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A heuristic-based approach for reliability importance assessment of energy producers

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ABSTRACT

Reliability of energy supply is one of the most important issues of service quality. On one hand, customers usually have different expectations for service reliability and price. On the other hand, providing different level of reliability at load points is a challenge for system operators. In order to take reasonable decisions and obviate reliability implementation difficulties, market players need to know impacts of their assets on system and load-point reliabilities. One tool to specify reliability impacts of assets is the criticality or reliability importance measure by which system components can be ranked based on their effect on reliability. Conventional methods for determination of reliability importance are essentially on the basis of risk sensitivity analysis and hence, impose prohibitive calculation burden in large power systems. An approach is proposed in this paper to determine reliability importance of energy producers from perspective of consumers or distribution companies in a composite generation and transmission system. In the presented method, while avoiding immense computational burden, the energy producers are ranked based on their rating, unavailability and impact on power flows in the lines connecting to the considered load points. Study results on the IEEE reliability test system show successful application of the proposed method.

1. Introduction

Power systems traditionally were operated in a vertically integrated or regulated structure. In this structure, few utilities are responsible for generation, transmission and distribution of electricity. Each utility has a monopoly for the supply of electrical energy over a given geographical region (Kirschen and Strbac, 2004; Shahidehpour et al., 2002). In order to enhance economical efficiency and fulfill growing expectation of service quality, many power systems worldwide have undergone restructuring or deregulation. In the restructured environment, generation, transmission and distribution activities and services are unbundled and hence, several entities or market players are engaged in a power market (Kirschen and Strbac, 2004; Shahidehpour et al., 2002). Generation companies (GenCos) own generating units or power plant(s) and play prominent role of the energy producer in the power system. Transmission companies (TransCos) own transmission grid where electrical energy is transferred from GenCos to bulk load points. Distribution of the electricity among customers in a specific geographical region is the duty of distribution companies (DisCos). Efficiency and reliability of the power system operation is delegated to the independent system operator (ISO) (Batlle et al., 2007; Chow et al., 2005; Kirschen and Strbac, 2004; Shahidehpour et al., 2002). The ISO administrates the energy markets, the ancillary service market and the transmission system (Shahidehpour et al., 2002). ISO and TransCo may be integrated into one organization, which plays roles of market and transmission system operator (Attaviriyanupap and Yokoyama, 2005; Kirschen and Strbac, 2004). Also, ensuring system reliability may be assigned to a regional transmission organization (RTO) (Chow et al., 2005).

Service quality, and specially reliability or risk, are important issues in the regulated environment and a challenge in the restructured power system. Task of maintaining reliability is more straightforward in the regulated environment where each utility has a monopoly for generation, transmission and distribution of the electricity. This task is more difficult in the restructured environment. On one hand, customers have different valuation of service quality and prefer to select suitable service providers, who can satisfy their desired price and reliability (Ahmadi-Khatir et al., 2009; Billinton et al., 1997; Kirschen and Strbac, 2004; Read et al., 1999; Wang and Billinton 2004). On the other hand, it is technically very difficult for the ISO and DisCos to deliver different levels of reliability (Batlle et al., 2007; Kirschen and Strbac, 2004). The reason is that the system components have different rating and availability and hence, their effects on the system and load points'

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reliability indices are not the same. So, in the restructured environment, reliability is generally not uniform and the load-point reliability is of more concern than the total system reliability (Wang and Goel, 2003).

Considering different effects of the system components on the reliability and close correlation between risk and asset management, it is valuable for power system planning and operation to evaluate "asset criticality" or "reliability importance" of system components. The reliability importance is usually defined as the contribution of a component on the system or load-point reliability (Espiritu et al., 2007). Assessment of reliability importance has a variety of applications in the power system planning, operation and maintenance.

One of the main features of the conventional methods for assessment of reliability importance is employment of the risk sensitivity analysis. For instance, methods presented in (Espiritu et al., 2007; Hamoud et al., 2004; Hamoud, 2009) are on the basis of the sensitivity analysis. In these methods, a reliability parameter of the considered components is changed and the risk index is calculated for each of the new conditions. The relative change in the risk index with respect to the base or initial condition is interpreted as the reliability importance of the studied components. Since risk calculations should be repeated in each of the new conditions, the risk sensitivity analysis often imposes prohibitive computational burden in large composite (generation and transmission) systems. Another feature of the conventional reliability importance methods is that many of them have been developed on the basis of the "cut-set" concept and hence are less useful for composite systems (Espiritu et al., 2007; Hamoud et al., 2004; Hamoud, 2009).

In order to alleviate the calculation burden of risk analysis, Wang and Billinton (2001, 2004) propose a tabular method in which models are developed for generation and transmission service providers at each load point. The models are in the form of a table, which contains different available capacities with their probabilities and frequencies at the considered load points. These models can be applied to recognize service providers, which have greater impacts on the demand side reliability. The main simplification feature of the tabular method is the combination of system states which have similar available capacity at the considered load points. The tabular method loses its computational efficiency in large systems with complex power transactions where the number of combinable states at the considered buses is not considerable.

In order to mitigate the above mentioned limitations of the conventional methods, this paper proposes a computationally efficient method for reliability importance measure of generation buses (Gen-buses) in a composite power system. The reliability importance is evaluated from the perspective of bulk load points. In the proposed method, Gen-buses are ranked according to their impacts on the power flow through boundary lines between the selected load points and the remaining parts of the system. A detailed description and formulation of the proposed method is presented in Section 2. Further explanation on aspects of the proposed method is provided in Section 3. Implementation results of the proposed method on a standard test system are illustrated in Section 4. Finally, Section 5 presents concluding remarks relating to the applicability of the proposed method and its features.

2. Formulation of the proposed method

As shown in Fig. 1, it is assumed that a composite power system is partitioned into two areas designated as the "selected area" (SA) and the "external area" (EA). The SA contains the load points (buses) which are under consideration and their reliability is taken into account in the system studies. The selected load points can represent a group of customers that are supplied by a load serving entity such as a DisCo or a retailer. Large customers who are allowed to purchase electrical energy directly on the wholesale market can also constitute the SA. In a regulated environment, the SA can be defined based on customers served by a utility. The EA represents the remaining parts of the power system. It is intended to evaluate the influence of the EA Gen-buses on reliability of the SA load points. Gen-buses in a composite power system usually represent power plants. In the regulated environment, the EA Gen-Buses can be owned by a utility. The Gen-buses of the EA can be considered as energy producers or GenCos in the restructured environment.

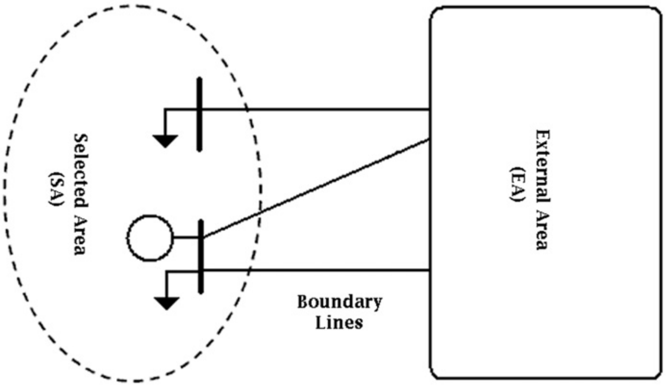

Fig. 1. Partitioning a power system into selected (load-points) and external area.

In the proposed method, the EA Gen-buses are ranked based on their impacts on risk of the SA load points. Two key points have been considered in the developed method. The first point is the primary effect of the active power-flow patterns in the system on load point risk indices. The second point is the active-power interaction between the SA and EA, which merely can take place through the boundary lines. The boundary lines are the only ways that the SA and EA can affect each other. Considering these points, ranking the EA Gen-buses in the proposed method is performed based on their effect on the active power-flows in the boundary lines. From the perspective of SA load points, the higher ranked Gen-buses of the EA have more reliability importance, i.e. more impact on the SA risk.

In order to rank the EA Gen-buses, Generation Shift Factor (GSF) is utilized in this paper. The GSF determines change of the power transfer in a branch due to the power injection change at a bus. This is a well known sensitivity factor with wide applications. The GSF is defined as follows (Wood and Wollenberg, 1996):

$$\Delta P_{ij} = a_{ij,b} \times \Delta P_b \tag{1}$$

$$a_{ij,b} = (X'_{ib} - X'_{jb})/x_{ij} \tag{2}$$

where ΔP_{ij} is the change in active-power flow of branch ij; ΔP_b is the Change in active-power injection at bus b, $a_{ij,b}$ is the GSF between branch ij and bus b, $x_{ijb}$is the series reactance of branch ij, X'_{rc} is the element in row r and column $c$of the DC load flow reactance matrix.

In the conventional definition of the GSF, it is assumed that the reference (slack) bus exactly compensates the change in power injection at bus b while the power output of other generators remains fixed. This assumption is not valid for reliability evaluation where all generators participate in the power balance and remedial actions. In order to adjust the GSF in this regard, the modification procedure in Wood and Wollenberg (1996) is utilized. In this reference, it is supposed that the remaining generators pick up the injection change at bus b in proportion to their maximum MW rating. Accordingly, the GSF is modified as follows:

$$\hat{a}_{ij,b} = a_{ij,b} - \sum_{k \neq b} \left(a_{ij,k} \times P_k^{\max} \Big/ \sum_{r \neq b} P_r^{\max} \right) \tag{3}$$

where $\hat{a}_{ij,b}$ is the modified GSF between branch ij and bus b; $P_k^{\max}$ is the maximum MW rating of generator at bus k.

If index ij in Eq. (3) refers to the boundary lines between the SA and EA, this equation can be used for ranking the EA Gen-buses based on their effects on boundary-line power flows.

It is also necessary to discriminate the EA Gen-buses based on their rating and unavailability. The EA Gen-buses with higher unavailability are more prone to outage and hence have a higher probability to change the power in the boundary lines. In addition, according to (1), an outage of an EA Gen-bus with higher capacity has a greater impact on the boundary-line power flows. Considering these points, the following ranking factor is defined for grading the EA Gen-buses:

$$GR_g = \frac{P_g^{\max}}{S_{base}} \times \frac{U_g}{U_{EA-g}^{\min}} \times \sum_{ij = Boundary\ Lines} \left|\hat{a}_{ij,g}\right| \quad (pu) \tag{4}$$

where $P_g^{\max}$ is the MW rating of Gen-bus $g$in the EA; U_g is the unavailability of Gen-bus g in the EA, $U_{EA-g}^{\min}$ is the minimum unavailability of Gen-buses in the EA, $\hat{a}_{ij,g}$ is the modified GSF between Gen-bus g in the EA and the SA–EA boundary-line ij, S_{base} is the base of power in per unit calculations.

The GR_gfactor determines the expected value for the maximum cumulative impact of Gen-bus g on the SA–EA boundary lines.

As noted earlier, Gen-buses in this issue correspond to power plants. Each power plant in the power system can include a number of generating units, which in turn will increase the number of GSF to be calculated. In order to reduce the GSF numbers and the calculation burden, a GSF factor is determined for each Gen-bus instead of each generating unit. Hence, $P_g^{\max}$ and U_g in (4) are the total MW capacity and unavailability of Gen-bus g, respectively. The $P_g^{\max}$ is equal to the sum of MW rating of the generating units connected to busg. The unavailability of bus g can be estimated by the statistical mean of the MW capacity at bus g as follows:

$$U_g = 1 - \sum_{k = Bus\,g\,units} P_k^{\max} A_k / P_g^{\max} \tag{5}$$

where A_k is the availability of generating unit k connected to busg. At buses where all the connected units are fully reliable, the fraction of $U_g/U_{EA-g}^{\min}$ in (5) is considered as 1.0. Eq. (5) is mainly suitable in case where all considered generating units are owned by a single entity such as a utility or a GenCo.

Since the GSF of different EA Gen-buses may have opposite signs, they can eliminate each other in an ordinary summation process. On the other hand, the cumulative effect of the EA Gen-buses on the SA–EA boundary lines is required (and not their net effect). Hence, absolute value of the GSF has been used in the summation in (4).

Eq. (4) can easily be adapted to the operational model of a power market. For instance, the definition of $P_g^{\max}$ in (4) is suitable for long-term market operation or planning. In short-term condition, the $P_g^{\max}$ can be considered as the maximum assigned energy or reserve to bus g.

3. Further description of the proposed method

3.1. Reliability and N–k criteria

The N–k is a well known criterion related to power system reliability. In this criterion, it is assumed that simultaneous outage of k out of N system components can be tolerated. Since higher order contingency levels have dispensable probability of occurrence, k is usually limited to 1 or 2. Also, it is not technically justifiable to meet higher values of k. Based on the N–k criteria, in probabilistic risk or reliability evaluation, system states are analyzed up to contingency level k. The purpose of this analysis is to recognize unavoidable load or demand interruptions.

In the proposed methods, it is required to rank each Gen-bus according to its outage effect on power flow in the boundary lines. So, outage impacts of Gen-buses on the boundary lines are individually analyzed by utilization of the GSF. Consequently, formulation of the proposed method is in fact on the basis of the $N-1$ contingency level. Study of two or more simultaneous outages of Gen-buses is beyond the scope of this paper.

3.2. Adequacy and security

The reliability of a system is conventionally categorized into adequacy and security requirements. Adequacy is interpreted as the existence of sufficient facilities to supply the system demands under static conditions. Security is a measure of system capability to withstand dynamic or transient disturbances (Billinton and Li, 1994; Shahidehpour et al., 2002). Adequacy evaluation is a mid- or long-term problem whereas security analysis is considered in the short-term studies.

In the formulation of the proposed method, dynamic behavior of system components is not considered and hence, the proposed method is more suitable for mid- or long- term system studies. It can be concluded that reliability has been taken into account having the same meaning as adequacy in the proposed method.

3.3. Unavailability of a Gen-bus

Eq. (5) can be more explained with consideration of the concept of capacity-outage-probability-table (COPT). The COPT is widely utilized in reliability analysis of generation system (Billinton and Allan, 1996). Fig. 2 is applied in this section to illustrate the matter. In this figure, two generating units designated by G_1 and G_2 are connected to bus g. It is assumed that capacity, availability and unavailability of generating unit k are represented by $C_k = P_k^{\max}$, A_k and $U_k = 1 - A_k$, respectively where k=1 or 2. Table 1 shows COPT at bus g. Due to random failures of generating units, different generation states can occur. The COPT includes capacities and corresponding probabilities of these generation states. Based on the determined COPT, expected available capacity can be calculated as follows:

$$\overline{C}_{available} = (C_1 + C_2)A_1A_2 + C_2U_1A_2 + C_1A_1U_2$$
$$\overline{C}_{available} = C_1A_1(A_2 + U_2) + C_2A_2(A_1 + U_1)$$
$$\overline{C}_{available} = C_1A_1 + C_2A_2$$

Average unavailability of power generation at bus g can be determined in the following manner:

$$A_g = \frac{\overline{C}_{available}}{C_1 + C_2} \Rightarrow U_g = 1 - \frac{\overline{C}_{available}}{C_1 + C_2}$$

As it can be noticed, similar result is obtained from Eq. (5).

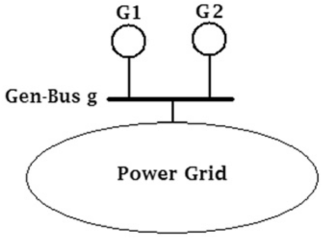

Fig. 2. An example for determination of the unavailability for a Gen-bus.

Table 1
Capacity-outage-probability-table (COPT) for considered Gen-bus in Fig. 2.

Generation state	Capacity outage	Available capacity	Probability
G_1 and G_2 operate	0	C_1+C_2	$A_1 \times A_2$
G_1 fails	C_1	C_2	$U_1 \times A_2$
G_2 fails	C_2	C_1	$A_1 \times U_2$
G_1 and G_2 fail	C_1+C_2	0	$U_1 \times U_2$

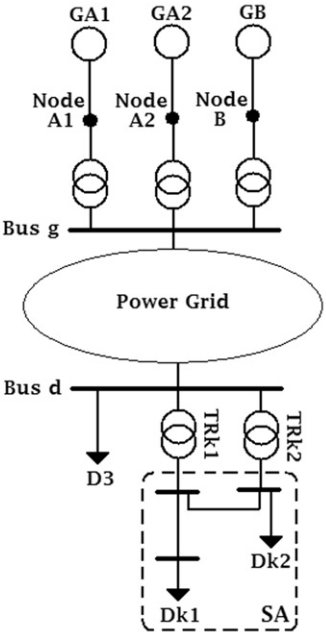

Fig. 3. Applicability of the proposed methods in cases where generating units connected to a main bus and customers supplied by a main bus are owned by different market players.

3.4. Generating units with different owners at a bus

This issue is related to application of the proposed method in case that all generating units connected to a main Gen-bus are not owned by a GenCo. In this case, it is reasonable to avoid using Eq. (5) for the Gen-bus. For instance, in Fig. 3, it is assumed that generating units G_{A1} and G_{A2} belong to $GenCo_A$; and G_B is owned by $GenCo_B$. In accordance with usual practice, these generating units are connected to bus g through (power plant) transformers. Auxiliary nodes between the generating units and the transformers can be considered as auxiliary Gen-buses in the proposed method for obtaining separate rankings for G_{A1}, G_{A2} and G_B. Nodes A1 and A2 are assumed as auxiliary Gen-buses for $GenCo_A$ during ranking process of G_{A1} and G_{A2}. For $GenCo_B$, node B is considered for G_B. So, by definition of the auxiliary Gen-buses, the proposed method can be easily extended for the case where generating units connected to a main bus are owned by different market players. Since it is unusual that generating units in a power plant belong to different market entities, the mentioned extension of the proposed method is not studied in this paper.

3.5. Loads with different suppliers at a bus

It is evident that the definition of the SA depends on the geographical or technical correlation among the customers. The SA is logically defined in accordance with territory of a DisCo in the restructured environment. Consideration of distribution transformers and related auxiliary nodes can facilitate the definition of the SA when customers connected to a main bus are supplied by different DisCos. For instance, in Fig. 3, the SA at bus d is defined according to territory of $DisCo_K$which includes D_{K1} and D_{K2}. In this example, transformers TR_{K1} and TR_{K2} constitute the SA–EA boundary lines.

3.6. Independency from the system operating points

Instead of power generation at an operating point or loading condition, maximum rating of Gen-buses have been utilized in the formulation of the proposed method. This means that the Gen-buses are ranked according to the extent that they can affect the SA reliability. So, it is not necessary to repeat the ranking process at different system operating points. However, in case it deems necessary (such as for hydro Gen-buses), the user could also apply different values for maximum rating of Gen-buses that are more often available.

4. Study results

4.1. Test system

The IEEE reliability test system (IEEE-RTS), shown in Fig. 4, is used to illustrate the applicability of the proposed method (Applications of the probability methods subcommittee, 1979). This is a standard test system which is widely used in literatures to

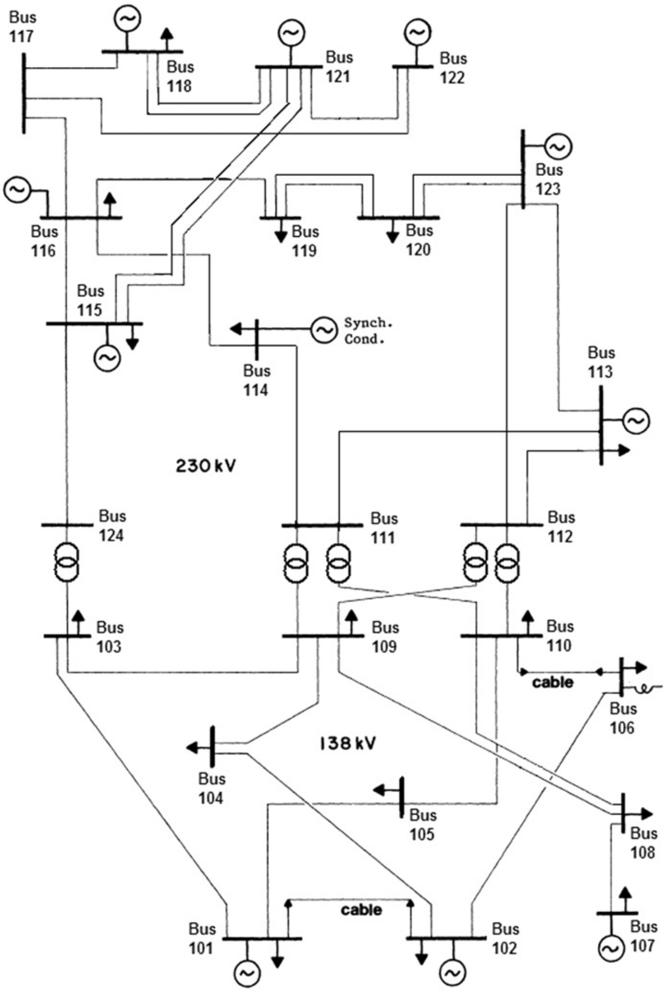

Fig. 4. The IEEE reliability test system.

Table 2
Supplementary data for generation buses according to (5).

Bus	P_g^{max}(MW)	U_g
101	192	0.037
102	192	0.037
107	300	0.040
113	591	0.050
115	215	0.034
116	155	0.040
118	400	0.120
121	400	0.120
122	300	~0.00
123	660	0.061

perform reliability studies. The IEEE-RTS has 24 buses out of which 10 are Gen-buses. Table 2 shows supplementary data for the Gen-buses according to (5). Since the unavailability of bus 122 is 4 times less than the minimum unavailability, in calculating Gen-bus rankings, the unavailability of this bus is assumed to be zero.

4.2. Validation check

Risk sensitivity analysis has been applied in order to validate the ranking obtained for the EA Gen-buses in the proposed method. In the sensitivity analysis, the Gen-buses (according to their order in the ranking list) are sequentially assumed to be fully reliable. For each case of a fully reliable generation bus, risk index is calculated at the SA load points. Then, average relative error of the risk index at the SA load points is determined as follows:

$$\overline{RE}_{SA}=\frac{100}{N_{SA-b}}\sum_{\substack{b=SA\\ Buses}}\frac{\left|Risk_b^{new\ \ case}-Risk_b^{base\ \ case}\right|}{Risk_b^{base\ \ case}} \qquad (6)$$

where, $Risk_b^{new\,case}$ is the Risk index at bus $b$of the SA when a Gen-bus of EA is assumed to be fully reliable, $Risk_b^{base\,case}$ is the risk index at bus b of the SA in the base case or initial condition, N_{SA-b} is the number of the SA load points (load buses).

If ranking values of the EA Gen-buses determined by (4) and values obtained from (6) have similar descending trend, then the determined ranking of the Gen-buses is considered as valid.

The risk index of Expected Energy Not Supplied (EENS) is considered in this paper. The EENS is a comprehensive index which contains aggregated information on the probabilities, durations and consequences of outages (Li, 2005). Reliability evaluations in the studies presented in the next sub-sections are implemented with the "reliability module" of NEPLAN software version 5.4.2 (www.neplan.ch).

Since it is not intended to consider the impact of load variation on reliability at load points, annualized EENS is applied in the following studies. During calculation of annualized risk indices, bus loads are often assumed to be at their annual peak values. Annualized risk indices are usually applied in order to compare reliability of different alternatives in power system planning and operation studies (Li, 2005).

4.3. Case study A

In the first study, it is assumed that the SA contains the load buses 103 and 109. Remaining buses, i.e. 101, 102 and 104 to 108 and 110 to 124 constitute the EA. There are six boundary lines between the SA and EA, i.e. 101–103, 103–124, 104–109, 108–109, 109–111 and 109–112. Eq. (4) determines ranking (reliability importance) of the EA Gen-buses based on their cumulative impacts on power flow through the boundary lines. Fig. 5 shows the calculated rankings. The y-axis in this figure is the GR_g value, defined in (4).

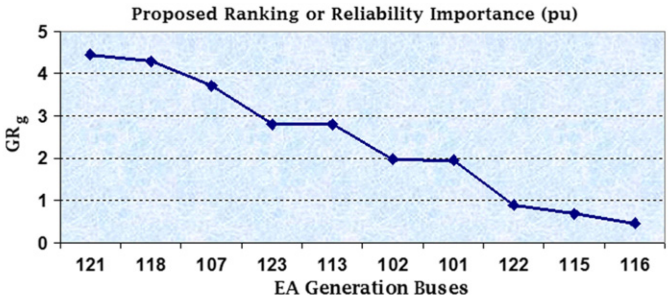

Fig. 5. Ranking of the EA generation buses in case study A according to (4).

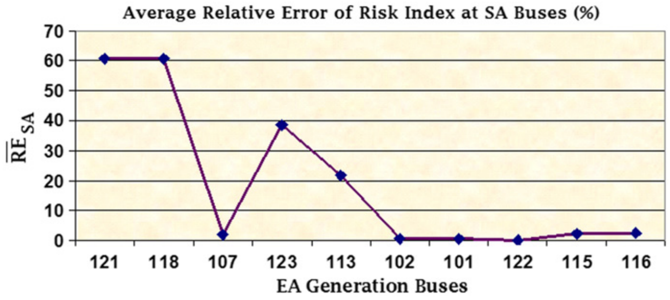

Fig. 6. Results of the risk sensitivity analysis at the SA in case study A according to (6).

In order to check the effectiveness of the proposed method, the calculated ranking has been compared with the results obtained by (6). Fig. 6 shows average relative error of the risk index at the SA buses ($\overline{RE}_{SA}$) when Gen-buses (in the sequence of 121, 118, … and 116) are assumed to be fully reliable.

Except for bus 107, $\overline{RE}_{SA}$ in Fig. 6 and GR_g in Fig. 5 generally follow similar pattern. The reason for this exception is the radial connection of bus 107 to bus 108. Due to this connection, the subtraction of $X'_{107,108}-X'_{107,109}$ and consequently the $\hat{a}_{108-109,107}$ has high value. So, an unrealistic ranking value is obtained for bus 107 in the proposed method.

4.4. Case study B

In the second study, buses 116, 119 and 120 are considered as the SA. Boundary lines between the SA and EA are 114–116, 115–116, 116–117 and 120–123. Fig. 7 shows the calculated reliability importance of the EA Gen-buses (GR_g) according to (4). The results obtained by (6) are shown in Fig. 8. The latter figure demonstrates the $\overline{RE}_{SA}$ when generation buses are assumed to be

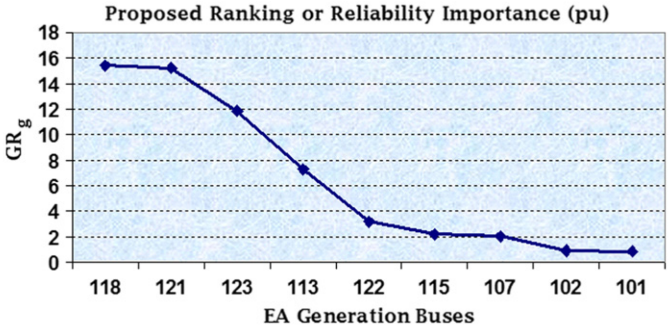

Fig. 7. Ranking of the EA generation buses in case study B according to (4).

fully reliable in the order of the proposed ranking. It is pertinent to note that there is a noticeable consistency between Figs. 7 and 8.

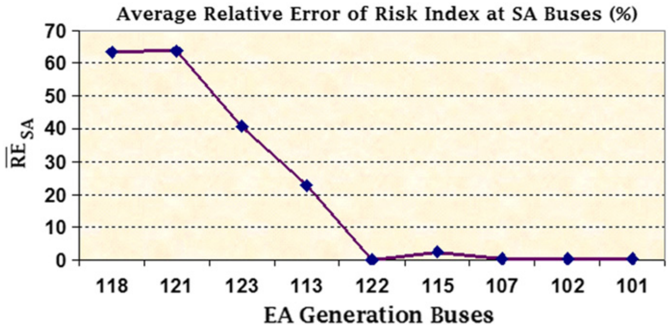

Fig. 8. Results of the risk sensitivity analysis at the SA in case study B according to (6).

4.5. Case study C

In the third study, lower voltage level of the IEEE-RTS (buses 101 to 110) is included in the SA. Higher voltage level of the IEEE-RTS (buses 111 to 124) constitutes the EA. There are 5 coupling transformers between upper and lower voltage levels which are considered as the boundary lines (103–124, 109–111, 109–112, 110–111 and 110–112). This case study is similar to the interconnection of two power systems and demonstrates that the proposed method can handle cases in which SA constitute a large portion of the system. Ranking of the EA Gen-buses (GR_g) and the corresponding results of risk sensibility analysis ($\overline{RE}_{SA}$) are shown in Figs. 9 and 10, respectively. Almost similar descending trend is observed in these figures and hence the proposed ranking for the EA Gen-buses is considered as valid.

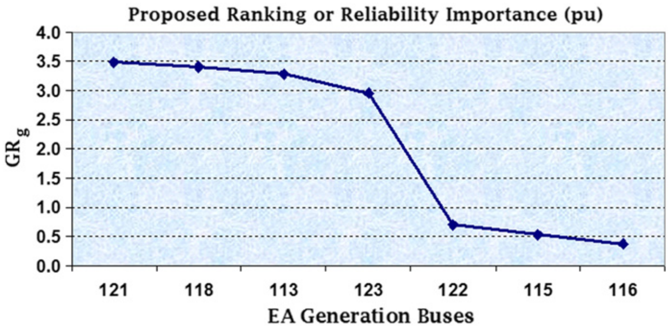

Fig. 9. Ranking of the EA generation buses in case study C according to (4).

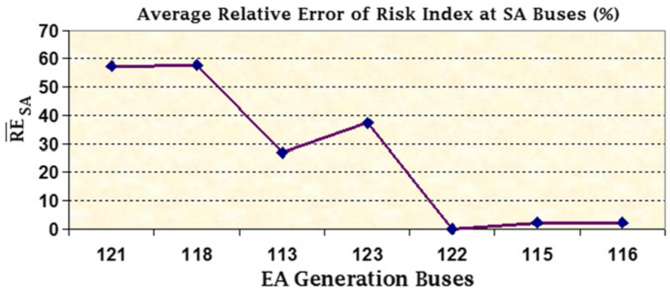

Fig. 10. Results of the risk sensitivity analysis at the SA in case study C according to (6).

5. Conclusion

A method for determining reliability importance of power plants (Gen-buses) or energy producers in a composite power system is presented in this paper. The following features can be stated for the presented method:

- The proposed method does not impose immense computational burden. This can be considered as an advantage over the conventional methods which are based on risk sensitivity analysis and suffer from massive computational burden. At the same time, an acceptable degree of accuracy is observed in the ranking determined for energy producers in the presented method.
- Implementation of customer choice of reliability level is generally difficult and still has no widespread application in restructured power systems. So, consideration of the reliability at load points can be regarded as an advantage of the proposed method.
- The presented method can be utilized as an analytical tool to facilitate decision making in a variety of issues with consideration of reliability, i.e.:
    - Determination of proper locations for generation system planning (where are better choices for investment leading to more improvement in reliability at selected load points?)
    - Selection of proper energy producer candidates for allocation of power generation or reserve by ISO (the proposed method identifies energy producers which have greater impacts on reliability and hence ISO gives higher priority to such producers to participate in energy and reserve management).
    - Assignment of reliability incentives to the GenCos that have more impacts on the reliability.
    - Determining priority list of power plants for maintenance scheduling (Gen-buses with lower impacts on reliability can be considered as first candidates for implementing maintenance).
    - Choice of preferable GenCos for conducting bilateral contracts in a power market (based on preferences of selected customers in the SA, a DisCo can select a GenCo which can meet customers' requirements).
- Two determining parameters, i.e. MW rating and unavailability, are considered in the proposed method. Hence, the calculated ranking for Gen-buses is generally consistent with the actual impact of these components on the reliability.

Further investigations have revealed that the proposed method provides more realistic results in meshed networks with full connectivity between the network nodes. This feature is in accordance with the structure of composite power systems. In radial networks (for instance bus 107 in case study A), the precision of the results is reduced. This is due to the fact that in radial networks, connectivity criterion (concept of cut-set) is more determinant for reliability whilst this criterion has not been considered in the proposed formulation.

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