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A dynamic Bayesian network based framework to evaluate cascading effects in a power grid

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ABSTRACT

In recent years, the growing interest toward complex critical infrastructures and their interdependencies have solicited new efforts in the area of modeling and analysis of large interdependent systems. Cascading effects are a typical phenomenon of dependencies of components inside a system or among systems. The present paper deals with the modeling of cascading effects in a power grid. In particular, we propose to model such effects in the form of dynamic Bayesian networks (DBN) which can be derived by means of specific rules, from the power grid structure expressed in terms of series and parallel modules. In contrast with the available techniques, DBN offer a good trade-off between the analytical tractability and the representation of the propagation of the cascading event. A case study taken from the literature, is considered as running example.

1. Introduction

Dependencies increase the risk of failure and the vulnerability in a complex critical infrastructure and among infrastructures. As an example, most major power grid blackouts that have occurred in the past were initiated by a single event (or multiple related events) that gradually led to cascading failures and the eventual collapse of the entire system (Pourbeik et al., 2006). Rinaldi et al. (2001) classify dependency-related disruptions or outages as cascading, escalating, or common cause outages. A cascading phenomenon occurs when the failure of one component of the system induces an overload in adjacent components increasing their failure probability. If the overload can be compensated by the strength of the adjacent components, the cascade may be arrested, otherwise the cascade may become an avalanche causing a progressive and rapid disruption of all the system. Recent electrical blackouts that occurred both in USA and Europe are typical cascading phenomena; since their effect has been catastrophic for millions of citizens, they have stimulated further research as also witnessed by the launch of public research programs in the EU (CRUTIAL (http://crutial.erse-web.it), IRRIIS (http://www.irriis.org), MANMADE (http://www.manmadenet.eu)) and USA (The Complex Interactive Networks/Systems Initiative (CIN/SI), funded equally by EPRI and U.S. Department of Defense (DOD)).

Developing modeling frameworks for understanding interdependencies among critical infrastructures, and analyzing their impact are necessary steps for building interconnected infrastructures on which a justified level of confidence can be placed with respect to their robustness to potential vulnerabilities and disruptions. Modeling can provide useful insights of how component failures might propagate and lead to disturbances on the service delivered to the users.

The definition and implementation of a modeling framework for the propagation of cascading failures is an open problem in the study of the dependability analysis of critical infrastructures. Two approaches can be accounted in the literature: (1) a pure statistical approach; (2) a phenomenological approach. The aim of the *statistical approach* is to model how the appearance of a failure and the consequent overload can be redistributed, and to study the propagation of the cascade. A series of papers (Dobson et al., 2002, 2004, 2005) proposes a statistical model called *CASCADE* which is based on an abstract view of the cascading phenomenon. The system is assumed to be composed of many identical components randomly loaded. An initial disturbance

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causes some components to fail by exceeding the loading limit. The failure of a component causes a fixed load increase for other components. Models of the dynamic redistribution of the load have been explored also in Motter and Lai (2002), Crucitti et al. (2004), Kinney et al. (2005) where the load redistribution is based on the definition of node efficiency which is a centrality measure based on shortest paths computation. The idea of computing centrality measures using only the shortest paths has been criticized in Newman (2005) with the motivation that the intrinsic redundancy of the network is neglected. Woolf et al. (2007) consider networks transporting generic packets, that are constructed in such a way to be affected by avalanche-like breakdown originated by the congestion of a node. Given a source node and a destination node, the packets are transported following the shortest path between the two nodes. The load (or flow rate) of a node is based purely on the topology of the network, and in particular on the number of shortest paths passing through that node. The introduction of new nodes or links in the network may cause the congestion of a particular node causing its fall. This event determines the redistribution of the load among the nodes of the network, possibly causing other congestions, and in the worst case, the disconnection of a subnetwork.

In the *phenomenological approach*, an attempt is made to build a physical scenario that leads to the comprehension of the propagation of the cascading phenomenon. Typical examples of this approach in the literature can be found in DeMarco (2001), Chowdhury and Baravc (2006), Lininger et al. (2007), Faza et al. (2007). In particular, Chowdhury and Baravc (2006) discuss the possible evolution of various failure scenarios related to the IEEE 118 bus test system. An effort to propose a formal approach to a failure scenario is discussed in Faza et al. (2007) resorting to a chain of conditional probabilities. However, the proposal is incomplete: it does not take into account the dynamic of the cascade and it is not suitable for quantitative evaluations. In Bobbio et al. (2009), we showed that *Bayesian Networks* (BN) (Langseth and Portinale, 2007)—and more properly *dynamic Bayesian networks* (DBN) (Montani et al., 2008)—can provide a very valuable framework for modeling and analyzing dynamic phenomena as those arising in the propagation of cascading failures. DBN represent the evolution of the cascading phenomenon in a more physical way with respect to the abstract statistical models. In particular, in Bobbio et al. (2009), we showed how a series/parallel diagram representing the structure of the power grid, can be converted into the equivalent DBN which undergoes inference procedures in order to compute predictive or diagnostic measures concerning the state of the general system, or the state of its elements.

It is worth noting that the work in Torres-Toledano and Sucar (1998) introduced an algorithm for automatically converting a *reliability block diagram* (RBD) (Sahner et al., 1996), with series and parallel connections, into a BN. In particular, according to Torres-Toledano and Sucar (1998), lines in parallel have to be connected through an AND node (since the overall parallel circuit fails if all the lines are outaged), while lines in series have to be connected through an OR node (since the overall series circuit fails if at least one of the lines is outaged). With respect to our methodology, such an algorithm is limited to binary variables. On the other hand, in Bobbio et al. (2009), we represented the state of lines and modules by means of multi-state (namely three-states) variables, and we generalized the OR and AND nodes into the nodes representing the state of series or parallel modules. Moreover, if a line *l* gets outaged or overloaded, the lines affected by *l* get overloaded, and do not directly fail: they might fail subsequently. An ordinary BN, which could manage multi-state variables, cannot deal with this kind of temporal dependency, and this justifies our choice of relying on a DBN.

This paper extends Bobbio et al. (2009) in several directions: (1) in Bobbio et al. (2009), we did not consider the possibility to repair outaged lines; in this paper, we take into account such possibility in the case study and in the DBN model. (2) In Bobbio et al. (2009), the rules to convert a series or parallel module into DBN were limited to the case where the module is composed by two lines; in this work, we generalize the rules in such a way to be applied to a module composed by any number of elements which can be lines or in turns modules. The rules consider the possibility of repair. (3) For the sake of brevity, in Bobbio et al. (2009), we proposed a small case study (Fig. 3) to be modeled and evaluated in form of DBN; in the current paper, we deal with a larger example (Fig. 2), still inspired to the power grid case study presented in Chowdhury and Baravc (2006).

This paper has the following structure: Section 2 describes how a power grid can be structured in terms of series and parallel modules, and presents the case study. Section 3 describes in details the assumptions we make about the dependencies arising among the elements of the power grid as a consequence of their organization in series or parallel modules; such assumptions determine the state of each element of the power grid. Section 4 presents the main features of DBN models, while Section 5 provides the rules to map the series/parallel diagram of a power grid into the equivalent DBN, taking into account the outage or repair events, and the dependencies defined in Section 3. According to such rules, in Section 6 we present the DBN model of the case study. Finally, Section 7 presents the quantitative values of prediction and diagnostic measures computed on such model by means of inference procedures.

2. Series and parallel modules

The aim of an electrical power grid is transporting the electrical power from the generators to the consumers. This can be done by means of the electrical lines composing the power grid and connecting its nodes. We assume that such lines can be structured in series or parallel modules, in such a way that more than one path may be available between two nodes of the grid. This mechanism allows the delivery of the electric power to a node, even though the outage of a subset of lines has occurred.

The elements composing a module can be single electric lines or inner modules. A series module requires that the power is transported along all the elements composing the module. So, if one element of the series fails, the transport of power along the series is interrupted. On the other hand, in a parallel module, the elements (branches) composing it, establish several parallel ways to transport the power; therefore if one elements fails, the other elements can still be exploited to this aim.

The case study: The IEEE 118 bus test case depicted in Fig. 1 and described in Chowdhury and Baravc (2006), is an example of a power grid. In this paper, we concentrate on a subpart of this test case composed by the nodes 11, 12, 15, 17 only, and the electric lines realizing the connections among such nodes, as shown in Fig. 2a. For the sake of simplicity and to facilitate the comprehension, we consider such a subpart in isolation; this means that we do not take into account the other nodes and the other lines connected to 11, 12, 15 and 17, that are instead present in the complete power grid in Fig. 1. For instance, in Fig. 1, the node 11 is connected to 4 by means of the line 4–11, or by means of the series composed by 4–5 and 5–11, but we omit them in the case study. Still for the sake of simplicity, we assume that the aim of the power grid portion in Fig. 2a, is the transport of the electrical power from the node 11 to 15. We also suppose that this can be done by means of the direct line 11–15, or through the node 12: the electrical power can be transported from 11 to 12 by means of the line 11–12, then the node 15 can be reached by