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A New Protection System Design of Active MV Distribution Network

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Abstract: The increasing implementation of renewable energy sources (RES), along with the diversity of energy source types, has additionally imposed significant operational and management problems in distribution networks. These problems are manifested in voltage regulations, system stability and coordination of protection, both in the distribution and transmission networks. For the medium voltage (MV) network, this includes new energy sources and higher amounts of fault currents, invisibility of several faults in the existing protection scheme, reduction of the range of protection devices and reduction of the possibility of detecting small fault currents with existing protection relays. Such changes significantly reduce the possibility of proper distribution system protection, both in subordinate and superior networks. The subject of this paper is the presentation of a new concept of the use of automation in the management and arrangement of power system protection dependent on the scheme and configuration of an active MV network. The goals of this analysis and research are to find and define the necessary architecture in which the scheme and appearance of the MV network should be automatically detected, and based on network topology to establish new settings of protection devices (ground fault, overcurrent and short circuit protection). The contributions of generation units of RES in the MV network must be considered. This paper specifically analyses the problems of power system management with simultaneous harmonization of protection systems both in the transmission and in the radial distribution network, offering optimization algorithms that have the ability of achieving the optimal solution. The implementation of the proposed technique was tested on a radial connection integrated with a microgrid (MG) which has the possibility of two-way power supply. The obtained results indicate that the proposed technique can solve described problems in the coordination of protection system and network management, even with the dynamic character of operation mode of the networks.

Key words: automated fault analysis; digital fault recorder; distributed production; fuzzy expert system; guidance automation; optimization algorithms

1 INTRODUCTION

In the last decade, technological advances in the power system has brought the possibility of using intelligent and autonomous devices to upgrade the system to keep it safe in the event of breakdowns or disturbances. This involves sudden changes in the network characteristics due to various unforeseen events - i.e., overloads, frequent interruptions, long-term failures, etc. [1]. Traditional MV networks, which are radial and passive and thus very exposed to external disturbances, maintain their safety by using conventional protection devices, as shown in Fig. 1.

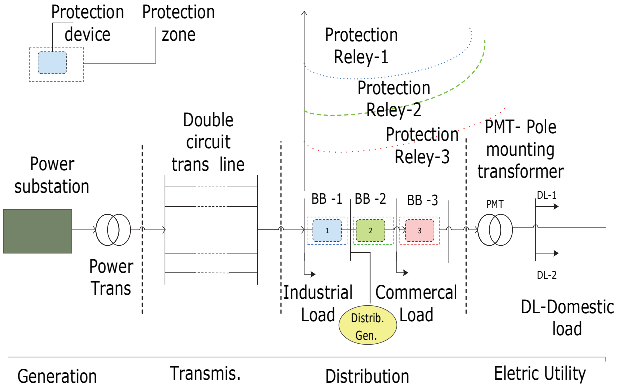


Figure 1 Power system architecture with effective relay protection using distributed sources (DGs)

Such conventional protection devices, due to the two-way power flows in the networks, lose their selectivity when operating in the event of failures with intermittent distributed sources (DGs) [2].

The current operation of the distribution network works in such a way that in the event of a fault, protection devices quickly and efficiently disconnect from the source (transmission network) the entire part of the system in which the fault occurred. Contrary, the new concept allows the distribution network to operate in island mode during the failure of the power line which connects transmission and distribution network or power line which connects two parts of the distribution network, if the power of the distributed source is sufficient to cover consumption. In this case, the defective component is mutually switched off.

There are several strategies available to upgrade already existing protection schemes: (1) online-network change of internal relay settings, (2) addition of a directional element of protection or (3) communication approach based on mutual relay coordination. The most often used of above-mentioned strategies is application of directional element of protection relay which ensures optimal operation and coordination of protection devices in the event of failures [3]. With the occurrence of faults, there is a voltage drop in the network and caused by that sensitive equipment must be switched off if the level of voltage drop is higher than allowed. The parameters that characterize the voltage drop are its size, duration and change of the phase angle. The value of the voltage drop depends on the type of fault and the impedance of the network, while the fault duration and change of the phase angle depend on the time of troubleshooting and the total X/R ratio of the network. It is to be expected that during voltage failures caused by unforeseen events, installed distributed generation sources (DGs) would maintain voltage in that part of the system [4, 5] in case of island mode of the distribution system operation. When a fault occurs on a power line with a distributed source installed between the fault point and the protection devices, the protection relay monitors only reduced fault current due to the high fault impedance. Setting up a more sensitive protection scheme as a solution is not desirable in that case because it leads to oversensitive or to false relay operation even in the event of transient faults or faults occurring in the vicinity of adjacent networks [6].

The first point of protection system in the distribution network is at the interface of the transmission network, which, in addition to the agreed functions and setting parameters, ensures the safe and reliable operation of both networks. The analysis of competencies and protection requirements are carried out by considering the basic principles of harmonization of relay protection, where the design and dimensioning of devices and relay protection must be harmonized and performed with the associated software tools. Since there are many possible applications of failure analysis, it is of high importance to predefine the achievability of the analysing algorithm and possible improvements of its applications [7-9].

In this work, it is clear to see that failure analysing technique can be used to achieve variety of applied solutions. Primarily, this can be achieved online, by a combination of changes in the online internal settings of the protection device using a communication approach. That online communication approach considers the possibilities of its implementation and emphasizes the most important characteristics of the distribution power system and its protection. Also, it is obvious that different set of measured signals and information from different protection devices, with modern communication infrastructure, can create different analysis options and choose the best solution for the stated state of the network.

2 STRUCTURE OF APPROACH IN COORDINATION OF PROTECTION AND NETWORK MANAGEMENT

The analysis of protection coordination with regard to the level of failure and distributed production in the MV network has been investigated in a large number of papers [10-12], all for the purpose of eliminating the consequences of unwanted events. In [13], researchers analysed the impact of integrated power source integration on protection coordination and voltage drop in the distribution network. However, these analyses considered only the subsequent effects of the installation of distributed energy sources without considering its outages in cases of failure.

The influence of the exclusion of distributed energy sources on the coordination of protection in the radial distribution network is reported in [14]. The proposed solution is satisfactory considering the failures in the superior network, but its function is compromised in the event of the subordinate network.

The idea of using a phase angle between fault current and voltage, which defines relay settings for determining the direction of fault current for both cases of fault location, was proposed in [15]. However, the proposed approach solves only transient failures, and is deficient for permanent failures.

The authors of [16] have developed an effective technique for coordinating the characteristics of Automatic Circuit Reclosers (ACR) installed for transient and permanent failures. This technique can very quickly locate faults in the distribution network. ACR, in conjunction with the remote-control function of the switch, quickly eliminates the failure, achieving fast power feeding in the faulty part of the network from the other side and thus further shortens the power outage. The new network scheme given by ACR ensures the selectivity and speed of operation of relay protection system.

In order to accelerate the tripping of directional overcurrent relays and ensure greater reliability and safety in such networks, a cost-effective and efficient solution is proposed [17]. The proposed method offers a passive but effective way to alleviate coordination constraints to obtain a rapid response of protection devices but does not offer agnostic access to the network and requires different strategies for different network topologies.

A general strategy that uses fault current limitation by fault current compensation and protection coordination in the event of faulty overcurrent relays in MV networks is discussed in [18]. This approach uses passive elements such as fault current limiters to ensure optimal coordination between primary and auxiliary relays. This approach requires manual calculation of the impedance of the limiter during installation and operation of each distributed energy source and is thus inefficient in the event of failures in the superior network.

The application of automation in the management and coordination of protection with network-online change of internal settings of protection devices and the use of communication approach for all these methods, techniques and strategies requires the transmission and processing of information and data for right timed and correct actions.

In essence, the basic functions of measured signals and information and their analysing are as follows:

- Signal and information conversion into acceptable data format,
- Processing of data,
- Failure recognition and type of failure identification based on the fuzzy expert system logic,
- Data transfer protocol between protection devices, SCADA and switching devices examination,
- Operation switching state of all devices determination,
- Fault location determination and/or fault component's defining,
- Determining the sequence of sending records and data.

Additionally, in the case of stored recorded data and records in non-original data form such as COMTRADE, it is necessary to perform data conversion and adopt file naming conventions. The following steps are required to obtain complete and correct information about the network status:

- Calculation of power flow and voltage drops in focused power subsystem in periods before failures, during failures and after failures, determination of time and duration of failures, determination of the time of topology change on digital channels, etc.
- Identification of the fault type (AG, BG, CG, AB, BC, AC, AB-G, BC-G, AC-G, ABC, ABC-G) and the type of event outcome (local disconnection, remote disconnection, reconnection, unsuccessful reconnection/deactivation).
- Evaluation of the protection relay operation, of the communication signals and of the protection operation schemes.
- Evaluation of the circuit-breaker operation and identifying of possible problems during the circuit-breaker operation (circuit-breaker failure, slow velocity of switching-off operation of the circuit-breaker, etc.).

All above described steps are performed by using an algorithm to determine fault location with two options:

- Recording analysis is performed by digital fault recorder (DFR) installed at one end of the faulty line,

- recording analysis is performed by DFR recording at both ends of faulty lines, with possibility to synchronize the recorded signals.

Critical and non-critical event data should be considered to determine the order in which records and data obtained from the DFR are sent. DFR records are marked with a priority flag (high, medium, low) and are sent for further processing in this order of priority.

2.1 OPTIONS OF DEFECTIVE NETWORK ELEMENT DETECTION

In the event of a fault or disturbance in a part of the distribution network, the protection devices of the monitored network element must switch off the faulty network element by an executive device (circuit breaker), isolate that part of the network from the active network which also shortens time of active fault and overcurrent stress of components. Thus, in some cases, after the operation of protection relays and switching breakers, the distribution network or part of it may, depending on the configuration, be separated in two or even more power subsystems or remain de-energized. Mainly there are two or three power subsystems that occurred as a result of a fault or disturbance. In case of separate power subsystems, failure currents are limited by power sources inside its subsystem, so many of the problems can be mitigated or remedied. Additionally, with the help of real-time switching state information of the breaker and the application of the real-time power system topology assignment procedure, an expert system has been developed to identify the island operation of the network [19]. The basic form of this effective procedure is explained in next three steps:

- Set of power system initial states (buses and branches),
- Determination of normal power system,
- Identification of the island part of the power network.

The state of the power network before failure is recognized by the expert system as the optimal functional state which processes the procedure for determining the topologyof the power system in real-time [19]. At the moment of failure, the state of the power system changes by activating the protection device and changing the state of the circuit breaker. The next step is to identify the network topology of the "normal" part of the power supply system after a failure using the procedure for real-time determination of the power system [20]. Differences obtained on the basis of comparison of the initial power system topology and the network topology at the moment after a failure could be identified as the island part of the power network.

2.2 DETERMINING OF FAILURE LOCATION

When there is a new failure of the power network component, the stimulation of the protection device changes, the switching state of the circuit breaker changes which causes activation of the fuzzy expert system. After fault occurs, the switching devices are assigned either in the set without switching state change or in the set with the switching state set as defined by Eqs. (1) to (4).

The failure function F_i is formed based on the previous description as follows:

$$F_i = F_i\left(CB\right) \cup F_i\left(RL\right) = \left\{\left(C_i, \mu_{P_{\text{fault}}}\left(Ci\right) C_i \in S_{\text{island}}\right)\right\} \quad (1)$$

$$P_{\text{fault}} = \left\{F_i\right\} \quad (2)$$

$$F_i\left(CB\right) = \left\{C_i, \mu_{P_{\text{fault}}}^{CB}\left(C_i\right)\right\} \quad (3)$$

$$F_i\left(RL\right) = \left\{C_i, \mu_{P_{\text{fault}}}^{RL}\left(C_i\right)\right\} \quad (4)$$

where C_i is one of the possible defect parts of the power system under consideration; P_{fault} is an indistinct set containing all faulty subsections and also belonging membership functions; $F_i(CB)$ presents a fuzzy subset of switched off breakers devices; $F_i(RL)$ presents a fuzzy subset of controlled relays. A series of input data is created and sent to the fuzzy controller, where the fault component is located based on the fuzzy rules of inference and on expert experienced knowledge.

3 POSSIBILITIES OF DFR DATA AND ITS APPLICATION

Digital fault recorders (DFRs) record disturbances of the basic electrical quantities of voltage, current, frequency as well as changes in the state of the circuit breaker. Changes to these values can be used as trigger of disturbance logs. The programmed conditions for running a fault record are most often initially set to use technical possibilities of DFR to record available information even in case of normal power system function (without failures) [21-25], consequently enormous DFR data files storage is recquired. One example of such initial settings for online failure and disturbance monitor systems based on the DFR system is shown in Fig. 2.

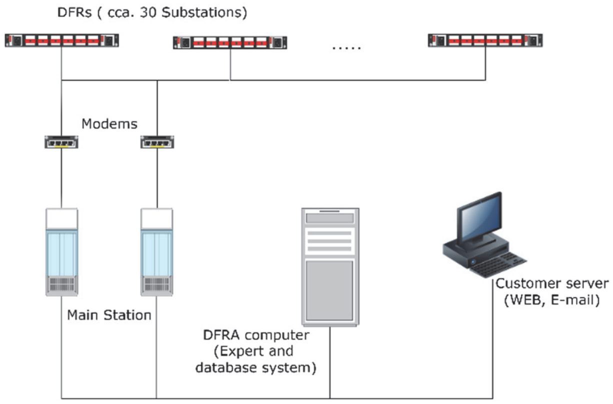


Figure 2 DFRs system for automated fault analysis in distribution network

The record copying routine transfers new records from the DFR to the computer where the automated data analysis software is installed. To perform automated fault analysis using DFR, there are several conditions that must be met, and they are as follows:

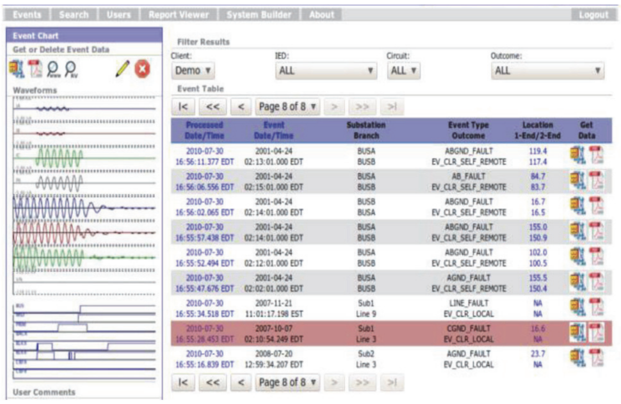
- Real-time DFR event retrieval,
- Retrieval data of the network configuration,
- Saving analysis reports.

Failure analysis of power system components based on DFR information is triggered by the new DFR data file appearance. In order to usefully apply DFR data produced by different types, models, or manufacturers of intelligent electronic devices (IEDs), DFR data files should be transformed from the submitted source data format to a common source data format - for example COMTRADE format [26-29]. Besides the usefully applied records, the analysis function requires DFR configuration information as well as a description of the power system sections and their components monitored by the DFRs.

DFR configuration data contains component name, its role, bus incidency, phase data, rated and nominal power, distance of and connection to transmission power system, power nodes, transformer units, etc. For power network parts, namely in the case of transmission power lines, technical parameters are needed such as length, resistance and line impedance. After the fault analysis has been performed, the output data given by the online data processing need to be archived in a central SCADA database.

There are various data display modes inside fault analysis software. Some brief information can be used to inform and worn several users (maintenance, investments, dispatching). At the same time, event reports are generated and sent to chosen users by priority weights (number of consumers without voltage, energy not supplied etc.). The IED data network interface of the integrated transformer station has been customized to allow easy access and review of results as presented in Fig. 3.

Events are archived in the records table and sorted in chronological order. By the selection of an analyzed event, the data preview is changed. COMTRADE browser network application is used for simple searching and manual analysis of IED records regardless of the type of IED: DFR (Digital fault Recorder), DPR (Digital Protective Relay), CBM (circuit breaker monitoring) and allows analysis of DFR data errors.



Client: Demo
IED: ALL
Circuit: ALL
Outcome: ALL

Processed Date/Time	Event Date/Time	Substation Branch	Event Type Outcome	Location 1-End/2-End	Get Data
2010-07-30 16:56:11.377 EDT	2001-04-24 02:13:01.000 EDT	BUSA BUSB	ABGND_FAULT EV_CLR_SELF_REMOTE	119.4 117.4	
2010-07-30 16:56:06.556 EDT	2001-04-24 02:15:01.000 EDT	BUSA BUSB	AB_FAULT EV_CLR_SELF_REMOTE	84.7 83.7	
2010-07-30 16:56:02.065 EDT	2001-04-24 02:14:01.000 EDT	BUSB BUSA	ABGND_FAULT EV_CLR_SELF_REMOTE	16.7 16.5	
2010-07-30 16:55:57.438 EDT	2001-04-24 02:14:01.000 EDT	BUSA BUSB	ABGND_FAULT EV_CLR_SELF_REMOTE	155.0 150.9	
2010-07-30 16:55:52.494 EDT	2001-04-24 02:12:01.000 EDT	BUSA BUSB	ABGND_FAULT EV_CLR_SELF_REMOTE	102.0 100.5	
2010-07-30 16:55:47.676 EDT	2001-04-24 02:02:01.000 EDT	BUSA BUSB	AGND_FAULT EV_CLR_SELF_REMOTE	155.5 150.4	
2010-07-30 16:55:34.518 EDT	2007-11-21 11:01:17.198 EST	Sub1 Line 9	LINE_FAULT EV_CLR_LOCAL	NA NA	
2010-07-30 16:55:28.453 EDT	2007-10-07 02:10:54.249 EDT	Sub1 Line 3	CGND_FAULT EV_CLR_LOCAL	16.6 NA	
2010-07-30 16:55:16.839 EDT	2008-07-20 12:59:34.207 EDT	Sub2 Line 3	AGND_FAULT EV_CLR_LOCAL	23.7 NA	

Figure 3 Customized web-based user interface [24]

The exceptional advantages of online failure analysis using DFR can be discussed in two ways:

- Accelerate fault information to all company segments and to all SCADA terminals and improve drawing conclusions,
- Improve the quality and accuracy of power system control.

With the occurrence of failures and disturbances, various cases and events in the distribution power network generate a large amount of DFR records. Instantly performed online analysis enables power engineers to make priority schedule of the subgoals and shortens the time for the power system to reenergize in their integrity. Online data processing and user notifications indicate problems in specific conditions which makes this analysis consistent to decrease time in reenergizing the whole power system.

4 POSSIBILITIES OF APPLICATION OF FAULT RECORDS AND DATA IN PLANT MANAGEMENT

For the needs of automated fault analysis, a system for automation of management of power system was introduced as shown in Fig. 4.

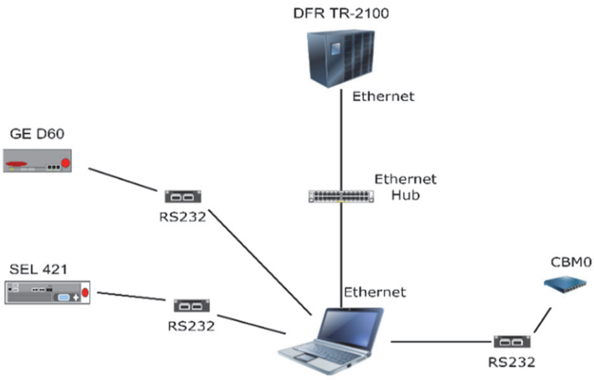


Figure 4 IED data processing device setup

IEDs are mounted in a transformer station equipped by circuit breakers (CB) to whose buses a transmission line is connected and feed the rest of the network.

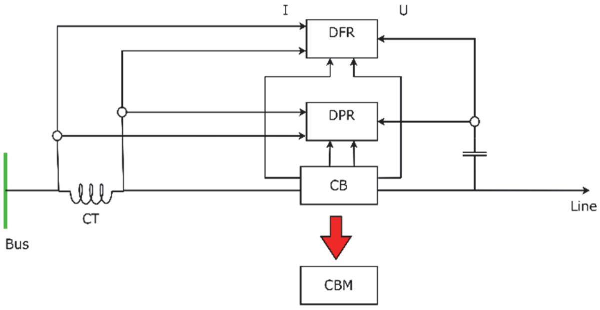


Figure 5 IED configuration implementation on the distribution network element

The IED configuration, presented in Fig. 5 gives connections between in its containing elements in detail - transmission power line termination connected at the transformer substation, where the included components of the power system are power bus, transmission line, measurement transformers (current and voltage) for obtaining analogue line measurements and circuit breaker (CB). According to presented design several IEDs are connected and integrated in their function:

- DFR (Digital fault recorder) that monitors voltage and current of power line, switch contact status signals, incentive data of protection device function, auxiliary contacts of circuit breaker and status of transmission send/receive signals,
- DPR (Digital Protective Relay) that records bus voltage and also current and power factor in power

lines, contact states depending on the protection mode of the relay (data transfer in mobile network) and also external / internal states of relay device status (initial values, warning values and work values),
- CBM (circuit breaker monitoring) that monitors the currents of the power lines, the currents passing through the circuit breaker, the currents of the coil contacts, data of the DC power supply of the switching device.

The DFR records the signal change for the entire transformer substation while each protection device monitors only the signals related to the power line where it is installed. The CBM in this configuration records the control signals related to the addressed switching device. In similar way as the DPR enables detailed report of protection device function, the CBM enables detailed report of each working action of the monitored switching device. Moreover, circuit breakers depending on manufacturer and type can be controlled and monitored at various sampling rates also with various length of the control digital signal. So, it is of great importance to syncronise all IEDs based on external time reference to enable comparison of voltage and current variables along the power lines and buses in the power system. External time reference allows all data files given by IED devices inside specific transformer substation to be synchronized and ensembled.

Recorded data files given by all IED devices are automatically sent to the transformer substation computer in accordance to communication protocols and via internal communication cables which are parts (master and client units) of the transformer substation automation software - AEAClient and IED devices. AEAClient software is constantly active on the substation computer and enables IED datafiles to be transferred automatically immediately after failure arises.

Afterwards, classification of generated data is accomplished depending on IED manufacturer, reported datafile type (waveforms, failure report, error report) and integrity of the report (completed data report or incomplete data report). Incomplete data should usually be rejected. Data are sent to a remote centralized computer (Control Centre, Office Engineer) inside the intranet network of the distribution power system by highly secure data transfer. All abovementioned data are analysed to get right information about all power system components and their function in failure period.

The failure analysis is committed by AEAServer located in the control center and is fed by collected IED data from each transformer substations of the distribution power system. The AEAClient view contains a detailed list of IED data presenting failure type, failure location and/or various relevant failure data.

The applied control system alows on-line data collection, data incorporation, data analysis, and data storing of all IED records obtained from the transformer substations of the power network. All IED data records need to be applied to advance the quality and exactness of present failure detection and location procedures based on:
- assignment of weighting factors between failure reports of the same failure from several transformer substations (IED) - based on comparison of failure data (several incident branch currents, several bus voltages before and after failure occurs, states and changes of states of switching devices, data generated by protection relays),
- Review the weights of all information (measured continual variables like currents and voltage and on/off states of circuit breakers in the power network get from several transformer substations), reported by different IEDs.

Here described system architecture enables to use various relay device types and several analysis techniques integrated inside the transformer substation control system or inside the power network control system.

5 AN EXAMPLE OF THE POSSIBILITY OF AUTOMATION USAGE

Every radial MV network, regardless of the voltage level, has the usual power supply scheme, i.e., network configuration, which must satisfy the safety and reliability of production and consumption. The configuration of the network is determined by the technical characteristics of the power network, voltage conditions, and power network losses.

During the failure condition, a particular component of the power network has inability to function which means that power subsystem should be reconfigured to maintain a safe function of electricity supply and proper operation of protection devices. In the case of an active MV network with distributed generation, during the fault circumstances - it is required to recognize the new scheme and configuration of the power network and to adapt initial technical parameters of the protection devices. Also, it is necessary to determine the new optimal power supply scheme and adjust the relay protection in accordance with the new configuration, in all phases of power system management. Fig. 6 shows an example of one radial power network that has the possibility of two-way power supply.

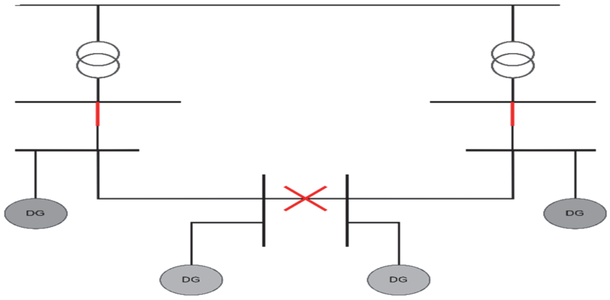


Figure 6 MV network configuration with DG in nodes

It is necessary to enable protection devices to detect a fault component and disconnect only that defective power network element or only minimum part of the power subsystem while retaining and preserving electricity supply in all other parts of the power network, providing the necessary information and data from the power network, so that a decision on a new optimal network scheme and topology could be made. The most important thing is to meet the new requirements that are set for ground fault, overcurrent and short circuit protection. To enable this, it is necessary to install recording devices or DFRs in the very important transformer substations that have numerous connections for events to other transformer substations. They measure and store the voltage and current values, power factor and similar data on the desired power lines.

Protective relays are installed in almost each transformer substation, distributed along the power network, but some of them do not continually measure and/or store measured data. Sometimes, after the fault there are no records available nearby the location of failure, and in the other hand sometimes precise and good quality measurements on several incident points of the power line are on disposition to use.

Fig. 7 shows power network and optimal location of DFRs [30]. DFR records fault and disturbance information and each one is located far away from the real failure point.

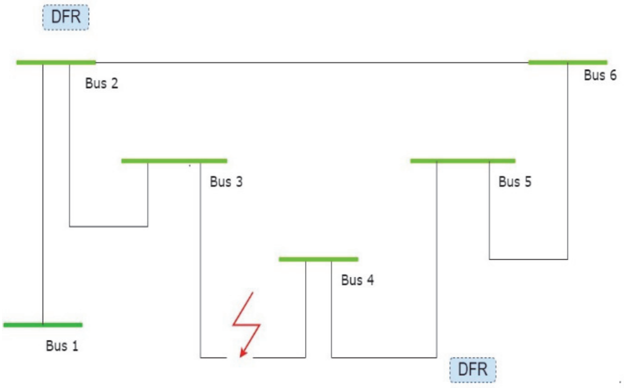


Figure 7 Layout of DFR installation and fault location

Based on the dispositional input signals (measured variables and states), various mathematical and logic optimisation procedures can be applied simultaneously and the optimal technique may be choosen to meet the defined set of real conditions. Complex software tools are required to enable the described approach, in order to fulfil optimal solution of each individual procedure. Any used external software tool usually contains SCADA module, DFR Assistant module, condition estimation module and/or short circuit module.

Fig. 8 shows the implementation of DFRs from the node and the central place for data processing and determining the optimal network topology and parameters of the power network protection scheme.

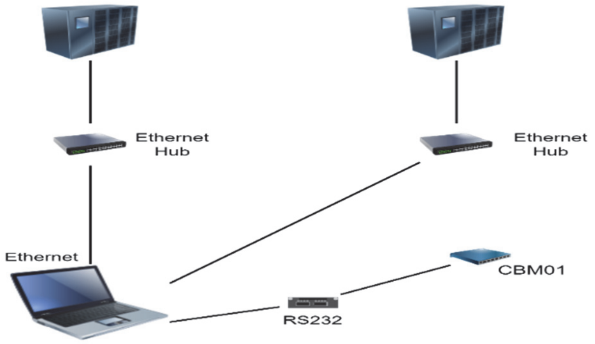


Figure 8 Overview of DFR implementation from hub and central location

Once the DFR data is got, the failure detection module is immediately started. The connection branch states inside the power network are updated based on the data received from the SCADA system and the optimal failure location procedure begins to calculate the exact fault location. Aiming to achieve the most accurate calculation of the fault location, an automated procedure for selection of the most suitable fault location calculation procedure has been developed in a specifically defined fault event.

In this way, in addition to the previously defined possible network states and topologies with determining the optimal state, information, data and orders for changing the switching state are sent back to the protection devices and switching devices corresponding to this new network configuration.

Finally, based on the new topological scheme, from the previously defined states on possible protection settings, a new optimal state is selected with new protection parameters that are directed to the protection devices.

6 CONCLUSION

The paper introduced a new perspective to the application of the information in automated analysis and determination of the optimal topological scheme of an active distribution network after failures in the network or at the interface of the transmission network. It is shown that this approach with the application of automation can significantly contribute to progress in network management, fault detection and fault location determination and more efficient protection.

The paper emphasizes the importance of considering all aspects and steps of the proposed approach to the solution. It is important to satisfy all decision aspects before implementation of solution, because it mostly depends on the type of available information. In case of failure inside the distribution power network, protection relays protecting a section or part of the power network must provide an incentive to circuit breakers to disconnect the protected network elements in order to isolate the defective power network component from bad consequencies of the failure`s short circuit currents.

Sometimes, such distribution network or its subsystem would be divided into several parts or left without power feeding and by the above described procedure it is easy to detect the resulting island parts of power system.

With better quality and faster determination of the exact fault location, also by the optimal configuration of the power network and by the accurate and efficient operation of protection devices, important contribution toward outage's duration reducing and also reduction of end-user's power supply interruptions could be achieved. As a result, it can significantly contribute to increasing the security of the entire active distribution power system.

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