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Simulation of operational reliability of thermal power plants during a power crisis: Are we underestimating power shortage risk?

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HIGHLIGHTS

- A failure probability model for intensively used thermal power plants was developed.
- Repetitive accidents were modeled with accident probability using records.
- Higher probability of two or more accidents on specific plants was estimated during crisis.
- Bootstrap simulation was used to estimate risk of power shortages after disaster.
- Supply capacity should be underestimated during crisis to have citizens and business better prepared.

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ABSTRACT

The unscheduled outage of thermal power plants following the Great East Japan Earthquake in 2011 greatly degraded the reliability of the power supply. As thermal power plants were a major part of the supply capacity after the disaster, especially under peak load conditions, consumers located both within and outside the severely damaged area had to reduce power usage to meet power consumption targets and avoid major blackouts. Therefore, experts and decision makers should use the records available from such accidents to determine appropriate margins of supply capacity and demand constraint policy during a crisis. Here, we constructed a probability model describing the likelihood of accident occurrence for thermal power plants based on the actual accident and recovery data obtained after the Great East Japan Earthquake. The lognormal and Weibull hazard models fit the observed data well, where the accidents tended to occur for many times at the same power generation unit under heavy-duty conditions. We then applied the developed probability model to Japanese thermal power plants in a bootstrap framework to understand the potential risk of power shortages during such events and to derive policy implications.

1. Introduction

After a large-scale disaster, the stable operation of thermal power plants is critical for achieving rapid recovery of the damaged area. The Great East Japan Earthquake (March 11th, 2011) and the following power crisis [1–4] are a good example of this issue. To secure supply capacity in a situation where several thermal power plants are damaged simultaneously, it is necessary to operate unaffected plants effectively and restart old decommissioned plants after long-term shutdown. These measures can lead to an increased probability of accidents. In addition, damaged units of power generators must be quickly fixed in times of emergency. However, resuming operation of units after damage or accident without taking appropriate measures to ensure safe long-term operation can increase the risk of failures.

Records of damages resulting from disasters and subsequent unscheduled outages of thermal power plants in such a situation provide valuable information for preparing for future disasters or other scenarios involving power crises (e.g., long-term shutdown of nuclear power plants). For example, after the Great East Japan Earthquake, the Japanese government imposed legally binding electricity consumption restrictions on large-lot electricity users (contracts exceeding 500 KW). The appropriate usage limit should be determined based on analysis of power shortage risks and estimated probabilities of unexpected outages of power plants. This information is also practically important for

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periods of normal operation to evaluate the risks of intensive use and enhance the availability of thermal power plants.

Considering this background, we collected data of unscheduled outages of thermal power plants after the March 11th earthquake, constructed failure probability models, and studied the effects of the type of power generation, plant age, capacity, and history of accidents using the probability models. Several studies have addressed the modeling of accident occurrence in subsystems of a thermal power plant (e.g., steam and power generation facilities [5,6], gas or/and steam turbines [7,8], water feeding or treatment systems [9], and ash handling systems [10]. However, to the best of our knowlege, no previous studies included repetitive occurrence of accidents in the probability model parameters.

Using our model, we demonstrated that the failure probability increases if power generation is interrupted by an accident and the system temporarily recovers. While many previous stuides have constructed probability models, we demonstrate the viability of the model using specific data from a real crisis situation. Although, nonparametric models could be suitable, parametric model has some advantages for understanding the impact of important variables and applying the constructed model to other cases where original data is not available.

The major purpose of this study is to derive policy implications by analyzing the potential impact of unscheduled outages of thermal power plants on the power supply-and-demand balance. In particular, we discuss the risk of power shortages and the possibility of relaxing the demand constraints, which was in place after the disaster. The bootstrap method is employed for this purpose and the developed accident prediction models of thermal power plants are applied to actual units to understand the potential risks of supply shortages.

2. Review of previous studies

Many previous studies have evaluated the reliability of thermal power plants for the purpose of assessing the adequacy of power supply systems or devising appropriate maintenance schedules. Thermal power plants are complex engineering systems that consist of many parts, including coal handling, steam generation, electricity generation, cooling, and ash handling systems [5]. Therefore, reliability studies require a comprehensive understanding of the interconnections between subsystems and components of the overall plant. The complicated system has been visualized and modeled using Markov models, fault trees, Petri nets, and graph theory in an attempt to elucidate the reliability of thermal power generating systems based on the reliability of individual components.

Arora and Kumar [5] evaluated the reliability of steam and power generation systems in a thermal power plant by dividing each system into subsystems and modeling the relationships between the overall system status (good/reduced efficiency/reduced capacity/failed) and subsystem status (full capacity/reduced capacity/failed) using a Markov model. They estimated the availability of the systems by defining a status transition probability (failure and repair rate) for each subsystem. Other studies also employed the Markov model to evaluate the reliability of coal-fired power [11] and combined-cycle power plants [7] using sensitivity analysis of the failure and repair rates of components to identify critical components. A fuzzy Markov model has also been used to determine the uncertainty in data reliability and applies the methodology to evaluate the availability of condensed systems in thermal power plants [12]. In general, the Markov model has been widely applied for modeling the reliability of subsystems of thermal power plants [9,10,13,14].

Krishnasamy et al. [15] evaluated the reliability of an operating steam power plant in Newfoundland based on fault tree analysis by dividing the system into seven major subsystems and components. The failure probability of each component was modeled as Weibull or exponential distributions and their parameters were set based on the plant records. In addition, they estimated the risk level of components based on the function of failure probability and cost of failures to identify the critical components and design an optimal maintenance schedule. Such reliablity models are often used in developing risk-based maintenance policies.

Panchal and Kumar [6] presented an integrated framework to analyze the behavior of process plant systems using a Petri net model. The reliability of each component was calculated based on plant log book using a fuzzy $\lambda\!-\!\tau$ approach, and various measures of system reliability were quantified (e.g., failure rate, availability, MTBF). In addition, qualitative analysis such as failure mode and effect analysis was conducted to enumerate failure scenarios and they validated the methodology by applying it to the water treatment plant of a coal-fired power plant in India. Dev et al. [16] modeled a combined cycle power plant as a digraph assuming nodes as subsystems and edges as flows of materials (e.g., air, gas, or water) between subsystems. The digraph was translated into a matrix defining the value of diagonal elements as the reliability of subsystems and that of the off-diagonal elements as the reliability of connectedness.

The proportional hazard [17] and accelerated failure time models [18], which have been traditionally used in survival analysis, are also popular approaches for assessing failures that depend on time (lifetime). In these hazard models, the distribution of failure time depends on the assumed probability distribution and covariates. For evaluating the deterioration status of a 750 kV transformer, Wang et al. [19] employed a proportional hazard model and semi-Markov model (discrete deterioration criteria with working time memory). Among the covariates, aging has been shown to be a critical component for determining the system life [20]. As power plants can be affected by severe natural events, this should be incorporated in analysis of power plant failure in order to achieve more realistic and valuable predictions [21].

Power shortage analyses are often used for developing policies to be applied during a power crisis. Bo et al. [22] reviewed previous blackouts around the world and summarized their impacts and recovery measures. Rolling blackouts can be an effective policy during a power crisis; however the impact on society depends on whether clear information regarding the blackout schedule is provided to citizens [23]. The power crisis after the Great East Japan Earthquake has been intensively investigated considering the energy savings implemented by businesses and citizens [3,4]. The effects of increasing renewable energy supply to reduce the impacts of a crisis has also been studied [24]; this solution is currently a trend in Japan and other countries. From the perspective of the developed world, Eti et al. [25] reviewed the importance of analyzing thermal power plant failure risks and risk-based maintenance policies.

Our approach also follows the traditional probabilistic modeling method, especially in the field of survival analysis. The major purpose of modeling power accidents is to understand functionality losses of power plants as a group, especially under the heavily-used conditions during a crisis, and apply the model to power shortage analysis to identify hidden risks. Gils et al. had a similar aim [26]; they analyzed the securiy of the future power supply in Germany using a stochastic power availability model, but did not focus on power crisis situations. A limited study of power plant failure during a power crisis was presented [27], which investegated the effect of heavy use of thermal power plants during the California electricity market crisis of 2000–2001. Theiy demonstrated that the outage rate decreased significantly compared to historical outage rates at counterfactual conditions and concluded that high electricity prices motivated the power supply companies to emphasize generator maintenance.

Although our research aim was similar to Harvey et al. [27], we observed conflicting results for the Japanese disaster case study. We observed that short maintenance periods resulted in two or more continuous accidents for the same generation units. We investigated whether the failure probability depended on when the first accident occured for each power generation unit. In addition, we employed bootstrap methods to generate potential regional power shortages. In particular,