

A Windows-based Simulation Tool for Reliability Evaluation of Electricity Generating Capacity*

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Reliability evaluation techniques are broadly categorized into analytical and Monte Carlo simulation (MCS) methods. This paper presents a PC-based MS Windows application software for evaluating the reliability indices of electrical power generating systems using the MCS technique. The reliability indices obtained are the loss of load expectation (LOLE) and loss of energy expectation (LOEE). The algorithms for random generation of artificial generating unit history, modeling of system capacity, convolution of load and capacity models, and calculation of reliability indices have been implemented in Borland C++ Version 3.1. The software can perform simulations for a progressive period of time which is user-specified; it can perform sensitivity studies in terms of varying peak loads, varying generating units' forced outage rate (FOR), different downtime probability functions, partial outage states of units, etc. The developed tool was tested using two reliability test systems, and the results were found quite comparable to those available in the literature using analytical methods. Selected results of the software using the IEEE Reliability Test System (RTS) are also presented in the paper for illustration purposes. The developed software is intended for use by final year undergraduate power engineering students for a design module on generating capacity planning using Monte Carlo simulation techniques. It is also expected to be used by graduate students conducting research in the area of power system probabilistic planning.

SUMMARY OF THE EDUCATIONAL ASPECTS OF THE SOFTWARE DESCRIBED IN THIS PAPER

1. The paper describes software applications useful in reliability evaluation of generating capacity in electrical power systems engineering.
2. The paper is suitable for teaching/classwork/self-study for engineering students at the final year of B.Eng. courses.
3. The aspect of the software which is new is the user-friendly Windows-based software using Monte Carlo simulation.
4. The material as presented is for engineering teaching in a laboratory, to complement concepts taught in lectures and have been tested in project work.
5. The software has proved very useful to explain basic concepts to students.

INTRODUCTION

Many electric power utilities utilize deterministic or rule of thumb methods to qualitatively assess system performance. The practice of obtaining

system reliability in qualitative terms is slowly but surely being replaced by probabilistic methods [1, 2]. A majority of the probabilistic methods are direct analytical methods which generate system performance indices. The advent of fast and efficient digital computers, however, has also led to increasing use of another class of methods called the Monte Carlo simulation (MCS) methods for power system reliability assessment [3, 4]. Analytical methods represent the system by a mathematical model and use numerical solution techniques to calculate the indices. MCS, on the other hand, estimates the indices by simulating the actual process and random behavior of the system by treating the problem as a series of real experiments. Generally, MCS methods require a significant amount of computer memory and time and are therefore not used if direct analytical techniques are available and easily applicable. An important limitation of the analytical techniques is that component up and down times are assumed to be exponentially distributed, i.e. component failures and repairs are assumed to take place during the useful life period of the components. MCS, however, is not so restrictive and can model various types of probability distributions for failure and repair times. MCS is therefore preferred if realistic non-exponential distributions need to be modeled (especially for outage times which are known to be

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non-exponentially distributed). Another specific advantage of the MCS techniques is that they provide the probability distributions associated with the output reliability indices, while the analytical methods can only provide the average values of such indices. This paper illustrates the development of a MCS-based software for generating capacity reliability evaluation.

The developed software evaluates the two basic system indices of loss of load expectation (LOLE), i.e. the expected number of days or hours in a given period that the generation will not be able to meet the expected demand, and the loss of energy expectation (LOEE), i.e. the expected energy unsupplied due to those occasions when generation is less than the expected demand [1]. The generation system is modeled by specifying a set of events which are random occurrences that change the system states. The various events recognized are change in load, failure and repair of generators and derated (partial output) states of generators. The generation and load models are convolved using the MCS approach, and the software package is developed for use in an interactive, user-friendly environment such as MS Windows. This paper describes the basic features of the software before illustrating the capabilities of the software by applying it to the IEEE Reliability Test System (RTS) [5, 6].

BASIC CONCEPTS OF MONTE CARLO SIMULATION

The basic principle of MCS is that it simulates the operation of a power system over a period of time. This involves the generation of an artificial history of the model which is then used to draw inferences in respect of the characteristics of the actual system. The hourly load demand is then compared to the available system capacity in that hour for the entire period of simulation. It is assumed that the system state remains constant during the specified period of interval, selected as 1 hour in all studies described in this paper. The evaluation of hourly capacity shortage in chronological sequence provides a convenient approach

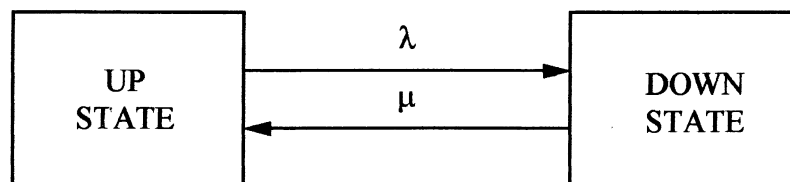
for including system operational characteristics. The period and capacity of deficiency are then used to evaluate the system risk (LOLE and LOEE).

In the simulation model, the power system is modeled by specifying a set of 'events'—an 'event' being a random occurrence that changes the 'state' of the system. The following 'events' were recognized in the simulation models developed in the project:

- change in load
- failure of a generating unit
- completion of repair of the failed unit
- derating (partial output) of units
- completion of a derated-unit's repair.

Each of the above-mentioned events causes the system state to change—the basic measure of the system state used is the 'available margin', i.e. the difference between the available capacity and load. The simulation model studies the behavior of the system during a specified period of time which is divided into specified intervals; during these intervals the system state is assumed to remain constant. An hourly interval was utilized in all studies reported in the paper. The normal simulation period is one year (8760 hours), and this is replicated several thousand times to attain sufficient confidence in the obtained results. If some uncertainty exists in the forecast load then it can be easily incorporated in the Monte Carlo simulation model by simulating the probability distribution of the forecast load.

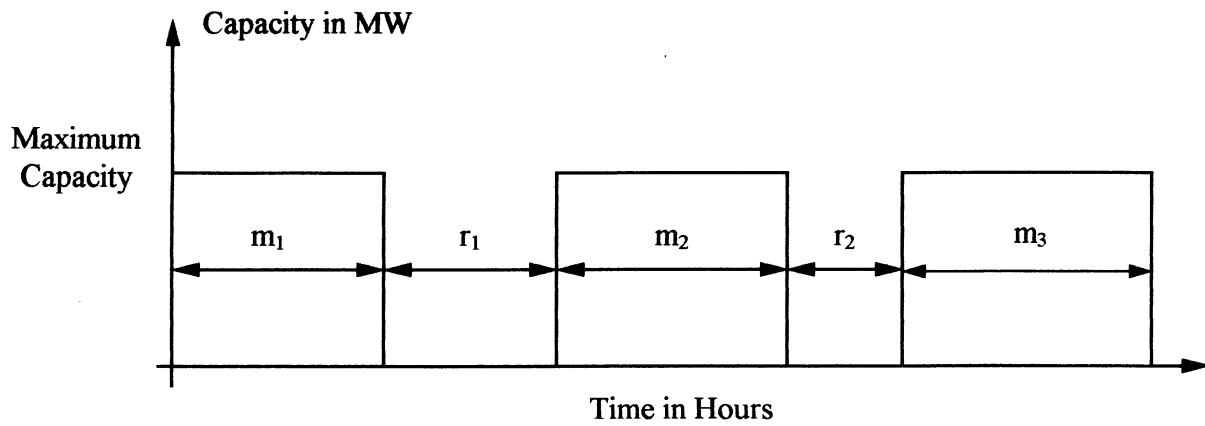
The basic 2-state and 3-state models [1] of generating units have been used to create the capacity model for the system. These models describe the states in which the unit can exist for any interval of time. In the 2-state model, the unit is either fully available (up state) or fully unavailable (down state). The 2-state model and a typical unit outage history using this model are shown in Figs 1 and 2 respectively. In actual operations, however, a unit may not operate at its rated capacity but may operate somewhere between the full output state and the zero-output state. Figure 3 shows a 3-state model [1] which incorporates a single derated state, whereas Fig. 4 shows the unit



where λ = expected failure rate (failures/yr),

μ = expected repair rate (repairs/yr).

Fig. 1. Two-state model of a generating unit.



where $m_1, m_2, m_3, \dots, m_n$ = random periods of time when unit is in operation,

$m = 1/\lambda$ = mean time to failure (MTTF) (yr),

$$= \left(\frac{m_1 + m_2 + m_3 + \dots + m_n}{n} \right)$$

r_1, r_2, \dots, r_n = random periods of time when unit is under repair,

$r = 1/\mu$ = mean time to repair (MTTR) (yr),

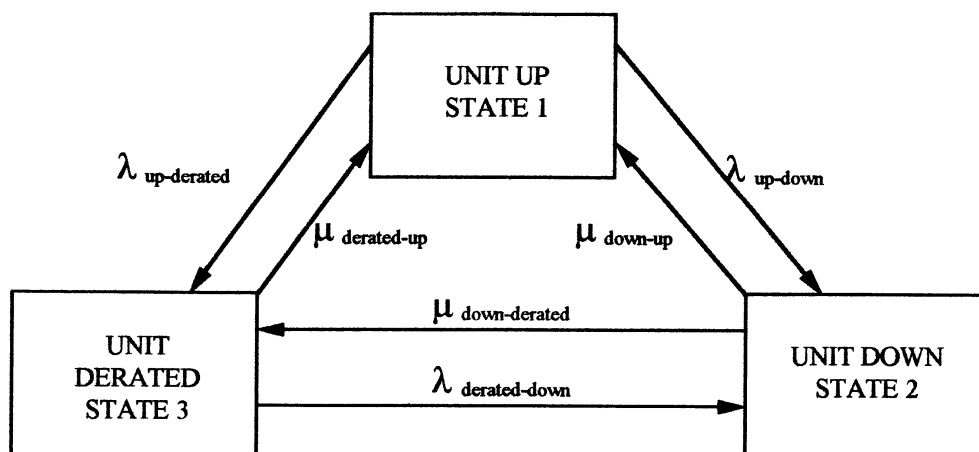
$$= \left(\frac{r_1 + r_2 + \dots + r_n}{n} \right)$$

Fig. 2. Generating unit outage history using a two-state model.

history obtained using this model. The up and down times were assumed to be exponentially distributed for the 2-state model, whereas the down times were assumed to be Weibull distributed for 3-state models. In addition, Normal and Rayleigh distributions were also used to simulate the generator down times.

The general procedure for generating the outage history is as follows:

- The unit is initially assumed to be in the up state (time $t = 0$). A random variable m_1 is drawn from the specified distribution of the up time (see Fig. 2).



where λ = expected failure rate (failures/yr),

μ = expected repair rate (repairs/yr).

Fig. 3. Three-state model of a generating unit.

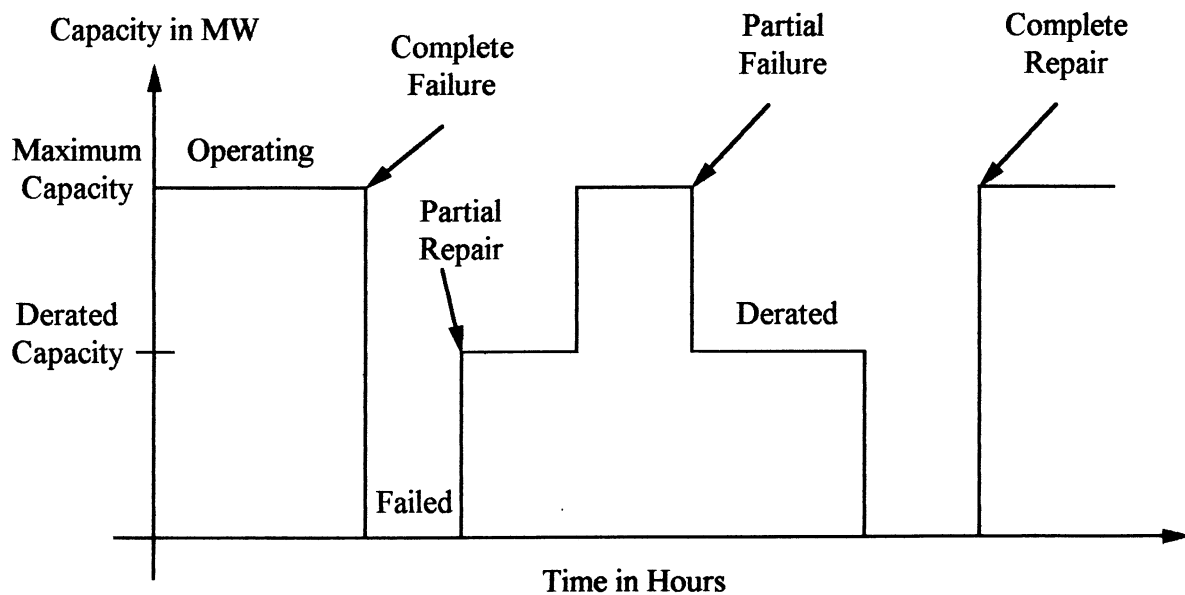


Fig. 4. Generating unit outage history using a three-state model.

- After time m_1 , the unit enters the failed (down) state (2-state model) or a derated state (3-state model), and stays in that state until it is repaired. A possible repair time r_1 can be obtained from the probability distribution of the down time.
- The unit is back in the up state after repair time r_1 . Steps 1 and 2 are repeated until sufficient up and down times are created for the simulation. This step can be terminated by specifying a certain period of time in years for which simulation is to be conducted.

It must be emphasized that for the case of a 3-state unit, once it enters the derated or failed state, it can exist in any of the three states so long as it is not in the same state as the immediately preceding one. The details of the generation models utilized in the simulation are described in References 3 and 7. The emphasis in this paper is more on the software tool and its capabilities. The up times of generating units have been assumed to be described by exponential distributions, whereas the outage (down) times are described by Weibull, Normal, Rayleigh or exponential distributions. The random generation of the failure/outage/repair times for simulation of unit histories was achieved using the built-in random generator available in the libraries of Borland C++ Ver. 3.1 software. The Linear (Multiplicative) Congruential Generator [3] was utilized to generate the random numbers. In terms of generating the load models, the chronological hourly loads were utilized. The capacity model and the load model are superimposed to evaluate the capacity excess or insufficiency for different hours, as shown in Fig. 5. The LOLE index is calculated as the ratio of the summations of all times t_i that there were capacity deficiencies by the total simulation time (in years). The LOEE index is calculated as the ratio of the

summation of all unsupplied energies x_i by the total simulation time.

The next section describes the Software Implementation of the tool, and subsequently the results obtained by using the developed tool on the IEEE RTS are presented.

SOFTWARE IMPLEMENTATION

The software application was designed in such a way so as to provide the user an interface which could do all analysis tasks ranging from creating the generation system model to the evaluation of the reliability indices. In addition, built-in utilities were created for printing and/or viewing/editing the computed indices. The package was coded in C language and compiled using Borland C++ 4.0 [8] compiler, and made to run under the Microsoft Windows 3.1 environment. The Borland C++ Windows Applications Programming Interface (API) was selected (since it offers more flexibility compared to object-oriented Windows programming). The fundamental features/capabilities of the developed software application package are as follows:

- a utility to create the generation system model;
- a utility to create the load model;
- basic indices of LOLE and LOEE can be evaluated;
- selected sensitivity analyses can be performed by varying the peak load, or varying the unit forced outage rates (FOR), or by changing the probability distribution function (PDF) used for generating unit outage times;
- results can be presented both graphically as well as in text format;
- analysis can be saved and retrieved for later use;

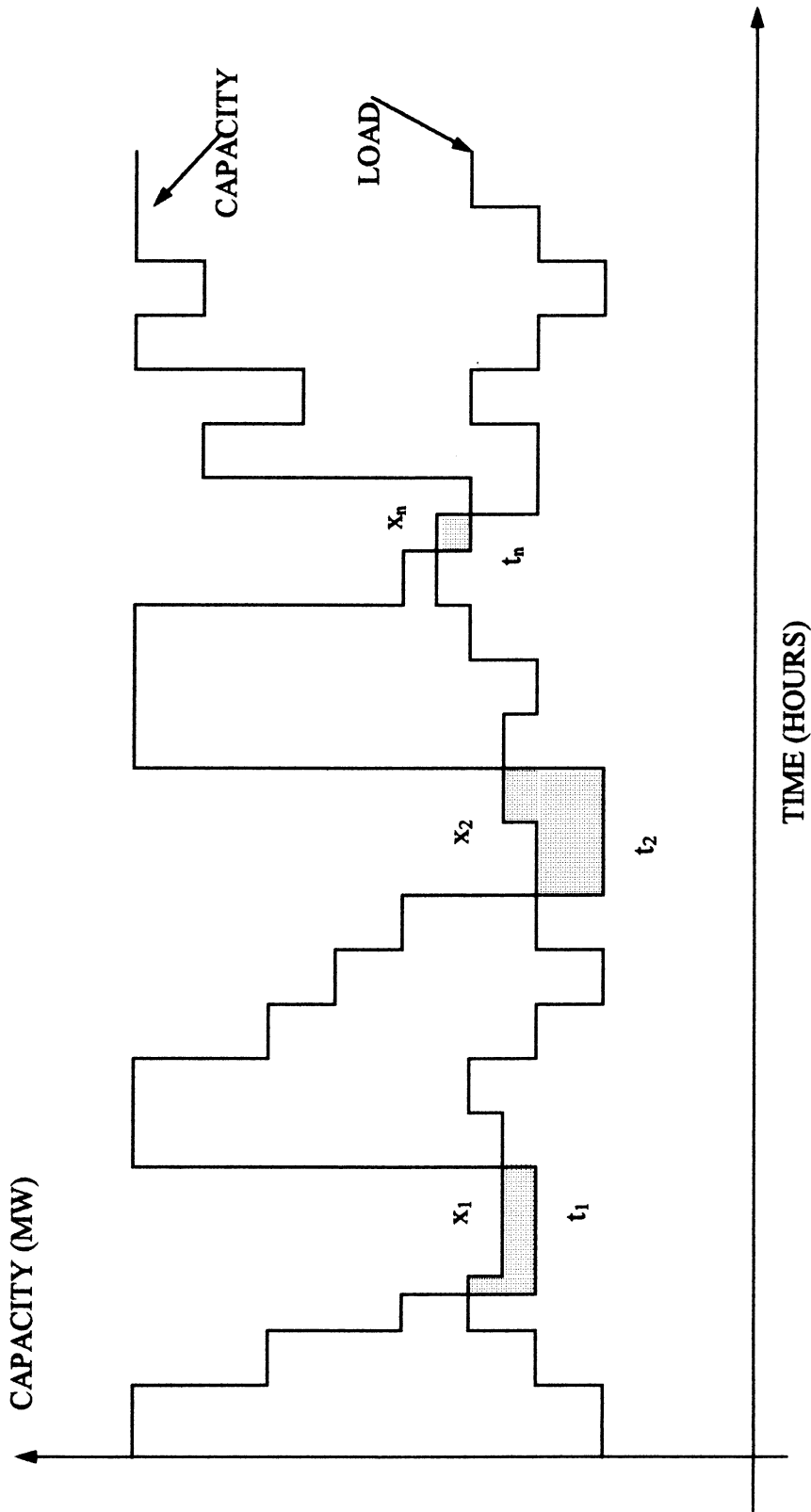


Fig. 5. Superposition of capacity model and identical yearly load cycle.

- an on-line hypertext help system is incorporated to guide novice users.

The basic limitations of the software are that the graphical analysis need to be captured by another software before they can be printed, and that the computational time can be quite excessive for large systems especially if the application is run on a 386-based PC. In general, however, the software runs on any IBM or compatible PC with 80386SX and above microprocessors, with a minimum of 2MB of RAM, and with MS Windows 3.1 installed—a math co-processor can speed up the computations tremendously.

The usability and hence acceptance of a computer application is generally very dependent on its interface design. The desired features led to the development of the following major aspects of the application program:

- the use of a menu bar to interface with program modules;
- design of dialog boxes for all modules that require interaction;
- design of a module to facilitate the plotting of one or more graphs simultaneously;
- ability to print a hardcopy of the results/graphs;

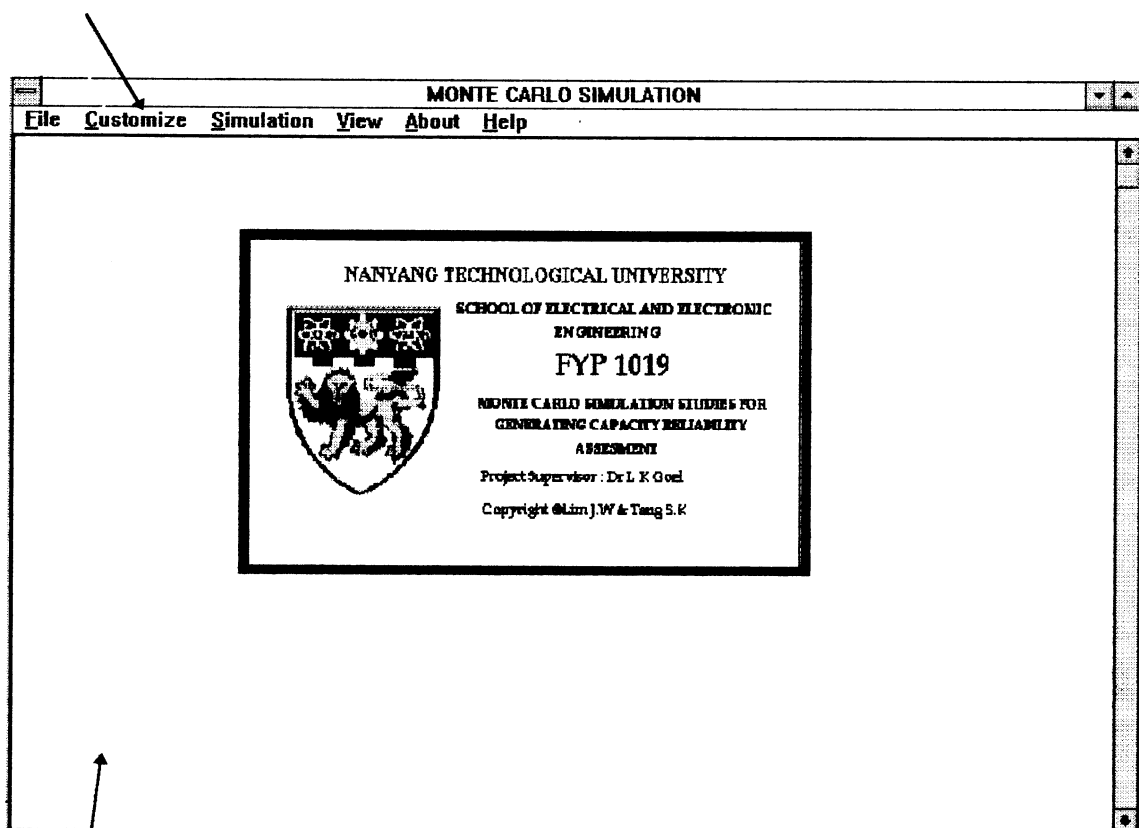
- design a simple utility module that allows the user to edit text files;
- the ability to save to and retrieve analyses from computer files;
- the manual coding and compilation of the customized Windows help file.

Figures 6–9 show some of the sample screens from the developed software, to show the basic Windows applications such as starting the application (Fig. 6), defining the generation system model (Figs 7 and 8), and performing sensitivity studies (Fig. 9). The details of the software together with the User's Manual are provided in Reference 7. The next section illustrates the application of the software tool to the IEEE Reliability Test System (RTS) [5, 6].

APPLICATION TO THE IEEE RTS

The RTS is a comprehensive test system containing generation, transmission and load data [5, 6]. The generation system consists of 32 units of various types and sizes, with an installed capacity of 3405 MW and a suggested system peak load of

Menu Bar



Client Window

Fig. 6. The application's main window.

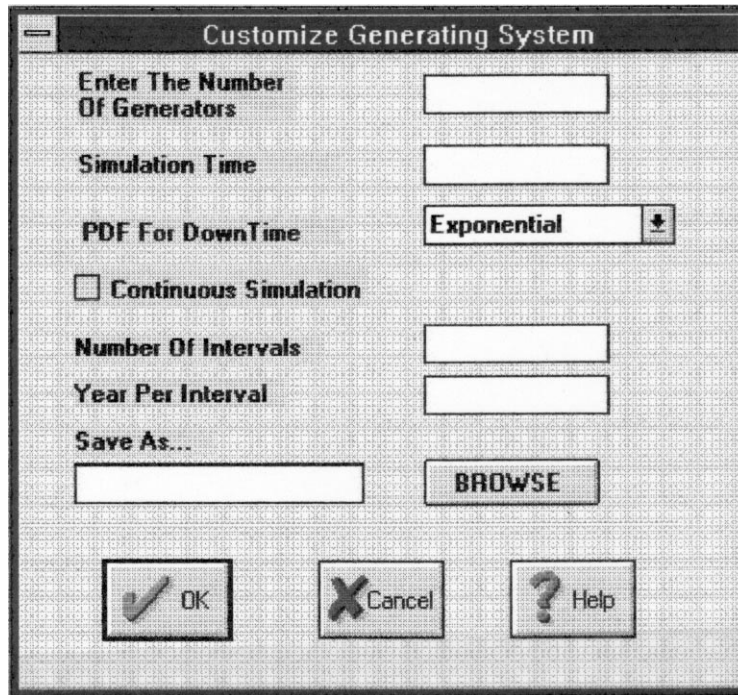


Fig. 7. Customization of generation system model.

2850 MW. The load data, in terms of hourly loads, as provided in Reference 5 is utilized in chronological order so that daily, weekly and seasonal patterns can be modeled. The developed software was applied to the RTS to evaluate the reliability indices, and the results obtained are shown in Table 1. The simulation results are also compared with the analytical values published in the literature [6], as shown in Table 1, and it can be seen that the MCS results are found to be quite comparable to their analytical counterparts. One important

observation is that with a variation in the simulation period (years), the reliability indices generally tend to approach the analytical values, i.e. if the number of simulation years is low, then the percentage error in the indices (with respect to the analytical values) is quite high.

An important feature of the software is the concept of progressive simulations—to study the effect of number of simulation years on the accuracy of the risk indices. The program basically carries out simulations for a required period of

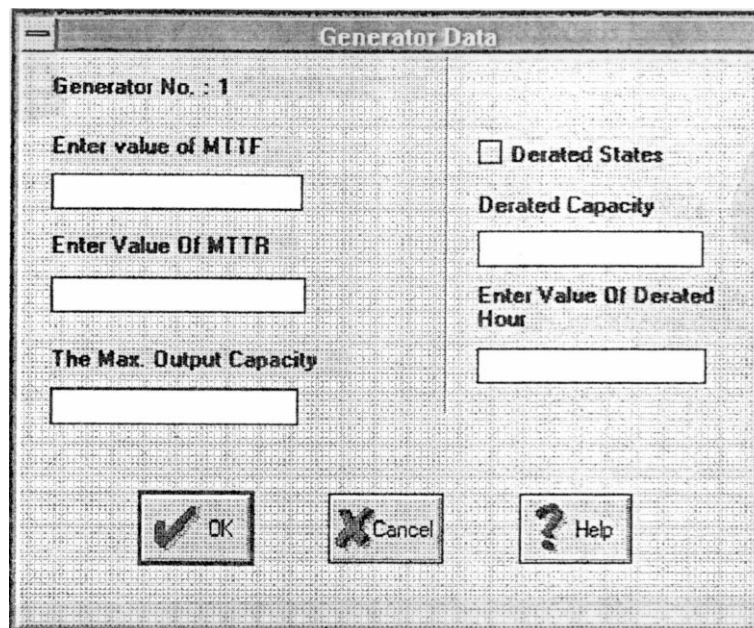


Fig. 8. Individual generating unit data window.

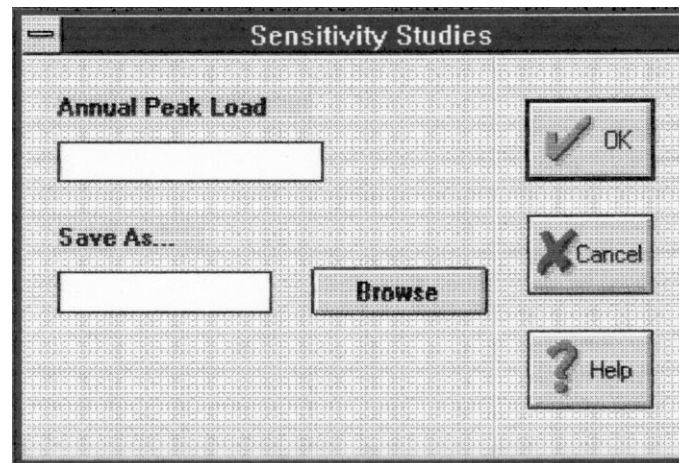


Fig. 9. Sensitivity studies for peak load variation.

time in a progressive manner for fixed intervals, and produces the indices after each interval. The program, however, does not terminate the simulation by itself, i.e. it will perform the number of simulations as specified by the user. In other words, no stopping criteria have been implemented in the software—the general objective being that the user can select any number of simulation years and do any number of sensitivity studies.

Figure 10 shows the variation of the LOLE and LOEE indices with the simulation period. Table 2 shows the computing times for different simulation times on different computers—it can be seen from this table that for a specified number of simulation years the computing time is the lowest with a Pentium PC with 8 MB or more RAM. It is therefore obvious that the accuracy of the results depends largely on the number of simulations performed. While a larger number of simulations generally tends to give more accurate indices, it is at the expense of greater computing times. The optimum solution, perhaps, is to define an acceptable accuracy limit and stop the simulations once that accuracy limit is reached.

Sensitivity studies

The software, as stated previously, can cater to three main sensitivity studies, namely variations in unit forced outage rates (FOR), variations in system peak load, and last but not least the consequences of partial generator unavailability of selected units (i.e., inclusion of derated states) on the risk indices. The basic objective in providing

these facilities in the developed software is to estimate the generating capacity required to satisfy the load demand in conjunction with corrective and preventive maintenance on the system generation facilities. Selected results of the sensitivity studies using the derated states variation are described in this paper.

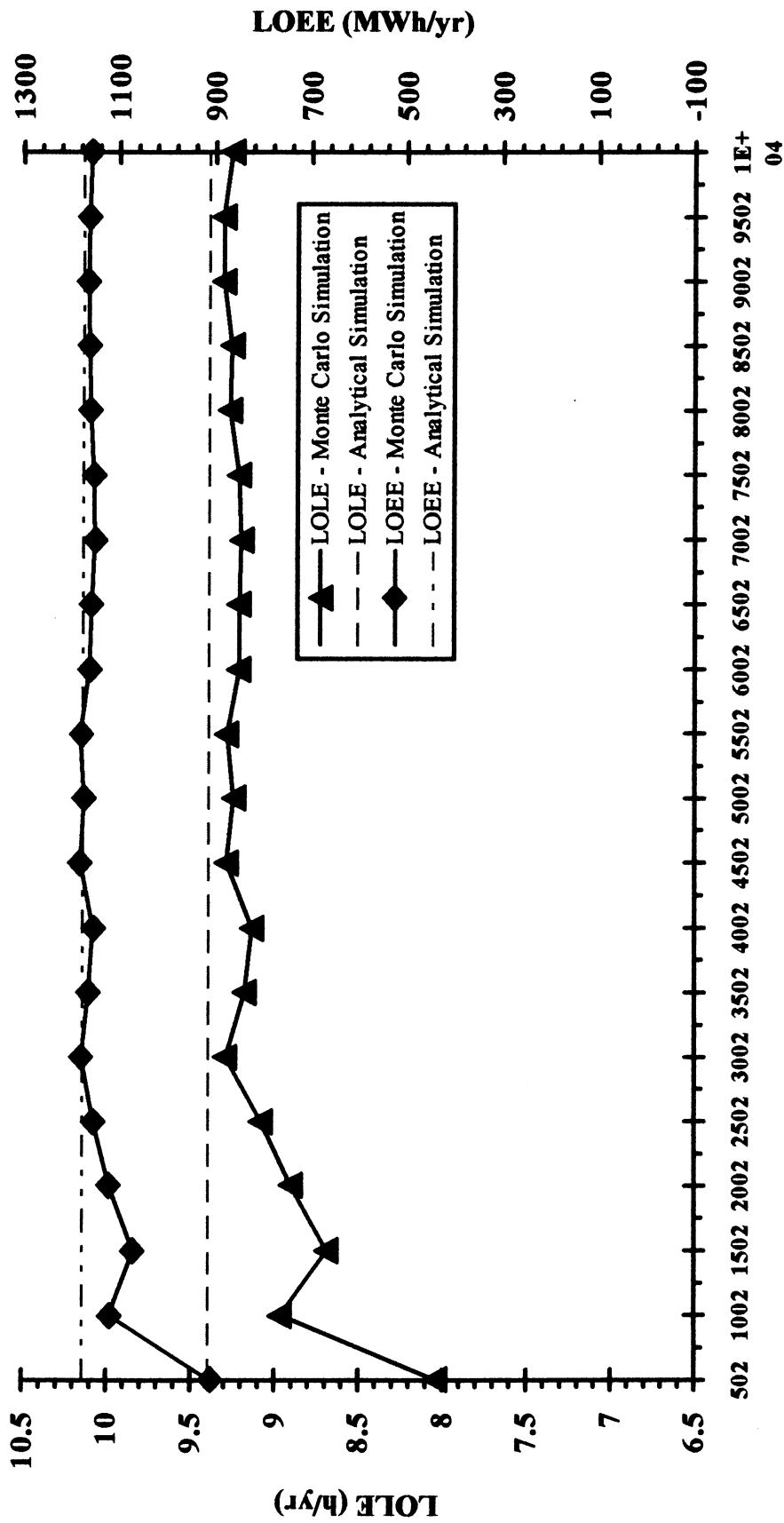
A 3-state derated model of selected generating units in the RTS was used and implemented in the software. Three cases are considered here for illustration purposes—Case 1 considers a 3-state model for only one 400 MW nuclear unit, Case 2 considers 3-state models for both the 400 MW nuclear units, and Case 3 considers 3-state capacity models for the 400 MW units and the 350 MW coal-fired unit. The reliability indices obtained are shown in Table 3, together with the simulation values published in the literature [9]. It was observed that the indices generally improved for systems with partial outages, i.e., the system reliability increased with the inclusion of partial outages. This suggests that the modeling of 2-state units gives a pessimistic appraisal of the system performance in terms of LOLE and LOEE. The results obtained by the developed software are found to be quite comparable to published results, within specified tolerances.

EDUCATIONAL OBJECTIVES

Educational objectives include the following:

Table 1. Reliability indices for the IEEE RTS

Index	Published results	Simulation time (yrs)					
		500		5000		10000	
		Simulation results	% Error	Simulation results	% Error	Simulation results	% Error
LOLE (h/yr)	9.39418	8.03856	14.45921	9.247501	1.56138	9.258200	1.44429
LOEE (MWh/yr)	1176.0	909.493835	22.66209	1172.51245	0.29656	1157.98645	1.53176



Number of Simulated Years

Fig. 10. Variation of system LOLE and LOEE with simulation time (IEEE RTS).

Table 2. Computing times for different simulation periods on different computers (IEEE RTS)

Types of computers	Computing time (mins) for different simulated years		
	Simulated years = 500	Simulated years = 5000	Simulated years = 10000
Pentium PC (8 MB Ram on-board)	0 : 28 : 71	4 : 47 : 23	10 : 15 : 42
486DX2—66 Mhz (8 MB Ram on-board)	1 : 08 : 62	11 : 52 : 04	23 : 55 : 60
486DX—33 Mhz (4 MB Ram on-board)	2 : 14 : 03	22 : 01 : 06	51 : 53 : 56

Table 3. Reliability indices considering partial outages of selected generators (IEEE RTS)

Risk index	Derated capacity (MW)					
	1 × 400 MW		2 × 400 MW		2 × 400 MW + 1 × 350 MW	
	Developed software	Published results	Developed software	Published results	Developed software	Published results
LOLE (h/yr)	7.480008	7.46933	6.171531	5.97523	5.517593	5.13909
LOEE (MWh/yr)	930.69843	869.718	725.56335	682.139	623.1189	594.246
No. of simulation years	5000	326	5000	444	5000	604

- to introduce the student to the basic concepts of reliability assessment of generating systems;
- to enable the student to interactively create and utilize different types of load models and generation models;
- to enable the student to define derated states of generating units, and also to study the impacts of these deratings on the system reliability;
- to enable the student to compare the software-based results with analytical values available in the literature or calculated using a Markov method-based analytical software;
- to enable the student to appreciate the effects of various pertinent factors such as unit size, unit forced outage rate (FOR), system peak load, simulation time, different probability distributions of unit downtimes, etc.;
- to help the student understand Monte Carlo simulation principle *vis-à-vis* analytical methods;
- to enable the student to interpret the results that are presented both graphically as well as in a tabular form;
- to enable the student to link the simulation time with the reliability indices, and to identify how the number of simulations depends on the size of the generating system.

The developed software is intended to be used by undergraduate electrical engineering students at the final year level, i.e., in the fourth year of the four-year degree program—particularly those that take power engineering as their area of specialization. It is being considered at the Institute of the first author as part of a ‘design’ class (details of the design module are provided in Reference 11) where the power engineering students are required to use the software in order to understand the basics of generating capacity reliability assessment and determine the reliability indices such as loss of load expectation (LOLE) and loss of energy expectation (LOEE). As the software was developed only recently, implementing it in the

undergraduate curriculum at the Institute of the first author will take some time but the process has been initiated. Furthermore, the first author intends to use the software for educating his postgraduate students on the concepts of Monte Carlo Simulation in generating capacity planning. It can therefore be easily appreciated that the developed software has versatile teaching and educational uses.

FURTHER IMPROVEMENTS

The following improvements are envisaged for the developed software, so that it can cater to more options for system planners and also for educational purposes:

1. Load forecast uncertainty (LFU) will be implemented in the software to account for the uncertainty that exists in the forecast load.
2. Spinning reserve requirements will be incorporated.
3. Probability distributions of LOLE and LOEE will be generated.
4. Stopping criteria for ending the simulation will be incorporated.
5. The software will be extended to include the interconnections between neighboring systems [10].

CONCLUSIONS

This paper describes a Windows-based reliability evaluation software using the Monte Carlo simulation (MCS) technique. The developed software enables the evaluation of two fundamental risk indices in generating capacity planning, namely the loss of load expectation (LOLE) and the loss of energy expectation (LOEE). The software was implemented in different modules

before being integrated into a single application. The software is highly user-friendly, has many capabilities to create and view generation and load models, can compute the indices for a progressive period of time, can consider partial output(s) of units and different load models, can perform various sensitivity studies, can generate and plot graphs, etc. The indices computation program has been successfully linked with the user graphic interface to provide an appealing software package for power utilities as well as for

educational purposes. The software was tested using two reliability test systems, and selected results using the IEEE Reliability Test System (RTS) are presented in the paper. The simulation results obtained from the software are in good agreement with published results obtained using analytical methods.

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