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Fast fault section estimation in distribution control centers using adaptive genetic algorithm

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ABSTRACT

This paper presents a novel mathematical model for fast fault section estimation in a Distribution Control Center (DCC). The mathematical model is divided into two parts, namely: (1) a protection system operations model based on operator's heuristic knowledge of the protection system performance and (2) an optimization Unconstrained Binary Programming (UBP) model based on parsimonious covering theory. In order to solve the UBP model, an Adaptive Genetic Algorithm (AGA) using crossing over and mutation rates that are automatically tuned in each generation is proposed. An Alarm Probabilistic Generator Algorithm (APGA) is developed and a real four-interconnected distribution substation system is used to test exhaustively the approach. Results show that the proposed methodology is capable of performing fault section estimation in a very fast and reliable manner. Furthermore, the proposed methodology is a powerful real-time fault diagnosis tool for application in future Distribution Control Centers.

Introduction

The task of fault detection, isolation and network restoration (FDIR) may be very complicated in a DCC environment mainly in emergency conditions, where a large simultaneous flow of information from several monitored substations may overwhelm the operator. Also, the FDIR task becomes increasingly complex either in multiple fault scenarios or in situations presenting protective devices malfunction. Therefore, advanced Distribution Management Systems (DMS) must have computational tools to provide fast and accurate automated fault analysis in a DCC environment to enhance the operator decision making process [1].

The first step in FDIR task is called fault section estimation or fault diagnosis [2] and operators are required to use their knowledge and expertise on the operation of protection system in order to perform this task.

In order to aid substation operators, and due to the combinatorial complexity of the fault section estimation problem, a number of computational intelligence-based methods and solutions techniques have been developed in the past years. Expert Systems (ES) [3–6] and Artificial Neural Networks (ANN) [7–10] are among the most traditionally used methodologies. ES use rule-based knowledge models to represent the operator expertise in dealing with protective systems and an inference engine to estimate the sections under fault. Although ES are widely used, the acquisition, validation and maintenance of knowledge bases from large power systems impose serious difficulties and otherwise the inability of generalization limits the ES to producing results based solely on its knowledge base. Although an ANN overcomes the generalization incapability found in ES, ANN requires a training process carried out in a pre-processing manner for weighting and preparing the neural network to perform the fault diagnosis. Although advances have been made, some difficulties related to fault section estimation problem for large electric power systems still persist such as slow convergence in the training process, size of training sample to ensure reliable results, determination of the network parameters as hidden units, and the quantity of layers.

Fuzzy Logic (FL) is robust in the face of dealing with uncertainties of protection systems and the majority of works use FL combined with other techniques such as ES [11,12], ANN [13], cause-effect network (CE-Net) [14–16], Petri Nets (PN) [17] and Fuzzy Reasoning Spiking Neural P Systems (FRSN P systems) [18]. Ref. [14] presents the combined use of the cause-effect network (CE-Net) and the FL in which the CE-Net is used to model the operation logic of the protection system while FL performs the process of classifying faults using currents and voltages. In same way, [15,16] use FL to model the uncertainty relationship among protective devices operated and fault sections. However, the major drawback of FL is the modeling of membership functions generally based on historical data, experience or trial-and-error.

Similar to CE-Nets, the PN and FRSN P System model the protection system operation through graphic representation [17–20].

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Although CE-Nets, PN and FRSN P Systems present a clarifier idea about the cause-effect relationship of protective devices, the graphical mapping of protection system operation is a drawback when applied to a large electric power system employing a complex protection system.

Immune Algorithms (IA) [21,22], Genetic Algorithms (GA) [22–27], and more recently Artificial Bee Colony (ABC) algorithm [28], Biogeography-Based Optimization algorithm (BBO) [29] and Enhanced Honey-Bee Mating Optimization (EHBMO) algorithm [30] have proved to be suitable approaches for solving such problem. Although IA and GA techniques present robustness, easiness for coding and reduced processing time, however, their major drawback is their high number of control parameters necessary to be tuned. Because these parameters must be tuned in an exhaustive trial-and-error basis, an expressive number of parameters make this process laborious.

In this paper a novel mathematical model suitable for fast fault section estimation in DCC is proposed. The model is intended for advanced DMS (Distribution Management System) [1] and takes into account a meshed subtransmission system and the several protections and control layers of distribution substations.

The proposed model is divided into two parts: (1) a protection system operations model, and (2) an Unconstrained Binary Programming (UBP) model. The protection system operation model is composed of a set of expected state equations of the protective relay functions based on the operation logic of protection functions such as overcurrent, differential, distance along with in the protection philosophy employed for the protection system. On the other hand, the UBP model, which is an extension of [22], is established through an objective function based on the parsimonious covering theory [23,31] for associating alarms of protective relay functions informed by SCADA system with the expected states of the protective relay functions formulated in part (1). The model of the protection system operations is based on the operator's heuristic knowledge of the performance of protection system, and the optimization UBP model is used to formulate the solution hypothesis based on abductive inference logic. Differently from the model proposed in [22] the model herein developed is another model much more complex and takes into account the number of protection and control layers presented in modern distribution substations. The AGA carries out the process of fault diagnosis by minimizing the UBP model in each generation, having a dedicated stopping criterion based on fault classification, only two control parameters to tune and crossing over and mutation rates are automatically tuned in each generation based on population saturation. Comparing with AGA, solution techniques based on optimization such as IA [22] and GA [22,25,27] presents a much more number of parameters to be tuned.

In order to test and validate the overall methodology, a large number of alarms from a real four-interconnected distribution substation system are automatically generated using the proposed Alarm Probabilistic Generator Algorithm (APGA). The aim of using AGA is to verify and validate the mathematical model developed and the efficiency of algorithm is compared with a dedicated GA [22]. Obtained results confirm the efficiency and accuracy of the proposed methodology in enhancing operator decision making process in the fault diagnosis task in real time.

Mathematical model for the fault section estimation problem

The protection system operation model is a set of expected state equations of the protective relay functions in each equation of this set mathematically models the operation logic of the protective functions located at the distribution substations. The set of expected state equations are obtained in an off-line manner and developed taking into account: (1) heuristic knowledge which intuitively describe the operation logic of protective functions; (2) protection philosophy used by experts in protection specification, selectivity and coordination [32]; and (3) data from electric power system.

Fig. 1(a) presents a diagram of a typical distribution substation used to clarify the mathematical model development. The protection system is compound of multifunctional digital relays and the function numbering is based on the ANSI/IEEE C37.2 standard [33]. Fig. 1(b) illustrates the schematic diagram to model multifunctional digital relay.

Heuristic knowledge of protection logic operation

In order to obtain the expected states of the protective functions for a distribution substation is necessary to state in a comprehensive mathematical manner the heuristic knowledge describing the operation logic of every protective function when a fault occurs in different parts of electric power system [32]. We translate this knowledge for every protective device as follows.

Digital Relay: Based on the schematic diagram from Fig. 1(b), it is considered that any protective function of any relay r does not operate if there is any problem with DC/AC power supply, i.e., a DC protection alarm appears ($pvcc^{r}\ ^{A} = 1$), or an AC protection alarm appears ($pvca^{r}\ ^{A} = 1$), or an auto-diagnosis signal appears ($aud^{r}\ ^{A} = 1$). This rule defines the behavior of digital relay in the protection system. If the digital relay presents any problem, it is expected that the protective functions of the relay do not operate.

Circuit Breaker: A circuit breaker is considered defective only if after a tripping signal, it does not open. In Fig. 2(a) is depicted the relationship between protective functions and circuit breakers.

Breaker Failure Protection: 50BF will only operate if the following events occur simultaneously: (1) there is a fault in a given section that is protected by a relay whose functions include function 50BF; (2) any of those functions operates due to the fault; and (3) the tripped circuit breaker is defective. In Fig. 2(b) is depicted the operation logic of 50BF protective function.

Auto reclosing: Function 79 will only operate if the following events occur simultaneously (Fig. 2(c)): (1) there is a fault in a given section that is protected by a relay whose functions include function 79; (2) any of those functions operates due to the fault; and (3) either function 50BF of the relay does not operate or function 50BF of any other relay that trips the same circuit breaker tripped by function 79 does not operate.

Overcurrent and distance protection: Overcurrent functions 50/51, (50/51)N, 67/67N, 46, (50/51) NS (sensitive ground-fault detection), function 61 and distance functions 21/21N are formulated considering the following: **(A)** The protective function will only operates if there are faults in its protection zone provided the functions have no Logic Selectivity (LS) input. Even with a fault, the function will not operate if it is blocked by LS. This logic input/output is considered in order to coordinate relays too near or, in other words, where a short circuit level is very similar. For example, in Fig. 1(a), functions 50/50N of r07 and r09 are blocked whenever the functions 50/50N of r10, r11, r12 and r13 operate. This blocking ensures that relays r07 and r09 do not operate and de-energize busbars M-MV and T-MV incorrectly even if a short circuit occurs in feeders or capacitor banks; **(B)** The protective function will operate due to short circuit current if at least one circuit path between a reference node and protected section has all switchgears and circuit breakers closed (except for circuit breakers tripped by the protective function considered). A reference node is considered as: (1) an installation point of the Current Transformer (CT) that supplies current to the relay with the protective function considered or (2) a reference busbar. A reference node takes into account the radial feature of distribution substations as well as