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Using a software package to enhance composite power system reliability teaching

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ABSTRACT: This article presents a comprehensive road map for using a software package to facilitate the teaching and learning of composite power system reliability evaluation. The software package permits students to explore the effect of different outage contingencies, generation and transmission, on system reliability. In addition, the effect of the contingency level and load model component can be illustrated.

INTRODUCTION

Composite system reliability assessment is usually concerned with evaluating the adequacy of generation and transmission facilities to satisfy system load requirements. Composite systems are becoming increasingly complex; there is a critical need for tools to train power system engineers and analysts. Over the years, computer simulation programs have played an important role in providing students with a better understanding of power system analysis. As a result of the rapid advances in computer hardware and software, computer-based power system educational tools have grown from being very simple implementations to a very detailed representation of the power system with an extensive graphical user interface. Computer-based power system analysis tools keep most of the tedious and repetitive calculations in the background, allowing the user to spend more time in the analysis of the results obtained. A number of software packages have been developed for educational purposes [1-3]. These packages were found to be effective in providing students and trainees with an intuitive feel for power system evaluation. However, these packages were developed to address only the reliability assessment of the system. Power system operation and planning requires the outcome of reliability assessment studies and the outcome of other power system analysis including protection coordination, short circuit analysis and other common power system analysis. Consultancy firms recognised the needs of the electricity market and have developed a comprehensive software package that can be used for the most common power system analyses, such as EDSA and ETAP.

Incorporating these packages in the teaching of power system courses prepares the student with proficiency to utilise them in power system planning and operation once they graduate. This article presents a comprehensive road map to utilise EDSA to facilitate the teaching and learning of composite power system reliability evaluation.

COMPOSITE SYSTEM RELIABILITY ASSESSMENT

The main objective of an electrical power system is to supply its customers with electrical energy as economically as possible and at an acceptable level of reliability. Power system reliability covers both adequacy and security [4]. Adequacy is mainly concerned with the ability of the electric system to supply the aggregate electrical demand and energy requirements of customers. On the other hand, security deals with the ability of the system to withstand sudden disturbances such as short circuits or unanticipated system component failures [5]. This article deals with system adequacy.

A power system can be divided into functional zones in order to focus on specific problem areas and to simplify the analysis. The three basic functional zones are those of generation, transmission and distribution. These functional zones can be combined to form hierarchical levels (HL) for conducting system reliability analysis [4]. Reliability assessment at HL I is concerned with the generation facilities [6]. Reliability assessment at HL II considers the generation and transmission as a composite system. The effect of load growth, configuration changes and facility additions can be studied and reliability indices can be evaluated for the overall system, as well as for the individual buses [7-10]. All three of the functional zones are involved in an HL III assessment. The main objective of an HL III study is to conduct adequacy assessment at consumer load points [4]. The work described here deals with HL II assessment. The main objective of this assessment is to assess the adequacy of the generation facilities to meet the load and the adequacy of the transmission line to deliver the energy to the load points.

Composite system reliability assessment can be conducted using contingency enumeration methods and the Monte Carlo simulation [4]. Both approaches assess the adequacy of a system state using a power flow to identify the system deficiencies and to assess the effects of remedial actions. EDSA utilises the contingency enumeration method for composite system reliability evaluation. The basic concept used in the contingency enumeration algorithm is that a contingency is selected and its adequacy assessed. Each contingency may be composed of a number of components on outage at the same time. The outages that are assessed are generator outages, branch outages or combination of generators and branches. The severity of system problem is assessed by calculating the reliability indices for a contingency. Detailed explanation for this approach is presented in Reference [4]. This technique can be explained fairly well for the students. However, application of this technique is tedious when conducted for a small system; conducting sensitivity analysis using hand calculation is even more tedious and impractical. The study of composite system reliability analysis can be greatly enriched by the use of computer software. Such software should enable students to experiment with different designs and parameters.

TEACHING COMPOSITE SYSTEM RELIABILITY ASSESSMENT USING EDSA

EDSA advanced composite power system reliability program uses the state enumeration approach to assess the adequacy of generation and transmission facilities. The program enumerates and examines a list of contingencies that cause the outage of generating units and/or lines/cables. For each contingency, the power system state is examined using power flow analysis to identify the system deficiencies and calculate reliability indices.

The program can be used by instructors as a lecture tool to conduct a basic reliability assessment to introduce both load point reliability indices and system indices. The effect of different factors on system reliability can be explained to students: the aging of equipment, different loading conditions and the effect of generation and transmission facilities outage. The instructor could also demonstrate some reinforcement and planning alternatives such as adding new generation or transmission facilities to the system.

Moreover, the students or trainees outside the classroom can use the program to gain a more intuitive feel for power system planning and reliability. The student can run the software for a test system, obtain an introduction to the system indices, and load point indices. They can identify the weak areas in the network. The students can observe the effect of changing loading condition on the reliability of the system. This would assist the students in getting a physical feel for the interaction between system load, the generation and transmission facilities and the different reliability indices. Then, rather than being passive observers, the students might be challenged to perform system expansion planning for the system to meet future load growth. In addition, the use of such a tool helps the students to appreciate the impact of the different parameters on system reliability.

To start the advanced reliability program select *Analysis->Advanced Reliability* from the menu as shown in Figure 1. This will activate the program and the icons of the reliability analysis program will appear.

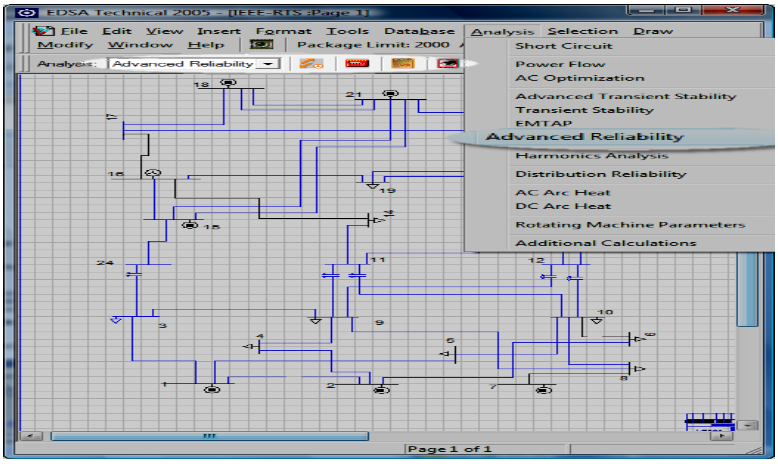

Figure 1: Starting the reliability assessment program.

Entering the data of the components, generators, lines, etc, can be done easily by double clicking on a component. This will open a window that enables the student to enter the required data for a particular component. More details on how to create the system and data entry can be found in Reference [11].

In order to conduct composite system reliability analysis using the contingency enumeration approach which is utilised by EDSA, the level of contingency needs to be identified. As mentioned earlier, contingencies can be outages of generators, lines or combination of both. The reliability assessment computation time increases quickly as the contingency level increases. In order to limit the number of contingencies, selecting and specifying the level of overlapping outages that can be considered, reduces the number of contingencies. EDSA can consider simultaneous independent outages for up to four generators or three branches. If the contingency of generators and branches to be combined, a combination of 3 generators and branches can be incorporated. The student can specify appropriate levels within this range to suit the system requirements.

Two important models must be considered in order to perform composite system reliability evaluation. These are the component outage model and the load model. Combinations of the component outage models form the contingencies which are convolved with the load model and the reliability indices are produced.

Independent Outage Models

A component is considered to be on outage when it is unavailable to perform its intended function. A component outage, however, may or may not cause load interruption. Independent outage events including the outage of two or more components are referred to as overlapping outages. The basic component model used in these applications is the two-state representation shown in Figure 2, in which the component is assumed to be either up or down. The rate of departure from the component up state to its down state is the component failure rate λ. The restoration of the component to its operating state is denoted by another transition rate, termed the component repair rate μ. The actual restoration process could be high or low speed automatic reclosure, repair or simple replacement of the failed component by a spare. Different restoration rates are associated with each of these activities. The two parameters, λ and μ can be expressed in terms of Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR) respectively, where, MTTF is the reciprocal of λ and MTTR is the reciprocal of μ.

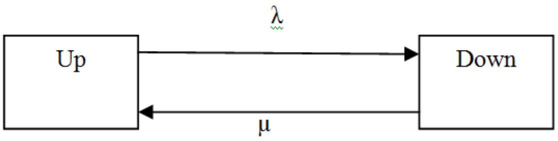

Figure 2: Two state model for a single component.

Failure rate and repair rate for the different components can be identified in EDSA by double clicking on a component and selecting the reliability tap where the student can enter the values of failure and repair rates or the MTTF and MTTR as shown in Figure 3.

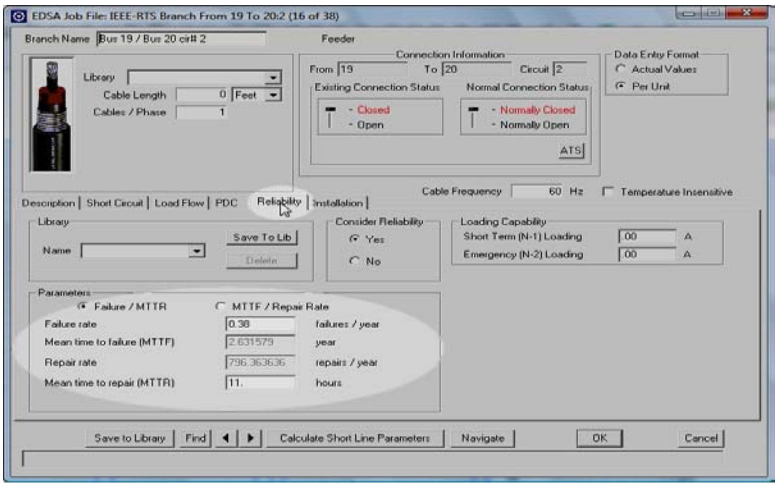

Figure 3: Component's reliability data.

Overlapping independent outages of two components can be modelled as shown in Figure 4. This model can be extended for three or more components. EDSA utilises this modelling concept to model outage contingency events. As noted earlier, up to four generators, three branches simultaneous independent outages are considered in EDSA. In addition, a combination of three generators/branches can be incorporated.

The level of contingency and the combined generation and transmission contingency option can be accessed in EDSA by clicking on the *options* icon from the main window shown in Figure 1. Another window will pop up for contingency level selection. Figure 5 shows the window to select the desired contingency level and load model.

Students can explore the effect of contingency level on system reliability. The contribution of generation or transmission or both can be investigated. This will permit students to evaluate the root cause of system unreliability, which gives the student a thorough understanding of the effect of the different components on system reliability.

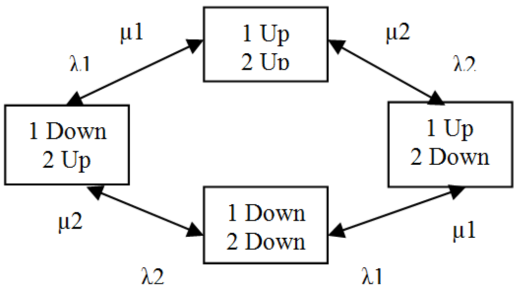

Figure 4: Model for overlapping independent outages of two components.

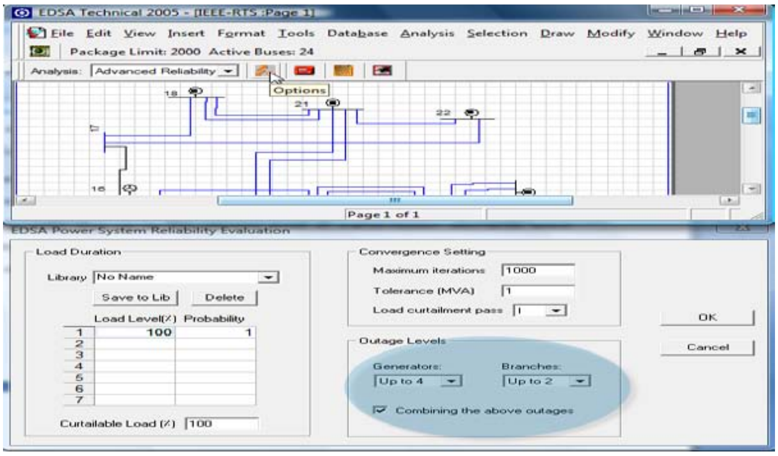

Figure 5: Level of contingency selection.

Load Model

Load model is another important element that is required to perform composite system reliability analysis. This model can be a constant load model and in this case the resulting indices are the annualised indices or it can be variable load. Variable loads can be rearranged to produce the load duration curve which is usually used for power system analysis. The load duration curve can be represented using a multi steps load model [4]. Constant load and the load duration curve can be modelled in EDSA. Composite system reliability assessment can be introduced to the student using the constant load. Then the effect of variable load models can be demonstrated for the students.

Load model can be modelled in the window shown in Figure 5. A constant load model is defined by setting the load level to 100% of system peak load with a probability of 1.0 as shown in Figure 5. This means that the load is constant at the peak load level for the entire period under study.

Composite System Reliability Indices

Composite system reliability assessment can be simulated for a given power system by clicking the *Analyze* icon shown in Figure 6. Once the computation completed the program will display the result. Two types of indices are produced, load point indices and system indices.

Composite system reliability indices are categorised into system indices and load point indices. Both sets of indices complement each other. Overall system indices provide an appreciation of global system adequacy and can be used by planners and managers for comparing the adequacies of different systems. However, these indices cannot be used to assess the adequacy of particular system load points. Therefore, load point indices are required to assess the reliability of load points, which is useful for benchmarking load points and identifying weak areas in the system. Load point indices can be used to identify the contribution of each load point to bulk system unreliability.

These indices are evaluated by conducting load flow analysis for each contingency. This is a tedious process to undertake. With the features incorporated in EDSA, composite system reliability indices are calculated and produced at the end of the analysis. This will permit students to investigate system reliability considering different options.

BASIC COMPOSITE SYSTEM RELIABILTY ANALYSIS USING EDSA

The features described above have been used to illustrate the utilisation of EDSA for basic composite system reliability analysis. The IEEE Reliability Test System (IEEE-RTS) is used. It is a 24 bus system with 10 generator buses, 17 load buses, 33 transmission lines, five transformers and 32 generating units. The system peak load is 2,850 MW and the total generation is 3,405 MW. Detailed system data are included in Reference [12].

In this section, constant load is considered. Independent overlapping outages are considered up to the fourth level for generating units, and up to the second level in transmission elements. Contingencies with combined generation and transmission line outages are enabled. By following the procedures described above to set the reliability data for the components, the load model and the required contingency levels, EDSA was executed for the IEEE-RTS (reliability testing system) and the resulting indices are shown below. Note that among the many system and load point indices, only representative indices have been presented. Table 1 shows the system reliability indices, while Figure 7 shows the expected load point reliability indices.

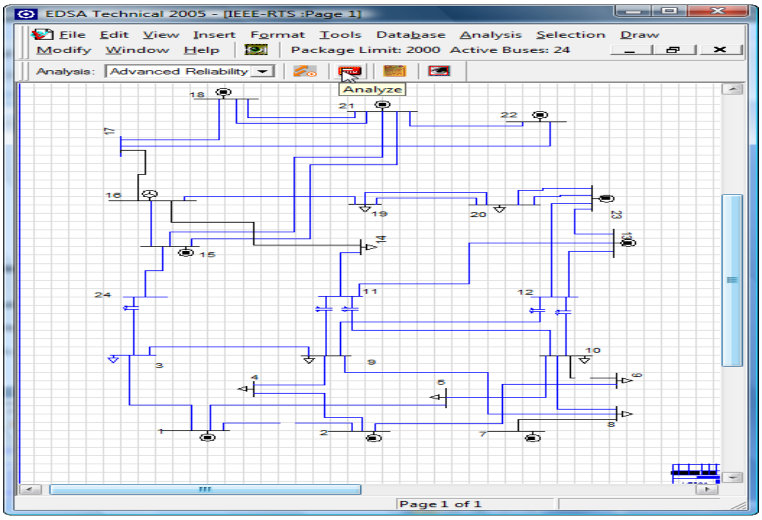

Figure 6: Analysis icon of the advance reliability program.

Table 1: System reliability indices for the Base Case.

	Base Case
Power system interruption index (Mw/Mw-yr)	3.841876
Power system energy interruption index (Mwh/Mw-yr)	53.734638
Severity index (Sys-Min)	3224.078369
Expected loss of load probability	0.110995
Expected power not supplied (Mw/occ)	17.482121

Table 1 shows the system indices. These indices can give a global assessment of the entire system. This set of indices is very useful for benchmarking different systems and is valuable for examining the effect of different reinforcement schemes and different operational policies on the overall system reliability.

The importance of load point indices can be explained to students by using the results shown in Figure 7. These can be used to illustrate that these indices are useful for benchmarking the different load points within a system. This set of indices can be used to rank the load point indices to identify the weak areas in the system that require reinforcement. For instance, Figure 7 shows that Load Points 18, 13 and 15 are among the most unreliable load points in the system. This can be very useful for teaching planning system reinforcements to students. The results shown in Table 1 and Figure 7 can be verified and compared with those presented in References 13 and 14.

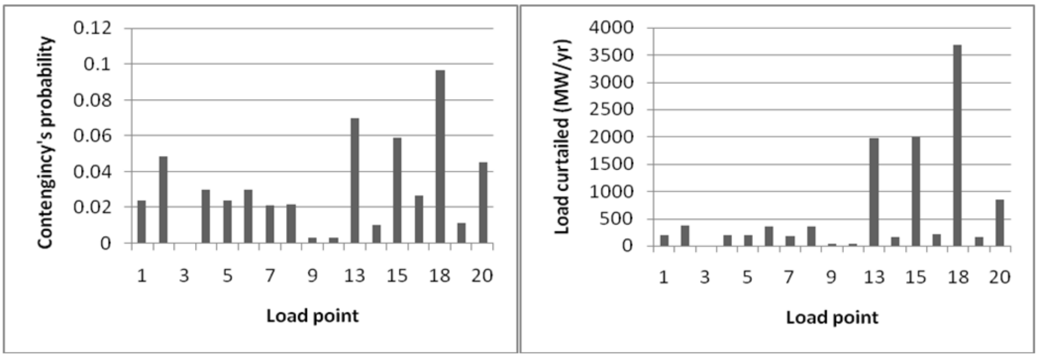

Figure 7: Load point indices for the base case.

CASE STUDIES

As mentioned earlier, EDSA uses the contingency enumeration approach for composite system reliability assessment. This technique results in a list of contingencies. These contingencies can be first order or higher. Each contingency can be outages of generators, lines or a combination of both. This feature can be used to illustrate to students the effect of line outages and generation outages on system reliability. In addition, the effect of different contingency levels can be examined. The reliability of the system can be evaluated considering one, two, three or four generating units outages. In addition, the reliability of the system can be evaluated considering one, two or three line independent outages. Then combinations of generation and transmission line outages are considered. Comparison of the resulting indices is conducted to explore the contribution of these outages to system unreliability.

Different cases are considered and shown in Table 2. Case 1 represents the first order contingencies in which one unit is considered on forced outage at a given time. However, there were no load curtailments in this case; therefore, it was not shown in Table 2. Case 2 represents the first and second order contingencies in which up to two units are considered on forced outage at a given time. Case 3 represents the first, second and third order contingencies in which three units or less are considered on forced outage at a given time. Case 4 represents the first, second, third and forth order contingencies in which up to four units are considered on forced outage at a given time.

It was found that first order contingencies in which one line is considered on forced outage at a given time do not result in load curtailments, thus, this system satisfies the N-1 criterion and therefore, this case was not shown in Table 2. Case 5 represents the first and second order line contingencies in which up to two lines are considered on forced outage at a given time. It was found that there is no significant incremental change in system reliability with higher line contingences; therefore, only up to two lines is shown in Table 2.

Case 6 represents the combined second order generating units outages and first order line outages. Case 7 represents combined first order generating units outages and second order line outages.

Table 2: System reliability indices considering generation facilities outages.

	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Power system interruption index (Mw/Mw-yr)	0.607270	2.274572	3.839348	0.000090	0.611713	0.000949
Power system energy interruption index (Mwh/Mw-yr)	13.058096	37.419792	54.875687	0.000864	12.736711	0.006840
Severity index (Sys-Min)	783.485779	2245.1875	3292.5410	0.051813	764.20263	0.410408
Expected loss of load probability	0.043100	0.090211	0.112632	0.000005	0.042065	0.000049
Expected power not supplied (Mw/occ)	4.248354	12.174238	17.853434	0.000281	4.143793	0.002225

Table 2 shows that the outage of single unit including the largest unit does not cause load curtailment. However, the higher the contingency level, the lower the reliability. This indicates that this system is N-1 secured with respect to the generation facilities. It can be seen from Table 2 that transmission line outage events have limited contribution to system unreliability. From Table 2, it can be seen that Case 6 with two units on forced outage simultaneously with one line affected the system's reliability more than Case 7 in which there was one unit on forced outage simultaneously with two lines. Also, by comparing Case 2 with Case 6 and Case 5 with Case 7, it can be seen that line contingences do not add significantly to system indices. On the other hand, considering generation contingences with line outages reduces system reliability significantly.

The effect of generation contingencies considered in the above cases has been illustrated as a sample. Similar figures can be generated for the other contingencies. Figure 8 shows the load point indices for generation outage contingencies. It can be seen from Figure 8 that the system was bifurcated from a reliability point of view. The first group of load points comprises Load Points 1 to 10 and the second group comprises Load Points 13 to 20. The first group has higher reliability than the second group. In fact by looking at the single line diagram of the system it can be seen that the system is actually divided into two areas with transformers between them. This is very useful in helping students to understand the system, as it indicates that the first region requires more attention and reinforcements.

Also, it can be seen that some of the load points within a group require more attention. For instance, Load Points 13, 15, 18 and 20 need to be considered for reliability improvement due to that fact that these load points contribute most to system unreliability. The same conclusion applies to Load Point 2 from the first group. On the other hand, there are load points at a high reliability level compared to other load points such as Load Points 3, 9 and 10. A complete ranking can be produced for benchmarking purposes.

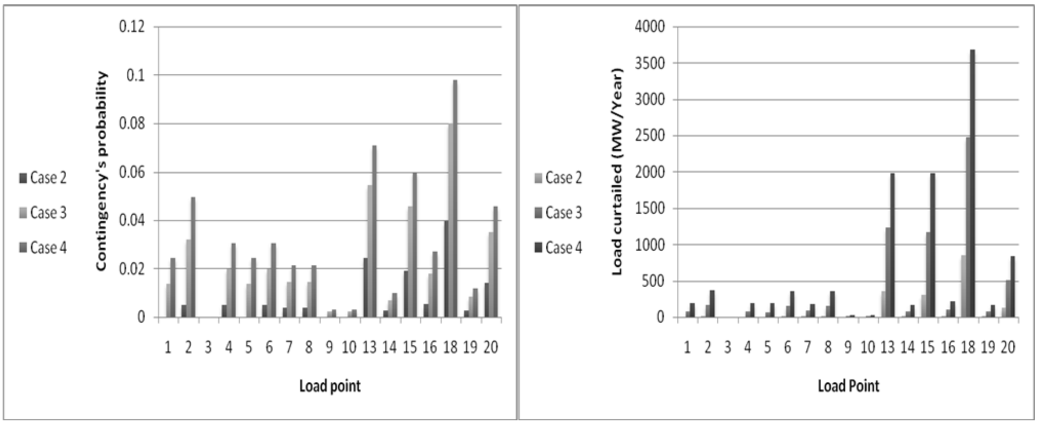

Figure 8: Load point indices for the generation contengincies.

Figure 8 shows that all load points are N-1 secured. There were no load curtailments resulting from first order generation contengincies in Case 1. With forced outages in up to two generating units to be considered, which is the situation in Case 2, most of the load points were affected by N-2 outage events. However, Load Points 1,3,5,9, and 10 did not experince any load curtailement in this case. With up to three generating unit outage contengincies, Case 3, all load points were effected except Load Point 3. With up to four generating units outage events (Case 4), all load points were affected, with no exceptions.

This thorough analysis conducted using EDSA is very useful in helping students to grasp the concepts of generation facilities system planning based on reliability constraints.

COMPOSITE SYSTEM REINFORCEMENT

In Sections 4 and 5, the students were introduced to composite system reliability evaluation, considering the effect of generation, transmission and combined outages. System reinforcement is another concept which can be introduced to help students to understand the causes of system unreliability.

It was found from the base case shown in Table 1 and the Cases 1 to 7 that the most unreliable Load Points are 20, 18, 15, 13, 8, and 2. The common factor between for Load Points 20, 18, 15 and 13 is that they receive supply from the largest units in the system which are connected to Bus 18 (400 MW), Bus 21 (400 MW) and Bus 23 (350 MW). The outage of one of these units with smaller ones affects the reliability of the buses connected to them and other buses. The reliability of Load Points 8, 6 and 2 can be affected by generation outage events and by outage events in second order line, and combined line and generating units. Based on this discussion, a range of scenarios can be considered.

However, two scenarios can be introduced into this section. Scenario 1 incorporates the addition of a transmission line between Bus 6 and Bus 2. Scenario 2 incorporates the addition of a generating unit at Bus 13 with a capacity of 197MW. These additional components are identical to those in the same location. The effect of the scenarios noted above was explored at the individual load points. Figure 9 shows the load point indices for Load Points 20, 18, 15 and 13, 8, 6 and 2 with the above noted reinforcement schemes.

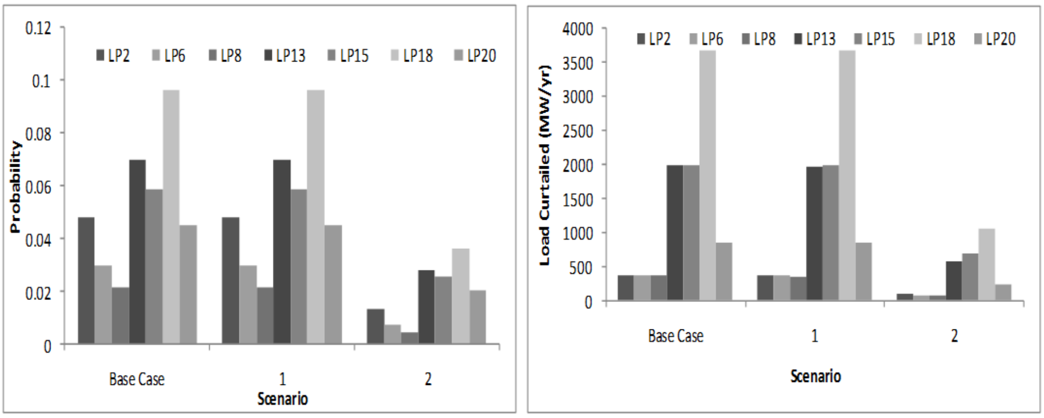

Figure 9: Reliability indices for Load Points 20, 18, 15, 13, 8, 6 and 2 with different reinforcement scenarios.

Figure 9 shows that the addition of an additional line in Scenario 1 did not improve system reliability significantly. Moreover, the reliability of Load Points 2 and 8, which are adjacent to the reinforcement location, did not improve. This gives a strong indication that generation inadequacy in the system is the major contributor to system unreliability. As can be seen from Figure 9, the addition of a generating unit in Scenario 2 improves system reliability appreciably.

The scenarios considered were created and investigated using EDSA. Teaching power system planning is an important aspect. However, studying the effect of different scenarios could be a tedious process for the student and the educator. Using this tool can ease the process and lead to a better understanding of this issue.

CONCLUSIONS

In this article, a methodology that utilises EDSA to facilitate the teaching and learning of composite power system reliability has been described. EDSA was shown as an interactive tool for educational application. Reliability assessment was conducted on the IEEE-reliability test system. Using EDSA simplify the process of identifying the vulnerable areas in the system. The students were able to identify the effect of different load model, outage levels, generation, transmission and combined facilities outage contingencies on system reliability. This study recommends investigating the possibility of using other software packages as an educational tool.

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