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Progresses and Prospects for Fault Processing in Distribution Grids

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Abstract
Progresses in fault processing technologies for electrical power distribution grids are overviewed, including progresses in local, distributed, and centralized intelligence-based interphase short circuit fault location and isolation, and service restoration, as well as progresses in single-phase-to-ground fault processing. The prospects for fault processing technologies in electrical power distribution grids are discussed.

Keywords
distribution grids, overview, prospects, interphase short circuit fault, single-phase-to-ground fault, fault location, fault isolation, service restoration, relay protection, distribution automation system (DAS), feeder automation (FA)

1.1 Introduction

According to statistics, failures in distribution grids cause more than 85% of outages due to faults. Thus, fault processing technologies for distribution grids are of great importance in improving service reliability.

Faults can be divided into two categories: interphase short circuit faults and single-phase grounding faults. These faults can then be further divided into permanent and temporary faults.

Fault Location and Service Restoration for Electrical Distribution Systems, First Edition. Jian Liu, Xinzhou Dong, Xingying Chen, Xiangqian Tong, Xiaoqing Zhang and Shiming Xu.

As for earth-neutral systems, fault processing technologies for interphase short circuit faults and single-phase grounding faults are the same. However, for neutral ineffective grounding systems, such as those in China, systems are allowed to operate under single-phase grounding fault conditions for no more than 2 hours in order to ensure service reliability. The position of a single-phase grounding fault should be located and repaired in time to avoid causing an interphase short circuit fault. Interphase short circuit faults should be cleared immediately and as many affected healthy regions should be restored as quickly as possible.

The fault processing technologies can be classified into three types: (1) fault processing based on local intelligence, (2) fault processing based on distributed intelligence, and (3) fault processing based on centralized intelligence.

Fault processing approaches based on local intelligence were the earliest technologies in which neither a communication system nor master station is needed. The decision is made based solely on the information collected at the local position. Fault processing approaches based on local intelligence are still used today and include relay protection, automatic reclosing control, and backup automatic switching control. They have the advantage of fast speeds. However, the coordination of over-current protection is rather difficult in some cases, such as the feeder trunk in an urban area. Automatic reclosing control is suitable for feeders with overhead lines. Backup automatic switching control may switch the load to the backup power supplying route in several seconds, but it is only effective for loads with more than one power supplying route.

Feeder Automation (FA) based on recloser and voltage-delay type sectionalizers, reclosing with a fast over-current protection mode, and the fast healing approach based on neighbor communication, are three typical technologies of fault processing approaches based on distribution intelligence. FA based on recloser and voltage-delay type sectionalizers was invented by Japanese engineers in the 1970s and has been successfully used in Asia for several decades, but it needs reclosing twice. Reclosing with the fast over-current protection mode is an improved approach that only needs reclosing once, but requires circuit breakers instead of the former's load switches. Both FA based on recloser and voltage-delay type sectionalizers and reclosing with a fast over-current protection mode do not require communication systems and the whole feeder must undergo a period of outage. With the fast healing approach based on neighbor communication, the fault area can be located and isolated immediately and the healthy areas are hardly affected by the fault. However, high speed communication and reliability are both needed. Besides, the sectionalizing switches should be circuit breakers.

The typical technology of fault processing based on centralized intelligence is the Distribution Automation System (DAS), which consists of a master station, some sub-working-stations, a large number of Feeder Terminal units (FTU), and the communication system. Since global information can be collected, the fault location area of DAS can be much smaller and the service restoration schemes may be optimized. But DAS based fault processing needs a rather long time period, typically several minutes.

With the increasing of the amount of Distribution Generations (DG) in distribution grids, fault processing technologies coping with such challenges have been achieved.

In this chapter, the progress in fault processing technologies will be overviewed, and included is most of the literature written by the authors, which is also included in the following chapters of this book.

1.2 Progresses in Local Intelligence-Based Fault Processing

Although relay protection technologies have been used in electrical power systems for a long time, the coordination of relay protection is rather difficult in some distribution grids, such as short length urban feeders.

In many utilities, one over-current relay protection is coordinated with one or two fuses. Even on the output circuit breaker of a feeder in the substation only one over-current protection is installed. Coordination and setting of three-section overcurrent protection is investigated in References [1]–[4]. It is pointed out in [5] that interphase short circuit currents along the sectionalizing switches of a short length urban feeder are almost the same, thus the coordination of three-section overcurrent protection is difficult. An approach of time-delay coordination of the over-current relay protection scheme is suggested, in which outage on the trunk can be avoided in case of branch fails and outage on the branch can be avoided in the case of lateral fails. Four modes of hybrid schemes of three section overcurrent protection and time-delay over-current coordination are proposed in [4], which are commonly used in Chinese utilities. The coordination of over-current protection with FA based on recloser and voltage-delay type sectionalizers is described in [6].

Automatic reclosing control and backup automatic switching control also have a rather long history of application. Reference [7] describes a scheme suitable for switches on the branches or laterals of a feeder. Reference [8] describes a coordination scheme of backup automatic switching control with DAS for an area requiring high service reliability.

The local intelligence-based fault processing technology will be detailed in Chapter 2.

1.3 Progresses in Distributed Intelligence-Based Fault Processing

A family of switches with distributed intelligence are described in Reference [9] including FA based on recloser and voltage-delay type sectionalizers, FA based on coordination of reclosers, and FA based on recloser and over-current counting type sectionalizers.

FA based on recloser and voltage-delay type sectionalizers invented by the Toshiba Co. is the most widely used technology. Hai and Chen imported the technology from Japan to China and set up production lines for mass manufacture. The basic principle of FA based on recloser and voltage-delay type sectionalizers is described in References [10]–[12]. The appropriate setting of the recloser and voltage-delay type sectionalizers is the critical application problem, which is investigated based on a hierarchical model in Reference [13] and a program is also used to calculate the setting values for arbitrary grid topologies is developed.

Reclosing with a fast over-current protection mode is another distributed intelligence-based fault processing technology, the basic principle of which is described in Reference [14]. But the method in [14] has some limitations, such as long restoration time for temporary faults and enlargement of fault isolation area due to overload. Improvements are made in [15]. The duration time of temporary fault restoration is considerably reduced by adding a time delay mechanism to the tripping procedure of sectionalizers in the case of out-of-voltage. The drawback of enlarging the outage area due to overload is avoided by introducing an out-of-voltage lock mechanism into sectionalizers and loop switches, respectively. A linear planning approach is also proposed for optimizing the setting values in [15].

The approach of FA based on recloser and voltage-current mode switches is described in [16], which can be regarded as the combination of FA based on recloser and voltage-delay type sectionalizers and reclosing with a fast over-current protection mode.

These distributed intelligence-based fault processing approaches do not need communication systems and have played a great role, but they have some drawbacks, such as setting values should be adjusted in the field when the operation mode is changed.

Some distributed intelligence-based fault processing approaches with communication systems are published in [17]–[20]. A fast healing approach based on communication with GOOSE among the adjacent FTUs is described in [17], which is the typical scheme for distributed intelligence-based fault processing approaches with communication systems. The basic approach in [17] is improved in [18], in which both temporary fault and permanent fault can be located and isolated immediately without override tripping and it works well even in cases where a few switches fail to control. Other progresses also requiring communication systems are described in [19]–[20].

The distributed intelligence-based fault processing technology will be detailed in Chapter 3.

1.4 Progresses in Centralized Intelligence-Based Fault Processing

Centralized intelligence-based fault processing is the core technology of centralized intelligence-based distribution automation systems, which is always a hot topic of research, and there have been many achievements.

1.4.1 Fault Location

A unified matrix based algorithm for fault section detection and isolation in distribution systems is put forward in [21], which is improved in [22]. But the matrix based methods require both space and long calculation times for large scale distribution grids.

A fault location approach based on a directed graph is proposed in [23] without calculating a matrix. In [24], a large scale distribution grid is divided into many small scale connected systems consisting of some connected feeders and a fault may be processed in its corresponding connected system, thus the space and calculation time can be greatly reduced no matter how large scale the distribution grid is.

In [25] a hierarchical model based algorithm of fault section diagnosis for distribution networks is suggested. A fault location method based on pattern identification is described in [26]. A multi-objective distribution network restoration using an heuristic approach and a mixed integer programming method is proposed in [27]. A multi-agent based fault processing approach is described in [28].

In the field of robust fault location in case of insufficient information, there have been many achievements, which make the fault location program more usable in practice. In [29] and [30] a genetic algorithm is introduced into fault location to improve its robustness. A data mining approach based on the combination of a rough set with a neural network is described in [31] to solve the fault section identification problem in cases of insufficient information. A fuzzy reasoning approach for robust fault location in a distribution automation system is introduced in [32] and [33]. Uncertainty reasoning approaches based on Bayes probability theory for fault location in distribution grids are put forward in [34]–[37]. An integrated intelligent service restoration system for a distribution network with an auto-learning fuzzy expert system is described in [38].

As for the field of fault location for distribution systems with Distributed Generation (DG), many progresses have been reported. In [39] and [40], the influence of Distributed Generation (DG) on relay protection is investigated. The influence of DGs on types of synchro generator, asynchronous generator, and invertor on the short circuit current of distribution grids and the corresponding analyses are investigated in [41]–[43]. In [44], the suitable range of the traditional fault location approach based on over-current information for distribution systems with DGs is investigated, showing that the suitable range is rather wide, especially for overhead lines. In [45], an improved fault allocation process is proposed for overhead line-based feeders, in which the reclosing procedure and escaping DGs in fault situations are coordinated.

1.4.2 Fault Isolation and Service Restoration

Heuristic approaches are widely used to solve service restoration problems very quickly. In [46], a multi-objective distribution network restoration approach using an heuristic approach and mixed integer programming method is put forward. In [47], an optimal restoration algorithm of distribution systems using dynamic programming is described. In [48], the priority of customers is considered in service restoration. In [49], service restoration is improved through load curtailment of in-service customers. An approach to location and restoration of a short circuit with two phases grounded to the earth in non-effectively earthed distribution systems is described in [50].

Modern optimization methods [51]–[58], such as genetic algorithms, evolutionary algorithms, NSGA-II, expert-systems, Tabu searches, and so on, have been introduced into the service restoration field, which improve the restoration performance, but calculations are greatly increased.

To improve power supplying capacity, modeled topologies are built in many countries, such as three-sectioned and three-linked grids, three-supplying and one back-up grids and a 4 × 6 connection grids. But the advantages of modeled topologies may be realized by the corresponding service restoration schemes, which are described in [59] and [60].

Service restoration to avoid a breakdown over a large area – in cases of one or more bus loss of voltage due to a fault on the bus, substation, transmission line, or a transmission tower collapse – is also investigated. In [61], a mathematical algorithm for service restoration to avoid a large area breakdown is put forward. In [62] and [63], a Tabu search-based algorithm of restoration for large area blackout is described, which may form more complicated index and constraint conditions than the approach in [61]. A switching operation sequence management method is also suggested in [63]. A CSP-based model and algorithm of service restoration for large area distribution system blackout is introduced in [64]. An Agent-Environment-Rules (AER) model-based algorithm of service restoration for large-area distribution system blackout is described in [65].

Centralized intelligence-based fault processing technology will be detailed in Chapter 4.

1.5 Progresses in Single-Phase Grounding Fault Processing

A single-phase-to-ground fault is a kind of fault commonly happens in a power distribution system. Depending on the different types of neutral grounding in a power distribution system, the fault characteristics and effects are different, which require different solutions.

For single-phase-to-ground faults in power distribution systems with effective neutral grounding, zero-sequence over-current protection can detect the fault correctly. However, if it is a high impedance fault, which occurs frequently in power distribution systems, the fault characteristics are not obvious and over-current protection may malfunction. References [66]–[68] discuss high impedance faults in power distribution systems with effective earthing, zero-sequence inverse time over-current protection and third harmonic current based protection, which lays the foundation for high impedance fault detection.

A single-phase-to-ground fault generated zero sequence current is small in non-earthed power distribution system, which requires a protection-issued alarm signal, sometimes the trip signal. In order to compensate for the capacitive current when a single-phase-to-ground fault occurs, the Peterson coil is installed at earth, which may minimize the loss but makes it more difficult to protect the single-phase-to-ground faults in such a system.

For a single-phase-to-ground fault in power distribution systems with ineffectual earthing, reference [69] studies a single-phase-to-ground fault feeder selection using a zero-sequence current in all feeders radiating from the same bus bar and proposes a feeder selection method based on all feeders' current amplitudes and phase comparison. References [70]–[72] analyze single-phase-to-ground fault generated traveling waves in a fault superimposed network and verify that the initial traveling waves generated by single-phase-to-ground faults are independent of the method of neutral grounding, which presents a novel approach to solving the problem of single-phase-to-ground fault feeder selection in power distribution systems with poor earthing and a novel technology based on traveling waves.

Up to now, current traveling wave analysis based on single-phase-to-ground fault feeder selection in non-earthed power distribution systems have been widely used in the field. Traveling wave information during a permanent fault is recorded, which lays the foundations of research of fault prevention. References [73] and [74] propose the idea of single-phase-to-ground fault prevention based on traveling wave analysis. The idea can prevent faults based on fault precursors.

After a single-phase-to-ground fault occurs, accurate fault location can help maintenance staff to arrive at the fault point to remove the fault and recover power supply, which can improve power supply reliability but also reduce the workload for the line patrol and improve efficiency. References [75] and [76] analyze single-phase-to-ground fault generated initial traveling waves and present single-phase-to-ground fault location based on the time difference between single-phase-to-ground faults generated at the initial line module traveling wave and initial zero module traveling waves, which makes it possible to locate single-phase-to-ground faults in non-earthed power distribution systems.

Chapter 5 introduces single-phase-to-ground fault types and their protection strategies, focuses on high impendence fault in power distribution system with earthing through resistance and single-phase-to-ground faults in ineffective earthed power distribution systems, analyzes high impendence fault detection methods, and presents single-phase-to-ground fault feeder selection, and single-phase-to-ground fault protection, prevention, and location.

1.6 Prospects

Centralized intelligence, distributed intelligence, and local intelligence-based fault processing approaches have their respective advantages and limitations. Fault location and restoration approaches based on the coordination of centralized, distributed, and local intelligence are promising, in which the performance of fault isolation and restoration for distributed grids can be greatly improved. The coordination of centralized, distributed, and local will be detailed in Section 6.2.

The simpler a system, the more reliable it is. From another point of view, the fewer the terminal units, the more economical the system is. The planning approach to determine the amount of various kinds of terminal units to meet the reliability of service requirement is important, which will be detailed in Section 6.3 (Chapter 6).

Verification of fault processing performance of the centralized intelligence-based DAS, local intelligence-based relay protections, and distributed intelligence-based DAS is significant in guaranteeing the construction quality of DAS. The coal technology is the test technique, which will be detailed in Section 6.4.