An Alternative Approach to Earth Fault Protection on Remote Rural Feeders – AMI can Reduce Bushfires

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1 History

1.1 The Problem

Electricity has caused a number of large, dangerous bushfires, including in 1969, 1977, 1983 and the 2009 Black Saturday bushfires. For example, in Victoria, Australia, the 2009 Kilmore East fire killed 119 people after a 43-year-old conductor broke. An alarming thing about these fires is that they tend to start on the same day, in widely-separated areas. This makes it difficult to coordinate conventional responses. (2009 Victorian Bushfires Royal Commission 2010).

Traditional protection methods used to reduce the likelihood of broken conductors and other sources of electrical ignition rely on sensitive earth fault protection. Sensitive earth fault protection is almost instantaneous for short 3 phase medium voltage lines but is not as reliable for longer 3 phase lines, single phase two wire lines, single phase suspended neutral lines and single wire earth return lines.

1.2 Rural Power Infrastructure

Most of Victoria's distribution system consists of 22 kV distribution lines and includes 19.1 kV and 12.7 kV single-wire-earth-return (SWER) lines. Similar SWER systems are used in New Zealand, Canada, Brazil, Lao PDR, Mozambique and South Africa.

Suspended neutral (SN) systems are electrically and mechanically similar, except that they predominately return current on a second wire or suspended neutral, which is earthed periodically along the length of the line. They are used in the U.S., Canada, Latin America, Western Australia, Bangladesh and other places.

All these systems distribute power for rural pumps, lights and other equipment. In developing countries low cost rural electrification greatly assists poverty reduction by lowering the costs of water, food, energy and labour.

Rural power distribution must be low cost to be financially and economically viable. The major cost items include poles, conductor and labour. Therefore, to minimise costs, overhead medium voltage systems carry relatively large voltages on relatively small wires while maximising the spans between poles. Since these lines are rural, they are exposed to the wind and weather lack shelter and large dependent populations. So, both inspections and service are needed, more expensive and lower priority than comparable systems in urban areas. The historical result has been greater failure rates, and unfortunately in some cases, fires.

2 Failure modes and effects

The 2009 Royal Commission spent a considerable amount of time evaluating system electricity faults. They recommended improving the infrastructure, accelerating inspections and maintenance, and modifying the operation of reclosers. (2009 Victorian Bushfires Royal Commission 2010)

2.1 Wire-breaks and their effects

A simple wire-break is one of the more common and dangerous forms of failure. These are made more likely by aged conductors, long spans and high winds. Mechanical solutions include dampers for vibration, and reinforcement to reduce fatigue near the supporting insulators. Retrofitting spiral vibration dampers on rural lines is expensive and may require outages.

Earth fault protection (also called ground fault protection) is the usual method for detecting and isolating earth faults. However, discrimination between normal earth return current and earth fault current can be an issue. SWER distribution systems are connected between phase and earth and the earth fault current from a fallen wire can be similar to the normally expected earth return current.

A failure, a live wire on the ground, causes power loss, sparking, electrocution hazards, liabilities from these and unrecoverable generation costs. The sparking may start a fire, with all of its attendant costs and possible loss of life.

2.2 Shorting objects and effects

Foreign objects such as trees can contact the wire. The resistance of the object is purely random. The resistance may be high enough to prevent the protection from sensing an earth fault. In at least one bushfire, a charred tree was found in contact with the wire, and it presented a resistance indistinguishable from the line's designed load.

2.3 Insulator and tie wire failures

Insulator failures (e.g. cracked porcelain or glass insulators) have effects very similar to a high resistance short to ground, and add the possibility of pole top fires if left undetected, noting that a pole top fire is more likely where there are wooden poles and crossarms. A pole top fire can also occur due to tie wire damage or failure resulting in a phase conductor resting on a cross arm. Difficulties with sensing earth faults remain due to the often high earth resistance of the earth fault path.

2.4 Line Clashes

Line clashes are a bright spot with SWER, because its single wire can't clash with others. However suspended neutral systems can clash, and the sparks can cause fires. Ground fault detection usually fails to handle line clashing because the fault is intermittent, and reclosers restore power.

3 Existing Solutions

Electrically, a downed wire should be sensed as an earth fault, and disconnected by the feeder breaker or reclosing circuit breaker further along a feeder. However, SWER systems operate distribution transformers connected phase to earth. Also, the conductivity of the ground at grade is low in the dry conditions that favour fires. This makes the current less easy to detect. The small, intermittent current changes caused by a grounded wire in dry fire conditions can be very difficult to distinguish from normal load changes and line noise.

The problem is increased if the fault is a wire break that disconnects a large part of the SWER line, because customer loads are removed as well. Absolute distributed current can decrease, and the break can still cause a fire and other hazards.

Suspended neutral systems at first appear to be theoretically superior. However, they often have unrepaired high resistance faults from phase to ground[1]. These are difficult to locate and may not interfere with normal service. It is very easy for an operator to put them at the end of his service queue. However, these high resistance earth faults can fail to be detected by the earth fault protection in a similar manner to earth faults on SWER systems.

[1] One of the benefits of suspended neutral systems is that a failed conductor, on its way down, can contact or come to rest on the under-strung neutral resulting in a low resistance earth fault path that will initiate a protection trip.

3.1 Inadequacy of Sensitive Earth Fault Protection

The obvious solution is to improve earth fault protection. However, this is problematic.

Systems with high impedances or a wide range of loads usually use some kind of small-signal SEF protection. The most reliable type of small-signal SEF sense leakage current from phase to earth. SEF protection requires the main return to the generator to be metallic (or at least very low impedance). The SEF then monitors an auxiliary current path from ground to the return. If the ground current exceeds a low minimum for a defined time, the SEF trips the associated recloser or breaker.

SWER systems lack the metallic return. Without exemplary maintenance, suspended neutral systems often lack the metallic return as well, while ironically, depending on it for safety.

Even when they are usable, SEF can be difficult to set, because some utility distribution systems have significant leakage from, stray capacitive current, dirty insulators, improperly installed equipment, etc. Also, in solar storms, used with long lines, feeders can trip from geomagnetically-induced common-mode currents.

Another form of small-signal ground fault detector depends on the fact that intentional, bonded metallic connections should not have variable resistances. In contrast, most accidental connections tend to be intermittent, arcing at high voltages. These arcs make and break in synchrony with the AC voltage.

Arc signature detection usually examines the line near the zero-crossing times of the AC voltage. The detector trips if a high differential voltage or current is found at the line frequency. Other variations look for wide-band radio-frequency noise modulated at the line frequency. This is an active area of research.

Arc signature detection works well with loads consisting of motors and incandescent lights. However switching power supplies, fluorescent ballasts, neon signs, dimmers, and other equipment make emissions that strongly resemble arc signatures. Even if an arc signature is proven to be absent, a customer may plug in new equipment the day after and cause false trips.

Another issue with arc-sensing is that a real ground fault might not arc. The charred tree, for example, had quite a reliable connection.

These difficulties and the value of rural power motivated us to review solutions for more reliable sensitive earth fault protection.

4 Fault Location, Isolation and Service Recovery

The generic name of the smart grid function that responds to equipment failures is "fault localisation, isolation and service restoration," or FLISR. The efficiency function of a smart grid is usually a voltage and power factor assurance system.

A smart grid consists broadly of sensors, controls and effectors. The sensors are usually voltage transformers and current transformers with smart meters. The effectors are usually remote-controlled high voltage switches on distribution points, transformers and capacitors. Some HV switches reconfigure the network after a fault is detected. Others adjust the grid voltage by open point optimisation and adjusting transformer secondary voltage. Others optimise reactive current flows by switching in capacitors, generically referred to as volt/var optimisation.

A smart meter usually consists of two systems-on-chips (SOC), each on its own printed circuit. These are a computerised meter and a network modem. The parts are separated so that meters can be mixed and matched with modems adapted to local networks. The switches utilise similar technology.

Existing systems usually centralise control at a convenient location. This is not an issue for grid efficiency, but if the grid's control manages safety, centralised controls are a single point of failure. There is a proposal addressing this later in this paper.

4.1 Distributed Communication and measurement

A smart grid permits a grid operator to measure voltage, real and reactive currents over a wide area. The information is not instantaneous because of communication delays. Operators usually try to reduce the communication times by limiting the number of devices used for monitoring.

4.2 Imminent roll-out in Victoria.

Adapting FLISR to reduce rural bushfires would be an irrelevant proposal if rural smart grids were impracticable. However, Victoria is committed to a smart meter roll-out, so at least the sensors and control computers for a rural smart grid should be in place shortly. (The Age 2011)

4.3 Communication Issues (Coverage)

In cities, the normal smart-grid modem may be a power-line communication system, or a system such as GPRS or LTE. Rural areas are problematic, but connectivity problems in rural areas are normally solved by piggybacking on existing telecommunications. Even if mobile service is not available, several smart grid devices might communicate to a shared satellite terminal using low-frequency GMRS radios or power line communications. All parts of Australia, at least, have internet service via satellite. (youcompare.com.au n.d.) Rural satellite terminals could be justified if they could save lives or prevent significant property damage.

5 Detecting Rural Infrastructure Failures

5.1 Multipoint Voltage Monitoring

Since conductors are minimised, a wire break or insulator failure is likely to cause a voltage-sag for a large part of a rural network downstream of the fault. Smart meters can clearly measure voltages. Ideally, this is just what's desired to detect a line failure (wire break, etc.) However, the meters are powered from the line. They clearly cannot send voltage measurements when unpowered.

There is a standard solution. Many models of smart meters can send a sag warning message as voltage falls. In some cases this feature costs more, because a meter's power supply must store enough power to send the required message. Any required network infrastructure also needs robust power supplies.

Smart meters' voltage sag warnings are the conventional triggering events for a FLISR response.

5.2 Power Line Communication Continuity

One of the most reliable methods to discover the extent of a grid failure is to attempt to communicate with smart meters in the affected zones. When a meter does not respond, it is very likely to indicate a voltage sag in a particular part of an affected distribution line. This is a normal method to confirm and localise the extent of a service failure.

Because of communication delays, and time-outs, the polling should occur in parallel. That is, the FLISR's control system should send to all the interesting meters rapidly, and then note responses as they are received.

5.3 Load Monitoring

We have discussed wire breaks and insulator failure. Another type of ground fault simply shorts the line to ground, possibly through a low-resistance earth fault. In this case, voltage need not sag. Instead, a large amount of current is likely to be used in an unexpected, unmetered way.

Smart meters measure currents very well. It is entirely possible for a FLISR system to periodically sum currents and detect unmetered current usage, say, from a charred tree fallen across a line.

5.4 Line Clash Detection

Line clashing commonly occurs when lines begin resonant vibrations powered by wind. Since lines are rarely identical in mass and tension, they have different frequencies. Also, the vibrations are fed only at particular wind speeds. If the vibrations grow large enough, the lines touch, causing transient arcing. The conventional solution places aerodynamic dampers on the wires, however these are not always sufficient. Other forms of line clashing exist, but they resemble other forms of ground faults.

If the clashes could be detected, lines might be isolated temporarily. An efficient detection system seems possible. The clash itself would induce very high currents for times of roughly 100-400 ms. These should be detectable by adding appropriate digital signal processing to the meters and FLISR equipment. (Blackburn 1985)

Adding a basic anemometer would reduce false positives caused by legitimate faults. There are now very inexpensive anemometers based on air cooling of heated thermistors. The combination of clash detection on a line, and high winds would be a reason to isolate sections of feeders until the wind fell several percent in speed. (Fujita 1994)

5.5 Distributed FLISR

If FLISR is used for safety, a single control facility is a single point of failure. The conventional solution would place two locations in different cities with redundant access to power and networks. However, this does not fully address the safety of rural data networks. Upgrading such networks to full redundancy could be very expensive.

Another approach to FLISR is to have the meters, reclosers and circuit breakers use their embedded communication and computation to monitor the grid for health, and then respond.

For example, FLISR communication polling and switch control is done from a central location. However, most smart meters and modern FLISR breakers use internet protocols to communicate. The internet is a peer-to-peer network. It is very feasible for a FLISR recloser/circuit breaker to communicate with several preselected meters. If some do not respond, it could then consult a configurable decision table about whether to turn off, turn on or send a warning to a central system. The complex part of this firmware is the communication logic, which is already present to provide remote control.

A distributed FLISR response seems possible for current-monitoring as well. In this case, a FLISR switch would poll a selection of down-stream meters and switches, and then compare the sum of currents to its own sum. If the result varied by a questionable amount, it could turn off or send a warning to the central system.

This form of decentralised FLISR is suitable for safety-critical rural FLISR. It does not depend on a centralised control system. It is also very fast, because the configuration is decentralised and the communication delays all occur in parallel.

Decentralised FLISR seems likely to be more complex to configure than a centralised system. One of the more complex issues would be how the FLISR responses interact, and how to assure that the system reaches a stable end-point. Similar problems are commonplace in the design of digital logic, so a solution seems possible. Specialised software for configuration is likely to be helpful.

6 Preventing Bushfires

6.1 FLISR for Bushfire prevention

So, how would FLISR help prevent bushfires? There has to be at least a short interval between the occurrence of a fault in the grid, and the start of a bushfire. With automated controls, many bushfires could be prevented when the FLISR turns isolates the MV network in the area feeding a high resistance earth fault.

Voltage and communication monitoring should be able to detect downed conductors. Localisation should be able to isolate them, and FLISR control of reclosers and circuit breakers should be able to isolate the faults. A similar procedure seems possible with both earth faults, and in suspended-neutral systems, line clashing.

6.2 Cost of Monitoring, false alarms

The present methods of identifying downed conductors and other faults on rural feeders rely on line patrolling. This can be a costly and time consuming exercise, especially for intermittent faults. Line fault indicators can be used to assist in finding the fault, however these are not always triggered for high-resistance, low-current earth faults. Smart meters that can communicate voltage sags will assist in narrowing the focus of the line patrol and so reduce the cost of finding, identifying and rectifying faults.

6.3 Mechanical prioritisation of warning in Bushfire season

Recommendation 32 of the final report of the 2009 Victorian Bushfires Royal Commission included:

Disabling the reclose function on the automatic circuit reclosers on all SWER lines for the six weeks of greatest risk in every fire season and adjusting the reclose function on the automatic circuit reclosers on all 22 kV feeders on all total fire ban days to permit only one reclose attempt before lockout.

Proof positive of a downed SWER conductor as provided by smart meters communicating voltage sags directly with the upstream recloser could be used to adjust the number of reclose attempts even outside the six week period noted above.

6.4 Effects on Maintenance

Voltage and current data received from smart meters on SWER systems could be used to give an indication of distribution transformer overload and earth bank resistance. Earth bank resistance is important for voltage regulation and safety in SWER systems. If the supplied voltage is lower than it should be at times of peak demand this will prioritise maintenance of the associated MV and LV earth bank and a review of the associated distribution transformer loading.

7 Conclusion

A basic, centralised FLISR system with bushfire management should provide a better solution than any that presently exists. Such a system would be able to identify downed conductors, insulator failures, and ground faults, and automatically initiate the operation of the upstream reclosers and circuit breakers, isolating the affected feeder within a few minutes.

A distributed, autonomous FLISR system would add additional safety by automating the central control function for certain feeder faults. Configuration of the grid, network and FLISR would still be centralised, but isolating feeder faults would be automatic, faster and more reliable.

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