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Combining Fault Mitigation Strategies Substantially Improves Overhead Medium-Voltage Feeder Reliability

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SUMMARY

Overhead medium-voltage feeder MAIFI, SAIFI and SAIDI indices are accruing unnecessarily. The two primary strategies for reducing them are fault prevention and fault mitigation. While fault prevention solutions are well known and commonly applied, their effectiveness differs because feeder construction practices and geographic location vary. Consequently, fault-prevention priorities will be different among distribution companies due to the incidence and impact of preventable fault causes. Conversely, fault-mitigation objectives are more uniform among distribution systems. As a result, the reliability improvements and cost benefits they produce are generally more consistent and effective, regardless of where they are applied. Therefore, this paper begins by reviewing the reasons some mitigatable fault causes are misidentified or misunderstood and why conventional fault-mitigation strategies can be ineffective. It then continues by introducing new cost-justified and field-proven solutions that appreciably improve reliability. Finally, the individual reliability benefits achieved are extrapolated to demonstrate the reliability improvements that are possible if just some of these fault-mitigation strategies were applied.

KEYWORDS

Persistent, transient, cutout-mounted recloser, sympathetic tripping, miscoordination, distributed intelligence, fused-laterals, feeder, faults, recloser

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BACKGROUND

Effective fault mitigation ideally begins by qualifying and quantifying the percentages of transient and persistent faults. But this can be difficult to determine because considerable time and effort are required to correlate and analyze fault-response data to determine what actually happened.

For instance, if fuse saving is practiced, breakers or reclosers are configured to trip before downstream fuses protecting main feeder extensions or laterals operate in response to faults. The breaker or recloser then automatically recloses in expectation the lateral fault was transient. However, the probability of this method preventing fuse operation is dependent on fault current levels, meaning higher fault currents typically result in both fuse and recloser or breaker operation.

Therefore, if a transient fault occurs downstream of a lateral fuse fed by a recloser, both the fuse and recloser can operate due to an unfavorable fault current level. If the subsequent successful reclose operation is never associated with the fuse operation, this single fault occurrence becomes both a transient and a persistent fault.

The conclusion usually reached is the recloser responded to a transient fault because it didn’t lock out. And although the fault downstream of the fuse was actually transient, it’s generally categorized as persistent because of the extended outage that occurred.

Another misidentified event is the sympathetic tripping of substation feeder breakers. This occurs because repeated reclosing collapses and restores the substation bus voltage to the degree inrush currents from motor loads on healthy feeders cause unexpected breaker tripping.

In this case, the cause of the healthy feeder interruption was actually a transient or persistent fault on an adjacent feeder. But in all likelihood, the event is either recorded as unknown or, even worse, as another transient fault.

After appreciating which events produce the greatest reliability impact, implementing the optimal mitigation solution can mean departing from convention. For example, feeder fault sectionalizing has conventionally been limited to the number of reclosers that can be coordinated. However, within the last 10 years, the tighter fault-response tolerances and innovative fault testing technology of one revolutionary fault interrupter have overcome this previous limitation.

Another example is automated load restoration. This strategy might be disregarded because some loads cannot always be recovered due to periodic capacity constraints. However, for the past 20 years, feeder-based distributed intelligence has overcome this periodic constraint by using real-time data to ensure load transfer was within source limits. Further, distributed intelligence enables multiple support feeders to aid in load recovery, accomplishing this in less than one minute.

Ultimately, MAIFI, SAIFI, and SAIDI indices are accruing unnecessarily. Consequently, if the following system improvements are implemented, a 73% reliability improvement is reasonably achievable.

FUSED LATERAL FAULTS

Using an extremely conservative estimate of 50% for the percentage of transient fused lateral faults, cutout-mounted reclosers reduce SAIFI by 50% where a fuse-blowing strategy is observed. As a reminder, a fuse-blowing strategy means fuses always operate for downstream faults before upstream breakers or reclosers trip, regardless of whether the fault was transient or persistent.

As an example, presume there are six fused laterals with 100 customers per lateral, and there is one persistent and one transient fault per lateral annually. Because fuse blowing is practiced, both persistent and transient faults produce an annual SAIFI of 1,200 (6 x 100 x 2 = 1,200). By installing cutout-mounted reclosers in lieu of fuses, each transient lateral fault no longer accrues to SAIFI (6 x 100 x 1 = 600), and a 50% improvement occurs.

Further, using the previous transient and persistent lateral fault statistic, MAIFI contribution from fused laterals is substantially reduced where fuse saving is practiced. Because there is no longer a fuse to save, all customers downstream of a fuse-saving recloser no longer experience a momentary interruption – only customers served by the cutout-mounted recloser experience a momentary disruption.

Using the previous SAIFI improvement example, Table 1 illustrates a 90% MAIFI benefit results when lateral fuses are replaced with cutout-mounted reclosers. *Note: The reason customers are removed from fuse-saving and cutout-recloser MAIFI accruals is they cannot accrue to MAIFI, SAIFI, and SAIDI indices; therefore. they only accrue to SAIFI and SAIDI.*

Cutout-Mounted Recloser vs. Fuse-Saving MAIFI Accrual (6 Laterals; 100 Customers/Lateral; 6 Persistent Faults; 6 Transient Faults)	
Fuse-Saving MAIFI Due to Persistent Faults (Removes 100 customers per fault that accrue to SAIFI & SAIDI)	(600 – 100) x 6 = **3,000**
Fuse-Saving MAIFI Due to Transient Faults (Presumes a 50% fuse-saving success rate and removes 300 customers that accrue to SAIFI & SAIDI)	(600 x 6) – (100 x 3) = **3,300**
Total Fuse-Saving MAIFI Accrual	3,000 + 3,300 = **6,300**
Cutout-Recloser MAIFI Due to Persistent Faults (All customers accrue to SAIFI & SAIDI)	= **0**
Cutout-Recloser MAIFI Due to Transient Faults	6 x 100 X 1 = **600**
Total Cutout-Recloser MAIFI Accrual	0 + 600 = **600**
Percent MAIFI Improvement Due Cutout-Recloser	5,700 ÷ 6,300 = **90%**

Table 1. Comparing fuse-saving vs cutout-mounted recloser MAIFI accrual.

Significant SAIDI improvements are also realized after installing cutout-mounted reclosers. This is absolutely true for a fuse-blowing scheme because transient faults no longer require field crews to be dispatched. This results in substantial savings to utilities because the one to two hours of field crew expense are eliminated, and customers no longer experience a one- to two-hour outage.

And this is equally true for transient faults if fuse saving is practiced. Table 1 presumed a generous 50% fuse saving success rate that, if true, means half of all transient lateral faults still produce an extended outage, result in costly truck rolls, and accrue to SAIDI.

Finally, the consequences of persistent lateral faults could be further mitigated by additional lateral circuit segmentation. This means installing secondary cutout-mounted reclosers downstream of primary cutout-mounted reclosers located at the main feeder tap.

Users that have deployed these devices are enjoying greatly improved reliability and more satisfied customers. And the investment is being justified by the savings from reduced truck rolls to replace fuses.

SYMPATHETIC TRIPPING

The practice of repeatedly reclosing to test for the continued presence of faults (also known as fault multiplication) has undesirable consequences beyond stressing the system and reducing the service life of substation power transformers. Frequently unrecognized, 80% of one utility's unexplained substation breaker tripping can be attributed to this fault-testing method. The reason it occurs is because repeated faulted feeder reclosing can sag substation bus voltages, resulting in inrush currents that unexpectedly trip breakers on adjacent healthy feeders.

What is typically happening is motor loads on healthy feeders experience depressed voltage levels and phase-angle shifts on the phases of an adjacent feeder fault. After each tripping sequence, the bus voltage returns to pre-fault levels and phase angles, whereupon motor loads react, producing phase and neutral currents that exceed the healthy feeder's pre-fault load levels.

As these higher phase currents can persist for some time, and will recur with each tripping and reclosing sequence, sensitive feeder-breaker protection can occasionally trip. The probability this occurs is higher where electromechanical relays are applied or modern electronic relays use electromechanical reset characteristics.

Thankfully, a new fault-testing technology called pulse-closing mitigates these conditions. Pulse-closing 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.

A pulse is immediately analyzed 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, and the next phase is tested, and so on.

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

The reason pulse-closing 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.

INCREASING FEEDER FAULT SECTIONALIZING

Improving reliability for transient and persistent main-feeder faults begins with increasing feeder fault sectionalizing. This further segments the feeder, reducing the number of customers affected by faults and improving SAIFI and SAIDI.

Unfortunately, the number of series reclosers that can be conventionally coordinated severely limits the quantity of feeder segments. However, pulse-closing overcomes these coordination restrictions, enabling numerous series fault interrupters.

The electromagnetic energy (I^2t) of two fault pulses is 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. But equally important, it also prevents subsequent miscoordination with upstream protection.

For example, presume a pulse-closing fault interrupter is downstream of a breaker, recloser, or another pulse-closing fault interrupter, and both devices (intentionally or unintendedly) miscoordinate and trip in response to a fault. The upstream device recloses and holds, avoiding a SAIFI and SAIDI hit because the pulse-closing device has isolated the fault.

The downstream pulse-closing device then begins its fault-testing sequence to determine whether the initial fault is still present. However, unlike reclosing, which would recreate the initial miscoordination and eventually lock out the upstream device, the upstream device remains closed because the pulse's 0.25 to 0.5 cycles of 0.5 per-unit fault current is undetected.

Consequently, multiple series pulse-closing devices can substantially increase feeder fault-sectionalizing for both radial and looped feeders. By configuring their protection the same, they automatically recover from any miscoordination, reenergizing feeder segments in less than one second per section.

This pulse-closing device also has the tightest fault-response tolerances in the industry, enabling more conventionally coordinated series fault interrupters than reclosers. And if peer-to-peer communication is used, numerous series pulse-closing devices are automatically coordinated.

PERSISTENT MAIN FEEDER FAULTS

Increasing radial feeder fault-segmentation using any one or more of the preceding protection-coordination concepts produces the SAIDI benefits shown in Table 2. These improvements occur because persistent faults in downstream feeder segments are always isolated, enabling load in upstream segments to be automatically restored [2]. *Note: The Table 2 base case is an unsegmented radial feeder with uniform fault and customer distribution and fault repair times.*

SAIDI Improvement Due to Increased Radial Feeder Fault-Sectionalizing	
2 Feeder Segments	**25% SAIDI Improvement**
3 Feeder Segments	**33% SAIDI Improvement**
4 Feeder Segments	**38% SAIDI Improvement**
5 Feeder Segments	**40% SAIDI Improvement**

Table 2. SAIDI benefits due to increased radial feeder fault-sectionalizing.

SAIDI Benefit Due to Looped Feeders with Distributed Intelligence Load-Restoration Software	
2 Feeder Segments	**50% SAIDI Improvement**
3 Feeder Segments	**67% SAIDI Improvement**
4 Feeder Segments	**75% SAIDI Improvement**
5 Feeder Segments	**80% SAIDI Improvement**

Table 3. SAIDI benefits due to looped feeders with distributed intelligence load-restoration software.

SAIDI would further improve if two feeders were tied or looped together at their ends using an automated normally-open device. Equally segmenting these two looped feeders so customers are evenly divided among feeder sections and equipping all feeder-sectionalizing devices with distributed intelligence load-restoration software produces the SAIDI improvements shown in

Table 3. *Note: The Table 3 base case is the same as that in Table 2 and presumes there is sufficient spare capacity to recover the number of segments indicated.*

These improvements are realized because the load in downstream un-faulted feeder sections is automatically transferred to the adjacent feeder when persistent faults occur in upstream segments [2]. And comparing Table 3 with Table 2, SAIDI improvements double by looping two feeders.

This reliability-improvement strategy is occasionally overlooked because the spare capacity required to achieve these SAIDI benefits is periodically unavailable because of seasonal peak loading. However, distributed intelligence load-restoration software overcomes these periodic restrictions by ensuring unfaulted load recovery remains within a support feeder's spare capacity.

Additionally, this software enables an unlimited number of feeders to be intertied to aid in the recovery of unfaulted load. And even with multiple feeder interties, this solution can recover unfaulted load in less than one minute.

Distributed intelligence-equipped devices communicate locally among one another in a peer-to-peer manner. By communicating load and supply measurements to each other in real time, these devices collectively "know" the load in their feeder segments and the spare capacity of all support feeders at all times.

Consequently, when a persistent fault occurs, and it has been successfully isolated, unfaulted feeder segments are only added to support feeders, provided they don't overload the source. Should initial load transfers produce subsequent protracted overload conditions, remedial load transfers and/or prioritized load shedding can be enacted to rebalance loads within available source capacities.

CONCLUSION

Combining just some of the fault-mitigation strategies presented in this paper results in a very conservative total reliability improvement of 73%. This improvement will be demonstrated using the data shown in Figure 1.

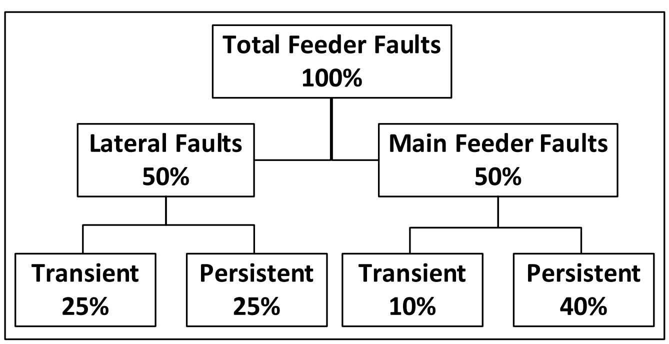

Figure 1. Transient and persistent feeder fault distribution.

Figure 1 presumes 50% of all feeder faults occur on fused laterals and 50% occur on the main feeder. Half of the lateral faults are estimated to be transient and half persistent. In contrast, 10% of main feeder faults are presumed transient and 40% persistent. *Note: If main feeder faults were to total 100%, 20% would be transient and 80% persistent. Equally, 100% lateral faults equates to 50% transient and persistent.*

Consequently, a 35% improvement occurs by installing cutout-mounted reclosers and pulse-closing fault interrupters. This is true because 25% of transient lateral faults and 10% of transient main feeder faults no longer contribute to SAIFI and SAIDI.

A further 32% improvement is realized by increasing main feeder segmentation and deploying distributed intelligence load-restoration software. As a reminder, five equal feeder segments having devices equipped with distributed load-restoration software resulted in an 80% SAIDI benefit. Consequently, 80% of the 40% or 32% of persistent main feeder faults no longer accrue to SAIFI and SAIDI.

And finally, if fused lateral circuits also had a midpoint cutout-mounted recloser, another 6.3% SAIFI and SAID improvement would be realized. Presuming an equal persistent lateral fault and customer distribution, a 6.3% improvement results because dividing a radial circuit into two equal segments produces a 25% SAIFI/SAIDI benefit. And 25% (SAIFI/SAIDI benefit) of 25% (persistent lateral faults) equals 6.3%.

So, totaling these reliability improvements, a 73% reliability can be realized if just some of the fault-mitigation strategies outlined in this paper were implemented.

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