Teaching reliability analysis of HV/MV substations and distribution feeders using educational software

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Abstract In this paper, educational software for the reliability assessment of high/medium-voltage (HV/MV) substations and distribution feeders is presented. It is a useful tool for learning the utility of reliability indices of the HV/MV substations and their distribution feeders, and their influence on the electrical power system operation. By means of an interactive graphical interface, multiple configurations of HV/MV substation layouts can be selected. The Monte Carlo method and the equipment outages have been used to calculate the expected reliability performance of substations and primary distribution feeders. The proposed educational tool has been evaluated to measure students' satisfaction, and questionnaire and results of this evaluation are presented and discussed.

Keywords distribution feeders; engineering education; HV/MV substations; reliability assessment

Nowadays, in restructured power systems the deployment of distributed generation and smart grids implies that distribution systems have the overall responsibility to manage power exchange and load curtailment bids to fulfil the reliability commitments and the reliability requirements of customers.[1,2] In this new scenario, HV/MV substations play an important role due to meshed networks ends and radial supply system begins (i.e., feeders) in these substations.

Future distribution networks require novel concepts and systems for their planning, design, monitoring and control architectures to ensure the security and resilience of the infrastructures supporting this deployment and to evaluate their impact on the reliability of the distribution systems.

From the educational point of view, it is necessary to include this new paradigm and concepts in electrical engineering studies. In relation to this approach, educational software is presented in this paper for improving not only the teaching of reliability assessment of HV/MV substations and their distribution feeders, but their effects on the electrical power system and the quality of service.

To develop general-purpose software to assess the reliability of substations and their distribution feeders, the educational tool uses various substation components such as breakers, busbars and transformers. By means of a graphical user interface, it is possible to perform failure modes and to provide a concise and orderly description of the various combinations of occurrences.[3,4] Once the reliability assessment is performed, the results are checked out to determine the remedial actions that can be carried out to bring the system back to a normal state, and to reach acceptable reliability indices. Besides, it is possible to perform remedial actions to prevent

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http://dx.doi.org/10.7227/IJEEE.49.4.2

contingencies and to obtain acceptable reliability indices to avoid possible penalties due to the new restructured power systems.

A special emphasis has been placed by the authors on attaining the new educational paradigm demanded by the Bologna process.[5] In the subject of engineering, not only maintains the technical knowledge base of the field (i.e. mathematical and scientific), but also stresses the implementation of educational tools as a reinforcement of learning done by hand. In contrast to the real world, students using this kind of tools are able to 'step outside' of the process to review and understand it better.[6–8]

Based on the idea presented above, the aim of developing a new educational tool to help the students in the learning of the reliability assessment theory was focussed on a piece of educational software (training simulator). This tool is being applied, with successful results, in the training of undergraduates in the Electrical Engineering Department, and it leads to more interest in the exercises applied in the subject of reliability analysis of HV/MV substations and their distribution feeders.

The rest of the paper is structured as follows. In the next section a brief description of reliability analysis is introduced. A section on the educational tool follows, and in a further section the classroom practice is described and the development of the educational experience. Finally conclusions are drawn, and an appendix has been used to include a basic theory of probability, the Monte Carlo method, and the results given by the educational tool.

Background theory

The application of probabilistic techniques in the analysis of unscheduled and scheduled events provides a quantitative prediction and information of the system performance, and, more important, a way of consistently evaluating both the reliability level of alternative operational arrangements and network reinforcements.[9,3]

In order to understand the effects of substation component failures, it is necessary to study station component outage processes. For this purpose, the continuous Markov process is the most popular probabilistic method to study a component in continuous discrete states.[3,4,9,10] This is a specific stochastic process independent of all the past states except the immediately preceding state. An example of a two-state system, with failure and repair rates λ and μ, respectively, is shown in Fig. 1. Usually, the inverse of λ is known as the Mean Time To Fail (MTTF), and the inverse of μ is known as the Mean Time To Repair (MTTR).

In a Markov process, the probability of failure or repair for a fixed interval of time is considered constant. The steady-state probabilities of residing in the

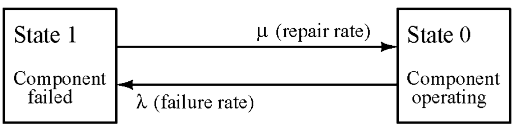

Fig. 1 *Two-state space diagram of a component.*

operating state, 'State 0', and in the failed state, 'State 1', are designated as p0 (availability) and p1 (unavailability) respectively. The p1 probability is also called Forced Outage Rate (FOR). In Appendix A a brief explanation to obtain p0 and p1 has been included.

It is clear that substation failure assessment is highly dependent on the component outages. Therefore the collection of station component outage data (failure rate and repair rate) and their assembly on a real database is an important and necessary activity for the evaluation of reliability.[11,12] In the presented tool, the corresponding data, i.e. failure and repair rates, have been obtained from Refs 13 and 14, including all the necessary information for the calculation of the independent outages of generating units, transmission lines, transformers, busbar and feeders.

Typical reliability indices

The Monte Carlo technique (see Appendix B) has been implemented in the educational tool, and the calculated probability, frequency and duration indices associated with the states of the substation are the traditional indices LOLP [pu] (Loss of Load Probability), LOLF [occ./y] (Loss of Load Frequency), and EPNS [MW] (Expected Power Not-Supplied).

The reliability indices obtained with the proposed tool are related to particular supply and load scenarios of the distribution system in which the analysed substation is located.

If a system state S is considered, then the functions representing the LOLP, LOLF and EPNS reliability indices are:

$$F_{\mathrm{LOLP}}(S) = \begin{cases} 0 & \text{if } S \text{ is an availability state} \\ 1 & \text{if } S \text{ is an unavailability state} \end{cases}$$

$$F_{\mathrm{LOLP}}(S) = \begin{cases} 0 & \text{if } S \text{ is an availability state} \\ \mu & \text{if } S \text{ is an unavailability state} \end{cases}$$

$$F_{\mathrm{LOLP}}(S) = \begin{cases} 0 & \text{if } S \text{ is an availability state} \\ \mathrm{P}_{\mathrm{LS}} & \text{if } S \text{ is an unavailability state} \end{cases}$$

where P_{LS} is the load shedding [MW] in the S unavailability system state.

By using the preceding functions, the reliability indices are estimated as follows:

$$\overline{\mathrm{LOLP}} = \frac{1}{N_S}\sum_{S\in G} F_{\mathrm{LOLP}}(S);\ \overline{\mathrm{LOLF}} = \frac{1}{N_S}\sum_{S\in G} F_{\mathrm{LOLF}}(S);\ \overline{\mathrm{EPNS}} = \frac{1}{N_S}\sum_{S\in G} F_{\mathrm{EPNS}}(S) \quad (1)$$

where G is the set of system states and NS is the number of sampled system states.

Other reliability indices as LOLE [h/year] (Loss Of Load Expectation), LOLD [h/occ.] (Loss of Load Duration), and EENS [MWh/year] (Expected Energy Not Supplied) can be obtained as:

$$\overline{\mathrm{LOLE}} = \overline{\mathrm{LOLP}}\cdot \mathrm{T};\ \overline{\mathrm{LOLD}} = \frac{\overline{\mathrm{LOLP}}}{\overline{\mathrm{LOLF}}};\ \overline{\mathrm{EENS}} = \overline{\mathrm{EPNS}}\cdot \mathrm{T} \quad (2)$$

where T is the period of time over which the analysis is extended (by default this is one year).

Spanish reliability indices

Apart from the reliability indices shown above, the tool also gives the TIEPI and NIEPI indices, which are the reference reliability indices in Spanish electrical regulation. The former is the time of the interruption equivalent to the load shedding of all the demand in the studied area, and the latter is the number of interruptions equivalent to the load shedding of all the demand in the studied area. These Spanish reliability indices are calculated as follows:

$$\overline{\text{TIEPI}} = \frac{\overline{\text{LOLP}}}{\text{PI}}; \overline{\text{NIEPI}} = \frac{\overline{\overline{\text{TIEPI}}}}{\overline{\overline{\text{LOLD}}}} \tag{3}$$

where PI is the sum of the power of all the MV/LV stations in the area where the TIEPI and NIEPI indices are calculated.

The Spanish electrical regulation fixes maximum values for both reliability indices (TIEPI and NIEPI), and, obviously, the corresponding penalties when utilities operate with reliability indices higher than these maximum values.

In relation to penalties, the versatility of the proposed educational tool facilitates to teach students in what way it is possible to propose remedial actions to obtain acceptable reliability indices under the point of view of the electrical regulation. Remedial actions are corrective/preventive maintenance programs, and reinforcement operations on weak points of the distribution system.

Description of the educational tool

The educational tool presented in this paper focuses on the reliability assessment problem faced by electrical utilities when dealing with the meshed sub-transmission networks and the supply points of the distribution facilities.[1,2,15,16]

The corresponding flowchart used by the tool to systematically obtain the reliability assessment of HV/MV substation is shown in Fig. 2.

The part of the software related to Monte Carlo Simulation has been carried out in the preceding section and Appendix B. In this section the graphical user interface will be described. For this purpose, the most significant interactive screens are shown performing the same steps that students do to obtain the reliability indices of the HV/MV substation configuration and their distribution feeders.

Before embarking on the determination of reliability indices of substations, it would be helpful to be familiar with some of the common substation layouts and their corresponding names. Certain configurations may be more suited to a specific task, and, therefore, the equipments in each type of substation may vary, but with the exception of switching stations, they generally include transformers, circuit breakers, isolation switches and measurement equipments.

Figure 3 shows the interactive screen which permits us to select the basic substation configuration (bus layout) included in the educational tool: Single Bus (with

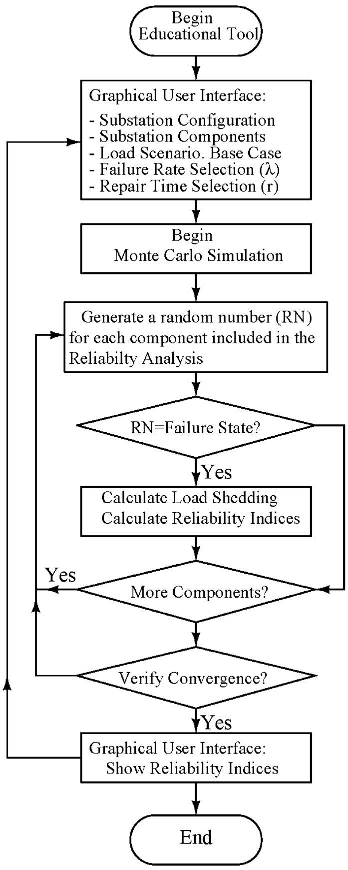

Fig. 2 *Flowchart of the educational tool.*

switches or breakers), Double Breaker Double Bus (with or without transfer bus), Ring Bus and Breaker-and-a-Half. For example, in the same Fig. 3 a Double Breaker-Double Bus configuration has been selected.

Once a basic configuration is selected, in the next phase the student must complete the remainder of substation characteristics by selecting the position of measurement equipments and other electrical components of the substation (number of transformers and their power, circuit breakers, and isolation switches). For this process, the student has to complete various screens. As an example, the selection of the number of transformers and their power assigned in MVA is shown in Fig. 4.

The selection of electrical characteristics of the HV lines (supply side of the substation) is presented in Fig. 5, and Fig. 6 shows how the number of substation MV feeders and their length and thermal capacity are selected. In the case of the HV lines and MV feeders, the position of the measurement equipments (current and voltage transformers, etc) also are assigned. All this information is used in order to

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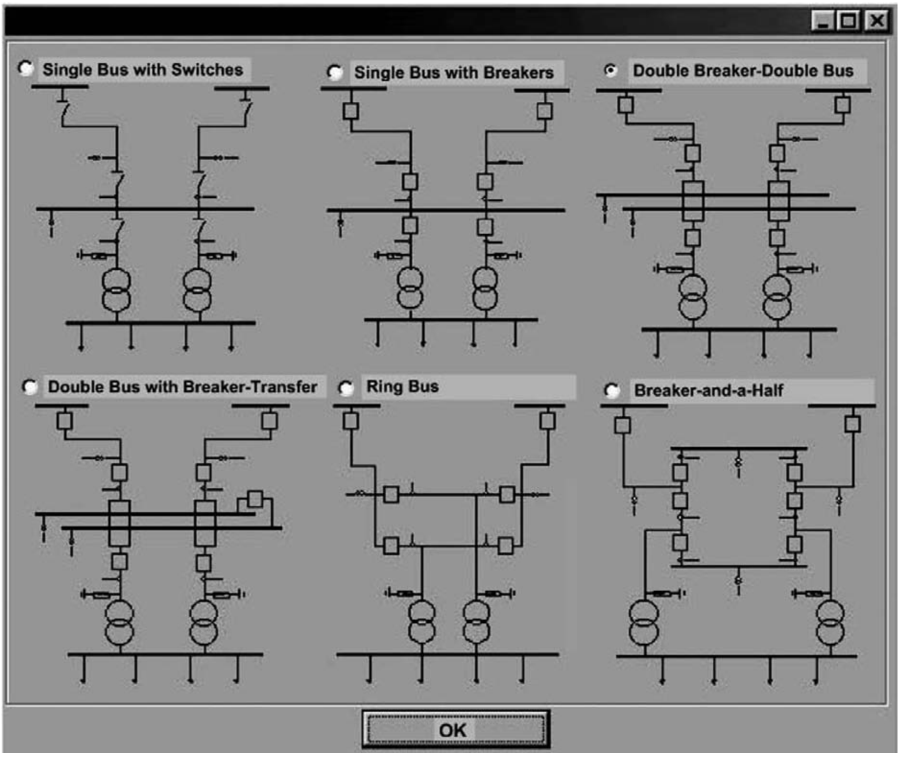

Fig. 3 *Selection of the basic configuration of a substation.*

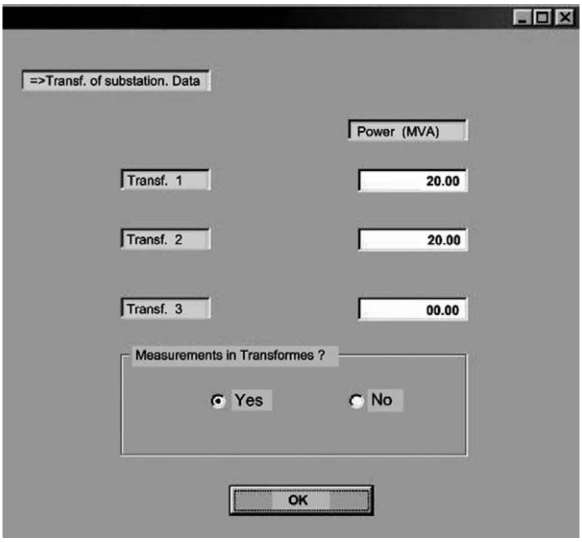

Fig. 4 *Selection of transformers and their electrical characteristics.*

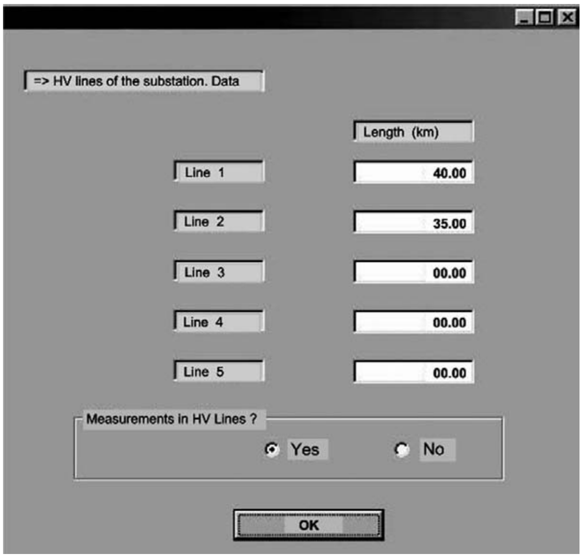

Fig. 5 *Selection of HV line parameters in the substation.*

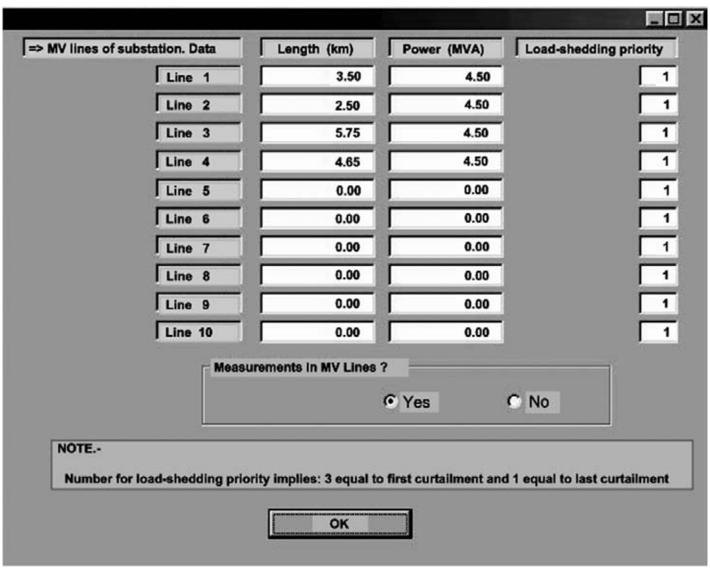

Fig. 6 *Selection of MV line parameters in the substation.*

obtain the failure rate, repair rate, and load shedding, this last whether it is necessary to be applied in the reliability evaluation.

In the next phase, the values of the failure rates (λ) and repair times (r) of the substation equipments must be selected (Figs 7 and 8). These values are included

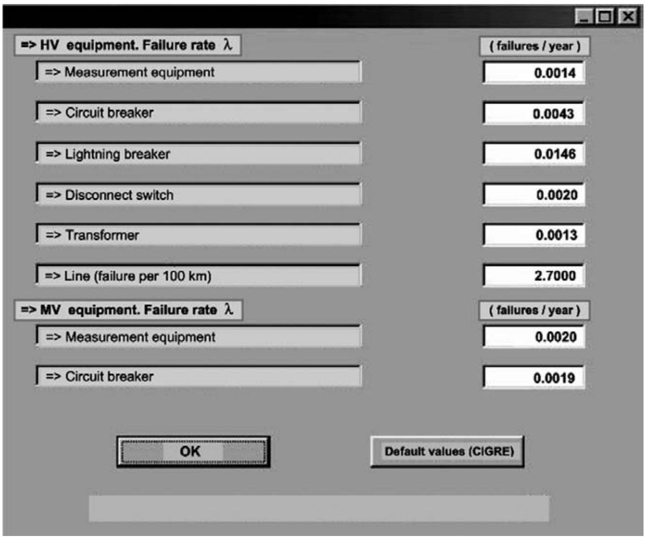

Fig. 7 *Selection of failure rates of substation components.*

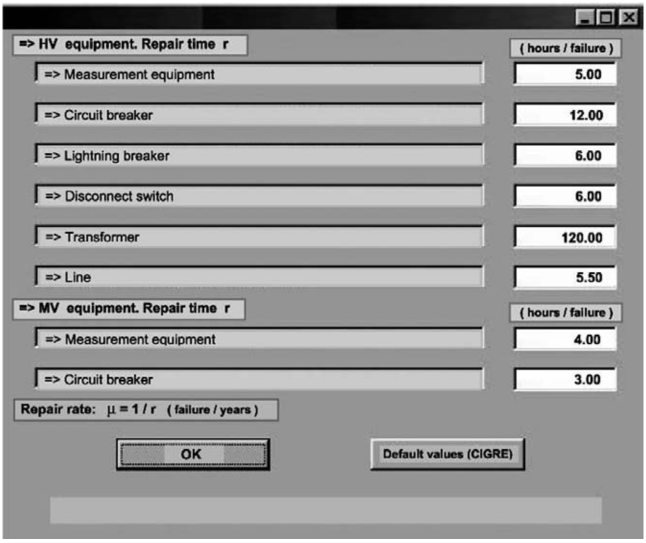

Fig. 8 *Selection of repair times of substation components.*

by the student in two steps. In the first step, Fig. 7, the student has to complete all the fields relative to the failure rates of whole substation components (HV lines, MV feeders, transformers, measurement equipments, etc), and in the second step, Fig. 8, a similar process has to be repeated for the fields relative to the repair times of whole substation components. By default, the tool presents the standard failure and repair rates of CIGRE[13] (Figs 7 and 8).

It is important to note that, as Fig. 6 shows, the tool includes a module to select the priority order to load shedding for each one of the MV feeders of the substation. The load bus priority order is in accordance with agreed load-shedding protocol. The priority order of the load buses is established based on economic factors that recognise the customer costs associated with failure of supply. The most convenient index for this purpose is the interrupted energy assessment rate (IEAR),[16] which measures the monetary loss for the customer in terms of a function of the energy not supplied (ENS).

The priority order is related to the TIEPI and NIEPI Spanish reliability indices, and hence, to the penalties that the utilities must pay according to Spanish regulations. There are three levels of priority order to load shedding,[16] and each MV feeder connected to the load bus is assigned a priority order. Level 3 implies the first load to shed, level 1 corresponds to the last load to shed, and level 2 is equivalent to indifferent load shedding. By including this information in a corresponding screen, it is possible to study how selective load shedding can modify the reliability indices of the substation MV feeders, assuming all other parameters are unchanged.

In the last phase, the reliability indices are carried out, in a first stage, for the HV side of the substation (substation reliability indices), and in a second stage, for the MV-feeder supply points (load reliability indices). The results of the reliability assessment are presented in window form (Fig. 9), which shows the reliability indices of the analysed substation using overall indices and the individual reliability indices of a MV demand point connected to the substation.

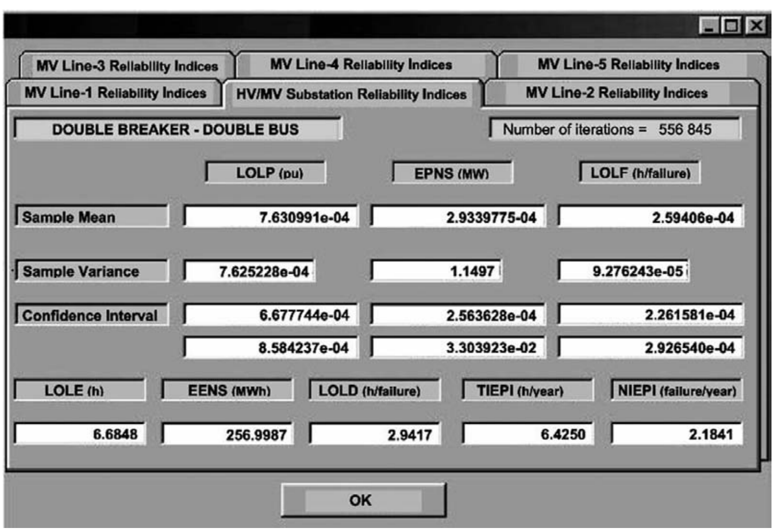

Fig. 9 *Reliability indices of substations and MV feeders.*

Once the process has finished, the students must explain the significance of the overall reliability indices obtained in relation to the suitability of the selected configuration of the substation. In relation to the individual reliability indices, the students must perform a comparative analysis in accordance with those individual reliability indices referenced in Spanish regulation. Finally, they must program adequate remedial actions (corrective/preventive maintenance programs, and reinforcement operations on weak points of the distribution system), to yield lower TIEPI and NIEPI reliability indices and avoid the corresponding Spanish regulation penalties.

It is important to note that by repeating the same process, but choosing new values of the failure and repair rates for the substation equipments, the student can evaluate the influence of these rates on the reliability indices of the substation and the MV distribution feeders.

Finally, it is necessary to comment that the educational tool provides a record of data and results in txt format.

Classroom practice development

This section presents the application of the software tool intended to help the student to progress in the study of reliability assessment of HV/MV substations and their distribution feeders. Two study cases are proposed to the student wishing to start using the tool. These exercises are conceived as an orientation about the possibilities of the tool; these possibilities are not limited to the exercises exposed here.

The session is structured in two parts (about 60 minutes each). It begins with a presentation, revisiting the theory developed in previous sections. Afterwards, by means of two study cases, the students are invited to work on reliability assessment of HV/MV substations with the proposed educational tool.

After the theoretical part, the students are invited to reflect on two main topics:

- What is the effect of winds and ice storms on failure rate and repair time and reliability indices?
- What is the effect of priority-order load shedding on reliability indices?

At this point, a brief round table is opened in which each student presents his argument.

After that, the students have to resolve the two study cases by using the educational tool. These study cases focus on storm influence and the priority order to load shedding. For this purpose, the applied base case corresponds to the data shown in Figs 3 to 9. In this base case, for a pre-specified layout of a substation, the weather is considered in normal conditions and the priority order to load shedding is equal for all the distribution feeders.

Case 1. Storm influence

In this case, the students analyse the influence of storms on the reliability indices. By means of the changes in the repair rates and repair times, the storms are taken into account. In this case the new values of the repair rate and the repair time have been considered two times higher than the values of the Case-Base for the lines of the distribution system.

By comparing results obtained in the base case (see Appendix C) with those obtained taking into account storms influence (see Appendix D), the students learn that higher reliability indices are involved with storms. Once the comparative has been realised, the students learn the importance of the weather prediction and its influence over the program of corrective/preventive actions. In order to maintain acceptable reliability indices in relation to the maximum values fixed by the electrical regulation, the students are invited to locate the weak point of the distribution system and to specify the reinforcements to avoid the effects of adverse weather conditions.

Case 2. Priority load shedding

In this case, the students analyse the influence of the priority order load shedding on the reliability indices. For this purpose the priority order of the MV line 1 is changed to 3 and this condition carries out an increase in the reliability indices of this MV line.

By comparing results obtained in the base case (see Appendix C) with those obtained by varying the priority load shedding (see Appendix E), the students learn the relation between the feeder with the maximum order to load shedding and its reliability indices.

Once the comparison has been realised, the students learn that hospitals, airports, police stations, etc. have the minimum order to load shedding, and the maximum order to load shedding is associated with specific clients by means of bilateral contracts. In consequence, the students learn in what way the distribution utilities maintain acceptable values of their reliability indices thanks to paying clients with bilateral contracts at a lower cost than the penalties.

Finally, the students have to print the results of the simulations, and based on these have to propose the mentioned remedial actions to yield better reliability indices than the obtained in the simulations.

At the end of the more recent semester, the students were interviewed and completed an anonymous student satisfaction evaluation form: a questionnaire comprising 6 items and aimed at measuring the satisfaction level with respect to the class project. It was based on a typical five-level Likert-scale (Table 1).

Figure 10 shows the results corresponding to the present academic course (10/11), based on an attendance of 22 out of 29 students (about 76%) registered on the Electrical Power Systems course of the Electrical Engineering degree at the University of Seville, Spain. Figure 10 shows that all of the questions got a positive assessment: 70% of answers were 'Agree' and 'Strongly Agree'. Question 1 obtained the worst rating, as slightly over 5% of students 'Disagree'. The authors found that the reason is the duration of the theoretical class (60 min). For future years a longer time for this part will be proposed. Special attention is paid to the questions Q3 and Q4. About 80% of students are totally agree or agree with the number of proposed study cases. The same number of students has viewed increased your knowledge about reliability in the power systems.

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TABLE 1 *Satisfaction questionnaire*

		Answer				
No.	Question	SD	D	I	A	TA
1	Does the theoretical section properly illustrate the main concepts of the reliability in power systems?					
2	Is the graphical program user friend]y?					
3	Do you consider the number of proposed study cases are sufficient?					
4	Has your knowledge about reliability in the power systems increased with this class project?					
5	Should this project be repeated m the next years?					
6	Do you consider this project relevant for your education?					

SD-Strongly Disagree; D-Disagree; I-Indifferent; A-Agree; TA-Totally Agree.

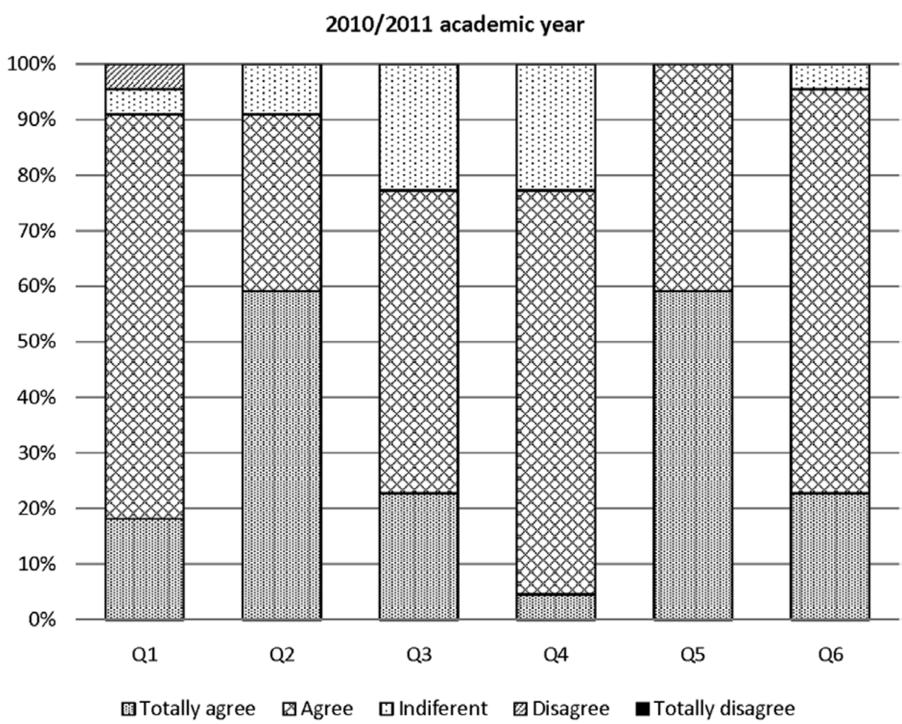

Fig. 10 *Results of the student questionnaire for the academic year 2010/11.*

Almost all of the students consider that the presented tool is easy to use, and relevant for their education. This opinion has convinced authors to insert the tool files in the web site of the Electrical Engineering Department of the University of Seville.[17]

Overall, the answers received are very positive, from which it can be inferred that students consider the proposed method a valuable tool for their education. In general, the perception about the improvement in learning and the subject development has been positive, and over 100% of students clearly think that this practice should be repeated in future years.

Conclusions

In this paper an educational tool is described for the reliability assessment of high/medium-voltage (HV/MV) substations and distribution feeders. The use of this tool not only redresses the shortcomings of the traditional lecture methodology in performing a description of substations and their reliability assessment, but also improves the application of learning theory for the interpretation of results.

It is important to note that the proposed tool can help to design the distribution system with the best global reliability index, and to locate weak points that must be reinforced to get acceptable individual reliability indices. Hence, to learn how the remedial actions are related to the reliability indices, and how they can be modified to get acceptable reliability indices regarding to regulation.

The outcomes indicate that the use of this tool has enriched students' experiences, facilitated greater student engagement, and created an effective feedback system between instructors and learners. In forthcoming courses, such evaluative studies would also contribute towards determining how best to deploy this teaching and learning tool in electrical engineering education.

Acknowledgements

The authors would like to acknowledge the financial support provided by the Spanish MEC under grants ENE2007-63306, ENE2007-66072 and ENE2010-18867.

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Appendix A

Basic theory of reliability assessment

Reliability, in general terms, is defined as the probability of a device performing its intended function adequately over a period of time intended under the operating conditions encountered. It therefore indicates the overall ability of the system to perform its intended function.

In classic reliability theory, the time of failure τ of a given piece of equipment is modelled as an exponentially distributed random variable.[4,10] The probability p_0 that none of the pre-selected contingencies occur during the scheduling horizon T is calculated as

$$p_0 = \prod_{k=1}^{K} e^{-\lambda_k \cdot T}$$

where the parameter λ_k represents the reciprocal of the mean time lapse for the occurrence of contingency k (a quantity estimated from historical data), and K is the total number of pieces of equipment.

Furthermore, since repair times usually exceed the scheduling horizon T, repairs are ignored. Hence, assuming that all other system components are available, the p(k, τ) probability that contingency k occurs during the interval τ is

$$p(k,\tau) = e^{-\lambda_k \cdot T} \cdot (e^{-\lambda_k \cdot T} - 1) \cdot \prod_{z \neq k} e^{-\lambda_z \cdot T}$$

Assuming that the λ failure rate and μ repair rate[4,10,11] of each piece of equipment of the system are known, then the probabilities p0 and p1, availability and unavailability respectively, are obtained as follows

$$p_0 = \frac{\mu}{\mu+\lambda}; \quad p_1 = \frac{\lambda}{\mu+\lambda}$$

where p_0 is the probability of a component being in operation, and p_1 of being in the failed state. These two probabilities are complementary to each other and, obviously, verify the following relationship: $p_1 = 1 - p_0$

Appendix B

The Monte Carlo technique

Two main approaches[9,3,4] are used for probabilistic reliability assessment of electrical systems: State Enumeration and Monte Carlo technique.

The main difference between the two approaches is the way that states are selected and, consequently, the way adequacy indices are evaluated. In State Enumeration, states are selected in an increasing order of contingency level (*N*-1, *N*-2, *N*-3, etc.), stopping the process when the probability of the remaining states becomes negligible, or at a given order of failure states. On the other hand, in the Monte Carlo approach, states are selected using random numbers such that states which have a greater probability of occurrence are more likely to be simulated. The process is usually stopped after a fixed number of simulations, and the adequacy indices are obtained by averaging the indices corresponding to individual simulations**.**

The Monte Carlo approach has been used in the proposed training simulator in order to show the random behaviour of the failure of the electrical equipment, and hence, of the substation outages.

Let S_i denote the *i*th component of an electrical system and FU_i be its Forced Unavailability. A random number generation method is used to draw a random number U_i distributed uniformly under the interval [0, 1].

$$S_\mathrm{i} = \begin{cases} 1 & \text{if} \quad U_i \geq FU_i \\ 0 & \text{if} \quad 0 \leq U_i \leq FU_i \end{cases}$$

The state of the system containing *t* pieces of equipment is expressed by the vector *S* as:

$$S = \{S_1, S_2, \ldots\ldots\ldots.. S_\mathrm{i}, \ldots\ldots\ldots.. S_\mathrm{t}\}$$

Under normal operating conditions, all equipment is available and all the customers are energised. When *S* is equal to zero, the system is in the normal state. When *S* is not equal to zero, the system is in a contingency state. Assuming that each system state has the probability *P(S)* and the reliability index *F(S)*, then the mathematical expectation *E(F)* of the reliability index of all system states is given by

$$E(F) = \sum_{S\in G} P(S)\cdot F(S) = \sum_{S\in G} F(S)\cdot \frac{n(S)}{N_s}$$

where G is the set of system states, N_S is the number of the samples and *n(S)* is the number of occurrences of state *S*.

In the Monte Carlo method the accuracy level of the simulation process is expressed by the β variation coefficient[9,4] The β coefficient and the required number of samples N_S for reliability evaluation in real systems are related to each other as follows

$$\beta = \frac{\sqrt{V(\bar{Q})}}{\bar{Q}}; \quad N_S \approx \frac{1}{\beta \cdot \bar{Q}}$$

where $\bar{Q}$ is the estimate of the system unavailability (failure probability), and $V(\bar{Q})$ its variance.

It can be observed that for a desired accuracy level, β, the required number of samples N_S depends on the system unavailability ($\bar{Q}$) but is independent of the size of the system.

Appendix C

2 Base case results in format txt

```
*** SUBSTATION BASIC CONFIGURATION ***
⇒ Double Breaker Double Bus
*** HV Lines parameters ***
⇒ Length[Km] Line01 HV, 0,4000E+2
⇒ Length[Km] Line02 HV, 0,3500E+1
*** Transformers HV/MV parameters ***
⇒ Power[MVA] Trafo01, 2,0000E+1
⇒ Power[MVA] Trafo02, 2,0000E+1
*** MV Lines parameters ***
⇒ Length[Km] Line01 MV, 0,3500E+1
⇒ Length[Km] Line02 MV, 0,2500E+1
⇒ Length[Km] Line03 MV, 0,5750E+1
⇒ Length[Km] Line04 MV, 0,4650E+1
⇒ Load[MW] Line01 MV, 0,4500E+1
⇒ Load[MW] Line02 MV, 0,4500E+1
⇒ Load[MW] Line03 MV, 0,4500E+1
⇒ Load[MW] Line04 MV, 0,4500E+1
⇒ Priority order Line01 MV, 1
⇒ Priority order Line02 MV, 1
⇒ Priority order Line03 MV, 1
⇒ Priority order Line04 MV, 1
*** Failure rate (failures / year)] ***
⇒ Measurement Equipment HV, 1,4000E-3
⇒ Circuit Breaker HV, 4,3000E-3
⇒ Lighting Breaker HV, 1,4600E-2
⇒ Disconnect Switch HV, 2,0000E-3
⇒ Transformer HV/MV, 1,3000E-3
⇒ Line HV (per 100 km), 2,7000E+0
⇒ Measurement Equipment HV, 2,0000E-3
⇒ Circuit Breaker HV, 1,9000E-3
*** Repair time (hours/failure)] ***
⇒ Measurement Equipment HV, 5,000E+0
⇒ Circuit Breaker HV, 1,200E+1
```

```
⇒ Lighting Breaker HV, 6,000E+0
⇒ Disconnect Switch HV, 6,000E+0
⇒ Transformer HV/MV, 1,200E+2
⇒ Line HV (per 100 km), 5,500E+0
⇒ Measurement Equipment HV, 4,000E+0
⇒ Circuit Breaker HV, 3,000E+0
**** Number of stochastic experiments, 2466822
*** SUBSTATION. RELIABILITY INDICES ***
⇒ LOLP[pu] (sample mean), 1,721557E-4
⇒ LOLP[pu] (confidence interval), 1,506388E-4, 1,936726E-4
⇒ EPNS[MW] (sample mean), 5,137111E-3
⇒ EPNS[MW] (confidence interval), 4,490042E-3, 5,784180E-3
⇒ LOLF[h/f] (sample mean), 4,797454E-4
⇒ LOLF[h/f] (confidence interval), 4,112965E-4, 5,481943E-4
⇒ EENS[MWh], 4,500109E+1
⇒ LOLD[h/f], 3,588480E-1
⇒ TIEPI[h/year], 1,500036E+0
⇒ NIEPI[int/year], 4,180144E+0
*** LINE01 MV. RELIABILITY INDICES ***
⇒ LOLP[pu] (sample mean), 3,431994E-4
⇒ LOLP[pu] (confidence interval), 3,128208E-4, 3,735780E-4
⇒ EPNS[MW] (sample mean), 6,863989E-4
⇒ EPNS[MW] (confidence interval), 6,256417E-4, 7,471561E-4
⇒ LOLF[h/f] (sample mean), 5,096408E-4
⇒ LOLF[h/f] (confidence interval), 4,410971E-4, 5,781845E-4
⇒ EENS[MWh], 6,012854E+0
⇒ LOLD[h/f], 6,734144E-1
⇒ TIEPI[h/year], 3,006427E+0
⇒ NIEPI[int/year], 4,464453E+0
*** LINE02 MV. RELIABILITY INDICES ***
⇒ LOLP[pu] (sample mean), 3,482390E-4
⇒ LOLP[pu] (confidence interval), 3,176418E-4, 3,788363E-4
⇒ EPNS[MW] (sample mean), 6,964781E-4
⇒ EPNS[MW] (confidence interval), 6,352835E-4, 7,576726E-4
⇒ LOLF[h/f] (sample mean), 5,107745E-4
⇒ LOLF[h/f] (confidence interval), 4,422260E-4, 5,793230E-4
⇒ EENS[MWh], 6,101148E+0
⇒ LOLD[h/f], 6,817862E-1
⇒ TIEPI[h/year], 3,050574E+0
⇒ NIEPI[int/year], 4,474385E+0
*** LINE03 MV. RELIABILITY INDICES ***
⇒ LOLP[pu] (sample mean), 3,436320E-4
⇒ LOLP[pu] (confidence interval), 3,132366E-4, 3,740274E-4
⇒ EPNS[MW] (sample mean), 6,872640E-4
⇒ EPNS[MW] (confidence interval), 6,264731E-4, 7,480548E-4
⇒ LOLF[h/f] (sample mean), 5,099194E-4
⇒ LOLF[h/f] (confidence interval), 4,413758E-4, 5,784629E-4
⇒ EENS[MWh], 6,020432E+0
⇒ LOLD[h/f], 6,738948E-1
⇒ TIEPI[h/year], 3,010216E+0
⇒ NIEPI[int/year], 4,466894E+0
*** LINE04 MV. RELIABILITY INDICES ***
⇒ LOLP[pu] (sample mean), 3,404136E-4
⇒ LOLP[pu] (confidence interval), 3,101593E-4, 3,706679E-4
```

D

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⇒ EPNS[MW] (sample mean), 6,808272E-4
⇒ EPNS[MW] (confidence interval), 6,203187E-4, 7,413358E-4
⇒ LOLF[h/f] (sample mean), 5,092436E-4
⇒ LOLF[h/f] (confidence interval), 4,407016E-4, 5,777855E-4
⇒ EENS[MWh], 5,964046E+0
⇒ LOLD[h/f], 6,684691E-1
⇒ TIEPI[h/year], 2,982023E+0
⇒ NIEPI[int/year], 4,460974E+
```

Appendix D

Test case 1 results in format txt

```
**** Number of stochastic experiments, 506822
*** SUBSTATION. RELIABILITY INDICES ***
⇒ LOLP[pu] (sample mean), 3,421557E-4
⇒ LOLP[pu] (confidence interval), 3,006388E-4, 3,836726E-4
⇒ EPNS[MW] (sample mean), 9,137111E-3
⇒ EPNS[MW] (confidence interval), 8,490042E-3, 10,784180E-3
⇒ EENS[MWh], 9,500109E+1
⇒ LOLD[h/f], 7,088480E-1
⇒ TIEPI[h/year], 3,250036E+0
⇒ NIEPI[int/year], 8,380144E+0
```

Appendix E

Test case 2 results in format txt

```
**** Number of stochastic experiments, 496751
*** LINE01 MV. RELIABILITY INDICES ***
⇒ LOLP[pu] (sample mean), 4,431994E-4
⇒ LOLP[pu] (confidence interval), 4,128208E-4, 4,735780E-4
⇒ EPNS[MW] (sample mean), 7,863989E-4
⇒ EPNS[MW] (confidence interval), 7,256417E-4, 8,071561E-4
⇒ LOLF[h/f] (sample mean), 6,096408E-4
⇒ LOLF[h/f] (confidence interval), 5,610971E-4, 6,951845E-4
⇒ EENS[MWh], 7,012854E+0
⇒ LOLD[h/f], 6,984144E-1
⇒ TIEPI[h/year], 4,256427E+0
⇒ NIEPI[int/year], 6,235453E+0
```

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