Electric Power Systems Research 134 (2016) 47–55

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Multiple line outages identification: A customized quantum inspired approach

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ARTICLE INFO

Article history:
Received 25 June 2015
Received in revised form 16 October 2015
Accepted 1 December 2015
Available online 30 January 2016

Keywords:
PMU
Line outage identification

ABSTRACT

Accurate and prompt identification of power line outages plays an important role in the reliability and robustness of smart power grids. Line outage identification problem has been traditionally formulated as a combinatorial optimization problem and requires an exhaustive search to find an optimal solution. However, this suffers from huge computational complexity as the size of the search space grows exponentially with the number of line outages. This work proposes a computationally efficient optimization technique based on Quantum Inspired Evolutionary Algorithm (QIEA) for the identification of multiple power line outages in smart power grids. In addition to the classical QIEA, a customized version of QIEA is also proposed and its effectiveness is validated against various IEEE bus systems with multiple line outages scenarios. The simulation results demonstrate the validity and accuracy of the proposed solution.

1. Introduction

Phasor measurement units (PMUs) [1] are sophisticated devices that have found a great interest in electrical power sector. They provide accurate, real time and synchronized (to a common time source [2]) measurements of voltage and current phasors at the monitored buses of smart power grids. In recent years, a large number of utility companies have installed PMUs in their power grids where they are used to perform numerous tasks including power system protection, monitoring and control [3]. In addition, there is a growing research interest on how the massive data from PMUs can be exploited for new applications in power system studies.

An important application of PMUs in power system protection is the identification of line outages in power grids spread over a large geographical area. An outage on one or multiple transmission lines disturbs the system power flow and changes the phase angles measured at the system buses where PMUs are located. Certain lines become overloaded and consequently fail. Later on, a cascading tripping may spread over interconnected lines and result in a complete system collapse [4]. Therefore, an accurate and prompt identification of line outages is mandatory to ensure a reliable and secure operation of a power grid.

The state-of-the-art proposes a number of techniques to avoid costly grid-wide blackouts. This includes (a) PMU placement algorithms which are aimed to obtain a complete system observability with minimum number of PMUs and (b) methodologies which exploit rich PMU data for line outage identification. Some considerable works are discussed as follows. In [5], the authors propose a hybrid approach for optimal PMU placement. At first, an upper bound estimate on global optimum is obtained with the help of linear programming. Then a near optimal solution is achieved by using greedy heuristic method and branch and bound (B&B) algorithm. Integer linear programming is considered in [6] to find the optimal PMUs placement. Moreover, it also investigates the effect of a single line outage or the loss of a single PMU on the optimal placement of PMUs. The work in [7], investigates the optimal placement of PMUs as well as PDCs (phasor data concentrators). To get the optimal number of PMUs, at first it is assumed that PMUs are installed on all system buses. Then, a step wise elimination process is carried out to remove the redundant PMUs. In [8], the authors demonstrate on the basis of B&B algorithm and greedy heuristic that the complete system observability could be achieved if only one third of the optimal buses are provided with PMUs. The work in [9], proposes a binary search algorithm for optimal PMU placement under normal conditions and studies the effect of single line outage on network observability. In [10], the authors first show that an integer linear programming approach is equivalent to the exhaustive search based PMU placement. Further, they also show how network observability could be preserved following a single PMU fault or line

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http://dx.doi.org/10.1016/j.epsr.2015.12.001
0378-7796/

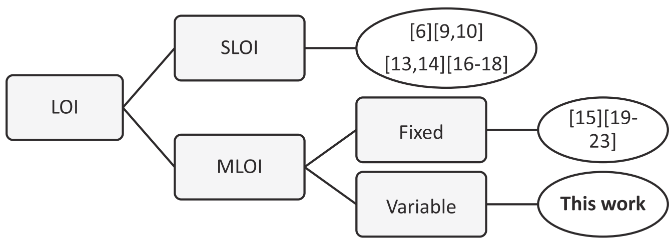

Fig. 1. Summary of state of the art solutions for line outage identification (LOI). Single line outage identification (SLOI), multiple line outage identification (MLOI).

outage. This work is extended in [11], where the authors modeled the power system equations as a system of equations instead of merely investigating for their individual resolvability, and showed it to be capable of reaching the globally optimal solution. In contrast to the conventional topological observability based approaches, the work in [12] proposes an information-theoretic approach based on the mutual information (MI) between the PMU measurements and power system states. The proposed method includes observability as a special case and rigorously models the uncertainty reduction on power system states from PMU measurements. Further, a greedy PMU placement algorithm is also proposed.

The work in [13] adopted support vector machines (SVM), a machine learning algorithm for identification of single-line outages. The algorithm uses the output data of PMUs and trains all possible candidate topologies for single line outage under several different loading conditions. In [14,15], the authors proposed single and double line outage identification methods respectively, using PMU phasor angle measurement and system topology information. In [16], a quickest change detection (QCD) algorithm is proposed to identify single line outages in near real-time. An out of killer algorithm (OKA) is proposed in [17], to solve the security analysis method to search all the cases in which constrained levels have been crossed for all single line outages. In [18], a mixed integer programming approach is proposed for the solution of single external line outage identification problem.

Mathematically, the line outage problem is well formulated and can be modeled as a combinatorial optimization problem; an optimal solution of which can be obtained from exhaustive search over all possible line outage combinations. However, the computational complexity of exhaustive search increases exponentially with the number of lines in the system. In order to get a solution of such combinatorial problem, a number of meta-heuristic approaches are also proposed in literature. However, the main difficulty lies in the accuracy i.e. number of line outages successfully detected by the solution. In [19], the authors propose a least absolute shrinkage and selection operator (LASSO) based on compressed sensing technique. Although LASSO approach is capable of identifying multiple line outages, it requires an a-priori parameter related to line outage probability and perturbed noise. This parameter becomes very difficult to tune up in the absence of a-priori information and significantly affects the accuracy of the proposed algorithm. In [20], a cross-entropy optimization (CEO) technique is considered for multiple line outage identification. CEO outperforms LASSO in terms of percentage of successfully identified multiple line outages. In [21], the authors presented a non-iterative method for the line outage contingency ranking of integrated multi-terminal AC–DC systems. [22] proposes an algorithm based on compressive sensing homotopy for smart grid health monitoring. Compressive sensing has an advantage that it successfully bypasses the exhaustive comparison problem. The work in [23], uses PMU data to find the location of multiple line outages inside a specific area of a power system.

Fig. 1 summarizes the state of the art for line outage identification (LOI). Broadly, the published works on LOI can be classified into two categories namely, single line outage identification (SLOI) solutions and multiple line outage identification (MLOI) solutions. MLOI solutions can be further classified into (a) fixed solutions and (b) variable solutions. Fixed solutions are those in which the maximum number of lines in outage is fixed and usually known in advance to the algorithm. To the best of our knowledge, all of the published works on MLOI fall into the category of fixed solutions.

In this work, we propose a novel approach based on Quantum inspired evolutionary algorithm (QIEA) to solve MLOI problem. QIEA is categorized as a probabilistic evolutionary algorithm [24]. In addition to applying the classical QIEA to line outage identification problem, we also propose a customized QIEA algorithm named as QIEA-Individual. The main contributions to this work are highlighted as follows.

- The proposed solution is the first solution that falls into the category of variable MLOI solutions i.e. the solution is capable to identify any (arbitrary) number of line outages with any possible combination.
- The proposed QIEA-Individual algorithm avoids the local optima, thanks to an efficient quantum rotation scheme at chromosome as well as individual Q-bit level.
- The simulations are performed for various IEEE reference bus systems. It is demonstrated that the proposed QIEA-Individual solution is more accurate as compared to various other meta-heuristic approaches.

The rest of the paper is organized as follows. In Section 2, we describe the system model and its formulation for power line outage identification problem. Section 3 discusses in detail, the basics of quantum computation and QIEA. Section 4 discusses QIEA formulation for multiple line outage identification problem. Numerical results are discussed in Section 5. Finally, Section 6 concludes the paper.

Notations: Lower-(upper-) case boldface letters denote matrices and vectors respectively; calligraphic letters stand for sets; upper normal letters denote single values; $(.)^T$ denotes the matrix/vector transpose operation; $(a_1 : a_2,\ b_1 : b_2)$ denotes the rows from a_1 to a_2 and columns from b_1 to b_2; $(:,\ :)$ denotes all rows and columns; $\lceil . \rceil$ denotes the ceil operator; $<$ and $>$ are logical operators (less than and greater than respectively) and return 0 or 1.

2. System model and problem definition

2.1. Linear DC power flow model

Note: All notations used in this section are listed in Table 1. A power transmission network with N buses and L lines can be modeled as a directed graph $\mathcal{G} = \{\mathcal{N}, E\}$, where $\mathcal{N} = \{1, \ldots, N\}$ denotes the set of nodes (buses) and $E = \{(m, n) \subseteq \mathcal{N} \times \mathcal{N}\}$ denotes the set of edges (lines). The incidence matrix M of $\mathcal{G}$ is a matrix of size $N \times L$, whose entry at nth row and lth column is given as:

$$M_{nl} = \begin{Bmatrix} 1, & \text{if } \mathit{line}\ l \text{ is from bus } n \\ -1, & \text{if } \mathit{line} l \text{ is to bus } n \\ 0, & \text{otherwise.} \end{Bmatrix} \tag{1}$$

In this work, we consider the linear DC power flow model defined in [19], which assumes the conservation of power flow i.e. the power injected into bus n must be equal to power flowing out of it. Mathematically,

$$P_n = \sum_{m \in \mathcal{N}(n)} P_{nm} = \sum_{m \in \mathcal{N}(n)} \frac{1}{x_{nm}} (\theta_n - \theta_m), \tag{2}$$