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Design of SCADA water resource management control center by a bi-objective redundancy allocation problem and particle swarm optimization

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ABSTRACT

SCADA[1] is an essential system to control critical facilities in big cities. SCADA is utilized in several sectors such as water resource management, power plants, electricity distribution centers, traffic control centers, and gas deputy. The failure of SCADA results in crisis. Hence, the design of SCADA system in order to serve a high reliability considering limited budget and other constraints is essential. In this paper, a bi-objective redundancy allocation problem (RAP) is proposed to design Tehran's SCADA water resource management control center. Reliability maximization and cost minimization are concurrently considered. Since the proposed RAP is a non-linear multi-objective mathematical programming so the exact methods cannot efficiently handle it. A multi-objective particle swarm optimization (MOPSO) algorithm is designed to solve it. Several features such as dynamic parameter tuning, efficient constraint handling and Pareto gridding are inserted in proposed MOPSO. The results of proposed MOPSO are compared with an efficient ε-constraint method. Several non-dominated designs of SCADA system are generated using both methods. Comparison metrics based on accuracy and diversity of Pareto front are calculated for both methods. The proposed MOPSO algorithm reports better performance. Finally, in order to choose the practical design, the TOPSIS algorithm is used to prune the Pareto front.

1. Introduction

SCADA systems are used to monitor, control, and save the information about quantity and quality of water at pump stations, water treatment plant, reservoirs and distribution networks in water resource management in big cities. These tasks are not trivial in big cities in which there are lots of stations. RAP has been utilized in many parts of SCADA systems, such as radio modems and servers, to increase the reliability.

SCADA control center consists of a set of hardware, software and communication networks which control the industrial processes through remote data. Stability and high reliability in intelligent systems to monitor key installations in major cities and to restore order, prosperity, and health are very important issues controlled by SCADA. Failure and downtime of SCADA system can be catastrophic. Failure of any part of SCADA system can lead to a disruption in the process control [2,3].Therefore, a proper design of SCADA system to enhance the reliability of the control center considering several constraints on budget, volume, and weight is essential. Enhancement of reliability has mainly two options: (1) using more qualified components which results in higher cost of the designed system, and (2) using RAP to assign redundant component using a reasonable cost. Due to these facts, this paper introduces the RAP as a methodology used to increase reliability of SCADA systems. The classic form of RAP was proposed by Misra and Ljubojevic [23]. The RAP was presented to be an NP-hard problem by Chern [5].

In this paper a multi-objective version of RAP model is proposed. The proposed RAP model has two objectives called reliability and cost and several constraints on minimum and maximum number of allowed components in each sub-system, cost, weight, and volume of the system. The proposed RAP model is customized for the design of SCADA in water resource management in a real case study. As the problem is hard to solve optimally using exact algorithms a multi-objective meta-heuristic algorithm, called the multi-objective particle swarm optimization (MOPSO) algorithm is proposed. The proposed MOPSO generates a set of non-dominated solutions on Pareto front. These non-dominated solutions are associated with different designs of SCADA system considering both objective functions and all constraints of the systems. The result of proposed MOPSO is compared with the result of an efficient algorithm, called epsilon-constraint. Several

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metrics are introduced to compare the accuracy and diversity of re-generated Pareto front.

The remaining parts of the paper are organized as follows. In Section 2, a brief literature of related past works is reviewed. In Section 3, the mathematical formulation of proposed RAP model is presented. The proposed MOPSO algorithm is also presented in Section 3. In Section 4, the real case study of SCADA system for water management resource is presented. The proposed MOPSO and an efficient exact algorithm are applied on the real case study in Section 4 and the results are discussed and compared. In Section 5, conclusions and further research directions are introduced.

2. Literature of past works

Swarm intelligence is one of the artificial intelligence techniques that studies the group behavior in decentralized self-organized agents. Examples for such systems can be found in nature as ant colony, flock, herd animals, bacteria, and fishes. However, the principle of particle swarm optimization method (PSO) is relatively new [9], but since this method is the origin of biological research and simulating the behavior of living animals, there are several successful applications of this method in the literature [13–16]. The mechanism used to search the solution space in the PSO differs from the evolutionary computations. The simplicity and the applicability of the PSO method have added to the popularity of this method for solving a large number of engineering and management optimization problems [14–16].

In some real cases, the PSO method may suffer from the problem of premature convergence [28]. In order to overcome this problem, the MOPSO method makes use of smart techniques to maintain the level of diversity in the swarm population, thereby maintaining a good balance between the exploration and exploitation phenomena and preventing premature convergence [14–16]. One of a those smart techniques is gridding. The adaptive grid is used by the Pareto Archive Evolutionary Strategy (PAES) to maintain diversity [7].

A series–parallel system is basically characterized through a predefined number of sub-systems which are connected serially. Multiple component choices and redundancy levels are available to connect in parallel for each sub-system. A given component may have a binary-state or a multi-state in RAP [21,29]. In binary-state RAP, the problem of a proper structure can be handled by increasing the reliability of components or supplying parallel redundant components at some stages.

Konak et al. [20] represented an overview and tutorial describing genetic algorithms (GA) developed specifically for problems with multiple objectives. Different applications of meta-heuristic methods in RAP can be found in literature [22,25,30,31]. Gen and Yun [10] surveyed the GA-based approach for various reliability optimization problems. Li et al. [22] proposed a two-stage approach for solving multi-objective system reliability optimization problems. In the first stage, a Multi-Objective Evolutionary Algorithm (MOEA) generated non-dominated solutions. Then, a self-organizing map (SOM) was supplied to cluster similar solutions and finally a DEA represented to select the most efficient solutions in each cluster. Khalili-Damghani and Amiri [13] proposed a hybrid approach based on efficient epsilon-constraint, multi-start partial bound enumeration algorithm, and DEA to solve the binary-state multi-objective reliability redundancy allocation series–parallel problem. Khalili-Damghani et al. [14] proposed the decision support system for solving reliability redundancy allocation problems. Khalili-Damghai et al. [16] proposed a new multi-objective particle swarm optimization method for solving reliability redundancy allocation problems.

Due to aforementioned literature of past works and our best knowledge PSO reported relatively better performance for handling RAP in different settings [16]. These facts as well as simple implementation and software coding of PSO in comparison with other existing procedures persuade us to use PSO in order to handle a real life problem, called SCADA.

3. Redundancy allocation problem (RAP) and proposed bi-objective RAP

In this section, the single objective RAP is described. Then the proposed bi-objective RAP is illustrated and customized for SCADA systems.

3.1. Single objective RAP

The following notations, indices, parameters, and decision variables are introduced for RAP:

m: number of sub-systems;
i: index of sub-systems, $i=1,2,\ldots,m$;
j: index of types of components in each sub-systems, $j=1,2,\ldots,n$;
r_{ij}: reliability of component j in sub-system I;
c_{ij}: cost of component j in sub-system i;
w_{ij} : weight of component j in sub-system i;
R_s : overall reliability of the series 2 parallel system;
C_0 : allowed cost of system;
W_0 : allowed weight of system;
a_i: number of available component choices for sub-system i;
x_{ij} : quantity of component j used in sub-system i;
n_i: total number of components used in sub-system i;
n_{max} : maximum number of components in each sub-system;
n_{min} : minimum number of components in each sub-system;
R_s : reliability of the series–parallel system;
C_s : cost of the series–parallel system.

Single objective RAP for a series–parallel system is formulated as the following:

$$\max R_s = \prod_{i=1}^{m}\left(1-\prod_{j=1}^{a_i}(1-r_{ij})^{x_{ij}}\right)$$

$$\text{S.T.} \tag{1}$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}x_{ij} \le C_0 \tag{2}$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} w_{ij}x_{ij} \le W_0 \tag{3}$$

$$\sum_{j=1}^{a_i} x_{ij} \le n_{max}, \quad i=1,2,\ldots,m \tag{4}$$

$$\sum_{j=1}^{a_i} x_{ij} \ge n_{min}, \quad i=1,2,\ldots,m \tag{5}$$

$$x_{ij} \in Z^{+}, \quad i=1,2,\ldots,m;\ j=1,2,\ldots,n \tag{6}$$

The schematic form of the series–parallel system is shown in Fig. 1.

3.2. Proposed bi-objective RAP for SCADA systems

The following bi-objective RAP models (7)–(13) are proposed for SCADA system. It is notable that the description of the