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Power system protection with digital overcurrent relays: A review of non-standard characteristics

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ABSTRACT

Power systems are experiencing structural changes induced by the integration of distributed generation units and the operation of microgrids. This transformation has posed new challenges in well-established power system practices and especially on the design and coordination of protection systems. At roughly the same time, technological advancements in protective equipment have constituted the basis for the emergence of digital overcurrent relays which enable alternative approaches to standard protection schemes. As a consequence, recent studies aimed to provide a reliable protection system capable of responding to the modern power system conditions by propounding the utilization of non-standard characteristics (N-SCs), as opposed to the standard characteristics, i.e., characteristics that are not described in the currently used standards. Despite the fact that the effects of the aforementioned changes on the protection of power systems have been thoroughly analyzed in the technical literature, the requirements for devising N-SCs have not been discussed in detail so far. To address this gap, this paper classifies and analyzes the related studies with respect to their potential advantages and disadvantages. Moreover, based on the literature review, recommendations for further research in this area and a list of the requirements for devising robust non-standard relay characteristics are presented.

1. Introduction

1.1. Motivation

The evolution of power systems has accelerated in the recent years. In conventional power systems, planning and operation may be achieved in a central manner because the bulk amount of power is generated by central power plants, and is then transferred to consumers through transmission and distribution system. However, due to several reasons such as the depletion of fossil fuel reserves, growing concerns about the climate change, the conventional power systems have been exposed to the proliferation of distributed generation (DG), which allows power to be generated in small portions and to be injected at various location in power system [1]. In addition to the increasing number of DG connections, the recently introduced concept of microgrids (MGs) brings about extra challenges, especially when considering that power systems are on the eve of islanded MG operation [2].

Apart from the challenges induced by the integration of DG, power systems are likely to be exposed to a more dynamic way of operation. The constantly decreasing switching costs of circuit breakers will probably provide an opportunity for more frequent reconfiguration of power systems in the near future [3]. In addition to that, the growing importance of engaging individual consumers in electricity market operations will possibly enforce more dynamic changes in the topology of the power system with the purpose of loss minimization or producer-consumer interaction [4].

The aforementioned evidence suggests that the power system of the future will be more dynamic compared to the current grid structure. The main features are listed as follows:

- Increased penetration of DG technologies,
- integration of MG with the potential for operating in islanded mode,
- dynamic reconfiguration for operational purposes,
- the significant role of electricity market operations.

These features raise concerns as regards the suitability of the existing perceptions of protection, stability, power flow management, etc., which should be evaluated in terms of their ability to reflect and

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accommodate these features.

One of the primordial challenges faced by power systems due to the changing structure is the protection issue because of the change in load and fault currents. The conventional approach to power system protection which is based on both the calculated load and fault currents is no longer valid under varying topology. Taking into account that the distribution systems have many branches possibly with different kinds of protective equipment, and also, that distribution systems are prone to structural changes such as integration of DG, or MG operation, it may be deduced that the conventional protection systems are likely to malfunction in distribution system applications. As a consequence, questions have been raised about protection systems, especially for distribution systems [5].

The most common type of protection apparatus used in distribution systems is the overcurrent relay (OCR). An OCR is a device that measures the current which passes through it and determines whether or not to send a signal to open a circuit breaker [6]. There are several types of relays such as distance relays, directional relays, and, definite time OCRs. However, inverse-time OCR is the most preferable type of protection relay in the distribution systems because of the grading time characteristic that allows some specific loads to draw higher currents for a short period of time [7]. As the name implies, the operating time (OT) of the inverse-time OCRs is determined inversely proportional to the fault current seen by the relay. There are both digital and electromechanical OCRs. Until two decades earlier, the market was dominated by electromechanical OCRs because they were inexpensive and their performance was well-known as a result of the many years of application. However, digital OCRs are now more likely to replace with the electromechanical OCRs in the following years due to reasons listed below [8,9]:

- *Economically competitive:* their cost is as low as electromechanical OCRs.
- *Increased reliability:* they are able to avoid malfunction operation by detecting and reporting internal problems in the relay itself.
- *Smart grid natives:* their digitalized nature makes them compatible with the smart grid concept.
- *Multifunctionality:* they are able to perform additional tasks such as measurement voltage and current values along with protection.

The protection of distribution systems was thoroughly achieved by using standard characteristics until recent structural changes. However, standard characteristics (SCs) were designed to protect the conventional power systems in which the power flow is unidirectional, and are therefore prone to threats arising from new concepts such as power systems including DG, MG operation, and, more dynamic reconfiguration. The main reason that renders SCs obsolete is the bidirectional power flow when DGs are present. Moreover, in the new generation of power systems, significant fault characteristic changes may be observed due to the MG operation. Yet, as a result of inexpensive switching cost, power system operators may want to increase reconfiguration frequency of the system in order to decrease power system losses or meet the electricity market demands. These reasons have pushed the researchers to investigate other protection schemes, which are referred to as non-standard characteristics (N-SCs) in the rest of the paper, as opposed to the standard ones [10]. As a consequence, a considerable amount of effort has been devoted to making protection systems robust against the aforementioned changes by using N-SCs. Some of the remarkable attempts aimed to tackle the technical issues raised by new generation of distribution systems used N-SCs which are now more likely to realize by the digital relays [11–13] owing to recent developments. It is quite common to program the digital relays to reflect the same characteristic with their electromechanical counterparts concerning the coordination with non-programmable downstream devices such as fuses or reclosers [14]. Nevertheless, this situation might change in the near future due to the evolving distribution systems, especially the ones fully equipped with numerical relays [15].

1.2. Relevant literature

Several studies which highlight the recent challenging developments on protection issue have been presented in the literature. The review study presented in [16] investigated fault characteristics of both AC and DC distribution systems. The DG effect on protection along with possible protection techniques as the solution were also reported. However, it was not intended to present a review about N-SCs. Manditereza et al. [17] presented an accurate synopsis of DG effects on protection coordination. The study argued that conventional protection systems suffer from DG connection while offering the use of different characteristics instead of standard ones. Nonetheless, the research tended to focus on listing the general solutions rather than on the development of N-SCs. Another comprehensive review which presented the protection coordination techniques both in systems with and without penetration of DG, was carried out in [18]. The study covered the protection methods for radial distribution network as well as subtransmission systems while addressing the arising protection issues when DG units are connected to the system. Nevertheless, giving details about the construction of a new protection characteristic was out of the scope of this paper. Apart from these studies, several attempts have been made to address the MG protection issue. The general principles of MG protection along with the impact of DG was reviewed in [19,20]. Yet, another study addressed the challenges in the coordination between different protective equipment in MGs including DG [21]. Also, methods dealing with the challenges in coordination strategies of MGs were summarized in [22]. Last but not least, the fault protection solutions were thoroughly assessed particularly for ungrounded AC MGs in [23] and for uni-grounded AC MGs in [24]. These studies addressed the protection issues caused by MG operation, nevertheless, none of these studies aimed to cover N-SC specifically.

1.3. Contributions and organization of the paper

The aforementioned studies provide evidence that there are a growing urgency and interest in the topic of the coordination of protection in distribution systems that are undergoing transformations. The focus of these studies was on capturing the current picture of the protection systems and suggest solutions. However, the utilization of N-SCs as a remedy to these challenges has not received much attention. As a result, there is a gap in the literature regarding the key elements of devising a N-SC which is within the scope of this study. More specifically, the contribution of this study is threefold:

- It summarizes the recent research that is aiming to explore opportunities that have emerged because of the advancement of digital OCRs in conjunction with the development of N-SCs.
- It identifies gaps in the technical literature and proposes future research directions.
- It compiles the basic features that constitute a robust characteristic and should be taken into account by researchers who would like to deal with the protection problem.

The remainder of the paper is organized as follows: Section 2 provides basic knowledge of conventional protection philosophy while addressing the recent impacts on it. Section 3 introduces standard relay characteristics published by the IEC and the IEEE. Section 4 summarizes the studies which aimed to use N-SCs for power system protection. It is then presented in Section 5 that the recommendations for future studies. Finally, conclusions and final remarks are presented in Section 6.