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Method to decide a multi-fault rush repair robust strategy in power distribution networks

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ABSTRACT

The multi-fault rush repair problem (MRRP) in power distribution networks is a discrete dynamic combinatorial problem with topology constraints and a series of uncertain factors in repairing process. This paper aims to obtain a robust repairing strategy by studying the uncertainty of fault repairing time in order to minimize the outage loss and total repairing time. To solve the above problem, sensitive faults will be considered to obtain the robust repairing. The robust repairing time model is proposed based on timed Petri Net model with inhibitor arcs, which is adopted to analyze the repairing process to obtain the impact factor of every fault in a power distribution network. To simulate the uncertainties of repairing process, a Latin hypercube sampling method combined with the simultaneous backward reduction algorithm is used to generate simulation scenarios. The continuous bacterial colony chemotaxis (BCC) optimization algorithm is revised to be applicable for integer variables so as to find the optimal solution of each scenario in MRRP. Then the improved minimax regret criterion is applied to decide the final optimal robust repairing strategy. This approach is verified by the standard IEEE 33-bus system and a real-world power distribution network. Scenarios with deterministic and uncertain repairing time are discussed and the simulation results show the robustness and effectiveness of the approach.

1. Introduction

Power distribution network (PDN) is connected to the end users directly, so its normal and economical operation is crucial to the entire power system (Baxevanos and Labridis, 2007). In recent years, earthquakes, snowstorms, heavy rain and other natural disasters have brought great damages to the power distribution system. The failed power equipment, collapsed towers, and damaged substations have caused serious economic damage to the affected areas. Thus, it is very important to restore power supply of the outage zones quickly after any of such system failures. Due to the diversity of outage load at fault sites, the repairing personnel and resources may be insufficient to repair sites quickly, and also existing methodologies on fault restoration and reconstruction cannot fully meet the needs of MRRP. Therefore, it is necessary to propose an efficient multi-fault rush repairing strategy under limited repairing resources.

There have been many studies on power system restoration and fault diagnosis, while studies on MRRP in power distribution systems are quite limited. The tactical model, short-term strategic model, and long-term strategic model of the repair-unit location problem are presented in (Ming-Jong Yao and Min, 1998), but the repairing strategy is not considered. Other existing studies on PDN multi-fault rush repair focus mainly on two types of problems: the allocation of fault tasks and the modeling of multi-fault rush repair. For the allocation of fault task problem, an optimization model with a single squad is established in (Zhang et al., 2008), which cannot be applied to practical situations with multiple squads. A multi-squad cooperation mechanism is given in (Lu and Wang, 2013), and a repairing scheduling multi-agent approach is proposed to archive an emergency repairing plan quickly. According to the characteristics of squads and faults, utility theory is introduced in (Lijun et al., 2014) to achieve an efficient allocation of fault tasks. For the second problem on the modeling of multi-fault rush repair, a tie switch is taken as a virtual fault and a multi-fault rush repairing model is built in (Lu et al., 2011) and (Li et al., 2013), which assume there are sufficient repairing personnel and resources, and assign fault tasks to each squad randomly. This approach increases significantly the solution searching range and thus computing time. Sometimes it does not match well with the actual role of tie switches in PDN, and may not be able to repair all the faults. The MRRP is mainly solved by BCC optimization algorithm for its excellent performance (Zhang et al., 2008; Lu and

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Wang, 2013; Lijun et al., 2014; Lu et al., 2011; Li et al., 2013).

Existing literatures generally propose the pre-fault repairing strategies based on deterministic fault repairing time. However, in an actual rush-repair the pre-fault repairing strategy is optimal only when the faults could be repaired at the expected time duration. When the actual repairing time is longer or shorter than expected, these repairing strategies will become worse or even unfeasible. Usually multiple squads will repair several faults at the same time. If the repairing time of any fault assigned to one squad is different to expected, the other squads' process will be affected. For example, assume there are three squads repairing the faults at the same time, if the repairing time of the fault repaired by Squad 1 changes, then the power restoration process in the other two squads will be affected due to the topology constraints. Then the repairing strategies will become worse or even unfeasible, and the total outage loss and repairing time will be bigger. Therefore, this paper proposes a robust repairing strategy in the rush-repairing process which allows uncertainties on repairing time.

As multiple squads will repair several faults at the same time, repairing process is therefore a parallel discrete event, and the task allocations between faults and squads make the strategy decision more complicated. Note that Petri net (PN) is an efficient modeling tool to describe and analyze discrete-event dynamic systems (Peterson, 1981; Lin et al., 2006) and has the characteristics of parallel information processing and concurrent operating function (Sun et al., 2004), therefore, it is widely used in power system study (Yu et al., 2004a, 2004b; Chen et al., 2015, 2014; Ramírez-Treviño et al., 2007; Chen et al., 2016; Zhu et al., 2016). Considering the topology constraints in MRRP, a timed PN model with inhibitor arcs is adopted to represent the concurrent and parallel behavior of different squads in multiple error conditions of power distribution systems. Then the impact of each fault on the repairing process is analyzed with the aid of PN.

It is important to note that MRRP is indeed a high dimensional nonlinear integer programming problem, and therefore it is very difficult to be solved by traditional gradient based algorithms. Therefore, new algorithms based on intelligent computing are applied to solve MRRP, and this paper focuses on the application of the Bacterial Colony Chemotaxis (BCC) optimization algorithm. The chemotaxis algorithm is initiated by Bremermann (1974). Based on the results of Bremermann, Müller et al. (2002) developed the bacteria chemotaxis (BC) optimization algorithm and applied it to the solution of inverse airfoil design in 2002. BC is a simple and robust algorithm. Li et al. (2005) developed Bacterial Colony Chemotaxis (BCC) optimization algorithm by introducing the bacteria colony to improve the basic BC algorithm, this BCC performs better than BC in terms of convergence and computational speed. BCC algorithm is a type of intelligent optimization algorithm for continuous variables that has been widely used in nonlinear programming (Guzmán and Delgado, 2010). The convergence and comparison of BCC against other algorithms have been investigated by more complicated problems with various constraints (Lu et al., 2013, 2015, 2014), and it can effectively to solve many complex and high-dimensional problems. It is also verified that BCC algorithm has better performance than non-dominated Sorting Genetic Algorithm (NSGA-II) and MOEA/D (Lu et al., 2015). Thus, bacterial colony chemotaxis (BCC) optimization algorithm is implemented to solve the MRRP. However, the repairing process is discrete, thus this BCC is revised to cater for discrete scenarios (i.e. integer variables), and a discrete bacterial colony chemotaxis (DBCC) is proposed in this paper.

Multiple scenario technique is an efficient way to represent uncertainties, and it has been used in unit commitment (Wu and Li, 2007) and economic dispatch (Aghaei et al., 2013) in power systems. Scenario analysis can be used to deal with robust optimization and it will guarantee the robustness of the solutions (Mulvey et al., 1995). Latin hypercube sampling (LHS) (Shu and Jirutitijaroen, 2011; Jirutitijaroen and Singh, 2008; Iman and Conover, 1982) and the simultaneous backward method (Aghaei et al., 2013) are used for scenario generation in this paper. After generating the possible scenarios, a final repairing strategy needs to be obtained in these scenarios by certain decision rule. Note that the minimax regret criterion is an alternative subjective decision rule in decision theory (Jiang et al., 2013), it is less conservative and can guarantee the same robustness as the minimax criterion. However, every scenario has a probability of occurrence in the paper, which makes the minimax regret cannot be applied directly. Thus the minimax regret criterion is improved by adding probability distributions to the scenarios and then applied to decide the optimal repairing strategy.

The remainder of the paper is organized as follows: In Section 2, the multi-fault rush repair problem is introduced. The robust fault repairing model and the applications of PN model in repairing process are discussed In Section 3. In Section 4, the scenario generation, DBCC algorithm and the improved minimax regret criterion to solve the problem are presented. The standard IEEE 33-bus system and a real-world power distribution network are studied to demonstrate the performance of the proposed approach in Section 5. Conclusions are drawn in Section 6.

2. The multi-fault rush repair problem

The multi-fault rush repairing management system and the MRRP model are introduced in this section.

2.1. Multi-fault rush repairing management system

The framework of multi-fault rush repairing management system is shown in Fig. 1. Repairing Control Headquarter (RCH) is responsible for leading and organizing the multi-fault rush repairing work when multi-fault happens in PDN.

When multi-fault happens, the management system will work as follows:

(1) RCH will send order to all centers for information collection.
(2) Information Collection
  Data Collection Center (DCC) is mainly responsible for collecting data of fault information, outage load information and distributed generation (DG) information which will be sent to RCH.
  Weather Service Center (WSC) collects weather information of the future hours and sends it to RCH.
  Repairing Resources Center (RRC) is responsible for collecting the available repairing resources and sending it to RCH.
  Geographic Information Collection Center (GICC) is in charge of gathering road information in the fault region and sending information to RCH.

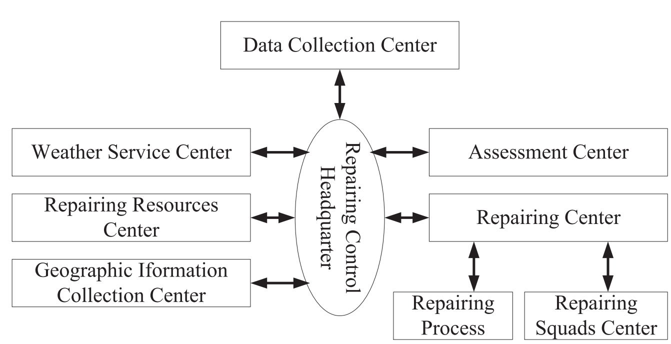

Fig. 1. Framework of multi-fault rush repairing management system.