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Importance analysis of off-grid wind power generation systems

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ABSTRACT

Importance analysis is conducted for an off-grid wind power generation system, due to the lack of similar studies particularly on renewable energy systems. Birnbaum importance (BI) and criticality importance (CI) evaluation methods are used to evaluate the importance level of each component and investigate the impact of associated factors. Results reveal that 1) an increase in failure rate of component would cause a corresponding growth of the impact on system reliability, no matter which connection mode is selected; 2) connection mode plays a more important role than failure rate; 3) importance level would be increased with a decrease in the number of identical components connected in parallel; 4) a longer operational time would cause a higher probability of system failure. The implication in this study could drive a transfer of our major concern from the traditional 'system analysis' to the current 'component analysis'. This transfer could help to seek more theoretical bases in support of system design, process optimization, probability safety assessment, reliability analysis, etc.

Contents

1. Introduction

A number of studies have been undertaken to systematically analyze power systems from the perspective of 'system analysis', including numerical simulation, reliability analysis, system optimization, multicriteria analysis, etc. [1–9]. For example, Wangdee et al. introduced a methodology for reliability assessment of bulk electric systems containing large wind farms with sequential Monte Carlo simulation to simulate hourly wind speeds. Vaurio proposed that a component could have different roles in different phases and the reliability function would have discontinuities at phase boundaries [3]. Paliwal et al. proposed a probabilistic model for battery storage systems for facilitating implementation of analytical technique for reliability assessment of renewable energy sources; the proposed probabilistic battery state model comprises of multiple states of battery state of charge and probability associated with each state; to demonstrate the effectiveness of model, reliability assessment was further conducted based on a

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hypothetical autonomous PV-wind-storage system located in Jaisalmer, Rajasthan, India [6].

However, little effort has been taken for power systems from the perspective of 'component analysis'. Importance analysis, as one of such tools, can be used to prioritize components in a system, by mathematically measuring the importance level of each of the components. It is also helpful in identifying critical components in the system and developing design schemes to enhance system reliability. Different from the traditional 'system analysis', importance analysis is proposed from another perspective of 'component analysis', with the focus on each of the components and components' combinations. Outputs from 'component analysis' can be used to answer some key questions like: how important is a component, how should the components be interconnected, how many components should be used, what is best operational time for a selected component, etc.

Some studies have been undertaken regarding importance analysis [3,10–23]. Mathematically, importance analysis tools have been proposed to deal with coherent systems, where components are assumed to be statistically independent, without negations or mutually exclusive events [3,22]. Indices should be defined to measure the importance level of a component in a system. Birnbaum first proposed the concept of importance measure for quantitatively ranking the importance levels of components in a multi-component system [10]. It is usually defined as the partial derivative of the system reliability with respect to component reliability. As the most commonly-used definition, Birnbaum importance (BI) of a component indicates the change in the system unavailability given that the component went down [12,15]. Criticality importance (CI) is developed to prioritize reliability improvement activities and identify weak-links in the system with high efficiency. Aven and Nøkland investigated the rationale of uncertainty importance measures and proposed a combined measures sets, based on an integration of a traditional measure and a related uncertainty importance measure [13]. Borgonovo built a unified framework in both coherent and non-coherent systems; the total order importance measurement was proposed and in association with the utilization of joint and differential reliability importance measures are to provide reliability analysis with a complete dissection of system performance [14].

Si et al. also stated that importance analysis could be used in an engineering system, where the system components were ranked according to their contributions to proper functioning of the entire system; the most effective way of reliability enhancement could thus be explored based on the importance analysis results [23]. This can not only help determine which components merit more additional efforts to improve the overall system reliability at the minimum cost, but suggest the most efficient way of diagnosing the system failure by generating a repair checklist for an operator. Though importance analysis is significant and necessary for guaranteeing a normally working system, it should be noted that no importance analysis is universally the best irrespective of usage purpose.

Despite the abovementioned efforts, few of them have attempted to use importance analysis to assist in design of a renewable energy system. The lack of utilizing information regarding importance to design a system may lead to a difficulty in figuring out which components or which configurations of components are major contributors to system reliability or system failure. Actually, a well-designed system should guarantee not only the most cost-effective component numbers and configuration, but also identifying the most critical components among them. Only such a system is capable of working with good performance, even if unexpected system failure events occur accidentally.

Therefore, this study aims to present our investigation results obtained from the application of importance analysis to an off-grid power system. Birnbaum importance (BI) and criticality importance (CI) evaluation methods are used to evaluate the importance level of each component and further investigate the impact of the associated factors. Results from the investigation are expected to provide an insight into system design, process optimization, probability safety assessment and reliability analysis for renewable energy systems. The structure of the paper is shown as follows: Section 2 presents materials and methods; Section 3 detailed the obtained results from the application of importance analysis to an off-grid wind power system; Section 4 gives the conclusions.

2. Material and methods

Joint importance analysis based on the BI and CI is developed to analyze the reliability and failure rate of an off-grid wind power system. As both of the measures can effectively evaluate the reliability of system components, further analysis on the importance level of each component within the whole system can be conducted through comparative ranking, and then it is good for guaranteeing the system running normally and effectively (Table 1).

2.1. Birnbaum importance

Firstly, the Birnbaum importance definition for computing importance of system components is given as follows [24]:

$$I_k^B(t) = \partial R(t)/\partial R_k(t) = E[\delta_k(X)] \quad (1)$$

Thus, one can obtain the following equation to compute the BI for a system:

$$(0_k, X) = (x_1, x_2, ..., x_{k-1}, 0, x_{k+1}, \ldots, x_n) \quad (2)$$

$$(1_k, X) = (x_1, x_2, ..., x_{k-1}, 1, x_{k+1}, ..., x_n) \quad (3)$$

where x_k represents operational state of component C_k; for $1 \le k \le n$, X represents operational state of the system, $X=\{x_1, x_2, \ldots, x_n\}$. Component C_k works when $x_k=1$, and does not when $x_k=0$. The concept of $r(X)$ elaborates the working condition of C_k that supports the system being running stably, assuming that all system failure states are absorbing throughout interval [0, t]. This can be well explained from the view of statistics, i.e. the contribution or probability of C_k ensuring the whole system being operating normally. Thus r_k(X) is also introduced in the model to represent $r(X)$ for component C_k.

Table 1
Basic symbols.

Acronyms and notation	
C_k	Component k in a system
X	System state, $X=\{x_1, x_2, \ldots, x_n\}$
x_k	Operational probability of component C_k
BI	Birnbaum importance
CI	Criticality importance
$r_k(X)$	Operational probability of the system to component C_k
$F(t)$	Unreliability function of the system
$F_k(t)$	Unreliability function of component C_k
$R(t)$	Reliability function of the system
$R_k(t)$	Reliability of component C_k
$I_k^B(t)$	Birnbaum component importance of C_k
$I_k^{CR}(t)$	Criticality importance of component C_k
$P_x(t)$	Operational probability of the system at time t