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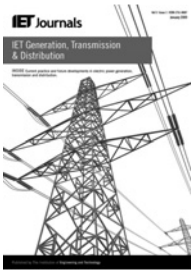

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Adequacy equivalent development of composite generation and transmission systems using network screening

A. Akhavein[1] *M. Fotuhi-Firuzabad*[2] *R. Billinton*[3] *D. Farokhzad*[4]

[1]*Department of Electrical Engineering, Islamic Azad University-South Tehran Branch, Tehran, Iran*
[2]*Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran*
[3]*Department of Electrical and Computer Engineering, University of Saskatchewan, Saskatoon, Canada*
[4]*Deputy for Planning and System Security Monitoring Iran Grid Management Company, Tehran, Iran*
E-mail: fotuhi@sharif.edu

Abstract: Reliability evaluation of a large composite generation and transmission system involves extensive and time-consuming calculations. Application of reliability equivalent networks therefore seems necessary in the reliability evaluation of large power systems. An approach is presented to develop an adequacy equivalent of a composite system using network screening. In the proposed method, a power system is divided into two portions designated as the study area and the external area. The goal is to find the adequacy equivalent of the external area in order to facilitate extensive reliability studies in the study area. The elements in the external area are ranked or screened based on their impacts on power flows in the tie lines between the two areas. Owing to their less impact, the lower ranked elements are considered to be involved in a network reduction technique. Simulation studies are conducted on the IEEE-RTS-96 and the performance of the developed procedure is thoroughly discussed.

1 Introduction

It is a common practice to divide large power systems into subsystems with manageable sizes and apply simplification methods based on the study purposes. One of these simplification methods is the substitution of a subsystem by its equivalent network. The interest to apply an equivalent network increases as the size of the power system and the complexity of the required analysis increases.

Reliability evaluation in a composite generation and transmission system requires complex analysis with a massive calculation burden, and hence it is a clear candidate for the application of equivalent networks. For instance, in Fig. 1, a large power system is partitioned into two areas designated as the ‘study area’ (SA) and the ‘external area’ (EA). It is required to perform detailed reliability studies in the SA and the EA is not of direct concern. The EA is important up to the extent where it affects the SA studies. Since the EA usually constitutes the larger portion of the system, its size and calculation burden can be an obstacle in the SA studies. One way to overcome this impediment is the substitution of the EA by a reduced equivalent network.

The reliability of a system is conventionally categorised 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 [1]. Adequacy evaluation is a mid- or long-term problem, whereas security analysis is considered in the short-term studies. In the adequacy evaluation, dynamic behaviour of system components is not considered, and hence static models are applied in the system studies. This paper deals with the problem of finding an adequacy equivalent for an EA in a composite generation and transmission system. Reliability, risk and adequacy have been used interchangeably with the same meaning in this paper.

The issue of determining equivalents for the EA by network reduction techniques proved to be successful in load-flow studies. Methods that are solely based on the load-flow network reduction techniques, however, are not sufficient for finding an adequacy equivalent as there is no pre-defined procedure in these methods to include stochastic outages of the network elements.

Based on the literature review presented in [2], methods for determination of the composite system adequacy equivalent can be categorised into three types. The first type methods employ load-flow reduction techniques in one of their stages. However, according to the above-mentioned limitation, these methods apply supplementary procedures in conjunction with the load-flow reduction techniques. In the second type methods, which can be designated as tabular methods, the adequacy equivalent in the form of a capacity-probability table is obtained at the selected buses. The third type methods apply risk sensitivity analysis to classify system elements based on their impact on system risk.

Examples of the first type methods are presented in [3–5]. The proposed method in [3] has two stages. In the first stage,

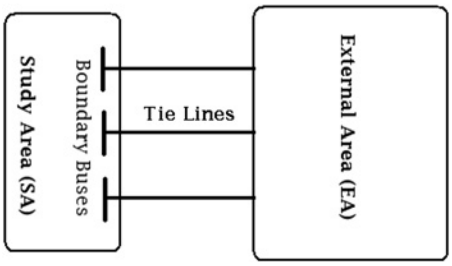

Fig. 1 *Partitioning a power system into EA and SA*

statistical means of the admittances are calculated to simulate random branch outages. These mean admittances are then used to find the AC Ward equivalent of the EA in the second stage. Calculation of these statistical means loses efficiency and accuracy in large systems with numerous contingencies. In [4, 5], a power system is divided into the three regions of equipment outage area, optimisation area and EA. The probabilistic behaviour of generators and transmission lines are completely considered in the equipment outage area. In the optimisation area, it is assumed that equipments are fully reliable and involved in the remedial actions. Using the assumption of fixed generators and loads, the EA is substituted by its DC Ward equivalent. The proposed method in [4, 5] has high precision for adequacy evaluation in the SA. However, in these references, system partitioning is implemented based on engineering judgement and not on the basis of a numerical criterion.

The second type or tabular methods are applied in [6–9] for developing an adequacy equivalent of the EA in the form of a table. This table contains different available capacities with their probabilities and frequencies at the selected buses. The main feature of the tabular methods is the combination of states with similar available capacity and not real network reduction. The adequacy equivalent tabular methods lose their efficiency in large systems, where the number of combinable states at the considered buses is not considerable.

The third type methods, such as the procedures developed in [10, 11], need immense risk calculations and hence do not seem to be attractive for determining the adequacy equivalent. These methods cannot guarantee reduction of the time and computation burden compared to the conventional network reduction methods.

It may be argued that continuous enhancement in computer capabilities can obviate the need for adequacy equivalents in composite system reliability evaluation. This is not generally true. The reason is the continuous increase in the size of interconnected power systems and in the complexity of their operation procedures. In addition, it is usually difficult for technical PC-based software to cope with reliability evaluation of very large systems. It is therefore useful to apply adequacy equivalents for the purpose of system size reduction.

This paper proposes a method for determining the adequacy equivalent of an EA which is based on the active-power interaction between the SA and EA. In the proposed method, the EA elements are screened according to their impacts on the power flow through tie-lines between the SA and EA. The EA elements that have no or little impact on the tie-line flows are considered as candidates for network reduction. 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, concluding remarks are presented in Section 5.

2 Proposed method for developing an adequacy equivalent

The basic idea of the proposed method is to screen the EA elements for determination of the proper candidates to participate in the network reduction process. In order to implement this idea, two key points have been considered in the developed method. The first point is the predominant effect of the active power-flow patterns in the system and load point risk indices. The second point is the active-power interaction between the SA and EA, which merely can take place through the tie-lines between them. The tie-lines are the only ways that SA and EA can transmit active power. Considering these points, screening the EA elements in the proposed method is performed by ranking generators, branches (lines and transformers) and loads in the EA based on their effect on the active power-flows in the tie-lines. Elements of the EA with higher ranks are completely modelled in the adequacy evaluation of the whole system. The lower ranked EA elements are considered to be fully reliable and are selected for the network reduction.

In order to rank the EA elements, two factors relating to the active-power interactions, designated as generation shift factor (GSF) and line-outage distribution factor (LODF), are utilised in this paper. The GSF shows the effect of a generating unit outage at a bus on the power flow in a branch. The LODF represents variation of the power flow in a branch due to outage of another branch. These are well-known sensitivity factors with wide applications and are defined as follows [12–14]

$$\text{GSF} = a_{ij,b} = \frac{\Delta P_{ij}}{-P^0_{G,b}} \tag{1}$$

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

$$\text{LODF} = d_{ij,mn} = \frac{\Delta P_{ij}}{P^0_{mn}} \tag{3}$$

$$d_{ij,mn} = \frac{x_{mn}}{x_{ij}} \times \frac{(X'_{im} - X'_{in}) - (X'_{jm} - X'_{jn})}{x_{mn} - (X'_{mm} + X'_{nn} - 2X'_{mn})} \tag{4}$$

where ΔP_{ij} is the change in active-power flow of branch ij, $P^0_{G,b}$ is the active-power generation at bus b before generation outage at this bus, P^0_{mn} is the active-power flow in branch mn before outage of this branch, $a_{ij,b}$ is the GSF between branch ij and bus b, $d_{ij,mn}$ is the LODF between branch ij and branch mn, x_{ij} is the series reactance of branch ij, x_{mn} is the series reactance of branch mn and 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 change in power injection at bus b is exactly compensated by an opposite change in the reference (slack) bus and the power output of other generators remains fixed. This assumption is not generally valid for adequacy evaluation, where all generators can participate in the remedial actions. In order to modify the GSF in this regard, the modification procedure in [13] is utilised. In this reference, it is assumed 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

$$\hat{a}_{ij,b} = a_{ij,b} - \sum_{k\neq b} \frac{a_{ij,k} \times P_{G,k}^{\max}}{P_G^{\max} - P_{G,b}^{\max}} \tag{5}$$

where $\hat{a}_{ij,b}$ is the modified GSF between branch ij and bus b, $P_{G,k}^{\max}$ is the maximum MW rating of generation at bus k, $P_{G,b}^{\max}$ is the maximum MW rating of generation at bus b and $P_G^{\max}$ is the total capacity which participates in the remedial actions.

If index ij in (4) and (5) refers to the tie-lines between the SA and EA, these equations can be used for ranking the EA elements based on their effects on tie-line power flows.

It is also necessary to discriminate the EA elements based on their rating and unavailability. Based on (1) and (3), an outage of an EA element with higher capacity has a greater impact on the tie-line power flows. In addition, the EA elements with higher unavailability are more prone to outage and hence have a higher probability of changing the power in the tie-lines. If rating and unavailability of the failed elements are considered in (1), (3) and (5), then the expected maximum change in the branch flow due to the failure can be determined as follows

$$\Delta P_{ij}^{\max} = P_{G,b}^{\max} \times U_b \times |\hat{a}_{ij,b}| \tag{6}$$

$$\Delta P_{ij}^{\max} = P_{mn}^{\max} \times U_{mn} \times |d_{ij,mn}| \tag{7}$$

where $P_{G,b}^{\max}$ and $P_{mn}^{\max}$ stand for MW rating of generation at bus b and power transfer in branch mn, respectively. Unavailability of the mentioned elements is represented by U_b and U_{mn}. Based on (6) and (7), the following factors are applied to rank the EA generators, loads and branches in the proposed method

$$GR_g = \frac{P_{G,g}^{\max}}{S_{\text{base}}} \times \frac{U_g}{U_{G,\text{EA}}^{\min}} \times \sum_{ij=\text{Tie Lines}} |\hat{a}_{ij,g}|\ (pu) \tag{8}$$

$$DR_d = \frac{P_{D,d}^{\max}}{S_{\text{base}}} \times \sum_{ij=\text{Tie Lines}} |\hat{a}_{ij,d}|\ (pu) \tag{9}$$

$$BR_{mn} = \frac{P_{mn}^{\max}}{S_{\text{base}}} \times \frac{U_{mn}}{U_{B,\text{EA}}^{\min}} \times \sum_{ij=\text{Tie Lines}} |d_{ij,mn}|\ (pu) \tag{10}$$

where $P_{G,g}^{\max}$ is the MW rating of generation at bus g in the EA, U_g is the unavailability of generation at bus g in the EA, $U_{G,\text{EA}}^{\min}$ is the minimum unavailability of generation buses in the EA, $\hat{a}_{ij,g}$ is the modified GSF between generation bus g in the EA and the SA–EA tie-line ij, $P_{D,d}^{\max}$ is the MW peak load at bus d in the EA, $\hat{a}_{ij,d}$ is the modified demand shift factor (DSF), between load bus d in the EA and the SA–EA tie-line ij, $P_{mn}^{\max}$ is the MW rating of branch mn in the EA, U_{mn} is the unavailability of branch mn in the EA, $U_{B,\text{EA}}^{\min}$ is the minimum unavailability of the EA branches, $d_{ij,mn}$ is the LODF between branch mn in the EA and the SA–EA tie-line ij and S_{base} is the base of power in the per-unit calculations.

Using the above ranking factors, the EA elements can be ranked according to their maximum cumulative impact on the SA–EA tie-lines. The parameters $U_{G,\text{EA}}^{\min}$ and $U_{B,\text{EA}}^{\min}$ in (8) and (10) are very small values that are selected by the user (for instance, a very small fraction of the minimum unavailability among the elements with the same type in the EA). These parameters enhance the effect of unavailability of elements in the ranking values (the more the unreliability difference to $U_{G,\text{EA}}^{\min}$ or $U_{B,\text{EA}}^{\min}$, the higher the ranking).

Each generation bus in the power system can include a number of generators, 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 generation bus instead of each generating unit. Hence, $P_g^{\max}$ and U_g in (8) are the total MW capacity and unavailability of generation bus g, respectively. The $P_{G,g}^{\max}$ is equal to the summation of MW rating of the generators connected to bus g. The unavailability of bus g can be estimated by the statistical mean of the MW capacity at bus g as follows

$$U_g = 1.0 - \frac{\sum_{k=\text{Bus } g \text{ units}} P_{G,k}^{\max} A_k}{P_{G,g}^{\max}} \tag{11}$$

where A_k is the availability of the generator k connected to bus g. At buses where all the connected units are fully reliable, the fraction of $U_g/U_{G,\text{EA}}^{\min}$ in (8) is considered as 1.0. This is useful in order to avoid zero ranking for the generation bus 'g' in (8).

Any load in the power system can be considered as a negative power injection at its related bus; hence, formulation of the DSF in (9) is similar to that of the GSF in (5).

Since the GSF and DSF of different EA elements may have opposite signs, they can cancel each other in an ordinary summation process. On the other hand, the cumulative effect of the EA elements on the SA–EA tie-lines is required (and not their net effect). Hence, absolute values of sensitivity factors have been used in the summations in (8)–(10).

Fig. 2 shows the flowchart of the proposed method in which the foregoing ranking factors are applied to determine the adequacy equivalent of the EA. Priority lists of the EA generators, loads and branches are determined using (8)–(10). An effective way to select the higher ranked or important elements of the EA from these lists is to observe the distinguishable levels of ranking in their corresponding curves. These ranking levels are distinct by slope changes in the ranking curves. So, different ranking levels or their corresponding slope changes in these curves can be used to categorise the EA elements based on their importance. The ranking levels or slope changes can be found either through inspection or by a simple computer code which calculates the curve slopes. The lower ranked or less important elements of the EA are considered to be fully reliable. The EA buses that are not connected to the tie-lines and to the important generators, loads or branches are selected for use in a load-flow reduction technique from which an AC Ward equivalent is obtained [15].

One way to assess precision of the EA adequacy equivalent is to determine average relative error of risk index at the SA buses as follows

$$\overline{\text{RE}}_{\text{SA}} = \frac{100}{N_{\text{SA}-b}} \sum_{\substack{b=\text{SA}\\ \text{Buses}}} \frac{|\text{RI}_b^{\text{new case}} - \text{RI}_b^{\text{base case}}|}{\text{RI}_b^{\text{base case}}} \tag{12}$$

where $\text{RI}_b^{\text{new case}}$ is the risk index at bus b of the SA when adequacy equivalent of the EA is applied, $\text{RI}_b^{\text{base case}}$ is the

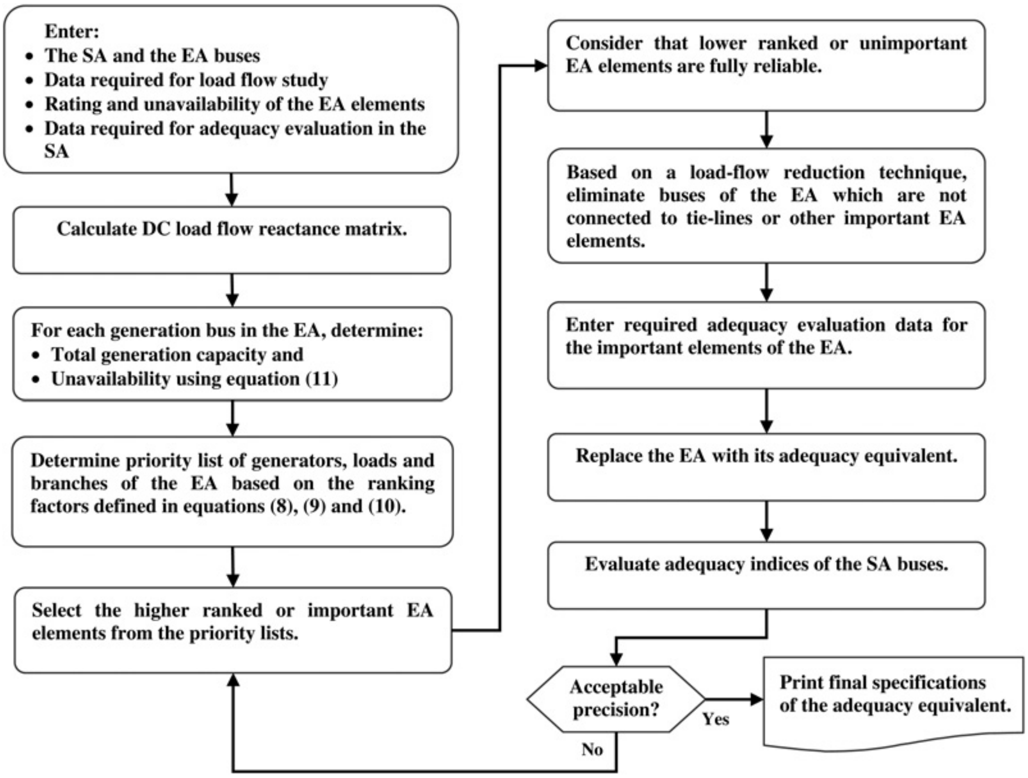

Fig. 2 *Flowchart of the proposed method for adequacy equivalent development*

risk index at bus b of the SA in the base case or when the EA is fully modelled, $N_{\mathrm{SA}-b}$ is the number of the SA buses.

In order to utilise (12), risk analysis of the system with the EA fully modelled must be performed once before the SA extensive studies. In case of not utilising (12), other criteria based on the user's engineering judgment could be applied. This paper applies (12) for precision assessment of the proposed method. If the 'acceptable precision' block in Fig. 2 reveals that the relative errors of risk indices at the SA buses are more than a pre-specified threshold, more elements of the EA from the priority lists are considered to be retained in the system (excluded from load-flow reduction). This means that lower ranking levels of elements are observed in the selection process in order to increase the number of EA important elements.

3 Further description of the proposed method

The first issue is the intentional avoidance of voltage and reactive power (V–Q) sensitivities in the proposed method. Several reasons can be stated for this avoidance. One argument is the secondary effect of reactive power flow on the system adequacy. The reasoning for this statement is the common application of a DC load-flow model in the load curtailment minimisation problem during adequacy evaluation. Another point is the high non-linearity and complexity of V–Q equations and hence the lower precision of the linearised version of these equations [16]. It also cannot be assumed that only generation units are responsible for reactive power balance in the system. Another reason is the unrealistic ranking of elements which may be obtained when V–Q equations are combined with active-power equations. There are many instances in which a bus has determinant impact on voltage but has little effect on the system adequacy. It can therefore be concluded that the benefits of including V–Q equations in the adequacy evaluations may not justify the calculation cost.

The second issue is in relation with (5). Equation (5) can be modified to accommodate a more general or comprehensive dispatching procedure during remedial actions, if required in a particular application. For instance, if not all of the generation units participate in the remedial actions, the summation in (5) can be confined to the generation units that are involved in these actions. Based on (5), it can be shown that if rating of the excluded generation buses is small in comparison with the total installed generation capacity, then GSFs will have negligible variations. Thus, change in ranking of the generation buses is not noticeable.

The third issue is the differences between the proposed method and the contingency selection/screening methods. In the conventional contingency selection methods, a deterministic performance index (PI) is utilised to rank power system elements based on their outage impacts on the system [13]. Contingency selection methods differ from the proposed method as they are not developed to consider outage impacts of one part of the system on the other part. The PI formulation is based on constraint violations and no procedures are defined in the PI to rank elements based on rating and unavailability. In addition, and contrary to the proposed method, the ranking approaches based on the PI require the solution of the load flow.

The fourth issue is the indirect introduction of a buffer zone in the EA using the proposed method. Higher ranked or important EA elements constitute a buffer zone between the SA and the lower ranked EA elements. As discussed in [15, 17], incorporating a buffer zone, which mostly includes elements of the EA that are close to the SA, increases the result accuracy.

The final issue is the definition of (9), which is on the basis of bus peak loads. According to this equation, it is not necessary to determine ranking of the EA load buses for different loading conditions. However, in case it deems necessary, the user could also apply load values for other operating conditions that more often occur.

4 Study results

The IEEE-RTS-96, shown in Fig. 3, is used to illustrate the applicability of the proposed method. The load flow and reliability data of the system have been extracted from [18, 19]. Bus loads are assumed to be at their peak values. In the first and second IEEE reliability test systems, buses are labelled as 101–124 and 201–224, respectively.

Since it is rare in practice that the SA and EA have the same size, different sizes for the SA and EA were intentionally considered, namely, the SA contains buses 111–124. Remaining buses, that is, 101–110 and 201–224 constitute the EA. There are seven tie-lines between the SA and EA, that is, 103–124, 109–111, 109–112, 110–111, 110–112, 113–215 and 123–217.

Table 1 shows supplementary data for the generation buses in the EA according to (9). Since the unavailability at bus 222 is 4 times lower than the minimum unavailability, in calculating ranking factors, the unavailability at this bus is assumed to be zero. This assumption can also be useful to check the performance of the proposed equations when faced with a fully reliable generation bus.

Equations (8)–(10) determine the priority lists (rankings) of the EA elements based on their cumulative impacts on power flow through the tie-lines. Figs. 4–6 show rankings for generators, loads and branches of the EA, respectively. The y-axis in these figures are the GR_g, DR_d and BR_{mn} values, defined in (8)–(10). It is pertinent to note that the rankings of the EA generators are consistent with the results noted in [20, 21].

Table 1 Complementary data for generation buses of the EA according to (11)

Bus	$P_g^{\max}$, MW	U_g
101 and 201	192	0.037
102 and 202	192	0.037
107 and 207	300	0.040
213	591	0.050
215	215	0.034
216	155	0.040
218	400	0.120
221	400	0.120
222	300	~0.000
223	660	0.061

Important elements of the EA can be specified based on the distinguishable levels of ranking values or slope changes in Figs. 4–6. For instance, in Fig. 4, the first six generation

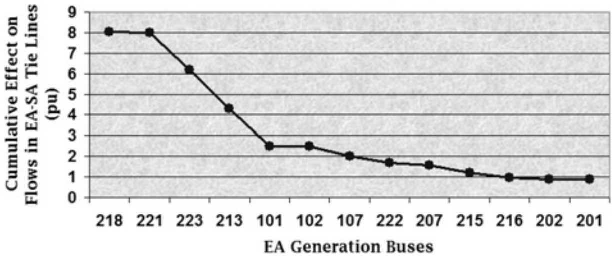

Fig. 4 *Ranking of the EA generation buses according to (8)*

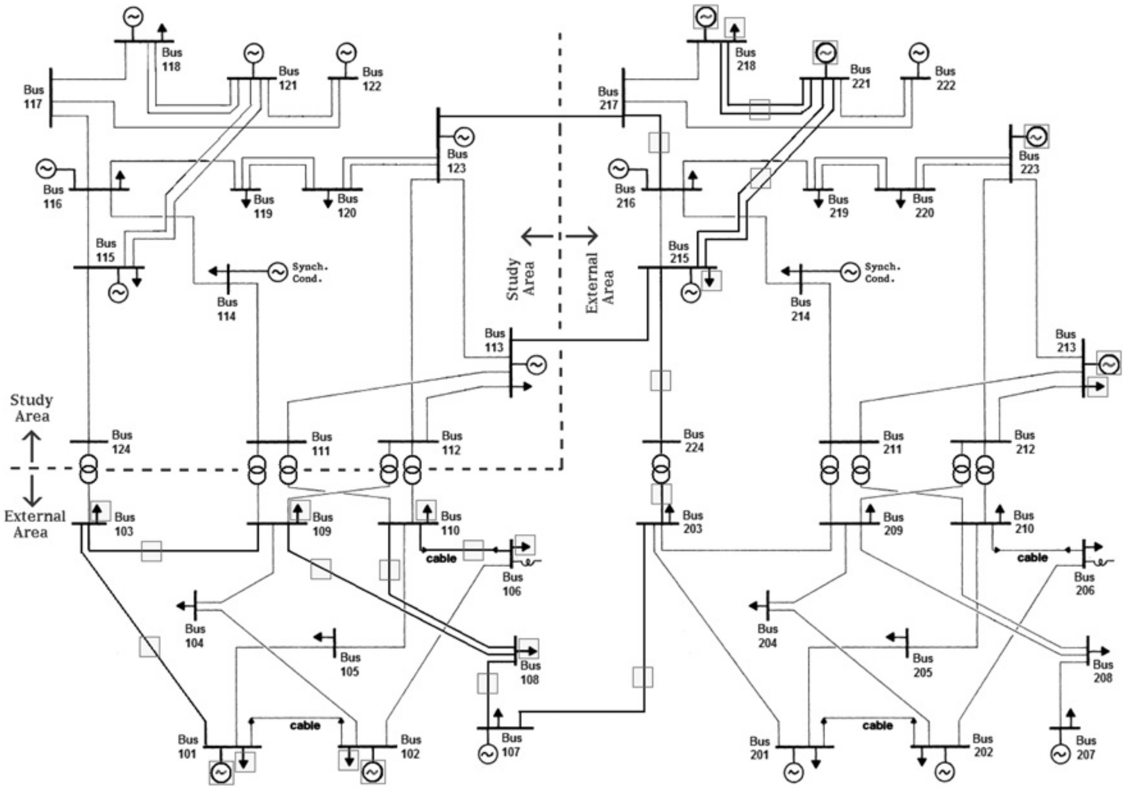

Fig. 3 *Power system studied (two interconnected IEEE-RTS)*

Higher ranked (important) elements of the EA are designated by squares

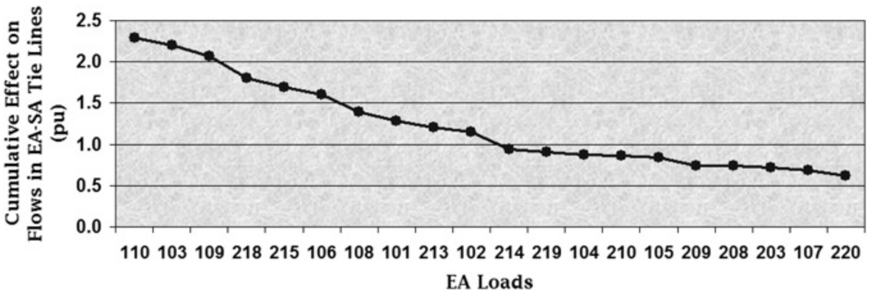

Fig. 5 *First 20 EA load buses from priority list obtained using (9)*

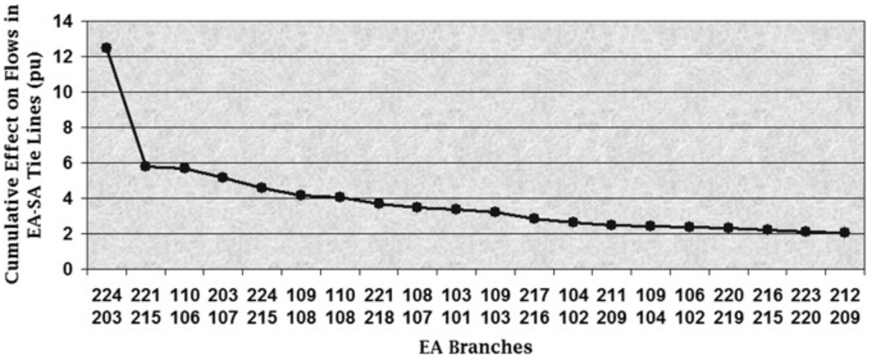

Fig. 6 *First 20 EA branches from priority list obtained using (10)*

buses are situated in four different ranking levels. These ranking levels are distinguishable by three slope changes for generators 221, 101 and 102. After the first six generation buses, it seems that the remaining generators have little impact on the tie-line power flows. The first six generation buses are therefore considered as important buses. In a similar way, the first 10 load buses in Fig. 5 and the first 12 branches in Fig. 6 are designated as important EA elements. The important EA elements are designated by squares in Fig. 3.

Reliability evaluations are implemented with the 'reliability module' of NEPLAN software version 5.4.2, which employs the state enumeration method [22–24]. In order to limit the computation time, contingencies with probabilities less than 10^{-6} are ignored. Expected energy not supplied (EENS) is considered as the risk index in these studies since this is a comprehensive index which contains aggregated information on the durations, frequencies and consequences of outages [25]. In this paper, annualised EENS is applied for which the index is calculated at the system peak load level and is expressed on a base of one year.

In the base case, it takes 1595 s to evaluate the adequacy indices in the system of Fig. 3 on a PC with dual-core 2.66 GHz CPU and 2 GB RAM, and without application of the adequacy equivalent. In the next stage, which is designated by Case A, important elements of the EA are completely modelled in the adequacy evaluation and the lower ranked EA elements are considered to be fully reliable, As shown in Table 2, the time required to evaluate reliability is reduced to 558 s in Case A. Considering that 4 s is required for calculating ranking factors, the required time for adequacy evaluation in Case A is reduced by about 65% in comparison with the base case. Equation (12) gives average relative error at the SA buses or $\overline{\mathrm{RE}}_{\mathrm{SA}}$ for Case A, which is less than 1.40%. Compared with the risk indices at the SA buses in the base case, this considerable saving in time is accompanied with a quite acceptable relative error. The high accuracy obtained is an indication of the proper selection of the EA important elements from the priority lists.

In the final stage, which is designated by Case B, the EA buses that are not connected to the tie-lines and to the important generators, loads or branches are eliminated by the NEPLAN 'network reduction' module; from which AC Ward equivalents for the omitted buses are determined. As can be recognised in Fig. 3, buses 104, 105, 201, 202, 204 to 214, 219, 220 and 222 could be eliminated. This elimination process results in the adequacy equivalent of the EA. The EA elements that are not involved in the network reduction (for instance, generation bus 101, load 101 and branch 101–103 in Fig. 3) constitute a buffer zone between the SA and the reduced portion of the EA. This buffer zone increases the accuracy of the results. Tables 2 and 3 show

Table 2 Execution time in the base case and Cases A and B

	Execution time			
	Adequacy, s	Sensitivity factors, s	Network reduction, s	Decrease relative to the base case, %
base case	1595			
Case A	558	4		64.76
Case B	381	4	3	75.67

Case A: unimportant (lower ranked) EA elements are assumed to be fully reliable

Case B: adequacy equivalent of the EA is applied

Table 3 Reliability index (EENS) of the SA buses in the base case and Cases A and B

Bus no	EENS (MWh/year)				
	Base case	Case A	Absolute error relative to the base case, %	Case B	Average error relative to the base, %
113	11 171.460	11 136.300	0.315	11 201.135	0.266
114	7059.444	7017.284	0.597	7034.825	0.349
115	3007.127	2965.052	1.399	2939.394	2.252
116	3827.268	3813.995	0.347	3823.036	0.111
118	1788.296	1788.296	0.000	1788.293	0.000
119	6437.888	6413.864	0.373	6430.230	0.119
120	4507.118	4490.129	0.377	4501.702	0.120

Case A: unimportant (lower ranked) EA elements are assumed to be fully reliable
Case B: adequacy equivalent of the EA is applied

results of applying the determined EA adequacy equivalent. The required time for the reliability evaluation reduces by about 75%, whereas average relative error ($\overline{RE}_{SA}$) is less than 2.25%. Table 3 compares the reliability indices of the SA buses before and after application of the EA adequacy equivalent. Study results indicate that the proposed method provides significant time efficiency and an acceptable degree of accuracy.

It is useful to compare the precision of the proposed method with the three types of methods defined in the Section 1. The reported results of studies on the IEEE-RTS96 in [4, 5, 9] show that the average relative error of types 1 and 2 methods is less than 5%. This error is less than 15% for type 3 method that was developed in [11]. As illustrated in Table 3, the proposed method has acceptable degree of accuracy comparing with the mentioned errors. At the same time, the presented method obviates some of the limitations of these methods, namely:

- System partitioning is implemented based on the SA–EA tie-line sensitivities to the EA elements and not merely on engineering judgment.
- It is not necessary to investigate capacity-probability of numerous system states at the SA–EA boundary buses.
- There is no need to perform immense risk studies to identify important or higher ranked EA elements.

Since applied equations are on the basis of DC load-flow model, the proposed approach may suffer from the masking problem, that is, the calculated ranking may not be completely matched with real priority of components based on the risk sensitivity analysis. This, however, is not a severe problem in the proposed method. For instance, Fig. 7 shows the result of risk sensitivity analysis for the six important EA generation buses, that is, 218, 221, 223, 213, 101 and 102. Generation buses in the horizontal axis of Fig. 7 have the same order as Fig. 4. The vertical axis of Fig. 7 represents average relative error of the risk index at the SA buses ($\overline{RE}_{SA}$) according to (12). The $\overline{RE}_{SA}$ has been calculated for each of the new cases in which the generation buses are sequentially assumed to be fully reliable. It can be seen from this figure that there is a noticeable consistency between the ranking obtained by risk sensitivity analysis and that determined by (8).

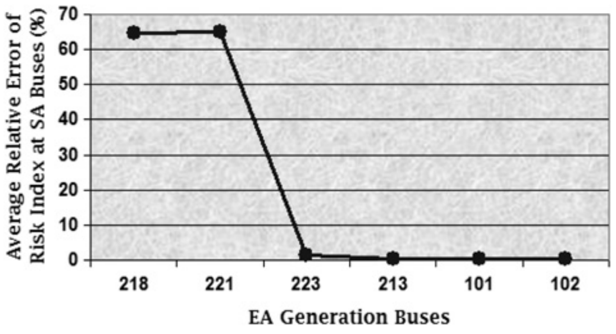

Fig. 7 *Average relative error of risk index at SA buses when EA generation buses in the sequence determined by (8) are assumed to be fully reliable*

5 Conclusions

A method for developing adequacy equivalents in a composite power system is presented in this paper. Application of the presented method shows satisfactory results through adequacy evaluation, namely:

- Two reasons can be stated for the applicability of the proposed method in large-scale systems. First, the assumptions and formulations of the proposed method are not dependent on the system size. Second, the commonly used GSF, LODF and Ward equivalents, which have been utilised in the proposed method, have been widely applied in different utilities to analyse large-scale power systems.
- The proposed method introduces a buffer zone between the SA and the lower ranked EA elements. This zone includes higher ranked EA elements, and hence identifies elements of the EA that their reliability data has vital role in the SA risk studies. If reliability data of the EA elements changes in future, there will be no need to have the data updated for the whole EA in the SA studies. The process of updating reliability data could be confined to the buffer zone. Since obtaining reliability data from neighbouring or external networks is a difficult task for power utilities, this considerable reduction in the required up-to-date reliability data of the EA can be considered as an advantage of the proposed method (for future SA studies).
- The proposed procedure can be easily implemented in ready-made or commercial power system reliability

evaluation software and there is no need to develop new codes for adequacy evaluation.

- Since determination of the EA important elements is based on the interpretable parameters of MW rating, unavailability and the SA–EA power interactions, then the ranking given to the EA elements is generally consistent with the actual behaviour of these elements and can be technically justified.

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