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Towards self-healing in distribution networks operation: Bipartite graph modelling for automated switching

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ABSTRACT

The concept of self-healing has been recently introduced in power systems. The general self-healing framework is complex and includes several aspects of networks' operation. This paper deals with automated switching in the context of autonomous operation of distribution networks. The paper presents a new network data model that allows effective reconfiguration algorithms to be designed. The model is based on bipartite graph representation of switching possibilities. The model properties and capabilities are illustrated for simple self-healing algorithms and a small real world medium voltage distribution network.

1. Introduction

Self-healing is a key feature of the upcoming distribution networks. This feature is defined as the capability to identify, diagnose and recover from system disruptions with the objective of maximizing system availability, survivability, maintainability and reliability [1]. Self-healing in power systems often refers to automatic fault detection, isolation and restoration. The healing process consists in isolating faults and restoring power both upstream and downstream the faults by analyzing and automatically undertaking switching operations to maximize restored load [2–4].

The problem of fault identification and diagnosis is a well studied one [5,6]. In this paper we focus on the recovery problem and on the solution techniques that would bring the system back to normal without human operator intervention. Several approaches have been proposed in the past. These can be classified into two main groups:

(1) solutions based on network optimization algorithms [7,8]; and
(2) solutions based on data storage of pre-defined switching schemes [9,10].

The first group of approaches usually lacks speed of response. This is because data structures and algorithms have not been designed appropriately for fault recovery. These were rather inherited from off-line applications used in operations planning. The second group of approaches lacks flexibility of response. This is because topology of a network changes frequently and that requires frequent updating of the switching schemes. Moreover, faults may occur in many different operating configurations (due to maintenance and previous faults), which makes the database updating very demanding.

The solution proposed in this paper belongs to the group of optimization based approaches. We propose new data structures upon which effective algorithms can be designed. With the new data structures, we resolve the problem of speed while keeping the flexibility of optimization approaches.

The new data structures are based on bipartite graph theory. A special bipartite graph that represents the switching possibilities can be built. This graph is not built to represent the physical network itself, but rather to abstract the switching dynamics. This paper will present the necessary framework for building such graphs and, based on this framework, we will propose an approach to automated switching of distribution networks and illustrate its application. By using the new bipartite graph data structures, the high solution quality of the first group of recovery approaches is preserved, while achieving the speed of response of the second group of approaches.

The paper is organized as follows. In Section 2 we outline the necessary background on graphs. In Section 3 we introduce

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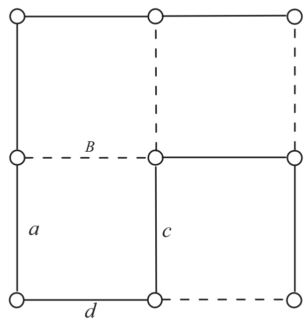

Fig. 1. Schematic representation of a distribution network G with its operating configuration T in solid line.

the bipartite graph model. Reconfiguration dynamics is described, as well as the model representation and initialization. Section 4 presents some algorithms to illustrate how the model can be used for self-healing in distribution networks. In Section 5 we show results from real world distribution network and illustrate the proposed procedures with practical examples. Section 6 concludes the paper.

2. Terminology

Most of the following terminology on graph theory can be found in [11–13].

2.1. Graph terminology

A *graph* is a pair (N, A) of a finite set N of *nodes* and a set A of *arcs* with $A \subseteq \left\{\{n_1, n_2\} | n_1, n_2 \in N\right\}$. In the power system context, the graph is to represent the network. The nodes are the load, substations and connection points; and the arcs are the cables, lines, busbars and switch devices. Fig. 1 shows an example of a graph.

A graph G is said to be *bipartite*, if its nodes can be partitioned into two sets $\{N_1, N_2\}$ so that $A \subseteq \{\{n_1, n_2\} | n_1 \in N_1, n_2 \in N_2\}$. It is also denoted as a (N_1, N_2, A) graph. For an example of a bipartite graph see Fig. 4.

Bipartite graphs are used to support the new model of distribution network. This model is different from the classical (WYSIWYG) representation of network topology. To make the text more clear, we refer to nodes of the bipartite graph as *vertices* and to its arcs as *edges*. The terms *nodes* and *arcs* will be reserved for the graph G and its spanning trees. The term *b* ranch will be used for the distribution network itself. Then we get a graph $G = (N, A)$ and a bipartite graph $B = (V_1, V_2, E)$.

A *tree* is such a graph (bipartite by its nature), that contains no cycles.

A *spanning treeT* of a graph G is a pair (N, A') where A' is such that every node of N can be reached from any other node of N in a unique way, i.e., T is acyclic. In the distribution context, spanning trees are to represent radial network configurations. Solid lines in Fig. 1 show a spanning tree.

A *co-tree* arc c is an arc of a graph G that is not an arc of its tree T. If a spanning tree T represents a radial configuration, then the co-tree arcs represent arcs that can be closed to create a mesh, i.e., possible switching ON operations. For example, see arc B, or the other dashed arcs in Fig. 1.

A *fundamental cycleY* of G with respect to a spanning tree T is a set of arcs defined by a co-tree arc c and the path in T between the two endnodes of c. In the distribution context, the fundamental cycle induced by a switching ON operation represents the corresponding mesh. In Fig. 1, the lower right square *aBcd* is a fundamental cycle with respect to T (where the corresponding co-tree arc would be B).

2.2. Matching terminology

Let G be a graph, $G = (N, A)$, and M a set of arcs $M \subseteq A$. Denote by ∂M the set of end nodes of the arcs in M. We say M is a *matching* in G if different arcs of M do not have an end node in common, i.e., if $|\partial M| = 2\,|M|$, where $|\cdot|$ denotes cardinality. For example, in Fig. 1, the set of arcs a and c is a matching, while the set of arcs a and d is not, as they have a node in common.

A path $(a_i)_{i \in \{1,...,k\}}$ in graph G is M-alternating if for any $i \in \{1, \ldots, k-1\}$ exactly one of the arcs a_i and a_{i+1} is in M. An M-alternating path $(a_i)_{i \in \{1,...,k\}}$ in G is *M-augmenting* if its end nodes are not in ∂M. For example, considering Fig. 1 and matching $M_1 = \{a, c\}$, the path (adc) is M_1-alternating. Considering a different matching $M_2 = \{d\}$, the same path (adc) is M_2-augmenting.

3. Network model

This paper proposes a new data model that captures the topological properties of radially operated networks and supports completely autonomous decision making on network operating reconfiguration. Our model consists of the data structures representing the bipartite graph and the methods that are necessary to work with such a graph.

The model is based on the idea of reconfiguring radial networks by undertaking *switching steps*, i.e., such pairs of switching operations that consist of closing one (arbitrary) branch of the network and opening another so that the resulting configuration is also radial.

Choosing the branch to close is arbitrary, while the branch to open has to be one of the branches lying on the mesh thereby created. Recall that the mesh can be defined in graph theory as a fundamental cycle (see Section 2). If so, then a switching step is defined as in the following.

Definition 1. Let $G = (N, A)$ be a graph representing the distribution network. Its operating configuration is a spanning tree, say $T = (N, A_T)$, where $A_T \in A$. Let Y_T^B be a fundamental cycle with respect to T, defined by a co-tree arc element B. A *switching step*$\{B, c\}$ is then defined as an exchange of an arc element c, that lies on the fundamental cycle Y_T^B, for a co-tree arc element B, i.e.,

$$\{B, c\}| \;\; c \in Y_T^B \cap A_T,\, B \in Y_T^B \cap (A \setminus A_T). \tag{1}$$

One can say, that for a given switching ON operation represented by an arc $B \in (A \setminus A_T)$, a feasible switching step can only be composed by those switching OFF operations that lie on the fundamental cycle (Y_T^B) of the graph G with respect to T defined by (closing) B.

For instance see Fig. 1, where the lower left square is a fundamental cycle of G with respect to T defined by the branch B. Switching OFF operations that can be found on this cycle are a, c and d.

Notice that all the branches represented in G by $A \setminus A_T$ are co-tree arcs of the spanning tree T, i.e., network branches currently not in use.

The following result summarizes the relationship between switching steps and topology feasibility.

Result 1. By proceeding in switching steps, the network is guaranteed to be topologically feasible, i.e., radial and connected.

Without loss of any feasible solution, applying the switching steps dramatically reduces the reconfiguration search space and gives the model the opportunity to explore all the topologically feasible configurations in order to find those that would be also electrically feasible (i.e., not violating the operating constraints: minimal node voltages, maximum branch and transformer currents), or optimal with respect to chosen criteria. Notice that any