



# Statistical trend tests for resilience of power systems

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## ARTICLE INFO

### Keywords:

Trend test  
Resilience  
Frequency of occurrence  
Performance loss  
Recovery time

## ABSTRACT

Through applications of relevant trend tests in the context of resilience analysis, this study conducts an empirical evaluation on the resilience of the U.S. power grid based on the database of the Electric Disturbance Events. To assess trends in systems resilience, we look into three key components associated with each black-out and recovery of power systems, i.e., the time between disruptions, the performance loss of each disruption and the time needed for recovery. We present a combined measure that takes into account all the three components. A modified Lewis–Robinson test is then developed for trend detection in this combined measure. To support the trend analysis of this combined measure, we further perform trend test for the performance loss and the recovery time. It is found that, among various North American Electric Reliability Corporation (NERC) regions of the U.S. power grid, the resilience in the Northeast Power Coordinating Council (NPCC) region has become better. Empirical evidence from the government financial support is used to substantiate these statistical findings.

## 1. Introduction

Electric power systems provide essential services for our daily life, and they have played a key role in the modern society and economy. However, they are exposed to various natural and man-made hazards, such as hurricanes, floods, earthquakes, and terrorist attacks. As power systems become increasingly complex, major disruptions are more damaging due to the interdependency within the systems. For example, during the 2003 Northeast blackout, a widespread power outage in the United States and Canada, 50 million people lost power for up to two days with estimated total damage up to \$6 billion. The blackout was initiated by a software bug in the alarm system, which then cascaded into a massive widespread power outage. Another example is Hurricane Sandy in 2012, the second costliest hurricane in the history of the United States, during which over 7.5 million people lost power.

Because of their importance, much research effort has been devoted to quantifying and enhancing the resilience of power systems to external shocks. Generally speaking, a resilient power system should have a low probability of failure upon a shock. Even if disrupted from a shock, it should incur minimum consequences and it should be able to quickly recover from the disruption to ensure sustained service deliveries. Based on these considerations, several definitions of resilience have been proposed. Among these definitions, resilience is commonly defined as the ability of the system to reduce the chances of shocks, to absorb a shock if it occurs and to recover quickly if a shock causes disruption. From a qualitative perspective, the main features of resilience are robustness, redundancy, resourcefulness, and rapidity [1,2].

For example, the U.S. Department of Homeland Security defined resilience as the ability to resist, absorb, recover from or successfully adapt to adversity or a change in conditions [3]. From a quantitative perspective, system resilience can be characterized by the resistant, absorptive and recovery capabilities. To quantify resilience, several resilience measures have been proposed. Bruneau et al. [1] introduced the resilience triangle paradigm to measure seismic resilience of communities. Some studies used probabilistic modelling approaches that integrate hazard models, component fragility models and restoration models [4,5]. A comprehensive review on the qualitative definition and quantitative measures of resilience can be found in [6].

Most of the existing literature focuses on the definition, modelling and analysis of system resilience. However, scant attention has been paid to its empirical evaluation and quantification, especially for power systems. The gap between the methodological studies and the practical applications motivates the empirical study in this work. In this study, we focus on testing possible trends in the resilience of the U.S. power systems using data. Useful information from the database of the Electric Disturbance Events (OE-417) is extracted and used in our analysis. We consider several important factors that are available in the database and closely related to the resilience of the power systems.

The first important factor of resilience is the ability to resist external shocks. External shocks, such as earthquakes, can be regarded as a stationary process in the long run. If the resistivity to external shocks decreases, the system would fail more frequently and the time between consecutive failures becomes shorter and shorter (in the stochastic sense). On the contrary, the disruption frequency of the system is

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**Notation**

|           |                                                 |
|-----------|-------------------------------------------------|
| $Z_{MH}$  | Military Handbook test statistic                |
| $Z_{MHP}$ | Pooled statistic for the Military Handbook test |
| $Z_L$     | Laplace test statistic                          |
| $Z_{LP}$  | Pooled statistic for the Laplace test           |
| $Z_{LR}$  | Lewis–Robinson test statistic                   |
| $Z_{LRP}$ | Pooled statistic for the Lewis–Robinson test    |
| $r$       | Number of disruptions                           |
| $Y_j$     | Severity level of the $j$ th power outage       |

|                   |                                                                        |
|-------------------|------------------------------------------------------------------------|
| $S(t)$            | Cumulative severity at time $t$                                        |
| $T_j$             | The $j$ th occurrence time                                             |
| $W_j$             | Inter-arrival time between the $(j - 1)$ th and the $j$ th disruptions |
| $X_j$             | Rate of increment of the cumulative severity during $(T_{j-1}, T_j]$   |
| $\tilde{Z}_{LR}$  | The modified Lewis–Robinson test statistic                             |
| $\tilde{Z}_{LRP}$ | Pooled statistic for the modified Lewis–Robinson test                  |

expected to drop when the resistivity increases. In this study, we will first look into the recurrences of disruptions in each of the eight North American Electric Reliability Corporation (NERC) regions in order to detect possible trends in the disruption pattern. Qualitatively, a simple and informative way to observe a trend is to plot the cumulative number of failures versus time, which is known as the Nelson-Aalen plot [7–9]. An upward trend reveals deterioration in the system while a linear line implies stable system conditions. In addition to graphical tools, the trend detection can be formulated as a hypothesis testing problem and so quantitative methods can be invoked. The null hypothesis is that the disruptions come from a stationary point process, e.g., a Homogeneous Poisson process (HPP) or a renewal process (RP). A HPP has independent and exponentially-distributed inter-arrival times, while the RP extends the HPP by allowing any positive distribution for the inter-arrival times [7]. When the null hypothesis is a HPP, the Military Handbook (MH) test, the Laplace test, and their generalizations are usually used [10]. When the null hypothesis is a RP, the Lewis–Robinson test is widely used [11]. A brief review of these tests is given in Section 3 of the paper.

Other than the rate of occurrence, the severity level of each disruption is also crucial for the assessment of system resilience. In this work, both the performance loss in terms of service deliveries and the recovery time are used to represent the severity of a disruption. The performance loss is dependent on the shock magnitude as well as the system's ability to absorb the shock. A big shock is expected to result in a large loss and a long recovery time. The duration of the recovery depends on the level of the performance loss as well as the resources available for the recovery, such as the maintenance team and emergency routines. A trend in the performance loss might reveal an improvement (or degradation) of the ability of the system to withstand the

shocks. On the other hand, a trend in the recovery time might reveal an improvement (or degradation) in the recovery capability.

In addition to the separate analysis of the disruption intensity and the disruption severity, we derive a composite index to measure resilience. Specifically, we define the cumulative severity of a system at a given time  $t$  to be the summation of the severity levels of all disruptions prior to  $t$ . The cumulative severity at time  $t$  is thus determined by the disruption frequency and the disruption severity. If either the disruption frequency or the severity increases while the other remains fixed, the cumulative severity would exhibit an upward trend over time. Therefore, it would be reasonable to use this index to represent the system resilience. In the paper, we develop a modified Lewis–Robinson test to detect trends in the cumulative severity function.

The rest of this paper is organized as follows. In Section 2, the background and the power grid data are introduced. In Section 3, three popular trend test methods are reviewed. In Section 4, we propose a composite index and develop a modified Lewis–Robinson test to detect possible trends. In Section 5, we perform trend tests on the performance loss and the recovery time. Some empirical evidences are given in Section 6. Section 7 provides conclusions and directions for future research.

## 2. Background and the power grid data

Fig. 1 provides a general schematic to understand the key elements in the definition of system resilience. A system is supposed to operate with a target performance  $TP(t)$ . In most methodological research, the target performance is assumed to be a constant with  $TP = 100\%$ . Disruptive shocks are observed during the time period  $[0, T]$ . For instance, the first disruptive shock occurs at time  $t_1$ , and the system enters into a

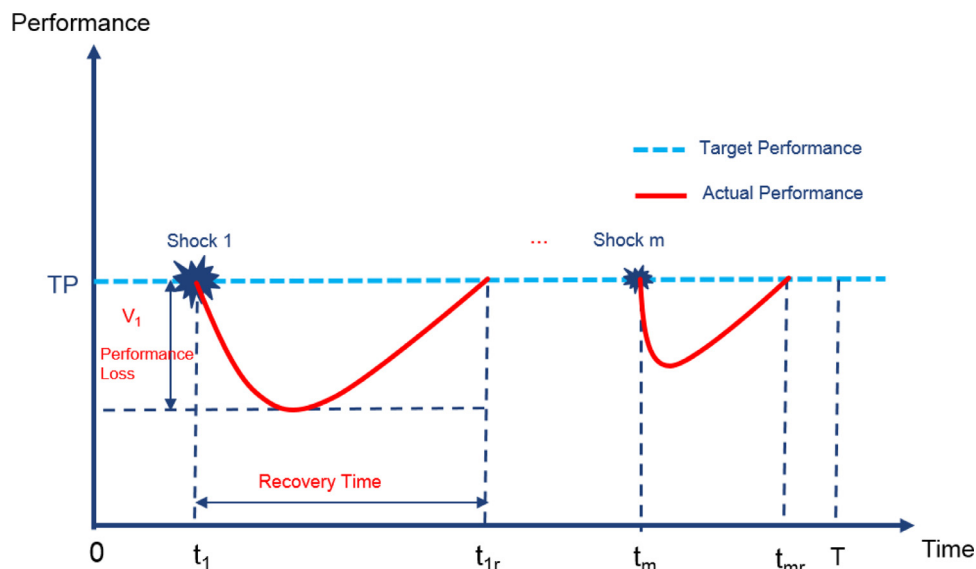


Fig. 1. Graphical depiction of the system performance over multiple shocks in time.

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