Internet of Things & Distribution Infrastructure: Self-Healing Grid Automation System

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ABSTRACT

The Internet of Things is transforming many aspects of our day-to-day lives and businesses. The Industry and Energy sectors are increasingly exposed to the new technologies where IT (Information Technology) and OT (Operating Technology) are converging and increasing in complexity.

In fast growing economies, utilities need efficient solutions and qualitative services to decrease the outage durations and its occurrences. The MV network should have the intelligence to reconfigure itself if there is a problem, the faulty part should be automatically isolated and the healthy part stays energized or will be re-energized automatically.

The principle of the Self-Healing Grid (SHG) is to start an automatic sequence of re-energizing the healthy part of the MV ring network after a trip due to a short circuit or an earth fault. These operations must happen fast (few seconds) to reduce customer inconvenience and with the high level of safety. The SHG is based on a de-centralized architecture and the intelligence is distributed in the switchgear or associated RTU. The RTUs in different substations communicate together in peer to peer and take local decision to control the switchgears. Deploying the SHG automation system can largely contribute to compliance with the requirements of NRS 047-1 regarding the restoration of the supply after unplanned interruptions.

Index Terms—Self-Healing, Supply Restoration, Reliability, Distribution Automation

INTRODUCTION

Between 1990 and 2013 worldwide energy use increased by about 54 percent, more than the 36 percent increase in the global population. Access to energy is fundamental to development, but as economies evolve, rising incomes and growing populations demand more energy.
This situation, coupled with strict regulations on the quality and reliability of supply mounts increasing pressure on the distribution network operators to keep the network at the best possible state which includes investments on replacing the aging infrastructure to prevent equipment failure however, failure of equipment cannot be completely eliminated.

For the faults that can't be prevented, it is therefore necessary to minimize the impact by keeping the outage time minimal and the affected customers as few as possible.

Recent advances in computer and communication technology have allowed manufacturers to make field devices that are more and more intelligent. Chollot et all (2015) stated "The Internet of Things (IoT) has made better communication feasible and devices like smart devices and sensors are now more affordable." This paper describes the application of these intelligent devices for automatic Fault Location, Isolation and Restoration (FLIR) which is one of the expectations for a Smart Grid. Moreover, the incorporation of distributed generation and various types of unconventional power sources (solar, wind, geothermal, among others) add more complexity to the electrical power system. To solve the problems described previously different techniques have been proposed that can be divided into two categories, centralized approach and decentralized approach.

In the case of centralized control, all the network information is connected to one point, the control centre. The main advantage of this model, is that optimal or efficient solutions can be obtained.
However, among its disadvantages is the possibility of a single point failure that shuts down the whole system. This situation can happen if the control centre has a failure or if the communication is lost. Moreover, due to the high volumes of information that is obtained from

the network devices, in the case of large networks the response time can be significantly increased.
The second approach, decentralized control, in comparison has a shorter response time because it does not require all the system information to solve a problem in a small part of the network as the intelligence is distributed between RTUs and/or controllers. In addition, the loss of one distributed control device does not necessarily mean that the entire control system will fail, as in the centralized control case. The decentralized control require sophisticated communication techniques between the RTU devices.

1.0 SMART GRID PHILOSOPHY AND SELF-HEALING APPLICATION

The smart grid should have an intelligent security control function which isolate faults to prevent the occurrence of blackout and improve the reliability of grid operations with minimum human intervention.
The American Electric Research Institute (EPRI) gives in the definition of the smart grid some of its related properties such as; self-healing, security, integration, collaborative, forecast, optimization and interaction.

Furthermore, in the definition given by European Commission, the smart grid could support distributed and renewable energy access, supply more reliable and secure electricity, have a service oriented architecture and flexible grid applications, possess an advanced automation and distributed intelligence, be able to locally interact with the load and the power, adhere to customer-centric.

Self-Healing can be defined as the property that enables a distribution system to realise incorrect operation and, without (or with) human intervention, make the necessary adjustments to restore itself to normal. Healing systems that require human intervention or intervention of an agent external to the system can be categorized as assisted-healing systems. It makes it possible to attain resilience for different types of failures.

European Technology Platform SmartGrids define the word "Self-Healing" as not only automated network restoration strategies that consider the impact of high penetration of distributed generation and demand side participation, but also high level decentralized preventive control methodologies that will address options for the management of unplanned outages.

"Self-Healing" is also interpreted as an engineering design that enables the problematic elements of a system to be isolated and, ideally, restored to normal operation with little or no human intervention. The Self-Healing Grid is a system comprised of sensors, automated controls, and advanced software that utilize real-time distribution data to detect and isolate faults and to reconfigure the distribution network to minimize the number of customers impacted.

One of the main goals of a Self-Healing Grid is to improve system reliability. This can be accomplished by reconfiguring the breakers, switches and reclosers installed on the distribution feeder to quickly isolate the faulty section of the feeder and re-establish service to as many customers as possible from alternate sources/feeders.

1.1 OVERHEAD LOOP WITH RECLOSER

For the 1st range of solutions & transient faults on overhead lines, a popular solution is to use reclosers with loop automation. Restoring supply to your customers in time is the focus of Recloser Solutions' Loop Automation Scheme.

The Loop Automation Scheme can automatically reconfigure a network to return supply to fault free sections that have lost supply due to a fault in another part of the network. It achieves this through the following steps:

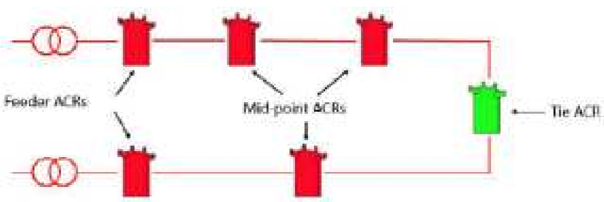
- Isolate the faulted section.
- Reconfigure the network so that the un-faulted sections receive supply.
- Automatically restore the normal configuration when the fault has been removed.

Classic Loop Automation (LA) is the original implementation. In a Classic LA scheme each Automatic Circuit Reclosers (ACR) or Automation Switch (AS0 is configured as a particular device type and operates independently according to the rules for that type. Classic LA does not require communications between devices and utilities with or without SCADA can easily introduce Classic LA into most ring networks without having to add any additional equipment. Classic LA is a software feature. The distributed intelligence embedded in each device operates the scheme using built-in voltage detection.

Intelligent Loop Automation (ILA) represents an evolution of the Classic Loop Automation algorithm. Intelligent LA also requires each device to be assigned a device type but in addition utilizes peer-to-peer communications between devices to eliminate the possibility of a device closing onto a detected fault while the network is being reconfigured. The implementation of Intelligent Loop Automation may require that additional communications equipment is installed in each device. e supply to customers and minimise electricity outage time.

Both Classic and Intelligent Loop Automation schemes require that each device be assigned a particular device type depending on its position in the network.
Each device, whether an ACR or AS needs to be configured as one of the following:

- Feeder – This device is positioned closest to the substation or source of supply. A Loop Automation scheme would have at least two Feeder type devices, one for each source.
- Tie – This device is used where two feeders meet and is normally the open point in the network.
- Mid-Point – A device positioned anywhere on the network between a Feeder and a Tie is a Mid-Point device. A Loop Automation scheme can have multiple Mid-Point devices.



Loop Automation scheme with device types

1.2 UNDERGROUND WITH CIRCUIT BREAKERS

The 2nd range of solution is often used in private industrial grid with a very high reliability expectation (microelectronic plants, hospitals ...). It is a quasi "reflex" solution since the fault is eliminated thanks to circuit breakers tripping action.
Discrimination is performed through differential, directional protection and / or logical discrimination. This solution is efficient but expensive since circuit breakers are used instead of switch disconnectors for the backbone secondary distribution network. Moreover, this is not always an acceptable solution since the loop is closed and circulation currents can appear, not always acceptable especially for a utility grid.

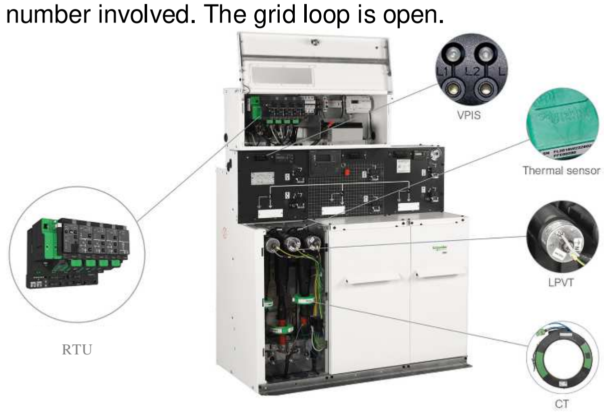
1.3 UNDERGROUND WITH SWITCHES

For the 3rd range Martinez R. et all (2018) defined distinguish 3 approaches:

Centralized: The Supervisory Control and Data Acquisition (SCADA) manages the decision and send restoration control orders to the Remote Terminal Unit (RTU). The RTU are passive in this solution. This can be used for all kind of grid from simple to very complex network schemes. The reconfiguration time is basically lower than 5 minutes. The grid loop is open.

Semi centralized: in which both RTU and SCADA/DMS are involved in the decisions. This kind of architecture is well adapted for simple to complex network schemes. In this kind of configuration, the loop reconfiguration time is lower than a few minutes. The grid loop is open.

Full decentralized: in which the RTU's react automatically to reconfigure the network and might possibly inform the SCADA. The logic is distributed in the switchgear or associated RTU in the MV/LV substation. This architecture is well adapted for simple network schemes and the reconfiguration time can be less than 20s, depending on the MV/LV substations number involved. The grid loop is open.



The scheme described in this paper is a fully decentralized architecture where the intelligence is distributed between several RTUs and controllers. The communication architecture mirrors the electrical network which makes it easy to add or remove nodes. One of the key design principles is to define a system that can be easily configured to work with different utility networks.

2.0 OPERATION PRINCIPLES OF SHG

There are two main principles for the fault location and isolation algorithm:
a) If the fault detectors indicate that the fault is located between two nodes, then this is due to a cable fault and switches are opened in both nodes.
b) If the fault detectors indicate that the fault is located within a node, then this is probably due to a fault in the RMU cable termination. In this case, opening switches within the node will not guarantee that the fault is isolated. The system therefore opens (or leaves open)

switches in the two neighbouring nodes. The SHG algorithm is based on 3 types of substations "nodes".

End Node: The MV supply feeders (from the primary substations or from a CB in the loop). The circuit breaker is tripped by an over-current relay when a fault occurs downstream of the breaker.

Middle Node: A node on the ring where 1 or 2 or 3 switches can be operated to isolate the fault

Normally Open Point (NOP): The point at any node where a Switch is in the open position during normal working condition. One of the Nodes which is specifically used to communicate with the SCADA is called the Master Node.

A Master Node has the capability to change the status of SHG Scheme and report to the SCADA. The information for the location of the NOP is in the Master Node. The SCADA may operate a change of NOP through this Master Node.

2.1 NORMAL OPEN POINT LOCATION

The location of the normal open point in a loop may be changed for various operational reasons. An operator can send a "Topology Validation" command to tell the SHG system that the current open point is the normal open point. Each controller checks the status open/closed position of its load break switches and responds with information on the number of open points. If the number of open points is valid (one less than the number of feeders), then a "topology valid" status signal is sent back to SCADA. If there are no other inhibit conditions (missing MV status, unit in local state etc), the operator can then proceed to switch on the system.

2.2 FAULT LOCATION, ISOLATION AND RESTORATION

The Self-Healing algorithm is based on the same approach used by a field crew if they travelled from the primary HV/MV substation towards the open point, checking the fault passage indicators at each MV/LV substation. The sequence is started when a controller at the primary substation detects that the protection relay has operated. The algorithm works in two phases. The first phase is the "upstream isolation" phase. Each node analyses if the fault is located upstream of itself, and if necessary isolate it. The second phase is the "downstream isolation" phase. Each node analyses if the fault is located downstream of itself, and if necessary isolates it. Coster E. et all (2013) described the algorithm is based on a number of principles:

- If the fault detectors indicate that the fault is located between two substations, then this is assumed to be due to a cable fault and the system will open a switch in each of the substations.
- If the fault detectors indicate that the fault is located within a substation, then this is assumed to be due to a fault at a cable termination. In this case, opening switches within the substation will not guarantee that the fault is isolated. The system therefore opens (or leaves open) switches in the two neighbouring substations.
- If the fault upstream of the normal open point has been isolated then it is safe to close the open point.
- If the fault downstream of the primary substation has been isolated then it is safe to reclose the circuit breaker.

The Self-Healing system will rapidly restore unaffected feeder sections and customers automatically but leave faulty feeder section isolated. Location of the actual fault within this section and restoring supply to the remaining customers is performed using a manual process. The FLIR algorithm described above is not new, but the implementation using distributed controllers has some novel features. One important safety/security feature is that none of the units send direct requests to open or close switches remotely.

The information directly available to each substation controller is only a partial picture. A fuller view of the state of the feeders is provided by the peer-to-peer communication. During operation messages are transferred which contain information on whether the fault is located and/or isolated upstream or downstream of the sending substation. When a message is received, the RTU uses this information plus the local status measurements to determine the fault location relative to itself, and then whether it is necessary to open one of the switches for isolation, or whether it is safe to close a switch for restoration.

2.3 OTHER REQUIREMENTS

In addition to fault location, isolation and restoration functions, each system has to satisfy several other requirements.

- Safety: the scheme must be automatically disabled when the electrical network is not in the correct state, or the switch position is unknown.
- Safety: control room staff can use SCADA commands to switch the Self-Healing scheme on or off.
- Safety: the scheme must be automatically disabled when any unit is put in local mode by maintenance staff.
- Robustness: if a switch fails to open to isolate a fault, then the SHG controller should try the next appropriate switch.
- Tolerant to measurement faults: the system should handle at least some scenarios where fault detectors give the incorrect status.
- Tolerant to communication faults: the system should

automatically recover following temporary communication failures.

3.0 COMMUNICATION ARCHITECTURE

The Self-Healing requires communication between the intelligent controllers. There are several choices for communication architecture. A common choice is to use a “Star” topology where one node is a local master which communicates with all the others. This means the “leaf” nodes are fairly simple but the local controller has to handle many communication channels.

The system described in this paper uses a “daisy-chain” communication topology that mirrors the electrical network topology. Each unit communicates only directly with its neighbours. This makes it easier to reconfigure the system, if and when more controllers are added.

Chollot et all (2013) in the framework of GreenLys smart grid emphasised that the system should be based on a standard, commercially available product. The communication used is standard, well established Modbus communication protocol. To reduce the packet size and hence costs, messages are sent as packed bit strings. Normally Modbus is used in polled mode where the master repeatedly issues a read request to its slaves for data.
The system uses write requests that are only sent when values change. One important safety/security feature is that none of the units send direct requests to open or close switches remotely. Instead each message only reports the state of the sender. The receiving unit always uses its own status measurements in combination with the information in the received messages in order to make a decision whether to operate a switch

4.0 TEST SYSTEM

Berry T. and Chollot Y. (2016) stated that it is impractical to test these types of system on a real network, so the system was thoroughly tested in a laboratory environment using a simulated network. The simulator used a number of interconnected relays to mimic the feeders with their load break switches. The voltage presence signals were derived from this circuit as a function of the switch positions.

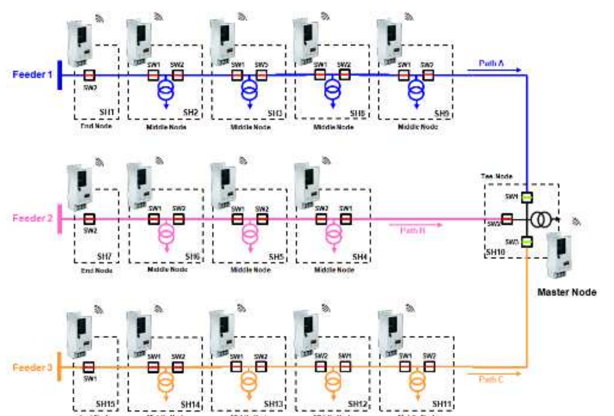
Fault currents were injected from test boxes via a set of routing relays. These relays were controlled by a programmable logic controller which was under the control of a master PC. Tests scenarios were described in scripts on the PC allowing rapid and repeatable testing.

Test system with 15 RTUs

4.1 TESTING STRATEGY

The SHG system is designed to work with a number of electrical network topologies, and different numbers of MV/LV substations. It was clearly impossible to test all possible permutations. The test strategy adopted was to test “qualitative” combinations. A small number of representative electrical network topologies were chosen:

- Two-feeder topology with 7 controlled nodes
- Two-feeder topology with 13 controlled nodes
- Three-feeder topology with 15 controlled nodes and equal length feeders (4,5,5 nodes)
- Three-feeder topology with 15 controlled nodes and unequal length feeders (2,4,8 nodes)



Example test network topology

For a topology with N nodes, there are N-1 sections with 2N possible locations for the open point, and 2N-1 possible fault locations. For testing single network faults, the strategy was to select a limited number of open point location, and then test for all possible fault locations.
For tests of operation when a switch fails to operate, a representative sample of fault locations was chosen.

The system was then tested with simulation of the failure of one or two upstream isolating switches or one or two downstream isolation switches. A similar strategy was used for test cases simulating failures in fault detectors.

Function tested	Topologies	Test cases
Changes in position of NOP	3	80
SHG Switch-On Inhibit conditions	10	97
SHG Switch-Off	9	94
Single Network Faults	11	275
Double Network Faults	3	25
Switch command failure	8	57
Inconsistent fault detection	3	34
Overload Alarm	6	15
Communication failure	4	28
Total		705

Over 700 test cases were executed. Of these 40% tested the fundamental Self-Healing algorithm for different combinations of topology, location of open point and location of the fault. The other test cases were testing that the system worked safely and correctly for various error conditions.

4.2 PERFORMANCE

GPRS communication typically takes 1-2 seconds but can be 3-4 seconds. The typical performance is 3s per "communication hop". The execution time is therefore a function of the number of SHG nodes along a feeder.

Basic topology	Ethernet	GPRS
2 Feeder, 7 T200s	14	22
2 Feeder, 13 T200s	17	47
3 Feeder, 15 T200s	16	42

Measured performance: average restoration time (s).

For a real system, the switch operation time need to be added. With a Schneider RM6 ring main unit, the switch operation time is about 2 seconds, however for some retro-fit actuators the switch operation time can be 8-10 seconds.

5.0 CONCLUSIONS

It is common that in most countries, delivering electricity with high level of quality and availability is becoming a priority challenge. For many years the utilities have experimented various solutions. The remote control of substations and the fault detection are two of the primary solutions. The introduction of Smart Grid requires pragmatic and optimised solutions where the intelligence is distributed among the equipment to locally perform the Self-Healing function.

The cherry on the cake when using RTUs fitted with load measurement and feeder automation, is that utilities can easily optimise their power generation and chase non-technical losses. The global concept described here synthesise the experience cumulated from various utilities worldwide. (France, Spain, UK, Australia, Canada and etc). The components which are associated to a SHG concept, such as RTU, remote controlled FPIs, reclosers and sectionalizer are readily available on the market. It is difficult or impossible to test Self-Healing or automatic supply restoration schemes on a live network. This paper has described how such schemes may be tested with a network simulator with many different fault conditions. The validation process has also demonstrated that a number of local switch controllers can be easily reconfigured for different network topologies. The obtaining of pre-tested and validated solutions reduces the installation and commissioning costs of deployment on utility networks.

Industry specialists in power equipment and associated IT applications can help utilities identify the most appropriate solutions and advise them on the most suitable and safest deployment process. Pre-engineered solutions offer the benefit of commission time savings, reduce the number of voltage outages during installation, and are flexible enough to accommodate future network development.

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