MORSI, D.M., ABBASY, N.H. and ABUL ELLA, M.S. 1994. A hybrid expert system assisting decision making for distribution system load forecasting. In *Proceedings of the 1994 Mediterranean electrotechnical conference (MELECON '94), 12-14 April 1994, Antalya, Turkey*. Piscataway: IEEE [online], pages 893-896. Available from: https://doi.org/10.1109/MELCON.1994.380958

A hybrid expert system assisting decision making for distribution system load forecasting.

MORSI, D.M., ABBASY, N.H. and ABUL ELLA, M.S.

1994

A HYBRID EXPERT SYSTEM ASSISTING DECISION MAKING FOR DISTRIBUTION SYSTEM LOAD FORECASTING

D.M. Morsi — Student
N.H. Abbasy — Assistant Prof.
M.S. Abul Ella — Associate Prof.

Electrical Engineering Department
University of Alexandria
Alexandria, P. No. 21544, Egypt

Abstract --This paper introduces a typically intelligent hybrid expert system (ES) for an annualized distribution system load forecasting. The proposed ES has the capability of predicting the annual distribution substation load growth, and patterns of subsequent load shifts, in case of a substation overload. Also, possible expected system expansion plans are introduced. The parameters of the load growth model are estimated for each substation. The load transfer model is chosen to follow the Weibull distribution function and to simulate different factors affecting the transfer process. The ES is developed using an artificial intelligence language (PROLOG), and is applied to Alexandria city, 66/11 KV power distribution network.

I. INTRODUCTION

Load forecast plays an important role in all aspects of electric utility operations. In particular, distribution system load forecast (DSLF), for a number of forecast years to a defined horizon year, is necessary for maintaining an efficient and reliable power distribution system (DS). Proper analysis of the locations and amounts of future load growth, as well as the expected transfer, are important since they can impact the expansion of the DS.

A variety of computerized load forecasting methods for distribution planning has been developed during the last decade [1] through [4], [6]. Distribution planning is usually met by dividing the utility service area into a number of sufficiently small areas [2]. Those areas can be either a grid of uniform rectangular cells, or equipment oriented areas, such as feeders or substations areas. A load forecast for each area is then produced and finally, the future system can be planned. Generally DSLF is performed using one of the following basic approaches:

1-Trending methods which involve extrapolation of annual peak load history on a small area basis using curve fitting.

2-Multivariate techniques which encompass methods that extrapolate on the basis of other variables as well as the annual peak load. This can be applied on large utility systems and give good results.

3-Simulation approaches which generally work by predicting the load on a small area basis after the customer is classified as residential, commercial, or industrial.

In this paper, a hybrid heuristic/mathematical algorithm is developed to implement a coupled annualized load growth and load transfer for the distribution system. The developed ES performs the following tasks:

1-A load growth forecast for each substation area, with the calculation of the associated model parameters using a nonlinear least square estimation algorithm [20].

2-A load transfer process, including descriptors of the expected load transfer to model separation distances, geographical obstacles, saturated corridors, etc.

3-A proposed system expansion plan, with a load transfer process in case of a new substation addition to the system under study.

In addition to the above tasks, the developed ES also includes a method for measuring the goodness of fit of the historical data for each substation. Also a provision that permits adjustments of the individual small areas yearly forecast to meet a specified total area demand is included in the body of the knowledge base. The proposed ES allows the user to observe each substation load growth every year within the defined horizon, and the overloaded substation (if any). When an overload is predicted the ES proposes solutions that can be adopted for relieving that overloaded substation. It also allows the user to interfere during the algorithm execution to update the ES knowledge base or redirect the solution path whenever is required.

This paper is organized as follows. A review of the structure of the proposed ES is given in section II. Mathematical models are developed in section III. The proposed search strategy is depicted in section IV. A typical case study is given in section V. Conclusions and references are given in sections VI and VII respectively.

II. STRUCTURE OF THE PROPOSED ES

A simplified diagram that shows the components of a typical ES is shown in Fig. 1. In the present work, the developed ES is divided into two modules;

(1) A knowledge base

(2) An inference engine and user interface (shell)

The knowledge base comprises the fact and rule bases. It contains information specific to the application considered (load growth, load transfer, substation addition). Details concerning the knowledge base are extended in section IV. The inference engine uses its capabilities to satisfy the examined rules. The inference mechanism operates through forward or backward chaining. The user interface represents the explanatory part that allows the user to interfere with the system.

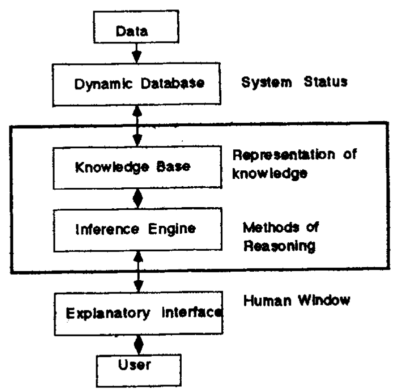

Fig. 1 A Typical Expert System

III. MATHEMATICAL MODELS

The mathematical models [11], [13] for substation load growth and the expected load sharing between substations are summarized as follows

A. Load Growth Model:

The load growth in a small area is not a smooth continuous process. Usually it forms a sharp "burst" of growth taking a few years, resulting in the so called "S" or Gompertz curve [8], [9], [10], [12]. This curve has been shown to adequately model the load growth of urban substations. However, other models are more applicable to particular loads such as industrial substations. The Gompertz model is given by:

$$S(t)=G_A*G_B^{G_C^{t}} \quad (1)$$

where S(t) = function load value for year t. G_A, G_B, G_C are the Gompertz model parameters. In this research, these parameters are calculated for each substation using a nonlinear least square estimation algorithm (Marquardt algorithm [20]). This load growth model allows a considerable flexibility of data fitting. Unfortunately there is no statistical measure which can indicate whether the historical data represent an appropriate base for data fitting or not. Thus it is the user responsibility to select from the input only the historical data that is thought to be representative of future years. A method of measuring the goodness of fit of historical data is implemented. This measure is evaluated by the coefficient of determination R^2 expressed as follows:

$$R^2=\frac{\sum_{T=1}^{N}(S_T-\bar{S})^2-\sum_{T=1}^{N}(S_T-S)^2}{\sum_{T=1}^{N}(S_T-\bar{S})^2}*100 \qquad (2)$$

where T = Years of historical data, N = Number of historical points used and $\bar{S}$ = The mean value for all points. A value close to 100% is indicative of a good fit, whereas a value close to zero is a poor fit. This measure of goodness of fit is evaluated for each substation, and reflects the accuracy level of the forecasted demand.

B. Load Transfer Model:

Load transfer is a function of the distance of separation between substations, age of substations (year of installation), as well as many other factors. A technique similar to Markov process [14], [15], is employed to determine the amount of load transfer between substations. A Weibull distribution ([16] through [18]) is used to model the expected level of load transfer between substations in terms of their separating distances. This model is given by:

$$F(X)=(\frac{W_A}{W_B})(\frac{X-W_V}{W_A})^{W_B-1}\exp(-(\frac{X-W_V}{W_A})^{W_B}) \qquad (3)$$

where F (X) is a function value for a random variable X. W_A, W_B, W_V are the Weibull parameters, which represent statistical functions determined by standard and operational practices. The Weibull distribution allows maximum probability of load transfer at some finite inter-separation distance. Further details of the adopted load transfer may be found in [7], [8]. Other factors that express an estimation of the willingness of substations to share load are considered by the proposed ES through tie factors (see Appendix A). During the execution of the algorithm, these factors can be adjusted by the user to dictate his view of the system updated situation.

C. Substation Forecast Adjustment:

In order to meet the specified total demand of a large area, adjustments of individual substations projections have to be made. After yearly forecast have been predicted for each substation, the diversified sum can be compared to the total large area forecast. If there is no agreement, each substation forecast would be adjusted as follows:

$$ADJS_{iT}=S_{iT}*\frac{TotS_T}{(DF*\sum_{i=1}^{n}S_{iT})} \qquad (4)$$

where; $ADJS_{iT}$ is the adjustment for substation i at year T, S_{iT} is the projected demand for substation i at year T, $TOtS_T$ is the total area projected demand for year T, DF is the diversity factor and n is the number of substations considered.

IV. THE ES SEARCH STRATEGY

The first task performed by the proposed ES is a load growth forecasting for each substation. If a substation is found to approach its maximum loading limit at any year (within the forecasting horizon), one of the following solution alternatives will be proposed:

1. Adding further capacity to the heavily loaded substation.
2. Transferring load to one or more of the neighboring substations that already has an excess capacity.
3. Increasing the overall system capacity by adding a new substation, and in most cases, transferring load as well.

These alternatives are ordered according to their economic feasibility, and are handled using a knowledge base frame of work. However, the choice of the proper alternative will be guided by the user through a proper interface with the ES. The strategy considered for the ES decision making is a depth-first search technique [23]. This technique is illustrated by the representative tree shown in Fig. 2.

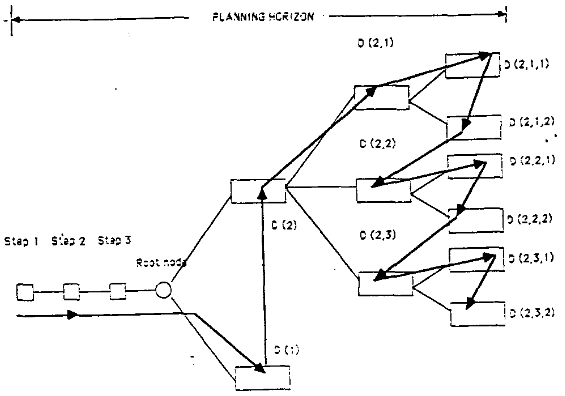

Fig. 2 The Proposed ES Decision Tree

Definitions of the different steps of the search procedure shown in Fig. 2 are summarized as follows.

Step 1: Call data base

Step 2: For each substation calculate the individual load forecast.

Step 3: For each substation check if the load forecast exceeds the specified restricted capacity (RC), where RC is the defined capacity above which the substation is considered overloaded.

D(1): If the load forecast does not exceed RC, then accept the forecast results and continue for the following year.

D(2): If the load forecast does exceed (RC), then one of the following decisions will be proposed:

D(2,1): Expand the capacity of the loaded substation, and modify the data file accordingly if D(2,1,1) and D(2,1,2) are satisfied.

D(2,1,1): The ultimate capacity (UC) is greater then the installed capacity (IC).

D(2,1,2): The system planner accepts D(2,1).

D(2,2): Transfer load to neighboring substations and recalculate the forecast values for all substations using the given load transfer model, if D(2,2,1) and D(2,2,2) are satisfied.

D(2,2,1): The geographical and economical situation allows load transfer.

D(2,2,2): The system planner accepts load transfer.

D(2,3): Suggest the addition of a new substation and modify the data file accordingly and reforecast, if D(2,3,1) and D(2,3,2) are satisfied.

D(2,3,1): The neighboring substations approach critical loading.

D(2,3,2): The system planner accepts D(2,3).

The decision tree shown in Fig.2 is formulated in terms of a number of rules. This is explained in the following subsection.

A. Rule Base for the DSLF

The rule base provides tools for calculating different attributes associated with each planning situation. Some of the rules describing the load growth, load transfer and new substation addition processes are given below.

i) Rules for Load Growth

RULE 1:	
IF	Gompertz model
Then	Call the fact base
AND	Calculate the forecasted load growth for year t
AND	Check overload for each substation
RULE 2:	
IF	Calculate the forecasted load for year t
Then	Call FORTRAN program "Gompertz model"
AND	Check overload for all substations
RULE 3:	
IF	Check overload for each substation
Then	Substation unloaded
OR	Substation loaded

RULE 4:

Substation unloaded
AND Continue check overload for other substations
IF Forecast for each substation < restricted capacity defined for the substation under check

RULE 5:

Substation loaded
AND Check possibility of capacity addition
IF Forecast for that substation > RC

RULE 6:

IF Check possibility of capacity addition
THEN Additional capacity
OR No possible addition

RULE 7:

Additional capacity
AND Increase IC to UC
AND Modify data files
IF It is possible to increase IC
AND Planner decision is YES
AND More economic additional capacity

RULE 8:

It is possible to increase the IC IF
Call the fact base
AND $IC_i < UC_i$

RULE 9:

More economic additional capacity IF
Not more economic load transfer
AND Not more economic installing new substation

RULE 10

No possible addition
AND Check load transfer possibility
IF Not possible to add capacity
OR Planner decision is NO
OR Not economic

ii) Rules for Load Transfer to Neighboring Stations:

RULE 11:

Check load transfer possibility to neighboring substations
AND Forecast using transfer model
IF Loaded substation
AND No possible addition
AND Planner decision

RULE 12:

Planner decision
IF Call user interface
AND No obstacles
AND Neighboring stations are neither of same age, nor approach their critical loading

RULE 13:

IF Forecast using transfer model
THEN Use Markov transfer model, call the FORTRAN program

iii) Rules for Installing New Substations

RULE 14:

Add a new substation
AND Recalculate the forecast, taking this into consideration
IF Loaded substation
AND Neighboring substations introduce growing loads approaching critical loading
AND No possible additions
AND No possible load transfer
AND Economic installing a new substation

RULE 15:

Neighboring substations introduce growing loads approaching critical loading IF Forecasting values are not within the restricted capacity

RULE 16:

Forecasting values are not within the restricted capacity IF
Gompertz model
OR Markov transfer model forecasting
AND Loaded substation

RULE 17:

Economic installation of new substation IF
Cost of installation can be reduced
OR Load transfer and other overload relieving methods are not more economic

V. A CASE STUDY

The proposed interactive load forecasting of distribution systems load growth and load sharing methodology handled by the proposed ES is applied to Alexandria City, 66/11 KV power distribution network. The given system consists of 27 substations. Some of these substations may share load, according to the assigned tie relation parameters(see Appendix A). Each substation is set to shift load to other substations when its forecasted load exceeds the prescribed restricted capacity. The load forecast calculations are presented for 10 years, following to year 1993 as a base year. A diverse sample of results are presented. Table 1 summarizes data for each substation [22]. To show the accuracy of the results, Table 2 depicts the load forecast for 1993, compared with the given actual load values. A small and practically permitted overload is indicated at substation # 2 for that year. Table 3 presents the forecasted load for year 1997. In this year the overload at substation # 2 increases to 4.1664 MVA. Since the tie factors of that substation with all neighboring ones are set to be 100, then the ES reasoning proposes an addition of a new transformer (1 X 25) MVA to that substation. Meanwhile overloads of 2.5809 and 0.02595 MVA are indicated at substations # 11 and 24 respectively. If the first proposed reasoning is accepted then capacities of substations # 11 and 24 would be raised to their ultimate values (50 and 35 MVA) respectively. Doing so, the indicated overloads would be relieved. However, if that proposal was rejected by the user (system planner), then the ES would suggest transferring the overload to neighboring substations. The forecasted values after load sharing takes place are given at the last column of Table 3.

Results of previous tables indicate that substations # 24, 25, and 27 are subject to rapidly growing loads. Adding an extra 25 MVA transformer units to those substations to increase their capacities to 100 MVA each will help in overcoming the overloads only until year 2003. Results of the forecasted load for year 2003 are shown in Table 4. The highly growing loads depicted in Table 4 direct the ES to propose the installation of a new 100 MVA substation, and initiating a load transfer as well. The resulting load forecast values at that stage, with the new added substation (substation #28), are given by the last column of Table 4. It is clear that no overloads are indicated after the new substation addition.

TABLE 1
Specifications of Alexandria City 66/11 kV Distribution Network

Substation No.	IC (MVA)	UC (MVA)	Installation Year	GA	GB	GC
1	50	75	1990	10.817	0.191	0.7757
2	10	10	1966	479.370	0.0017	0.9812
3	75	100	1987	621.476	0.1260	1.0213
4	75	100	1985	398.866	0.1201	0.9908
5	25	25	1989	16.634	0.8705	0.1952
6	75	100	1990	57.771	0.8581	0.5410
7	75	100	1980	275.781	0.1516	0.9927
8	50	75	1990	20.843	0.2452	0.3240
9	75	100	1982	272.825	0.1370	0.9883
10	30	50	1986	304.652	0.0823	0.9969
11	25	50	1990	48.850	0.2871	0.8944
12	75	100	1990	39.540	0.3157	0.4920
13	60	80	1969	135.180	0.2451	0.9954
14	50	75	1990	26.246	0.2307	0.4606
15	75	100	1977	8190.16	0.0132	1.0193
16	75	100	1988	527.84	0.1095	1.0083
17	75	100	1982	242.054	0.0809	0.9960
18	75	100	1986	60.918	0.0551	0.8866
19	75	100	1983	171.514	0.0267	0.9558
20	30	40	1964	182.654	0.0002	0.9642
21	25	50	1986	21.165	0.0000	0.2398
22	25	50	1986	63.120	0.0811	0.9630
23	25	50	1990	551.280	0.0101	0.9636
24	25	35	1977	0.068	10.282	1.0475
25	75	100	1988	5.406	2.2084	1.0956
26	25	50	1988	4.247	0.7061	0.1815
27	25	50	1983	0.540	3.2983	1.0808

TABLE 2
Forecast Values for Year 1993

Substation No.	RC. (MVA)	Loadforecast (MVA)	Overload (MVA)	actual capacity (MVA)
1	50	5.000	0.0	5.0
2	10	10.730	0.730	11.0
3	75	62.172	0.0	62.0
4	75	56.473	0.0	57.0
5	25	16.633	0.0	16.0
6	75	56.388	0.0	54.0
7	75	49.607	0.0	45.0
8	50	19.862	0.0	18.0
9	75	47.525	0.0	48.0
10	30	26.465	0.0	25.0
11	25	20.000	0.0	20.0
12	75	34.467	0.0	32.0
13	60	38.396	0.0	34.0
14	50	22.742	0.0	23.0
15	75	26.576	0.0	27.0
16	75	52.639	0.0	52.0
17	75	21.795	0.0	22.0
18	75	17.482	0.0	16.0
19	75	17.115	0.0	17.0
20	30	10.779	0.0	10.0
21	25	21.155	0.0	20.0
22	25	9.165	0.0	10.0
23	25	9.044	0.0	7.0
24	25	9.196	0.0	6.0
25	75	18.88	0.0	18.0
26	25	4.247	0.0	4.0
27	25	7.260	0.0	5.0

TABLE 4
Load Forecast for Year 2003

Substation No.	Load Forecast (MVA)	Final Overload (MVA)	New RC (MVA)	Load Forecast After Transfer
1	10.17	0.0	50.0	11.664
2	20.69	0.0	35.0	20.695
3	72.73	2.737	70.0	70.000
4	72.77	0.0	75.0	73.130
5	16.63	0.0	25.0	16.636
6	57.76	0.0	75.0	58.084
7	55.96	0.0	75.0	56.271
8	20.84	0.0	50.0	20.842
9	57.62	0.0	75.0	57.620
10	28.50	0.0	30.0	28.504
11	36.45	0.0	50.0	36.452
12	39.53	0.0	75.0	39.536
13	40.63	0.0	60.0	40.636
14	26.24	0.0	50.0	26.244
15	18.31	0.0	75.0	18.315
16	43.11	0.0	75.0	43.113
17	23.91	0.0	75.0	23.918
18	41.87	0.0	75.0	41.876
19	39.56	0.0	75.0	78.463
20	25.59	0.0	30.0	59.059
21	21.16	0.0	25.0	21.165
22	16.78	0.0	25.0	16.789
23	32.28	0.0	50.0	32.285
24	166.93	66.936	100.0	100.000
25	122.06	22.066	100.0	100.000
26	4.24	0.0	25.0	4.247
27	154.18	54.185	100.0	100.000
28	—	0.0	100.0	70.799

TABLE 3
Forecast Values for Year-1997

Substation No.	RC (MVA)	Load Forecast (MVA)	Overload (MVA)	New. Capacity (MVA)	Forecast after load transfer
1	50	8.185	0.0	0.0	8.185
2	10	14.166	4.166	35.0	14.166
3	75	66.294	0.0	0.0	66.704
4	75	62.749	0.0	0.0	62.749
5	25	16.636	0.0	0.0	17.165
6	75	57.651	0.0	0.0	57.651
7	75	52.112	0.0	0.0	52.112
8	50	20.831	0.0	0.0	20.831
9	75	51.470	0.0	0.0	51.745
10	30	27.270	0.0	0.0	27.525
11	25	27.580	2.580	0.0	25.000
12	75	39.223	0.0	0.0	39.223
13	60	39.289	0.0	0.0	39.289
14	50	26.077	0.0	0.0	26.077
15	75	23.027	0.0	0.0	23.440
16	75	48.695	0.0	0.0	48.685
17	75	22.630	0.0	0.0	22.630
18	75	28.164	0.0	0.0	28.164
19	75	25.056	0.0	0.0	26.334
20	30	15.826	0.0	0.0	16.084
21	25	21.165	0.0	0.0	21.165
22	25	12.003	0.0	0.0	12.003
23	25	15.930	0.0	0.0	15.930
24	25	25.025	0.025	35.0	25.025
25	75	32.781	0.0	0.0	32.781
26	25	4.247	0.0	0.0	4.2437
27	25	18.732	0.0	0.0	18.732

VI. CONCLUSIONS

An ES that implements an efficient, comprehensive, and interactive load forecasting plans for distribution systems has been developed in this paper. The proposed ES provides an input to long-term planning issues, with the capability of adjusting the individual substation load forecast according to a reliable total load area forecast. It is the authors view point that the best distribution systems planning results would be achieved if an on-line programming "link" is handled by the proposed expert system to combine daily & monthly forecasting programs with the long-term one. Further research is also expected to include the optimal sizing and locations of the newly added substations in the knowledge base of the proposed ES.

VII. REFERENCES

[1] J. E. D. Northcode-Green, "Comparison tests of fourteen distribution load forecasting method," IEEE Trans. power Apparatus and Systems, Vol. AS-103, No. 6, June 1984, . 1190-1197.

[2] H. L. Wills, "Load forecasting for distribution planning-error and impact on design," IEEE Trans. power Apparatus and Systems, Vol. AS-103, No. 3, March 1984.

[3] H. L. Wills and J. E. D. Northcode-Green, " Spacial electric load forecasting: A tutorial review," proceedings of IEEE, Feb. 1983.

[4] "Research into load forecasting and distribution planning," EPRI report El-1198, Electric power Research Institute, Palo Alto, CA 1979.

[5] J. A. Morris, "Optimization of power line conductor through the use of computerized feeders network program." proceedings of 10th Annual Modeling and Simulation conference, Pittsburgh, April 1979.

[6] H. A. Smolleck and K. C. Kim, " An interactive distribution load forecasting methodology for minicomputer use based upon a Markov type process," IEEE Trans. power Systems, Vol. 3, No. 1, . 52-59, Feb. 1988.

[7] H. L. Wills, R. W. Powella, and D. L. Wall, "Load transfer coupling regression curve fitting for distribution load forecasting," IEEE Trans. power Apparatus and Systems, Vol. AS-103, No. 5, May 1984.

[8] K. D. C. Stoodley, T. Lewis, and C. L. S. Stainton, Applied Statistical techniques, John Wiley & Sons, 1980.

[9] E. Vennard, Management of the Electric Energy Business, 2ed ed., New York : Mc Graw-Hill Book company.

[10] E. Vennard, The Electric power Business, 2nd ed. New York : Mc Graw Hill Book Company, 1970.

[11] R. L. Sullivan, Power System Planning, New York, Mc Graw-Hill Book Company, 1977.

[12] C. Derman, A Guide to Probability Theory and Applications, Holt, Rinehart and Winston Inc., 1973.

[13] "Research into load forecasting and distribution planning", EPRI Report EL-1198, Vol. 1,2,3, Westinghouse Electric Corporation, August 1980.

[14] M. Iosifesca, Finite Markov process and Their Applications, John Wiley & Sons, 1980.

[15] D. L. Isoascn, Markov Chains : Theory and Applications, John Wiley & Sons, 1976.

[16] L. R. Kirk, "Technical study summary, substation planning program SUBLO", El Paso Electric Company, El Paso, Texas, November 2, 1978.

[17] H. A. Smolleck, "A new distribution system load prediction methodology and analytical methods for distribution system planning and operation," Final Report to El Paso Electric Company, 1982.

[18] Springer, Herlinty and Beggs, Mathematics for Management Series, Irwin, 1965.

[19] E. Masud, " An interactive procedure for sizing and timing distribution substations using optimization techniques," IEEE Trans. power Apparatus and Systems, Vol. AS-93, september/October 1974, . 1281-1286.

[20] D. W. Marquardt, "An algorithm for least squares estimation of nonlinear parameters,"Chem. Eng. progr., 55 (1959), No. 6, .65-70

[21] D. marcelli, Expert System programming in Turbo PROLOG, technical Science center, Tarryton, New York, 1989.

[22] Egyptian Electric Authority EEA, Egyptian Ministry of Electricity and Energy. The Annual Electrical Statistics, 1990.

[23] S. Rahman and M. Lauby, "Expert systems and their role in power system planning, "Proc. EPRI Conf. on ES Applications for Electric Power Industry, Boston, MASS, September 1991.

APPENDIX A

The tie relationship factor between substations i,j is a subjective value and is determined by the system planner. This factor reflects the presence or absence of an available interconnection between the two concerned substations. The value of T_{ij} is assigned to one of the following values:

T_{ij} = 1 for normal situation. A normal situation implies the existence of a direct interconnection between the two substations, no geographical obstacles, no difference in voltage levels, and non of the two substations has a rapidly growing loads.

T_{ij} = 3 for a low possibility of load transfer. This implies that the interconnection between the two substations is not direct (i.e. if the interconnection asses through a third substation).

T_{ij} = 100 for no possibility of load transfer. This implies that the two substations are not interconnected at all, or there exists geographical obstacles or difference in voltage levels between substations, or load is growing rapidly in one of the two substations feeding areas so that it can not afford any extra transferred load.