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Reliability Importance of Renewable Energy Sources to Overall Generating Systems

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ABSTRACT Over the years, probabilistic nature of renewable energy sources (RES) and its influence on power system adequacy have been well studied. However, rather less attention has been paid to the impact of RES unit itself's and its power conversion system's (PCS') reliability, as well as their various connection topologies. This paper devises a comprehensive sensitivity study on how each of these elements can affect overall generating system reliability. given the plethora of RES configurations and components, it is of import to identify the most vulnerable element in RES. In this work, *component importance* is extended, for the first time, to generating capacity adequacy assessment (HLI). Measurement index is the centerpiece in reliability importance. New indices have to be introduced to facilitate the study. While the physical meaning of previously developed indices is lost, in this study indices are proposed based on traditional importance measures, of which the physical meaning are strictly retained and consistent with the definitions. With the proposed assessment technique, components in various RES configuration can be ranked according to their reliability importance. It is found in the numerical study that different importance measures (such as risk-achievement based measures and risk-reduction based measures) can result in different rankings. Studies on contributing factors of the reliability importance are also performed. As more and more RES gaining foothold in generating systems, the proposed technique assist to achieve targeted reliability level of the system, by easily identifying and prioritizing reliability improvement tasks among various units/components in the increasing complex system.

INDEX TERMS Component importance, converters, generating capacity reliability evaluation, importance measures, power electronics, reliability importance, renewable energy resources.

I. INTRODUCTION

Renewable energy sources (RES) are taking up power generation's role as their penetration level waxes year by year. The effect of RES powered generator on overall generating capacity adequacy is determined by several factors including probabilistic representation of RES, reliability of RES units and their power conversion systems (PCS) and formations of RES units. Probabilistic characters of RES and its impact on generating system are well studied for the past decades [1]–[3]. The reliability of RES generators has been recognized [4], [5]. Power electronics (PE) systems for power conversion are also important as they are indispensable for grid connection of almost all RES units. Historically, the industry resorts to standards such as Military-Handbook-217 [6] for reliability evaluation of PE systems. However, reliability of PE devices depends on design, and operational and environmental condition and use of empirical models can lead to inaccurate results. Standardized models are no longer in favor [7] and even officially canceled [8]. The paradigm is shifting from empirical-based approaches to physics-of-failure analysis of reliability evaluation for PE devices. However, the accuracy of physics-of-failure analyses depends upon the experimental test-bed setup and simulation modeling, such as electro-thermal and electro-mechanical models. Under such circumstances, a sensitivity study on

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system reliability that taking into account PE reliability along with the probabilistic nature and reliability of RES power generation is desired.

In previous studies, efforts have been made to incorporate various elements into generating capacity reliability study. A Monte Carlo simulation is carried out to assess system adequacy with RES penetration. In [1], Karki *et al.* propose a common wind power generation model. Later, the model is used in unit commitment risk analysis [9] and adequacy assessment [2], [10] for wind integrated generating systems. Billinton and Huang [3] gave a detailed comparison on different models that interpret capacity states of wind farms in reliability evaluation. In these studies wind turbine generators (WTGs) are assumed 100% reliable while the reliability and formation their power electronic interfaces are considered. Recently, the significance of the reliability of RES units and PCS is recognized. In [4] and [5], surveys on wind power systems failure in Sweden are presented, where causes of failures are analyzed. Analytical methods for modeling wind variability and PE interface in reliability assessment are proposed by Wang *et al.* [11]. Recently, a Monte Carlo approach is proposed in [12]. Different formations of PE interface for RES units are reviewed in [13]–[15]. Three system topologies for PV systems are compared by Alferidi and Karki [16] with respect to system adequacy. Reliability impact of electric vehicle (EV) charging and discharging is studied in [17]–[20]. In the existing studies, the possible failure of power conversion system is often not considered. Moreover, failure rates of the new element such as PV and WTGs are assumed constant.

In this paper, methodologies are proposed in order to study the effect of RES units and PCS on generating capacity reliability. Not only the reliability but also formations of RES units and their PCS are taken into account. This is the first work to adopt the concept of reliability importance into generating system reliability evaluation. Unlike tradition reliability assessment, reliability importance helps to gain insights of reliability impact at component level. It is well suited when a system with multiple elements of interest (e.g. RES) is involved in reliability assessment. With importance measures, reliability impact of various RES generating units and PCS can be easily appraised. A component with highest importance has the biggest impact on system reliability. As a result, the reliability of the whole system can be enhanced through the reliability improvement of that component first. The study of reliability importance helps to achieve targeted level of reliability of a system.

A. COMPONENT IMPORTANCE AND RELIABILITY IMPORTANCE

The concept of *component importance* is first proposed by Birnbaum [21] and categorized into three classes. The first class is *structure importance*, which considers the relative importance of components in a system without the knowledge of the component reliabilities. It can be done completely by examining the design of a system. For example, in a PV system shown in Fig. 4(a), the central converter is of highest structure importance. The second class is *reliability importance*. Reliability importance of a component depends both on its position (as determined by system design) and its failure rate. Following the above example, components on one branch may have higher reliability importance than the central component. Consequently, priority will be given to that component instead to improve the overall PV system reliability. The third class *lifetime importance* considers life-length study period. It requires the knowledge of life distribution for each component. In this paper, *reliability importance* is used as it considers both the system structure and component reliability.

B. IMPORTANCE MEASURES FOR GENERATING SYSTEM RELIABILITY

importance measures is the centerpiece of component importance study. When applying traditional importance measures into power systems, extra factors need to be considered. The reliability of a generating system depends on unit type and its capacity. One can imagine that a small RES unit will have the least reliability importance even if it is highly unreliable. The Venn diagram Fig. 1 illustrates factors to be considered in traditional reliability importance and in the study of generating capacity system reliability. The distinct difference is that a generating unit often has multiple capacity states whereas traditional reliability importance only considers components with binary states.

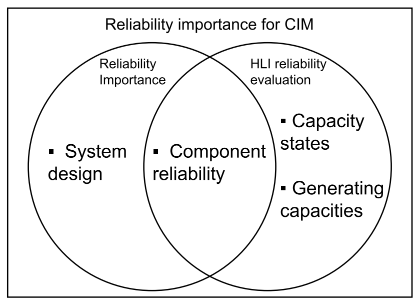

FIGURE 1. Factors considered in reliability importance for generating system.

While relatively little work has been done on component importance in power systems, most of the relevant work use reliability importance to identify critical components in transmission systems. In [22], traditional importance measures are directly used to rank components in transmission systems. However, limited perspective is gained as those measures are only suitable for system components with binary states. Hilber and Bertling [23], [24] propose importance indices based on interruption cost. A similar monetary measure is employed in [25] to rank lines in IEEE-RTS system. Importance indices based on breakdown frequency is introduced in [26]. Unlike previous studies, Setréus *et al.* [27] propose separate importance indices based on security margin, expected energy not served (EENS) and disconnected generation for transmission system component. However, the physical meaning of importance measure is not retained in the proposed indices. Recently, resilience-based importance indices are presented by Fang *et al.* [28].

In this paper, indices are proposed in order to measure from different angles component reliability importance to generating systems. The proposed measurements are developed based on probability (loss of load probability (LOLP)) and energy(loss of energy expectation (LOEE)), respectively. Moreover, traditional reliability importance also have a diversity of measures each of which has different emphasis. On this account, archetypal importance measures are extended to generating systems while their physical meaning is retained.

C. ANALYSIS PROCEDURE

Analysis of traditional component importance includes two steps [29]: 1) Identify system structure and, 2) Rank components with importance measures. The first step if to show how component reliability contributes to failure or success of the whole system. Two methods are widely used: Reliability block diagram (RBD) and fault tree analysis (FTA). In the second step, a importance measure is chosen and components are ranked based on that. The ranking may vary with different importance measures. Given the aforementioned considerations, however, this conventional procedure cannot be directly applied to generating systems. Therefore, a new analysis procedure for reliability importance in power generation system is proposed in this paper.

In the proposed procedure, the reliability of RES units and PCS are considered. Capacity states for RES units are also know. While the generating units and PCS are components with binary states, multiple states-capacity space of a generating unit corresponding to probabilistic distribution of RES is accommodated. Provided a RES system is composed of multiple components, the first step is to simplify the system without compromising the accuracy of the probabilistic model for RES units. Different formations—such as a standalone RES unit, or a group of units with and without a central components—are taken into account. Calculation of multi-state model for RES penetration can be facilitated in the second step. Unlike conventional multi-state model, formations of RES unit need to be considered at this step.

The remainder of this paper is structured as follows. Methodologies for these first two steps are given in Section II and Section III, respectively. Importance measures for generating system reliability are proposed in Section IV and the third step is to calculate importance measures for each RES branches. The rank with respect to different importance measures can then be obtained.

II. SYSTEM SIMPLIFICATION

Billinton and Hossain [30] proposed the concept of reliability equivalents. The technique reduces multiple connected components with binary states to one equivalent that retains the pertinent system parameters. In this paper, only components with two states can be reduced using reliability equivalent technique because simplifying components with multiple states result in reduced system states. An exception is when a single unit's capacity is insignificant to the whole system, such as a PV panel. In that case, an aggregation of small units can be modeled as one unit with a limited number of capacity states.

A. SINGLE BRANCH FORMATION

A typical single branch formation is given in Fig. 2(a). Most standalone RES units and power electronic are in series connection [14], [15], [31], [32], which is also the simplest form from the standpoint of reliability evaluation. It denotes a standalone unit or a group of small units of which only the aggregate capacity is of significance.

FIGURE 2. Single branch formation with series connection. (a) System diagram. (b) Block diagram of the equivalent model.

The equivalent B can be represented by a component with a failure rate q_B, Fig. 2(b),

$$q_B = q_{gen} + q_{conv} \tag{1}$$

where q_{gen} and q_{conv} are forced outage rate (FOR) of the generating unit and PCS, respectively. The equivalent mean time to failure (MTTF) is the reciprocal of the equivalent failure rate. It should be noted that other component such as transformers and line filters and fuses in PV systems [13], [16] can also be included. In such occasions the equivalent FOR of a series system with n components can be calculated using (2) [30].

$$q_B = \sum_{i}^{n} q_i, \tag{2}$$

where q_B is the equivalent FOR of that branch and q_i is the FOR for component i.

B. MULTI-BRANCH FORMATION

Large renewable penetration often comes in the form of farms that composed of identical RES units. Parallel connection is most common, such as wind farms. Such configuration is made up of multiple branches. Fig. 3 shows three types of multi-branch formations with components on each branch replaced by the equivalence model (Section II-A). While most wind farms can be represented by the formation as in Fig. 3(a) where the model of each branch is the same as in Section II-A, formations with a central component (Fig. 3(b)) can also be popular in applications with string of smaller units or HVDC grids [15]. Fig. 4 gives three examples where central components are used. Dependent upon transmission/distribution network types the central components can be a DC-AC or AC-DC converters or even

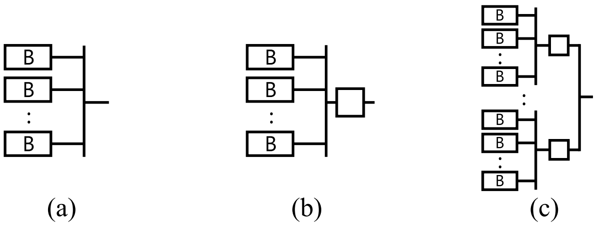

FIGURE 3. **Formations of multiple branches. (a) Multiple branches without a central component. (b) Multiple branches with a central component. (c) Multiple branches with multiple central component.**

a DC-DC transformer [15], [31], [32]. In these formations PCS are applied on both sides of the bus. Units can also be formed into multiple groups with a central converter in each group, Fig. 4(c).

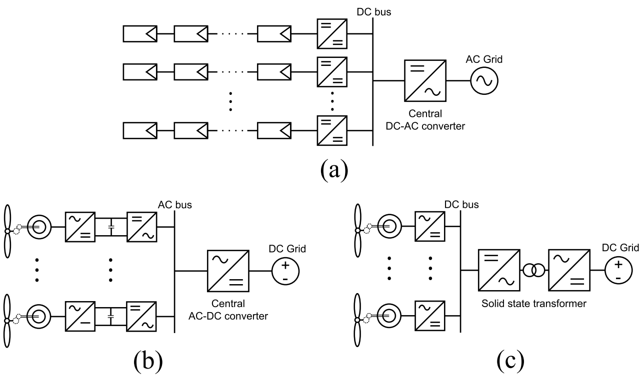

FIGURE 4. **Examples of formations with a central component. (a) Multistring converter for PV system [31], [32]. (b) Full-scale converter system with transmission DC grid [15]. (c) Full-scale converter system with both distribution and transmission DC grids [15].**

Branch and central components need to be retained from further simplification lest reduction of systems states and accuracy. Thus models shown in Fig. 3 will not be reduced using reliability equivalent. It can be concluded that, before the simplification a typical branch has three separate probabilistic models: 1) capacity states and 2) up and down states of the generator, and 3) up and down states for PCS. After the simplification there are two: 1) capacity states of the generator and 2) up and down states of that branch.

C. RELIABILITY EQUIVALENT FOR PV SYSTEMS

As mentioned in Section II-A a group generating units with small capacities such as PV panels can be aggregated to form one equivalent unit. Three common PV system configurations are string/multistring converter, center inverter and module converters [13], [16], [32]. These configurations can be easily simplified using equivalent technique [30]. Other configurations for PV arrays include total-cross-tied and bridge-linked systems [33]. The reliability equivalent can be obtained using *minimal cut set* method. For details, readers are referred to [33].

III. STATE SPACE CALCULATION

A. SINGLE BRANCH

Let us assume that originally each branch unit has N_s non-zero capacity states $c_s \in \{c_1, c_2, \ldots, c_{N_\mathrm{s}}\}$. There are total $N_\mathrm{s} + 1$ states with probability $\Pr(c_s)$ for each state s, letting $c_0 = 0\,\mathrm{MW}$. The zero state c_o represents occasions where RES is insufficient to start the unit, e.g., wind speed is below the cut-in speed of a WTG.

With the consideration of power generation and conversion failure, probability $P(X)$ associated with output level X of the single branch formation are:

$$\Pr(X) = \begin{cases} \Pr(c_s) \cdot (1 - q_\mathrm{B}), & X = c_s,\ s \neq 0 \\ \Pr(c_0) + \big(1 - \Pr(c_0)\big) \cdot q_\mathrm{B}, & X = c_0 \end{cases} \tag{3}$$

It can be found in (3) that probabilities of non-zero states reduces while the probability of zero state increases. Now the zero output can be ascribed to not only insufficient RES but also failures of branch.

In the case of a single branch, the output level of each state X as well as the total number of states remain the same.

B. MULTIPLE BRANCHES

Consider a farm of renewable generating units composed of N_B branches. The Probability of having $n_\mathrm{B} \in [0, N_\mathrm{B}]$ branches functioning is given by (4)

$$\Pr(n_\mathrm{B}) = \binom{N_\mathrm{B}}{n_\mathrm{B}} {q_\mathrm{B}}^{(N_\mathrm{B} - n_\mathrm{B})} (1 - q_\mathrm{B})^{n_\mathrm{B}} \tag{4}$$

where q_B is the FOR for all branches.

For each capacity state c_s the exact probability of n_B branches available is

$$\Pr(c_s \cap n_\mathrm{B}) = \Pr(c_s) \cdot \Pr(n_\mathrm{B}), \tag{5}$$

given the output level of each generating unit and number of healthy branches are independent. The total capacity for this set of $c_s \cap n_\mathrm{B}$ is $c_s \times n_\mathrm{B} = X$. Therefore, (5) is actually $\Pr(X \mid c_s \cap n_\mathrm{B})$ and $\Pr(X)$ is c_s-n_B combinations that result in the same X.

$$\begin{aligned} \Pr(X) &= \sum_{c_s \cdot n_\mathrm{B} = X} \Pr(X \mid c_s \cap n_\mathrm{B}) \\ &= \sum_{c_s \cdot n_\mathrm{B} = X} \Pr(c_s) \cdot \Pr(n_\mathrm{B}) \\ &= \sum_{s}^{N_\mathrm{s}} \Pr\left(\frac{X}{c_s}\right) \cdot \Pr(c_s). \end{aligned} \tag{6}$$

Provided discrete output levels for each unit, the value of X is non-arbitrary. The number of possible combination is $N_\mathrm{B} \cdot N_\mathrm{s} + 1$, including one zero output state. Thus, (7)

$$2 \leq N_\mathrm{TS} \leq N_\mathrm{B} \cdot N_\mathrm{s} + 1. \tag{7}$$

where N_TS is the total number of states of this group.

C. MULTIPLE BRANCHES WITH A CENTRAL COMPONENT

After obtaining $P(X)$ without the central component, the final $P(X)$ considering central component outage is

$$\Pr(X) = \begin{cases} \Pr(X) \cdot (1 - q_C), & X \neq 0 \\ \Pr(X) + \big(1 - \Pr(X)\big) \cdot q_C, & X = 0 \end{cases} \tag{8}$$

The calculation of $P(X)$ is in the same way as for single branch formation (3). The failure of the central component nullifies power output regardless of branches' availability, raising the probability for zero output. When there is no central component q_C is equal to 0 and $P(X)$ in (8) stay the same as in Section III-B. So (8) can be used as the general expression for $P(X)$. For RES units aggregated under several central components, the same calculation (4)-(8) repeats for each group.

IV. RELIABILITY IMPORTANCE MEASURES FOR GENERATING SYSTEM

In essence, component importance measures the consequent change on system reliability as a result of state changed of component. There is a diversity of measures based on different interpretation of component importance. In principal, most of frequently used importance measure are variations of 1) partial derivative 2) risk achievement and 3) risk reduction [34]. There is no single dominant measure that is superior to the other. Different measures are advisable depending on applications.

In this paper three popular measures are chosen: 1) *Birnbaum's measure of Importance* I^{B}, 2) I^{B}, 2) *risk achievement worth (RAW)* I^{RAW}, and 3) *risk reduction worth (RRW)* I^{RRW}. Birnbaum's measure is based on partial derivative. RAW and RRW are, as the names suggest, variations of risk achievement and risk reduction, respectively. Their original definitions are given in Appendix as Definition 1.1, 1.2 and 1.3, respectively.

On the other hand, indices for generating capacity reliability is neither singular. Based on the four original importance measures, four sets of new measures are derived. In each set measurements are derived from system LOLP and LOEE, respectively.

A. BIRNBAUM'S IMPORTANCE MEASURES FOR GENERATING SYSTEM RELIABILITY

Birnbaum's measure is partial differentiation of system reliability with respect to a component's reliability. It can also be defined as the difference between the system reliability when the component of concern is functioning and in a failed state, A3. Thus, Birnbaum's measures for generating system reliability are defined as follows.

Definition 4.1: Birnbaum's measures of component i for generating system reliability in respect of LOLP ($I^{\mathrm{B}}_{\mathrm{LOLP}}(i)$) and LOEE ($I^{\mathrm{B}}_{\mathrm{LOEE}}(i)$) are:

$$\begin{cases} I^{\mathrm{B}}_{\mathrm{LOLP}}(i) = \mathrm{LOLP}(0_i, \boldsymbol{p}) - \mathrm{LOLP}(1_i, \boldsymbol{p}) & \text{(9a)} \\ I^{\mathrm{B}}_{\mathrm{LOEE}}(i) = \mathrm{LOEE}(0_i, \boldsymbol{p}) - \mathrm{LOEE}(1_i, \boldsymbol{p}) & \text{(9b)} \end{cases}$$

This paper follows the convention of notation in component importance: $(x_i, \boldsymbol{p})$ denotes component i's denotes component i's reliability is specified as x while reliability of other

$$(0_i, \boldsymbol{p}) = (p_1, p_2, \ldots, p_{i-1}, 0, p_{i+1}, \ldots, p_n)$$
$$(1_i, \boldsymbol{p}) = (p_1, p_2, \ldots, p_{i-1}, 1, p_{i+1}, \ldots, p_n).$$

$\mathrm{LOLP}(0_i, \boldsymbol{p})$ is the system LOLP when it is known that component i is $\mathrm{LOLP}(1_i, \boldsymbol{p})$ is the system LOLP when component i is in a failed state. The same applies to $\mathrm{LOEE}(0_i, \boldsymbol{p})$ and $\mathrm{LOEE}(1_i, \boldsymbol{p})$.

When one branch i is assumed to be 100% reliability $(1_i, \boldsymbol{p})$, calculation of $\Pr(n_{\mathrm{B}})$ ((4)) is changed to (10),

$$\Pr(n_{\mathrm{B}}) = \binom{N_{\mathrm{B}} - 1}{n_{\mathrm{B}} - 1} q_{\mathrm{B}}{}^{(N_{\mathrm{B}} - n_{\mathrm{B}})} (1 - q_{\mathrm{B}})^{(n_{\mathrm{B}} - 1)}. \tag{10}$$

In such case at least one branch is available, so $n_{\mathrm{B}} \in [1, N_{\mathrm{B}}]$. Subsequently, value of Subsequently, value of X lies in $[c_s, N_s \cdot c_s]$ in (6). Similarly, (11) is for $(0_i, \boldsymbol{p})$ where i is one of the branches.

$$\Pr(n_{\mathrm{B}}) = \binom{N_{\mathrm{B}} - 1}{n_{\mathrm{B}}} q_{\mathrm{B}}{}^{(N_{\mathrm{B}} - 1 - n_{\mathrm{B}})} (1 - q_{\mathrm{B}})^{n_{\mathrm{B}}}, \tag{11}$$

where $n_{\mathrm{B}} \in [0, N_{\mathrm{B}} - 1]$. in (6).

B. RAW AND RRW FOR GENERATING SYSTEM RELIABILITY

Risk achievement worth of a component is the risk increase if the component is assumed to be failed. It is defined as the ratio of system risk for such event to the actual (baseline) system risk (Appendix A-A).

Definition 4.2: RAW of component i for generating system reliability are

$$\begin{cases} I^{\mathrm{RAW}}_{\mathrm{LOLP}}(i) = \dfrac{\mathrm{LOLP}(0_i, \boldsymbol{p})}{\mathrm{LOLP}(\boldsymbol{p})} & \text{(12a)} \\ I^{\mathrm{RAW}}_{\mathrm{LOEE}}(i) = \dfrac{\mathrm{LOEE}(0_i, \boldsymbol{p})}{\mathrm{LOEE}(\boldsymbol{p})} & \text{(12b)} \end{cases}$$

Risk reduction worth is the decrease in risk if the component is assumed to perfectly reliable. Its original definition is given in Append A-B.

Definition 4.3: RRW of component i for generating system reliability are

$$\begin{cases} I^{\mathrm{RRW}}_{\mathrm{LOLP}}(i) = \dfrac{\mathrm{LOLP}(\boldsymbol{p})}{\mathrm{LOLP}(1_i, \boldsymbol{p})} & \text{(13a)} \\ I^{\mathrm{RRW}}_{\mathrm{LOEE}}(i) = \dfrac{\mathrm{LOEE}(\boldsymbol{p})}{\mathrm{LOEE}(1_i, \boldsymbol{p})} & \text{(13b)} \end{cases}$$

V. EVALUATION PROCEDURE

The proposed concept of reliability importance is incorporated in HLI reliability evaluation program using analytical technique.

1) Read system info and calculate reliability indices for the conventional generating system (without RES penetration);
2) Simplify RES system according to Section II. Form system RBD. Calculate q_{B} for each branch;

3) Calculate capacity states for RES penetration corresponding to their topologies (Section III) and calculate LOLP($\boldsymbol{p}$) and LOEE($\boldsymbol{p}$) using updated COPT (with RES penetration);
4) For each branch of concern, obtain LOLP and LOEE for LOEE for $(1_i, \boldsymbol{p})$ and $(0_i, \boldsymbol{p})$ by repeating 3 with its FOR set to 0 and 1, respectively.
5) From indices obtained from the 4, calculate importance indices $I^{\mathrm{B}}_{\mathrm{LOLP}}(i)$, $I^{\mathrm{B}}_{\mathrm{LOEE}}(i)$, $I^{RAW}_{\mathrm{LOLP}}(i)$, $I^{RAW}_{\mathrm{LOEE}}(i)$, $I^{\mathrm{RRW}}_{\mathrm{LOLP}}(i)$ and $I^{\mathrm{RRW}}_{\mathrm{LOEE}}(i)$ for each component.
6) Ranking components as per importance measures.

VI. NUMERICAL STUDY

The case study from [3] is used, to which the consideration of RES unit branches and a central component is added. A 20 MW wind farm is integrated to Roy Billinton Test System (RBTS) and designated as WRBTS. The cut-in, rated, and cut-out speeds used in the following studies are: 14.4, 36, and 80km/h. The wind speed probability distribution of Observed96-03 at Swift Current site is used. The resultant 11-state model for each WTG is given by Table 13 in [3].

A. RELIABILITY SENSITIVITY OF BRANCH AND CENTRAL COMPONENTS

It is first assumed there are 10 WTGs with each rated at 2 MW. A central PCS is also considered (Fig. 4(b) and (c)). The branch represent WTGs units and PCS on the branches, (1). The reliability sensitivity of branches is obtained by uniformly increasing the FOR of all branch (q_{B}) from 0 to 0.3 while fixing central component's FOR (q_{C}) at 0. The sensitivity of central component can be obtain in the same manner by changing the value of its FOR while fixing FOR of branches. The results are shown in Fig. 5 as solid lines. For reference, LOLP and LOEE of RBTS (without WTG penetration) are 1.0916 hr/yr and 9.8614 MWh/yr, respectively.

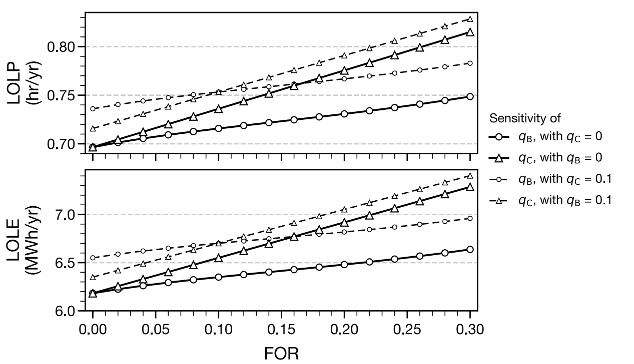

FIGURE 5. WRBTS generating system reliability sensitivity of q_{B} and q_{C}.

When both branch and central components are 100% reliable (i.e. $q_{\mathrm{B}} = q_{\mathrm{C}} = 0$), LOLP and LOEE at current wind penetration level are 0.6965 hr/yr and 6.1823 MWh/yr. System reliability reduces linearly with the increasing of components' FOR. The trends for LOLP and LOEE are similar. System reliability is more sensitive to central component (q_{C}) than branches (q_{B}). In the two figures, the slopes for q_{C} is more then double of that of q_{B}. This can be easily explained by the fact that all WTGs fail to supply when their central component fails and the chance for all the branches fails is slim. Increasing q_{C} and q_{B} to 0.1 respectively, the reliability sensitivities are changed, as depicted by dashed lines in Fig. 5. Each dashed line shifts from the position of it correspondent solid line almost by a same extend across all values of FOR. Again, system reliability deteriorates more remarkably with increased q_{C} than increased q_{B}.

B. BIRNBAUM'S IMPORTANCE MEASURE

In order to find out factors that affect reliability importance, the wind farm of WRBTS is assumed to have 18 WTGs with six rated at 1 MW, six 2 MW and six 3MW, totaling 36 MW. Each WTG represent a single branch connecting to RBTS. For WTGs with same capacity their branch FOR q_{B} varies from 0.05 to 0.3 in step of 0.05. Fig. 6 shows ranking of the 18 branches with regard to Birnbaum's measure for generating system reliability.

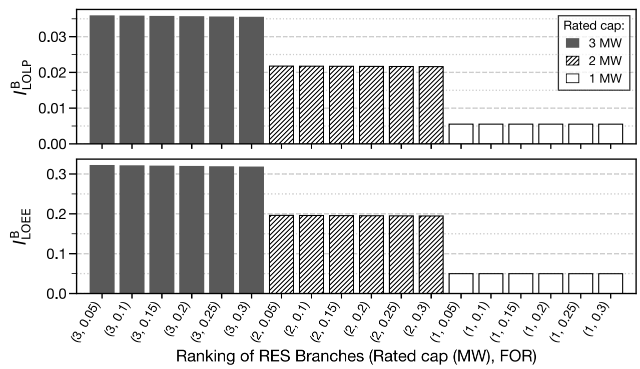

FIGURE 6. Ranking of components according to $I^{\mathrm{B}}_{\mathrm{LOLP}}$ and $I^{\mathrm{B}}_{\mathrm{LOEE}}$.

Birnbaum's measure compares the situations where the component is 100% and 0% reliable. The ranking result shows that for a same RES unit type branches with higher capacities have higher reliability importance and thus higher in the ranking. In the figure, all WTGs of 3 MW rated capacity have highest importance values while 1 MW units have lest importance. For all group of units with same capacities, branches with the lowest FOR are more important and ranks higher. However the differences made by various q_{B} values are far less prominent then these made by unit capacity. It implies that for Birnbaum's measure for power generation system the unit capacity is the dominant factor, followed by component FOR. Measuring from either system LOLP ($I^{\mathrm{B}}_{\mathrm{LOLP}}$) or LOEE ($I^{\mathrm{B}}_{\mathrm{LOEE}}$) end in the same ranking.

C. RISK ACHIEVEMENT WORTH AND RISK REDUCTION WORTH

Applying the proposed RAW measures to the same 18 branches, the results are given in Fig. 7. Measure of RRW lead to the same ranking as partial derivative-based Birnbaum's measure. The differences q_{B} made for branches

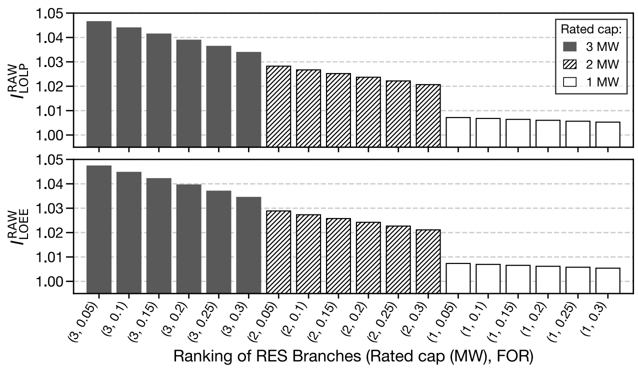

FIGURE 7. Ranking of branches according to RAW.

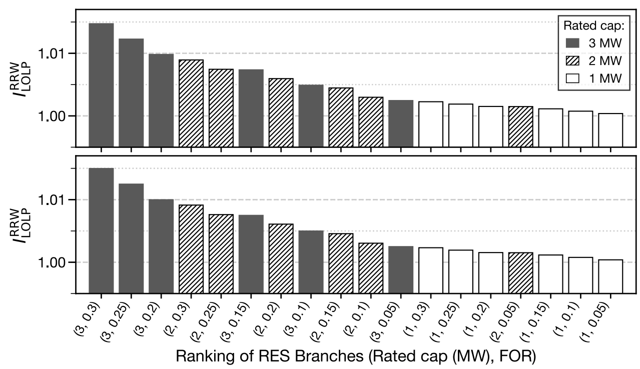

FIGURE 8. Ranking of branches according to RRW.

with same capacity are more noticeable as compared to Birnbaum's measure. As defined in Section IV-B, branch of (3 MW, 0.05) has the highest importance value because the system reliability would have the largest change when it is assumed not working.

Fig. 8 shows the ranking results for RRW measures. The risk reduction-based ranking is a far cry from those of risk achievement-based and partial derivative-based ranking. Generally higher capacity branch has higher importance values, yet the most distinctive difference of RRW ranking is that rated capacity is no longer a dominate factors. With I^{RAW}_{LOLP} and I^{RRW}_{LOEE}, branches with different capacities intersect in the ranking. The other observation is that RRW does not favor components with higher reliability. Instead, branched with highest FOR is ranked at the top. For example, branch of (3 MW, 0.3) has the highest importance value here. The ranking results by RRW measure seems conflicting the results by Birnbaum's and RAW measures. However, it can be reasoned by the vary definition of RRW given in Appendix A-B and Section IV-B. Risk reduction worth, as its name implies, measures the how much the system risk would be reduced when component i is replaced by a perfect component. It is this reliability potential that RRW weighs. Naturally, more credit would be given to components with higher risk (FOR) due to higher potential of reliability improvement. Ranking results based on both LOLP and LOEE are identical among three importance measures.

D. BRANCH COMPONENT VERSUS CENTRAL COMPONENT

For system such as given in Fig. 4, one might intuitively come to the conclusion that components at central position is the most importance. However, as mentioned in Section I-A, component importance differs from structure importance as the former considers not only position but also reliability of a component. To demonstrate this, WRBTS in Section VI-A is used where there are ten identical WTG branches. The branch FOR are 0.3 while q_C is varying from 0 to 0.03. With each pair of q_B and q_C, both the importance of central component and branches vary.

Table 1 gives reliability importance of the central component and one of the branches with varying q_C. All three sets of importance measurements are listed in the table. It is noted that Birnbaum's measure for the central component (upper part of Table 1) remains the same regardless of q_C's value. It is because both $I^B_{LOLP}(i)$ and $I^B_{LOEE}(i)$ only i is perfect reliable or failure, Section IV. Consequently their values do not reflect the reliability changing of component i itself. This can be regard as the shortcoming of Birnbaum's measure, as is elaborated in Appendix A-A.

TABLE 1. Reliability importance of central versus branch component.

q_C	I^B_{LOLP}	I^B_{LOEE}	I^{RAW}_{LOLP}	I^{RAW}_{LOEE}	I^{RRW}_{LOLP}	I^{RRW}_{LOEE}
Central component						
0			1.4581	1.4858	1	1
0.005			1.4548	1.4822	1.0023	1.0024
0.01			1.4515	1.4787	1.0046	1.0049
0.015	0.3430	3.2245	1.4482	1.4751	1.0069	1.0073
0.018			1.4462	1.4730	1.0082	1.0087
0.02			1.4449	1.4715	1.0092	1.0097
0.025			1.4416	1.4680	1.0115	1.0121
0.03			1.4384	1.4645	1.0137	1.0146
Branch						
0	0.0208	0.1853	1.0195	1.0195	1.0084	1.0084
0.005	0.0207	0.1844	1.0194	1.0194	1.0084	1.0084
0.01	0.0206	0.1835	1.0192	1.0193	1.0083	1.0083
0.015	0.0205	0.1825	1.0191	1.0191	1.0082	1.0083
0.018	0.0205	0.1820	1.0190	1.0190	1.0082	1.0082
0.02	0.0204	0.1816	1.0189	1.0190	1.0082	1.0082
0.025	0.0203	0.1807	1.0188	1.0188	1.0081	1.0081
0.03	0.0202	0.1798	1.0187	1.0187	1.0081	1.0081

Comparison between the results for the two components one can find that the central component's importance overwhelms that of the branch when Birnbaum's measure and RAW are used. However, the two components are comparable when it comes to their risk reduction worth (the last two columns). It is observed that when the central component is highly reliable (i.e. $q_C = 0 \sim 0.015$) the $0 \sim 0.015$) the branch can have higher reliability importance, given that branch FOR is Fig. 9 visualized the RRW of two components with increasing q_C. At some point the two have the same RRW value (around $q_C = 0.018$ for $I^{\mathrm{RRW}}_{\mathrm{LOLP}}$ and 0.017 for $I^{\mathrm{RRW}}_{\mathrm{LOEE}}$). As the central component's FOR getting larger its importance getting higher than the branch.

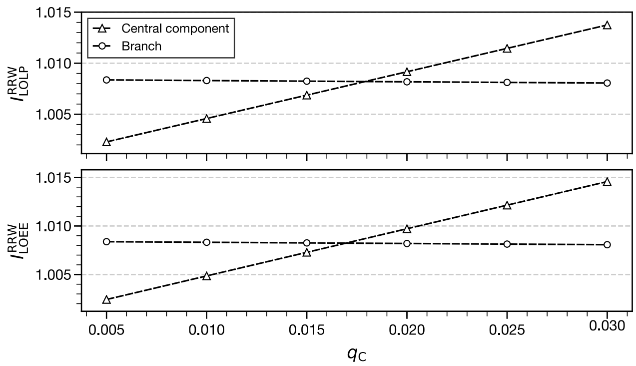

FIGURE 9. RRW of central component and branch.

VII. CONCLUSION

Results of numerical study shows that the reliability importance is dependent upon unit capacity and FOR, system formation as well as importance measurement itself. In this paper, partial derivative-based and risk achievement-based measurement gives the same results, in which higher MW and lower FOR lead to higher importance. risk reduction worth provides a different perspective on component importance as it measures the reliability potential of components. Finally, it is demonstrated that a central component—the one with higher structure importance—can actually have less risk reduction worth than a branch—the one with lower structure importance. This happens when the central component has already achieved high reliability and the branch reliability is relatively low.

With the introducing of reliability importance for generating systems, one is able to identify critical components for system reliability. This is especially useful to evaluate and prioritize reliability improvement tasks for RES penetration given the fact that RES penetration often represents a large number of units/components with various system formations.

APPENDIX A COMPONENT IMPORTANCE MEASURES

For a given *structure function* $\phi(\boldsymbol{x})$, the value of $\boldsymbol{p}$ determines the probability that the system will function

$$\Pr\{\phi(\boldsymbol{x}) = 1 \mid \boldsymbol{p}\} = h_\phi(\boldsymbol{p}).$$

$h_\phi(\boldsymbol{p})$ is the *reliability function* for ϕ. In situations when the known, i.e. $\phi(\boldsymbol{x})$ is given, $h_\phi(\boldsymbol{p})$ can be written as $h(\boldsymbol{p})$. Then we have the following Definitions [21], [35]–[37]:

A. BIRNBAUM'S MEASURE

Definition 1.1: Birnbaum's measure of importance of component i is

$$I^{\mathrm{B}}(i) = \frac{\partial h(\boldsymbol{p})}{\partial p_i}. \tag{A1}$$

Using pivotal decomposition, $h(\boldsymbol{p})$ can be written as a linear function of p_i when the n component is independent.

$$h(\boldsymbol{p}) = p_i \cdot h(1_i, \boldsymbol{p}) + (1 - p_i) \cdot h(0_i, \boldsymbol{p}) \tag{A2}$$

where $h(1_i, \boldsymbol{p})$ is the probability that the system is functioning when it is known that component i is functioning, and $h(0_i, \boldsymbol{p})$ is the probability when it is in a failed state.

Substituting (A2) into (A1) gives

$$I^{\mathrm{B}}(i) = h(1_i, \boldsymbol{p}) - h(0_i, \boldsymbol{p}). \tag{A3}$$

This procedure of determining Birnaum's measure is in many cases more simple to calculate than (A1).

It can be seen from (A3) Birnbaum's measure is the difference between system reliability with and without component i functioning. It is independent of the actual reliability of that component. This may be regarded as a weakness of Birnbaum's measure [35].

B. RISK ACHIEVEMENT WORTH AND RISK REDUCTION WORTH

The risk achievement worth (RAW) of a component is the worth of the component in achieving the present level of system risk. The risk reduction worth (RRW) is the worth of the component in further reducing system risk. The two risk worth measures complement one another with regard to their characterization of what is important to risk.

Definition 1.2: RAW of component i is

$$I^{\mathrm{RAW}}(i) = \frac{1 - h(0_i, \boldsymbol{p})}{1 - h(\boldsymbol{p})}. \tag{A4}$$

The RAW is the ratio of the system unreliability if component i is not present with the actual system unreliability.

Definition 1.3: RRW of component i is

$$I^{\mathrm{RRW}}(i) = \frac{1 - h(\boldsymbol{p})}{1 - h(1_i, \boldsymbol{p})}. \tag{A5}$$

The RRW is the ratio of the actual system unreliability with the system unreliability of component i is replaced by a perfect component.

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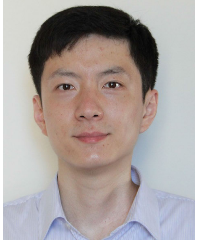

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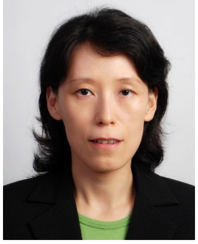

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