DESIGN & ANALYSIS OF AN IMPROVED FAULT LOCALIZATION SCHEME FOR SECONDARY SUBSTATION AUTOMATION

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ABSTRACT

The increasing penetration of inverter-based, volatile dispersed generation units in distribution level creates technical challenges for a secure and reliable power supply. The modernization of secondary substation technology represents a prominent technical solution in order to master the effects of this trend. This paper presents the joined research results of an intelligent secondary substation design including improved methods for voltage control, fault detection and localization. Thereby the work's focus is on the novel secondary substation's characteristic function and its impact on the fault clearance process in medium voltage level. Simulation results emphasize its benefits for modern grid operation.

INTRODUCTION

The expanding deregulation of electricity market along with the advent of power generation from renewable energy sources lead to a widespread promotion of distributed generation units. However, the increasing penetration with distributed generation in low and medium voltage level causes new technical challenges for voltage control, grid loading and reliability. While system operators are bound to optimize their grids and thus reduce existing costs, an appropriate grid reliability, which in general requires corresponding equipment and staff, is an essential requirement by quality regulation [1]. These constraints lead to a conflict within the grid optimization process.

In this context a collaborative research project promoted by the German federal ministry for economic affairs and energy investigates solutions for an intelligent secondary substation. The focus of the project lies in part on the improvement of grid reliability through newly developed functionalities to detect and to locate faults. Although the intelligent secondary substation can be connected to the information and communication network of the grid operator, the newly developed functionalities work exclusively with information available inside the substation to detect and to locate faults. This characteristic of the new functionalities enables the implementation in substations with and without a communication link to the regional operating centre and give the grid operator thereby more flexibility in its grid planning process.

In this paper the newly developed functionalities of the intelligent secondary substation will be introduced as well as an algorithm to simulate the benefit of these new functionalities. Special attention will be paid to the accuracy of the functionalities and the benefit, which arises from these for the fault clearance process in specific grid configurations.

CURRENT PROCESS OF FAULT DETECTION, LOCATION AND CLEARANCE IN MEDIUM VOLTAGE GRIDS

The medium voltage (MV) grid shows two significant differences compared to the high voltage (HV) grid during the fault clearance process. First redundancy can in most cases only be realized by switching operations and second the protection concept based on protection relays and switch gear facilitates no direct selective disconnection of faulty equipment. In medium voltage grids fault detection and localization are therefore of much importance.

To determine the faulty equipment or fault location a fault area will be defined at first. By using this method the number of possible fault locations shall be reduced significantly. The fault locating is completed as soon as the fault can be linked to a specific equipment or group of equipment. Those groups of equipment can be differentiated in groups determined by a protection area and groups determined by a work clearance area (see figure 1). The work clearance area is delimited by isolating switches and the protection area is determined by combinations of protection relays and circuit breakers. Since common secondary substations are usually not equipped with protection relays and circuit breakers, the protection area includes several work clearance areas in most cases.

In common grids overcurrent relays are placed in primary substations to ensure selectivity on a high level and will trigger in case the measured current exceeds a pre-set threshold. Thereby short circuit indicators will allow to evaluate the fault's direction. Technical staff will then manually inspect the short circuit indicators in secondary substations within the effected feeder to identify the faulty equipment and work clearance area [2].

The fault clearance process depends on a number of different factors as can be derived from the descriptions above. In general these factors can be divided into two groups fixed grid factors, which cannot be changed easily by the grid operator, and flexible grid factors, which can be changed by the grid operator with a tolerable amount of effort.

Fixed Grid Factors

These factors include grid layout, reliability of equipment and neutral point earthing.

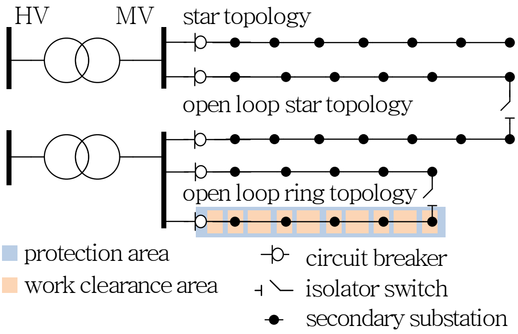

Figure 1: Grid Layouts

Grid layout
The grid layout may vary between open loop ring topology, open loop star topology and star topology as show in figure 1. In general common grids are realized as combination of the above mentioned layouts. The layouts differ especially in the amount of redundancy which they may be able to provide. Open loop ring and star topologies provide a basic amount of redundancy because any grid customer can be supplied via two possible electrical paths. In case of a fault the faulty equipment can be isolated over the switching of isolators and the rest of the topology can be resupplied. Pure star topologies provide no redundancy. In case of a fault customers, whose path of supply have been interrupted by the faulty equipment, have to be resupplied over an emergency power diesel aggregate for example.

Reliability of Equipment
The reliability of equipment also influences the overall quality of service in a MV grid. Overhead lines for example tend to be less reliable than underground cables [3]. In case of a fault however the faulty overhead line can be detected and repaired much quicker than the underground cable. Since the relation between underground cable and overhead line may vary significantly between different grids and countries, but even between feeders of the same grid, the focus of this paper will be on the fault clearance time rather than the interruption frequency.

Neutral point earthing
The influence of the neutral point earthing on the frequency of a faults with protection tripping is shown in figure 2 [4]. Since its influence is also directly connected to the used line type of underground cable or overhead line, it will not be examined in this paper.

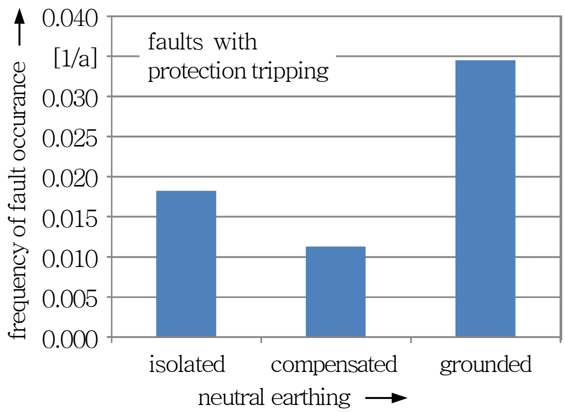

Figure 2: Reliability and Neutral Earthing of 10kV Cable

Flexible Grid Factors

The equipping of a secondary substations and the method of fault search are flexible grid factors which can be changed with tolerable effort by the grid operator.

Equipping of Secondary Substations
In addition to the equipment needed to carry, transform and distribute electricity the grid operator can include short circuit indicators as well as equipment for remote fault indication, remote switching and fault locating in secondary substations. Certainly the grid operator can also include additional protection relays and circuit breakers in secondary substations to increase selectivity. This measure however would require significant additional investments and is therefore no feasible option especially since [5] showed that additional investments in protection relays and circuit breakers do not pay off under German quality regulation. According to quality regulation the awarded increase in grid fees due to higher quality of service don't compensate for the additional investment. The installation of additional protection relays and circuit breakers is therefore not considered as an option to reduce fault clearance time in this paper.

Method of Fault Search
During fault clearance the location can be determined using one of the methods shown in figure 4 [2].

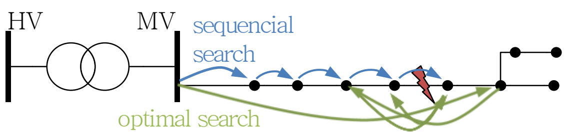

Figure 4: Methods of Fault Search

In case of a sequential search the technical staff will start the search for the fault at the primary substation and will examine the feeder equipment by equipment based on its electrical distance to the primary substation until the fault is found.
If the grid operator decides to use the optimal search, the

technical staff will chose the next secondary substation always according to the following principle: Which substation leads to the highest acquisition of additional information?

Overall Assessment

Overall it can be summarized that the operator has little information about the fault location in the current process and that checking of short circuit indicators eventually leads to the locating of the fault. This procedure takes a lot of personnel effort and time [2]. Even worse, in case of distributed generation and its contribution to the short circuit current the supplied directional information can be messed up. Thus, the influence of distributed generation might endanger the integrity of protection systems and power supply restoration schemes. Therefore alternative solutions for fault localization and an increased level of substation automation are required to improve the accuracy of fault isolation and thus reduce the downtime.

METHODE OF FAULT DETECTION AND FAULT LOCATION

Since common MV grids usually lack an overall communication infrastructure, no recorded measurement can be exchanged between neighboring secondary substations. Therefore a self-sufficient solution for fault detection and localization must be realized. Furthermore the operational frequency range of available current transformers for MV application is limited to some kHz. Thus, only local process values can be used without the benefits of high frequency component information. Under consideration of those given constraints an impedance-based approach has been chosen to achieve fault localization in MV level. By the means of a local impedance measurement, comparable to the distance protection function in HV level, an indication about the distance between measurement node and fault location can be calculated. While current transformers are rather standard equipment in secondary substations at MV level, an additional voltage measurement needs to be integrated to provide voltage data. In contrast to electromechanical short circuit indicators the complementary voltage information facilitates reliable fault detection. Especially for isolated grids the gained voltage information is beneficial to detect earth faults through zero sequence voltage U_0. Although modern short circuit indicators offer additional voltage signal interfaces to guarantee directional fault detection, the measured fault impedance can define a fault area in finer resolution and therefore has a greater impact on the achievable restoration time. Thereby the fault loop according to the determined fault type is chosen and its corresponding fault impedance calculated. Table 1 lists the essential six impedance loops for the common fault types that need to be processed [6].

Table 1: Fault Impedance Loops

Fault type	Conductor	Fault loop
1-pole	A-GND B-GND C-GND	A-GND B-GND C-GND
2-pole	A-B B-C C-A	A-B B-C C-A
2-pole with ground	A-B-GND B-C-GND C-A-GND	A-B B-C C-A
3-pole	A-B-C	A-B
3-pole with ground	A-B-C-GND	A-B

For the considered symmetrical and 2-pole fault cases the impedance Z_i^k and fault distance d can be calculated according to

$$\underline{Z}_{x-y}^k = \frac{\underline{U}_{xy}}{\underline{I}_{xy}} \rightarrow d = \frac{Imag\{\underline{Z}_{x-y}^k\}}{X_1'}$$

with the phase-to-phase voltage $\underline{U}_{xy}$, the phase-to-phase current $\underline{I}_{xy}$ and the MV line reactance X_1'. For a 1-pole fault loop a residual compensation must be set due to the line impedance ratio of positive and zero sequence system. The fault impedance and its corresponding distance can be calculated according to

$$\underline{Z}_x^k = \frac{\underline{U}_x}{\underline{I}_x + \underline{I}_r \frac{\underline{Z}_0' - \underline{Z}_1'}{3\underline{Z}_1'}} \rightarrow d = \frac{Imag\{\underline{Z}_x^k\}}{X_1'}$$

with the line to ground voltage $\underline{U}_x$, the faulty line current $\underline{I}_x$ and the measured rms-current $\underline{I}_r$ [7]. In both cases only the reactive part is considered to avoid disturbing influences of the fault's resistance. While 1-pole faults are the most frequent [4], they are most difficult to detect and localize as well. Especially in isolated and compensated grids 1-pole faults mean a small fault current. Typically short term neutral point grounding is used in order to increase the fault current flow and trigger the installed short circuit indicators. Following fault ride through principle for 1-pole faults, the grounding resistance limits fault current so that overcurrent protection tripping in MV level is avoided. Yet, even in compensated grids there is always a remaining fault current since complete compensation is avoided. Based on these insights a knowledge based method for fault detection and classification has been designed that works for all common neutral point treatments such as isolated, compensated and grounded [8]. It is extended by an impedance-based method for fault localization with reduced parameterization effort as described above. In the context of prototyping a fault detection, identification and localization scheme (FDIL) has been implemented on a dedicated hardware platform. In order to evaluate the hardware prototype's functionality, a real-time digital simulator (eMEGA-sim from OPAL-RT) has been used

(Figure 6). The real-time environment offers benefits of powerful Python programing language and rapid grid modeling with MATLAB/Simulink©.

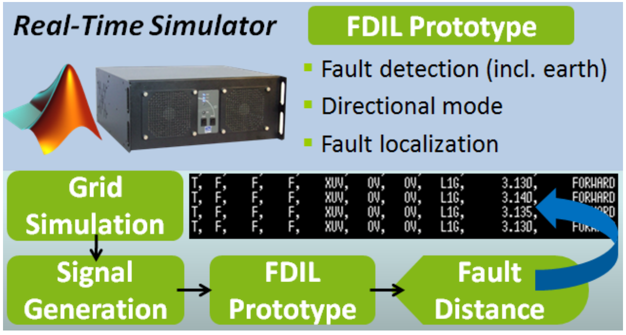

Figure 6: Online type testing process

The prototype's characteristic behavior has been tested under dynamic grid simulations of isolated, compensated and grounded neutral point treatment with a simulation step size of Δt=50µs. Thereby the five common fault types have been simulated under variation of their fault location along the distribution line of star topology. For further analysis purposes the simulated three phase currents and voltages as well as the processed FDIL-results have been recorded continuously by the prototype. While the disturbance recording scheme provides very good results for short circuit localization with accuracy better than ±10%, the same accuracy can't be reached for close earth faults. However, the accuracy for earth fault localization improves with the fault's distance and can reach ±10% for more distant fault locations in simulation. Thus, the localization results can help to optimize the navigation of technical staff during fault occurrence.

SIMULATION OF FAULT CLEARANCE PROCESS WITH FAULT LOCATION

Exemplary Grids

For simulation purposes several representative feeders for rural and urban MV grids have been modelled based on prior analysis of real MV grids. The feeders differ in total length, line type, number of secondary substations and number of branches to cover the above mentioned fixed grid factors. It is assumed that there are distributed generation units connected to the grid. Thus, common short circuit indicators without directional indication will no longer provide useful information and are therefore not included in the following illustration. Figure 7 shows two exemplary feeders of a rural MV grid as well as different equipment for fault location and clearance.

In order to determine the benefit of the fault locating functionality in the fault clearance process three scenarios have been simulated. The scenarios shall in part cover the flexible grid factors and their influence. First the fault clearance time was calculated only with consideration of remote indication (ri). Second in addition to remote indication remote switching (rs) was integrated at key secondary substations within the feeder. Third the remote switching functionality was paired with a fault locating (fl) functionality in one central secondary substation in the feeder.

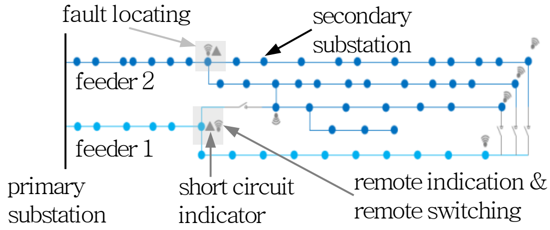

Figure 7: Exemplary Rural MV Grid

Simulation Algorithm

In order to evaluate the benefits of these features an algorithm has been developed to simulate the fault clearance process considering all aspects of a common fault clearance procedure as well as the fault location determination. The algorithm is based on [2] and enhanced by the fault location functionality taking into account its previously described accuracy.

In the algorithm a fault on every line and for every substation will be simulated. At first the protection area in which the fault occurred will be determined. Afterwards the protection area will be separated from the main by circuit breakers. Next the fault clearance process will be started. Remote indication and remote switching will be used to resupply as many customers as possible. Thereafter the available information will be used together with the previously defined search method to simulate the actions of the technical staff. At the end of each fault simulation the fault clearance time for every secondary substation can be determined. From these values a mean fault clearance time over all customers can be calculated. For the evaluation of the simulations a graphic representation was chosen, which shows the distribution of all the mean fault clearance times. For scenarios 1 and 2 the optimal search method is used. In scenario 3 the sequential search is chosen since it is most likely to be used in combination with the fault locating functionality. The search starts at the fault location determined by the new functionality.

Simulation Results

The results of the three scenarios for the exemplary grids are illustrated in figure 8. The results of these simulations show that the fault clearance time can be reduced by integrating additional equipment like remote switching and fault locating into the feeders. The amount of the reduction depends on different aspects. In case of the integration of remote switching the mean fault clearance time can be reduced because parts of the feeder, which can be determined as not faulty, are resupplied by remote switching operations in several minutes. Afterwards the fault will be located by the technical staff within the remaining part of the feeder.

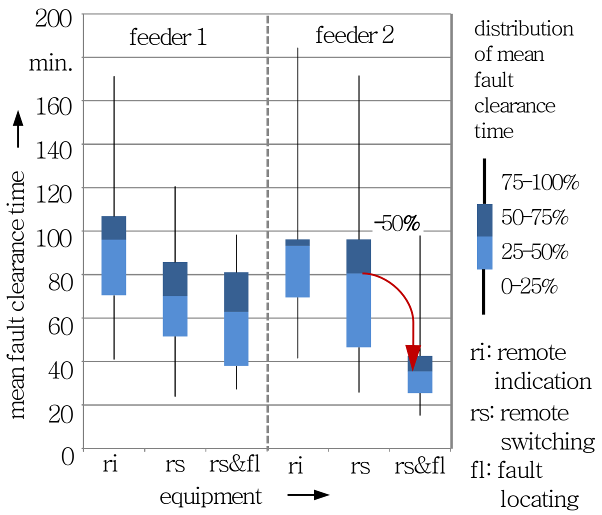

Figure 8: Mean Fault Clearance Time

As can be seen in the results for the first feeder the fault clearance time can be reduced significantly because a high percentage of the customers can be directly resupplied by remote switching operations. In case of feeder 2 the mean value of the mean fault clearance time also decrease, but the amount of the reduction is less than for feeder 1 because of the more complex structure of the lower part of feeder 2. This structure requires a lot more effort in the fault locating process even though the feeder is separated into 3 parts instead of 2 by remote indication and switching. The fault locating functionality leads in this feeder to a significant reduction of 50% of the mean value of the mean fault clearance time compared to a setup with only remote switching. Especially faults in the lower part of the feeder with its complex structure can be located faster by the technical staff. Since the amount of customers affected by these faults is high compared to the total number of customers in feeder 2 the effect on the fault clearance time is significant. In feeder 1 the installation of fault location functionality decreases the mean value of the mean fault clearance time only by a few percent. The reason for the small decrease lies in the simple structure of the feeder and the low number of secondary substations in the 2 parts of the feeder.
Overall it can be concluded that the amount of the reduction is depended on the structure of the feeder, its length and the number of secondary substations.

CONCLUSION & OUTLOOK

The tests of the new features for a novel intelligent secondary substation design show that fault type and fault location can be determined with a sufficient accuracy to improve the fault isolation and power restoration process. The simulation results for different grid scenarios prove that the fault clearance time can be significantly reduced compared with a fault clearance process based on short circuit indicators and partly remote switching. Especially in grids with a complex structure consisting of several branches in one feeder and a high number of secondary substations within the area defined by the fault indicators the fault locating functionality can reduce clearance time.
Overall it can be stated that the results of this project enable system operators to identify potential use cases of the new features for an intelligent secondary substation and improve both effort and reliability at the same time.
For future research works the rise of dominating harmonics in fault current signal and the impact of IVDGs' dynamic grid support should be analyzed to assess their influence on the fault clearance process.

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