APPLYING A CENTRALIZED SELF-HEALING ARCHTECTURE TO A DISTRIBUTION NETWORK – A REAL CASE

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ABSTRACT

Advanced Distribution Managements Systems (ADMS) that employ the Smart Grids technology need to perform an essential task called self-healing function. A self-healing grid can detect and identify faults, overload or equipment outage; diagnose and isolate faulty network component; and automatically restore the service to consumers using healthy sections of network. This paper presents a conceptual approach to the concept, and a modular, scalable control architecture for a self- healing solution in a smart distribution system. To illustrate the proposed architecture, we report the experience with developing and implementing a centralized self-healing system in a regional distribution utility in Brazil, called ENERGISA MS. The self-healing is performed on a network with 293 reclosers, installed along 82 overhead feeders connected to nine substations with 357 MW peak load, supplying energy to 300,000 consumers.

INTRODUCTION

Many modern distribution systems have been adopting the Smart Grids concept, which has become a crucial way to face future challenges for achieving a safer, more reliable operation in smart distribution networks [1]. Recent advances in automation, computer, communications, and equipment technology (e.g. sensors and smart devices) have allowed implementing intelligent architectures for improving the monitoring and control actions in distribution grids [2]. In a power distribution system applying the Smart Grids concept, an essential ability of moderns ADMS (Advanced Distribution Managements Systems) [1] is the self-healing function. A Self-healing grid can detect, identify, diagnose, and isolate faulty network sections and components, and provide automatic service restoration to consumers using healthy sections of the network. Occasionally, some actions that involve human operation can be introduced to validate maneuvers. Reference [1] present a background and describe the importance of networks equipped with a self-healing function.

Self-healing is an essential concept when the main concern is to maintain high quality of services and improve reliability indexes, since unplanned interruptions on the network will cause penalties for distribution utilities, reduce unsupplied energy, and affects the consumer's well-being.

Several self-healing projects have been designed and implemented by power utilities as part of a new approach to smart grid networks, as well as to improve operational performance. Self-healing schemes can be implemented to use either centralized or decentralized control.

This paper presents a centralized architecture that was employed to develop and implement a self-healing system. By the end, we present a reflection upon the lessons learned from this experience and the limitations inherent to this type of solution; and the future development actions planned are discussed.

CENTRALIZED SELF-HEALING

The centralized self-healing approach described on this paper is based on the integration of information provided by SCADA (Supervisory Control and Data Acquisition), GIS (Geographic Information System) and OMS (Outage Management System) systems. The process employed by self-healing is very similar to the one taken by the operator in real time, which is: detect the fault based on signals from the equipment on the field, analyze the fault based on the one-line diagram, assess all transfer maneuvers that can be executed with the remote control resources available, choose the best course of action based on them, and then issue the necessary commands. In order to execute these tasks automatically, the self-healing module uses algorithms based on Load Flow and Topological Processor to identify the best set of action to be taken in order to restore the maximum amount of load in a safe and reliable way.

The self-healing module proposed in this paper start the operation with three types of events: reclosing lockout, substation busbar de-energization, or equipment overload. The module then searches for maneuver sequences that don't violate any device's current limits, and first tries to reestablish the maximum amount of load with the minimum number of maneuvers. As soon as the maneuver to be executed is identified, the module start sending commands to open, close, and fit the protection adjust group in the equipment. Figure 1 illustrates the system's operational flowchart.

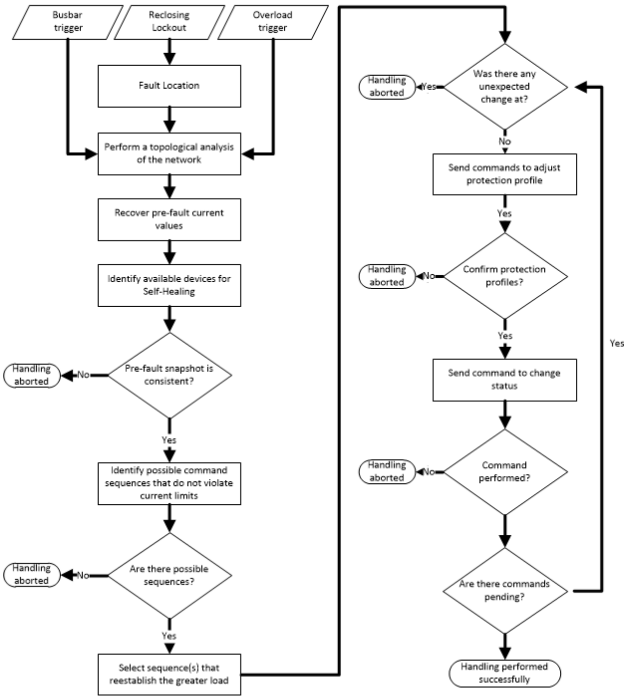

Figure 1 – Centralized self-healing flow chart.

Problem Identification

The self-healing module starts its operations under well-established situations, which are identified from the values at the IEDs (Intelligent Electronic Device) controlled remotely. The three conditions that trigger the self-healing module are described below.

Reclosing Lockout Trigger

This condition trusts on the selectivity of the distribution network protection system, using ground and phase fault trip indication due to overcurrent. Additionally to signaling protection, it is checks if the devices status is open and reclosing cycle has finished.

Overload Trigger

This condition is programmed to start whenever the current value sampled in real time overcomes the pre-established threshold, which is usually set to 90% of the IED's pickup current. Since this operational condition is not urgent, because costumers haven't been de-energized yet, it can be configured to start only after the operator pre-evaluates the calculated maneuvers plan and approves its automatic execution. This allows the operator to anticipate risky situations and to even coordinate their actions with the field teams.

Busbar de-energization Trigger

This condition is triggered by: voltage level under a pre-established limit (e.g., 70% base voltage) on the substation busbar, power transformer is not on maintenance, and current flow at feeders equal to zero. Due to the great impact of this condition, the module also allows that the automatic execution only takes place after the operator pre-evaluates and approves the maneuvers plan.

Fault Location

The only trigger condition mentioned in the previous section that requires locating the faulted block, it is the Reclosing Lockout. When the Self-healing initializes due to this condition, the module considers the fault is located in the protection zone immediately downstream from the device, trusting on the selectivity of the protection system. If other protection zones downstream do not indicated fault, these zones will be considered healthy zones for restoration. If two faults are detected simultaneously in interconnected protection zones, the module is aborted, because there is a risk of a system's selectivity error or of two different events.

Consistency in the Pre-Trigger Scenario

After the Self-healing module has detected a trigger condition, a validation process of the topological and loading scenario takes place, which is used as input for the load flow algorithm. Based on the values stored in a time buffer, the module restores past operational scenario, checking items such as radiality, protection selectivity, human interventions on the network, and inconsistency in sampled measurements. In a Reclosing Lockout situation, the scenario is captured outside the fault's window of influence, since it can corrupt the loading scenario. In this case, the system needs to search for a scenario that is previous to the first shutdown in the reclosing cycle, obeying a security time window that ensures the sampled values are not being influenced by the short-circuit current. Another issue analyzed by the module is how consistent the electric paths from load blocks to their respective sources are. Inconsistent paths are removed from the solution.

Finding Out Possible Solutions

Based on the loading scenario and the identification of equipment that can be operated, the module executes a power flow algorithm for each set of maneuvers that can be executed. The set of alternatives to be simulated is retrieved by an analysis of graphs and heuristics encapsulated by the module, in order to reduce the number of simulations and to shorten the module's response time. After each simulation, the module checks for any solutions capable of re-energizing healthy blocks without current limits violation. If more than one alternative is found, the module checks for the one with fewer switches operation and, whether the multiple alternatives persist, it opts for the one with more current surplus in the bottlenecks. If no alternatives are feasible, the module aborts trigger treatment.

Maneuver Execution

Once the set of maneuvers to be executed is selected, the modules checks for other actions (Open/Closed status) on the network or in nearby feeders. In case of unexpected changes, the treatment is automatically aborted for security reasons.

Before sending each Open/Closed commands, the module executes an algorithm that checks if need to change the protection group. To decide the protection group selection, the algorithm checks if the equipment is submitted to increased load or flow inversion. After executing this command, the Self-healing maneuvers the selected equipment. To proceed with the commands, the module waits for the issued command status to be read. If no information is returned, the Self-healing module aborts the action after the configured timeout and number of retries. This procedure is repeated as many times as needed for each calculated maneuver, until all of them are executed successfully.

CASE ENERGISA MS

The Self-healing module presented in this paper was implemented in a regional distribution utility in the Brazilian Mid-West called Energisa MS. This system controls 293 reclosers, installed along 82 overhead feeders connected to nine substations with 357 MW peak load, and supplies energy to 300,000 consumers. The module was integrated to SCADA, GIS, and OMS systems pre-existing in the control center. It uses the existent communication infrastructure and the reclosers from different vendors already installed, which no requires new hardware to be installed in the field.

Integrating to the SCADA System

The integration to the SCADA system took place via a DNP3 communication gateway installed between the SCADA system and the equipment in the field; the existing tags and devices addresses were maintained, and only the IP and slave DNP3 ports were changed. Therefore, no alterations were required in the SCADA system in the control center, except for the new status information available in the Self-healing module for each device, such as: available for operation, action initialized, overload treatment; etc. Communication with the equipment in the distribution network takes place via digital radio, whose hubs are installed in the substations linked to the control center via optical fiber. The architecture of this integration is illustrated in Figure 2.

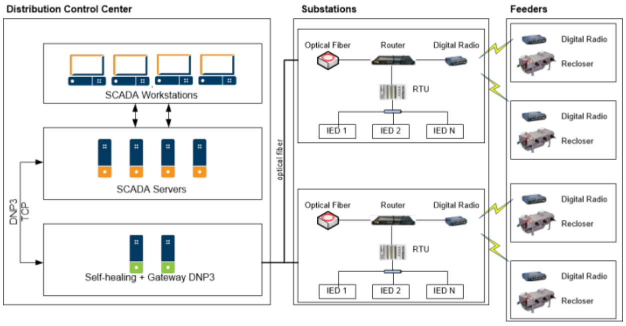

Figure 2 – Centralized self-healing communication integration.

Integrating the Electrical Model

Since a centralized Self-healing module requires the electrical model to identify the connectivity between devices, a driver was developed to read this information from the GIS system and create an internal data structure. The driver reads the data via SQL (Structured Query Language) queries and created a data structure based on the CIM (Common Information Model) IEC-61970 standard [3]. The electrical model is synchronized by the Self-healing module maintenance responsible in the company. Right after the data structure is created/updated, a script automates the creation of measurements and commands provided by the DNP3 communication command. Figure 3 is a simplified depiction of the electric model on the controlled network.

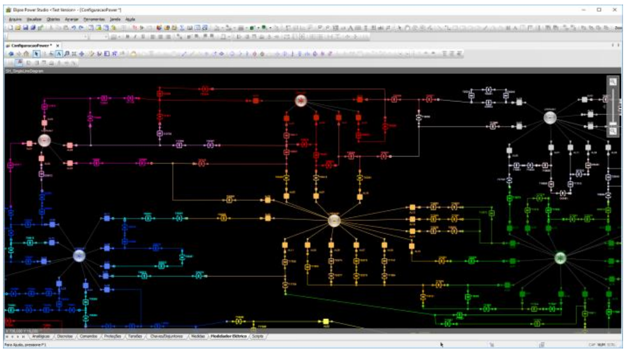

Figure 3 – Self-healing one-line diagram.

Integrating Unsupervised Switches

Most maneuver devices on the distribution network are not able to be remotely controlled or supervised, however can change significantly the network topology. Taking only its normal status into account may cause the Self-healing module to act incorrectly, which can endanger the company's assets and the population in general. Although these devices are not supervised by the SCADA system, their statuses are maintained in the OMS system, where operators register all maneuvers executed by the field teams. In order to guarantee the Self-healing module will also interpret these statuses, a driver was developed to read the statuses of all switches registered in the OMS cyclically, every 30 seconds, which updates the topological model online. The driver executes a SQL query in a database view provided by the OMS system.

Availability Conditions of the Equipment

To ensure the Self-healing module operates safely and efficiently, the centralized module must be able to identify when the equipment is ready for remote control, as well as when an automatic load transfer maneuver may pose a threat to field teams or to the population. After analyzing all possible operational conditions in the network and the information available in each IED model, the technical staff (operation, automation, and protection) has defined a set of DNP3 points that are used to make the equipment available for operation and how it is propagated to the downstream devices.

Each IED manufacturer provides, via communication protocol, a different set of data, which can be used either to detect accident hazard situations (e.g., HotLineTag indication) or to indicate the device can not be operated remotely (e.g., Equipment in local operation only mode). In the 293 reclosers controlled by the Self-healing module, there are seven types of IEDs, each with specific data externalized via DNP3. After analyzing the available tags for each device, a set of criteria (for security and operational reasons) was established to interlock the operation of Self-healing, as showed in Table 1.

Table 1- States used to interlock the equipment for Self-healing operation.

Measurement	State
Autoreclosing	Blocked
50/51 Neutral	Blocked
Local/Remote	Local
Mechanical Locker	Locked
SF6	Alarm
HotLineTag	On
Hardware Defect	Detected
Battery State	Alarm
Communication Status	Error

The downstream unavailability propagation concept was applied so that every time a device is blocked for the self-healing operation, all downstream devices are blocked too, including the ones with interfaces from other feeders (tie equipment). This prevents the module to reenergize a block improperly in the event of protection trip.

Validation and Commissioning

To validate the system, the project team elaborated a set of test procedures that covers several different logical, topological, and loading situations. Because the system uses an electric model and the supervised variables to decide the set of maneuvers to be executed, the procedure was built to foresee the main situations that can happen in the network. Tests to validate the equipment unavailability for self-healing were also applied.

Test Execution in a Simulation Environment

Executing all tasks predicted in the test procedure on the real network is a significant cost and risk factor for the project; nonetheless, not executing a practical test and validation procedure can endanger the network operational security in the future. With that in mind, the project team created a simulation platform based on power flow module and DNP3 Slave I/O drivers, which allowed for a trustworthy representation of the system network when submitted to a centralized self-healing module. The simulator not only helped the team evaluate all steps in the procedure, but it also helped to spread the self-healing concept to other areas in the utility, which used it as a platform for training and validating the new concepts.

Based on the electric model and on the loading scenarios, the power flow module calculates the current and voltage values for each device on the network. These values are directed to a DNP3 slave driver with the exact same addresses from the IEDs in the field, which causes the self-healing centralized system to interact with the simulation environment the same way it would with actual remotely controlled devices.

In addition to the electric measurements calculated by the power flow module, the simulation environment also allows for manually change any measurement in the DNP3 map, allowing simulations such as communication failures, blocking function 79, equipment lockout, etc. The simulator was also programmed to respond to open/close commands, blocking protection functions, and changing a protection adjustment group.

Listening mode

Once the system was validated in the simulation environment, the centralized self-healing was enabled to work on listening mode integrated to the control center. In this mode, the Self-healing constantly analyzes the electric and telemetry systems, presenting the operator the actions that would be taken on possible power outages. In this operational mode is not possible to send any kind of command to field devices. In this stage operators could evaluate if communication availability and the IEDs statuses would impact in the system's response quality. Implementing this mode represented an important intermediary step for executing the module on automatic mode, especially due to its paradigm-breaking nature for the control center.

Executing Tests in the Field

After the listening mode validation, the equipment unavailability signals were simulated in the field devices. Since the DNP3 tag list is identical between IEDs of the same model, the tests took place in only seven devices, one for each model.

When the unavailability logic was validated, tests for actual performances by the self-healing module were set up to a feeder that had resources to be transferred to another nearby one. Since the tests were not allowed to cause any system outage, some maneuvers had to be executed in the field, using two electricians: one was placed at the substation, and the other at the NC (Normally Closed) isolation recloser. At the substation the load of selected feeder was maneuvered to an auxiliary transference breaker, and the CT (Current Transformer) signal used by the IED was replaced by a signal generated by a current source, in order to simulates load and short-circuit values. In the NC (Normally Closed) network recloser, downstream from the substation, a by-pass allowed executing open/close maneuvers with no risks of de-energizing consumers. The only inconvenient in this procedure is the reduced network selectivity during tests, but in a less risky environment due to meteorological conditions on the selected days and the presence of the electrician team in the maneuvered places. The tie switch (Normally-Open) was isolated from the network, allowing the equipment to be operated freely, with no operational costs for the network.

The self-healing actuation tests consisted of injecting current to the substation breaker and provoking the reclosing lockout, thus initiating the module activation. It was possible to analyze the calculated maneuver, the activation time, and the commands sent to the field. Overload tests also took place, which enabled the analysis of transfers and partial load shutdown when there is no leftover current from the nearby feeder. During tests, it was possible to detect and correct communication and timestamp issues (synchronizing the IEDs' clocks).

SELF-HEALING OPERATION – REAL CASE

On July 23, 2018, the self-healing module had its first operation in the system. When detecting a reclosing lockout at feeder 07 of CGC substation, the module was started. After waiting 30 seconds for receiving all signals from the field, in order to guarantee there had been no indication from other devices on the same network, the re-establishment sequence took 2 seconds of calculations from beginning to end. The maneuver executed automatically by the Self-healing module involved two devices and was over in 8 seconds. The complete operation time was 40 seconds, and it isolated 278 consumers in the outage block and reestablished 316 consumers successfully, which represents a 1.1 MVA load.

After this occurrence, it was verified that the waiting time for new messages in the field could be reduced from 30 to 5 seconds, since the communication system's results were satisfactory due to using the unsolicited messages resource from DNP3 protocol. Then, other event happened on August 8, 2018, when the breaker of the feeder 03 of DOD substation signaled reclosing lockout, which started the self-healing operation. The module took 3 seconds to calculate the best maneuver, and executed the isolation and reestablishment commands in 7 seconds, which made up a total of 15 seconds of operation. In this time 2,436 consumers were isolated and 3,093 of them had their energy reestablished, which represents a 0.5 MVA load.

CONCLUSIONS

In this paper, an application of Centralized Self-Healing architecture in a real distribution system has been presented. The implemented structure has been designed with 293 equiments on self healing control. Two cases of self-healing operation were presented. In the first case, the total time of operation was 40 seconds, successfully reestablishing 316 of 594 consumers, representing a load of 1.1 MVA. In the other, the complete cycle of self-healing action was 15 seconds, reestablishing 3093 of 5529 consumers, representing a load of 0.5 MVA. The results show that reliability index SAIDI and SAIFI was not violated for the restored customers, avoiding penalty for distribution utility and improve the quality of service.

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[3] IEC 61970, "Energy Management System Application Program Interface (EMS-API)- Part 301:Common Information Model (CIM) Base ". International Standard IEC, 2005.