Electrical Power and Energy Systems 78 (2016) 480–488

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

# Considering risk of cascading line outages in transmission expansion planning by benefit/cost analysis

Ebrahim Karimi *, Akbar Ebrahimi [1]

*Esfahan Regional Electric Company, Isfahan University of Technology (IUT), Department of Electrical and Computer Engineering, Isfahan, Iran*

ARTICLE INFO

*Article history:*
Received 2 July 2014
Received in revised form 25 May 2015
Accepted 17 November 2015
Available online 23 December 2015

*Keywords:*
Cascading outages
Blackout risk
Transmission expansion planning

ABSTRACT

It has been shown that large blackouts happen more likely than may be expected. Recent investigations revealed that cascading outages are the major cause of power system blackouts. Therefore, risk of cascading outages must be considered in the planning and operating procedures. In this paper a novel procedure is proposed for transmission expansion planning (TEP) by using the ORNL–Pserc–Alaska (OPA) model. Some improvements are introduced to this model for choosing more effective candidate transmission lines to be used in TEP regarding risk of cascading outages. A nonlinear estimation is used to assess the consequences of blackouts after cascading transmission line outages. The power law as a fingerprint of self-organized criticality in power systems is used to calculate the likelihood of blackouts. The benefit of each policy to expand the transmission system is derived from risk assessment and the best one is picked out using benefit/cost analysis. The simplicity of the proposed method makes it appropriate in real life. The proposed method is applied to test systems to investigate its applicability. The results provide motivation for considering the risk of cascading line outages in TEP that afford substantial saving to society.



## Introduction

### *Problem definition*

Planning is a procedure concerned with determining the resources required to achieve the predefined goals while minimizing invested cost as well as wasted time. Planning typically provides a unique opportunity for introducing new concepts and focused discussions between the various entities involved for later activities.

Cascading outages are the main cause of large blackouts [1]. Power system blackouts attained considerable attention among power system experts, because blackouts involve considerable impacts including direct and indirect to society [2]. Though engineers have performed valuable efforts in various fields to improve power system reliability, the number of blackouts increased over the world. Therefore, there are more tendency among electric power industry to consider cascading outages for improving the reliability of the system [3]. On the other hand, it was demonstrated that small and large blackouts are mutually coupled by complex dynamics [4], therefore investments to reduce small blackouts might increases large blackouts and vice versa even with similar budgets. We try to meet these questions:

- How shall planners consider blackouts caused by cascading outages in their planning?
- Does the decision maker should accept or reject the policies to suppress small blackouts?

### *Literature review*

SOC is a feature of complex systems and power law is a hallmark of SOC. A Power law is a region in the tail of PDF which seems as a straight on a log-log plot. Many diverse ranges of phenomena such as the strengths of earthquakes, population of cities, and forest fire sizes exhibit power law [5]. Power law indicates that occurrence of large events in the tail of PDF are more probable than Gaussian PDF [6]. In other words, power law shows that the outcomes of rare events are immensely high and more probable than might be expected. It has shown that SOC-like dynamics force correlation among failures in power systems [6]. Indeed, in power system, interaction between two opposing forces which are growing demand and engineering responses to that leads to complexity.

* Corresponding author. Tel.: +98 31 50104531; fax: +98 31 36271685.
*E-mail addresses:* e.karimi@ec.iut.ac.ir (E. Karimi), ebrahimi@cc.iut.ac.ir (A. Ebrahimi).
[1] Tel.: +98 31 33915437.

http://dx.doi.org/10.1016/j.ijepes.2015.11.101
0142-0615/

**Acronyms**

| | |
|---|---|
| BC | Base Case |
| CLM | Crucitti–Latora–Marchiori |
| ENS | Energy Not Supplied |
| IEAR | Interrupted Energy Assessment Rate |
| LP | Linear Programming |
| NERC | North American Electric Reliability Corporation |
| NPV | Net Present Value |
| OPA | abbreviation of the first letters of the authoring institutions: Oak Ridge National Laboratory, Power Systems Engineering Research Center at the University of Wisconsin, and University of Alaska |
| OPF | Optimal Power Flow |
| PDF | Probability Density Function |
| SOC | Self-Organized Criticality |
| TEP | transmission expansion planning |
| VRC | Visual Risk Criterion |

*Nomenclature*

| | |
|---|---|
| $C_n$ | investment cost of scenario $n$ in $M |
| $\Phi$ | maximum investment cost |
| $m$ | permissible number of lines in a cascade |
| $\Omega_m$ | set of all candidates for an arbitrary $m$ |
| $\Omega_g$ | set of generators |
| $\Omega_b$ | set of buses |
| $i, j$ | index of buses |
| $n$ | index of scenarios |
| $t$ | index of time steps |
| $E_{n,t}$ | ENS on day $t$ for scenario $n$ (0 for the BC) |
| $D_{n,t}$ | total duration of the blackout on day $t$ for scenario $n$ |
| $R_{n,t}$ | risk of blackout on day $t$ for scenario $n$ |
| $R_n$ | present value of the risk of blackouts in the network in scenario $n$ |
| $S_n$ | total saving of implementing scenario $n$ |
| $J$ | benefit/cost criterion |
| $n_{ol}$ | number of tripped lines in the cascade on day $t$ |
| $L_i$ | curtailed load of bus $i$ after OPF on day $t$ |
| $L_t$ | optimum curtailed load on day $t$ after OPF |
| $\delta_i$ | voltage angle of bus $i$ |
| $x_{ij}$ | reactance of branch connecting buses $i$ and $j$ |
| $P_{di}$ | load of bus $i$ |
| $P_{gi}$ | optimal injected power at bus $i$ |
| $P_{gi,min}$ | lower limit of injected power at bus $i$ |
| $P_{gi,max}$ | upper limit of injected power at bus $i$ |
| $T_{ij}$ | power flow of branch between buses $i$ and $j$ after OPF |
| $T_{ij,max}$ | emergency rating of branch between buses $i$ and $j$ |
| $k_{ij,m}$ | index represents upgrading times of the branch between buses $i$ and $j$ for an arbitrary $m$ |
| $D$ | PDF of simulated data by the OPA |
| $F$ | PDF of fitted power law to $D$ |
| $\alpha$ | scaling exponent of the fitted power law |
| $A$ | normalization constant of the fitted power law |
| $x_{min}$ | minimum value of a power law region |
| $N$ | total number of days in the planning horizon |
| $\beta$ | scaling exponent in the risk of blackout |
| $r$ | discount rate per day |
| $\lambda$ | rate of load growth per day |
| $\mu$ | line rating upgrade per day after a cascade occurred |
| $p_0$ | forced outage rate of lines |
| $p_1$ | probability of tripping overloaded lines |
| $p_{n,t}$ | probability of a blackout occurred on day $t$ for scenario $n$ |

As studying various possibilities of multiple contingencies or blackouts caused by cascading outages are inevitable for existing power systems, deterministic criteria are not adequate anymore. In the other hand, our calculation facilities are limited. Blackouts as rare events caused by cascading outages are more likely and must be regarded in power system studies and risk of blackouts could be assessed by using complexity science [4]. The OPA model is a useful tool constructed using SOC to study sequential outages of transmission lines for simulating blackout time series [7,8]. This model affords a passage for including cascading outages of transmission lines into TEP. TEP problem typically maximizes the benefits such as decreasing energy not supplied, and losses during minimizing investment and maintenance costs [9]. Refs. [10–12] have reviewed TEP problem. According to the planning horizon two types of TEP are static TEP, and dynamic TEP [13]. The latter as a more complicated method determines the time of constructing new lines.

TEP is a mixed-integer, large scale, non-linear programming problem, for which finding an optimal solution is extremely challenging [14]. Up to now different concepts have been included in. Reliability aspects were considered in TEP [15–18]. Ref. [19] proposed a model to include uncertainty of the generation and load scenarios in risk analysis of TEP. Also, Demand uncertainties effects on TEP were studied in [9]. However, considering new ideas such as cascading outages in TEP make it more complicated unless some simplifications are used.

Cascading failures defined in [20] as the sequences of dependent failures occur sequentially and decline power system. Small initiating failures in power network might spread through the system and cause large cascading failures [21]. CASCADE [22], Manchester [23], and CLM [21] are models proposed for simulating some known mechanisms of cascading failures in power systems. The OPA just models successive tripping of overloaded transmission lines [7] as simple as possible. Therefore, the OPA could be used with relative ease for simulating a time series of blackouts, which make it appropriate for exploiting in TEP.

*Contribution of this paper*

This paper addresses:

(1) Including the risk of blackouts in TEP.
(2) A nonlinear estimation of the blackouts risk.
(3) A modification to the OPA in order to identify effective candidate lines.

Accordingly, in the static proposed TEP procedure, a set of candidate lines is firstly selected using the OPA model. The probability of each state in the risk assessment is determined by fitting a power law. The risk of each scenario is calculated by cumulating present values of risks over the process. These values are then used in benefit/cost analysis to find optimal plan. The statistical manner of the proposed method which is borrowed from the OPA provides it the ability to deal with the uncertainty of generation expansion plans and load growth.

*Paper organization*

The organization of this paper is as follows. The next section presents the fundamentals of the proposed method. The proposed algorithm is described in section 'Proposed method'. The applicability of the proposed method is examined for two IEEE test systems in section 'Case studies'. Finally the conclusions of the paper are provided in section 'Conclusion'.