Adaptive Relay Protection Concept for Smart Grids

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Abstract

Smart Grid refers to an intelligent grid that employs modern information and telecommunication technologies to meet the challenges relating to the power delivery in the future. These challenges are due to, among others, increased use of renewable energy and power supply reliability requirements of modern digital society. In order to fully realise the Smart Grids a new kind of approach for the power system protection is also needed. In this paper the requirements for the protection of the medium voltage (MV) level of Smart Grid are discussed and a new type of adaptive relay protection concept is proposed.

Modern relay protection systems use so called intelligent electronic devices, IEDs. They are devices that have both data processing and telecommunication capabilities. This makes them suitable platforms for an advanced protection system design. The novel protection concept proposed in this paper is based on the distributed intelligence located in the IEDs and seamless messaging capabilities between all the IEDs in the system.

Keywords: *Smart Grids, relay protection, telecommunication, multi-agent systems*

Introduction

There exist various definitions for Smart Grid. From technical point of view Smart Grid refers to a vision of the future grid employing modern information, control and telecommunication technologies. The basic idea is that new and improved technology is needed in the grid to meet the challenges relating to the power delivery in the future. These challenges are arising, among others, from increased use of renewable local energy sources and the power supply reliability requirements of modern digital society.

Considering the above-mentioned challenges there is obvious need for new solutions for the power system protection. The use of local energy sources, or distributed generation (DG) and energy storages makes the system topology totally different especially at the distribution systems, i.e. at the medium and low voltage networks. The traditional protection arrangements are not always suitable for distribution systems including local production. Also the increased reliability and security of the supply is only achieved by mitigating the effects of faults better than before. Thus it is clear that a key part of the future Smart Grid is an advanced relay protection system.

The protection and control of Smart Grids especially from the transmission system point of view has earlier been discussed in [1], which also introduces the use of agent approach for this purpose. Recently the agent technology has also been applied for protection purposes, but usually to more limited applications, such as for the distance protection [2].

In this paper a new type of adaptive relay protection concept is proposed. The concept is also based on the agent technology, more specifically on the multi-agent approach. Furthermore, the focus is on medium voltage distribution networks and the aim is to introduce an overall concept instead of focusing on specific problems. This serves as an initial point for further development.

This paper starts with the basic features of Smart Grids which are then used for the determination of protection requirements. After that the essential functionalities are discussed and a suitable architecture is introduced. At the end it is presented how the proposed concept can be accomplished with the multi-agent approach. Finally a short example illustrates some of the basic functionalities of the concept.

Features of Smart Grids

Distributed Generation

A key feature of Smart Grid is that it can accommodate various amount of DG. Conventionally MV networks are operated radially with only one power source, i.e. the primary substation. The increased amount of DG changes these networks more towards meshed networks with varying direction of power flow. This leads to a situation where the fault detection cannot be based on the assumption of fault current from single source only. The same applies also for energy storages. When they are operating in the discharging mode where they supply electricity to the grid, they are from the grid point of view actually similar to the DG.

Many of the DG technologies are based on a DC/AC converter at the grid interface. These converters are usually capable of supplying only 2 - 3 times their rated current during the grid short circuit faults [3], which makes the traditional overcurrent based protection scheme infeasible. The main problems related to the DG protection are identified, e.g., in [4]. Very much the same issues are valid for the Smart Grid protection.

Controlled Island Operation

One of the protection problems with DG is the anti-islanding protection which is usually referred to as the loss-of-mains (LOM) protection. Various passive and active LOM protection methods have been developed and presented, e.g., in [5] and [6], but still the most secure solution is the use of some transfer trip scheme. In the Smart Grids this issue is a bit more complicated since a part of its functionality is based on controlled island operation.

One interesting feature proposed for the Smart Grid is self-healing, which was first introduced in [1]. This means that the system is capable of continuing the power supply after any kind of disturbances. Self-healing is in fact a broad concept including the stability of transmission grids, but here the focus is on the protection of MV distribution networks. In this context one way to achieve the self-healing functionality is to switch over to island operation in case of fault in some part of the network. The successful use of the local generation for achieving controlled island operation in some fault cases requires the use of suitable telecommunication between different parts of the system. In addition to this there is a need to adapt the protection configuration to the system state. Especially critical in this respect is the power generated by the local sources and the loading in various parts of the network. Depending on the load/generation balances the size of suitable islands to be used in fault cases may be different at different times.

Automatic Backup Connections

In addition to the controlled island operation the self-healing feature can also be achieved by using the intelligent re-routing of the supply in certain fault cases. In a radially operated distribution system with some normally open points (switches or line breakers) providing backup connections this would mean closing these switches automatically in fault cases. Additionally this requires that the faulted section is simultaneously isolated from both sides (see Fig. 1).

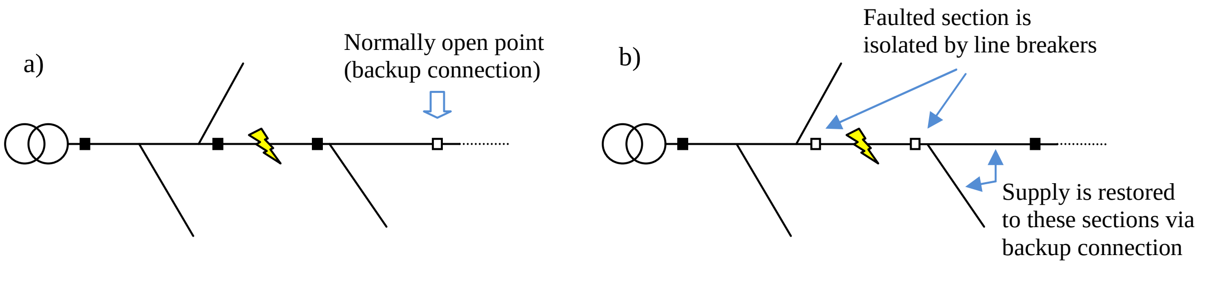

Figure 1. *Self-healing by using a backup connection. a) Fault occurs. b) Faulted section is isolated and backup connection is closed.*

This kind of feature requires that suitable methods and devices are provided for detecting accurately the faulted section in the network. Furthermore, suitable telecommunication capabilities are necessary to quickly operate the switches or line breakers involved.

Protection Requirements

In the above section the basic features of Smart Grid were discussed focusing especially on DG and self-healing. These are the initial points necessary to define the requirements for Smart Grid protection. These requirements apply both for the required infrastructure and the functionality of the protection system. These are discussed in the following.

System Infrastructure

In general it can be stated that in order to achieve the desired functionality of the protection devices, i.e. the IEDs, they should all be able to communicate with each other. Extension of the communication network deeper into the power system can be argued to be too expensive. However, in the future Smart Grids the telecommunication network will also be used for many other purposes and after all the total benefits will probably exceed the costs.

In this paper the basic assumption is that there exists a Smart Grid communication network where each IED in the system can be connected to. Thus there are seamless messaging capabilities between all the IEDs in the system. Communication media, protocols etc. are considered in this context irrelevant and they will not be further discussed in this paper.

Protection Functions and Measurements

In addition to the communication system the Smart Grid protection requires IEDs to have more functions than the IEDs used now in the distribution networks. For example the basic overcurrent function is not anymore capable to cover all possible fault situations. A set of relay functions that are still very seldom applied in distribution networks are needed (e.g., directional overcurrent). In some cases the complexity of system and the various operating states of it may also call for the combination of several protection criteria (e.g. overcurrent and undervoltage). One obvious outcome from this is that the IEDs will always need three phase voltage measurements in addition to the three current measurements. Considering the common communication system these measurements will also be available for other purposes in the Smart Grid if needed.

Adaptability

Since the Smart Grid concept means certain flexibility in the primary system, it is necessary that the protection system also adapts to the changes in the primary system. As stated in [7] this means some kind of "self-configuration" or "self-awareness". Here this kind of functionality is referred to as adaptability; the protection system constantly adapts its state to the state of the primary system, which in this case is the MV distribution network. From the protection point of view there are basically two things we need to know about the state of the primary system:

- Feeder configuration (location of open points),
- Running status of the generating units.

The first one defines the switching devices that are normally open, the borders of the network and ultimately the total length of the network connected to a primary substation. Since the amount of generating units in the Smart Grid is variable, it is essential to know which units are producing and thus connected to the network. This aids defining the expected behaviour of the measured quantities in the fault situations. For some type of units it is also possible that the operating point (amount of power produced or available) affects on, e.g., its ability to provide short-circuit current.

Functionality of the Protection System

Basic Functionalities

In a certain system state the functionalities of the protection system are fixed. This means that there is a set of active protection functions needed for accomplishing the primary target of the protection; to detect and isolate the faults. In this respect the fault types considered are:

- Three-phase short-circuit,
- Phase-to-phase short-circuit,
- Single phase-to-earth fault.

In addition to these shunt faults it is necessary to detect also the series faults (e.g. broken conductor in one or more phases).

In the traditional MV power systems the feeders are protected by protection relays at the primary substation. In the Smart Grid concept the MV feeders are divided in to several protection zones by circuit breakers located along the feeder. In order to gain full benefit from this kind of arrangement the circuit breakers must be equipped with IEDs containing all the necessary relay functions. Most part of the short circuit faults are detected by the overcurrent relay. Due to the fact that the power flow is not anymore unidirectional the directional overcurrent relay must be available for certain operating states. For this purpose the voltage measurement is needed. The voltage measurement is useful also in cases where there is not enough short-circuit current for proper overcurrent detection. In such cases the undervoltage gives an indication of the fault.

The arrangement applied for the earth fault protection depends on the system earthing practice. When the MV network is unearthed or earthed via the Petersen coil (so called compensated system) the selective operation of protection system is possible only with the directional earth fault functions. For this purpose the residual current and voltage must be measured. The situation may become a bit more complicated when considering the DG and possible island operation. In a case where a part of the system transfers to island operation it may be possible that the system earthing of the islanded part of the network changes considerably, e.g. from compensated system to unearthed system. This necessitates that the earth fault protection functions are adjusted accordingly.

The Effects of DG

The DG in the Smart Grid has a certain role for accomplishing the self-healing functionality as discussed earlier in this paper. If a part of the system contains enough power production capacity it can be disconnected from the faulted part of the grid and the supply continues in the islanded part of the system. Of course, this is only possible if suitable control arrangements are provided and probably the best way to achieve this is to define certain system parts as Microgrids and equip them with the Microgrid management functions presented in [8].

Due to the intermittency of some renewable sources there may be situations where the island operation is not possible. In such a case any remaining DG must be disconnected from the faulted system using the LOM protection in order to avoid any further damage and potential hazard to maintenance personnel. In the Smart Grid the protection system must constantly monitor the states of DGs in the system in order to select suitable protection approach: either LOM or self-healing by controlled island operation. The latter requires also some fault-ride-trough (FRT) capabilities from the DG units and their protection. It must be ensured that the faults that are external to the islanding part of the system do not cause any unnecessary disconnection of the DGs so that the possibilities to islanding are endangered.

Protection Zones

The proposed protection system consists of IED with associated measurements and circuit breakers dividing the power system into several protection zones. This is illustrated with the areas shaded with different colours in Fig. 2. Since the IEDs are always located in the border between two adjacent protection zones they must be capable of reacting to faults in both zones. In practice, each protection device reaches a certain amount beyond the next device so that the protection zones become overlapping. This kind of backup functionality is necessary to increase the protection security, but for the sake of simplicity it is omitted here and will be discussed more in later papers.

For an IED the basic functionality can be divided into forward and backward functionality. The forward direction is towards the faulted zone. In this direction the protection should be capable of indentifying all the different shunt fault types that are located within the zone.

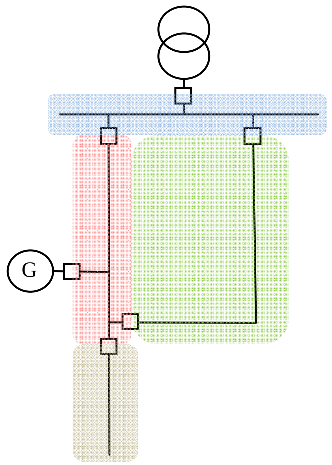

Figure 2. *Division of the power system to protection zones.*

Certain functionality is also needed for backward direction to enable proper selectivity. This could mean, e.g., the sending of interlocking signals to the previous IEDs. Backward direction has also an important role for achieving the adaptability of the system. From this direction the IED can receive information, e.g., about the fault current contribution capabilities of various sources.

System Architecture

The Smart Grid protection should be based on the efficient use of the computing power of the IEDs located at various places and connected to each other with a high speed communication network. Various tasks and functions should be distributed to various IEDs in a way that the system performance and flexibility are maximized. This kind of approach means that distributed intelligence is being used. The IEC 61850 standard [9] can be used as a framework for this kind of approach. It provides a consistent way to handle the protection and automation system information, communication and configuration. Applying well defined object oriented data model of the IEC standard enables interoperability between devices from different manufacturers. Although the IEC 61850 standard was initially focused on substation automation, new data models are developed to extend the application possibilities of the standard. One of the latest is the part IEC 61850-7-420 which defines the object models distributed energy resources (DER).

In the standard the smallest part of functions, the functional elements, are represented as logical nodes (LN). Logical nodes reside in certain physical devices (PD), which are usually the IEDs. Typically an IED contains several logical nodes. A set of logical nodes form the actual protection or control function. The LNs forming a single one function can be distributed among several PDs. This is enabled by defining logical connections (LC) between the LNs so that they can communicate with each other and act as a single entity. LC between different PDs uses either one or multiple physical connection (PC).

The distributed intelligence can be applied in this hierarchical object model so that the physical location of each LN in a function is carefully selected among the involved IEDs. In some cases it may be more convenient to have part of the measurement taken from some distant IED while in other cases it is necessary to operate the circuit breaker LN (XCBR) by an IED from other location. More advanced functionalities would be achieved by processing the measurements at various locations and transmitting only the processed data from various locations to the protection function making the final decision. These examples give some idea of the practical meaning of distributed intelligence.

In order to meet the requirements related to the protection system adaptability there must be certain control functions that take care of actions needed in the changes of the system state. These functions will continuously monitor the system status and adjust the other functions according to some predefined rules. Basically these master functions can

- Activate and de-activate protection functions,
- Adjust the settings of protection functions.

Since the system is heavily relying on the communication it is essential that the protection system operation is also secured in case of communication failure. This might be another task for the master functions, which could adjust the available functions in case there is indication of any malfunction in the system.

Since the IEC 61850 focuses on definition of the communication and data encapsulation it does not actually provide any basis for specifying functions. Thus it is not alone enough for developing applications where the active functions, such as the master function mentioned above, have a central role. A solution for this is presented in [10] where it is shown that the IEC 61449, a standard for function block definitions, can be used together with IEC 61850 to create flexible and adaptable protection and control system.

Multi-Agent Approach

A suitable way to accomplish the distributed intelligence based application is to use the agent technology. Generally so called multi-agent systems, consisting of several agents working together and communicating between each other to achieve a common goal, are applied. The agents are actually autonomous software entities that operate without human intervention and they are also able to react to the changes in their environment. An interesting feature of the multi-agent systems is that they are proactive, so they may take initiatives in order to achieve the goal. The capabilities of multi-agent approach for a smart grid control have already been successfully demonstrated in [11].

As indicated in [12] the LNs defined in IEC 61850 can also be viewed as intelligent agents. Here the proposed application is presented as an agent system that only slightly resembles the IEC 61850 object model. The aim has been to give generic description for the protection system functionalities without the possible limitations of IEC 61850.

In the proposed approach the basic unit of the protection system consists of a circuit breaker with associated measurement devices and the IED. This is illustrated in Fig. 3, where the blue blocks represent the individual agents residing in an IED while the thick vertical line represents the data bus that is extended beyond the IED boundaries by the telecommunication links. Also the primary system components together with their interface to the IED are illustrated in the figure.

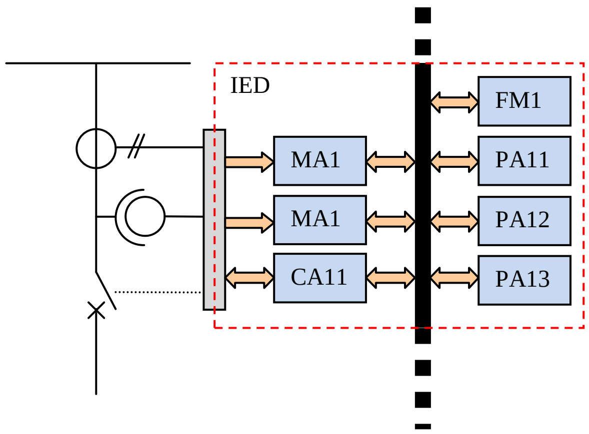

Figure 3. *Basic unit of the proposed protection system.*

The form and content of the basic unit (BU) depends on its location in the power system, but a common feature of it is that it contains at least a circuit breaker and an IED capable of controlling it. This enables the desired functionality of the system: disconnecting the faulted section and switching the backup connections. Another feature of the BU is that it contains both current and voltage measuring devices. As mentioned before, a key functional requirement for the Smart Grid protection is the voltage measurement. There can be even two voltage measurements, one in each side of the circuit breaker, which is necessary in certain cases (e.g., for synchronizing islanded part of the system back to the main grid).

In Fig. 3 the IED contains several basic functions which are various types of agents. In the figure the following naming has been used:

- Maxx : measurement agents,

- CAxx: control agents,
- PAxx: protection agents,
- FMxx: function management agents.

The measurement agent processes the raw measurement data and forwards it to the other agents requiring the data. Control agents take care of the actions applied for the primary system, e.g., by opening the breaker. Within an IED there are several protection agents taking care of the actual protection functions. The desired adaptability is achieved by the function management (FM) agents, which have the following tasks:

- Monitoring the system state,
- Adjusting the protection functions according to the changes in the system.

The adjustment of the protection functions means activation and deactivation of specific protection functions and specifying suitable protection settings as well as adjusting the associated communication between involved agents. The number and roles of the needed FM agents depends on the system design. A suitable principle could be that one FM agent takes care of one basic protection function (e.g. overcurrent) in one protection zone.

A schematic of a part of a power distribution system containing several BUs is shown in Fig. 4. There are three different types of nodes in this system:

- Switch station feeding a satellite distribution substation,
- Distributed generator,
- Line breaker.

In addition to the primary system the telecommunication system is also shown in the Fig. 4 (red lines). The key nodes of the telecommunication system shown here are either routers or Ethernet switches. In places where there are several BUs in one location (like in the switching station in this case) this kind of arrangement is the most convenient one. On the other hand at the places where there is only one BU, it might be possible to integrate the telecommunication interface to the BU.

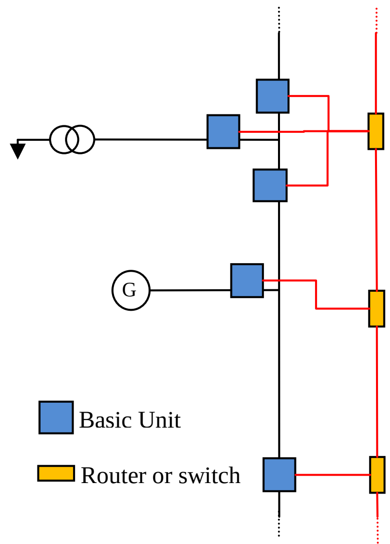

Figure 4. *Part of a distribution system with Basic Units.*

Example

The example depicts one fault situation where different kinds of actions from agents in the network are required depending on the surrounding conditions. The actions vary from fault clearance to determination of island size which will be formed. Basic Units (BU), see Chapter 6 (Fig. 3.), are embedded in the network as shown in Fig. 4. The BUs are connected with a fast telecommunication network which allows communication between all the devices in the network. The BU can contain several different protection agents which are all controlled by the

FM agents. The FM agents assess the situation continuously and change the settings of different agents and their operating status according to predefined set of rules.

To best suit the connection status of the network the rules have been created to match all possible network changes and faults beforehand. When a FM agent detects some change in the system which matches one or more of the rules it will trigger the corresponding settings for the protection agents.

The FM agents control the agents that are active and thus protection settings in use. In the example some of the basic functionalities of the protection system are demonstrated. The example network shown in Fig. 5 includes a DG that consists of possibly multiple generating units, one main supply point and one backup connection point. In addition, the network can be divided into several segments with circuit breakers connected along the line. Some loads, which are in practice the distribution substations supplying several customers are also shown.

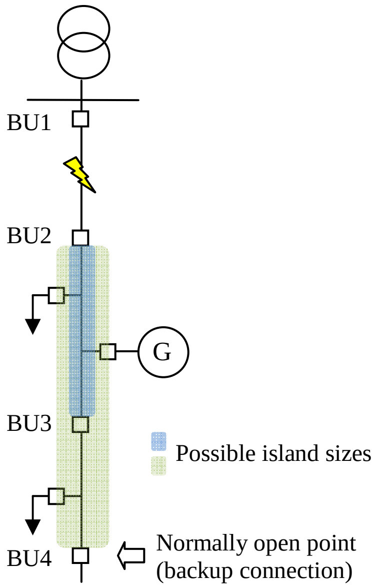

Figure 5. *The example network.*

A fault occurs on the network between the main supply connection point and the DG as shown in Fig. 5. The task of the protection agents is to clear the fault and disconnect the smallest possible part of the network. There are two different possibilities to maintain supply for the healthy part of the network. One is to isolate the fault and maintain supply for the healthy part of the network by closing the backup connection point (BU 4). The second possibility is to create an island from the healthy part of the network which is being energized by the DG.

Upon detecting a fault the protection agents compare directional information to make a decision of the faulty section. The sequence to detect the faulty section in the example starts when BU1 (in Fig. 5) detects the fault in the forward direction of its location and sends that information down the feeder to all of the BUs in line. In addition, the fault information is sent to the DG alongside with interlocking command for a short duration needed to clear the fault. This enables the necessary fault ride-through capabilities of the generating unit. BU2 detects the fault as being in backward direction and by comparing the directional information from BU1 it knows that the fault must be between BU1 and BU2. With this knowledge BU1 and BU2 can disconnect the faulty section from the network. Also a command to BU4 to close the backup connection point is sent to keep the healthy part of the network energized. After clearing the fault the interlocking of generating units is cancelled. The FM agents receive now information about the events and conclude that the network topology has been changed. As a result of this they request the associated protection agents to change their settings accordingly.

It is also possible that the telecommunications network has been broken which prevents the different devices in the network from communicating with each other. In order to properly handle this situation the telecommunication links must be continuously self-monitored. This feature is available also in the IEC 61850 standard [13]. In a situation where the communication links are down the BUs can revert to predefined backup protection settings. The backup protection settings have to be based on protection methods that do not require information from other sources i.e. measuring or fault direction data. These methods include directional overcurrent and earth-fault protection functions for the network while the DG has additional passive LOM protection functions active.

As mentioned earlier a controlled island operation is one way to achieve self-healing in Smart Grids. Instead of using the backup connection the power supply can be continued by the island operation of the healthy part of the network containing the DG. The possible island size varies with the amount of production capability and consumption in the island. Consequently, when creating an island the power consumption and production levels for both active and reactive powers need to be roughly equal in the presumed island. Vital information in the island forming process is the power flow at the circuit breakers which are supposed to disconnect the island from mains. The task of agents is to measure the power flow at different BU locations and dynamically change the possible island size to match the current production/consumption balance according to measurement data. One example of two possible sizes for island operation is shown in Fig. 5. The island sizes are displayed in different colours with one size spanning from BU2 to BU3 and the second sized island is formed between BU2 and BU4.

Conclusions

In this paper a new type of protection concept for MV Smart Grids based on multi-agent approach has been introduced. The basic feature of the proposed concept is that it is adaptive; any changes in the system configuration and state will automatically affect the relay settings and activation of the different relay functions if necessary. The presented concept is based on distributed intelligence but the adaptivity can also be achieved by centralized intelligence. However, it can be argued that a centralized system may be less reliable while the distributed system can be build to have high level of fault tolerance.

This paper presents an overall description of the proposed protection concept as well as a simple example application to illustrate the functionalities of the system. The definitions and framework presented here will be the basis for further development of the concept into a practical application. This involves detailed definitions for various functionalities related to the adaptability as well as several new types of protection methods enabling the described functionalities and also the Smart Grid key features such as the self-healing. Although the proposed approach is based on distributed intelligence it is also worth studying alternative automation architectures to achieve desired level of availability and security of the protection system.

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