IMPROVING OPEN-LOOP MEDIUM-VOLTAGE FEEDER SELF-HEALING

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ABSTRACT

This paper outlines the application of new technologies that enhance the benefits of the conventional looped distribution scheme by testing for feeder segment faults without using conventional reclosing. Pulseclosing technology, unlike conventional reclosing, reduces thermal and mechanical stress on substation transformers and other interim-feeder equipment by eliminating the repeated occurrence of high fault currents, thus also extending the life of legacy system assets. This revolutionary new technology also overcomes coordination constraints, allowing the expansion of a distribution loop or radial feeder to an unlimited number of series overcurrent protection devices. Maximum system restoration can be achieved within a few seconds after initial fault detection, and without the need for communication between devices.

INTRODUCTION

The enabling technology for the advancements in distribution system protection discussed in this paper is pulseclosing. Pulseclosing is a very fast closing and opening of distribution switchgear contacts to determine if the feeder is faulted without allowing full fault current to flow.

A key part of the technology is closing at the proper point on the voltage waveform to achieve only a minor loop of fault current. Closing in to a faulted circuit at a voltage zero results in fully asymmetrical current with a peak current approximately 2.6 times the symmetrical RMS fault current for an X/R ratio of 17. Closing just before voltage peak results in peak current approximately 1.4 times the symmetrical RMS fault current. [1]

The point-on-wave closing angle for a pulseclosing operation must generate enough current to be measured and analyzed while still keeping the energy let-through into the fault as low as possible. The timing of the chosen point-on-wave closing angle for pulseclosing is such that the largest current occurs in the second loop of current. However, the interrupters open before the major loop starts, so the system only sees a minor loop of fault current. The shaded area in Figure 1 represents the minor loop of current for pulseclosing.

Pulseclosing let-through I^2t energy for a given fault is less than 2% of what it would be for a recloser that times on a TCC curve and clears after an additional 2.5 cycles

Conventional reclosing puts the full fault current back on the system. Many cycles of fault current are used to determine if a fault is still on the system and to determine if the recloser should trip again. The lower currents and short timeframe for the pulse results in minimal energy let-through.

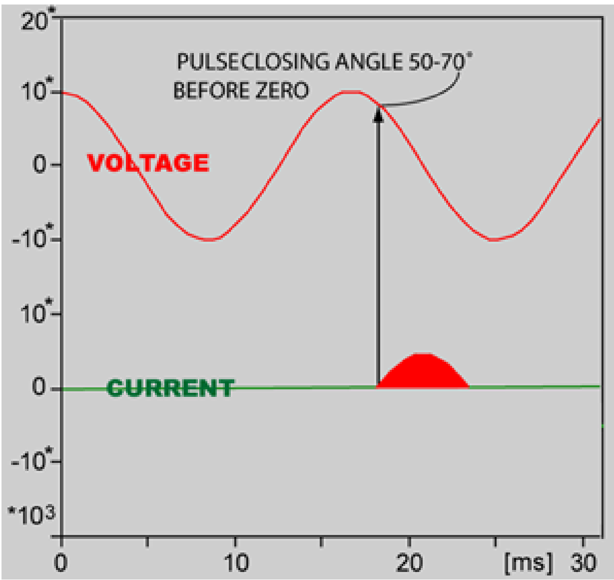

Figure 1. The pulse is the minor loop of current shaded in red.

A popular recloser total clearing TCC curve is shown in Figure 2, plotted with a 400 ampere minimum trip current. Three fault currents are chosen to demonstrate the magnitude, duration, and energy of a pulseclosing operation versus reclosing into the fault. For each of the three faults, the plot shows corresponding clearing times required for each reclose operation. Clearing times and RMS currents are used to calculate the approximate I^2t let-through value for each operation as shown in Table 1. The values compare the energy let-through for one conventional reclose into the specified fault current versus the let-through for a pulseclose operation under the same system conditions. Typical applications use two, three, or even four reclose operations. Since the forces experienced by transformer windings are also proportional to the square of current, these values are a reminder of the reduction in forces experienced during fault events due to pulseclosing.

Each conventional reclose attempt reignites arcing at the fault location, potentially causing more damage to power system equipment and nearby surroundings. The bus voltage sags, affecting customers on the faulted feeder and possibly those on nearby feeders as well. Every time a recloser closes into a fault, through-fault currents cause thermal and mechanical damage to substation transformers and other equipment. [2]

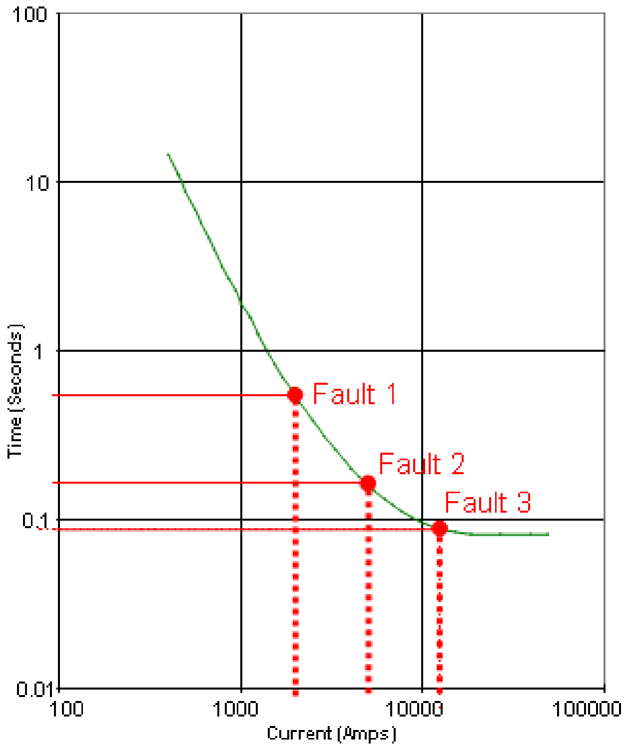

Figure 2. Example fault currents using a recloser TCC.

Fault 1	RMS Current	Duration (Sec.)	I^2T
Conventional Reclosing	2,000A	0.5420s	2,168,000 A^2s
Pulseclosing	930A	0.0053s	4,800 A^2s **(0.22%)**
Fault 2			
Conventional Reclosing	5,000A	0.1620s	4,050,000 A^2s
Pulseclosing	2460A	0.0055s	34,400 A^2s **(0.85%)**
Fault 3			
Conventional Reclosing	12,500A	0.0880s	13,750,000 A^2s
Pulseclosing	6380A	0.0056s	236,900 A^2s **(1.72%)**

Table 1. I^2t let-through for Figure 2 faults

The pulseclosing technique acquires the same key information as conventional reclosing – determining whether the system is faulted or not – but it does so while minimizing harmful side effects. This paper discusses the benefits that can be realized through application of pulseclosers on looped distribution systems.

CONVENTIONAL LOOPED DISTRIBUTION SYSTEMS

Looped distribution systems are designed to automatically restore service using a normally-open tie to a nearby feeder. Initial sectionalization occurs based on the responses of various overcurrent protective devices to faults on the system. Further reconfiguration to restore power to unfaulted feeder sections occurs using a combination of timers and fault interruption – but not communication. Returning to the normal configuration requires manual intervention to open the tie device and close the mid-line devices. Recloser loop systems are relatively simple to apply and eliminate the need for communications between devices.

Figure 3 shows the circuit topology for a 3 recloser loop with a normally-open tie recloser. Simple reliability calculations for loop systems assume a constant fault incidence rate in all feeder segments, equal segment lengths, even distribution of customers, and a constant restoration time throughout the system. Reliability indices System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) for radial feeders without the mid-line and tie point protective devices are used as the baseline. The benefit of a 3 device loop system over two radial feeders is a 50% reduction in SAIFI and SAIDI.

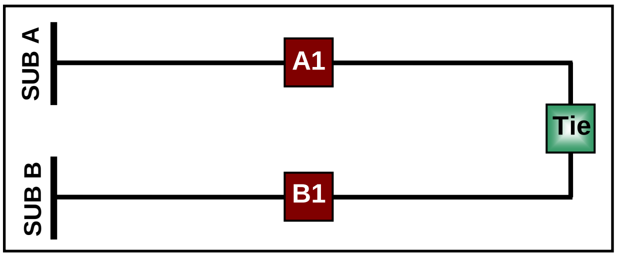

Figure 3. 3-Recloser loop, Relative SAIDI = 0.500 per unit

Conventional loop systems use loss-of-voltage timers to set the order of device operations. Closing into faults is the only way to know if the fault is still present. The first reconfiguration action to occur after the fault has been interrupted and isolated by the breaker and/or mid-line reclosers is the normally-open tie recloser closes based on expiration of a timer that is initiated upon loss of voltage on either side. In a 3-recloser loop system with equal segment lengths there is a 1-out-of-2 chance that the tie recloser sensed loss of voltage due to a fault in the adjacent line section. When the tie recloser closes, fault current flows through the entire previously unfaulted feeder until the recloser times on its TCC curve and locks open.

The same methodology can be extended to a 5-recloser loop. The faulted section is found when the tie recloser closes into the fault, or when the next mid-line recloser subsequently closes into the fault.

While the final result is an improvement from a SAIFI and SAIDI point-of-view, the manner of getting there results in power system equipment being frequently subjected to fault currents and high short-circuit forces, while customers endure the voltage sags that come along with such conditions.

PULSECLOSING AT THE TIE-POINT

Applying a pulseclosing device at the tie-point in an otherwise conventional recloser loop system addresses the number one complaint about loop systems since the tie device will no longer reclose to test for faults. Upon loss of voltage on either side of the tie, a timer is started. When the timer expires, a pulseclose is issued to test the line.

Whereas conventional loop systems require the tie device to lockout on the first trip to avoid multiple sags for the fault shown in Figure 4, it may be beneficial to issue additional pulsecloses over a period of time to give the fault a longer chance to disappear. The additional pulsecloses detect if the fault is still present without causing any further line disturbances. At the end of the sequence, if the fault persists, the tie device locks out without ever having closed in to the fault or disturbing the unfaulted feeder. If the fault is cleared at any time during the test sequence, then the tie device closes in and further reconfiguration can proceed as usual.

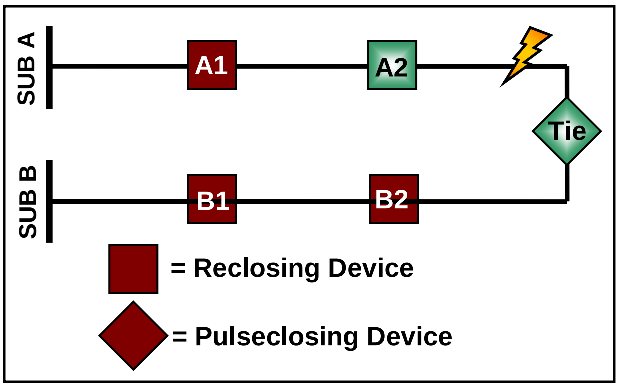

Figure 4. Using pulseclosing at the normally-open point

The rest of the loop system setup and operational characteristics remain the same as for a conventional loop. Overcurrent coordination of all devices in the loop is required, and return to normal condition requires manual intervention.

PULSECLOSING THE ENTIRE LOOP

Greater benefits are gained by applying pulseclosing at the mid-point devices, in addition to the tie point. Pulseclosing devices can be used to create the entire loop system. Mid-line faults result in a trip of the nearest upline device, followed only by pulsecloses until the fault is removed or the mid-line and tie devices lock out.

Consider again the permanent fault as shown in Figure 5 for a conventional recloser loop system. The fault results in multiple operations of device A2, causing 3 or 4 voltage sags to customers in the non-faulted sections of Feeder A. After A2 locks out, then the tie closes in to the fault, causing a voltage sag for all customers on Feeder B until the tie trips and locks out.

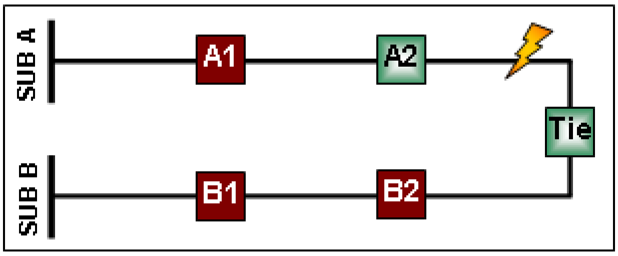

Figure 5. Faulted line segment in a conventional loop

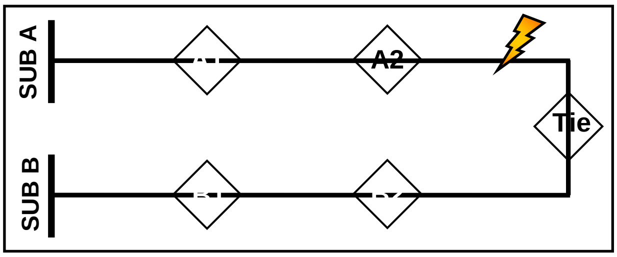

Figure 6. Faulted line segment in a pulseclosing loop

Contrast the large number of customer disturbances that occur for the conventional loop with the relatively benign behavior of a system of pulseclosing devices as shown in Figure 6. The same permanent fault causes the initial trip of device A2, causing a voltage sag to the non-faulted sections of Feeder A. Device A2 and then the tie device go through a sequence of pulseclosings to test the line several times, each without causing any further disturbances to customers on either feeder. If the fault is cleared at any time in the sequence, one of the devices will close, restoring service to the full circuit.

As established in the previous sections, the essence of pulseclosing technology is the ability to detect the presence of a fault without stressing the system or disturbing customers. Applying the concept not only at the device level, but at the system level, presents new ways to evaluate the use and benefits of pulseclosing.

OTHER PULSECLOSING APPLICATIONS

Closing After Fault Repair

Typical utility procedures call for patrolling a line to find the fault location when a recloser or breaker has tripped and locked out. A line crew patrols the line, tries to find the fault, and makes any necessary repairs. Then the crew closes the recloser or breaker to see if it holds. If the fault was not completely removed from the system, or in the event of a second faulted location, another surge of fault current flows through the system, potentially causing more damage at the fault location, stressing power system equipment, and causing power quality issues for customers. A pulseclosing device can eliminate these issues. Only a subcycle pulse of current is needed to determine if the device should immediately close or if it should remain open because the fault still persists.

Fault Hunting

A related concept is fault-hunting. When two or more devices trip for a given event, or when the substation breaker overreaches and trips for faults that mid-line devices should have cleared, crews may resort to closing one device at a time to determine if the downline section is faulted based on whether the recloser holds closed or trips open. Finding the fault location by closing reclosers or breakers always results in putting the fault on the system again. Pulseclosing devices can be operated in a similar fashion, except that locating the fault only involves a pulse of fault current on the line, not a fault of full magnitude and duration [3].

Overcoming the Coordination Constraint

A clever application of pulseclosing devices takes advantage of the ability to imperceptibly detect faults to improve system restoration by automatically performing fault-hunting. This technique is called pulsefinding. Pulsefinding automatically recovers from situations where an upline device overreaches or otherwise miscoordinates with a downline device.

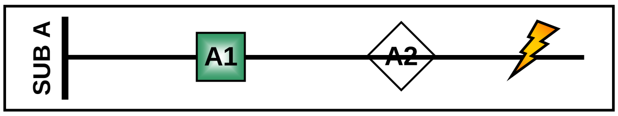

Figure 7. Pulsefinding with an upline recloser

If the fault shown in Figure 7 disappears at any time in the sequence, A2 closes back in and the system is fully restored. If the fault persists, A2 locks out, but the customers between A1 and A2 still have service. Pulseclosing saves the customers between A1 and A2 from a sustained outage. TCC coordination of the two devices needs to be close, but miscoordinations can be tolerated. Customers between the two devices will experience a brief momentary outage due to the upline device tripping, but the system automatically recovers and restores power to the maximum number of customers.

If device A2 were a recloser instead of a pulseclosing device, the system would not be able to recover from miscoordination between A1 and A2 because each reclose operation puts full fault current on the system and both devices would again time and trip. The end result would be A1 locking out.

Referring again to Figure 7, pulsefinding is a function of the downline device. It works with either a reclosing or pulseclosing device upline. Setting up pulsefinding is somewhat analogous to setting up sequence coordination, which is another non-communications-based method of having two devices working together to provide better operation and protection of the power system. Sequence coordination is enabled for the upline device and it does not matter if the downline device has sequence coordination enabled or not – in fact, the downline device may not even be capable of sequence coordination. Setting up pulsefinding is similar in that it is enabled for the downline device and it does not matter if the upline device is capable of pulseclosing, although it does need to have at least reclosing capability.

The feeder in Figure 7 has an upline recloser and a downline pulsecloser. Due to tight or improper coordination, both devices have tripped due to the fault downline of A2. Based on overcurrent sensing and loss-of-voltage logic, pulsefinding ensures that A2 will open when A1 trips, even if A2 did not fully reach its trip time. Next, when recloser A1 closes as the next step in its operation, it will not see the fault and so it remains closed. Device A2, upon sensing the return of upline voltage, will perform a sequence of pulsecloses. The pulses are too short to initiate time-overcurrent timing of any upstream protective devices, so A1 will not trip.

The pulsefinding feature allows the expansion of loop systems to incorporate any number of devices to provide the desired segmentation, which will improve reliability for critical customers or problem areas.

CONCLUSION

New tools give distribution protection engineers increased flexibilty and functionality to design protection systems that improve reliability where it is needed most. Pulseclosing technology is an innovative method to test overhead power distribution circuits for the presence or absence of a fault. It eliminates voltage sags that result from conventional reclosing.

Pulseclosing has merits on its own, but it is also an enabling technology that allows for new and better ways to perform distribution system automation and overcurrent protection. Pulseclosing and pulsefinding overcome the coordination constraints of conventional recloser loop systems and allow for an unlimited number of fault interrupting devices to be used in series.

REFERENCES

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[2] "Electric Power Distribution Handbook," T.A. Short, CRC Press, 2004. Pages 428-436 Reclosing Practices. Pages 467-469 Loops.

[3] "Practical Pulsecloser Applications," J. Huss, C. McCarthy, DistribuTECH 2011 conference paper.