A novel expert system to calculate reliability and bus failure frequency of composite power systems based on the tearing process

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This paper presents the expert modules which construct the novel Expert System (ES) used to calculate the reliability and bus failure frequency of composite generation and transmission power systems. Also a small rule-based ES is developed to help power system planning engineers in finding alternative solutions for improving the reliability of a specified bus. This is carried out by using a log file in which all the solution steps are recorded and using this file to find solutions to improve certain bus reliability without solving the network from the beginning which saves computing time. Pascal language is used to implement the developed system. The proposed ES is more efficient and faster than those analytical methods in which the execution of load flow programs requires hundreds of time to solve the composite system reliability problem. The proposed ES is tested on the IEEE-Reliability Test System (RTS), which have 24 buses, 38 branches and a load of 2850 MW.

تعتبر دراسات الاعتمادية و تردد الفشل عند كل نقطة من أجزاء شبكة القوى الكهربية المركبة (توليد+نقل) من أهم الدراسات التى يعتمد عليها مهندسو القوى الكهربية سواء فى التخطيط أو التصميم أو الأداء حيث أنها توضح نقاط الضعف فى أى شبكة كهربية. يقدم هذا البحث نظاماً خبيراً جديداً مبنياً على أساس الخوارزم الذى قدمه المؤلف فى بحث سابق لتقدير تردد الفشل لمنظومة القوى الكهربية المركبه باستخدام تقنية تجزئة الشبكة. و يقوم هذا النظام الخبير بحساب الاعتمادية و تردد الفشل عند كل نقطة حمل من أجزاء الشبكة شارحاً خطوات الحل و أسباب تنفيذه لكل خطوة. و تم عمل برنامج بلغة "البسكال" يمكن من خلاله التعامل المنسق بين المستخدم و الحاسب لتطبيق هذا النظام الخبير و الذى يتكون من أربع وحدات خبيرة تقوم بحساب الاعتمادية و تردد الفشل لأية شبكة قوى كهربية. و يتفاعل هذا النظام الخبير مع مستخدم البرنامج لإيجاد حلول لتحسين الاعتمادية لبعض نقاط الضعف فى الشبكة مستخدماً قاعدة بيانات متمثلة فى أرشيف ملفات مسجل فيها كل خطوات الحل. و قد تم اختبار النظام الخبير المقترح على النموذج القياسى لحساب معواليه نظم القوى الكهربية و المعروف ب IEEE-RTS و المكون من ٢٤ عقدة.

Keywords: Composite power system reliability, Failure frequency, Expert system, Network tearing

1. Introduction

The reliability studies of bulk power system indicate the ability of the composite generation and transmission system to satisfy the load demand at the major load points. Considerable effort has been applied over the two last decades to develop techniques and criteria for adequacy evaluation of composite power systems. A major burden in the developed methods used in evaluation of large composite system reliability is the computing time required to solve a large number of credible contingencies or outage states. Power system reliability evaluation techniques can be generally categorized as being either analytic or simulation. Analytic techniques represent the system by analytical models and evaluate the indices from these models using mathematical solutions. Mont-Carlo simulation methods estimate the indices by simulating the actual process and random behavior of the system. Composite reliability methods currently in use employ one of the following approaches, or combinations:

1. Contingency enumeration.
ii. Mont-Carlo simulation.
iii. State space decomposition.

Contingency enumeration consists of listing all contingencies of up to a given order, computing their probabilities, and evaluating the reliability indices from these probabilities as in [1]. A major concern in contingency enumeration method is the selection and testing of outage contingencies which occur frequently and have a sever impact on system performance. The computational time increases rapidly as the contingency level increases, particularly when an a.c. load flow is used to analyze each contingency.

The Mont-Carlo simulation is one of the most powerful available methods to evaluate system reliability. This method can be used to evaluate composite power system reliability by analyzing a large number of system states identified by sampling component outages. An approach using an annual chronological load curve for each load bus and a sequential Mont-Carlo approach for composite system reliability assessment was developed in [2]. A Mont-Carlo simulation approach to generation /transmission reliability evaluation assuming the loads are defined by fuzzy numbers was developed in [3]. In this approach data uncertainties were modeled more adequately, system component outages were represented by probabilistic models and load uncertainties were modeled by fuzzy numbers. For each sampled state, one can obtain the power not supplied membership function by running a fuzzy optimal power flow [4]. A major limitation associated with Mont-Carlo methods is the computational time required to obtain an acceptable degree of accuracy.

State space decomposition is an analytic method which recursively decomposes the system state space into sets of acceptable, unclassified, and loss of load states [5-7]. The coherency property, which requires that an acceptable set be homogeneous to the extent that it should have no loss of load states, and that a loss of load set should likewise be devoid of acceptable states, is a necessary condition for this method. This condition restricts the flexibility of the power flow model which can be used for composite reliability analysis, because for DC and AC flow models, changes in transmission line states result in non-coherency of the state space [8].

The objective of this paper is to develop an effective ES to assess the reliability and failure frequency of bulk power system and to find solutions for improving the reliability at certain buses. The main motivations to use rule-based ES are [9,10]:

i. It is open to inspection, both in presenting intermediate steps and in answering questions about the solution process.

ii. It is easily modified, both in adding and in deleting skills from the knowledge base.

iii. It is heuristic, in using (often imperfect) knowledge to obtain solutions.

To the knowledge of the author, the use of rule-based ES in composite power system reliability assessment was not tried before.

The developed ES is based on the algorithm described in [11] which is mainly based on the tearing process to calculate buses reliability of composite system [12]. In this developed ES the constraints which control the flow direction in the tearing elements, the initial calculation part and the process of adding the tearing elements are presented in three ES modules, each of which consists of a group of rules and each rule satisfies certain constraints. The developed ES also has an Expert Module (EM) to improve the calculated reliabilities of selected nodes. The implementation of the ES is achieved using the PASCAL language. The developed ES is applied to the IEEE-Reliability test system (RTS) [13] to compare results with other traditional methods.

2. The developed expert system

Three simple ES modules are developed based on the algorithm proposed by the author in [11]. This algorithm is divided into the following modules:

i. *Data-input module:* Power system configuration is presented in a text file. The computer program reads the data from this input file and saves them in records.

ii. *Generation failure frequency module:* In this module failure frequency of the installed generation capacity at each bus is calculated.

iii. *Tearing module:* The aim of this module is to tear the whole network into “a” trees and “b” tearing lines [12].

iv. *Initial calculation module:* The aim of this module is to calculate failure frequency at all buses of each tree. Two factors must be taken into consideration. The first is that the power flow in each line has only one direction, the second is that the power flow in each line must not exceed its maximum capacity.

v. *Repetitive calculation module:* In this module the tearing lines are added one at a time and after each the reliability vector of all system buses are updated. The addition of the tearing lines will be carried out in number of passes. In the first pass only the tearing lines whose addition results in feeding all the loads are added. In the second pass each load is fed again by another path constructed by adding the remaining tearing lines. Subsequent passes are carried out until all tearing lines are added. The steps and explanation of these modules are presented in [11].

The purpose of the first ES module is to specify the flow direction in each tree line and in each tearing element according to certain specified rules. The purpose of the second EM is to calculate nodes reliabilities and failure frequencies in each tree in the initial step. The purpose of the third module is to specify the order of adding tearing lines and calculate the final value of nodes reliability and failure frequency according to some heuristic rules. The block diagram of the developed ES including the EM for improving bus reliability is shown in fig. 1.

2.1. The initial knowledge base for the proposed ES

The initial knowledge base of the proposed ES is gained from the following sources:

i. The input text file from which the power network topology, maximum load and installed generation at each bus, transmission lines availabilities and capacities, and Forced Outage Rate (FOR) of each generator.

ii. From these data, by applying data-input module, generation reliability module, generation failure frequency module and tearing module, the virtual lines and their availabilities will be added to the knowledge base. Also the construction of each tree will be known.

iii. All the information about each line or node is saved in data record format.

2.2. The EM for specifying power flow direction in each line:

The goal of this EM is to specify the flow direction in each line of the system. Using pruning technique [10] the EM classifies the network lines into two groups:

- The first group contains the lines which belong to a certain tree (type 1).
- The second group contains the tearing lines (type 2 to type 7)

If a line satisfies certain rule then this rule specifies the first node in this line and accordingly the flow direction will be from the first node to the second one. This EM uses the following five heuristic rules:

i. Rule # F_1 which is used to specify the group which the line belongs to, will be as follows:
For each line in the system,
IF (its tree field higher than zero) THEN
- It belongs to the first group.
- The line is from type1.
- Let its first node field be the nodes whose order field is less than the other one.

IF (its tree field equals zero) THEN
- It belongs to the second group.
- Test this line under the following rules to see which of them it satisfies:

ii. Rule # F_2 will be as follows:
IF (the order of one of its two end nodes equals one) THEN
- The line is from type 2.
- Its first node is the second node of a virtual line.

iii. Rule # F_3 will be as follows:
IF (the order of each of its two end node equals one) THEN
- The line is from type 3.
- Calculate the difference between the installed generation and connected load at each end node. The first node will be the nodes which has the higher difference.

iv. Rule # F_4 will be as follows:
IF (its two end nodes belong to the same tree) THEN
- The line is from type 4.
- Let its first node field be the nodes that its order field is less than the other one.

v. Rule # F_5 will be as follows:
IF (the tree field of one of its two end nodes equals zero, i.e., an isolated node) THEN
- The line is from type 5.
- Let its second node be the isolated nodes.

If there is any line which belongs to the second group and does not satisfy any of the previous four rules then its type may be type 6 or type 7. The flow direction in it will be

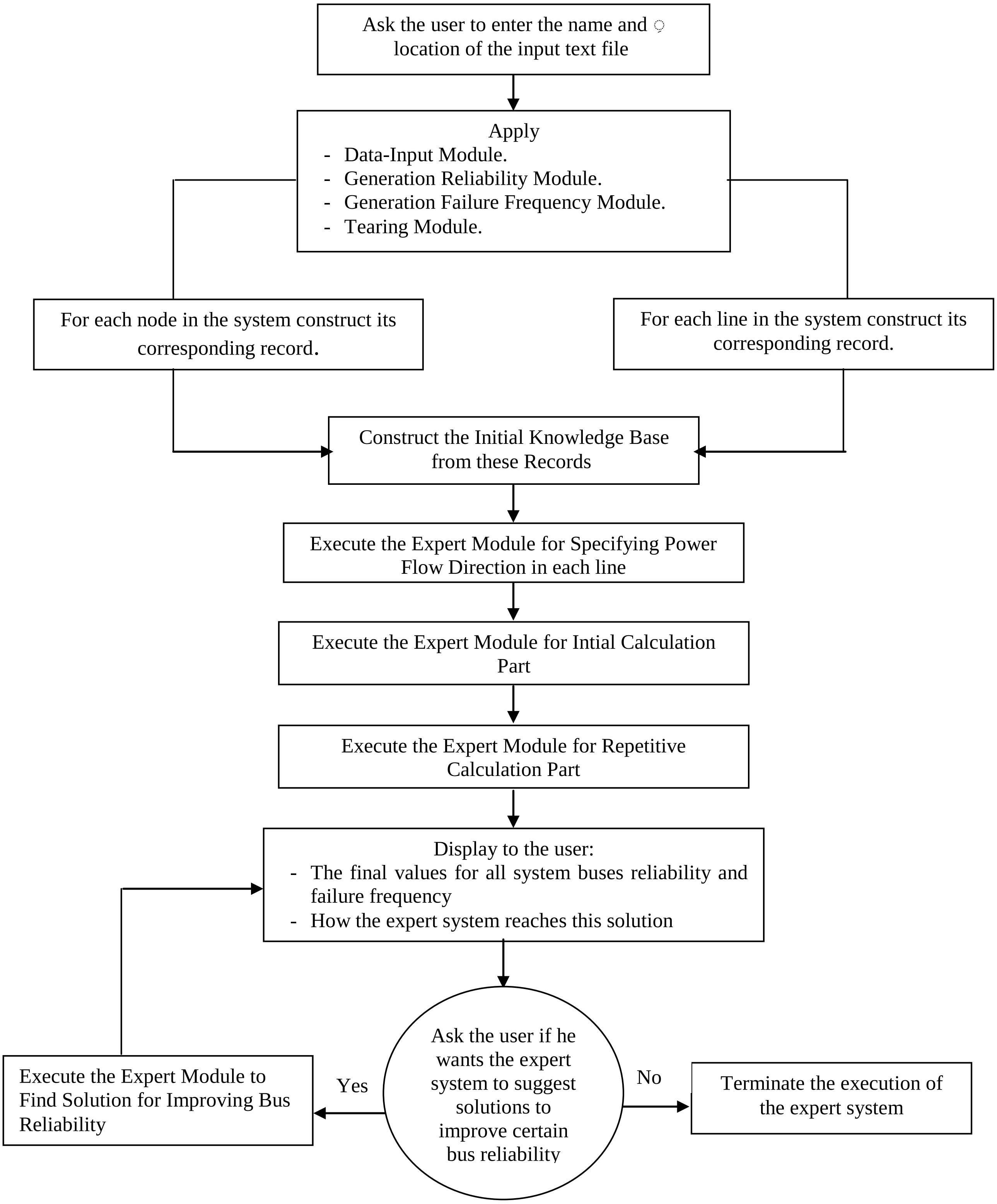

Fig. 1. Block diagram of the developed expert system.

specified in repetitive calculation EM. After applying the previous rules to all lines, the flow directions become known for them except those of sixth or seventh type.

2.3. The EM for initial calculation part

In this part the EM uses the initial knowledge base and the determined flow direction to calculate the nodes reliabilities and failure frequencies included in each tree taking the capacity of lines and maximum loads into consideration. Using the pruning technique the EM classifies network lines into a number of groups equals the number of trees, each of which contains the lines and nodes which belong to a tree, in addition to a group including the tearing lines.

2.3.1. Rules of the EM:

For each group # *j* except the last one, each line in the system is tested under the following rules:

i. Rule # N_1:

IF (the line belongs to group # *j*) AND (the line order =1) THEN

- The reliability of the second node of this line equals the availability of this line regardless of the connected load at this node.
- Assign the value one to the variable "ord" representing the line order.

ii. Rule # N_2:

Increase the value of "ord" by one, then each remaining line is tested under the following rule:

IF (a line belongs to group # *j*) AND (the line order = "ord") AND (the power capacities of this line and all other lines of less order in the group-except the first line-are higher than the line second node load) THEN

- The reliability of this line second node equals the multiplication of the availabilities of this line and all the lines of less order. The failure frequency of this node equals the multiplication of the reliability and the equivalent failure rate.
- Assign the value zero to the load connected at the second node of this line.
- Decrease the capacity of this line and the preceding lines-except the first one-by an amount equals the "Load Connected at the Line Second Node" (LCLSN).
- Let the pass flag for this node to be "true".

iii. Rule # N_3:

IF (the line satisfies rule # N_2) THEN

- Repeat rule # N_2 for another line.

IF (the line does not satisfy rule # N_2) THEN

IF (the line belongs to group # *j*) AND (the line order = "ord") AND (the capacity of this line and preceding ones belonging to this group, except the first line, are smaller than the value of LCLSN) THEN

- Calculate the minimum capacity (min_cap) of this line and preceding ones belonging to this group.
- Decrease the value of LCLSN by an amount equals (min_cap).
- Decrease the capacity of the line and the capacities of all other lines of less order and belong to this group-except the first line–by an amount equals (min_cap).
- The reliability of the line's second node will be left without change.
- The temporary reliability of the line second node equals the multiplication of the availabilities of this line and preceding ones belonging to this group. The temporary failure frequency of this node equals the multiplication of temporary reliability and temporary equivalent failure rate.
- Repeat the same procedures for another group.

2.4. The EM for repetitive calculation part

In the repetitive calculation part the tearing elements are added sequentially one line at a time and the nodes reliabilities and failure frequencies are updated accordingly. The line addition must not be random otherwise the final results will not be accurate. So an EM is developed to specify the suitable tearing line which has to be added at each step. The main function of this module is to use its knowledge base consisting of the initial knowledge base and ten heuristic rules to select the suitable line to be added at each step. These rules are generated from the experience gained through developing the proposed algorithm to reach accurate results in comparison with other methods. This EM uses a backward chaining technique as its goal is to select the optimal line to be added in a certain step. The EM gives also the reasons why this tearing line is selected in this step. After the suitable tearing line is chosen the rule calls certain calculation procedures to update nodes reliabilities and failure frequencies.

The decision tree for this EM is illustrated in fig. 2. Using the pruning technique the EM classifies the network nodes in the beginning of each pass into four main groups each of which is subjected to certain set of rules.

2.4.1. Calculation modules

This section describes the calculation modules called by the rules of the repetitive calculation EM. Each of these calculation modules has its own rules.

- *Calculation module CM_1.* This module is called by the Identification number (I.D.) of the active node and the I.D. of the tearing line. Once the I.D. field is obtained the other entire field's information are known.
- *Calculation module CM_2.* This module is called by the I.D. of the active node, the I.D. of the tearing line and the order of the tearing line second node *r*.
- *Calculation module CM_3.* This module is called by the I.D. of the active node, the I.D. of the tearing line, the order j of the tearing line first node and the tree which the tearing line first node belongs to.
- *Calculation Module CM_4.* This module is called by the I.D. of the active node, the I.D. of the tearing line, and the order j of the tearing line first node, the tree which the tearing line first node belongs to and the order of the tearing line second node *r*.
- *Calculation Module CM_5.* This module is called by the I.D. of active node, the I.D. of the tearing line which its second node is this node and the availability of the virtual line which its second node is the tearing line first node. The function of this module is to update the reliabilities and failure frequencies of all the nodes which are in the same tree and next in order to the node which the module is called by. This *CM* is repeated for each node next in order to the active node.

As an example the function of CM_1 is illustrated in fig. 3, where:

y: is the order of the active node as well as the order of the line which the active node is its second node.

$A_i(j)$: is the availability of the jth line which belongs to tree # i.

A_t: is the availability of the added tearing line.

$L_i(j)$: is the load connected to the jth node which belongs to tree # i.

3. Improving bus reliability

An additional EM is developed in this paper which suggests some solutions for increasing the reliability of a certain bus. When the execution of the previous expert modules is finished, nodes reliabilities are displayed. In the same time this EM is activated and the user has the opportunity to choose a node to improve its reliability value. The EM then uses its knowledge base, its own rules and some generated rules by inference mechanism to find suitable solutions to increase the specified bus reliability. Finally, it displays to the user the alternative solutions and allows him to select the best solution depending on his requirements and constraints.

3.1. Knowledge base of the developed EM

The knowledge base used by this EM can be classified into three parts as follows:

i. Initial knowledge base:

This knowledge base is explained previously in sec. 2.1.

ii. Log file data base:

The log file data base is a text file which is created during the execution of the expert modules described previously. This file resembles the black box in the airplane as it records the values of all the system variables at the end of each calculation step.

iii. Knowledge gained from the program user:

To activate this EM the program user must answer "yes" when the previous EM finishes its job and displays the final results and the current EM asks if he wants to improve certain node reliability. After its activation, the EM needs three parameters from the user; the first one is the I.D. of the node which the user wants to improve its reliability, the second one is the minimum limit of its reliability and the third one is maximum permissible line overloading as percentage of its rated capacity.

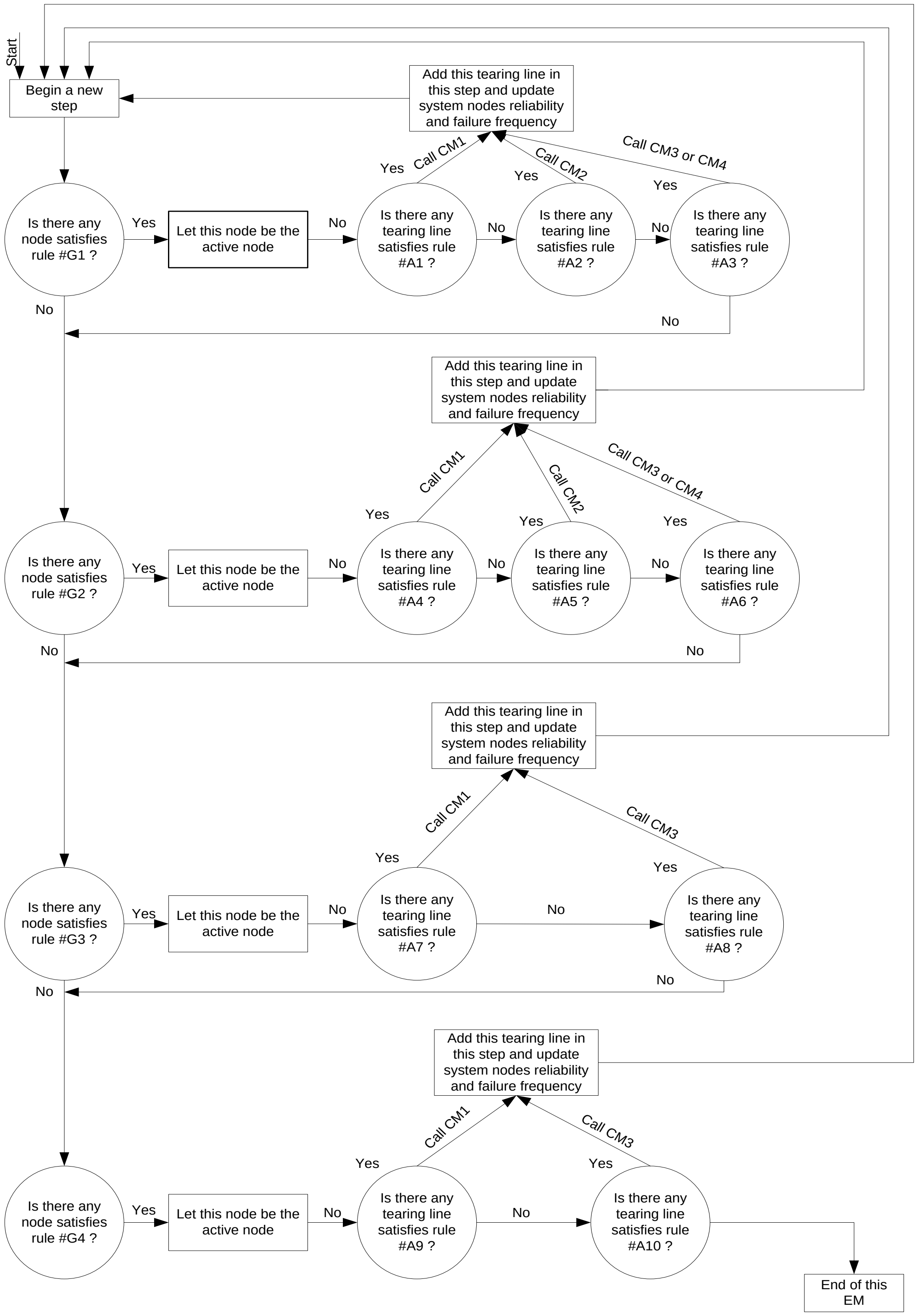

Fig. 2. The decision tree of the EM of repetitive calculation part.

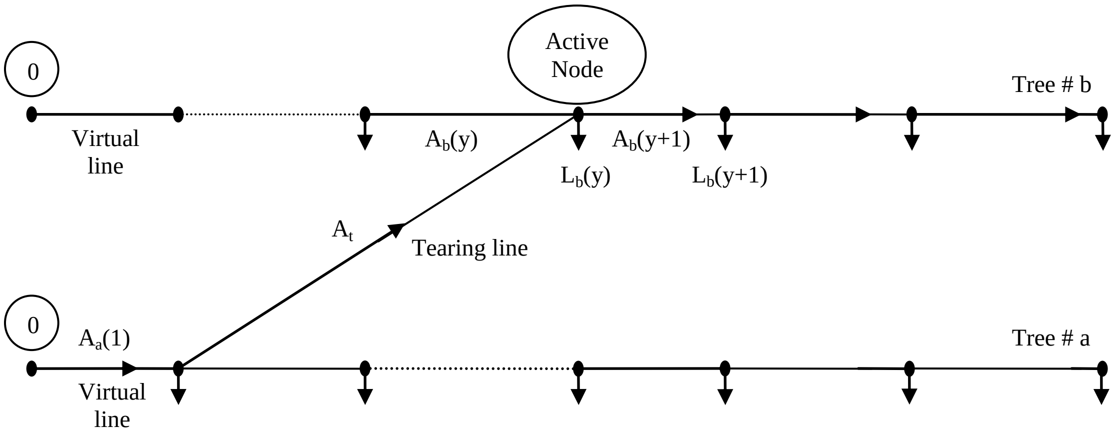

Fig. 3. Calculation module *CM₁*.

3.2. Solutions suggested by EM

The goal of this EM is to find suitable solution for increasing the reliability at a certain bus. This solution is based on one of the following techniques:

i. Adding a new transmission line between certain buses with power capacity greater than a certain minimum value specified by this EM.

ii. The second technique is used when the minimum capacity required for the new line is small. The solution is to adjust the protective system which protect the existing line to allow this line to operate under overload, which is given by the program user as a percentage of line capacity, for a certain period of time so that it will not be switched out of service.

4. Application

To show the validity and accuracy of the proposed ES, it is tested on the IEEE-RTS [13]. This system is developed by the IEEE Subcommittee on the Application of Probability Methods (APM) in 1979 so as to provide a consistent and generally acceptable set of data that can be used in composite system reliability evaluation [14]. The main aim to develop this system is to enable results obtained by different people using different methods to be compared. Ref. [15] represents two different approaches to solve the RTS to calculate different buses reliabilities and failure frequencies. The first one utilizes a Monte- Carlo simulation and the second uses a contingency analysis evaluation procedure. The results obtained from the proposed EM is compared with those obtained by the second method of [15] as, the first approach does not evaluate the failure probability at each bus. The results comparison is listed in table 1, in which bus failure probability is the complement to bus reliability. By comparing the results it can be noted that the values of failure probabilities for some nodes like nodes # 2 and 4 are consistent while for other nodes like nodes # 3,7,8 there are appreciable difference. Likewise the values of failure frequency of nodes 7,8,14,19, are consistent while for other nodes like nodes # 3, 6, 13 are different. The reasons for the deviation in results for some nodes are explained as follows:

i. The method presented in [15] takes some more constraints, for example, the failure of service at any bus in the system may result from the violation of the minimum accepted voltage at the bus and/or failure of the system to supply the total load connected to that bus after alleviating the overloaded lines, generators MVAR limit violation, etc.

ii. For each contingency state the authors of [15] used load flow analysis and if some lines are overloaded, they permit them to operate under overloading condition which yields optimistic results.

iii. Also, in [15] load curtailment has been allowed for some contingencies and it was found that the numerical calculated indices at each bus could vary widely when different load curtailments philosophies were used [16].

An attempt is made to improve the reliability of bus no. 9 to be higher than 0.95 and the permissible overloading for the power system lines is 5% of their rated capacities. Following the calculation procedures developed in sec. 3, the solution is:
"To improve bus #9 reliability from 0.84584 to 0.977, i.e., to reduce its failure probability from 0.15416 to 0.023, add new line between bus #12 and bus #9 with minimum capacity of 125 MW".

5. Conclusions

In this paper an ES consisting of three expert modules has been developed for calculating the reliability and failure frequency of composite power systems. The proposed ES is based on the algorithm developed by the author in [11]. This ES calculates each bus reliability index which is the complement to bus failure probability index and each bus failure frequency.

The ES also interacts with the user giving the reasons for each step it executes. Furthermore, when requested by the program user, it tries to find solutions for improving certain bus reliability using different techniques. One of the advantages of using the ES is the structure programming, i.e., it can consist of separate modules each of which has its own rules. Another advantage is that when it is required to make modification in the ES program, this is done by modifying certain rule, deleting a rule, adding new rules or even adding new expert modules without change the heart of the program. The proposed ES uses a log file in which all the solution steps are recorded and uses this file to find solutions to improve certain bus reliability without solving the network from the beginning which saves computing time. The execution time of the developed software package program, using Intel 486 machine and the compiler of the Pascal language, does not take more than 0.1 of the second in comparison with other analytical methods which requires the execution of load flow programs hundreds of time to solve the composite system reliability problem and the execution time on the same machine may take several hours.

Table 1
Results Comparison (system load = 2850 MW)

Bus #	Bus failure probability		Bus failure frequency occ/yr	
	Method in ref. [15]	Developed expert system	Method in ref. [15]	Developed expert system
1	0.022446	0.0024415	16.59	7.17
2	0.040999	0.049204	30.01	72.44
3	0.022640	0.1965993	16.73	83.12
4	0.022394	0.0496271	16.54	72.77
5	0.022446	0.0021301	16.54	3.62
6	0.022395	0.0497247	16.54	72.85
7	0.015922	0.115264	11.98	19.37
8	0.015950	0.1155669	12.01	19.63
9	0.003171	0.1541644	1.98	22.33
10	0.003171	0.0426063	1.98	9.49
11	*	0.0058549	*	2.34
12	*	0.0218419	*	6.87
13	0.071273	0.0217716	45.83	6.81
14	0.009556	0.0404579	6.7	9.12
15	0.056509	0.0016189	35.38	1.85
16	0.026011	0.04	18.35	8.76
17	*	0.0071636	*	3.55
18	0.083433	0.0144464	51.51	1.72
19	0.011667	0.0404097	8.05	9.08
20	0.046213	0.0232532	29.97	6.77
21	*	0.120000	*	7.01
22	*	0.0070515	*	3.45
23	*	0.1521280	*	21.93
24	*	0.0020861	*	4.86

* Not given

Is there any node satisfies rule #G2?

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