

# Improving Medium-Voltage Main-Feeder Reliability Using Automated Loop Restoration

## Introduction

S&C Technical Paper 766-T112, “Improving Medium-Voltage Main-Feeder Reliability by Increasing Fault-Sectionalizing,” focused on how increasing main-feeder fault-sectionalizing substantially improves reliability. As a reminder, this is traditionally the first step of a utility’s reliability-improvement campaign that implements the following fault-mitigation strategies and objectives incrementally using cost-justified solutions:

1. Increase main-feeder fault-sectionalizing to reduce SAIFI, SAIDI and MAIFI
2. Loop feeders to further reduce SAIFI and SAIDI:
  - a. Manually transfer unfaulted load to adjacent feeders initially
  - b. Automate load-transfer without using communication devices
3. Intelligently restore load quickly using communication to further extend SAIFI and SAIDI reductions:
  - a. Without overloading support feeders
  - b. Using multiple feeder inerties

Unfortunately, utilities often overlook choosing the best product that will satisfy all these objectives from the outset because they do not foresee the costs associated with the increasing challenges and complexities of subsequent goals.

So, rather than select a highly flexible product that incrementally and effortlessly achieves the first objective and ultimate goal, utilities frequently instead choose familiar low-cost products they expect will accomplish the easier initial strategies.

Eventually, utilities discover the significant hidden costs involved in making low-cost products more sophisticated and adaptive. And if they can’t augment the product with ancillary local and remote components that make it more intelligent, but subsequently add costs, utilities will end up replacing it as the reliability program progresses.

While the IntelliRupter® PulseCloser® Fault Interrupter is such a highly flexible product, this publication will only focus on its features when tackling the second strategy (2.b.) – automate load-transfer without using communication devices. Although this might be considered a fairly simple objective, this publication will demonstrate reclosers can limit a feeder loop-restoration goal.

Consequently, the following example will compare the capabilities of a 21st-century IntelliRupter fault interrupter with 20th-century recloser technology.

## Background

The example in Technical Paper 766-T112 segmented a 25-kV overhead feeder having 450 amperes of capacity and 300 amperes of peak load. IntelliRupter fault interrupters and reclosers were used to divide the feeder into equal segments so each segment had an equal number of customers. The segmentation strategy also had to reserve 150 amperes ( $450\text{ A} - 300\text{ A} = 150\text{ A}$ ) of the feeder’s spare capacity for future load-transfer purposes.

All devices were conventionally time-current coordinated with the existing substation circuit-breaker and each other, which ultimately limited the number of recloser feeder segments.

Referring to **Figure 1** on page 2, fault-sectionalizing the feeder using IntelliRupter fault interrupters, or IRs, (top one-line) resulted in five series devices and six segments with 50 amperes of load per segment ( $6 \times 50\text{ A} = 300\text{ A}$ ).

Unfortunately, segmenting the feeder using reclosers, or RCs, (bottom one-line) didn’t produce the same level of segmentation. Consequently, there were only three series reclosers and four segments with 75 amperes of load per segment ( $4 \times 75\text{ A} = 300\text{ A}$ ).

This reduced recloser segmentation occurred because reclosers have less precise time-current characteristic (TCC) tolerance bands than does the IntelliRupter fault interrupter.



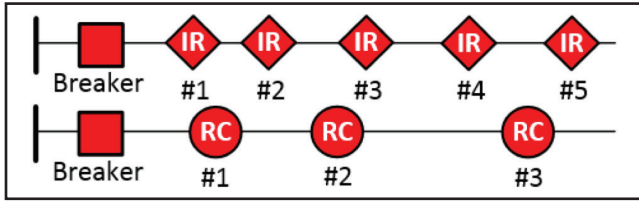


Figure 1. IntelliRupter fault interrupter (top) versus recloser (bottom) feeder segmentation.

## Looped Feeder Benefits

Once feeders have been segmented, the next step in improving reliability is to tie or loop them using a normally open fault interrupter, as shown in **Figure 2**.

Each feeder in **Figure 2** has the previously considered 450 amperes of capacity and 300 amperes of peak load. Consequently, this leaves a spare capacity of 150 amperes available for load recovery.

Referring to **Figure 3**, a persistent fault between IR #2 and IR #3 on feeder “A” has been isolated. Thus, feeder “B” can recover the three unfaulted feeder segments on feeder “A” (3 x 50 A = 150 A).

Likewise, an isolated persistent fault between RC #1 and RC #2 on feeder “C” will enable feeder “D” to recover two unfaulted feeder segments on feeder “C” (2 x 75 A = 150 A).

Although unfaulted load recovery is equal, it’s worth noting the load experiencing an extended outage is different (50 A instead of 75 A).

By equating load current to the number of customers, utilities can make a SAIDI-improvement comparison. If all feeder segments have uniform fault probability and fault-repair times, a 33% SAIDI benefit occurs when using IntelliRupter fault interrupters instead of reclosers [(75 A – 50 A) ÷ 75 A = 33.3%].

If the support capacity of Feeder B is 100 A instead of 150 A and the peak load on Feeder A remains the same (300 A), the increased feeder segmentation of the IntelliRupter fault interrupters enables more load to be recovered. This means the recloser-loop scheme could only recover one feeder segment, producing an extended outage for two segments (2 x 75 A = 150 A) and stranding 25 amperes of support capacity (100 A – 75 A = 25 A).

Alternatively, IntelliRupter fault interrupters would maximize the available support capacity by recovering two segments, leaving two unpowered (2 x 50 A = 100 A). Therefore, the previous 33% (IntelliRupter fault interrupter) SAIDI benefit would recur even though there was less support capacity [(150 A – 100 A) ÷ 150 A = 33.3%].

## Loop-Restoration Scheme Principles

After a persistent fault has been successfully cleared, looped feeders automatically transfer unfaulted feeder segments to the adjacent healthy feeder using their normally open tie-device. However, proper time-current coordination of series fault interrupters is required to ensure initial and subsequent faults are only isolated by the closest upstream fault interrupter.

Additionally, protection-response times are optimized for radial operation and not when feeders are looped. This means feeder devices are configured to clear faults faster for radial operation because radial operating conditions predominate.

Consequently, the faster fault responses of a few series devices under radial conditions conflict with the (slower) protection-response times required to coordinate multiple series devices during loop operation. Thus, an alternate means of coordinating devices that are transferred to the adjacent support feeder is necessary.

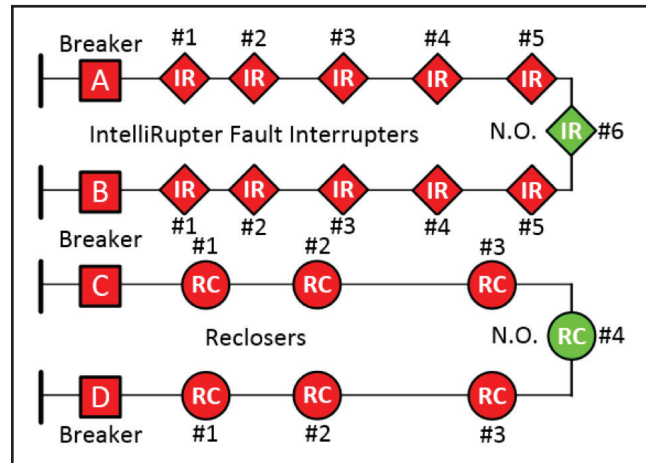


Figure 2. Looping neighboring feeders with IntelliRupter fault interrupters (top) or reclosers (bottom).

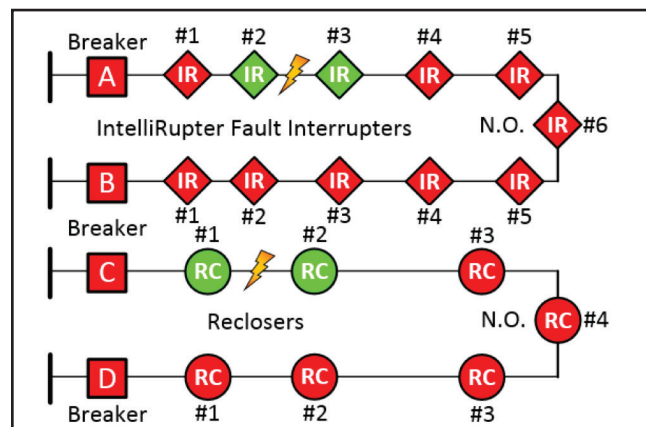


Figure 3. Looped feeders improve SAIDI because unfaulted load can be transferred to the adjacent support feeder.

Where feeders are sectionalized multiple times, devices that transfer to the adjacent support feeder must enable different directional-overcurrent protection settings. This is required because the amount of load a transferred device supplies changes. And fault-current levels differ because a device's location, relative to its normal or alternate power source, also changes.

Further, devices that transfer to the adjacent feeder must have three-phase voltage sensing on both sides of their fault interrupters (six-phase voltage sensing). This is necessary because pre-fault voltages are required to instantaneously determine fault direction. Therefore, a device must not only sense its normal source's pre-fault, three-phase voltage, but it also must sense the healthy three-phase voltage of the support feeder before transferring (closing). And, if these devices are to operate battery-free, both sides of the fault interrupter must also have a power source.

These voltage-sensing and powering requirements are necessary for the normally open tie-device. This is true because it must be powered by either feeder and determine that only one of the two feeders has lost supply; loss of supply for both feeders suspends automatic tie-device closing operations.

Likewise, normally closed devices must sense both the loss and return of supply and be powered from either source. To be clear, power from either source isn't typically required for opening a device because it generally has sufficient stored energy to open after an upstream device has progressed to lockout. However, this stored energy may be exhausted by the time the device is called upon to close.

After a device reaches lockout, feeder reconfiguration restores power to unfaulted feeder sections (without relying on communication) via loss-of-voltage (LOV) timer operations. Conventionally, two LOV times are used – a faster timer for opening all normally closed devices downstream of the fault and a slower timer for closing the normally open tie-device. **Note:** *Automated loop schemes limit the number of load segments that are transferred based on support capacity limitations. This requires predetermining which devices will participate to prevent overloading the support feeder.*

Using the recloser segmented feeders in **Figure 3** on page 2, “Step #1” in **Figure 4** on page 4 shows a persistent fault between RC #1 and RC #2 on feeder “C” has caused RC #1 to lock out.

“Step #2” shows the faster LOV timers expire and open normally closed RC #2 and RC #3.

In “Step #3,” the slower LOV timer expires and RC #4 closes blindly.

“Step #4” shows RC #3 closes blindly after it senses return of supply caused by RC #4 closing.

And finally, “Step #5” shows the persistent fault is subsequently transferred to feeder “D” when RC #2 also closes blindly.

After RC #2 closes onto the fault, it must now clear it before RC #3 begins responding. Note: This is not illustrated because the probability of reclosers in this example accomplishing this is highly unlikely without relying on high-speed communication-based protection.

## Recloser Loop-Restoration Scheme Limitations

Recloser loop schemes can be relatively simple to implement, provided there is only one midpoint recloser dividing each feeder in half. However, as fault sectionalizing increases, successfully maintaining conventional coordination becomes appreciably more difficult.

This is especially true when load is being transferred because several series devices can be added to a multi-segmented support feeder. So even if reclosers have six-phase voltage sensing and a control that enables different directional protection settings, they have much less precise TCCs (demonstrated in Technical Paper 766-T112) which discourages further conventional coordination of any transferred devices.

Also, the normally open tie-point or normally closed reclosers that open downstream of a persistent fault will always transfer the fault to the adjacent healthy support feeder. As was shown in “Step #5” of **Figure 4** on page 4, this occurred when RC #2 on feeder “C” closed. But this would also occur if the persistent fault was downstream of RC #2 or RC #3.

So, while load recovery of multiple recloser segments is possible, the process of transferring unfaulted feeder segments introduces conventional coordination challenges. These challenges resurface should subsequent faults occur in the transferred load sections. This happens because time-current coordination of the transferred reclosers is highly improbable without relying on high-speed communication-based protection schemes.

## IntelliRupter Fault Interrupter Automated Loop-Restoration

Use of PulseClosing® Technology and the PulseFinding™ Fault Location Technique are just two of the many innovative technologies differentiating the IntelliRupter fault interrupter from reclosers for loop-restoration schemes. Consequently, how they dramatically improve loop-restoration scheme performance will be explained.

### PulseClosing Technology

As a reminder, PulseClosing Technology generates a 0.25- to 0.5-cycle minor loop, or pulse, of current by rapidly closing and opening single-phase fault-interrupting contacts at specific voltage-point-on-wave angles. The device immediately analyzes the pulse to determine whether it reflects fault or load current. Two fault pulses suspend further fault testing until the

next open interval, as with breakers and reclosers. A load pulse closes that phase, the next phase is tested, and so on.

The electromagnetic energy ( $I^2t$ ) of two fault pulses are about 5% of what a recloser produces when it repeatedly recloses into a fault. The extremely low energy of a fault pulse substantially reduces system stress and helps extend substation power transformer service life.

This extremely low energy, coupled with the duration of a fault pulse, is equally important in preventing subsequent miscoordination with upstream protection. This means if an IntelliRupter fault interrupter is downstream of another fault interrupter, and both trip in response to a fault, subsequent downstream PulseClosing actions that test for the continued presence of the fault will not cause further tripping of the upstream device.

While the consequences of initial fault clearing cannot be avoided, subsequent fault testing using PulseClosing Technology never sags the feeder voltage. In fact, this revolutionary fault-testing method is so unintrusive, its operation is virtually imperceptible to all upstream loads.

The reason PulseClosing Technology is essentially transparent to upstream loads is the voltage dip caused by a fault pulse is a maximum of 0.5 cycles. As a result, once the initial fault is cleared, upstream loads and those on adjacent feeders are no longer affected by repeated testing for fault presence.

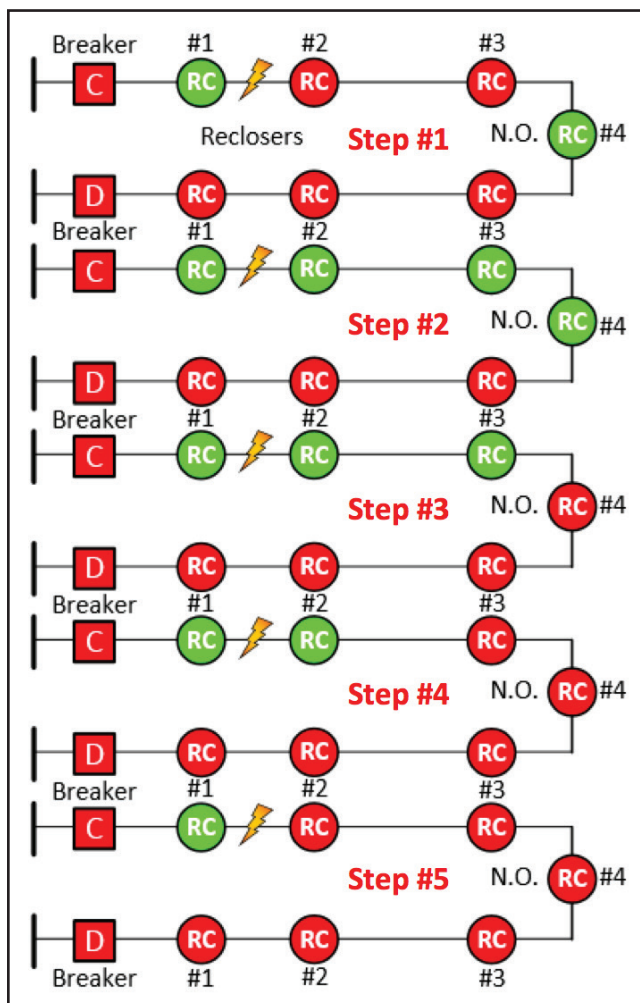
### PulseClosing Loop-Restoration Example

As with reclosers, two LOV timers control the opening and closing of IntelliRupter fault interrupters when a persistent fault occurs.

Using the IntelliRupter fault interrupter feeders of **Figure 3** on page 2, “Step #1” in **Figure 5** on page 5 indicates a persistent fault on feeder “A” has been cleared. And “Step #2” shows the faster LOV timers have operated.

In “Step #3,” the slower LOV timer begins the closing of normally open IR #6. However, unlike reclosers, “Step #3” shows IR #6 using the PulseClosing Technology to determine whether a fault exists between it and IR #5 on feeder “A.”

Detecting no fault in “Step #3,” “Step #4” shows IR #6 closes and IR #5 begins using the PulseClosing Technology upon reenergizing.



**Figure 4.** Recloser loop scheme sequence of operation. Note: The fault on feeder “C” is eventually transferred to feeder “D” in “Step #5.”

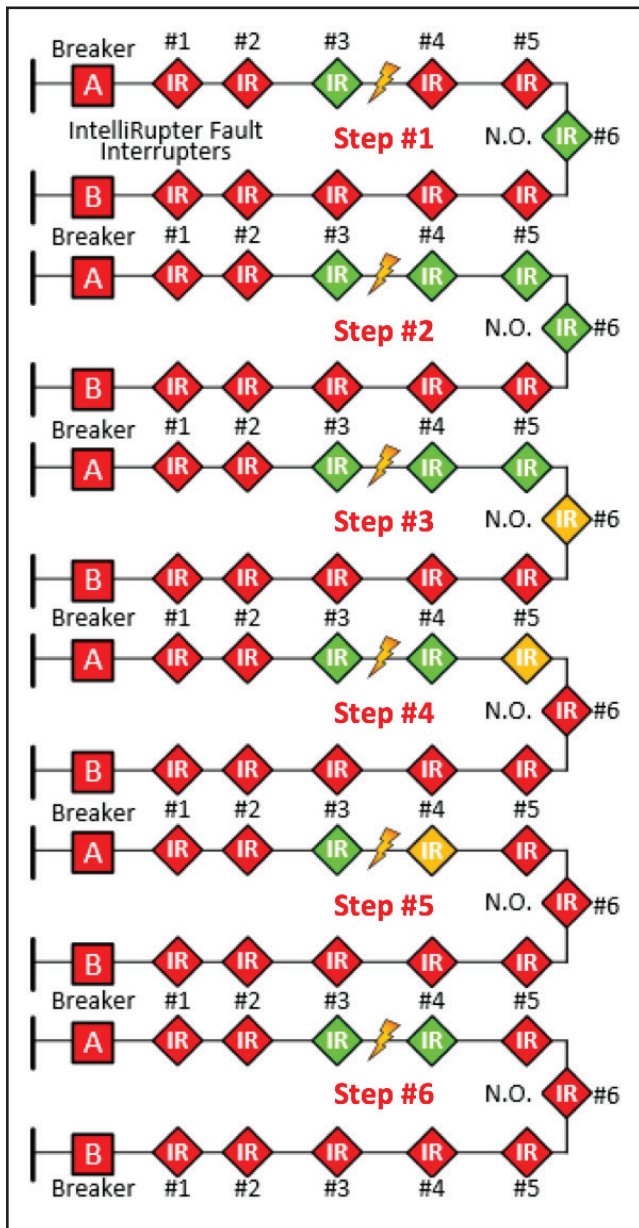


“Step #5” illustrates IR #5 detected no fault and closed, whereupon IR #4 on feeder “A” begins using the PulseClosing Technology. **Note: Each segment-transfer operation takes less than one second per IntelliRupter fault interrupter.**

And finally, “Step #6” indicates IR #4 on feeder “A” detected the fault, remained open, and locked out. So, unlike reclosers that always transfer faults, the PulseClosing Technology prevents fault-transfer.

### PulseFinding Loop-Restoration Example

The PulseFinding Fault Location Technique uses the PulseClosing Technology’s imperceptibility to improve system restoration by automatically hunting



**Figure 5.** IntelliRupter fault interrupter loop scheme sequence of operation. Note: Fault-transfer is avoided.

for faults. This means the PulseFinding technique automatically recovers from intended or unintended miscoordination with upstream devices. Consequently, the PulseFinding technique becomes an invaluable technology for loop-restoration schemes. This is true because it overcomes the coordination limitations of reconfigured recloser feeders.

So, unlike reclosers, IntelliRupter fault interrupters continue to isolate and recover from faults occurring in transferred feeder segments. As an example, **Figure 6** on page 6 considers the consequences of an initial persistent fault, “F1,” followed by a transient fault “F2.”

The **Figure 6** “T0” (faster) and “T1” (slower) designations adjacent to IRs #4, #5, and #6 signify their protection-response times when fed from feeder “B.” This indicates IR #4 and IR #5 share the same TCCs and will rely on the PulseFinding technique to recover when a subsequent fault occurs. This approach was taken because optimizing conventional time-current coordination for load-transfer conditions means normal radial operation protection (which is more prevalent) is slower.

So, while feeder “B” IntelliRupter fault interrupter TCCs could have been conventionally coordinated with those of feeder “A,” the PulseFinding technique is used instead. Consequently, downstream fused laterals in each feeder segment served by IRs #4, #5 and #6 can be successfully cleared without tripping IRs #4, #5 or #6.

Also, IR #5 is properly time-current coordinated with IR #6, and IR #6 is appropriately coordinated with IR #5 on feeder “B.”

“Step #1” indicates a transient fault “F2” occurs after the initial persistent fault “F1” was isolated and the downstream feeder “A” segments were transferred to feeder “B.”

“Step #2” shows IRs #4 and #5 trip in response to “F2” because they’re operating using the same TCCs. However, IR #6 doesn’t trip because it is properly coordinated with IR #5.

In “Step #3”, the transient fault “F2” has self-cleared and IR #5 begins its PulseFinding sequence.

Because IR #5’s PulseClosing operation resulted in no fault detected, “Step #4” illustrates IR #5 closes and IR #4 begins its PulseFinding progression.

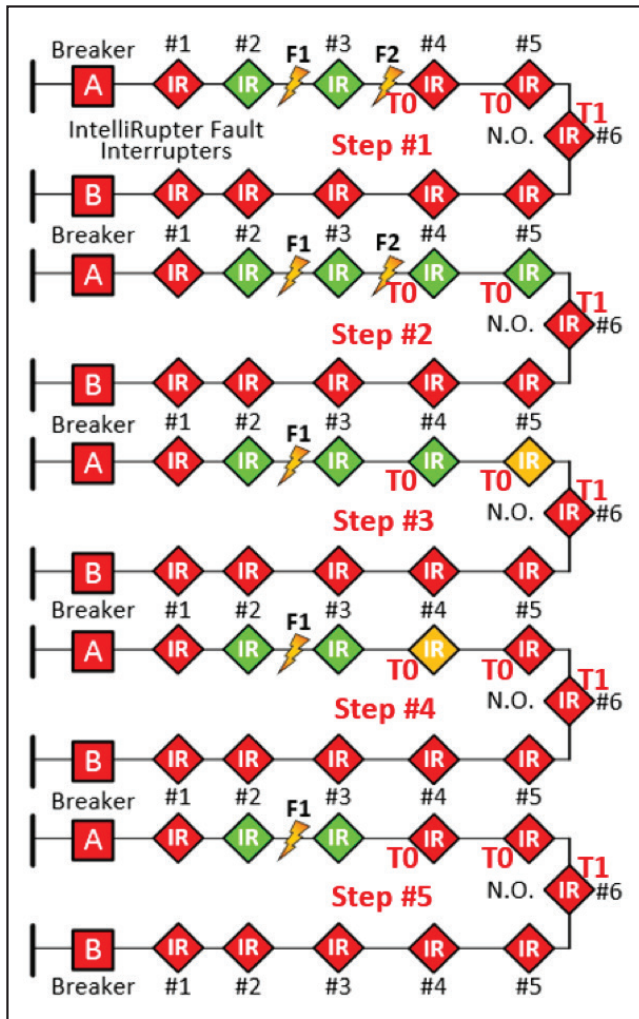
Finally, “Step #5” shows the PulseClosing operation of IR #4 indicated there was no fault present, so IR #4 closed.

## SAIDI Impact of Subsequent Faults

Faults occurring after an initial fault is isolated and load is transferred may be considered second-contingency events. As such, the value of addressing them is occasionally disregarded. But when feeders are looped and automated, this also means discounting the impact these subsequent faults have on SAIDI.

For example, a subsequent fault “F2” occurs in “Step #1 of **Figure 7**. This happens after fault “F1” has been isolated and unfaulted feeder “C” load is transferred to feeder “D.”

“Step #2 indicates if fault “F2” isn’t addressed by RC #3, RC #4 trips instead. Because RC #3 doesn’t isolate fault “F2,” the SAIDI benefits of loop restoration are basically nullified because the “Step #2” state of feeder “C” is the same as a radial feeder after RC #1 locks out because of fault “F1.”



**Figure 6.** Use of the PulseFinding technique addresses subsequent faults after loop schemes have operated.

## SAIDI Impact

SAIDI benefit percentages double when a fault-sectionalized radial feeder is tied to an alternate source with 100% spare capacity and automated loop-restoration is implemented [1].

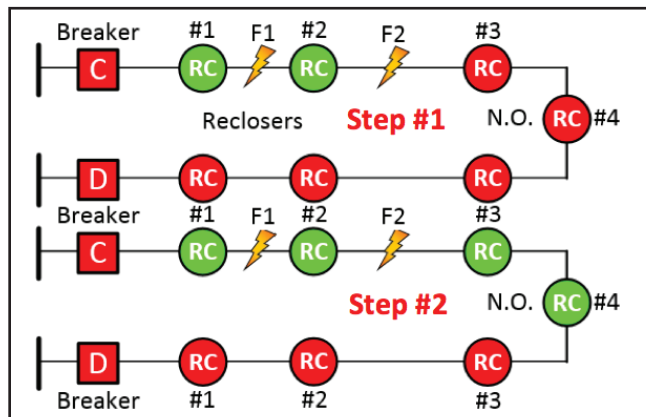
Referring to **Table 1** on page 7, this means a looped feeder with 300 amperes of peak load, four segments and 100% support capacity produces a 75% SAIDI benefit when compared to a radial feeder with no segmentation.

However, **Table 1** also implies the resources required to provide 100% support capacity (300 A) would be better used by reserving just 50% spare capacity (150 A) and adding two more (six) feeder segments – the SAIDI benefit is the same (75% vs 75%).

**Note: The Table 1 base case is an unsegmented radial feeder with uniform fault and customer distribution and fault repair times.**

But, if two more segments are added to a looped feeder with four existing segments (6 versus 4), this SAIDI improvement cannot be determined using **Table 1**. This is true because the **Table 1** base case is an unsegmented radial feeder and not a looped feeder with four segments.

Therefore, **Table 2** on page 7 indicates this incremental SAIDI improvement and the effect support capacity introduces. This also means if support capacity drops to 50%, the resulting four-segment benefit of 69% shown in **Table 1** can be improved by adding two more segments – 69% (**Table 1**) + 20% (**Table 2**). **Note: The Table 2 base case is a looped feeder with four segments, uniform fault and customer distribution, and fault repair times.**



**Figure 7.** The consequence of not addressing fault “F2” (top) is any SAIDI benefit is essentially lost (bottom).

Although not illustrated in **Tables 1** or **2**, the number of feeder segments and support capacity can significantly affect SAIDI benefits. For example, adding a third segment to a looped feeder with 300 amperes of peak load results in three 100-ampere segments. A support capacity of 100% would produce a 33% SAIDI benefit, but 50% support capacity only yields an 11% improvement.

This occurs because 100% support capacity (300 A) enables recovery of two segments (200 A) when a persistent fault occurs in the first feeder segment. Conversely, 50% support capacity (150 A) can only recover the third segment (100 A) when persistent faults occur in the first and second segments, stranding 50 amperes or 33% of support capacity.

## Conclusions

Many utilities believe transitioning feeders from radial to loop restoration is an easy and seamless process. While this is true for the IntelliRupter fault interrupter, there are additional hidden costs and complexities when accomplishing the transition using reclosers:

1. High-speed communication-based protection between all transferred reclosers, including the normally open tie-point – five of seven reclosers in this example
2. Communication hardware (required for item #1) – generally two per recloser if wireless
3. Different bi-directional overcurrent protection settings
4. Six-phase voltage sensing (required for item #3) – reclosers are replaced if not so equipped
5. Batteries and a battery charger or UPS
  - a. Required for item #2
  - b. Enables tripping when a recloser is closed, a fault is present, and supply returns
6. Ac power sources on both sides of the recloser (required for item #5)

Avoiding the expense of making a recloser more sophisticated means limiting reliability-improvement goals. This translates into reducing feeder segmentation objectives so they don't exceed the capabilities of a recloser's native components.

And even when a recloser loop scheme is restricted to basic feeder configurations (mid- and tie-point), reclosers will always transfer faults to the healthy support feeder unless communication between reclosers is used.

Conversely, the IntelliRupter fault interrupter is equipped with unique and innovative 21st century technologies, and these benefits make it ideal for loop-restoration applications:

1. PulseClosing Technology:
  - a. Prevents fault transfer
  - b. Substantially reduces system stresses caused by fault testing (reclosing)
  - c. Extends substation power transformer service life (because of 1(b).)
  - d. Enables the PulseFinding Technique
2. The PulseFinding Technique:
  - a. Enables multi-segmented feeders to be looped
  - b. Avoids high-speed communication-based protection schemes
  - c. Automatically recovers from subsequent faults occurring in transferred segments
  - d. Permits an unlimited number of series devices to recover from over-tripping

**Table 1.** Increased Segmentation Overcomes a Lower SAIDI Benefit When Support Capacity is 50%

Segments	Automated Loop vs Radial Feeder SAIDI Benefits – 100% Support Capacity (300 A)	Automated Loop vs Radial Feeder SAIDI Benefits – 50% Support Capacity (150 A)
4	75%	69%
6	84%	75%

**Table 2.** Incremental SAIDI Improvements for Six Versus Four Feeder Segments with 100% and 50% Support Feeder Capacity

Segments	Automated Loop vs Radial Feeder SAIDI Benefits – 100% Support Capacity (300 A)	Automated Loop vs Radial Feeder SAIDI Benefits – 50% Support Capacity (150 A)
6 vs 4	33%	20%

3. Optimal allocation of support-capacity resources for loop-restoration purposes:
  - a. Multi-segmented feeders use less support capacity to achieve SAIDI goals (see **Table 1** on page 7)
  - b. Support for more feeders from available spare capacity
  - c. Use of increased segmentation to offset diminished support capacity (see **Table 2** on page 7)
4. Different bi-directional overcurrent protection settings (standard)
5. Six-phase voltage sensing (standard)
6. Battery-free operation (dual integrated power modules)

So, unlike reclosers and their controls, the IntelliRupter fault interrupter has been designed to seamlessly transition from radial applications to highly segmented loop-restoration installations and beyond. And load-transfer operations take less than one second per IntelliRupter fault interrupter

Consequently, this automated loop-restoration comparison has demonstrated the best and truly “low-cost” choice for maximizing feeder reliability is the IntelliRupter fault interrupter. This is true because all the components and innovative features described above are native to the IntelliRupter fault Interrupter.

Therefore, the next step of the reliability-improvement program, which is implementing intelligent load restoration, will be significantly easier to accomplish using IntelliRupter fault interrupters instead of reclosers.

## Bibliography

[1] *M. G. Ennis, C. Williams, “Using Real-Time Outage Data to Understand How Protection and Coordination Affect Distribution Reliability Indices*

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