SELF-HEALING DISTRIBUTION GRID BASED ON ADAPTIVE PROTECTION AND IEC61850 DECENTRALIZED ARCHITECTURE

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ABSTRACT

Some faults and grid failures cannot be prevented, but when fault occurs, it is necessary to minimize the impact on the quality of the supply so that the number of interruptions is minimized and the time of interruption is as short as possible. In order to realize these requirements, a new approach to grid management and protection coordination is needed. By applying advanced grid technologies such as self-healing grid and adaptive protection, grid becomes active and adaptive. It will reduce time of interruption compared to conventional methods, and also it will introduce new opportunities and business models for better management and protection of the grid. This paper describes fast self-healing distribution grid based on communication protocol IEC 61850 in pilot project for HEP DSO Elektra Koprivnica in Croatia.

INTRODUCTION

Electricity consumption is increasing year by year. Share of distributed generation (DG) in the network is also increasing and regulatory requirements for quality and reliability of supply are becoming more and more demanding [1]. Distribution system operators (DSO) will be under high pressure to keep the grid stable with as little interruption as possible. When trying to increase capacity and reliability of existing grid, easy solution is to change existing primary equipment like transformers, cables, lines, etc. This solution requires high investment costs and can take long time to implement. Other approach is to make existing grid more efficient by implementing grid automation solutions.

NEW PROTECTION REQUIREMENTS

In smartgrid environment number of connected DGs to the grid is not fixed but varies on various conditions like weather, market situation, DG availability etc. Grid becomes active and new adaptive methods are necessary to satisfy these new conditions. To achieve full functionality of adaptive protection it is necessary that relay protection devices share data and communicate in real time. To achieve that one must use stable communication infrastructure which has high availability, latency and bandwidth. In conventional protection schemes, grid configuration is usually fixed and minimal interventions are possible during normal operation. Protection settings are calculated and implemented into protection relays. These protection schemes are passive and cannot take into consideration active changes in grid. For every change in grid new protection settings must be calculated and implemented. In advanced adaptive protection schemes all grid elements are continuously being supervised and when change in grid is detected (fault or grid topology), new protection settings in protection devices are activated accordingly [2].

SELF-HEALING GRID

Self-healing grid is a process to automate manual reconfiguration of the grid when fault occur and to reduce the time without power. Self-healing grid can be implemented in cable grid and also in overhead lines. In cable grid, remotely controlled switching units (Ring Main Units - RMU) are used as primary equipment, while in the overhead lines remotely controlled circuit breakers (Reclosers) and remotely controlled load break switches (LBS) are used.

Way of configuring self-healing grid is determined by primary and secondary equipment in the field, availability of communication infrastructure and general level of grid automation. From control standpoint self-healing grid can be based on decentralized or centralized system architecture, with or without communication infrastructure.

Peer-to-Peer model

Peer-to-peer is model of a decentralized controlled system, at the device level requires use of a horizontal communication infrastructure through which device coordination can be performed. To implement fast speed self-healing grid sequence of fault detection, fault isolation and network reconfiguration must be done in less than 300 ms. In that way grid users will not see this as power interruption.

The algorithm model can be applied on exapmle in Figure 1 on system based on the IEC 61850 communication protocol , with reclosers (RC) and RCtie as the normally open point. Coordination the protection relays, determining fault location and the sequence of switching will be determined by protection devices themselves. When fault F occurs, all relays from CB1 to RC11 will see a fault. First, RC11 will open, then RC12 will also open and immediately after the fault isolation, RCtie will close to energize the network up to the RC12. Then the ARC cycle begins at RC11. After the fault has cleared, the back up to "normal state" is performed in reverse order of isolation: first RC11 close than RC12 close and then RCtie open their state.

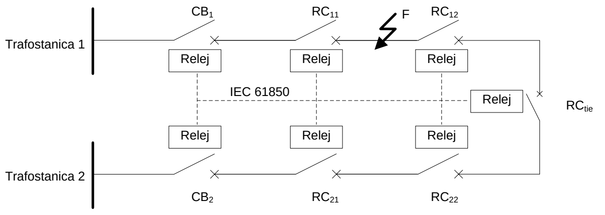


Figure 1 - OHL with communication

Using the Peer-to-Peer model significantly shortens the time of switching in relation to the Loop automation model, thus significantly improving the SAIDI and CAIDI indexes. Also, because of the direct switching (open and close operation) of the reclosers, only the part of grid affected by the fault is left without power supply.

SELF-HEALING GRID KOPRIVNICA

Substation SS 35/10 (20) kV Koprivnica 1 supplies the city of Koprivnica together with its suburbs in north-east part of Croatia. Two power lines *Jagnjedovac* and *Sokolovac* are forming a loop of about 60 km in length and supplying approx. 5.000 consumers. Prior to this pilot project, when a fault occurred in the loop, process of fault isolation, network reconfiguration and reenergization was done manually - the process which could have last for several hours. The main goal of pilot project "Self-healing grid Koprivnica" was to reduce the number of consumers affected by the fault and to reduce outage duration. To achieve this, it was necessary to install appropriate primary and secondary equipment for grid automation and select the communication technology that meets the requirements.

Technical requirements

The challenge was to implement and coordinate automation and protection systems while using wireless communication within the field of energy and communications technology.

Energy requirements were to establish a self-healing grid on an existing power line Jagnjedovac – Sokolovac using Peer-to-Peer model. It was necessary to install reclosers (i.e. vacuum circuit breakers) with remote control and possibility to communicate on two communication protocols, one for horizontal peer-to-peer communication, one for vertical communication to control center. The system had to detect and isolate the fault instantaneously. Immediately after the isolation of fault, the system had to re-establish power supply to the "healthy" parts of the line and issue an auto-reclose sequence to check if there was a case of transient fault. Time for re-energization "healthy" power lines had to be less than 300ms.

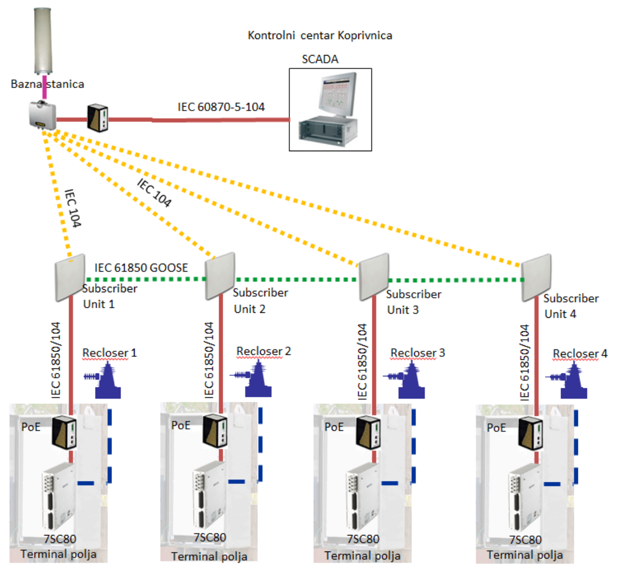


Figure 2 - Schematic diagram of selfhealing grid Koprivnica

In terms of communication technology, the requirements were to use wireless communication. Protection devices had to communicate with each other using secure IEC 61850 GOOSE messages to transfer digital and analogue information while IEC 60870-5-104 protocol was used for vertical communication with the control centre. Since IEC 61850 GOOSE is a demanding protocol, and some of information important for protection functions (jDiff) were transmitted via same protocol, the communication system for horizontal communication must have had high reliability (> 99%), high bandwidth (minimum 1Mb / s), and low latency (<10ms).

Technical solution

While making optimal technical solution multiple factors were considered: status and topology of the grid, and technical requirements for self-healing grid. The schematic diagram of the embedded system is shown in Figure 2.

The key elements of the self-healing grid DSO Koprivnica are 4 reclosers equipped with voltage and current sensors and control cabinet equipped with controller with integrated protection functions and system for uninterruptible power supply and communication modem. Reclosers are designed for outdoor installation. The drive mechanism uses a fast magnetic actuator, powered by a capacitor, without standby recovery time or power consumption if not in operation. They are built for the

high-speed auto-reclose (AR) with operating sequence O-0.2s-CO-2s-CO-2s-CO (-30s-CO) -lockout.
The control cabinet is installed at the foot of the same pole. Main cabinet elements are controller, power unit and communication equipment. The controller has integrated protection functions (ANSI 50/51, 50BF, 46, 49, 74TC, 37, 51c, 86, 79), possibility to define internal PLC logic (CFC), simultaneously work on two communication protocol: IEC 61850 and IEC 60870-5-104 [5]. The power supply unit consists of a battery UPS system which supports the operation of the circuit-breaker in case of power loss from the main power supply.

Communication equipment

Due to specific requirements on bandwidth, speed of communication, and the demanding terrain configuration, field analysis of each recloser location was made to select optimal solution. Analysis showed that best solution was to use microwave radio network in point-to-point and point-to-multipoint configurations. The radio system is equipped with a 10/100/1000 BaseT interface. Flexible system topology enables a simple and efficient upgrading of the radio network in point-to-point and point-to-multipoint operation mode. When calculating accessibility and redundancy of radio connections, radio and antenna systems were selected to provide high availability and reliability of the radio connection. The layout of the communication system linked to terrain configuration is shown in Figure 3.

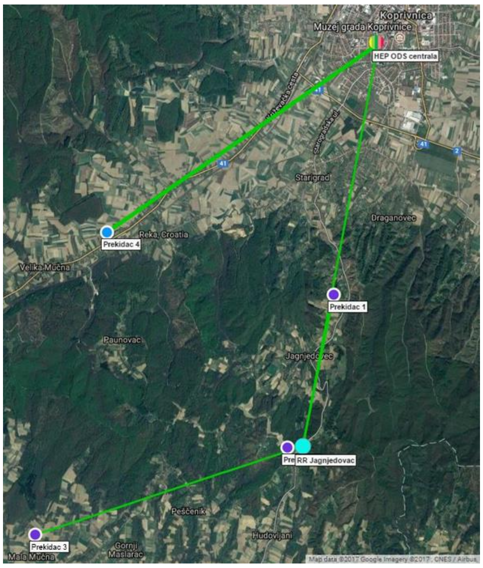


Figure 3 - Communication system layout

IEC 61850 PROTOCOL

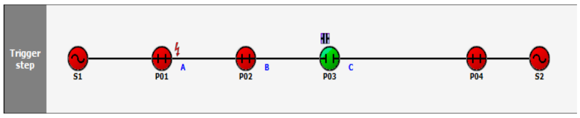
Although communication protocol IEC 61850 is primarily viewed as a substation protocol, due to the increasing automation of grid, it led to the development of standards for out of substation communication. In this case, GOOSE messages are designed to map on Ethernet Layer 2, which allows messages to be sent over WAN to other remote objects. Since GOOSE is very demanding in terms of speed and bandwidth, it is necessary to optimize GOOSE messages which are sent between the devices. Via the GOOSE message are transmitted the digital and analog data required for full functionality of the self-healing grid.

FLISR & ATS

Two main applications used in self-healing grid are “Fault location, isolation and service restoration” (FLISR) and “Automatic transfer source” (ATS). FLISR and ATS are performed by preconfigured automated sequences. Automatic service restoration is initiated at the time the power supply is disconnected. The system automatically finds the nearest point in the network as a new power source and runs the automation transfer source (ATS). After removing the fault that caused the network reconfiguration, the system has the ability to automatically return to the previously established normal state defined by the normal open point chosen by the user.

ADAPTIVE PROTECTION

Control system of self-healing grid in DSO Koprivnica is decentralized solution that is based on IEC 61850 communication protocol over wireless technology. Grid fault protection is achieved by numerical protection relay (controller) which is embedded in control cabinet of vacuum circuit breaker recloser. Controller is programmed to be fully adaptive on changes in grid (either trip on fault or grid reconfiguration), but also on changes in communication system (communication active or not) . In all cases, controller must have feeder protection set to be selective, independently of the communication system.



Step	P01	P02	P03	P04
Isolation during transient fault (first cycle of Auto Reclose successful)				
1	Open	Open	Close	-
2	Close	Open	Close	-
Isolation during permanent fault (first and second cycle of Auto Reclose unsuccessful)				
1	Open	Open	Close	-
2	Close	Open	Close	-
3	Open	Open	Close	-
4	Close	Open	Close	-
5	Open	Open	Close	-
Restauration after transient fault (return to initial state)				
1	-	Close	Open	-
Restauration after permanent fault (return to initial state)				
1	Close	Close	Open	-

Figure 4 - Switching sequence matrix for fault on section A

In order to program controller, analysis of possible operating grid conditions had to be done. A number of possible switching states and automated sequences for that part of grid were determined. By generating matrix of switching state for each sequence and configuring PLC logic in numerical relay (CFC), the functions of self-healing grid were achieved, as show in Figure 4.

Jump differential (jDiff)

Hybrid protection method called jump differential (jDiff) was developed by manufacturer Siemens and implemented in feeder terminal controller type 7SC80 for fault detection [4]. Functionality of jDiff is based on measuring principle of vector current value. According to these measuring results, the controller determines completely selective with no overreaching or underreaching the segment of feeder where is the fault location.

The jDiff algorithm utilizes the measured currents flowing through the primary switch unit current transformers and compares current measurement of the measured half cycle area to the memorized area of 3 cycles before as depicted in Figure 5.

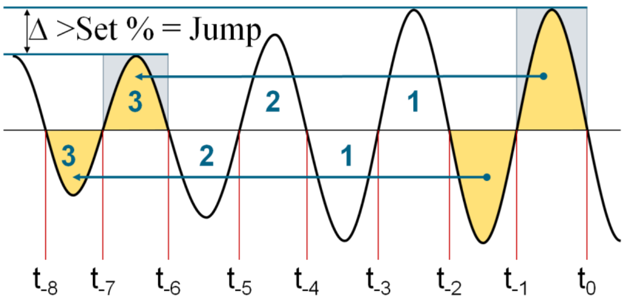


Figure 5 - Jump Differential detector

If the difference is greater than a predefined percentage threshold of hybrid function - *jDiff*, the device generates a positive or negative jump within a half cycle. The “Positive Jump” generate a positive jump “GOOSE” signal that is transmitted to the other line ends, conversely a sudden decrease in current causes the device to generate a “Negative Jump” and an associated negative jump “GOOSE” signal.

In example in Figure 4, fault is in the line section between controllers P1 and P2. The fault current will cause P1 to generate ‘’Positive Jump’’ signal which will provide a restrain to the algorithm. Controller P2 will record sudden decrease in current and then issue the ‘’Negative Jump’’. The jump differential logic evaluates its own signals as well as information coming from the opposite line end. The pickup equation is fulfilled if the controller detects the difference, having both its own “Positive Jump” condition and the “Negative Jump” GOOSE from the “neighboring side”. In our example, device P1 will have its own ‘’Positive Jump’’ and ‘’Negative Jump’’ coming from P2 and this will cause P1 to pickup and transmit the pickup signal to P2. Controller P2 will also detect two jumps, its own ‘’Negative Jump’’ and a ‘’Positive Jump’’ received from P1. Controller P2 will reply to P1 with pickup signal to confirm the fault in line segment between them. This ensure that jDiff will trip only for actual fault currents and not for possible sudden load changes of feeder switching operations. For proper operation of jDiff function, it is necessary to use appropriate communication infrastructure based on IEC61850 protocol that support exchange of GOOSE messages in real-time between all controllers in the loop. In case of communication loss, feeder protection relay must automatically block jDiff function and switch its way of working to normal working mode.

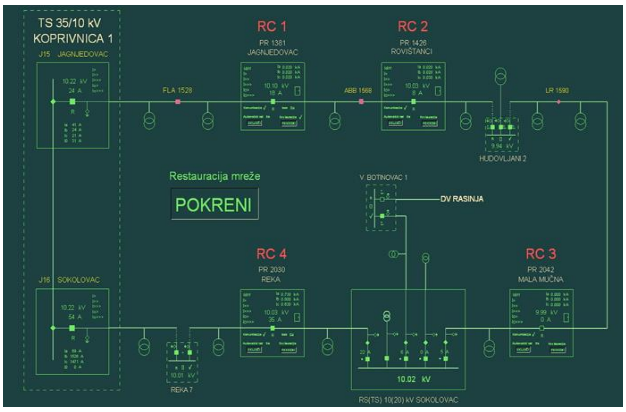


Figure 6 - SCADA scheme in control center

Selectivity and protection coordination

The main function of relay protection system is to detect and clear the fault in the shortest possible time. In case of failure of main protection system (relay failure or circuit breaker failure), the other protection device must react as backup in the same or next substation with time grading according to protection selectivity requirements. While communication system is active by using jDiff as main protection all faults in the loop all cleared instantaneously. In case of communication failure, FLISR automation is no longer available so controllers will adapt and switch to “local mode” without communication which also has to be selective for current grid configuration, but triping time in no longer instantaneously as show in Figure 7.

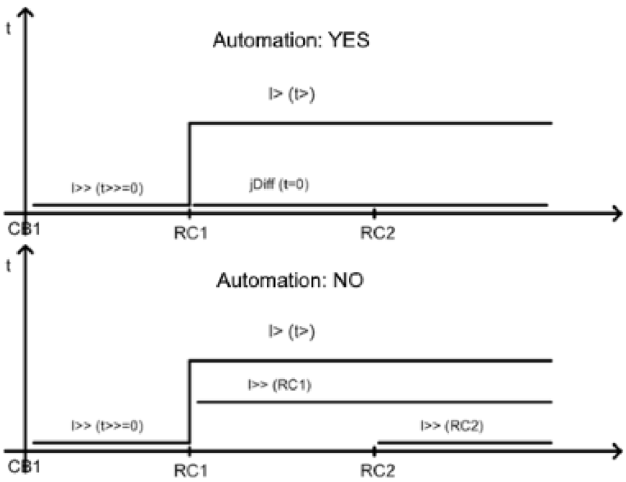


Figure 7. Protection coordination in zone 1 with and without communication (automation)

Two main conditions were used while relay settings are calculated. The first condition is that relay should operate only for faults in his zone. The second condition is that relay must not operate for faults out of his zone, except in case of operation like backup protection. For each of the proposed topology of the self-healing grid (switching state matrix) and for each numerical relay in the loop, a protection calculation study is applied. It has been shown that it is necessary to change the protection settings depending on the network condition, i.e. the protection must be adaptive to achieve proper work of self-healing grid.

The numerical relays are configured to adapt their settings depending on the grid state:

- Out of source
- Restoration (return to the initial state)
- Transient fault (first cycle of automatic reclose is successful)
- Permanent fault (first and second cycle of automatic reclose are unsuccessful)
- Restoration of transient faults (return to the initial state)
- Restoration of permanent faults (return to the initial state)

After configuration of all numerical relays are done, relays and configuration were tested to prove selectivity of protection settings for all switching sate of self-healing grid.

TESTING AND COMMISSIONING

Before field installation, the entire system with all switching states was tested locally with secondary values in laboratory together with established wireless communication. Laboratory tests already showed that trip and fault isolation will be less than 300 ms.

Event	
Event Type:	Interruption
Event Duration in Seconds:	0.147
Trigger Date:	2017/09/14
Trigger Day of Week:	Thursday
Trigger Time:	T 10:51:21.750
Trigger Channel:	L3-N
Trigger Threshold:	10.0% of nominal

Figure 8 - Record from power quality device

Once on-site installation of complete system was done, the entire system was tested first with secondary tests and later with primary tests to determine the time reaction during real primary fault. On each section between the reclosers the fault was simulated for each case and break time was recorded by power quality device, i.e. time without voltage supply. The test results showed that time for trip, isolation and grid reconfiguration for each section was less than 300ms (Figure 8 show interruption time of only 147ms) which means that all customer connected to system will not have power interruption during reconfiguration and only customers in fault section will be without power supply. Example of real fault by COMTRADE fault record can be seen on Figure 9 to follow up sequence during fault.

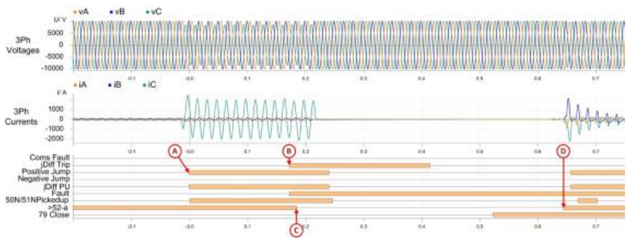


Figure 9 - COMTRADE Fault record from controller device

CONCLUSION

This paper shows new protection and control concepts in distribution grid implemented in pilot project in HEP DSO Elektra Koprivnica in Croatia. Due to fast communication system based on wireless, peer to peer technology and decentralized system architecture based on protocol IEC61850, it was possible to achieve fault isolation and grid reconfiguration in “blink of an eye” or less than 300ms. Adaptive protection with two protection levels was implemented in order to achieve higher grid availability.
To our knowledge at the time project was finished, it was one of the first self-healing projects in Europe to have decentralized system architecture based on wireless communication link and protocol IEC61850. This solution will help customers to reduce its SAIDI and SAIFI and also increase final grid capacity.

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