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Reinforcement of energy delivery network against natural disaster events

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ABSTRACT

Among all city infrastructures affected by natural disaster events, electric power grid is the most critical one. Most services on which disaster relief efforts depend, rely entirely on the availability of dependable and continuous supply of power. To achieve power grid resiliency against natural disasters, it is first necessary to perform a thorough analysis of interdependencies within the energy delivery network. This paper puts forth a graph-theoretic methodology based on fuzzy cognitive maps that models and analyzes the grid as an interconnected system of elements (i.e., energy resources and loads) that are connected through weighted and directional edges (i.e., lines and feeders). The developed model provides a mathematical framework for the analysis of the power grid during natural disaster events, and is used to devise optimal reinforcement strategies for the grid infrastructure via capacity enhancements and component reinforcement. The problem has been formulated as a constrained quadratic optimization one. The analysis and optimization approach are performed using abstract models so as to ensure the generic nature of the proposed methodology. A case study is presented using the IEEE 34-bus test distribution system. The system is mapped onto the floodplain map of the city of Boulder, CO, and is used to verify the applicability of the proposed methodology for grid reinforcement against flood hazards.

1. Introduction

Natural disasters such as hurricanes, tornadoes, floods, earthquakes, volcanic eruptions, snowstorms, and wildfires can cause temporary or permanent damages to the electric power infrastructure. In fact, natural disasters have been considered as one of the two main causes of the largest blackouts in North America (the other being cascading failures) [1]. This not only affects the supply of power to end-use consumers, it may also impact critical infrastructures such as water sanitation and sewage systems, transportation systems, telecommunication networks, and emergency response services whose uninterrupted operation is essential for post-disaster recovery. Human catastrophe that can potentially unfold as a result of failure to restore the power grid can far outweigh the financial damages incurred. To be resilient against natural disasters, the power grid has to be capable of withstanding a major disruption, with limited degradation, and be able to recover within a narrow timeframe with constricted costs [2]. Resilience may be further characterized through robustness, redundancy, resourcefulness and rapidity [3], which, in the case of power systems, means reducing the extent of damages incurred by natural disasters on power grid components, limiting the consequence of power system partial failure on the society,

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especially during post-disaster recovery activities, and finally, speeding up service restoration to the areas affected by the disaster.

Major research has been conducted on assessment of damages to power system components or other related infrastructures in the aftermath of natural disasters, and proposing design and/or operation countermeasures and remedies. Kwasinski et al. [4] studied the impact of Hurricane Katrina on the wire-line and wireless communication networks, and concluded that the lack of power was the main cause of a widespread telecommunication outage. Reed et al. [5] investigated the correlations of the power outage data in the aftermath of Hurricane Katrina with weather parameters such as wind speed, rainfall and storm surge. Xie and Zhu [6] studied the impact of severe windstorms, ice and freezing rain, and earthquakes on the transmission network in China, and recorded instances of towers twisting and collapsing as a result of tornadoes or ice accumulation on the line, as well as tower collapse, damage to hydroelectric dams or substation equipment as a result of earthquakes. Abi-Samra and Henry [7] studied the effects of flooding on the power system in the aftermath of the 1993 flood in Midwestern US, and concluded that many high voltage breakers, transformers, disconnect switches and substation control rooms had been affected by the flood water, requiring a long time and considerable manpower to be cleaned and restored. All these studies indicated the vulnerability level of the power grid against common disaster events that could lead to major blackouts and brownouts, requiring considerable manpower to repair the affected components and restore power.

To be proactive, damage and vulnerability assessment due to natural disasters is the first and most essential step. Some researchers have used techniques based on the concepts of hazard probability [8], flow disruption or connectivity [9], reliability analysis and importance degree [10], fuzzy graphical models [11], hierarchical systems models [12] or statistical learning theory models [13] in order to assess damages to grid components and perform risk analysis as a result of potential natural disasters. Research has also been performed to relate the fragility and quality of electric power delivery to lifeline infrastructure such as telecommunication, transportation, emergency, and healthcare systems [14]. Once the at-risk sections and components are identified, solutions need to be developed to strengthen them against potential natural hazards. With this objective in mind, some researchers have proposed solutions to strengthen the energy delivery link, using decentralized energy supply [15, 16]. Others have proposed solutions for making the IT infrastructure more robust [17–21]. It is also possible to reinforce the transmission and distribution lines by using redundant designs, deploying parallel paths, or adopting less vulnerable mechanical structures.

To strengthen the power grid against potential natural hazards it is first necessary to identify critical loads whose uninterrupted supply is necessary during and in the aftermath of an event. Next, network components need to be reinforced in order to ensure continuity of supply to these loads. This means the number/capacity of the generation resources that can feed those loads in conjunction with the capacity and availability of links connecting these resources to the loads. However, such reinforcement would usually be subject to budgetary constraints which forces utilities to choose the most cost effective strategy. Devising such solution is the focal point of this paper.

For this, graph theoretic concepts have been used to help model the power grid connectivity from an abstract point of view. This model based on fuzzy cognitive maps (FCM) provides an overall view of the weak links in the energy delivery network and candidate components for reinforcement. Then, a graph-dependent optimization problem is formulated that solves for the optimal reinforcement strategy against natural disaster events with different intensity levels.

Section 2 of the paper describes the fundamentals of fuzzy cognitive maps. Section 3 shows how FCM can be used to model the energy delivery network. The proposed methodology for grid reinforcement is explained in Section 4. Sections 5 and 6 present the case study and the simulation results. Finally, concluding remarks appear in Section 7.

2. Fuzzy cognitive maps

Political scientist Robert Axelrod introduced cognitive maps in the 1970s for representing social scientific knowledge [22]. These were signed directional graphs (digraphs) where a positive link from vertex i to vertex j would indicate that i causally increases j, whereas a negative link would mean that should i happen, the chances of j happening are reduced. Within this context, the *indirect effect* of i on j is defined as the causal impact of i on j over a specific path $P^k_{i\to j}$ that connects the former to the latter. However, in a typical cognitive map, often times there exists more than one path that connects a vertex to another. Therefore, the causal impact of i on j needs to be considered over all possible paths connecting the two. This is referred to as the *total effect* of i on j. In early cognitive map designs, the indirect effect of i on j was assumed to be negative if the number of negative signs (of the edges of $P^k_{i\to j}$) was odd; and positive otherwise. The total effect of i on j would then be considered negative if all the indirect effects were negative, positive if all the indirect effects were positive, and indeterminate otherwise [23]. It is safe to assume that in most real-world applications beyond a trivial level of complexity, the indeterminate case happens more frequently.

To solve this problem, Kosko [23] introduced fuzzy cognitive maps (FCM) which allowed for more efficient usage of expert knowledge and logical reasoning in defining the causalities between different vertices (elements). A FCM is a weighted directional graph whose edges have fuzzy (qualitative) weights (Fig. 1).

He defined the impact of vertices on one another based on the concepts of general fuzzy minimum and maximum operators (or the t-norm and t-conorm operators [24]). Assuming there are K causal paths $P^k_{i\to j}$ connecting vertex i to vertex j, each consisting of n_k intermediate vertices with weighted and directional links in between them, the indirect effect of i on j

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