Complex Networks Analysis of Indian Power Grid

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Abstract

The Indian power grid is vulnerable to cascading failures as evidenced by two major blackouts in July 2012. Indian power grid is also grossly underrepresented in complex network power grid literature. We have studied cascade failure simulations on the power grid to find out the vulnerable nodes and edges. We have further tried to validate the results with cascade failure simulations going from the purely topological to DC load flow simulations.

Introduction

The power grid is the lifeline of our economy and society. Everything, from trade, commerce, transport, communication, healthcare to entertainment depends heavily on the power grid. Like the air we breathe, we have come to accept it for granted, not realizing that everything would come to a screeching halt without it.

A number of recent large blackouts in Europe, North America and India have highlighted the need for better power grid safety measures. On 30 July, due to a massive breakdown in the northern grid, there was a major power failure which affected seven north Indian states, including Delhi, Punjab, Haryana, Himachal Pradesh, Uttar Pradesh, Jammu and Kashmir, and Rajasthan(1). On the very next day, 31 July, the July 2012 India blackout, which is being called the biggest ever power failure in the world, left half of India without electricity supply. This affected hundreds of trains, hundreds of thousands of households and other establishments as the grid that connects generating stations with customers collapsed for the second time in two days. This points to the vulnerability of the Indian Power grid for large cascading failures. The traditional methods for analyzing the power grid have failed to identify said vulnerabilities. This calls for newer approaches to predict and prevent future cascading failures of the grid.

While there still exists some controversy about the causes of large cascading failures, their frequency is clearly not decreasing over time(Hines et al., 2009). This has brought many researchers from as diverse fields as physics, sociologists, economists and biologists to pursue a resolution to this problem.

Network Theory is a promising new discipline that identifies the statistical and topological properties of complex networks. Still in its infancy, it has already found widespread application in fields as diverse as gene-expression, traffic congestion, the spread of diseases, social network dynamics and memetics to name a few. Less of a discipline and more a collection of mathematical techniques, it has also been applied to power grids to identify their vulnerabilities. Network metrics like betweenness centrality and its many electrically extended siblings have been used to predict the vulnerabilities of different nodes, especially to targetted attacks.

Literature Survey

The bulk of work is separable into two categories-topological approaches and hybrid approaches. Topological approaches look for just the structural properties of the network disregarding dynamical aspects, whereas the hybrid approaches add to the topological approach some modifications borrowed from electrical engineering to achieve a more realistic albeit still simplified situation.

There are many approaches to modeling the power grid. The brute force electrical approach is extremely computation intensive and this has led to a number of simplified models being proposed in the literature(Nardelli et al., 2014).

Recent studies that approach the analysis of power grids as complex networks have yielded contrasting results (Hines et al., 2010; Ouyang et al., 2014). In particular, there has been some controversy about node degree distribution, with researchers reporting exponential and power-law functions for the same power grid region. Some other authors have introduced new metrics that extend the topological analysis by characterizing electrical properties of power grids.

Theories based on Self Organized Criticality concepts have been proposed to explain the incidence of large blackouts. Menck et al. 2014 have suggested a new concept of basin stability to analyze the power grid stability. One shortcoming of their approach is that basin stability does not work for riddled basins.

Some of the literature has aimed at discovering what type of prevailing network structure underlies power grid networks, if any. However, there appears to be no predominant structure (except for the fact that many grids have a heterogeneous nature). In fact, throughout the review, we see that there are several graph structures aiming at abstracting the real power grid topology. For instance, we have seen that the research in (Watts and Strogatz, 2011) pointed out that the US western power grid seemed to be a small-world network, while the work (BarabÃ¡si and Albert, 2011) suggested that the degree distribution of the power grid seemed to be scale-free following a power law distribution function, although not all subsequent works have agreed on this.

But most of these studies have been concentrated on the western world. In particular, there have been no more than three studies done on the Indian power grid(Das et al., 2013; Himansu Das, 2013; Zhang et al., 2013), only one of which analyzed the entire country(Zhang et al., 2013). The countrywide study focussed just on the mechanism and prevention of July 2012 failures. The study, conducted in 2012 considered 572 nodes and 871 edges is definitely dated as the power grid has more than doubled in that time period. This calls for a newer study into the vulnerability of the power grid. Here we fill that gap.

Methods

The data for this study was collected from power grid maps available on CEA's website[4]. The maps indicate the high voltage part of the transmission and distribution network in India, including all generation, transmission and distribution substations and the HV lines connecting them. The future extensions of the grid are also indicated. We represented the Indian Power Grid as a weighted graph, with the stations as nodes and the lines as edges with weights commensurate to their respective voltages. Although CEA's maps had topological and voltage information of the Indian Power Grid, it did not have the typical power flows and power limits for lines and stations. We realized that for a faithful simulation of cascade failures on the grid, power information was necessary. Hence we approached the Eastern Regional Load Dispatch Centre (ERLDC) for load flows. They allowed us to use their state-estimation simulation dataset which included complete information about the high voltage part of the grid for Static Load Flow Simulations.

Even though calculating structural vulnerabilities have distinct advantages to full-fledged power flow simulation in terms of both time and resources, yet the evidence in its support is not yet conclusive in the literature. Particularly, desynchronization, an important cause of failures has no analog in the topological model. Hence to corroborate the results of the previous section necessitates a fully functional simulation of the power grid. We regard the electromechanical, protective and control layers as sufficient for faithful short-term predictions. We apply Kron reduction to reduce the grid to just the generators without any loss of generality. The generators are modeled by the well-known swing equation. A load flow study is conducted to find the steady state of the system. Next, we create a disturbance by adding random noise of various sizes to the power lines at time zero and observe the response. In the initial studies, the protection layer is kept off to observe if the grid re-synchronizes spontaneously. The simulation shows that the dynamics are very different in the two cases making the case for accurate modeling of the power grid. We conclude that predictions of vulnerability obtained from simulations not taking the controllers into account are unreliable.

Conclusions

The Power Grids of various nations are under tremendous new stresses in recent years. Be it the unpredictability of Wind and Solar Generations and Electric Cars in the developed nations or the manifold increase in demand in developing ones, the power grid has to adjust at a phenomenal rate to accommodate the new demands placed on it. In addition to the traditional methods for Steady state and transient analysis, we need newer methods for optimal topological expansion and optimal control of the grid. A lot of work needs to be done especially on the Indian Grid, where it is particularly lacking, in applying novel techniques and looking for better ways of failure prevention. As we explored the techniques of network theory, we found its applicability limited and sometimes misleading. A lot of work hence needs to be done to find methods with better applicability to the power grid. In particular, desynchronization and transient stability need to be incorporated in some form for a more faithful representation of power grid instability.

Future Work

The real test of any physical theory is experiment. The results presented here have various simplifying assumptions backing them. How those assumptions chip away from reality is hard to ascertain, especially because simulating reality is such a huge computational burden. Let alone the fact that the knowledge of the various elements is ideal at best and the control and protective equipment are not even accounted for in our dataset. The resolution of the problem is to test the same on power grids of arbitrary sizes, firstly on simple ones with generators, lines and loads and progressively getting more complex with power electronics switching gear, compensators, VARs and finally including the control and protection infrastructures. It is of great importance and interest to study how these various levels of abstraction obfuscate the real picture and how much of it can be done away with without consequence.

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