Fault Location, Isolation and Restoration in a City Distribution Network

Osmo Siirto, Jukka Kuru, and Matti Lehtonen

Abstract—**Active network management is based on distribution network automation systems like SCADA/DMS, distribution automation, microgrids, smart meters and home energy management systems. In fault situations, a lot of data is available and received to the control centre. To improve the fault management and in order to get the best benefit from high volume of monitoring data, the adaptation of new distribution network automation concepts are required. Automation systems will be integrated already on field to merge information for holistic distribution automation. Existing systems will be extended by additional functionalities. These functionalities can be located in different levels of control hierarchy: in Substation automation, in Distribution Management System (DMS) or in Network Information System (NIS). Helen Electricity Network Ltd., Aalto University and Tekla Corporation have been working together to help the control centre in fault management process to improve the reliability of supply. The idea is to combine network data, topology and distribution automation data and develop new fault management features, functions for automatic fault location, isolation and recovery in city distribution network.**

Index Terms—**distribution automation, fault location, self-healing, supply restoration.**

I. Introduction

Demand for high reliability of electricity has increased a lot with the modernization and computerization of the society. Electricity is for modern urban society like blood circling for humans, when the supply of electricity is interrupted the processes of urban society are interrupted. For a large shopping center the customer outage damage is totally different if the interruption lasts one minute or one hour. To mitigate the customer interruption costs (CIC) urban area distribution system operators (DSOs) have recently implemented distribution automation (DA). However, even with help of remote controls of DA, the human capability to resolve the fault situation with protection alarm and fault indication information combined with network topology information is limited. It takes few minutes for a control centre dispatcher to figure out the logic in order to start the first restoring control actions.

In [1] is presented three self healing fault detection, isolation and restoration (FDIR) schemes. In the simplest scheme the reclosers detect the loss of voltage and after preprogrammed time the recloser closes. This scheme does not require telecommunication, however it is possible to switch onto a fault. The second presented scheme solves the problem of closing onto a fault, but as a requirement is an advanced GOOSE technology and telecommunication. The third presented solution is a combined substation computer application and SCADA/DMS. The computer application makes a restoration plan based on information on feeder devices. Combined with this restoration plan and other information from the network, the SCADA/DMS can make decision on switching actions.

A self healing pilot medium voltage (MV) ring has been developed in Netherlands. The MV ring consists of 33 secondary substations of which five are equipped with remote terminal units (RTU) and automation. The automated sites divide the ring into two feeders and each feeder into three sections. In network fault the RTUs communicate with each other and execute automatically fault location, isolation and restoration (FLIR) steps [2].

Various agent or multiagent systems (MAS) have been introduced to help the utilities to support and enhance the fault management process. In [3] during outage the multi-agent system decides the target configuration and the switching sequence using local information only. An agent system using tokens handles fault management quite effectively reducing the needed communication hops and inhibiting cascading errors due to erroneous actions [4].

Self-healing control of urban power grid is presented in [5], along with an emergency control agent, restorative control agent corrective control agent and preventive control agent. A permanent fault in the network triggers protective actions as emergency control to isolate the fault. After receiving the return signal from emergency control, the self-healing control reads the latest data from database and activates the restorative control agent. The restorative control agent recovers the lost loads and then sends the mission success message to the self healing control agent.

II. Fault Management Model

The critical factor in the fault management process is the detection of the fault. In the case of short circuit faults, the protection is tripping and the fault is detected when the feeding circuit breaker is opened. This is the initiating event of the fault management process. On the contrary, earth fault protection may be tripping or in networks with sustained earth fault operation the protection is alarming. In the case of sustained earth fault operation, the fault detection is based on alarm obtained from the relay protection. This is a less reliable indication, and in this case the correct fault section location by fault passage indicators is of primary importance.

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The automatic fault management process is divided into two functional levels, which depend on the equipment at the secondary substations. The higher level is based on full automation, where all the switches are remote controlled. The automatic fault management requires that there is a reliable fault indication, which is based on local measurements. In practice, this means measurement of both currents and zero sequence voltages at the secondary substations. In short circuit faults, the fault detection can simply be based on current amplitude measurement and overcurrent relay principle. In single phase to ground faults, the directional relay principle based on measurement of zero sequence voltage and sum current and comparison of their phase angle is to be used. This is a proven solution and is regarded reliable enough to be used as a basis for full automatic switching actions. The applicability of this kind of full automation depends on the costs of implementation versus the benefits obtained. Both depend very much on the circumstances of the secondary substation considered, the costs depending on the easiness of retrofitting, the benefits on the criticality of the loads and on the expected fault density of the adjacent network.

It is not feasible to equip all the secondary substations with full automation, and after the higher level automation has been employed, there typically are several line sections feeding a number of distribution transformers which still are in the state of outage. The critical question is now, how the faulty line section can quickly be found among this group of candidates without causing extra disturbance to the rest of the network. In practice this requirement is satisfied only if reliable fault indicators are available. In this case, the costs are a strict limiting factor, and the voltage measurement is usually not an option. Cheap but reliable enough fault indicators are needed. These can be implemented based on current measurement only, provided that centralized algorithms are used, which utilize the comparison of the current measurements obtained from several neighboring secondary substations. Hence, reliable fault indication is the lower level core of the fault management as well as full distribution automation is the higher level core of the fault management. The need of fault indications to enhance the utilization of full DA is described in [6].

Next, the full automatic fault management process is first described for the case of short circuit faults. The steps of fault management are as follows:

1. The circuit breaker in opened due to overcurrent relay tripping. This identifies the existence of a fault and a faulty feeder.
2. The network topology is analyzed in DMS. This gives the network connectivity at the time of the fault and the topological hierarchy of the secondary substations.
3. DMS collects the information from the fully automated secondary substations. The fault indication data is based on local measurements, and is simply comprised of 0/1 indication whether the fault current was detected or not.
4. Next step is the recursive analysis of the fault indicator data. Here the active fault indications are followed till the faulty line section.
5. Next the switching sequence is created to isolate the faulty line section and restore the supply in the main feed direction if possible.
6. The topology is analyzed to check whether there is an automated line section behind the faulty line section that could be restored using a back feed supply. In the case such line section is found the corresponding switching sequence is added to the sequence created in the previous step.
7. Next, DMS submits the switching sequence to the SCADA system to be implemented in practice.
8. After a successful process of automatic switching, DMS analyses the network topology to see whether there are several line sections under outage. If so, the lower level automation is started and the fault indicator data, i.e. current measurements, are collected from the field.
9. DMS compares the fault indicator current measurements and displays the fault indication result on the network diagram.
10. Now the faulty elementary section can be isolated by a combination of manual and remote controlled switches, and the rest of the other line sections can be re-energized.

In the case of a sustained ground fault, there is no automatic switching, but the DMS only collects the network topology and fault indicator data, and gives an estimate about the faulty line section. The switching actions are in this case all implemented by the network operators.

III. Centralized FLIR Solution

Combining support solutions for the fault management includes real time network information, network modeling, topology information, fault management solutions and distribution automation. Network information is usually managed with information systems and utilities use SCADA for network controls and acquiring network status information. Modern advanced DMS include both network information and real time information and applications to support and enhance network operation.

Combined SCADA/DMS FLIR solution in real rural network has been presented in [7]. DMS composes switching sequence proposals and SCADA deploys them into real actions in the network.

Although the operating principles differ in many respects, the implementation of a self healing FLIR solution for urban distribution networks can be based on the same concept as the FLIR solution in rural networks. Two simplified run-time models from the actual faulted feeder and its surroundings are created: switch model and line section model. Both models are used when composing and running the switching sequences. Both models are dynamic in order to enable FLIR to adapt its functionality to unexpected changes in the network state. Another reason for the model dynamics is to reach a general-purpose engine applicable to various use cases, such as the higher level fault management (steps 2–7) and the lower level fault management (steps 8–10) described in Chapter II. During the higher level fault management, manually controlled switches are ignored and the related, elementary line sections are merged to form composite line sections. After the higher level fault management, manual switches are taken into consideration, in other words, the isolated composite line section is split back to elementary line sections, which the lower level fault management is then focused on.

The following sequence diagram in Fig. 1 presents the required interaction between the relevant actors in the automatic fault management.

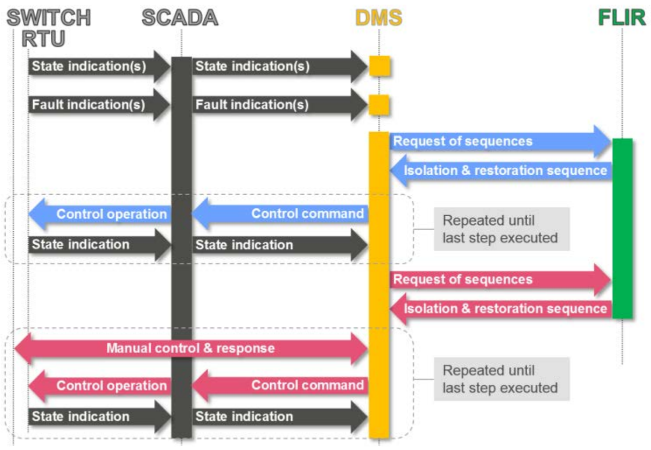

Fig. 1. Interoperability sequence diagram.

DMS receives indications of switch state changes and fault current detections via SCADA in real time. Regarding more extensive fault indicator measurements, a similar method is preferable but in practice, alternate data transmission methods with longer response time can be expected. The blue arrows in the sequence diagram deal with the higher level and the red arrows with the lower level fault management.

Regarding each step in the sequence, the switch model enables the system to perform certain precondition and post condition evaluations and the automation can be aborted on specific errors or exception conditions. On the other hand, the solution could be extended to overcome adversity by re-planning a new sequence, for example, to restore the supply by using the second best back feed route if the best one is unavailable at the very moment of intention.

The concept of the model dynamics enables the system to execute simultaneous FLIR cases, even when having shared objects in the main or back feed routes, without harmful interactions as long as the line section models do not overlap.

It is appropriate to have three different running modes to run the sequences. Manual confirmation, for example so that a control center operator must confirm the execution of every single step, is the preferable mode during a pilot project. For production use, auto-confirmation is the ultimate mode for the sequences of the higher level fault management of short circuits. The third one, called as assist mode, is suitable for the cases of sustained ground faults.

Regardless of the running mode in use, the status of the automatic fault management is visualized on the map and single line diagram having remote-controlled switches, alarming fault indicators, back feeds and other relevant objects highlighted. It provides also useful and detailed information relevant to outage management, such as customer outage costs and location of outage sensitive customers. This information helps operators also to take action after completed or aborted execution of the FLIR case in question.

IV. Case Study

Helen Electricity Network Ltd. (Helen) is responsible for the electricity distribution in Helsinki, the capital area of Finland. Helen has about 365 000 customers, among them are a lot of government buildings, head offices and companies with high financial value and heavy flow of customers. Previous study [8] has relieved that the customer interruption cost (CIC) values in urban core area are higher than previously assumed, so improving the reliability in Helsinki is appreciated. The medium voltage (MV) network of Helsinki is almost all cabled (99.7%). Fast and accurate fault isolation and power restoration are difficult tasks to accomplish, especially in underground distribution networks with a lot of interconnections [9]. To further increase the benefit of DA, intelligent solutions to support fault management have been selected as future smart grid methods to improve reliability in Helsinki. Helen Electricity Network Ltd. has together with Aalto University and Tekla Corporation researched and developed self healing methods and schemes to be implemented in the Distribution Management System of Helen.

DMS of Helsinki has a powerful engine for geospatial data management and applications to streamline network operation. The system is also integrated into DSO's other business processes, e.g. outage communication. It provides tools and automation to monitor and control the electricity distribution network efficiently. The network data in the Network Information System is the basis of all applications in DMS. The DMS also interoperates with SCADA enabling real-time data monitoring and control, thus forming an effective platform for self healing FLIR solutions for urban distribution networks.

The enhanced model was designed and tested with Tekla DMS, since Tekla DMS it is the tool of supporting network operation in Helsinki. The new FLIR program was tested with the whole MV network of Helsinki, a copy of a real Helsinki MV network database was used in the testing.

Demonstrated fault management steps are illustrated in Fig. 2. Protection detects a fault in the network, breaker opens and an interruption begins. DMS collects the information from the automated secondary substations. Based on network topology and the collected FPI indications, the FLIR program understands that a fault has passed the switch connecting the second distribution substation and the interconnected line to right. Collected active FPI information is displayed on DMS (upmost picture). No other active fault indications are found. The Tekla DMS then executes the actions one to six described in previous chapter. Based on these actions, a switching sequence is created. The switching sequence is then implemented in practice, the faulty line section is isolated with command DISCONNECT SWITCH TO RIGHT (second picture) and the supply is restored with second command CLOSE BREAKER (third picture).

The program is now in demonstrative and testing phase. Next target is to research and develop the model and the FLIR functions more for the needed features for automatic fault management in city networks, to create the so called CITY-FLIR solution. The final target is implementing the CITY-FLIR solution to the present rural FLIR solution so that the next level FLIR is able to handle fault situation not only in rural distribution networks, but also in urban distribution networks.

Fig. 2. Illustrated FLIR logic, □ is breaker, ◊ is manual operated disconnector and ○ is remote controlled disconnector.

V. Conclusions

In this paper various fault management and decision support models used in distribution networks are presented. The paper presents the functionalities and principles of the new model called CITY-FLIR for fault location, isolation and recovery in urban distribution networks. Also a study case in Helsinki is described. The CITY-FLIR has been developed in co-operation with Helen Electricity Network Ltd, Aalto University and Tekla Corporation. The model utilizes the present full DA with controls and FPIs and is also ready for the next generation inexpensive and reliable FPIs with telecommunication. The target of the CITY-FLIR solution is a comprehensive fault management and recovery process for urban distribution networks, first assisting the control centre and as a second phase managing the faults in an automatic mode. These development steps are supporting the concept of self healing city networks.

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