Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Quantitative analysis on the impact of nuclear energy supply disruption on electricity supply security

Shoki Kosai[a,*], Hironobu Unesaki[a,b]

[a] Graduate School of Energy Science, Kyoto University, Yoshida Honmachi, Sakyo-ku, Kyoto 606-8501, Japan
[b] Kyoto University Research Reactor Institute, Kumatori-cho, Sennan-gun, Osaka 590-0494, Japan

HIGHLIGHTS

- The electricity demand and supply model is constructed using system dynamics.
- The methodology of quantifying the nuclear vulnerability is established.
- The new electricity supply security index dedicated for nuclear power utilization is developed.
- The relationship between diversification, redundancy and nuclear vulnerability is analyzed.

ARTICLE INFO

Keywords:
Energy security
Nuclear
Diversification
Redundancy
System dynamics
Fukushima nuclear accident

ABSTRACT

Improvement of power supply security is of paramount importance to sustain human activities. Technical and engineering failures of power grid system have been analyzed to evaluate power system reliability hitherto. However, after Fukushima nuclear accident, the sudden electricity supply disruption particularly associated with nuclear energy utilization brings upon a new risk of electricity supply security arising from societal issues, or nuclear vulnerability. As such, a methodology of quantifying nuclear vulnerability is firstly established under varying both the magnitude and time instant of sudden stoppage of nuclear power operation. Through the nuclear vulnerability analysis, a new electricity supply security index dedicated for nuclear power utilization, named System Interruption Nuclear Vulnerability Index (SINVI) is developed. SINVI could be used to predict the risk of electricity supply disruption arising from the sudden stoppage of nuclear power operation corresponding to the different capacity combination of various energy sources. Finally, the widely proposed dimensions of energy security for undisturbed electricity supply – diversification and redundancy – are incorporated with nuclear vulnerability to design the more secured power system taking into account the risk of nuclear energy utilization. The established algorithm can be readily implemented in any other electricity grid network including nuclear power technology.

1. Introduction

In last decades, the global energy security has been critically threatened by heavy reliance on fossil fuels. The improvement of energy security is of paramount importance to achieve the sustainable development. Especially, given that the undisturbed electricity supply is essential for sustaining quality of human life, the design of strengthened electricity grid is vital to ensure continuous electricity supply.

Pertaining to the undisturbed electricity supply, power system reliability is one of the major aspects in the energy security narratives. Power system reliability is referred to the ability of the power system to deliver electricity to consumers within accepted standards and in the amount desired [1]. Based on frequency and voltage control of electric power grid illustrated as indicators of reliability dimension [2], numerous research works on power system reliability from the viewpoint of cascading outages under external disturbances such as short circuits are hitherto published [3–7]. These existing reports principally tend to address technical and engineering failures of power grid system. Following the technical analysis, the electric utility industry has developed several performance measures to evaluate power system reliability [8,9]. These reliability indices include measures of outage duration (System Average Interruption Duration Index (SAIDI), and Customer

Abbreviations: CAIDI, Customer Average Interruption Duration Index; CAIFI, Customer Average Interruption Frequency Index; HHI, Herfindahl-Hirschman Index; LNG, liquefied natural gas; SAIDI, System Average Interruption Duration Index; SAIFI, System Average Interruption Frequency Index; SINVI, System Interruption Nuclear Vulnerability Index

* Corresponding author.
E-mail address: kosai0203@gmail.com (S. Kosai).

http://dx.doi.org/10.1016/j.apenergy.2017.09.033
Received 16 March 2017; Received in revised form 6 September 2017; Accepted 9 September 2017
0306-2619/

Average Interruption Duration Index (CAIDI)) and frequency of outages (System Average Interruption Frequency Index (SAIFI) and Customer Average Interruption Frequency Index (CAIFI)) based on the past experience data. These existing indices are practically utilized as complex metrics for evaluating reliability in the energy security narratives [10]. In addition, probabilistic method has been also utilized for the evaluation of power system reliability [7,11,12]. Both loss-of-load probability (e.g. [13,14]) and loss-of-power-supply probability (e.g. [15,16]) are probabilistic models for examining the design of power system.

Notwithstanding the fact that technical and engineering failures of power grid system have been analyzed to evaluate power system reliability hitherto, the risk of electricity supply disruption caused by societal issues cannot be simply ignored [17]. Particularly, current societal issues of electricity supply are strongly associated with nuclear energy utilization [18]. The significance of nuclear energy supply disruption can be well observed through the energy situation of Japan after the Fukushima Daiichi nuclear power plant accident. In the aftermath of the Fukushima nuclear accident, all nuclear power plants in Japan, which had previously contributed approximately 30% of the electricity supply, were shut down due to the request for reevaluation of safety performances, which led to the nationwide electricity shortage [19]. In order to cope with unavoidable energy shortage, Japanese government conducted planned power cuts [20], which led to the immediate electricity supply disruption. This critical situation of electricity supply revealed that the sudden supply disruption particularly associated with nuclear energy utilization should be considered as a new and significant risk to domestic energy supply security. In addition, other several reasonable societal issues such as lawsuit arising from public opposition movement [21], and notice of nuclear terrorism [22] would have potential to cause sudden disruption of nuclear energy supply.

Given that nuclear power share is expected to expand worldwide even after the Fukushima nuclear accident due to the acceleration of energy demand [23,24] and the core of energy security concerns is the risk of national vital energy services [25], it would be crucial to consider possible consequences of the potential disruption of nuclear energy supply for evaluating the security performance of electricity supply system. However, quantitative analysis of a set of relation between the sudden nuclear energy supply disruption and its impact on continuous electricity supply security (hereafter referred to "nuclear vulnerability") has only been scarcely discussed.

This paper will quantitatively assess nuclear vulnerability based on the concept of power security which is a part of reliability. The power security is the ability of the power system to remain self-sufficient after the occurrence of sudden disturbances [26]. Hu et al. examined recovery process from localized disturbances for evaluating the reliability of power system [27]. Hazi et al. analyzes the maximum restoration time after interruptions as the electricity reliability indicator [28]. This paper focuses on the controllability of alternative energy sources such as thermal power and pumped-storage hydro. This characteristic can support the continuous electricity supply even after the sudden stoppage of nuclear operation occurs. As such, nuclear vulnerability is analyzed based on the condition of both different magnitude of sudden stoppage of nuclear operation and the different time instant of stoppage occurrence, where the whole grid ends up not being able to meet the demand despite of the full of thermal power operation. Nuclear vulnerability analysis can provide the prediction of continuous electricity supply, which will help the utility manager to make an appropriate action based on the information on both the magnitude and the time instant of sudden stoppage of nuclear operation.

It must be mentioned that the aforementioned existing reliability indices are computed based on the past experience of the whole grid system and have been seldom used to predict the risk of electricity supply disruption corresponding to the different capacity combination of various energy sources. These indices also do no cover the concept of sudden supply disruption. However, the grid operation will require the more sophisticated index particularly associated with nuclear power utilization in which the future prediction on the risk of electricity supply disruption is presented to ensure the continuous electricity supply security [3]. Hence, through nuclear vulnerability analysis a new predicted electricity supply security index dedicated for nuclear power utilization will be provided in this research. No academic works on an application of amount of time the system can remain self-sufficient after the occurrence of sudden disturbances into the reliability index has been hitherto published.

Besides power system reliability associated with nuclear energy utilization, both diversification of electricity mix and redundancy of capacity sizing of electricity generation have been widely reported as major attributes to evaluate the security of continuous electricity supply and to improve the design of strengthened power system [2,10,29,30]. Especially, nations heavily relying on fossil fuel imports suffer from severe vulnerabilities of geopolitical stability [31]. Diversification of electricity generation by energy source type is essential to improve energy supply security [32]. Meanwhile, the concept of redundancy represents the reserve margin which is incorporated into energy system for external disturbances [33]. Adequate power system with spare capacity achieves the uninterrupted physical infrastructure [34]. Based on these considerations, both of diversification and redundancy should be incorporated with nuclear vulnerability to design the power system taking into account the risk of nuclear energy utilization.

As such, the objective of this paper is to establish the methodology of quantifying nuclear vulnerability in order to develop a new electricity supply security index dedicated for nuclear power utilization. This paper also aims to analyze the relationship of three major attributes for evaluating stable electricity supply system; diversification, redundancy and nuclear vulnerability. This research work especially focuses on modeling and forecasting the security of electricity supply taking into account the risk of sudden nuclear energy supply disruption. In addition, the proposed approach for evaluating the optimal use of energy resources will deliver the valuable insights for policymakers to develop the well-grounded energy policy including the societal aspects.

This paper proceeds as follows. Firstly, the methodology of quantifying nuclear vulnerability is established to obtain the continuous electricity supply security index dedicated for nuclear power utilization in Section 2. Subsequently, Section 3 analyzes the nuclear vulnerability quantitatively. In addition, the relationship between diversification, redundancy and nuclear vulnerability is evaluated in Section 4. Finally, Section 5 concludes this paper.

2. Methodology

The methodology in this research consisting of establishment of quantifying nuclear vulnerability, development of the new electricity supply security index dedicated for nuclear power utilization and analysis of the three attributes comprising of diversification, redundancy and nuclear vulnerability is presented in this section.

2.1. Site identification and construction of electricity supply model

The location of a reference case in this study for analyzing the impact of continuous electricity supply security has been identified as Kansai area. Kansai area previously included a significant share of nuclear energy in the region's electricity supply mix. Fukushima nuclear accident indirectly had an unavoidable impact on the electricity supply security in Kansai area despite of no physical damage to the electricity grid components; nuclear power had a considerable share of approximately 25% of capacity and 44% of generated electricity in 2010 at Kansai area [35], but all of its capacity has been turned off after the Fukushima nuclear accident. Even though Kansai area has a large sized PV and solar power plants, the share of renewable power is a mere 1.5% at present and thus the renewable power contributing to centralized