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An interval type-2 fuzzy logic based strategy for microgrid protection

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ABSTRACT

The concept of microgrids has been introduced to facilitate the integration of the distributed energy resources (DERs) into distribution networks in a more economical, reliable and environment-friendly manner. One of the critical challenges associated with microgrids is devising an appropriate protection strategy. This is because the fault current level continuously varies owing to the existence of DERs and to the fact that the microgrid can operate in grid-tied and islanded modes. This paper proposes a new protection strategy for microgrids using an interval type-2 fuzzy logic system. The proposed strategy considers various uncertainties associated with faults and employs two different fuzzy systems to detect, classify, and locate the faults in microgrids. The phase angle between superimposed modal voltage and modal current is used as an input to the fuzzy system designed to identify the fault direction. The significant feature of the proposed strategy is that it can protect the microgrid after a single-phase tripping event. To validate the effectiveness of the proposed strategy, we have performed extensive simulations using MATLAB/SIMULINK. The simulation results show that the proposed strategy can detect, classify, and isolate various faults in the microgrid. Moreover, the strategy also provides backup protection in case of failure of the primary protection.

1. Introduction

One of the most significant changes that a power system is experiencing is the penetration of distributed energy resources (DERs) into distribution networks. A microgrid (MG) integrates the DERs in an efficient, cost-effective, and eco-friendly manner. An MG is a small-scale sustainable electric distribution system that contains DERs, energy storage systems, and controllable loads. MGs can be connected in parallel with the main grid or be operated independently in the islanded mode [1,2]. MGs are expected to improve the continuous operation of electrical power systems, reliability, and power quality as well as reduce power losses [3]. Nevertheless, the operation of MGs is associated with some major challenges from protection and control aspects [4,5].

The main challenge associated with microgrid protection arises owing to (1) bidirectional power flow, (2) the existence of looped feeder, and (3) reduced fault current level in islanded mode. In the islanded mode, the existence of DERs in the MG can cause non-directional current flows. Moreover, the fault currents produced by inverter based DERs are relatively small, approximately 2–3 times their rated current [6]. Therefore, traditional overcurrent protection based on the assumption of high fault current is ineffective to protect the MGs in the islanded mode. In particular, sensitivity loss of overcurrent relays, blinding of overcurrent protection, false tripping or sympathetic tripping of overcurrent protection, and protection coordination problems can occur in the MG protection system. On the other hand, the fault currents are comparatively higher in the grid-tied mode owing to the fault current contribution from the utility grid. Although conventional overcurrent relays can be used to protect the grid-tied microgrids, the presence of DERs changes the magnitude and direction of the fault current and may compromise the coordination among relays [7,8]. A protection strategy must guarantee secure, adaptable, and reliable working of MGs in both modes of operation.

Various MG protection strategies have been designed and reported in the literature [9,10]. In [11], a central controller-based online method was presented to calculate and update the settings of adaptive overcurrent relays by the change in the mode of the MG. The scheme required complex calculation each time when the MG changed its mode of operation. In [12], a multi-agent system was suggested to update the relay settings adaptively. The scheme considered various wind DERs connection and disconnection scenarios in the grid-tied mode of operation only. An intelligent relay with several elements was developed to protect the islanded MG in [13]. The strategy was applied on radially configured MGs only. In [14], differential relays with data mining algorithms were used to protect inverter based islanded MGs only. The authors in [15,16] developed time-frequency based energy differential protection schemes to protect the MGs. A differential protection scheme

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based on superimposed sequence components to protect grid-tied MGs was described in [17]. The authors in [18] developed a hybrid adaptive and differential protection scheme to protect the microgrids. Moreover, a communication bit error rate based pre-emptive switching procedures were developed for a seamless transition from adaptive protection to differential protection. The scheme was uneconomical due to extensive communication infrastructure and two different protection relays. In [7], superimposed sequence components of current along with superimposed reactive energy was presented to detect and locate various kind of faults in MGs. The authors in [19] presented a communication-based over-current and under-voltage relays to protect the MGs in grid-tied and islanded modes respectively. The scheme required an additional element (grounding transformer) inside the MG because zero sequence current was used to determine the direction of fault. In [20], mathematical morphology was suggested to extract the initial traveling wave to protect islanded MGs. The performance of the suggested scheme was reliant on high sampling frequency and accurate signal synchronization, which is unpractical because of the absence of economical DSP hardware. In [21], wavelet packet transform (WPT) was presented to extract high-frequency components of current and voltage waveforms to protect the radially configured MGs only. Moreover, the strategy employed high-pass filter for WPT realization. In [22], data mining was applied to the features extracted by wavelet transform to detect different faults in the islanded MG. In [23], energy storage devices and super-capacitors were used to increase the level of the fault current in islanded mode. Fault current limiters were presented to reduce the effect of DERs on fault current in [24]. High short-circuit ratings of devices were required, and hence these schemes are costly. In [25,26], phasor measurement units have been used to extract and communicate the current and voltage phasors to a central processing unit (CPU). The CPU performed the protection tasks, and the trip signal was issued to the appropriate circuit breaker remotely through communication. These schemes rely on extensive communication infrastructure and are prone to communication failure. The authors in [27] have suggested switching the converter control from droop to current control in case of faults in the MGs. The output current of each converter was monitored for fault location. The method was applied to islanded MGs only.

The aforementioned strategies protect the MGs in one mode either grid-tied or islanded mode. The strategies, which can protect the MGs in both modes, do not consider the uncertainties associated with faults. This paper presents a new protection strategy for MGs using an interval type-2 fuzzy logic system (IT2FLS). The proposed strategy considers various uncertainties associated with the MG faults. Two different fuzzy systems are developed to detect, classify, and locate the faults in MGs. The paper also attempts to modify the conventional phase directional scheme to determine the direction of faults. Extensive simulations are executed using MATLAB/SIMULINK to analyze the efficacy of the presented scheme. Simulation results validate that the presented strategy detects, classifies, and locates all types of faults in a very short time, which is less than one cycle for the test system considered in this paper. The main contribution of this study are as follows:

- The study considers various uncertainties associated with faults while developing a protection strategy for the MG.
- The proposed strategy also provides backup protection against all types of faults in case of malfunction of the primary protection.
- The scheme can operate after single-phase tripping events.

The rest of the paper is organized as follows. Section 2 discusses the uncertainties associated with faults. The background of IT2FLS is presented in Section 3. Section 4 discusses the proposed protection strategy. Section 5 describes the test system and the simulation results. Finally, the paper is concluded in Section 6.

2. Uncertainties associated with microgrid protection

The faults in an electrical power system are entirely random events and affect the system variables including voltage and current. The severity of the effect depends upon various factors, including fault location, fault resistance, fault type, and fault inception angle. There are always uncertainties associated with these factors, which are unpredictable and unavoidable. The level of these uncertainties and their impact affect the performance of protection schemes. The effect becomes more severe in MGs because of intermittent nature of DERs, various operating scenarios, and different fault current level in each scenario. Consequently, the protection schemes with a standard deterministic decision-making or fixed threshold may not perform satisfactorily for all conceivable operating conditions. Therefore, these uncertainties should be considered while designing a protection scheme for MGs.

3. Background of interval type-2 fuzzy logic system

In a fuzzy logic system, numerical or linguistic uncertainties can produce rule uncertainties. The IT2FLS can handle these uncertainties. The membership functions and the output process in the IT2FLS differ from their counterparts in the type-1 fuzzy system while the rest is the same [28]. Fig. 1 shows the basic schematic of an IT2FLS. An IT2FLS consist of a fuzzifier, an inference engine, a fuzzy rule base, and an output processor, which contains a type reducer and a defuzzifier [29]. The following subsections explain the details of each block.

3.1. Fuzzifier

The fuzzifier maps the crisp input vector $(x_1,x_2,...,x_n)^T$ into an interval type-2 fuzzy set. Unlike type-1 fuzzy logic, where the membership functions have a crisp number, the membership functions in the IT2FLS are themselves fuzzy in [0,1]. In the case of faults, the information is not sufficient to map the membership functions precisely; hence, IT2FLS is useful to incorporate the uncertainties in the variables.

3.2. Fuzzy rule base

The fuzzy rules are linguistic If-Then constructions with multiple antecedents and one consequent. Each rule provides a type-2 relationship between n inputs in the input space $x_1 \in X_1 ... x_n \in X_n$ and one output $y \in Y$. The kth rule of the IT2FLS can be represented as [30]

$$\textit{If } x_1 \textit{ is } F_1^k \text{ and } x_2 \textit{ is } F_2^k \text{ and} ... x_n \textit{ is } F_n^k \quad \text{than } y^k = G^k, \quad k = 1,2...,N \tag{1}$$

where F_i^k represents the IT2FLS of the input state i of the kth rule, $x_1, x_2, ..., x_n$ represent the inputs, G^k is the output of the IT2FLS for the kth rule and N is the number of rules.

3.3. Fuzzy inference engine

The fuzzy inference engine combines the fuzzy rules and maps a

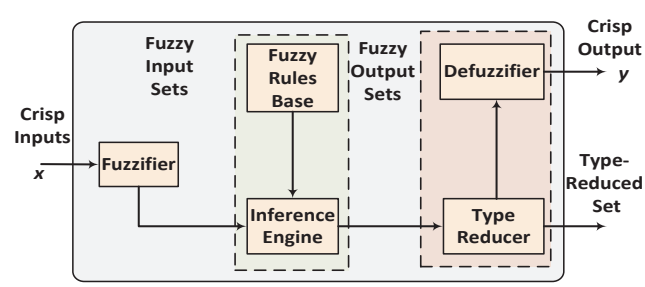

Fig. 1. Schematic of the interval type-2 fuzzy logic system.