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Published in:
IEEE Transactions on Power Systems

Link to article, DOI:
10.1109/TPWRS.2017.2704901

Publication date:
2018

Document Version
Peer reviewed version

Fractal Characteristics Analysis of Blackouts in Interconnected Power Grid

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***Abstract*—The power failure models are a key to understand the mechanism of large scale blackouts. In this letter, the similarity of blackouts in interconnected power grids (IPGs) and their sub-grids is discovered by the fractal characteristics analysis to simplify the failure models of the IPG. The distribution characteristics of blackouts in various sub-grids are demonstrated based on the Kolmogorov-Smirnov (KS) test. The fractal dimensions (FDs) of the IPG and its sub-grids are then obtained by using the KS test and the maximum likelihood estimation (MLE). The blackouts data in China were used to demonstrate the similarity of distribution characteristics and FDs of the IPG and its sub-grids. The results are consistent with the development of the power grids (PGs).**

***Index Terms*—Blackout, complex network, fractal dimensions, interconnected power grid, power failure models.**

I. Introduction

PREVENTING blackouts of power systems is a great challenge due to the complexity of interconnected PG. Various failure models have been proposed to discover the mechanism of blackouts. However, there are some assumptions in the models to simplify the analysis due to the complexity of the system [1], such as ignoring some of electrical characteristics, which may result in misleading conclusions.

The complex network theory is widely used to analyze global behaviors and dynamic features of power systems. Power systems have self-organized criticality (SOC) [2]-[3]. It is described by power-law (PL) relationship in (1) between the occurrence probability of blackout $P(x)$ and its size x, usually represented by the total loss of power.

$$P(x) = cx^{-\alpha}. \tag{1}$$

where c is a constant, and α is the FD which describes the relationships of blackouts in the IPG and its sub-grids. The PL distribution implies the self-similarity [4]. The parameters c and α estimated by curve fitting with free linear binning (CF-LB) of blackout data have deviations which affect the judgment of the fractal relationships of various grids.

The main complexity of failure models is the high dimension and high order due to large-scale networks. According to the fractal theory, fractal describes shattered geometries or evolving patterns whose components are similar to the whole in a certain way. Fractal is the result of dynamic evolution to the critical state of a system [4]. Some electrical characteristics, such as load in the same or different regions, have fractal features [5]. If PGs follow similar PL distribution, the dynamic process towards the SOC state will be similar [6]. Therefore, if similarity relationships among a large IPG and its sub-grids exist, the evolution model of the large IPG can be simplified with sub-grids with similar characteristics. In this letter, similarity of blackouts in IPGs and their sub-grids is discovered, which provides a new way to obtain reduced failure models.

II. Method of Fractal Analysis

The blackout data are grouped into various vectors by topology partitions of the grids. For non-normal distribution, the Kolmogorov-Smirnov (KS) test is a suitable method to quantify the differences between two distribution models, two data series, and the actual data and the fitting model. In the test, the null hypothesis H_0 is that the distribution characteristic of each sub-grid is the same as that of the IPG. Then, the KS test is applied to each group including two sorted data vectors. The maximum distance D between these two vectors is,

$$D = \max\left|F_1(x_i) - F_2(x_i)\right|. \tag{2}$$

where x_i is the sample of blackouts in various PGs, $F_1(x_i)$ and $F_2(x_i)$ are the cumulative distribution function of the IPG and the sub-grid, which can be calculated by,

$$f_{yj}(x_i) = \frac{1}{n_y}\sum \aleph[x_i \geq x_j](y = 1, 2). \tag{3}$$

where x_j is the jth interval point in the vector, and f_{yj} is the jth element in F_{yj}(y=1, 2). $\aleph[\bullet]$ is 1 if the statement in bracket is true, otherwise 0. n_y is the number of the samples. When D is less than the critical value at the given confidence level, the null hypothesis H_0 shall be accepted. The two data vectors follow the same type of distribution.

Using the statistical method in [7], the accurate FD of each grid can be obtained. By applying the MLE with the KS test (MLE-KS), the starting-point x_{th} of the PL tail is determined. Set x_i as the size of the ith blackout, n is the number of events above x_{th} in each sub-grid. The FD of each sub-grid is,

This work was supported by *the National Nature Science Foundation of China* (No. 51307148).

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$$\alpha = 1 + n[\sum_{i=1}^{n} \ln \frac{x_i}{x_{th}\text{-}0.5}]^{-1}. \quad (4)$$

III. Blackout Data Description

The blackout data in China from 1981 to 2002 are used to analyze the fractal characteristics. The blackout sequence including 124 major events from 1981 to 2002 is shown in Fig. 1. The total loss of power in MW is used to calculate the FD. The blackouts of four sub-grids, including the Northeast China Power Grid (CPG), Central CPG, Northwest CPG, and Southern CPG, are extracted. The first three belong to the State Power Grid Corporation (S_1), and the last one belongs to the Southern Power Grid Corporation (S_2).

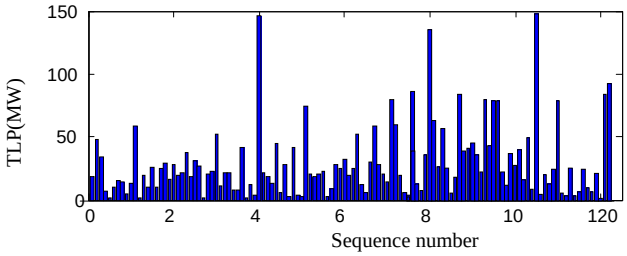

Fig. 1. Blackouts sequence

IV. Results and Related Development of PGs

A. Distribution Characteristics and Fractal Dimensions

By using the KS test, the results of *D* between each sub-grid and the IPG are shown in the third column of Table I. The distance *D* between Southern CPG and IPG is larger than the critical value at the given confidence level. However, others are less than the corresponding critical value. The sub-grids in S_1 and the IPG have similar distribution characteristics, and the Southern CPG has another distribution characteristic.

The FD of events in the IPG is obtained by two methods: the CF-LB in [6] and the MLE- KS. The distances *D* between real data and the fitting model are also given. The CF-LB method cannot meet the critical value requirement of *D*. The FD from the MLE-KS method is more accurate than that from the CF-LB because there is smaller D in the MLE- KS.

TABLE I Test results of *D* Between IPG and Sub-grids

Sub-grid	Number of events	*D*	Critical value (10% confidence level)
Northeast	26	0.1923	0.2632
Central	15	0.2129	0.3335
Northwest	34	0.1983	0.2362
Southern	26	0.2885	0.2632

TABLE II Fractal Dimensions with *D* of IPG

Method	α	*D*
CF-LB	2.2158	0.3237
MLE-KS	2.6221	0.0925
Critical value		0.1549

TABLE III Fractal Dimensions of Various Power Grids

Grid	IPG	Northeast	Central	Northwest	Southern
α	2.6221	2.5689	2.2338	2.9807	3.3751

The FDs of various sub-grids calculated by the MLE-KS are in Table III. The sub-grids in S_1 and the IPG have similar FDs if the FD values are within the typical range of scale-free complex network ($2 < \alpha < 3$).The results are consistent with the results in Table I.

B. Fractal Dimensions with the Development of Power Grids

The results above show the sub-grids in S_1 and the IPG have similar distribution characteristic and FD. However, the Southern CPG in S_2 does not. It matches the development of the PG in China. With the West-East Electricity Transmission Project, a special interconnection of the Southern CPG with corresponding operation and management is developed, which enhance the fault tolerance as indicated by the larger FD. The results using the CF-LB in [6] show the Central CPG and Southern CPG have similar FDs, however, other two sub-grids have different FD, which is inconsistent with the actual development of the PG.

A temporal and spatial power evolution model with different features in each sub-grid is developed. The FDs of simulation results of different sub-grid are consistent with assumptions in the evolving process. The consistency between real data and the evolution model proves the FD can reflect the structure and operation towards the SOC state. The similarity of FD can be applied to simply the evolving model of a high dimension power grid to a lower dimension one.

V. Conclusion

In this letter, based on the MLE-KS method, more accurate results of the distribution characteristics and FD of the IPG and its sub-grids are obtained, which can improve the evaluation of similarity of dynamic process towards the SOC state. The similarity can be used to reduce the dimension of the large scale evolving models by using small scale similar sub-grids. In the reduced failure models, comprehensive measures can be tested to prevent large blackouts.

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