Electric Power Systems Research 107 (2014) 144–152

Contents lists available at ScienceDirect

Electric Power Systems Research

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

# Inter-area frequency control reserve assessment regarding dynamics of cascading outages and blackouts

O. Alizadeh Mousavi*, M. Bozorg, R. Cherkaoui, M. Paolone

*École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland*

ARTICLE INFO

*Article history:*
Received 21 February 2013
Received in revised form 13 August 2013
Accepted 1 October 2013

*Keywords:*
Cascading outages
Monte Carlo simulation
Interconnected power system
Short-term dynamics

ABSTRACT

The study of the dynamics taking place during power system blackouts is a subject that receives continuous attention in view of its inherent complexity and relevant consequences. Within this context, the paper aims at studying the role of the frequency control reserves (FCRs) on the cascading outages and the relevant short-term dynamics associated with the blackout mechanisms. The relationship between the large and small blackout frequency with respect to the value of FCRs is assessed. More in particular, the main contribution of this paper is to study the influence of the power system interconnections on its pre- and post-blackout behavior. For this investigation, a statistical procedure, based on the Monte Carlo simulation (MCS), is proposed. It performs a blackout risk analysis considering cascading outages as well as generators/loads response to the frequency deviation. The proposed procedure is then applied to the IEEE 118 bus system as an interconnected network characterized by three areas. The distributions and expected values of the blackout size are assessed for the whole system as well as for each area.



## 1. Introduction

Power transmission networks are large and complex systems that have experienced wide blackouts in the recent two decades (i.e. the Northeast and Italy blackouts in 2003 and India 2012). Although large cascading blackouts are relatively rare events, the investigation of their mechanism calls for significant efforts in view of the relevant consequences. Understanding the dynamics of power system components through their interactions with different control methods are the main challenges to comprehend a blackout mechanism. In this respect, several investigations have been performed in the literatures [1–6]. An additional aspect that increases the difficulty of the problem is the operation of single power systems within an interconnected continental-scale grid (e.g. interconnected networks in continental Europe – ENTSOE and North America – NERC). The areas of an interconnected power system generally profit from (i) increased security and (ii) mutual economically efficient generation. The higher security margins are a consequence of shared active power reserves. However, the security of the resulting interconnected power system could decrease with the increase of the interconnection and, consequently, with the increase of the power systems operation-complexity due to propagation of events, inter-area oscillations, etc. Hence, the delivery of required control actions should be carefully evaluated due to the counter-intuitive effects of opposing driving forces in power systems.

The analysis of the times series of blackouts size measures, e.g. energy not served (ENS) and load not served (LNS), in North America, China, Sweden, Norway, New Zealand, and continental Europe has shown a power law region in their distributions. This peculiarity demonstrates that the dynamics of blackouts can be associated to complex systems with self-organized criticality (SOC) feature [1]. In the system with the SOC characteristic, there are different types of variables with opposing driving forces that, in certain conditions, could drive the system into a critical operation state. In this case, after the occurrence of an initial fault or disturbance, cascading outages could cause a blackout (e.g. [2]). Furthermore, the power law region in the distributions implies that the blackouts of different scales may take place and the extreme events cannot be overlooked. The system may experience large blackouts with certain probabilities and the occurrences of small/large blackouts are not independent but correlated to each other (e.g. [3,7]).

It should be noted that the study of power systems short-term dynamics assumes a system with a fixed topology. Therefore, the continuous evolution of the power system state and configuration under complex dynamics are, in general, neglected [8]. By making use of the above-assumption, and within the context of risk assessment, this paper investigates the role of frequency control reserves (FCRs) on cascading outages and short-term dynamics of blackouts with particular reference to interconnected systems. The structure of the paper is the following: Section 2 provides the problem definition, Section 3 describes the blackout risk assessment methodology, Section 4 illustrates and discusses the simulation

* Corresponding author. Tel.: +41 21 693 46 61; fax: +41 21 693 46 62.
*E-mail address:* omid.alizadeh@epfl.ch (O. Alizadeh Mousavi).

0378-7796/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsr.2013.10.001

results with reference to the IEEE 118 bus test system considered as an interconnected network with three main areas, Section 5 discusses the possible approaches to solve the analyzed problem and Section 6 finally concludes the main outcomes of this study.

## 2. Problem definition

The different aspects of the cascading dynamics could be investigated in different time scales, namely, long-term, short-term, and transient dynamics [2]. The long-term dynamic investigates the role of load growth and engineering responses as external opposing forces to evaluate the system margins from critical loading in monthly or yearly time scales. The short-term dynamic in the range between several minutes to an hour, represents the internal system driving forces while the external forces are approximately remaining constant. It is associated with redistribution of power flows after the event and the response of controllers designed beforehand. The transient dynamics from milliseconds to seconds represents the inductive factor initiated by transient instability subsequent to large disturbances. The successive transient dynamics may cause abrupt outages.

The understanding of these dynamics can help to analyze characteristics of disasters and catastrophes, to evaluate the distance between the system's current state and its critical state and then to design preventive control strategies. In this respect, the blackout dynamics of the power grid should be appropriately modeled. Various methods have been proposed to model and analyze different aspects of blackouts in long-term, short-term and transient dynamics [9], such as, hidden failure model, OPA (ORNL-PSerc-Alaska) model, Manchester model, optimal power flow (OPF) based model and OPF transient stability (OTS) model. Besides these research models, several commercial tools have been developed in the industry, for instances, ASSESS, CAT, POM-PCM, TRELSS [9].

In this paper we focus specifically on the short-term dynamics of blackouts concerning the FCRs. The main idea is to study the dynamics of blackouts regarding the counteraction of the FCRs and the load shedding (including load curtailment and under-frequency load shedding) and their impacts on the cascading outages. In traditional approaches, regardless cascading outages, it is considered that the higher amount of the FCRs leads to the higher system security. Whereas, on one hand, a smaller amount of the FCRs may cause successive actions of under-frequency load shedding which increase the number of small blackouts. On the other hand, an excessive amount of the FCRs avoids the operation of the under-frequency load shedding and decreases the probability of small blackouts. However, it can increase the probability of line overloads that produces a triggering of cascading outages and consequent large blackouts. One may state that, within the context of the real operation of a given power system, the operator should ensure, for the different time frames, the transferability of FCRs avoiding transmission lines overloading. However, in the provision of control actions of interconnected power systems operated by several operators with limited coordination, it is practically impossible to take into account all possible contingency scenarios $N-k$ ($k=1,\ldots,N$) together with cascading failures.

In order to study the aforementioned phenomena, a blackout risk analysis method based on Monte Carlo simulation (MCS) is proposed. It takes into account different aspects such as the effects of cascading outages and the response of generating units/loads to the power imbalance. As a result, appropriate modeling of the fast and slow progress events, and the corresponding response of controllers, are necessary to study the blackout dynamics in power systems [10].

In blackout dynamics, cascading outages of overloaded components can progress either quickly or slowly. Fast progress events,

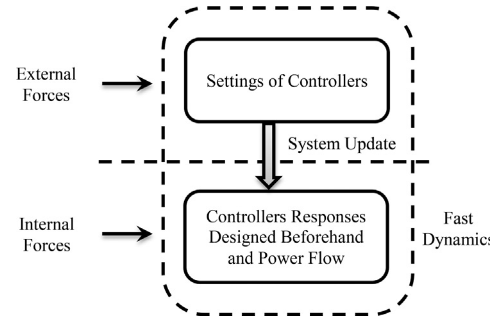


**Fig. 1.** Fast dynamics and external/internal forces.

initiated by large outages, involve different types of instability phenomena in time scales of seconds to several tens of seconds. Slow progress events are, typically, line tripping due to overloading in minutes time scales [11].

Concerning what FCRs entail, across different systems there are many different terms, definitions, and rules [12]. In this paper, the frequency reserve services are classified into automatically and manually activated FCRs given by $P_{gA}$ and $P_{gM}$, respectively. According to the hierarchical FCR classification (with primary, secondary and tertiary), the automatic FCR can be considered, in general, as primary and part of the secondary whereas the manual FCR is composed of the remaining part of the secondary and the tertiary. After a contingency occurrence, it is assumed that the automatic FCRs are decentrally activated in proportion to the frequency deviation to restore the equilibrium between generation and consumption in the operating time frame. Then, cascading outages progress in the system according to the re-established balance and the new power flows resulting from the activation of reserves. After a certain time, the system operator optimally deploys the automatic and manual FCRs to avoid the overloading and minimize the load curtailment in a centralized manner. Other control means, such as modification of line topology or adjustment of phase shifters, could also be used by the system operator. However they have been disregarded in the development of this paper for the sake of simplicity. In this respect, further investigations are needed.

In view of the above, the proposed model aims to effectively show the interaction between FCRs and load shedding as opposing forces in the short-term dynamics. The set points of the controllers designed beforehand, as external driving forces, are assumed to be fixed during fast dynamics. The general structure of this model is shown in Fig. 1.

From the practical point of view, the ENTSOE allows exchange, sharing and distribution of reserves between synchronous areas so that the activation of these reserves does not jeopardize the system security [13]. A survey study has been published in [6] concerning the assessment of inter-area FCR by means of different approaches that accounts for the system security. However, none of these approaches captures the dynamics of the cascading events and blackouts. Consequently the risk of large blackouts is not taken into consideration effectively.

## 3. Blackout risk assessment method

This section describes a statistical method which aims to numerically evaluate the risk of cascading blackouts regarding the FCRs. The method considers the following elements: (a) the effects of cascading outages due to overloads and hidden failure of protection systems, (b) the response of the FCRs of the generating units and the self-regulation of loads to power imbalance (i.e. frequency deviation) in each step of cascading outages. The preliminary version of this method is presented in previous works published by the