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A Software-Based Tool for the Reliability Evaluation of a Utility's Generation Capability

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Analytical reliability evaluation analyses can be broadly categorised into two main areas, namely static or long-term and spinning or short-term evaluation. The paper presents a PC-based Windows application software for evaluating the static reliability indices of practical power systems using the well-established generation inadequacy probabilistic techniques. The name given to this software which was developed using MATLAB 5.3 is Reliability Evaluation Tool (REST). The effects of the addition of energy limited systems to existing conventional power systems are also incorporated into the package. The two approaches for static evaluation; the loss of load and the frequency/duration have been applied to three power system configuration models. The algorithms for the building of the generation model, i.e., the capacity outage probability table (COPT), equivalent assisting and tie-constrained models are also implemented as well as the algorithms for the convolution of load and capacity models. REST was tested using two reliability test systems, namely the IEEE Reliability Test System (RTS) and the Roy Billinton Test Systems (RBTS). Selected results of the software using both test cases are presented in this paper for illustration purposes.

1. Introduction

1.1 General Background

Power system reliability evaluation is an important consideration for planners, designers and operators. Reliability evaluation software programmes have been developed and utilised in all aspects of power system planning, designing and operation. This is evident since over the years, most generation planning and expansion decisions made by utilities have been based on the indices provided by the use of such programmes.

Most of the software tools developed have been customised to the particular power system and they have been implemented based on the probabilistic approach to the evaluation of reliability indices as is evidenced in the published literature. This type of evaluation replaced the techniques first used in practical applications which failed to encapsulate the probabilistic nature of a system since they were all deterministically based.

1.2 Salient Features of REST

The generating capacity required to satisfy a particular load demand is a salient criterion which must be determined at the planning and operating level. Two requirements which must be satisfied for such a criterion are:

(a) Static Requirements

(b) Spinning Requirements

The static requirement can be considered as the installed capacity that must be planned and determined

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in advance of the system requirements and its reserve must include provision for overhaul (maintenance) purposes, unplanned outages, forced outages and load growth requirements in excess of the estimates. The spinning requirement consists of the reserve capacity that is spinning, synchronised and ready to take up load and analysis of this operating reserve encapsulates a short-term evaluation of the system [1].

Over the years, probabilistic concepts and techniques have been developed and applied to resolve these static and spinning capacity problems. For small power systems, the implementation of these techniques can be easily achieved by hand calculations, however, for larger practical systems, the computations involved become complicated and time-demanding. This problem can only be resolved by computerising the entire process or computational methods.

With the increased trend towards the use of reliability evaluation packages by utilities, the need for programmes which are user-friendly, portable and cater for different power system models has become increasingly important. These packages can also be used as teaching tools for persons interested in the reliability evaluation aspect of power systems.

This paper describes the development and functionality of a general-based, user-friendly software tool developed for static capacity reliability evaluation. The name given to this application is Reliability Evaluation Simulation Tool (REST). The specifications of this package are that it must include an interactive Graphical User Interface (GUI) that outputs the Loss of Load Expectation (LOLE) and Expected Energy Not Supplied (EENS) indices.

As part of acceptance of the final package, another salient objective is that the results of the entire software must be verified with the Institute of Electronic and Electrical Engineers Reliability Test System (IEEE RTS). The programme package must also be applied to produce the reliability indices of a practical power system which has undergone varying system models over the last eight years - The Trinidad and Tobago Electricity Commission (T&TEC).

Two well-established probabilistic techniques used in the static reliability evaluation of power systems are implemented by REST, namely:

(a) Loss of Load, and

(b) Frequency and Duration

The three system models that are implemented by REST using the two aforementioned techniques are:

(i) Single area capacity model

(ii) Two interconnected systems model

(iii) Three interconnected systems model

The above models were chosen since they represent and encompass the various models of the case study example - T&TEC over the last eight years.

The software chosen to implement the various system models is MATLAB 5.3 and this application was preferred primarily because of the following reasons:

(a) It is the current state-of-the-art software adopted by industries worldwide.

(b) It has powerful mathematical capabilities,

(c) It eliminates double-precision errors, and

(d) It facilitates the designing of GUIs from the individual m-files developed for each specific function.

2. Theoretical Considerations

Reliability may be defined as "the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered." [2].

From the above statement, it is evident that probability concepts and techniques play an important role in reliability evaluation analyses. A large number of papers applying probability techniques to generating capacity reliability evaluation have been published over the years. The two most widely adopted methods for static reliability evaluation utilising these probability concepts are:

(a) Loss of Load Approach, and

(b) Frequency and Duration Approach.

The basic methodology used to evaluate the adequacy of a particular generation configuration is depicted in the following representation shown on next page [1]:

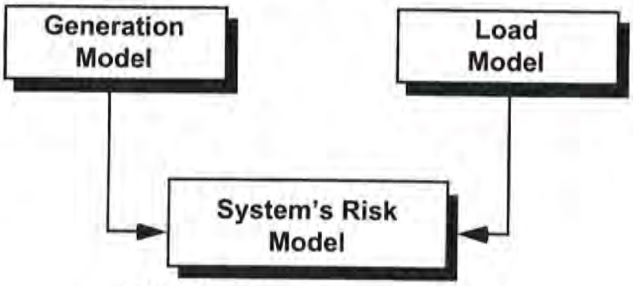

FIGURE 1: *Methodology for Capacity Reliability Evaluation*

The system's risk model in the above Figure is determined by convolving the generation and load models. This technique can be considered as the fundamental principle used in the analyses of both aforementioned approaches.

2.1 Single Area Capacity Model - Loss of Load Approach

In the single area capacity system, the generation model required for analysis using the loss of load approach is known as the Capacity Outage Probability Table (COPT). The COPT may be defined as an array consisting of the possible capacity outage levels of the system and their respective probabilities [1]. If all the units in the system have identical sizes and Forced Outage Rates[1] (FORs), this table can be easily obtained using the Binomial Expansion technique. It is extremely unlikely however, that the COPT in a practical case can be developed using the Binomial technique as most systems contain generator units of varying sizes and FORs. In this case, the units can be combined using recursive algorithms in which the units are added sequentially to produce the final model. The algorithm implemented by REST for the case where a multi-state unit is added to the capacity model is [1]:

$$P(X) = \sum_{i=1}^{n} p_i P^{\wedge}(X - C_i) \qquad ....(1)$$

where:

$P(X)$ - individual probability of the capacity outage state of XMW after the unit is added

$P^{\wedge}(X)$ - individual probability of the capacity outage state of XMW before unit is added

n - number of states of the unit

C_i - capacity outage of state is for the unit being added

p_i - probability of existence of the unit state i

Three load models are analysed by REST in the single area capacity system namely:

a) **Load Model 1** - *Daily peak loads for a given time period and the number of occurrences where these daily peaks were exceeded*
In this model, load data is in the form of the individual daily peak loads and their corresponding number of occurrences over a given time period.

b) **Load Model 2** - *Daily Peak Load Variation Curve (DPLVC)*
The Daily Peak Load Variation Curve represents a cumulative load model where each day is represented by its individual daily peak load, i.e., readings are taken every day for the peak load on the system. From this, the DPLVC is formed by arranging all the values in descending order.

c) **Load Model 3** - *Load Duration Curve (LDC)*
The Load Duration Curve is similar to the DPLVC except that each hour is represented by its individual hourly peak load. The readings are then arranged in descending order to form the final load model.

[1] The mean number of failures of a component per unit exposure time.

2.2 Loss of Load Expectation (LOLE)

This generation model (capacity outage probability table) can then be convolved with the appropriate load model to produce an expected risk of loss of load that is termed the Loss of Load Expectation Index (LOLE) index. For each load level L_k, the contribution to the LOLE index is found by summing all the individual probabilities where the capacity available, C_k is less than the particular load level. The entire process is repeated for all load levels in the time period and the final LOLE index is deduced by summing all these individual contributions [3].

The equation using load model 1 is shown below:

$$LOLE = \sum_{i=1}^{n} P_i(Ci - L_i) \text{ days/period} \quad \text{..........(2)}$$

where C = Capacity available
L = Load level

The LOLE analysis without maintenance using load models 2 and 3 (DPLVC and LDC respectively) is given by Equation (3):

$$LOLE = \sum_{k=1}^{n} P(C < L_i) \quad \text{..........(3)}$$

2.3 Sensitivity Study Analysis

A sensitivity study analysis demonstrates the variation in reliability index (LOLE) with the system parameters. The analyses performed by REST allows for the variation of two system parameters, namely, the peak load and the generators' FORs. These can be summarised as follows:

a) ***LOLE as a function of the system peak load***
The LOLE index is evaluated by REST for a range of system peak loads using load model 2 described in section 2.1. The results from this analysis can then be displayed in a graphical format where $\log_{10}$ (LOLE) vs. System peak load is plotted.

b) ***LOLE as a function of system peak load and FOR***
The system's risk index for a given capacity and forecast peak load is dependent on the forced outage rate values for the individual units [1].
In this analysis, the LOLE values for a range of peak load levels are evaluated as a function of unit forced outage rates. The results from this analysis are also displayed in a graphical format where $\log_{10}$ (LOLE) vs. System peak load is plotted for each FOR value used.

2.4 Loss of Energy Analysis

In addition to the LOLE analysis, load model 3 (load duration curve) when convolved with the COPT can also be utilised to calculate the expected energy not supplied by the system due to insufficient installed capacity. This principle is explained by considering the following load duration curve in **Figure 2** below.

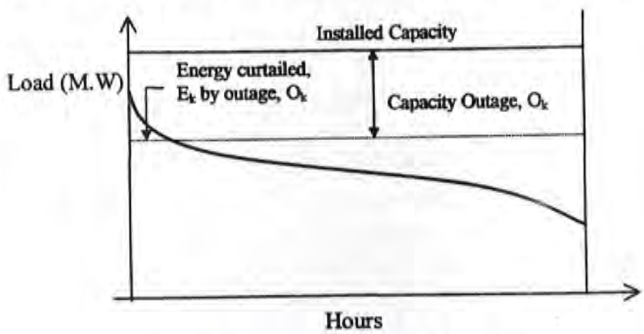

FIGURE 2: *Energy Curtailment due to a Given Capacity Outage Condition*

The total area under the curve represents the energy demanded over the given time period and consequently, a portion of this energy required E_k, would not be supplied for all load levels which are greater than a particular capacity outage O_k [3].

This analysis can be done with the addition of each generator to the system and the results of such evaluation can be used to determine the following energy related indices viz:

(1) Expected Energy Not Supplied (EENS)

(2) Loss of Energy Expectation (LOEE)

(3) Energy Index of Reliability (EIR)

An advantage given by this energy-based evaluation method is that production costs simulations can be performed since the output energy generated by each unit can be determined from the aforementioned indices.

2.4.1 Expected Energy Not Supplied (EENS)

The basic principle described in section 2.4 can be used to determine the expected energy not supplied by the system, with the addition of each generator unit to the capacity model. In this analysis, for each state of the capacity model, C_k, the energy not supplied, E_k, is obtained by summing all load levels which are greater than this particular capacity state of the system. The expectation is then obtained from the product of the energy not supplied E_k as a result of each capacity state and the associated probability of the system residing in that particular state [3].

The expected energy not supplied, EENS is then evaluated by numerically summing the individual mathematical expectations for each state of the capacity model.

In this analysis, it is important that the merit order of the units be maintained since the EENS is dependent on the particular loading order chosen for the units. This relates to the fact that the states of the generation model (COPT) vary with the addition of each unit of a particular capacity. The expected energy not supplied can be subsequently evaluated by REST using the following equation:

$$EENS = \sum_{k=1}^{n} E_k P_k \qquad \text{..........(4)}$$

2.4.2 Loss of Energy Expectation (LOEE)

When all the units have been added to the system's capacity model, the final value of the EENS represents the system loss of energy expectation (LOEE) [3]. This index depicts the probable energy not supplied by the system even after all generator units have been loaded to their respective capacities.

2.4.3 Energy Index of Reliability (EIR)

The EIR represents the probable ratio between the total energy that will be supplied by the system after all units have been added and the total energy demanded by the system to supply all the load levels in the specified time period. The following formula is utilised:

$$EIR = 1 - \frac{(LOLE)}{Total\ Energy\ Demanded} \qquad \text{..........(5)}$$

2.5 Production Cost Evaluation

The expected energy not supplied concept discussed in section 2.4.1 provides an approach to production cost modelling. The total expected production cost of the system can be determined by summing the expected energy output of each unit in the system multiplied by their respective energy costs per MWh. [4]. The algorithm implemented by REST for this analysis is shown in equation 6:

Total Production Cost =

$$\sum_{k}^{m} \text{(Energy output (MWh) of unit } k\text{)}$$

$$\text{x (Cost/MWh of unit } k\text{)} \qquad \text{..........(6)}$$

2.6 Energy Limited Systems

The EENS index discussed in section 2.4.1 can also be evaluated with the inclusion of an energy limited or a non-conventional system to the existing capacity model. An energy limited unit may be considered as a unit whose output at any point in time is dictated by the energy available or derated due to a technical problem. The analyses carried out by REST using energy limited systems are sensitivity studies where the system's EENS is evaluated for varying penetration levels[2] and for varying FORs of the unit. The results of such analyses are displayed in a graphical format by the software tool.

2.7 Single Areas Capacity Model - Frequency and Duration Approach

The method requires additional system information to that used in the loss of load approach technique. The latter method utilises the steady state availability, A, and the unavailability, U, parameters for its

[2] The ratio of the energy limited unit capacity to the total installed capacity (energy limited unit plus conventional).

generation model. The F&D technique utilises in addition to the A&U parameters, the transmission rate parameters λ and μ [1].

The generation model is similar in form to the capacity outage probability table required for the loss of load approach. This model, however, provides additional information on the frequency of encountering every capacity outage state and departure rates from each state to higher and lower capacity outage states. In the case where a multi-state unit is added to the capacity model, the algorithms are shown in equations (7) to (9).

$$p(X) = \sum_{i=1}^{n} p^{\wedge}(X - C_i)\, p_i \qquad \text{..........(7)}$$

$$\lambda_{+}(X) = \frac{\sum_{i=1}^{n} p^{\wedge}(X - C_i)\, p_i\, (\lambda^{\wedge}_{+}(X - C_i) + \lambda_{+}(Ci))}{p(X)} \qquad \text{..........(8)}$$

$$\lambda_{-}(X) = \frac{\sum_{i=1}^{n} p^{\wedge}(X - C_i)\, p_i\, (\lambda^{\wedge}_{-}(X - C_i) + \lambda_{-}(Ci))}{p(X)} \qquad \text{..........(9)}$$

..........(9)

REST implements one load model which is referred to as the individual load state model. In this model, the sequence of daily peaks is assumed to be a stationary random process and is represented by a Markov chain model.

2.8 *Two Interconnected Systems*

The adequacy of the generating capacity in a single area power system - System A, is normally improved when this system is interconnected to another single area capacity system - System B, via a tie line. For implementation purposes in this project, this tie line is assumed to be 100% reliable. Each interconnected system can then operate at a given risk level with a lower reserve than would be required without the interconnection. The technique used by REST for developing the model of the assisting system taking into account its peak load, is the equivalent assisting unit which can then be moved through the tie-lines and added to the existing capacity model of the assisted system. The computation of the LOLE index in the assisted system proceeds as in the case of a normal single area system study.

2.9 Three interconnected Systems

The adequacy of the generating capacity in a single area power system - System A, is further improved when this system is interconnected to two single area capacity systems - Systems B and C, via two tie lines. In this analysis, the equivalent assisting unit method is applied to develop the equivalent assisting units for systems B and C. The maximum assistances provided by systems B and C are however limited to the tie capacities AB and AC respectively. As a result, two tie constrained equivalent assisting unit moels were developed taking these tie capacities into account.

These tie constrained unit models are then added to the existing capacity model of System A and a new generation model is produced for the modified system A.

3. Software Design and Implementation

The software model adopted in the designing of REST was the Waterfall Model with Prototyping [5]. The MATLAB design for this tool consisted of designing a sequence of GUIs which would allow the user to select a particular system model for analysis and perform all the evaluations pertaining to that model. The three options provided for the user are:

(a) Single area capacity model.

(b) Two interconnected systems model.

(c) Three interconnected systems model.

In the case where the single area capacity model is selected, the user has the option to select between the two approaches: Loss of Load and Frequency and Duration. For the two and three interconnected systems model, the loss of load approach is automatically assumed.

Figure 3 shows the programme's main screen. This window allows the user to select the particular type of system model to be evaluated and in the case of the single area system, the approach to be utilised. Once a selection is made from the menu, the user is taken through the analysis via software prompts.

4. Software Testing

One of the major objectives of this tool was that the entire software must be verified against the results of the Institute of Electronic and Electrical Engineering

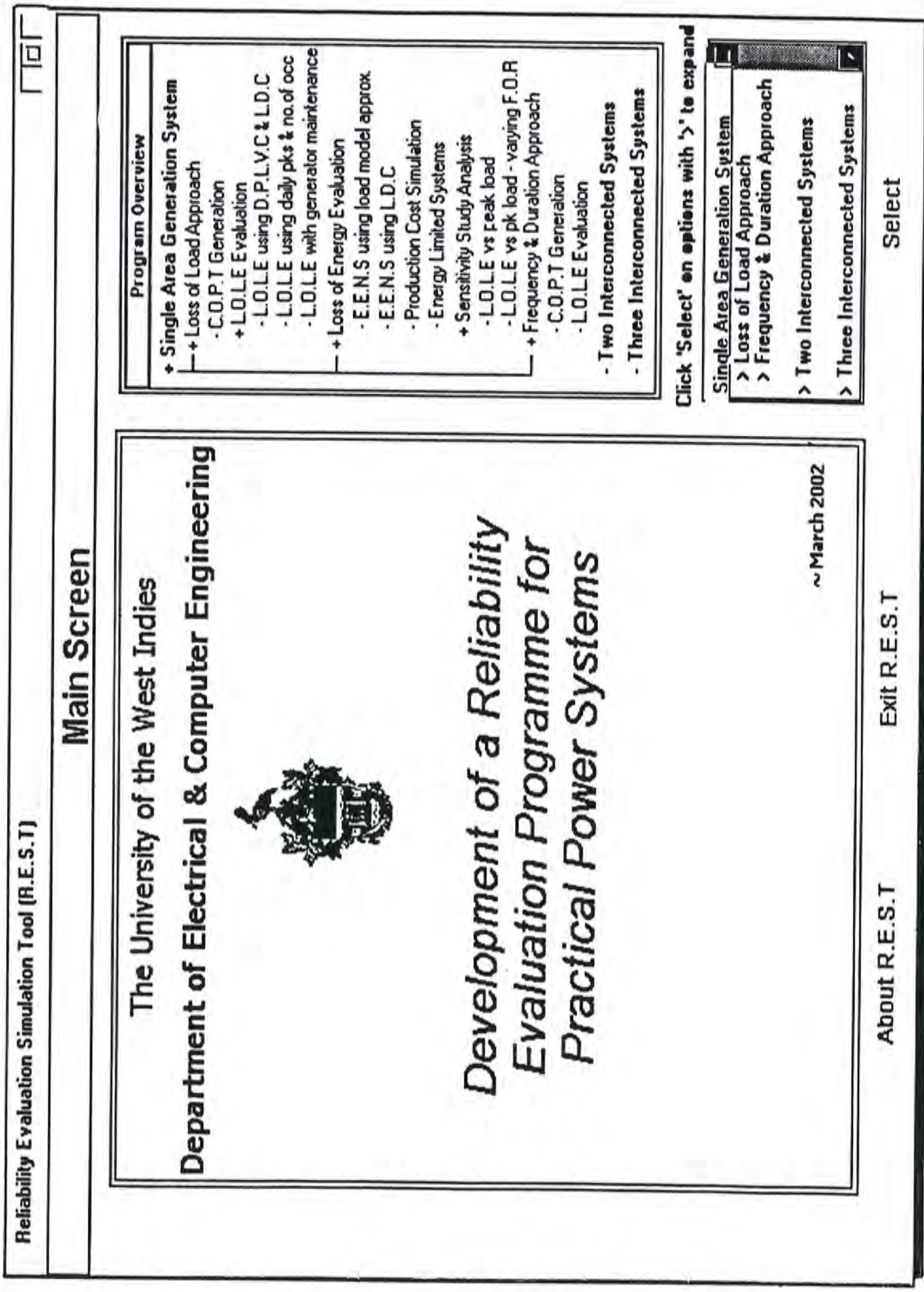

FIGURE 3: *Main Screen for REST*

Reliability Test System (IEEE RTS). This test system consists of 32 generators and an appropriate bulk transmission network. The results of this model primarily served as a reference case, which allows the results from programmes developed by users to be benchmarked or verified. For certain functions where there were no published IEEE RTS results, the Roy Billinton Test System (RBTS) was utilised for verification purposes.

The raw data required for simulation of the various functionality by REST must be obtained from the particular utility under study and consists of the following:

(a) The value in MW and the probability associated with each distinct state of the generators in the system. This is used for the generation of the COPT.

(b) Fifty-two (52) weekly peak load values expressed as a percentage of the annual peak load, seven daily peak loads expressesd as a percentage of the weekly peak load and 24-hourly peak loads expressed as a percentage of the daily peak load. This data is used in the LOLE and EENS analyses.

(c) The weekly maintenance schedule for the particular utility and the corresponding units on maintenance. This is used in the LOLE analysis which incorporates the effect of a scheduled maintenance.

(d) The range of peak loads or FOR values required for the sensitivity study analyses.

(e) The merit loading order of the units on the system used for the EENS analysis. (This is based on an economic despatch programme).

(f) The equations of the two or three straight-line approximations to the load duration curve also utilised for the EENS analysis.

(g) The model of the energy limited unit, its corresponding rating in MW and the range of FORs and penetration levels. This data is used for the analysis of an energy-limited unit when added to an existing system.

(h) The cost per MWh of each unit in merit loading order. This data is used for production cost analyses.

(i) The Mean Time To Failure (MTTF) and the Mean Time To Repair (MTTR) values which are used in the generation of the COPT utilising the Frequency and Duration method.

(j) The peak loads and the tie capacity (ies) of the systems used in the two or three interconnected systems models respectively.

4.1 Results of the IEEE RTS and RBTS Test Cases

Single Area Capacity Model - Loss of Load Approach (See **Table 1**).

TABLE 1: *Results for Capacity Outage Probability Table (COPT)*

Capacity Out (MW)	Individual Probability	Cumulative Probability	Individual Probability	Cumulative Probability
0	2.36395119E-001	1.00000000E+000	0.23639495	1.0
100	2.99915553E-002	5.47601144E-001	0.02999154	0.54760141
200	1.28665569E-003	3.81328100E-001	0.00128665	0.38132840
600	3.57691932E-004	6.21128606E-002	0.00035769	0.06211297
950	6.43059892E-005	7.49195264E-003	0.00006431	0.00749197
1200	2.41320686E-006	7.91252253E-004	0.00002413	0.00079125
1500	2.99150915E-007	4.04350770E-005	0.00000030	0.00004043

TABLE 2: *Selected States for Capacity Outage Probability Table for Powergen*

Capacity Out (MW)	Individual Probability	Cumulative Probability
0.0	3.40561626E-001	1.00000000E+000
20.0	7.16971845E-002	6.59438374E-001
708.0	4.70238908E-012	9.86584761E-011
709.0	3.47905350E-012	9.39560870E-011
1141.0	3.62396240E-026	3.67164612E-026
1151.0	4.76837158E-028	4.76837158E-028

4.2 *Results of Practical Case Study: T&TEC*

This case presents the salient results of a test case performed on the T&TEC system - results for Powergen Trinidad Generation System (21 Generator units). (See **Table 2**).

5. Limitations of REST

The entire software package was developed and implemented using MATLAB Version 5.3. This software was chosen primarily because of its powerful mathematical and GUI building capabilities. However, one limitation of using MATLAB is the method by which programmes are executed. Every time MATLAB runs a programme, it has to check the code for syntax errors, compile and then execute it. In programmes such as C and C++, stand alone executable files are created which does not require recompilation every time the programme is run. The effect of MATLAB's limitation is noticed when programmes containing a large number of inputs, e.g., IEEE RTS are run since now the execution time is significantly increased.

6. Recommendations

The proposals offered to extend the functionality of the present programme so that it can cater to more options for system planners are as follows:

a) Implement the frequency and duration technique to the analysis of the two and three interconnected systems models.

b) Implement the concept of tie line reliability in the development of the tie constrained models for the two and three interconnected systems models.

c) Implement the concepts of spinning capacity reliability evaluation and apply techniques such as the Pennsylvania New Jersey Maryland (PJM) approach to develop an analogous counterpart for the short-term reliability evaluation of a power system.

7. Conclusion

This paper described the development of a MATLAB-based software tool, REST, implementing the probability concepts of static capacity reliability evaluation. Three system models were developed, namely single area generation system, two interconnected and three interconnected systems. The developed software enabled the evaluation of two fundamental indices used in generating capacity planning, namely the Loss of Load Expectation (LOLE) and Expected Energy Not Supplied (EENS).

The software was implemented in different modules before being integrated into a single application. The developed software was highly user-friendly, had many capabilities to create and view the generation and load models, performed various sensitivity studies, production cost simulations, displayed graphical plots and examined the effects of energy limited systems. The results from the software also had a high degree of precision.

The individual m-files coded for the programme had been successfully linked with the graphical user interface (GUI) to provide an appealing software package for power utilities. The entire programme is portable since all files were easily stored on a single compact disc.

The entire software was tested using two reliability test systems, namely IEEE Reliability Test System (RTS) and the Roy Billinton Test System (RSTS). The simulation results obtained from REST were in good agreement with the published results for the two test systems.

The package was also successfully applied to determine the reliability indices of a practical power system, namely the Trinidad and Tobago Electricity Commission (T&TEC).

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