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How much spare capacity is necessary for the security of resource networks?

Qian-Chuan Zhao[a], Qing-Shan Jia[a,*], Yang Cao[b]

[a]Center for Intelligent and Networked Systems, Department of Automation, Tsinghua University, Beijing 100084, China
[b]Department of Automation, Tsinghua University, Beijing 100084, China

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Abstract

The balance between the supply and demand of some kind of resource is critical for the functionality and security of many complex networks. Local contingencies that break this balance can cause a global collapse. These contingencies are usually dealt with by spare capacity, which is costly especially when the network capacity (the total amount of the resource generated/consumed in the network) grows. This paper studies the relationship between the spare capacity and the collapse probability under separation contingencies when the network capacity grows. Our results are obtained based on the analysis of the existence probability of balanced partitions, which is a measure of network security when network splitting is unavoidable. We find that a network with growing capacity will inevitably collapse after a separation contingency if the spare capacity in each island increases slower than a linear function of the network capacity and there is no suitable global coordinator.

Keywords: Statistical physics of complex networks; Graph theory; Network splitting; Balanced partition; Network capacity

1. Introduction

Complex networks are essential parts of a modern society [1,2]. The resilience of complex network to the malfunctioning of its components and to external disturbances (simulated as the deletion of nodes or edges) has been the subject of a great deal of attention since the work of Albert et al. [3]. The question of resilience has been looked into for a large range of networks, including the Internet [3], metabolic networks [4], food webs [5,6], email networks [7], electrical power grids [8], infrastructure networks [9], and many model networks [3,10–15]. Refs. [13,16] gave good surveys on this issue. Different from previous models, in this paper we study the resource network, in which the balance between the supply and the demand of some kind of resource (e.g., electrical power, oil, and natural gas) is a critical condition for the functionality and security of the network. Local contingencies that break this balance condition may cause performance degradation and even global

*Corresponding author. Tel.: +86 10 62792491; fax: +86 10 62796115.
E-mail addresses: zhaoqc@mail.tsinghua.edu.cn (Q.-C. Zhao), jiaqingshan98@mails.tsinghua.edu.cn (Q.-S. Jia), caoy02@mails.tsinghua.edu.cn (Y. Cao).

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collapse of the entire network. One example is on the North American power infrastructure, which consists of 14 099 nodes (substations) and 19 657 edges (transmission lines) [8], and is considered by many experts as the largest and most complex network of the technological age. In such a large power grid, a transmission line outage due to lightning strike or short-circuit (*local contingencies*) leads to the overload of parallel and nearby lines, which then also trip off. Then the power generated by some generators cannot reach distribution substations and ultimately consumers. *The power generation and consumption in the network is not balanced.* If the control action (such as using the spinning reserve, backup generators, or load shedding) fails to bring the power generation and consumption back to balance in time, the lines continue tripping and the power grid is passively split into several islands. When the balance condition is not satisfied in an island, the splitting continues, and will cause a large-scale blackout (*global collapse*). This is what happened in the July 2, 1996 cascading outage of Western USA power network [17] and the August 14, 2003 blackout of the North American electric power network in the United States and Canada [18]. In the latter case, estimates of total costs in the United States range between \$4 billion and \$10 billion (US dollars) [19]. In Canada, gross domestic product was down 0.7% in August, there was a net loss of 18.9 million work hours, and manufacturing shipments in Ontario were down \$2.3 billion (Canadian dollars) [18].

Another example is on the US petroleum delivery network, which connects the domestic petroleum industries and imports (generation nodes) and the consumers (consumption nodes) together. In the summer of 2005, Hurricanes Katrina and Rita disrupted a substantial portion of production, refining, transportation and marketing sectors of the Gulf Coast oil and natural gas industries. These *local contingencies* broke the balance between demand and supply of the petroleum production, and greatly contributed to the record prices in the US oil market [20] and the decline of US petroleum delivery in 2005 (*global performance degradation*) [21].

Yet another and a most recent example is the pricing dispute between Russia and Ukraine on the natural gas. Russia supplies 25% of western Europe's gas. 80% of the supply comes through Ukraine. Central European nations also rely on Russian gas deliveries via pipelines through Ukraine. Due to a pricing dispute, Russia shut down some delivery systems and halted the gas delivered to Ukraine (*local contingencies*). This caused a shortage in Ukraine and throughout western Europe (*global performance degradation*). Although Moscow and Kiev officials praised a deal to end the pricing dispute on January 4, 2006, many European countries started to realize the vulnerability of their energy systems [22].

These examples show that local contingencies that break the balance between demand and supply can cause global performance degradation and even collapse. Spare capacity (e.g., the spinning reserve and backup generators in the electric power grid, the oil and natural gas reserved for the emergent demand) is usually used to bring the demand and supply back to balance in such emergent situations. However, spare capacity is costly, especially when it takes a big portion of the network capacity. Nowadays, many complex networks are with growing capacity, namely, power generation, oil and gas production are continuously being added. It is crucial to understand the relationship between the spare capacity and the collapse probability. This paper studies how this relationship changes as the network capacity grows.

To study the security aspects of resource networks under contingencies, we introduce the following terminologies. (Some of these terminologies are also defined in a more mathematically rigorous way in Section 2.) (1) A contingency that requires some nodes to be separated from some others will be called a *separation contingency*.[1] (2) The largest difference between the demand and supply that can still be brought back to balance later will be called the *tolerance* of the network.[2] (3) If a network can be partitioned into smaller sub-networks, which are balanced within a tolerance level, then the network is said to *possess the BP*

[1]For example, in a power grid a short circuit in the transmission line may cause the asynchronous among several generators. If the protection mechanism fails to bring these generators back to synchronous in time, then no protection measures can keep the integrity of the power grid. Some controlled system separation should be conducted to separate these asynchronous generators from each other, and keep the customers in each island continuing to be served, so that a blackout can be avoided. The shut down of part of the oil and gas delivery system may also separate some generation nodes from some others.

[2]Tolerance is a more general concept than spare capacity, which may have special meaning in engineering systems. When a contingency (e.g., loss of generation or line) happens, if the difference between demand and supply is no greater than the tolerance of the network, then there is some action (using spare capacity or cut off some unimportant demand) that can bring the difference back to zero. Otherwise, no action can keep the balance and the network starts passively splitting (some edges are removed continuously). So the tolerance describes the ability of a network to resist a contingency.