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A binary coded brain storm optimization for fault section diagnosis of power systems

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ABSTRACT

Fault section diagnosis (FSD) of power systems plays an important role in power system operation. In order to quickly and accurately diagnose the fault section or sections after the occurrence of an event, a novel variant of brain storm optimization (BSO) in objective space algorithm, referred to as BCBSO (binary coded BSO), is proposed in this paper. The FSD problem is transformed into a 0–1 integer programming problem. The difference between the reported alarms and the expected states of protective relays and circuit breakers is used as the objective function. In BCBSO, each population individual is directly encoded as a binary vector and thereby the transcoding process can be avoided when solving the 0–1 integer programming problem. In addition, logical operations instead of floating operations are employed for binary strings, making the evolutionary process more convenient. In order to verify the performance of BCBSO, three test systems, i.e., the typical 4-substation power system, IEEE 118-bus system, and a practical power grid in Jilin province of China with different fault scenarios including single fault and multiple faults with failed and/or malfunctioned protective devices are employed. Six popular metaheuristic methods including ABC, BBO, DE, GA, PSO, and BSO are utilized to validate the effectiveness of BCBSO. The experimental results comprehensively demonstrate the superiority of BCBSO in terms of successful rate, diagnosis error, robustness, computation efficiency, convergence speed, and statistics. In addition, the effect of population size is investigated as well.

1. Introduction

During the operation of a power system, fault is entirely inevitable. When a fault event occurs, the well-designed relay protection system will operate to isolate the fault section or sections from the sound part of the power system. After eliminating the fault event, how to quickly and accurately identify the fault section or sections is eminently important for recovering the operation and which is precisely the whole point of the fault section diagnosis (FSD) of power systems.

The FSD of power systems can be achieved by retrieving the states of a set of protective relays (PRs) and circuit breakers (CBs) from the supervisory control and data acquisition (SCADA) systems. This task is manageable if the fault scenario is simple. However, a complicated scenario accompanied by multiple fault sections, failed and/or malfunctioned operation of PRs and/or CBs, or even a simultaneous concurrence of them, will make the task tougher. In such a context, it is highly essential to turn to advanced diagnosis techniques such as expert systems (ESs) [1–3], artificial neural networks (ANNs) [4–7], Petri nets (PNs) [8–10], Bayesian networks (BNs) [11,12], Cause–Effect networks (CE-Nets) [13], spiking neural P systems (SN P systems) [14–16], and optimization based method. These methods possess their own exclusive advantages and disadvantages. ESs based method firstly constructs a rule-based knowledge base and then uses a reasoning engine to diagnose the fault section or sections. It can make full use of experts' empirical knowledge, but the acquisition and maintenance of knowledge database is burdensome. ANNs based method needs to extract numerous representative fault samples to train the ANNs. It has good fault tolerance and strong learning ability. But it also faces the same situation that the acquisition and main-

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tenance of comprehensive training data is onerous. With regard to the PNs, BNs, CE-Nets, and SN P systems based methods, their diagnosis principles are methodologically similar. They are graphical-based reasoning methods which firstly build a causal model to explicitly express the cause and effect connections between a fault event and the corresponding protective devices and then employ respective reasoning methods to diagnose the fault section or sections. They do not need to extract representative fault samples and the diagnostic procedures are transparent. However, how to establish a sound causal model and to improve the fault tolerance ability requires further studies.

The optimization based method, methodologically different from those aforementioned methods, creatively formulates the FSD as a 0–1 integer programming problem and then utilizes optimization algorithms to solve it. This method possesses some technological traits such as rigorous mathematical logic, strong theoretical foundation, easy to implement, and fast response time. In consequence, it is very promising to be applied in practice [17]. Up to now, many optimization algorithms have been successfully applied to the FSD problem. Among them, metaheuristic methods have gained considerable attention in recent years mainly due to that they have no strict requirements on the problem formulation and can avoid the influences of the initial condition sensitivity and gradient information. For example, Lin et al. [17] firstly proposed an improved objective function and then hybridized genetic algorithm (GA) with tabu search (TS) to solve it, which can improve the diagnosis accuracy. Bedekar et al. [18] presented a continuous GA with less storage to solve a Hebb's learning law based objective function. The objective function is simple but it is based on a number of extracted representative fault samples. Zhang et al. [19] utilized redundancy and temporal information of PRs and CBs to construct an improved analytic model and then solved it by the TS algorithm with the purpose of improving the correctness and efficiency. Leão et al. [20] used the parsimonious set covering theory to formulate an improved objective function which was optimized by an immune algorithm. Utilizing the same objective function, Escoto and Leão [21] designed an adaptive GA to further improve the diagnosis efficiency. He et al. [22] proposed an improved model which takes the failure of PRs and CBs into account and then employed a binary particle swarm optimization (PSO) to minimized it. Zhao et al. [23] firstly introduced the stochastic time domain simulation to generate an improved objective function which was then solved by a well-designed history driven differential evolution (DE). Huang et al. applied different optimization algorithms including honey-bee mating optimization (HBMO) [24], biogeography-based optimization (BBO) [25], and artificial bee colony (ABC) [26] to the FSD problem. Sobhy et al. [27] employed two test cases to verify the effectiveness of ABC in solving the FSD problem once again. Abdelaziz et al. [28] introduced adaptive reduction factor and heuristic workers to enhance the local search capability of HBMO. These methods have verified their own merits in the FSD problem, yet much remains to be explored with regard to consistently improving the diagnosis results with higher performance according to the famous No Free Lunch theorem [29].

Brain storm optimization (BSO), proposed in 2011 [30], is an efficient and versatile swarm intelligence algorithm. BSO is inspired by the human brainstorming process, in which a diverse group of people with different backgrounds and expertise gather together to come up with new ideas to solve a problem. In BSO, each population individual is represented as an idea and all ideas are clustered into several groups by *k*-means clustering algorithm. Then the ideas are updated based on one or two ideas in clusters by neighborhood searching and combination. Two functionalities, i.e. capability learning and capacity developing [31] make BSO have a good equilibrium between the exploration and exploitation. This fascinating feature soon makes BSO attract many attentions and be applied in various research fields [32–37]. However, to the best of our knowledge, BSO has not been applied to the FSD problem of power systems.

The original BSO utilizes the *k*-means clustering algorithm to cluster the population. It is implemented recursively in each iteration and thus is time-consuming. To reduce the computational burden, a variant of BSO algorithm named BSO in objective space (BSO-OS) algorithm [38] is proposed. BSO-OS replaces the *k*-means clustering algorithm with a simple grouping method. This grouping method is just based on the individuals' fitness values and can make the algorithm more efficient and easier to implement. Hence the BSO-OS algorithm is extended for the FSD problem in this paper. The contributions of this work are as follows:

(1) A binary coded BSO-OS algorithm, referred to as BCBSO, is proposed. In BCBSO, each idea is directly encoded as a binary vector and thereby the transcoding process can be avoided when solving the 0–1 integer programming problem.
(2) Logical operations instead of floating operations are employed for binary strings, making the evolutionary process more convenient.
(3) BCBSO is applied to the typical 4-substation power system, IEEE 118-bus system, and a practical power grid in Jilin province of China. It is comprehensively validated through various severe fault scenarios by different performance criteria. The comparison results with other popular algorithms consistently demonstrate that BCBSO can be used as a competitive alternative for the FSD problem of power systems.

The remainder of this paper is organized as follows. Section 2 briefly introduces the objective function of FSD problem of power systems. The proposed algorithm, BCBSO, is fully elaborated in Section 3. In Section 4, experimental results and comparisons are presented. Finally, Section 5 is devoted to conclusions and future work.

2. Problem formulation

When a power system suffers from a fault event, the well-configured relay protection system will quickly and accurately detect the fault and activate the corresponding protective relays (PRs) to trip off the circuit breakers (CBs) to isolate it. To know the detailed cooperative relationships among the main PR, primary backup PR, and secondary backup PR, one can refer to Ref. [39]. Those reported alarms, i.e., the operated PRs and the tripped CBs will be stored in the SCADA systems. Theoretically, the fault section or sections can be diagnosed by using the reported alarms. Therefore, the mathematical model of FSD is to adopt a backward reasoning method to build a fault hypothesis, in which the operating behavior of the reported alarms can be explained as logically as possible. Namely, when a fault event occurs under such a fault hypothesis, the expected states of PRs and CBs should be in agreement with the reported alarms as much as possible. The mathematical model can be expressed as the following 0–1 integer programming problem:

$$\min F(\boldsymbol{S})$$
$$s.t.\begin{cases} S_i = 0 \text{ or } 1 \\ \boldsymbol{S} \in Z^D \\ i = 1, 2, \ldots, D \end{cases} \tag{1}$$