DISTRIBUTED INTELLIGENCE PROVIDES SELF-HEALING FOR THE GRID

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ABSTRACT

The electrical distribution system is evolving, with distributed energy resources increasingly disrupting traditional one-way power flow. To maintain system stability, maximize energization of the network, and allow service restoration to be performed as quickly as possible after the loss of a source or occurrence of a fault, network conditions must be continuously monitored and the status of power switching devices communicated to the other devices on the network.

The problem can be addressed by introducing nodes and power switching equipment utilizing distributed intelligence within the network. Such equipment does not replace a central control system, but rather augments it by allowing "in-grid" decisions to be made and reported back within the operating criteria established. Imagine a storm sweeping through a network, with more and more monitoring alarms and information swamping the operator. With an in-grid distributed intelligence network, rapid switching, load transfers, and dispatch of renewable and/or stored energy sources can all be coordinated to automatically maximize energization of the network in a matter of seconds. The present status must always be reported back to the central control system for operator situational awareness.

As energy storage for system support within the distribution grid becomes more widespread, it will become another intelligent node, and allow sections of the grid to be disconnected during a disturbance. Alternately, sections can be deliberately "islanded" and remain energized and coordinated with other energy resources.

This paper establishes the problem, provides some examples, and makes the case for the further application of embedded in-grid intelligent devices.

INTRODUCTION

The characteristics of the Smart Grid are generally accepted around the world; the grid must accommodate multi-directional power flow and adapt quickly to changing conditions. A basic distribution grid is created when utilities add the capability to transfer loads to adjacent circuits. A *smart* distribution grid is created when the switching points between circuits, as well as several points along each circuit, have the intelligence to automatically - and quickly - reconfigure the circuits to reroute power to as many customers as possible in response to an event. More intelligent switching points yield more options to reroute power to serve the load. Communication between those points makes self-healing a practical reality.

Alternate routes, multiple switching points, and communications also enable loss minimization tactics and peak load management. And, the flexibility of an automatically reconfigurable distribution grid is required to accommodate the escalating levels of distributed generation and energy storage that are expected. Distributed generation comes and goes unpredictably, a dynamic activity that won't work on a distribution system in the traditional form of a radial circuit. The permissible timeframe for managing changes in the grid is ever decreasing. Although in some jurisdictions outages of five minutes or less are not recorded, the increasingly accepted measure is one minute of outage is the threshold for a sustained outage, and this was prior to 'smart grid'.

INTELLIGENT SWITCHING DEVICES

When a fault occurs on the distribution system, it is interrupted and cleared by a fuse, recloser, or relayed circuit breaker. On many occasions faults are temporary-by-nature, and would actually dissipate if given a short period of time with the system de-energized. An improvement was introduced during the 1940s when reclosers and reclosing relays offered dual-timing characteristics. The recloser is set to trip faster than the fuse, and then wait a few seconds before reclosing. If the fault is temporary, it will have disappeared before the first reclosing attempt. Service is restored to all sections of line, the fuse does not operate, and the recloser or relay resets and the system is back to normal. This protection technique of tripping a midline or substation reclosing device before the fuse operates is known as *fuse saving*.

There are a couple downsides to this approach. One is that hydraulically-controlled or electronically-controlled devices that are required to measure fault currents and then mechanically part contacts to interrupt the fault simply cannot perform this action faster than a fuse link at high fault currents, which will interrupt faults in as little as 8 ms, thus a large portion of faults result in the recloser tripping and the fuse blowing. This is actually worse than simply letting the fuse clear the fault, since the fuse blows *and* all customers down line of the recloser will experience a momentary interruption.

Another downside to the fuse-saving approach is that a typical implementation includes three or four reclosing attempts. If the fault is permanent-by-nature, each reclosing attempt re-ignites the short circuit, and full magnitude fault current flows through the distribution conductors, switches, splices, and perhaps most importantly of all, the substation transformer. Just at the time where utilities are utilizing their existing assets more, some of which are decades old; the additional shots of full short circuit energy shortens the life of those assets.

Reclosing has been a standard utility practice since it avoids many lockouts that would result from temporary faults. Today, there is an new alternative called pulseclosing. Pulseclosing represents the first major change in the power handling aspects of faults on the distribution system since reclosing was introduced in the 1940s.

The benefits of the pulseclosing technique are many:

- Reduce stress on power system equipment. The pulseclosing technique typically reduces the energy let through by more than 98% compared to the energy associated with a recloser's delayed TCC curve, and also reduces the peak fault current forces on transformer windings by up to 96% compared to a 'hard close' that results in a fully asymmetrical fault current with an X/R ratio of 17.

- Depending on the circuit configuration, reclosing cannot be implemented, such as in areas that include a mix of overhead conductors and underground cables. Cable faults are typically permanent and result in high magnitude fault currents. A common practice will be to immediately lockout the recloser or relay for faults above a specified threshold, such as a few thousand amperes. On a mixed overhead and underground system, this practice will result in undesired feeder lockouts for temporary faults that occur on the overhead portion of the system. This is another example of where the pulsecloser can be configured to test the line one, two, three, or four times after the initial fault interruption to determine if the line is faulted or if it is clear and safe to close in and restore service. The pulses do not initiate the high short circuit currents - it is acceptable to test underground circuits without fear of causing more damage.

- Fault currents cause significant voltage sags for upline customers on the faulted feeder, but the effects can also be seen on adjacent feeders served from the same substation bus as the faulted feeder. Pulseclosing is imperceptible to upline customers since the pulse duration and peak current is so limited. Customer power quality is improved.

- Pulseclosing is a natural choice in high fire risk areas since it puts significantly less energy into faults compared to reclosing.

- After a fault has been repaired, the crew or dispatcher will command a recloser or pulsecloser to close. In the event that the fault was not completely cleared, there was a secondary fault, or the line crew left the grounds on the system, a recloser will close into the fault and cause all the problems associated with faults as previously discussed. Alternatively a pulsecloser would detect the fault and inform the crews and dispatcher that the line is still faulted with no undesired fault effects.

- The ability to detect a faulted line section without relying on a Time Current Characteristic (TCC) curve leads to the realization that a virtually unlimited number of series pulseclosing devices can be coordinated even if proper TCC curve coordination cannot be achieved. Figure 1 is an example of a radial system with five devices in series. Assume that, due to coordination constraints, devices A2 through A5 all share the same overcurrent protection settings, including TCC curves and minimum trip settings. The steps in Figure 1 demonstrate how pulseclosing facilitates proper sectionalization in spite of the lack of coordination, and also without any type of communication between devices. The solid red diamonds are closed devices, the shaded green diamonds are open devices, and the yellow ovals indicate pulseclosing actions that "see" the current up to the next open device.

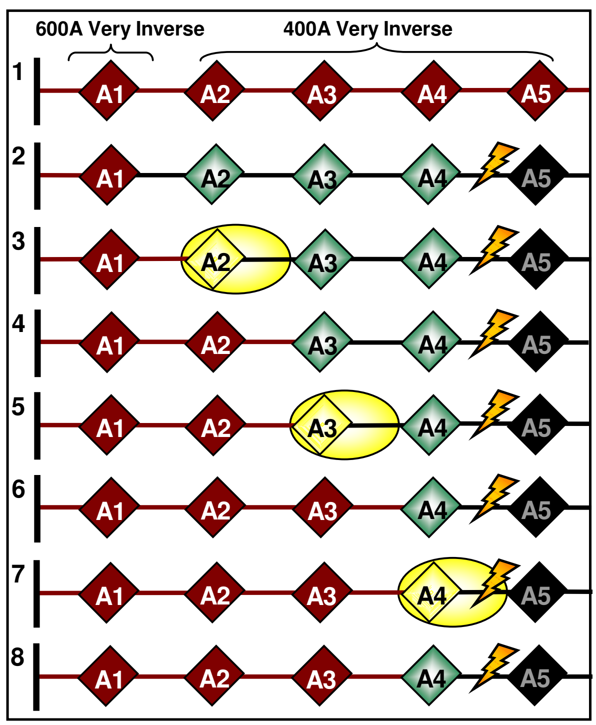

Figure 1: Pulsefinding

Maximum system restoration is achieved within seconds of the initial fault detection. Pulsefinding simplifies applications where coordination is tight or cannot be achieved – it is even possible to add devices without the need to consider time-overcurrent coordination.

DISTRIBUTION GRID AUTOMATIC SELF-HEALING

A smart distribution system is the link between AMI and the transmission grid. Industry experts estimate that 80% of customer outages occur due to problems on the distribution system, the 'self-healing' part of Smart Grid is a critical element for the distribution system - when customers are without power, then time of use rates becomes a little less important in the overall picture. We usually take reliable power for granted, but everything stops when the power goes out.

Self-healing technology enables the switching devices on the distribution system to automatically reconfigure the circuits to restore as many customers as possible, and isolate only the problem section of line. To accomplish this, Intelligent Electronic Devices are deployed on the distribution system, enabled with automatic restoration logic. These devices communicate and update each other on system conditions, e.g. load, voltage, capacity, switch status. During an event such as a short-circuit or loss-of-voltage, each device is self-aware of the system state and is able to make group or team decisions for self-healing.

Rapid self-healing restores service to all unfaulted line sections with the minimum amount of switching actions. Overcurrent protection clears the fault, the restoration logic opens the first switch downline of the fault to isolate only the faulted section, the system then reconfigures to restore all non-faulted sections. This self-healing action occurs within as little as a few seconds after the fault is cleared, depending on the speed of the communication system. For such quick actions, it is important that the system takes real-time loading into account so that transfers will not result in an overload.

One or two test operations (e.g. pulseclosing or reclosing) can be performed to determine if the fault is temporary or permanent before initiating the restoration action. If rapid self-healing reconfigures the circuit for a temporary fault, it can return the circuit to normal after the fault has dissipated.

During automatic restoration, real-time loading in each section is considered at the moment of transfer to prevent overloads. However, it is possible for an overload to occur at a later time, while the circuit is still in a reconfigured state. Post-restoration load management features can then transfer load to other feeders when possible, or shed load if necessary.

Overcurrent protection and automation are becoming more intertwined. Automated protection presents the possibility of truly dynamic and flexible distribution systems that can be reconfigured manually, or continuously and automatically monitored and reconfigured to optimize system performance such as reliability, voltage, loading, or protection.

A distributed intelligence based system keeps going for multiple events. There is no need to pre-script switching scenarios for a multitude of fault contingencies; it continues looking for alternate sources to restore unfaulted sections that are without service. This is especially useful during strong storms that sweep across a service territory and cause multiple outages. Line crews and dispatchers are flooded with event data coming in at times of rapidly changing events - it is a great advantage to have the distribution system immediately do the best restoration possible and report the *final* reconfigured state to the dispatchers.

COMMUNICATIONS

The industry is quickly moving toward a distribution system that is monitoring, recording, and reporting more data through the SCADA systems as intelligent controls and sensors become widespread. AMI traffic alone requires an upgraded communications system to handle the traffic. All the while, the performance of the distribution automation system depends heavily on the communication system.

A mesh topology is important for a distributed intelligence system, since it allows switching devices in the field to communicate directly with each other i.e. there is no requirement to communicate first back to a remote central location, and then all the way back through the system to the intended recipient. Instead, devices can communicate directly. In applications where speed of communication is important, such as those involving protection or restoration, the peer-to-peer mesh network is a superior design. Inherent in the mesh approach, there are redundant alternate paths for messages to travel in the event that one or more of the preferred communication links is down and therefore the network is not subject to the single point of failure of point-to-multipoint networks. The ability to automatically route around a missing node is another example of a "self-healing" system employed on the distribution system.

The increase in sensing will impact existing and future communication systems feeding into a centralized control center. A network of networks that integrates a number of different communication technologies can offer the optimal bandwidth and latency for different applications. For example, it is not acceptable to have 15 minute cycle times between communications for the operations of an electrical grid, although it can work for AMI. Communication systems need to have the ability to prioritize traffic by application needs. Low latency peer-to-peer messaging that gets messages routed to neighbouring devices in less than 10ms is a key enabler for powerful distributed intelligence functions, such as distribution automation, automated protection, and self-healing.

ENERGY STORAGE

Installations of energy storage are gaining momentum within in the grid both at the utility scale (MWs) and consumer scale (kWs). There are a number of features that energy storage presents to the grid, some of which include: load shaping, peak shaving, reliability improvements, power quality, frequency support and volt-var optimization.

Distributed intelligence facilitates the aggregation of these units, so when they are combined they provide system-level benefits. Energy storage also provides the ability to regulate renewable generation by providing 'smoothing' to the variable capacity and the option of regulation whether it be voltage or power.
Energy storage devices with built-in distributed intelligence provides the opportunity to deploy strategies to support different grid needs such as peak demand mitigation, it also provides the opportunity for energy to be dispatched during a self-healing event or operate completely disconnected from the grid and synchronize back to the grid when it becomes available.

SPEED OF REACTION

The speed of reaction to a set of events often defines how stable a system remains. For example, wind farms are required to 'ride through' system events depending on the grid code, e.g. 1 second ride-through. Within the distribution grid the ability to react and reconfigure quickly enables more users to remain online.

Distributed intelligence devices already exist within the grid. Smarter switching devices now use pulseclosing technology which offers self-healing even without communications, and it all happens within seconds. When smart switches are enabled with peer-to-peer communications, the self-healing feature set increases to allow for system-wide decision making for rapid self-healing using any number of alternate sources.

A distributed intelligence system is really based on having the right amount of intelligence at the right locations. In many cases the intelligence belongs right at the multitude of devices that are "in the grid" and performing the sensing and switching the power. It is also important that these same devices integrate into the centralized control systems. In this type of hybrid system, the field devices benefit from policy controls and oversight from the central system, and the central system benefits from a significantly reduced communications load and decision-making burden.

SUMMARY

Distribution networks are seeing a change in power flow, consumption patterns and increased performance expectations for both reliability and power quality. The "grid part" of the smart grid benefits from distributed intelligence both in switching power and decision making through improved sensing, computation and communications. The anticipated increase of energy storage as well as renewable generation provides further opportunity for a self-healing, decision-making enabled smart grid.

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