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Self-organized criticality and cascading failures in the topological model of power grids: a case study

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Abstract: *Recent studies suggest that power-grids experience a dynamical equilibrium named self-organized criticality as they evolve by their own means to a critical state in which a minor event can trigger a chain reaction affecting any number of elements. Considering the topological model of Eletrosul transmission system and a simplified model of cascading failures, we study the size/scope of blackouts relatively to the proximity of the system to its operational limits. Results indicate that the size and scope of blackouts are strongly related to the overall state of the system at the moment of an individual failure.*

1 Introduction

The proper functioning of a power system requires that power utilities deliver electrical power on demand, *i.e.*, generation should amount to the load at any given time. This mode of operation is called 'load following' and it has to deal with stochastic load demands produced by consumers. Besides, power utilities have to manage unanticipated power faults, which contribute to the genesis of instabilities and disturbances in the generation/load balance. As the balance condition is not quickly reestablished after disturbances, generation and/or load breakers trip, causing generators and power lines to become disconnected to avoid physical damage and/or the propagation of instability waves. As this process evolves, cascading disruptions may lead to blackouts ranging from local, short-lived unavailability to full system collapse lasting for several hours [1]. A recent example of a large-scale event was the 2009 blackout in Brazil due to the cutting of a key high-voltage line which ultimately caused Itaipu Dam, the largest hydroelectric plant in the country, to be shutdown for hours [2].

In terms of their consequences, the loss of a generation or transmission source is much the same, since they generally cause disruptions in supply [1]. In this context, extra generating and transmission capacity that can be available within a short period of time are generally used to avoid or minimize such disruptions. Nevertheless, the creation of substantial reserves opposes economical interests and, thus, are unlikely to occur. Moreover, the upgrades in the generation and transmission capacities are gradually absorbed by the natural growth of consumer demand, such that the system induces itself towards its operational limits again. Meanwhile, in response to outages, investments are more strongly directed towards specific elements recognized to act as triggers that already occurred. But the lack of relation among triggers makes specific remedial actions upon individual components rather ineffective against cascading events, which are argued to depend more heavily on the overall state of the system [3][4]. These facts add up to the indication that power-grids, thought as a set of operators, equipment, policies and consumers, might operate within the dynamical equilibrium of self-induced criticality, thus inflicting upon itself an intrinsic liability to major cascading events, *i.e.*, blackouts [5].

In this paper, we use a dynamical model of cascading failures to evaluate the relation between the size and scope of blackouts due to node failures and the level of load of the network relatively to its capacity, which may be thought of as a measure of the proximity of the system state to its operational limit. We apply the cascading model to the topological structure of a real power grid, namely, the Eletrosul transmission system [7]. The question under study is how the size and scope of a blackout relates with the state of the system and its proximity to the limit or critical point. The results show that cascading events are likely to have greater size and scope as the system operates nearer to its limits. Simulations of the same triggering event upon different system states indicate the existence of a threshold of major disruptions which can be thought of as a critical point that, ideally, the system ought to be maintained distant from.

2 Materials and methods

The model for cascading failures can be thought of as a law that decides whether a link or node will remain active or not upon a load redistribution process triggered by a failure. A node or link is set to inactive state as it is subject to overload, which simulates a line being tripped offline. A failure is modeled as the removal of a link or node and it is followed by the redistribution of the flow among the remaining links and nodes, which can cause links to be overloaded and induce new failures, in a process that can collapse any number of links and nodes in the network.

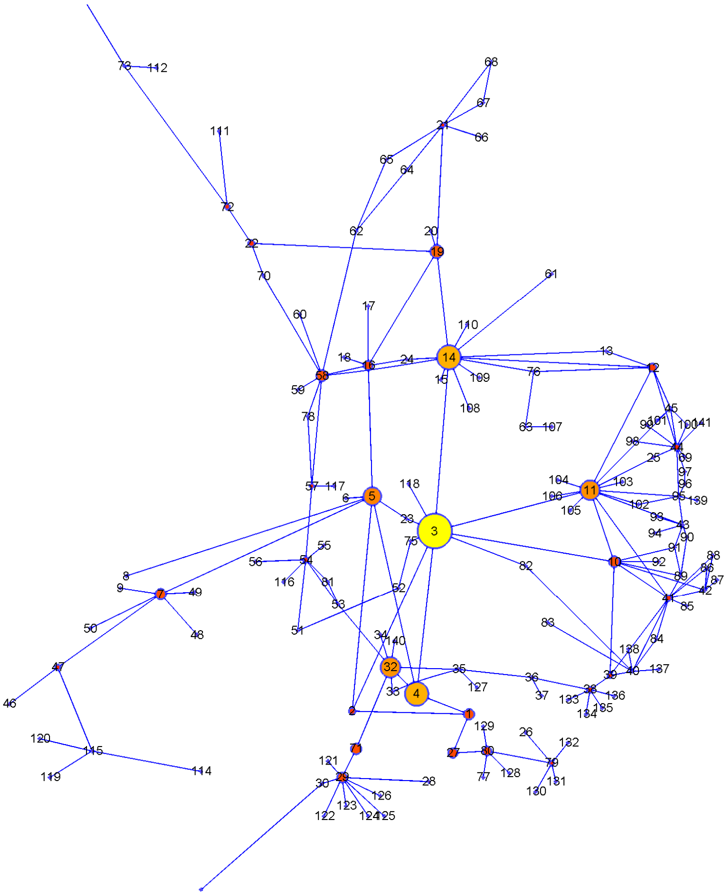

Figure 1 – Structure of Eletrosul high-voltage power grids: color gradient represents node loads, from red (lowest) to yellow (highest)

Consider a network with N nodes (generators, transformers, substations) and k links (high-voltage transmission lines) and assume that the evolution of the efficiency of transmission over time is based on the flow redistribution after the breakdown of a node, such that the flow between any two nodes always takes the most efficient path connecting them [6]. The links are modeled to reproduce the high-voltage power-grid, and the topology is represented by an adjacency matrix from which the load in each node (i.e., its betweenness centrality) can be calculated. Initially, as the efficiency of all existing links are set as $e_{ij}=1$, all the transmission lines are assumed to be working perfectly. Following the methodology proposed in [6], the efficiency of a path is modeled as the harmonic composition of the link it goes along, such that the average efficiency of the network is given by

$$E(G)=\frac{1}{N(N-1)}\sum_{\substack{j=1\\ j\neq i}}^{N}\frac{1}{d_{ij}} \qquad (1)$$

where d_{ij} is the shortest distance between nodes i and j. It follows that the load upon node i at time t, denoted $L_i(t)$, is defined as the total number of most efficient paths passing through i at time t. Further, each node is characterized by a capacity that defines the maximum load that the node can handle, given by $C_i = \eta L_i(0)$, where $L_i(0)$ is the initial load of node i and $\eta \geq 1$ is the tolerance parameter of the network, which can be thought of the system state at the time of the failure. The interplay among the removal of a node, the redistribution of loads and the tolerance against overloads determines how the network will react to the removal of a node. Note that the removal of a node changes the most efficient paths within the network, such that the efficiency, given by equation (1), is changed due to the redistribution of power-flow and loads over the network. This relation can be modeled as

$$e_{ij}(t) = \begin{cases} e_{ij}(0)\dfrac{C_i}{L_i(t)}, & if\ L_i(t) > C_i \\ e_{ij}(0), & if\ L_i(t) \leq C_i \end{cases} \quad (2)$$

such that a congestion in node i at time t causes the efficiency of all links passing through it to be reduced, such that energy flow shall take alternative paths [6]. Differently from the modeling in reference [6], we assume that links with efficiency below some threshold are removed. Such setting simulates the fact that overloaded power lines are tripped offline in actual electrical systems to avoid physical damage and the propagation of instability waves over the network. The system state is related to the value of the tolerance parameter η, such that at $t = 0$, when the failure occurs, the system is said to be operating at $1/\eta$ of its capacity. The topological structure of the Eletrosul transmission system is shown in Figure 1. The size and the color gradients in nodes represent loads, from lowest (red, smaller) to highest (yellow, larger). As the nodal load has more influence upon the size of blackouts comparatively to its degree, we regard the importance of a node in the network according to its load.

3 Results and discussion

The application of the cascading model in the topological structure of Eletrosul transmission system shows that the size and scope of blackouts de-scale with increase of the parameter η, which indicates that failures that give rise to disruption events tend to have lesser consequences when the system is operating well below its limit. Figure 2 illustrates this point by showing the evolution of degradation triggered by the individual removal of the nodes with highest loads. We perceive a tendency of blackouts to grow more steeply in size and scope as the system reaches about 80% of its capacity, corresponding to $\eta = 1.25$, which can be thought of as some kind of critical point for several of the network nodes.

Conversely, Figure 3 illustrates how network efficiency drops from unity as the removal of the node with largest load is performed. The values are expressed as a function of the tolerance parameter η. The mitigation effect of the tolerance parameter is observed to have the potential to minimize disruptions and contribute to decrease the size/scope of a blackout to the point of reducing it to a local event limited to the vicinity of the failing node/link. An example of such reduction is the reduction in the number of disrupted lines from 68,89% to 13,89% of the network links under the increase of the tolerance parameter from 1 to 2.6, as shown in the simulations in Figure 4 and Figure 7.

The exploration of the model indicates that the state of the network at the moment of a failure is a major indicator of the consequences of a failure. The closer to the operational limit the system is, the larger the scope and size of the blackout, even when it is triggered by a minimal failure in a seemingly unimportant node. This follows from the fact that nearly overloaded lines are likely not to be capable of handling any extra load, in which case they get tripped offline.

As power-grids are suspected to operate in self-organized criticality, in which it pushes itself towards its operational limits, the occurrence, frequency, size and scope of large blackouts are likely to be a consequence of the interplay among investments and demand more than it is likely to be one of individual triggers, such as equipment fails or bad weather conditions. Under this perspective, the overall state of the system is more important than the operating conditions of its individual components. Conversely, the investments made to avoid triggering events are likely to have little effect upon the occurrence of large blackouts in a power-grid operating too close from its limit.

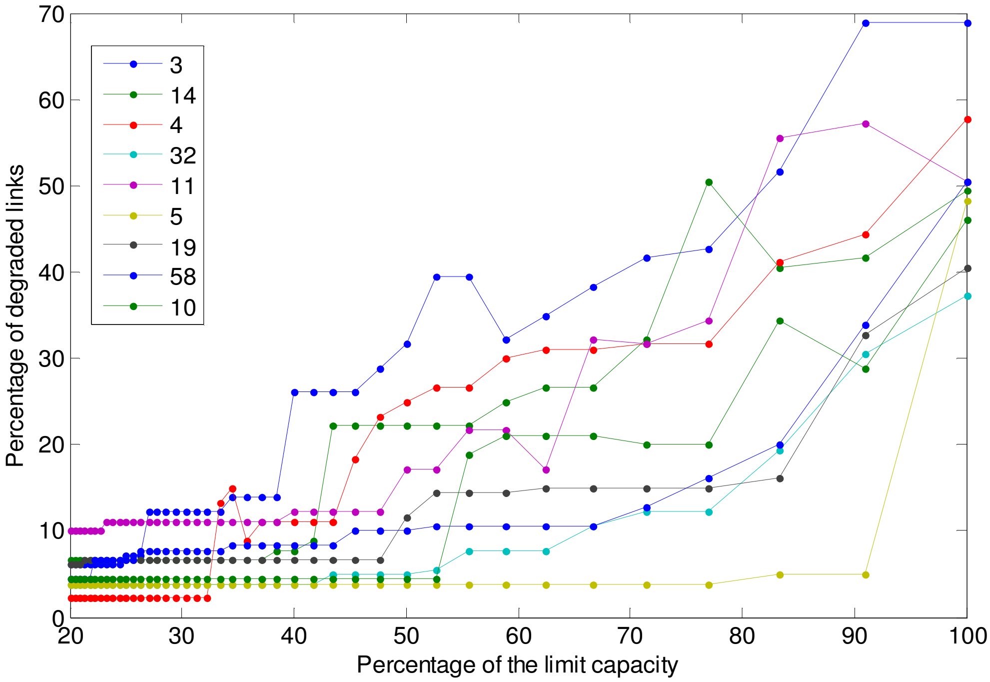

Figure 2 - The size of blackouts as a function of the percentage of the limit capacity under use in the moment of a failure: the lines show the evolution of the percentage of degradation for the nodes with highest loads, in descent order. The results indicate that the size and scope of blackouts are largely related to the proximity of the system state to its limit.

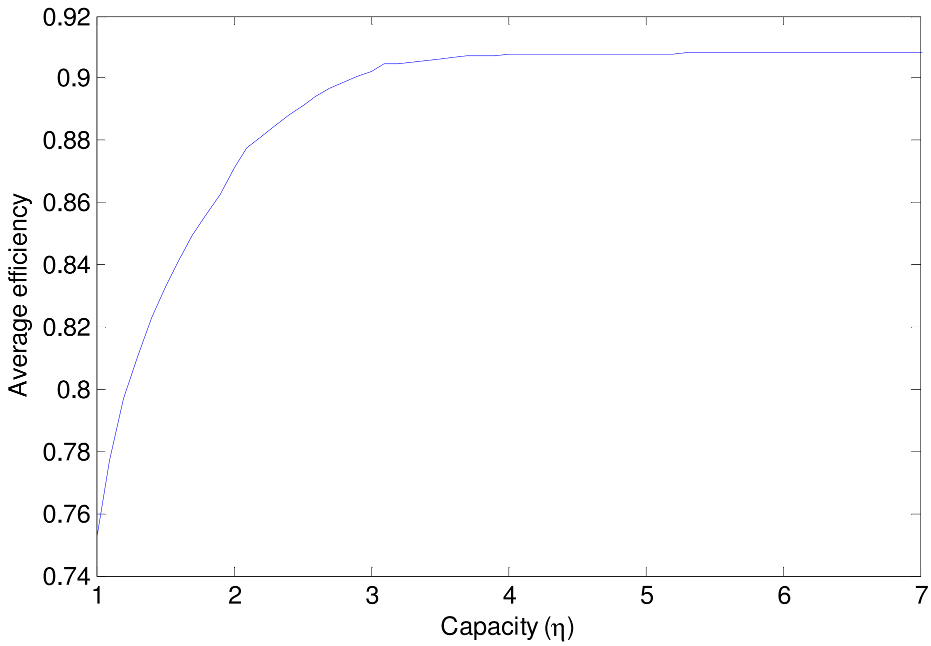

Figure 3 - Evolution of average link efficiency as a function of the tolerance parameter η : the system suffers severe efficiency drops as it gets closer to the operational limit ($\eta = 1$) and enters an operational regime in which major blackouts are imminent.

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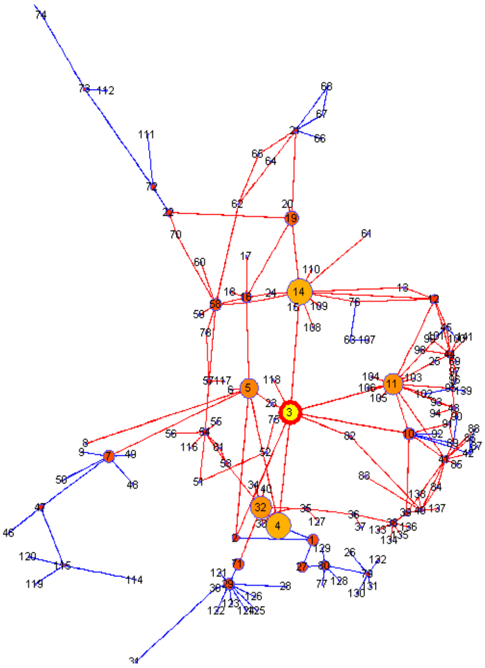

Figure 4 – Cascading failure due to the removal of the node with highest load (node 3, circled in red) for η = 1.0: 68.89% of the transmission lines are tripped offline (in red).

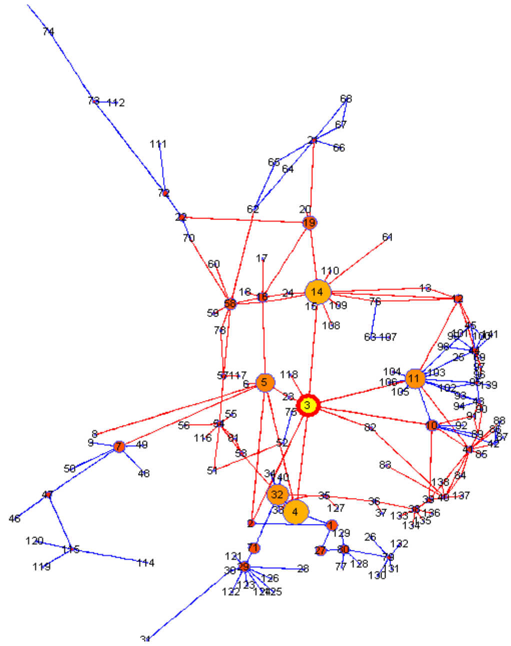

Figure 5 – Cascading failure due to the removal of the node with highest load (node 3, circled in red) for η = 1.2: 51.67% of the transmission lines are tripped offline (in red).

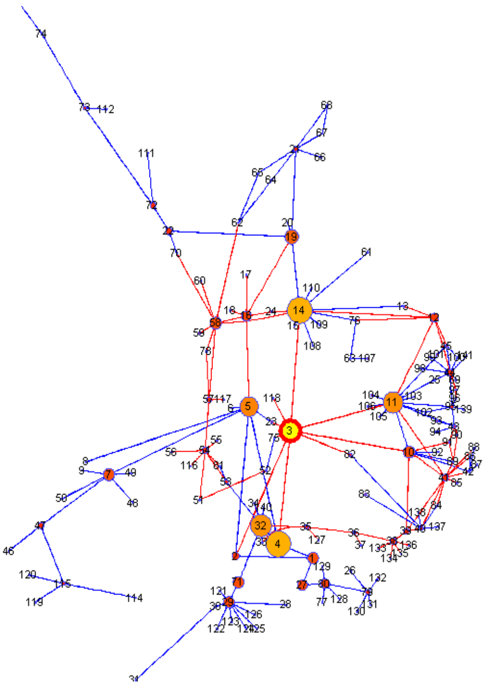

Figure 6 - Cascading failure due to the removal of the node with highest load (node 3, circled with a red line) for η = 1.5: 38.33% of the transmission lines are tripped offline (in red).

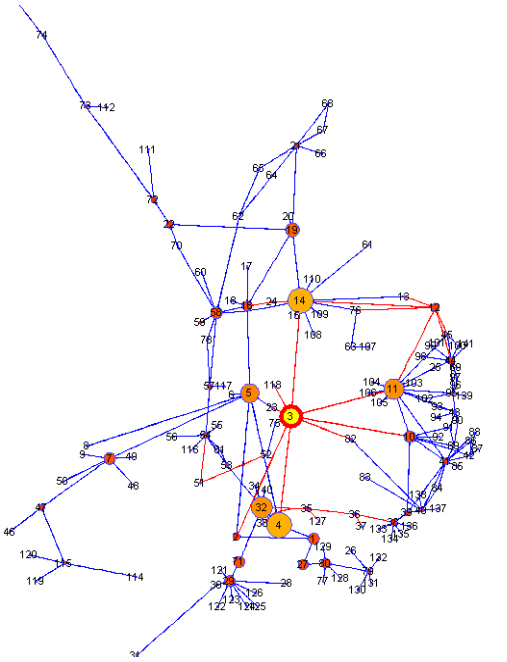

Figure 7 – Cascading failure due to the removal of the node with highest load (node 3, circled with a red line) for η = 2.6: 13.89% of the transmission lines are tripped offline (in red).

To illustrate the size and scope of blackouts, Figure 4, Figure 5, Figure 6 and Figure 7 show a sequence of simulations for increasing values of the tolerance parameter. The lines tripped offline are indicated in red and cascading effect caused by the removal of the node with highest load (node 3, circled in red) is considered. The de-scale in the size of the blackout reaches 80% as the tolerance is increased from $\eta = 1$ (grid operates at full capacity) to

$\eta = 2.6$ (grid operates at about 38% of the capacity). This means that the same topological structure can behave quite differently to individual failures, depending on the spare capacity of the remaining nodes and links. It follows that the vicinity of a node with large load should have large spare capacities to handle the redistribution that would follow its failure. A question that arises is what *vicinity* means in this context, since the redistribution process ends up affecting all the nodes in the network, either directly or indirectly, either immediately or after a time lag.

Considering that Eletrosul transmission system is part of a larger power-grid, namely, the Brazilian interconnected system (SIN), a suggestion for future research is the investigation of the cascading characteristics of SIN, which may help enhance the comprehension of power outages in the real grid and the design of mitigation strategies that take into account self-organized criticality dynamics.

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Keywords: *self-organized criticality, cascading failures, power-grids, blackouts, Eletrosul transmission system.*

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