# FUNCTIONAL REQUIREMENTS OF SMART GRID PROTECTION

Kimmo Kauhaniemi and Sampo Voima
University of Vaasa
kimmo.kauhaniemi@uwasa.fi
Finland

***ABSTRACT** – In this paper the functional requirements of the Smart Grid protection are discussed. These requirements arise from specific features of the Smart Grids. For example, Smart Grids include various types of distributed energy resources, which enable more flexible use of grid capacity. With the help of modern ICT technology it is also expected that the power supply reliability is shifted to some higher level. Especially in the distribution system level the changes will be relatively big. The traditional distribution systems are more or less passive while the Smart Grid technology brings in new active elements. The state of the system will be continuously changing and in order to set up suitable protection system some new requirements must be taken into account. The functional requirements of the protection future Smart Grids, especially for the smart distribution networks, are discussed in this paper by analyzing a fixed set of different types of basic protection zones.*

***Keywords:** Smart Grids, protection*

## INTRODUCTION

There are slightly varying definitions for Smart Grid, but the main characteristics are usually the same. One of the key features of Smart Grids is that it employs wide variety of distributed energy resources (DER). These include distributed generation (DG), energy storages (ES) and active customers. In practice active customers means primarily the demand response (DR). In this paper the focus is on distribution networks where the increasing local generation requires new type of approaches for the protection. But this is not the only thing that comes with the Smart Grid. With the help of modern ICT technology it is expected that the power supply reliability is shifted to some higher level. In distribution system this means increased automation deeper in the system. One way to achieve better reliability is the smart way of sectionalizing the network. With suitable design of the protection zones the self-healing functionality of distribution system can be enhanced. In practice the self-healing functionality means that the protection system first locates the fault accurately and then disconnects the faulted section after which the intelligent automation functions take care of restoring the power supply to the healthy parts of the network.

In this paper the functional requirements of the Smart Grid protection are discussed considering different affecting aspects of the future Smart Grid. This paper is prepared as a part of a national Smart Grid project in Finland, the SGEM (Smart Grids and Energy Markets) project, and thus the present protection practices applied in Finland are used as starting point. The focus is on the distribution systems and especially in the medium voltage (MV) level where relay protection is applied. The analysis presented in this paper can also be applied at the low voltage (LV) level where the protection is still mainly based on fuses.

At first the present protection system practice in Finland is reviewed and an introduction to the main features of Smart Grid is given. After that the main elements of the smart protection system are defined providing new possibilities in the system functionality. Before proceeding to the functional requirements of the protection system a generic set of different types of basic protection zones is introduced. These protection zone types are further applied when analysing and discussing the required functionalities.

## PRESENT PROTECTION PRACTICES IN FINLAND

In this paper the Smart Grid requirements for the protection system are reviewed from the point of view of typical electricity distribution system in Finland. The Smart Grid technologies cover also the transmission and sub-transmission systems, but these are omitted here because the major changes will probably take place at the distribution system level. The distribution systems vary from country to country but the Finnish system is rather similar to the systems in many other European countries. Still there are some aspects that can be particularly found only in Finnish system or at least only in the systems used in the Nordic countries. Although the focus is in Finnish system, this paper tries to present globally valid issues in addition to those that are more system specific.

The typical distribution system in Finland consists of two voltage levels, medium voltage (MV) and low voltage (LV). For the medium voltage typically 20 kV is used while the LV system has the standard voltage of 400 V phase-to-phase or 230 V phase-to-ground. The MV system is fed from primary substations where the power supply is usually from 110 kV sub-transmission system. Primary substations have on average around 11 feeders in urban areas and around 6 feeders in rural areas [1]. In rural areas mainly overhead lines are used while in urban areas the share of underground cables is around 60 %. A special feature of the Finnish system comes up from the sparsely populated country; in rural areas the MV feeders are relatively long. The average length of rural feeders is 31.6 km [1]. In forest areas the overhead line construction has shown to be vulnerable to storms and other weather related threats. Thus there is a growing tendency towards underground cables also in rural areas. Applying underground cables in long feeders causes some new challenges for the protection that will be further discussed later in this paper.

The medium voltage feeders are usually protected by protection relays located at the substation. Traditionally there have been no other protection devices along the feeder but recently the use of pole mounted reclosers or recloser stations has increased. These devices divide the long feeders into two or more separate protection zones enabling improved reliability. The effects of this kind of feeder sectionalisation to the system reliability and costs have been studied in [1].

In the LV system the feeders are protected by the fuses at the secondary substation. In the underground networks the customer service cables are connected to the junction boxes where there is also possible to have fuses in order to achieve proper protection level according to the safety regulations. At this point it is also worth to mention that the LV feeders always have three phases and four wires; the standard TN-C earthing system is applied in public LV networks.

## FEATURES OF FUTURE SMART GRID

### Distributed Generation

Smart Grid accommodates typically various amount of local generating capacity, typically DG but sometimes also ES. Conventionally MV networks are operated radially with only one power source, that is the primary substation. The increased amount of DG changes these networks more towards meshed networks with bi-directional 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 ES. When storages 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 [2], which makes the traditional overcurrent based protection scheme infeasible. The main problems related to the DG protection are identified, for example, in [3]. Very much the same issues are valid for the Smart Grid protection.

### Controlled Island Operation

One of the protection problems with DG is the prevention of un-intentional island situation with the anti-islanding protection also known as the loss-of-mains (LOM) protection. Various passive and active LOM protection methods have been developed and presented over the years. Good summaries of them can be found in [4] and [5]. However, it is obvious that still the most secure LOM 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 supposed to be based on intentional or controlled island operation.

One interesting feature proposed for the Smart Grid is the self-healing, which was first introduced in [6]. Self-healing means that the system is capable of continuing the power supply (at least partially) after any kind of disturbance. Self-healing is in fact a broad concept including the stability of transmission grids among others, but here the focus is on the protection of 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. Microgrids are good example of the parts of the system that are capable to controlled island operation In microgrids the successful use of the local generation for achieving controlled island operation after an external fault requires the use of suitable telecommunication between different elements of the system in order to handle the power balance of the islanded system. In the studies presented in [7] it is also noticed that static switches are needed in some cases in order to enable fast enough operation to maintain the stability of microgrids. In addition to this the protection system need to be quickly adapted to the new operating state after the islanding.

While microgrids are specially designed for controlled island operation an interesting idea is to use a part of the MV system as an ad hoc island in a fault situation. By monitoring the system state, both loads and generation, suitable MV feeder sections can be defined in advance and included in the self-healing strategy.  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 circuit breakers) providing backup connections this would mean closing these switches automatically in fault cases. Additionally this requires that the faulted section is automatically isolated from both sides (see Fig. 1).

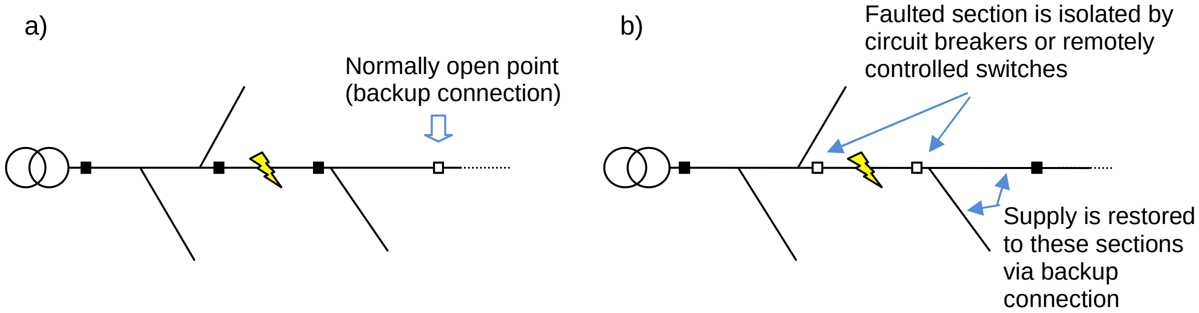



**Figure 1.** Self-healing by using a backup connection. a) Fault occurs. b) Faulted section is isolated and backup connection is closed.

Traditionally the operational sequence described above is achieved with the operator control actions after the protection relays operated. In Smart Grid the target is to have much higher speed in the supply restoration and in overall a system design where the number of customers affected by a fault is minimised. This means that both the fault section isolation and the connection of backup supply must be made automatically. The first one is the aim of the protection system while the latter can be handled by distribution automation system. In overall this kind of functionality 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.

New primary system solutions

When discussing Smart Grids the focus is usually in the applications of ICT technologies. However, there exist also primary system solutions that are taken into use or are developed under the paradigm of Smart Grid. These include both individual devices and system wide solutions. The main drivers for these solutions are better reliability, maintainability and lower total costs. In the following some examples of these are briefly introduced.

The electricity supply reliability problems have gained lot of attention recently in Finland, where the long overhead line MV feeders located in the forest areas have caused some major supply outages in the rural areas during recent storms. To increase the resilience of the MV networks against weather originated threats, the underground cables can be used instead of overhead lines. Thus the underground cabling has been seen as the main solution to improve the system reliability by the major distribution system operators. However, using underground cables in the long medium voltage feeders causes some new challenges to the protection. In the earth isolated system traditionally used in Finland the cable feeders would cause excessive earth fault currents considering the regulations relating to the allowed touch voltages. Thus the resonant earthed system must be applied. Still the setting up a selective protection system may pose challenges due to the characteristics of cables. These are further elaborated later in this paper.

Another way to increase the system reliability is to use DC voltage in certain places of the distribution system. For this purpose the low voltage DC (LVDC) distribution concept is introduced in [8]. The LVDC distribution system is beneficial, for example, in rural areas where it can replace the long and lightly loaded branch lines of MV networks [8]. The LVDC system creates naturally its own protection zone and thus it has a positive effect on the system reliability. The protection of the LVDC link requires technology that is not traditionally used in public power distribution systems. Furthermore, an interesting possibility is to integrate the necessary protection functions to the converters as discussed [9], where also a comprehensive solution to LVDC distribution system protection is introduced.

It can also be expected that all kinds of active components will be increased in the MV and LV levels of Smart Grid. It could be possible to use similar FACTS devices in the distribution level as it is used in the transmission systems are used nowadays. They could be used for managing the voltage levels as well as the power flow to maximise the use of available capacity. From the protection point of view these new active elements will change the system characteristic and possibly have some effect on the fault current. Together with the effects originated from DG it might be problematic to have the protection system that can handle the varying fault current levels. An interesting solution to this is presented in [10], where a fault current controller introduced. Such a device could be used to maintain some predefined fault level in the critical points of the system. However, the control system of it requires that the grid status is constantly monitored.

Integration of the ICT

The key feature of Smart Grid is that it integrates the primary electrical system with extensive ICT layer. It can also be said that Smart Grid employs a two-way flow of electricity and information to achieve its targets relating to the cooperation between different actors and integration of various elements into the grid [11]. In practice this means large number of control and automation devices that are interconnected with each other with modern communication systems. The protection system is based in the intelligent electronic devices (IED) with communication capabilities so it is only natural that the communication is also extensively applied in the protection. A separate question is whether the communication system applied for the protection should be separated from the communication systems applied for other purposes in Smart Grid. From security point of view this could be wise, but probably it is financially beneficial to use at least common communication media for different purposes while different applications are having their own virtual private networks.

## ELEMENTS OF SMART PROTECTION SYSTEM

Telecommunication

As stated above the telecommunication system has an essential role in the Smart Grid also from the protection point of view. Using telecommunication enables using more secure and selective protection functions. Traditionally telecommunication over longer distances has been used mainly in line differential schemes, which is also one useful scheme in Smart Grid environment. To achieve proper protection functionality in complex Smart Grid configurations it is necessary to apply transfer tripping or remote blocking/interlocking functions, which rely on telecommunication links between IEDs.

Adaptivity

The smart grid protection should also be adaptive since the configuration of the network and the state of the active elements is constantly changing. The radial configuration of the feeders may be changed to achieve minimum losses or to avoid congestion situations. The local generators participate actively on the energy markets and the production patterns vary according to the price signals. This means that the protection system must be aware of the normally open points (network radial configuration) and generation status of each DG. The latter provides information about the fault current sources active in the network. Any change in the primary system may need to be reflected by a change in the protection system.

The adaptivity relies on the telecommunication system and therefore it is vital also to take care of possible failures in the telecommunication links. In the approach presented in [12] the secure operation of the protection is ensured by default protection parameters that are taken into use in the case communication is lost. Of course this may lead to a less selective operation of the protection.

Relay software and algorithms

The requirements stated above mean that the IEDs must employ suitable software platform to enable flexible communication and adaptive use of several alternative protection schemes. From the relay software point of view one interesting way to accomplish the required intelligent system is to apply 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. An example of the use of agent technology is found in [13] where agent platform is used for analysing the system state and further assisting in adjusting the relay settings.

From telecommunication point of view it is essential to fully exploit the possibilities provided by the IEC 61850 standard. The common standard applied enables not only the interoperability of the IEDs from different vendors but also provides means to integrate various types of DER in the system. The latter is possible with the new part of the standard, the IEC 61850-7-420, which has so far implemented only in some research pilots such as those one in the MoreMicroGrids project, that are reported for example in [14].

In the IEC 61850 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). As discussed above a way to accomplish an adaptive protection is to apply the agent technology. In [15] it is said that the LNs defined in IEC 61850 can also be viewed as intelligent agents. This opens up interesting possibilities for the development of suitable software platform.

## PROTECTION ZONES

For analysing the functional requirements of the Smart Grid protection a proper division of the studied distribution system to protection zones is needed. The zone division must be made considering also the possibilities for self-healing functions. For example, there may be a part of the network with relative large amount of local generation and thus it may be reasonable to allow it to operate in controlled island operation mode in certain fault cases.

For each protection zone there are one or more circuit breakers operated by IEDs enabling the disconnection of the zone in any in-zone fault. In case there is only one circuit breaker the task is quite simple, but with the increasing numbers of circuit breakers the complexity of the protection scheme increases.

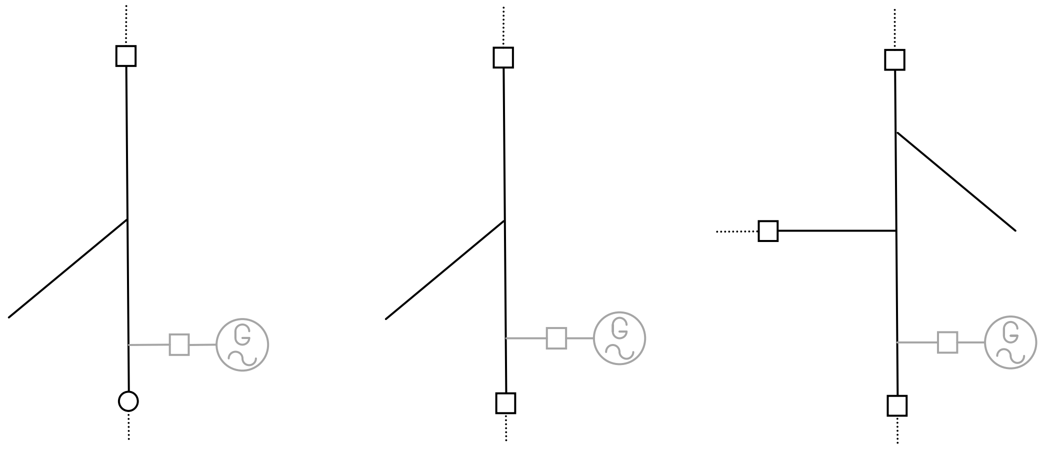
As an efficient way to analyse the Smart Grid protection requirements a systematic approach basing on a limited set of different types of protection zones is applied here. A protection zone is defined as a part of power system limited by the protection devices. It is also the smallest part of the system that can be separated from the rest of the power system – the healthy network – by the operation of the protection system.

The defined basic protection zones types are:

- Radial,
- Ring,
- Mesh.

In this case the protection zones are assumed to be a part of the distribution system feeder, i.e. feeder protection zones. Considering the whole distribution system there are also protection zones in the substations, typically separate zones for the buses and transformers. However, the protection requirements arising from the Smart Grid features are assumed to be mainly applicable also for these special zones and so they are not separately discussed in this paper.

The basic protection zones differ from each other only by the number of connections to adjacent protection zones. These are referred here as “zone borders” and they are assumed to contain an IED with necessary measurements and a circuit breaker enabling the disconnection of faulted zone. Two variants of all the three basic protection zones can be defined by considering whether the zone contains DG (power sources) or not. All the basic protection zones and their variants are illustrated in Figure 2. In the radial zone (a) there is only one zone border while the ring zone (b) has two zone borders. The mesh zone (c) has three zone borders in the figure, but this zone type can have *n* zone borders ($n > 2$).



a) b) c)

□ Zone border: IED and circuit breaker

○ Feeder border: Open disconnector or switch

**Figure 2.** Defined basic protection zones: a) radial, b) ring, c) mesh. Also the optional DG is shown. Loads along the feeder are not shown.

As can be seen these protection zones may contain branches so the form of the network between the borders is not fixed. The essential feature is the number of zone borders. In Figure 2 the ring type zone has a connection to other feeder via a normally open disconnector or switch. This element is not considered as a zone border since it does not have protection capabilities. However it is worth noticing that it can be applied for self-healing purposes, i.e. for connecting the backup supply after the faulted supply is disconnected. As a special case it may be considered a situation where there is a circuit breaker with IED that is kept open in order to have suitable radial network configuration. In such a case this device cannot be considered as a zone border since it does not have any protection functionality in the fault cases.

From protection point of view the situation is different when there is DG in the zone. It may also be argued that the DG is typically connected to the feeder with some protection devices and thus it forms a separate protection zone. This is a valid interpretation, but here the DG is only considered as a special node capable of supplying power and also fault current. In case there is a fault in the protection zone the power supply cannot be continued from the DG and it must be disconnected. Basically this means that it is necessary only to define the anti-islanding requirements for the DG. During a fault the current supplied from DG affects on the currents seen by the relays at zone borders. This must be taken into account in the protection scheme applied and thus it is reasonable to consider also variants containing DG.

## FUNCTIONAL REQUIREMENTS

During the life-cycle of a protection system there are different stakeholders involved having different types of requirements. The requirements can be divided in the user requirements, functional requirements and performance requirements [16]. The functional requirements discussed here must reflect the user requirements. The requirements of the user of future Smart Grid originate mainly from the Smart Grid features presented earlier in this paper. The most important requirements are:

- Easy integration of DG.
- Capability to adapt to changing system conditions.
- Higher supply reliability by applying self-healing.
- Utilization of the full potential of the advanced ICT technology.
- Enabling the application of primary system technologies that offer cost-efficient way to improve system reliability.

In addition to these it must be also remembered that the basic requirement for the protection system is that it can reliably detect any faults within the protection zone. In more general terms the protection security and dependability are always the primary requirements along with speed, selectivity etc. When the Smart Grid is simplified as a set of above described basic protection zones the main functional requirements can be elaborated. The functional requirements provide information how the protection system should operate in all the fault situations within the protection zone. The requirements depend first of all on the type of the zone, but also on type of the other zones in the system. Furthermore in some cases the requirements are affected by the characteristic of the whole galvanically connected system. When considering only functional requirements it is not necessary to yet specify the applied protection functions and their settings, but some conclusions about the applicable functions can be drawn.

The protection functions needed at the IEDs locating at zone borders may be quite different depending on the system configuration. Essentially the supply direction and location of local generators dictates which protection functions are applicable. For example, power supply from several directions makes the non-directional overcurrent function useless. When considering the earth fault protection, the location and type of system earthing dictates the functions and settings applicable. What makes the situation even more complicated is the dynamic nature of Smart Grid. Due to the energy markets, auxiliary services market and increasing efficiency requirements the state of the active resources and network configuration will be changing with time. This necessitates that the protection system should also be able to change both the active relay functions and/or their settings. Possibly there must be defined a separate protection system functionality for each possible system state and configuration.

Presumably in most cases the available protection techniques are capable to meet the requirements, but the proper coordination between the protection schemes applied other zones is still necessary. Thus a protection function and its settings applied in a protection zone are always dependent on the functions and setting of other zones in the system.

Requirements for the basic protection zones

Considering the first basic protection zone type presented above, the radial zone, we can see that it is the traditional system where the current protection arrangements are applicable. Basically all we need is overcurrent and earth fault protection and the latter only if the system is non-effectively earthed and thus requires a separate earth fault protection. There is only one protection relay taking care of the whole zone and thus it must be devised to detect all the faults within the zone. A new issue in the Smart Grid environment is that the system conditions are varying and the protection settings must either be adjusted so that they cover the whole variation ranges or several alternative setting and even functions may be applied according to the grid status variations. In practice the variations in the system configuration mean either a different radial configuration of the feeder so that the minimum fault current in the zone changes or changes in the supplying grid so that the fault level at the zone border changes.

The radial protection zone also has a variant where there is some DG within the zone. In this case the protection must consider the additional fault current provided by the generator. This may affect to the reach of the protection in short-circuit faults. Another important aspect is that the protection in the zone border needs to have directional capabilities. A fault current from DG to a fault in some other zone must not trip the zone protection. It is also worth noticing that in the zone border there might be a single one IED handling actually both zones. Thus from the IED point of view each direction is associated with different zone. The zone that contains DG may also be defined to have capability to island operation and in such a case it has effect on the protection of the neighbouring zone. The protection in between the zones must operate fast enough to enable successful transition to island operation in case there is a fault in the neighbouring zone.

As shown in Figure 2 the radial zone may have a backup connection (open disconnector or switch). In case there is outage in the main supply the automation system should close the remotely controllable disconnector or switch at the backup connection in order to energize the zone. This is one of the basic self-healing functions of Smart Grids and it is supposed to be taken care by the automation system. The self-healing procedure is initiated by tripping of the relays in a zone and as an outcome of it the zones are reconfigured. This means that in fact the types of some zones may change. Furthermore this necessitates that the protection settings and functions may need to be adjusted.

The second basic protection zone type, the ring zone, is already more complicated to handle. The protection arrangement depends on the capacities of the system behind both of the zone borders. One of the neighbouring zones may also be of radial type with no DG and thus there is no fault current supply from this zone border. The operation of the protection relay in this side of the zone is not necessary in the in-zone faults when considering only the traditional requirements for the protection. However, for enabling the fast reconnection trough a backup connection it would be beneficial if also the connection to the radial zone is opened as soon as the fault is detected. Since there is no fault current supply from this direction the detection of fault should be based on, for example, under-voltage detection in short-circuit faults. It is also worth noticing that when there is a sequence of ring type of zones with no DG ending to a radial zone with no DG the situation is analogous to the above. Thus the essential characteristic when deciding the protection requirements is the fault current supply capabilities from the whole system behind a zone border. If the neighbouring zone contains DG and has capability to island operation then there are requirements for the protection speed as discussed above. Considering the protection functions needed with this type of zone it is evident that in most of the cases directional overcurrent protection is needed. For systems with several protection zones the necessary time grading may lead to excessive operating times and thus the differential protection can be a good alternative. Also distance protection may be applicable, but the effect of DGs must be properly taken into account. If the zone has complex topology, with long branches and DG at various locations, then probably the only applicable protection function is the differential protection.

The third basic protection zone type, the mesh zone, can be handled generally very similarly as the ring zone above. The main difference is that with *n* different origins of power supply the design of the protection system becomes more complicated. For each zone border the applicable protection depends on the system characteristics behind the zone border and the justifications about the different protection functions given above for the ring type zone are also valid here. However, in most cases the only applicable protection function will probably be the differential protection.

From the analysis above it can be seen that the requirements for the protection system does not depend only on the protection zone itself but also on all the zones in the system. Essentially the settings of each protection relay in a protecting a zone is dependent on the whole system behind the zone border.

Special requirements for earth fault protection

The earth fault protection of non-effectively earthed systems cannot usually be based on overcurrent relays. Especially in the earth isolated or resonant earthed MV networks the earth fault current is usually smaller than the load current. Thus specific earth fault relays with directional capability are needed. They are typically based on the measurement of zero sequence current $I_0$ and zero sequence voltage $U_0$. During an earth fault the zero sequence voltage is in practice almost the same in the whole network while the zero sequence current depends on the location. In a Smart Grid consisting of the above described zones the necessary arrangement for earth fault protection would consist of directional earth fault relays in the zone borders. When setting these relays it must be noticed that the whole galvanically connected network behind the zone border and especially the total earth capacitance of it affects on the current seen by the relay in an earth fault situation. The DG does not have any contribution in this situation.

The use of resonant earthed systems or, in other words, earth fault compensation is rapidly increasing in Finland. One of the reasons for this is the cabling of rural medium voltage feeders which leads to increased earth fault currents in the existing earth isolated systems. The only way to limit the earth fault current is to use earth fault compensation, which means the addition of a Petersen coil to the system neutral point. Typically a centralized compensation is applied where there is one controllable coil at the substation. The schematic in Figure 3 illustrates this situation. In a fault situation the fault current consists of two components: the current trough the compensation coil ($I_L$) and the current trough the zero sequence capacitances of the conductors ($I_C = I_{C1} + I_{C2}$). These two currents are opposite and with perfect tuning of the coil the fault current $I_L$ tends towards zero. With long cable feeders the situation becomes more complicated since the zero sequence resistance of the feeder cannot be ignored as has been done in the following figure. This means that the fault current will have a resistive component that cannot be eliminated with a tuned coil. As a solution for this the decentralized compensation can be used, where several small coils are located along the feeder. This issue and the protection problems arising from the distributed compensation are further discussed in [17] and [18]. These references focus on the traditional radial distribution network, but considering the Smart Grid concept with several protection zones the managing of the earth fault protection and compensation when the network configuration is constantly changing introduces new challenges. One of them is the changing of the fault current seen by the relays when the total length of the network and the number of compensation devices connected are varying. Any changes in the network or compensation devices must be reflected to the settings of the earth fault relays. This is only possible by applying adaptive protection with telecommunication system connecting all the IEDS and compensation devices.

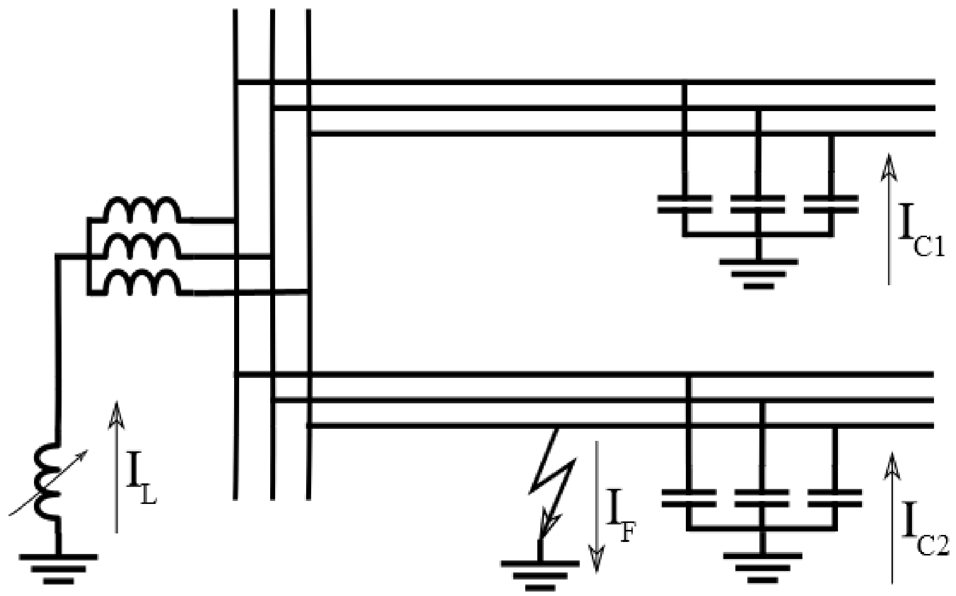



**Figure 3.** Earth fault in resonant earthed network.

Effect of DG

Traditionally current and voltage measurements provide enough information of the typical shunt faults and also about asymmetric series faults. However, a special case of series fault, the loss-of-mains situation, may be problematic to detect in certain circumstances. This issue has been widely discussed since the introduction of distributed generation and since DG is an essential part of the Smart Grid the problem is still relevant. Considering the functionality of the basic protection zones presented above it is required that all the DG in a zone is disconnected whenever the power supply to the zone is disconnected. Usually the reason for this is a fault and thus the DG can be devised to react any faults in the zone. For many faults the current seen by the DG may be about the same whether the fault is in the zone or outside it. Especially the correct detection of the earth fault situation in a non-effectively earthed system is usually not possible for a DG which can see only the increased zero sequence voltage. On the other hand the DG should stay connected when the fault is in some other zone. This is also vital considering the self-healing by applying controlled island operation. In order to manage these contradictory requirements a transfer trip scheme for the DG protection is in practice the only way to achieve the full Smart Grid functionality.

Telecommunication

In the fault isolation stage the relay operates and trips the circuit breaker. This is the traditional approach but in Smart Grid environment the situation may be more complex. The circuit breaker to be opened can be at some distant location, at the other end of the protection zone or at the DG as discussed above, and thus a transfer trip scheme need to be applied. Furthermore, when the zone is of mesh type then there may even be several breakers that need to be transfer tripped simultaneously. To enable high speed operation or to avoid excessive time based grading also interlocking signals may be transmitted to other IEDs to prevent false tripping.

As can be concluded from the protection requirements presented above it is also beneficial to apply adaptive protection, which relies on extensive communication system connecting various intelligent devices in the system. Thus the telecommunication is needed not only for the protection purposes but also for managing the protection system.

Self-healing

When self-healing is based on controlled island operation an advanced fault management system is needed. In reference [19] an approach is proposed where fault detectors are applied to define the suitable operation sequence. In overall it is essential to be able to determine where the fault is located with respect to the potential area to be islanded.

Protection system must provide support for the self-healing function applied in the distribution automation system. Depending on the situation the self-healing may be based on backup connections or controlled island operation. The operation time of the protection must be fast enough so that the suitable self-healing function can be applied in the healthy parts of the system. Also the fault ride trough requirements for the generators must be adequately set especially when the aim is to use the controlled island operation.

## CONCLUSIONS

In this paper the requirements for the Smart Grid protection were discussed. As a starting point the present Finnish system is used but main part of the presented requirements are also generally applicable. The key finding is that in order to enable the proper integration of DER and other new features of Smart Grid the protection system of the distribution networks must meet some new requirements. First one is the division of the grid to smaller protection zones, which enable improved reliability compared to the present system. Secondly, the fast and selective operation of the system is only possible by applying telecommunication based protection. Essentially this means that all the IEDs in the system must be able to communicate with each other. The use of telecommunication makes it also possible that we can have more up to date information of system configuration and status. This can be applied to better match the protection system to the current state of the primary system. Eventually some kind of adaptive protection system is necessary so that the protection settings and functions are always matched on the system configuration and the state of the various active elements in the grid.

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## REFERENCES

[1] H. Lågland, *Comparison of Different Reliability Improving Investment Strategies of Finnish Medium-Voltage Distribution Systems*, Dissertation, Acta Wasaensia No 256, University of Vaasa, 2012

[2] T. Loix, T. Wijnhoven, G. Deconinck, "Protection of Microgrids with a High Penetration of Inverter-Coupled Energy Sources", *CIGRE/IEEE PES Joint Symposium on Integration of Wide-Scale Renewable Resources Into the Power Delivery System*, 2009

[3] K. Kauhaniemi, L. Kumpulainen, "Impact of Distributed Generation on the Protection of Distribution Networks". *Developments in Power System Protection*, Amsterdam, 5 - 8 April, 2004

[4] M. Geild, *Protection of Power Systems with Distributed Generation: State of Art*, Technical Report, ETH, Zurich, Switzerland, 2005

[5] P. Naisani, D. Tholomier, T. Yip, G. Lloyd, "Protection of Distributed Generation (DG) interconnection", *63rd Annual Conference for Protective Relay Engineers*, 2010

[6] S. Massoud Amin, B.F. Wollenberg, "Toward a Smart Grid: Power Delivery for the 21st Century", *IEEE Power and Energy Magazine,* Vol. 3, No. 5, pp 34-41, 2005

[7] H. Laaksonen, *Technical Solutions for Low-Voltage Microgrid Concept*, Dissertation, Acta Wasaensia No 241, University of Vaasa, 2011

[8] P. Salonen, T. Kaipia, P. Nuutinen, P. Peltoniemi, J. Partanen, "An LVDC Distribution System Concept", *Proceedings of Nordic Workshop on Power and Industrial Electronics (NORPIE)*, Helsinki, 9-11 June 2008, available at http://lib.tkk.fi/Conf/2008/urn011603.pdf

[9] P. Salonen, P. Nuutinen, P. Peltoniemi, J. Partanen, "LVDC distribution system protection — Solutions, implementation and measurements", *13th European Conference on Power Electronics and Applications (EPE '09)*, 8-10 Sept. 2009

[10] M. C. Ahn, T. K. Ko, “Proof-of-concept of a smart fault current controller with a superconducting coil for the smart grid”, *IEEE Trans. Appl. Supercond*. , vol. 21, no. 3, pp. 2201-2204, May 2011

[11] B. Panajotovic, M. Jankovic, B. Odadzic, “ICT and smart grid”, *2011 10th International Conference on Telecommunication in Modern Satellite Cable and Broadcasting Services (TELSIKS)*, pp.118-121, 5-8 Oct. 2011

[12] S. Ritter, H. Ruttinger, S. Ritter, P. Bretschneider, D. Westermann, “New approaches for smart grid requirements: Grid protection and optimization of distribution grid operation”, *2011 IEEE Power and Energy Society General Meeting*, 24-29 July 2011

[13] F. Kawano, G.P. Baber, P.G. Beaumont, K. Fukushima, T. Miyoshi, T. Shono, M. Ookubo, T. Tanaka, K. Abe, S. Umeda, ”Intelligent protection relay system for Smart Grid”, *10th IET International Conference on Developments in Power System Protection (DPSP 2010). Managing the Change*, March 29 2010 - April 1 2010

[14] MoreMicroGrids, *DF1. Report on field tests for interconnected mode*, Final Report, January 2010, available at http://www.microgrids.eu/documents/658.pdf

[15] A. Apostolov, "Multi-Agent Systems and IEC 61850", *IEEE Power Engineering Society General Meeting*, 2006

[16] I. Abdulhadi, F. Coffele, A. Dyśko, C. Booth, G. Burt, “Adaptive protection architecture for the smart grid”, in *Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES,* Manchester, 2011, .

[17] A. Guldbrand, O. Samuelsson, “Central or Local Compensation of Earth-Fault Currents in Non-Effectively Earthed Distribution Systems”, *2007 IEEE Power Tech*, Lausanne, pp.1129-1134, 1-5 July 2007

[18] A. Guldbrand, O. Samuelsson, “Influence of Distributed Compensation on Earth Fault Protection in Cable Distribution Systems”, *IET 9th International Conference on Developments in Power System Protection (DPSP 2008)*, pp.615-620, 17-20 March 2008

[19] D.S. Popovic, E.E. Boskov, “Advanced fault management as a part of Smart Grid solution”, *CIRED Seminar on Smart Grids for Distribution*, IET-CIRED, 23-24 June 2008