionalizer has already isolated the faulted line. The rest of the high-risk zone and remote zone customers have continued service. The open sectionalizer provides the patrol crew a clear indication of where the fault was.
- Faults in the remote zone cause WPS E to send a fault-detected signal to R2. If no fuse operates to interrupt the fault, R2 trips and is permitted to reclose due to WPS E fault identification. If the fault current reappears after reclosing, R2 trips a second time and Sect E opens. R2 may reclose once more. Because the remote zone is isolated by WPS E, R2 stays closed, restoring service to customers in the high-risk zone.
- By default, reclosing is blocked and only enabled if R2 trips and the fault is detected by WPS N, WPS S, or WPS E. This fail-safe behavior provides a nonreclose state in cases of failed WPS signal reception.
- The protection planner must evaluate the reliability of the sectionalizers used in this scheme and ensure the sectionalizer fault pickup level is set below the WPS fault pickup level.

Fig. 21 outlines a logic implementation for R2 that provides reclose initiate supervision for one reclose attempt if any WPS N, WPS S, or WPS E fault signal is present for an initial trip operation. A second reclose initiation is allowed when the WPS E fault signal is present for a second trip operation.

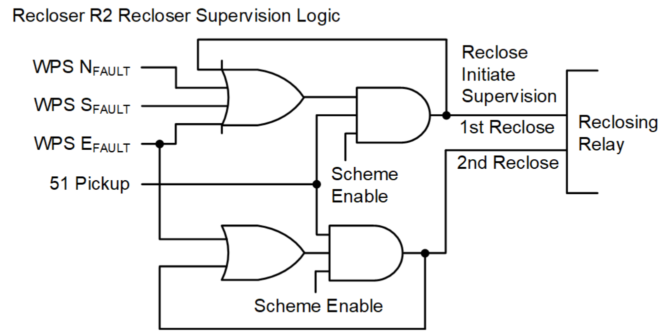

Fig. 21. Protection Logic Enabling Reclosing for WPS-Identified Faults Beyond a Sectionalizer

VI. WPS Description

A. WPS System

The WPS system has high-speed wireless communication capabilities to send fault information at protection speeds. The WPS system consists of WPSs mounted on an overhead line, a wireless receiver, and a protection device (such as a recloser control or relay), as shown in Fig. 22. When a fault occurs, the WPSs that detect the fault immediately send fault status to the receiver. The receiver sends the received fault status at a high speed to the recloser control.

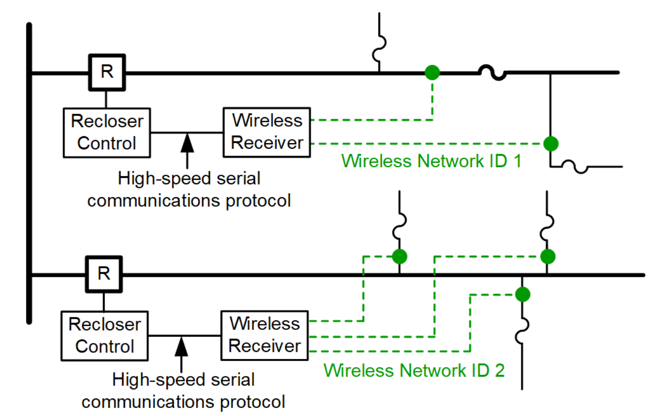

Fig. 22. WPS Systems on Adjacent Feeders

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 recloser control uses a high-speed serial communications protocol. To monitor WPS system health, the WPS periodically sends a heartbeat signal to the collector.

In this paper, a three-phase WPS installation is shown as a simple circle with a single label. For the examples discussed, the fault indication from a WPS installation does not require faulted phase information. The intelligent electronic device (IED) logic monitors a single fault status bit per three-phase WPS location.

B. WPS and Receiver Settings

WPSs require some configuration before installation. The protection behavior is defined by a fault detection overcurrent pickup threshold, which needs to be set according to the specific feeder and substation characteristics. When the current detected exceeds these setting values, the sensor communicates the fault signal to the receiver via high-speed wireless link [4]. The overcurrent pickup should be calculated based on the system protection scheme and other protective relays in the system. In general, the overcurrent pickup should be set as low as possible (to maximize sensitivity) while allowing an ample security margin above the peak steady-state load. The IED logic (relay or recloser control) should be designed to ignore cases where the WPS picks up transiently for inrush or switching conditions or during steady-state load conditions.

The wireless system requires unique sensor identifiers and network settings to ensure the wireless receiver recognizes messages from the WPS and to allow more than one system to be used in the same substation without conflict. Fig. 22 shows an example of a system that comprises two WPS systems installed in the same substation. These systems are expected to operate independently. Because the radio frequency communications between these systems cannot be isolated from each other, the equipment of each network requires a network identifier to allow co-located operation.

In the example in Fig. 22, one system has a network ID of 1, and the second system has a network ID of 2. Note that the wireless sensor and the receiver on the same network must be set to have the same network ID. Finally, the serial communications interface ports of the wireless receiver require bits per second (bps) and addressing settings that are compatible with the peer device, whether it is a logic processor or another IED.

VII. Conclusion

Traditional North American overhead distribution feeder protection schemes sacrifice speed for selectivity, and they provide a reasonable service continuity while limiting the number of affected customers. Although the same fuse-curve-based protection strategies have been in service for years, the long fault-clearing times and multiple reclosing attempts make them less suitable for environments sensitive to fault energy. In these situations, one solution is to permanently disable reclosing. While this does reduce fault energy, it can lead to unnecessary outages for certain fault locations and fault behavior.

This paper discusses a simple way to compare fault energy between these two proposals by defining fault dwell time. Adjusting the settings in existing protection designs can reduce exposure to fault energy, sometimes at the cost of system availability, generally accepting more outages to reduce fault energy.

This paper demonstrates fault energy reduction techniques that minimize this usual tradeoff and may not require a large equipment investment. This paper shows how to add technologies such as WPSs and electronic sectionalizers to the protection toolkit.

The WPS system provides a protection IED (relay or recloser control) with faulted segment information fast enough to change the response during a fault condition. In the high fault current system example, fault energy is calculated at selected fault locations, and the performance of traditional and improved protection strategies are compared. Some fault energy values were not improved, but others were much improved. The best fault energy reduction was 63 percent. The examples are designed to have minimal impact on (and in some cases improve) system availability.

The proposed schemes are presented for fail-safe operation or considered as solutions for single-contingency applications.

VIII. References

[1] J. M. Gers and E. J. Holmes, *Protection of Electricity Distribution Networks*, 3rd ed., The Institution of Electrical Engineering and Technology, London, United Kingdom, 2011.

[2] T. Gönen, *Electric Power Distribution Engineering*, 3rd ed., CRC Press, Boca Raton, FL, 2014.

[3] J. L. Blackburn and T. J. Domin, *Protective Relaying: Principles and Applications*, 4th ed., CRC Press, Boca Raton, FL, 2014.

[4] J. Fowler, S. V. Achanta, K. Hao, and D. Keckalo, "Apply a Wireless Line Sensor System to Enhance Distribution Protection Schemes," proceedings of the 43rd Annual Western Protective Relay Conference, Spokane, WA, October 2016.

[5] J. Blair, G. Hataway, and T. Mattson, "Solutions to Common Distribution Protection Challenges," proceedings of the 69th Annual Conference for Protective Relay Engineers, College Station, TX, April 2016.

[6] "Auto Reclosing of Power Lines and Types of Faults," *StudyElectrical.Com*, February 2020. Available: https://studyelectrical.com/2019/02/auto-reclosing-of-power-lines.html.

IX. Biographies

Kei Hao, P.E., received his PhD. in electrical engineering from the University of Wisconsin–Madison, his MSEE from the University of Wisconsin–Milwaukee, and his BSEE 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 development lead 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.

David Keckalo received his BS degree from the University of British Columbia in 1987. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 1998 and is a development lead engineer in research and development for distribution controls and sensors. Previously, 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 an IEEE member.

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