RELIABILITY AND PATTERN RECOGNITION TECHNIQUES
IN POWER SYSTEM SECURITY STUDIES

A Thesis

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requirement for the degree of
DOCTOR OF PHILOSOPHY (ENGINEERING)
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by

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Dedicated to my Parents:

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CERTIFICATE

This is to certify that the thesis entitled 'Reliability and Pattern Recognition Techniques in Power System Security Studies', submitted by Shri B.K. Dasgupta for the award of the Ph.D. Degree of the Institute embodies original work done by him under my supervision.

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B.K. Dasgupta

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ABSTRACT

This thesis has critically examined, compared and developed three approaches to power system security assessment viz. security indices through Markovian approach, fault tree analysis and pattern recognition techniques. The proposed security indices based on load shedding and voltage fluctuation are a distinct improvement over Patton's security index. Suitable computer logic is developed to identify the buses at which load is to be shed and the amount of load shedding. The use of the indices are illustrated through a planning problem. Fault tree analysis is applied for the first time in computing a reliability figure at nodes of an interconnected power system. In search for alternatives pattern recognition technique is explored to identify power system state - insecure or secure class. Four techniques, two based on deterministic and the remaining on statistical approaches are studied and compared with regard to their suitability to recognise power system patterns. The statistical technique with estimated pdf is found to be the most suitable. The use of pattern recognition is demonstrated by computing kvar injection necessary for a kvar deficient system.

A link between pattern recognition technique and security index is established and a global security index is proposed.

Chapter-I

INTRODUCTION:

1.1 GENERAL INTRODUCTION:

Ultimate objective of power system control is to maintain continuous electric supply of acceptable quality by taking suitable measures against a set of probable disturbances both at planning and operation stages.

Various aspects of large scale disturbances should be considered during the planning stage itself. While planning for future expansion of the system, a suitable configuration should be worked out such that generation and transmission capacities are sufficient to meet the expected demand in future. To ensure system security, it is necessary to perform a number of security related studies which can be grouped as long term planning, operational planning and on-line operation. Thus security assessment problem is of great significance to an electric utility system and has naturally received a wide attention amongst the power system analysts. The present thesis examines this problem critically and exhaustively and brings to bear upon it some of the latest techniques of reliability assessment.

1.2 OUTLINE OF THE THESIS:

Chapter II begins with a critical review of reliability models and security assessment. A suitable reliability model of standby generator is then devised which has been used extensively in the thesis to compute power system security alongwith the two-state model of normally operating generators. Further, a modification is incorporated in terms of load dependent failure rate in the two-state model. The chapter then goes on to review the existing literature on security assessment wherein load and voltage indices are used for this purpose. The problem, however, becomes highly complex when transmission lines are involved, because repeated load flow solutions under contingency are necessary.

The author in this thesis has proposed modified load security index which is applicable both from global and local bus point of view. Voltage security index is calculated after load security index and is found to be meaningful from local point of view only. These indices represent a step forward from the Patton's security index. In Patton's model for security, the state probability is weighted by a factor Q, which for a deterministic load takes a value of one when a state results in a breach of security. This leads to a higher estimate of risk involved, as in practice load is shed by a certain percentage to improve the state of the system under contingency. The proposed load security indices recognise this fact by introducing a weighting factor which accounts for the load shedding under contingency. To speed up the solution d.c. load flow for active and reactive power has been adopted. Suitable computer logic is developed to discover the quantum of load shedding needed and its proper location.

The use of load security indices have been demonstrated in planning problem for a 6-bus power system.

After the computation of load security indices, the voltage profile of the system is scanned. In case any bus voltage is found higher than the desired value, the reference voltage of the slack bus is reduced and load flow is recomputed. Using the results of the bus voltages obtained from load flow solution the voltage security index is computed at each bus. Whenever the value of the index becomes more than the specified limit, necessary amount of local kvar injection is found out by using precalculated sensitivity matrix.

Of late fault tree analysis has been used extensively in reliability literature. In chapter III this technique is adopted for the first time to the author's knowledge to compute probability of failure to meet a load demand in a power system. During the process of adoptation a simple radial problem is attempted wherein load flow is obvious. Later the technique is extended to a 3-bus system where load flow calculations become necessary to identify possible failure modes. Suitable computer programme is developed to translate fault tree into reverse polish expression and finally to Boolean failure function comprising terms which are generally not disjoint. A modified algorithm is then worked out to convert this function to a set of disjoint terms facilitating the probability evaluation. Compared to Bennett's approach the present algorithm needs less computation time and storage.

Improvement of this method over Markov's technique to assess reliability is then argued. It is noted that the fault tree has to be generated manually for a given system, but once a tree is formed only minor modifications are necessary when the system configuration is changed.

While the previous chapters have advanced security index and fault tree methods of power system reliability evaluation, chapter IV is devoted to adoptation of pattern recognition techniques to distinguish between secure and insecure states of a power system by means of decision surfaces. These techniques have recently attracted the attention of some power system analysts. The chapter starts with a survey of pattern recognition techniques. There is a multiplicity of techniques mostly heuristic available in the pattern recognition literature. Basically all techniques attempt to evolve a hyperplane or nonlinear surface, termed decision function, in order to separate the pattern classes. The weight vector of a decision function is either generated through iterative process or by directly exploiting some statistical properties of the labelled patterns. These patterns, known as training set, are generated by adjusting load level at various buses along with equipment outage for each load. The elements of a pattern vector, which together constitute a state of the power system, are magnitude and phase angle of bus voltages, total active and reactive power losses, total active and reactive power reserve, total active and reactive load, etc. Four powerful techniques - two based on deterministic and other two on statistical approaches, are then studied in detail for their suitability to recognise power system patterns. Decision functions determined by these methods are then compared on the basis of execution time, storage requirement and classification efficiency. Decision functions thus found can be suitably used for on-line and off-line classification of the power system patterns.

While the pattern recognition techniques have great potential for on-line studies their use is illustrated in this thesis for a specific off-line planning problem wherein quantum and location of kvar injection are determined for a kvar deficient system. In tackling this, the statistical technique which is the most efficient for power systems is used.

In a later part of this chapter Patton's security index and the decision surface, obtained from statistical approach to pattern recognition technique, are combined to evolve a global security index for a complex power system. This index is more powerful because the decision surface has the ability to sense the total health of the power system.

Chapter-II POWER SYSTEM SECURITY THROUGH INDICES.

2.1 INTRODUCTION:

Power system security assessment is a problem of great practical importance. It is, therefore, quite natural that it has attracted a great deal of research efforts during last two decades (9,10,16,19,25,36,43, 44,45,56,82,85,87,92,96,100,103,117). The above work may be grouped into two types - (a) optimal secure load flow or rescheduling of flow considering security as constraint, (b) projecting system security by means of one or more quantitative indices. While probability approaches had been used (117) earlier for capacity planning requirement, Descieno(116) was first to apply Markov process in evaluating reliability of series-parallel cascaded power system. It was as late as the year 1972 that Patton (43) extended the Descieno's approach to formulate for the first time quantitative indices for evaluating steady state security. In this chapter this work has been further extended through formulation of modified security indices.

During the course of the evaluation of these indices outages of lines and generators which transfer the power system from one state to other have been simulated. Because of the random nature of these outages the transference can be viewed as discrete state continuous time stochastic process. The state residence probabilities are determined by appropriate choice of reliability models of generator and transmission lines. Many models (8,25,32,34,38,44,45,68,74,80,81,89,97) are available in the literature. Apart from the calculation of the state probabilities, repeated load flow solutions are necessary for each contingency. This chapter begins by critical review of some reliability models of normally operating and standby generators, and then goes on to reveal some models developed by the author along with the necessary computation algorithms.

2.2 RELIABILITY MODELS FOR GENERATORS AND TRANSMISSION LINES

Review Of Existing Reliability Models:

Generator and transmission lines during their scheduled operation often meet chance outages. This is aptly described by the two-state model to obtain the probability of existence in any state. While doing so it is assumed in many cases (68,74,81,89,97,116,117) that these probabilities can be found by exploiting first order Markov process. Rigorous approach to this process takes considerable time and computer memory for large systems. Several approximation techniques were developed of which frequency and duration approach, initiated by R.J. Ringlee (97) in 1968, gained importance in the power systems reliability literature (50,51,68,69,89).

Economics and technological development have dictated the utilisation of large capacity generating units. Present day steam power plants can have single unit rating in the order of 1000 MW. Such a unit may require multi boilerturbine construction and a large number of auxiliary equipment and therefore, in general, steam power plants of large capacity may have partial outage (derated) states. This is because a unit may not be able to develop rated capacity due to outages of some auxiliary components. This was first accounted for in the reliability model of generating unit by Bigger-staff (80) in 1969 and used later by several others (32,35,44,50,68).

Generation reliability model is relatively small part of a bulk power system security problem. In this present thesis the two-state model based on exponentially distributed available and down states has been adopted. However, load dependent failure rate has been incorporated in the model.

Basic Two-State Model:

The two states: up i.e. fully available and down i.e. unavailable due to forced outage, in which a unit can reside shall be treated as a Markov process. The only practical approach to the computation of state i.e. residence probabilities in a large system is to assume that the components, scheduled for operation, fail and get repaired independent of each other. This assumption means that the probabilities of component states can be computed independently, then multiplied together as appropriate to yield the entire system state probabilities.

Suppose a system has n generators which behave independently of each other. State space diagram of any such unit is shown in fig. 2.1. It is assumed that the residence time of both the states is exponentially distributed. Probability of finding ith generator in the up or the down state at any given time t, provided it is initially at the operating state, is given as

$$p_{upi}(t) = \frac{c_i}{c_i + a_i} + \frac{a_i}{c_i + a_i} \cdot e^{-(c_i+a_i)t} \qquad (2.1)$$

$$p_{dni}(t) = \frac{a_i}{c_i + a_i} - \frac{a_i}{c_i + a_i} e^{-(c_i+a_i)t} \qquad (2.2)$$

where:

a_i = failure rate of unit i

c_i = repair rate of unit i

Typical state probability of the system consisting of n number of generators alone can be found as follows:

$$P_i(t) = \prod_{j \in A} p_{dnj}(t) \prod_{k \in B} p_{upk}(t) \qquad (2.3)$$

where:

A = set of generators which are down in state i.

B = set of generators which are up in state i.

The time dependent probabilities in eqns. (2.1) and (2.2) settle to steady state values practically at the end of a

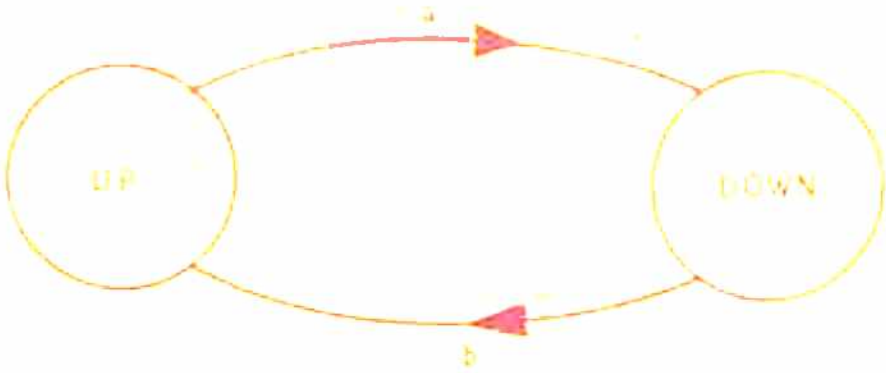


FIG. 2.1 TWO-STATE RELIABILITY MODEL OF A UNIT WITH CONSTANT FAILURE AND REPAIR RATE.

time given by

$$T = \frac{5}{c_i + a_i} \tag{2.4}$$

Usually repair rate of a unit is much higher compared to its failure rate during its useful life. Typical data of failure and repair rates are 8×10^{-4}/hr. and 8×10^{-2}/hr. respectively. These make the value of T to be about 62.5 hrs. Naturally any reliability study which involves larger time than T i.e. studies pertaining to planning type, eqns. (2.1) and (2.2) may be modified to consider only the steady state part as given below:

$$p_{upi} = \frac{c_i}{c_i + a_i} \tag{2.4}$$

$$p_{dni} = \frac{a_i}{c_i + a_i} \tag{2.5}$$

Failure of a machine being depended upon loading conditions, certain discrete failure rates are assumed depending on the load levels of generators. This needs the further revision of eqns. (2.4) and (2.5) to the extent of replacing proper value of failure rate at the proper load level. It is clear that the load distribution among the generator must be known apriori. For this purpose the author has adopted the work of reference 16 to obtain a unit commitment table for all load levels on economic basis. This also provides the economic loading of individual generator.

Reliability Model of Standby Generator:

Methods for modelling standby generators vary considerably depending on the security assessment method used. Unlike the normally operating generators the two-state model is not applicable in this case. This is because the standby generators are called upon to serve only in case a normally operating generator is not available, or when peak load is to be shared between these two types of generators. Thus for a larger portion of time a standby generator is kept in a state which may be called as ready for operation or reserve shut down. This state is different from the forced outage state of a two-state model or scheduled outage i.e. planned maintenance. A few papers (34,38,45,74) have been reported which deal with standby generator model. These may be classified as Markovian and non-Markovian models, each of which are discussed critically here followed by a proposed model which has been used to assess the security indices.

Models Based On Markov Process (34,38):

The state space diagram of this type of model is given in fig. 2.2. The four states identified are: (1) in operation, (2) ready for service (3) fail to start, (4) failed. It has been clearly indicated (38) that the

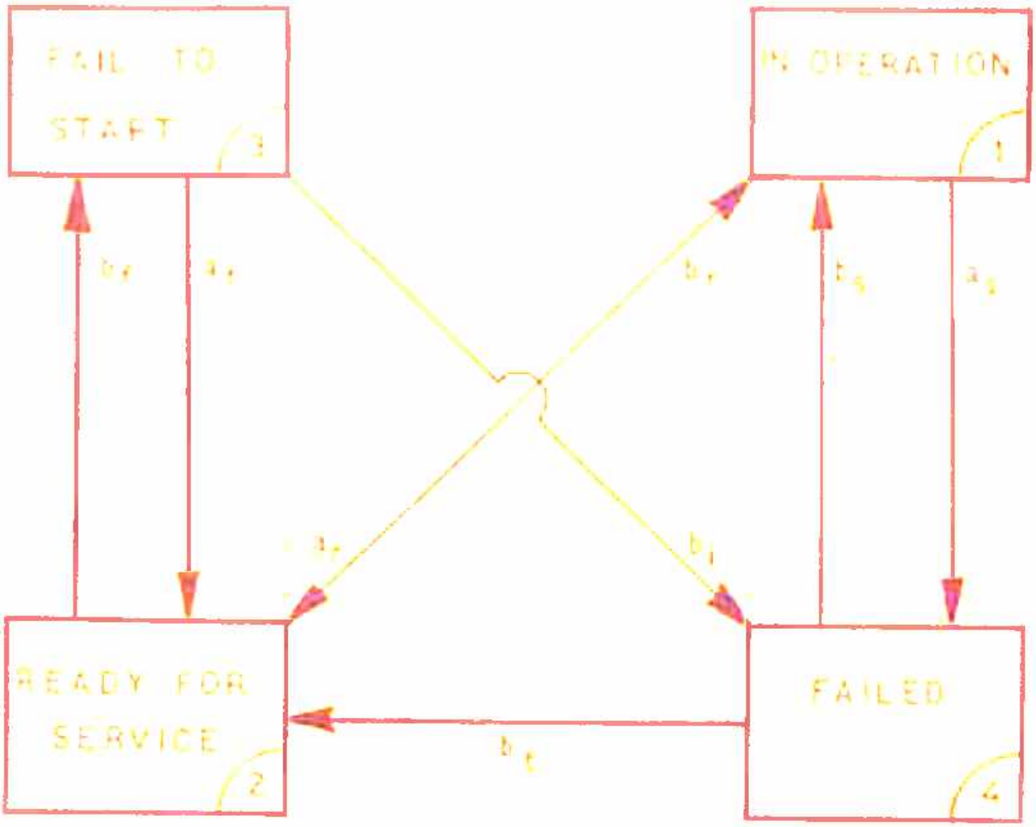


FIG. 2.2 STATE TRANSITION DIAGRAM FOR RAPID START STANDBY UNIT.

transition rates from one state to the other can be obtained from field data.

This model, though convenient computationally, is not suitable for high-starting time cold reserve standby unit. Moreover, the duration of the state 3, i.e. fail to start being very small its probability of occurence is practically zero, and hence this state can be neglected.

Patton's Model (45):

This is basically a two-state model, with the residence time in the repaired state distributed non-exponentially, given by Weibull. This model takes into account probability of starting failure. Starting time has been considered to be zero for hydro or gas turbine driven generators and constant but non-zero or a Weibull distributed random starting time for steam turbine driven generators. With the help of certain numerical approximation introduced in an earlier paper (44) by him, final state probabilities are found out. Joint probability of finding normally operating generator in ith state and standby generator in jth state has been found out by assuming the events are statistically independent. For a three-state model of normally operating generator and two-state for the standby, total number of combined states becomes 6. This in general is the product of i and j.

Analytical solution becomes exceedingly time consuming and tedious for these models because of non-exponential distribution of downtime. The method of 'device of stages' has been successfully used (32) to tackle non-exponential distribution of repair duration. The two-state model is basically inadequate to characterise a standby set. The assumption made by the author of reference (45) that the standby generator can be considered dependent upon the behaviour of one normally operating generator at a time is also contrary to real life. In general, a given standby generator usually backs up more than one normally operating generators. As assumed, the state of standby equipment is not entirely dependent on the state of normally operating components in the system. The load model also influences this.

Three-State Standby Model - Author's Model:

An alternative model of a standby generator is proposed here which is simpler than the Patton's model from the point of view of computation because the resident time is assumed to be exponentially distributed. Moreover, the probability of starting failure is considered which makes the model more powerful compared to Billinton's. The state space diagram of this model is shown in fig. 2.3, which shows reserve shutdown (when the standby generator is kept ready in a cold state waiting to be called for service), inservice and forced out during need to be

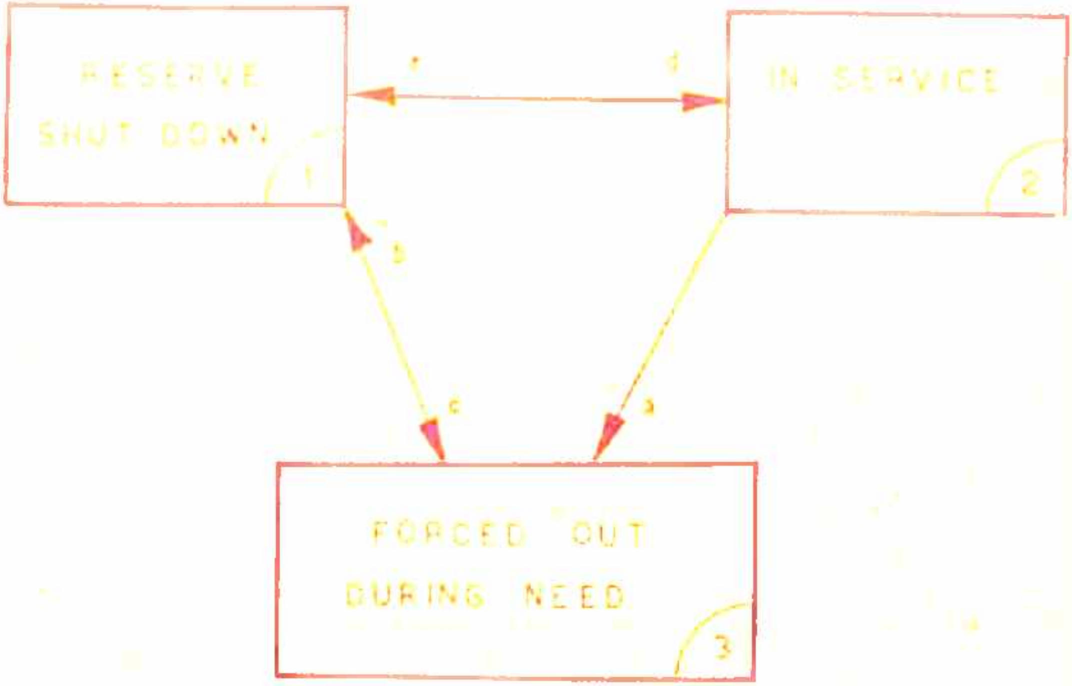


FIG. 2.3 STATE TRANSITION DIAGRAM FOR THE PROPOSED STANDBY UNIT.

the three different states. Transition rates are considered to be constant. These can be estimated from the field data and are expressed as:

$$a = \frac{1}{M}$$

$$b = \frac{1}{R}$$

$$c = \frac{P_s}{S}$$

$$d = \frac{1 - P_s}{S}$$

$$e = \frac{1}{D} \qquad (2.7)$$

where:

M = Average in service time per occassion of forced outages.

R = Average period of forced outage during off-peak load.

S = Average duration of reserve shut down state between periods of need excluding maintenance duration.

D = Average inservice time per occassion of demand.

P_s = Probability of starting failure.

As the total duration of the standby generator's requirement is short, the transition probability from state 3 to 2 is neglected. Possible reasons of transition from state 1 to state 3 are:

1. Standby generator fails to start or synchronise because of certain defects developed in some of the auxiliaries.

2. Time to synchronise is considered to be longer than expected.

In both of the above cases there is a definite risk that system load may not be met.

From fig. 2.3 using Chapman-Kolmogorov equation the following difference equations may be written to obtain the probability of occurence, of any state at a given time $t + \Delta t$.

$$p_1(t+\Delta t) = (1-c-d)p_1(t) + ep_2(t) + bp_3(t) \qquad (2.8)$$

$$p_2(t+\Delta t) = dp_1(t) + (1-e-a)p_2(t) \qquad (2.9)$$

$$p_3(t+\Delta t) = cp_1(t) + ap_2(t) + (1-b)p_3(t) \qquad (2.10)$$

The above difference equations are solved through Euler's technique as the standby unit operates for a smaller portion of time. Obviously a trade-off is made between accuracy and computation time. These time dependent state probabilities attain steady state for many of the planning problems because of larger time. In this model because of the constant nature of the state departure rates these can be easily obtained. However, it is necessary here to introduce a minor modification in the form of an additional transition rate from the field data pertaining to the mean repair duration between the periods of need, i.e.

$$f = \frac{1}{L} \qquad (2.11)$$

where:

L = average repair duration between the period of requirement.

To obtain the steps outlined eqns. (2.8) to (2.10) can be converted into three differential equations where the first derivative of the state occurence probabilities, these are replaced by zero to obtain the following set of linear algebraic equations

$$\begin{bmatrix} -(c+d) & e & b \\ d & -(e+a) & f \\ c & a & -(b+f) \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \qquad (2.12)$$

Any two of the above eqn. (2.12) along with

$$p_1 + p_2 + p_3 = 1$$

can be solved to yield the steady state probabilities. These are given in eqns. (2.13) to (2.15).

$$p_1 = (bd + fc + fd)/Z \qquad (2.13)$$

$$p_2 = (ba + be + fe)/Z \qquad (2.14)$$

$$p_3 = (ac + ad + ec)/Z \qquad (2.15)$$

where:

$$Z = ac + ad + ab + ec + eb + fc + fd + fe + bd$$

Illustration:

For illustrating the contribution of starting failure probability incorporated in the standby generator model, security of a generating system is calculated for a given load pattern of eight hour duration. It is assumed that the standby generator be available to help the normally operating generators during the peak load period. Patton's security model is adopted here to calculate the security of the given system. The state probability, necessary for this purpose, is calculated from the following equation:

$$P_k(t) = P_i(t).\ PS(j,T) \qquad (2.16)$$

$$j = 1,2,3.$$

where:

j = The total number of states generated by the normally operated generators.

k = Entire system states produced because of the combination of normally operating generator and standby generator.

T = Time during which standby is required and is zero at the instant of starting of this unit.

During the off peak period k will be equal to i but will increase by three times when standby unit is called upon. Load dependent failure rate with exponential up and down model is used to calculate P_i.

For the sample problem various input data necessary are listed in table 2.1 and 2.2. The system load curve is given in fig. 2.4. The security of the generating system is plotted in fig. 2.5. On scrutinising this graph it has been observed that the security function increases considerably when probability of starting failure is considered. The additional risk involved in the improved model needs to be accounted for in the power system planning and operational studies.

TABLE 2.1: INPUT DATA OF NORMALLY OPERATED GENERATOR

Generating Unit	Status	Failure rate/hr. Light load	Heavy load	Repair rate per hour
150 MW	Normally operating.	0.0017	0.0035	0.025
100 MW	- do -	0.0015	0.003	0.045
60 MW	- do -	0.002	0.004	0.015

TABLE 2.2: INPUT DATA OF STANDBY UNIT

Unit	P_s	S	D	M
60 MW	0.02	18.00 hrs.	4.0 hrs.	99.0 hrs.

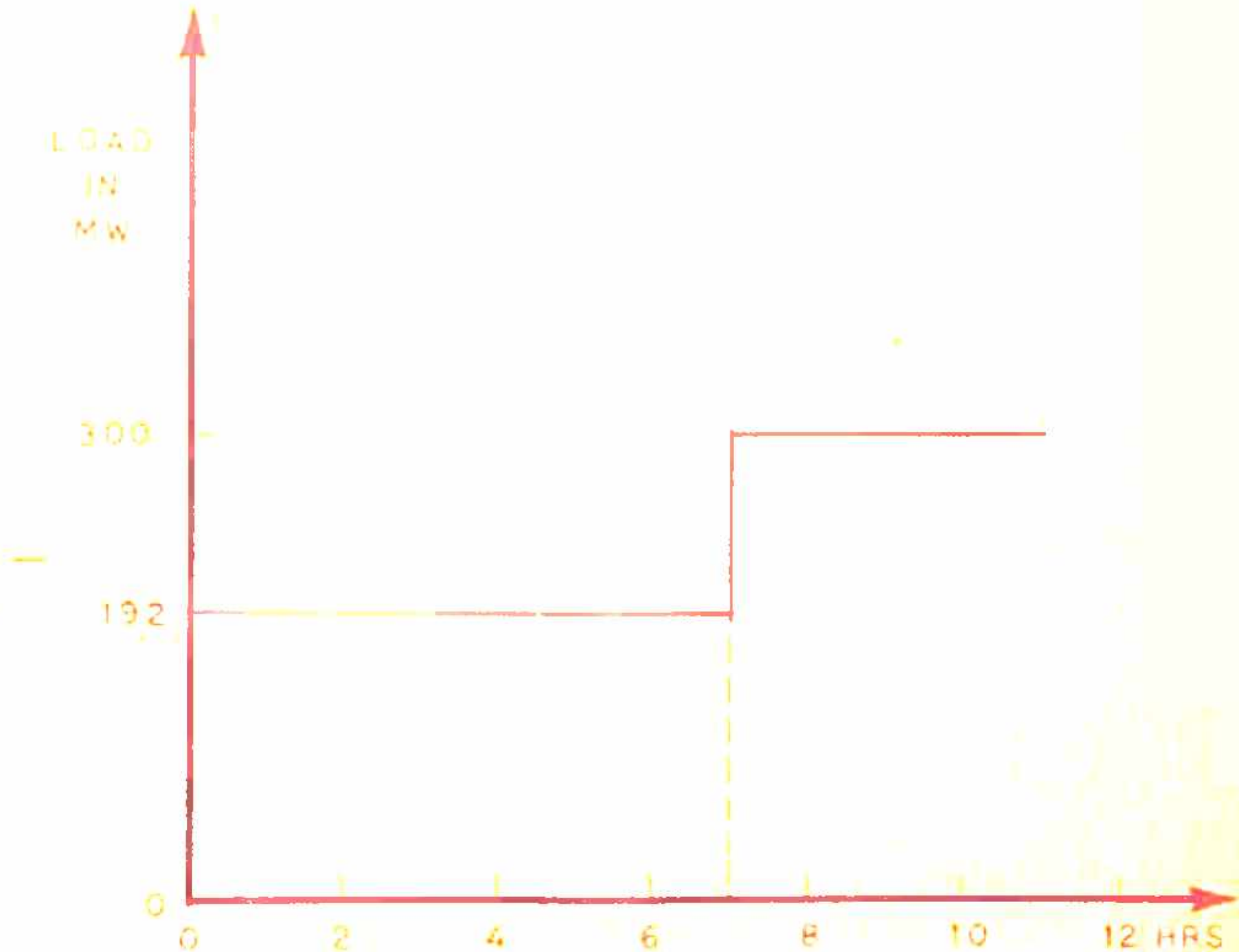


FIG. 2.4 LOAD CURVE

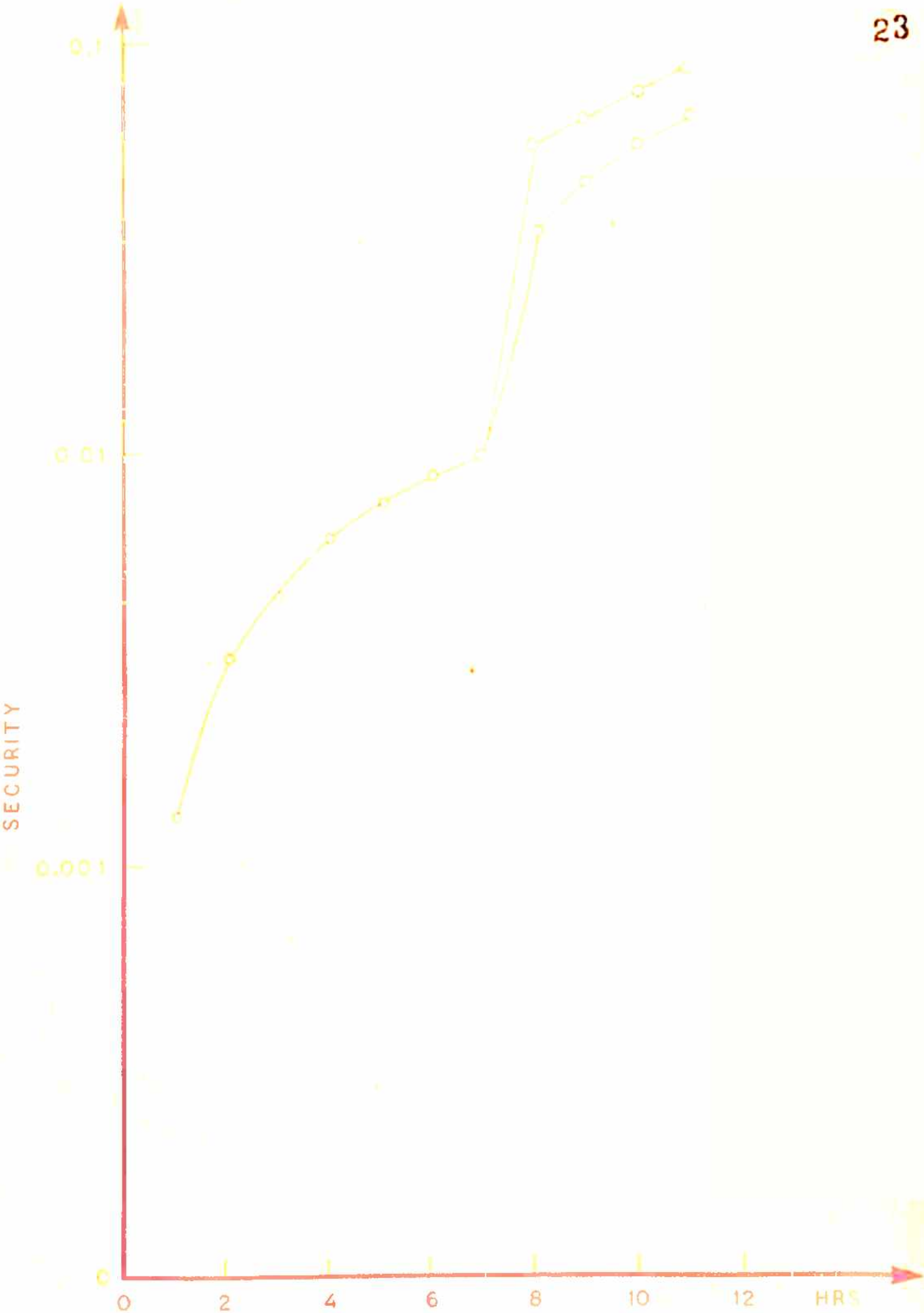


FIG. 2.5 SECURITY FUNCTION OF COMBINED NORMALLY OPERATING AND STANDBY GENERATORS.

2.3 SECURITY ASSESSMENT:

Review Of Earlier Work:

Power system, in India are getting rapidly interconnected. Though interconnected operation is advantageous in many respects, it also creates problems such as system blackouts which may result from cascaded trippings initiated by some component outage. To overcome such disastrous occurrences, the concept of security control has gained importance. Security control basically aims at ensuring the normalcy of electric supply by monitoring the system continuously and taking suitable preventive and emergency actions. The computer monitors system condition and notifies operator if one or more variables have crossed threshold values set in advance. Repeated trial simulations are made with new variables, the best results adjudged by the operator is picked up for operational changes.

In most of the published reports (19,36,79) three system states have been classified based on load constraints and operating constraints, which are normal, restorative (alert) and emergency. Figure 2.6 gives the state transitions and corresponding control strategies. If both the load and operating constraints are satisfied, the system is said to be in the normal operating state. In the emergency state the operating constraints are not satisfied while the system transits to restorative state

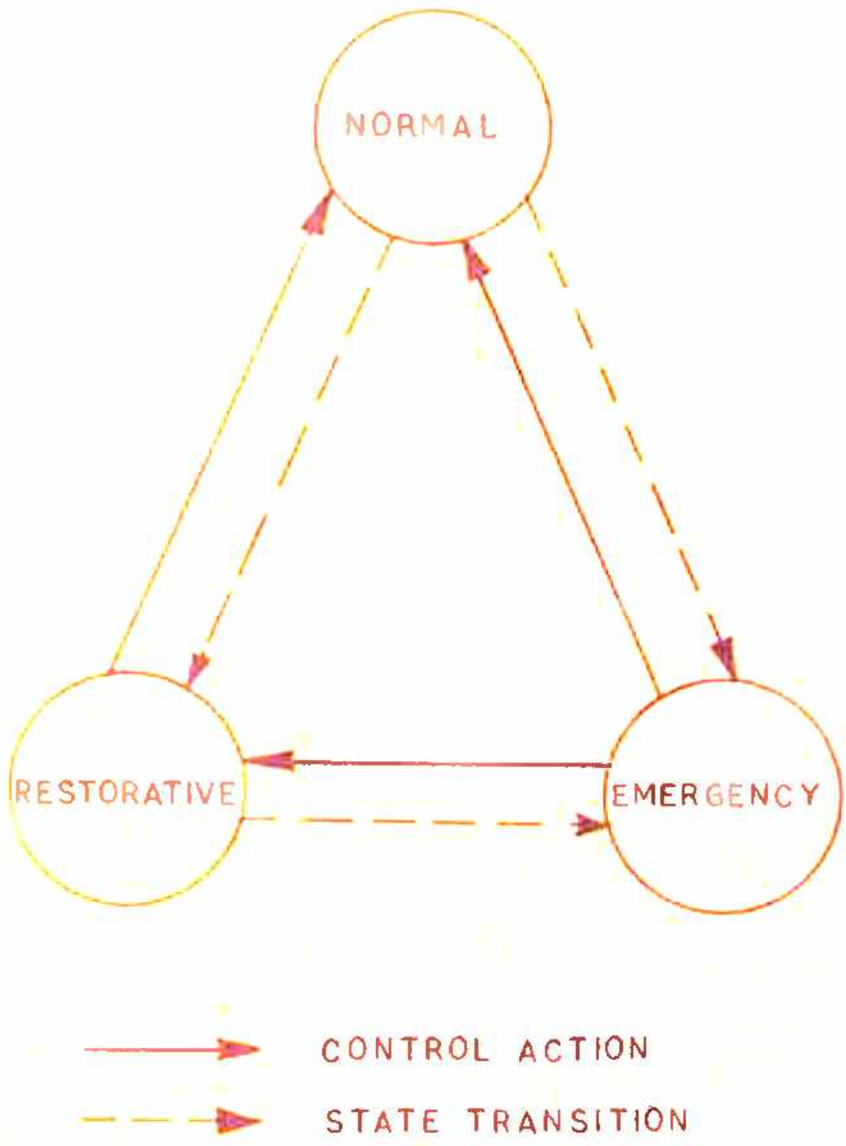


FIG. 2.6 STATE TRANSITION AND CORRESPONDING CONTROL STRATEGIES.

if load constraint is violated. As evident from fig.2.6, the overall objective of security assessment is to provide the operator with some guide lines such that he can maintain the system in normal state. To realise an effective strategy for carrying out this objective, it is essential to look more closely into the concept of system security. This may be defined as the ability of a power system, in normal operation, to undergo a disturbance without going into emergency condition. On the other hand, a normal operating system would be insecure if some disturbances can take the system into an emergency operating condition.

Optimal Secure Flow:

In the field of security assessment many work have been reported (13,14,15,18,19,30,55,59,60,64,77,82,93,96, 100). In most of these, security constrained optimisation is used as a convenient frame work for discussing approaches to system security enhancement. The constrained optimisation problem obtains the best operating condition which satisfies simultaneously load, operating and security constraints. These can be formulated as

Minimise:

$f(X,U)$ objective function

Subject to

$G(X,U) = 0$ load constraints

$H(X,U) \geq 0$ operating constraints

$S(X,U) \geq 0$ security constraints (2.17)

These functional constraints make the problem very much complex. Generalised reduced gradient (30) has been used for solving this problem. For quicker solution linearised models have also been used (13,55,59,60,64).

Comments:

System security is commonly assessed in these cases using some form of contingency rule. That is, if the system within a certain specified number of contingencies displays unsatisfactory operating condition, some form of security control action is required. The consequences of contingencies in the system may be evaluated using on-line computer techniques or may be estimated by the operator based on off-line studies of the system and experiences. The probabilities that contingencies causing unsatisfactory system operation are commonly evaluated, if at all, only through operator judgment. Thus, security assessment using a contingency rule cannot give a consistent assessment of the likelihood or probability of unsatisfactory system operation in the future.

Security Indices:

The method of security assessment presented here supplies, quantitatively, the probability ingredient missing from the contingency rule to create consistent indices of system security i.e. the probability of unsatisfactory system operation. The basic idea of a probability index for security appeared first in the year 1970 by Patton (74) which was used for finding generation spinning reserve. In the same year R. Billinton (69) proposed two reliability criteria to gauge the composite power system reliability as a whole. These two criteria: (1) probability of failure of a bus; (2) frequency of failure of the bus, were used for planning purposes. The weak point about this paper is total of 2n number of indices for an n-bus power system, which is quantitatively inconvenient for a large system. The system voltage profile, although included as one of the quality of supply of reliable power, has no direct bearing on any of the above indices.

In 1972 Pier. L. Noferi (41) proposed some indices in terms of curtailed energy and abruptly disconnected power. One of the indices is given by the expected value of the energy not supplied over a period of a year, assuming that the adjustment of the load to availability is carried out without any transient. The entire index is evaluated by Montecarlo simulation, and according to the author's claim it needed 100,000 trials lasting almost over an hour for a relatively small problem. Load shedding is being done in an indiscriminating way just to match the availability with demands. Load is shed for the less important load first. Now, if a transmission line terminated to a bus which supplies more important load gets overloaded and direct connection to the bus supplying less important load is not there, then the author feels the effect of load reduction will not be immediately felt in the overloaded transmission line and hence may need higher quantum of load shedding than actually needed. Moreover it is not clear how this index can be used for planning purposes. Probability of outages are not implicit in this method. Also the voltage dip of the system is not considered for the risk evaluation.

Steady state security assessment is defined as follows: given sufficient system data either through direct measurements or load flow studies and a list of contingencies with their probability of occurence determine some indices which can project the picture of system security. Contingencies may include loss of generation and transmission facilities. Possible problems include generating units operating at their reactive power limits with a consequent deviation from their scheduled voltage; transmission line overloads, generator overloads, voltage out side the normal limits at any bus. Most of these conditions will require corrective action by the operator. Clearly, more abnormal are the condition the greater will be the corrective action required, and less secure was the original operating state.

A printed output from a planning load flow program is clearly not suitable for presentation to an operator. It would be, therefore desirable to present to the operator a set of number or indices which in some way measures the security of the system in the sense described above. In this section indices are developed which measure the vulnerability of the system in terms of load voltages outside their normal limits and line or generator overloads.

Security assessment for a group of generators connected to a bus supplying load differs considerably when transmission lines are involved. This is because flow in transmission lines are unknown until load flow solutions are completed. It is felt that one single index is inadequate to assess the security of a composite power system. In this work two security indices have been employed for a combined generation and transmission system.

Entire power system transits from one state to the other, resulting from the random outages of generators at generating buses and the lines interconnecting them. This transition may cause the system to travel from a secure state to insecure or emergency state. For planning purposes the system designer has to be provided with suitable figures of merit to judge several alternative designs. These should be chosen such that the system exhibits a definite level of security in the advent of some probable contingencies.

Security function as proposed originally by Patton (43) is given as:

$$S(t) = \sum_i P_i(t)\, Q_i(t) \qquad (2.18)$$

where $P_i(t)$ is the time dependent state probability of the system which can be evaluated from the eqn.(2.3). $Q_i(t)$ is the probability that the ith state causes a breach of security. In this context $Q_i(t)$ may be either zero or one if the load is deterministic. Steady state breaches of security may result because the system is in a particular state at a given time or load level. Here state of the system is defined to be a particular operating configuration, consisting of certain generators running, certain generators unavailable, certain generators on standby, some transmission lines are in service yet other are out, etc. Steady state breaches of security includes:

1. steady state voltage at load buses outside the tolerable limit
2. steady state over load of transimission lines
3. insufficient generating capacity (real and reactive).

The security function calculated from eqn. (2.18) is compared with an upper limit of insecurity and when the value of this function exceeds the upper limit, in some future time, a control action is initiated depending on the lead time available to keep the system within the secure limit.

Comment:

For deterministic load, if at any state i, load is greater than the generation, $Q_i(t)$ is taken as unity and consequently the estimated risk is higher than the actual. In real life however, instead of conveying that the load cannot be met with probability one, a part load can still be met by shedding a proper percentage of load, under contingency.

For a bulk power system it is felt that single index is truly inadequate as it fails to bring out security of supply at any bus.

It has been assumed that the standby generator is available with nonzero probability as and when a normally operating generator fails. This merely indicates that starting time is taken to be a random value. In reality however, it is misleading, as the start-up time is fairly a constant value with a smaller value for gas or water turbine driven generators or a larger value for steam turbine set.

In case of lower security value only controlling action considered is the change in generating schedule. This approach while changing flow in a line to some extent may not provide a major relief for over-loaded line.

From the above discussion it is imperative that a new approach to security index must be evolved. Recognising the fact of load shedding under contingencies the security index for any state may be obtained by weighting the state probability by a suitable factor based on the amount of load shedding necessary. This approach gives a more realistic figure of security.

Repeated load flows are an essential feature for the calculation of the above proposed weighting factor, under different contingencies. As a result of certain overlapping generator outages or overlapping generator and line outages, transmission lines becomes overloaded, such that no transmission relief can be possible other than curtailing loads at certain buses even though enough generation capacity is available in the system. In order to assess the amount and location of the load to be shed suitable computer logic has to be developed.

2.4 PROPOSED MODELS OF SECURITY INDICES:

Load Security Indices (LSI):

As mentioned previously security evaluation by the proposed methods needs repeated load flow solutions to check equipment overloading and bus voltages. In such studies saving in computation time is more important than accuracy. It is precisely where d.c. load flow scores more over the a.c. Furthermore, less memory is required in case of d.c. flow. In this work the d.c. flows for active and reactive power are suitably adopted using the models advanced below,

$$\delta_k = \frac{PI_k + \sum_i B_{ki}\,\delta_i}{\sum_i B_{ki}} \tag{2.19}$$

$$\mathcal{V}_k = \frac{-QI'_k + \sum_i B_{ki}\,\mathcal{V}_i}{\sum_i B_{ki}} \qquad (2.20)$$

where:

PI_k = Net real power at bus k

QI'_k = Modified net reactive power at node k

δ_k = Phase angle at bus k

$\mathcal{V}_k$ = Deviation of voltage at node k from the nominal.

The details above eqns. (2.19) and (2.20) along with sensitivity matrix formations are discussed in Appendix A. It may be mentioned at this stage for greater accuracy at the cost of computation time and memory constant matrix method (46) may be adopted.

At most two simultaneous equipment outages are considered, as it is felt more than two do not contribute significantly to the risk. However, if needed, computer logic can be suitably modified to include such cases.

LSI for the ith bus is formulated as

$$S_i = \sum \prod_{g \in N_g} P_{dn}(g) \cdot \prod_{g' \in M_g} P_{up}(g') \cdot \prod_{l \in N_l} P_{dn}(l) \cdot \prod_{l' \in M_l} P_{up}(l') \cdot Q_i \qquad (2.21)$$

where:

M_g = total number of generators in up-state

N_g = total number of generators in down-state

M_l = total number of line in up-state

N_l = total number of line in down-state.

For a simulated outage case the computer programme scans all buses to see whether the load can be supplied satisfactorily. This requires that none of the terminating lines or the generators are overloaded. When a generator gets overloaded and does not get relieved by rescheduling of generation, a small portion of load at all buses are shed to improve the situation. However, to relieve the overloaded lines partial load at specific buses only need to be shed. A bus-wise weighting factor, in this case, is expressed as

$$Q_i = \frac{LS_i}{\sum_{i=1}^{n} PI_i} c_i \qquad (2.22)$$

$$i = 1,2,\ldots,n$$

where:

PI_i = Net power demand in ith bus

LS_i = Total load shed in ith bus.

Factor c_i is chosen to characterise the importance of the ith bus load which attempts to measure unsatisfaction of the consumers and is a subjective managerial decision. Equation (2.22) gives a measure of the local LSI. A global index of security is then expressed as a linear combination of local LSIs.

$$GLSI = \sum_{i=1}^{n} S_i \qquad (2.23)$$

Voltage Security Index (VSI):

It is important that voltage profile of a power system should be within a specified tolerable band. While this has been recognised by some reliability analysts (43,69) its effect had no direct impact on their reliability models. It is well known that lack of kvar deficiency at any bus leads to the deviation in the voltage. In this section a modified index is advanced which senses the deviation of actual voltage from the tolerable one. This has been used later to compute local kvar requirements.

Some form of index based on voltage profile of power system has been reported by Dewey (56) in 1971, Noferi (12) in 1975 and Savulescu (2) in 1976.

Dewey's Model (56):

In this case index based on the actual voltage of a bus is calculated with the help of a suitable model such that the value of the index becomes one for the tolerable range of voltages, and less than one otherwise. A linear combination of these bus indices are made to obtain an overall index which is then suitably weighted by the probability of contingencies.

Noefri's Model (12):

Here two indices have been proposed one is based on yearly energy curtailment and the other on weighted value of the yearly energy supply. Latter index has been referred as voltage irregularity factor. The author has used some form of reactive linear flow to calculate bus voltages.

Savulescu's Model (2):

Recently an article appeared while writing the thesis wherein the author has tackled the problem of evolving quantitative indices about var-voltage relation of power systems. Three indices are advanced in this paper: The Loss Sensitivity Index (LSI), Reactive Power Transmittance. Index (RPTI), Steady State Stability Index (SSSI). The RPTI appears to be the off diagonal elements of the $\partial Q/\partial V$ submatrix of the Jacobian and SSSI appears to be the diagonal elements of the same submatrix.

Comment:

A single index as proposed by Dewey is not at all convenient to consider any corrective action or alternative design strategy, since it is strongly felt that voltage indices are predominantly meant for reactive load adjustment or addition of reactive units at specific buses.

Noefri finally uses his first index to choose suitable var addition at some buses. The intended use of voltage irregularity index is not properly established.

Furthermore, the first index is based on yearly energy curtailment obtained through load shedding technique. From the experience of load shedding it can be stated that an unnecessary large load reduction is resulted making the method unsuitable.

The linearised indices proposed by Savulescu can, however, be suitably used to control the reactive power.

Voltage Security Index - Author's Model:

For a given contingency when it is found that some lines are over-loaded, load shedding is carried out to relieve these overloaded lines and local security index is calculated. The bus voltages are then scanned. Even after load shedding this value may still be out side the permissible limit. As proposed LSI is incapable of considering this type of insecurity, a separate voltage security index is evolved.

When a contingency occurs the voltage profile of the system is likely to change to one of the following:

a. bus voltage changes but remain within an acceptable band.

b. bus voltage is less than the minimum acceptable value, V^m.

c. bus voltage exceeds the maximum limit, V^M.

VSI should be such that its value becomes zero for case (a) and a positive quantity otherwise.

A nominal voltage V_n is defined, this is taken to be 1.0 p.u. The threshold voltage beyond which supply of load lacks quality, is given as

$$S^m = V_n - V^m \qquad (2.24)$$

$$S^M = V^M - V_n.$$

If V_i is the voltage of ith bus, then deviation of this voltage from nominal value is

$$\Delta V_i = V_n - V_i \quad \text{for} \quad V_i \leq V^m \qquad (2.25)$$

$$= V_i - V_n \quad \text{for} \quad V_i \geq V^M$$

Weighting factor of the ith bus for the entire spectrum of voltage is expressed as

$$W_{vi} = \begin{cases} 0 & \cdots\cdots \quad V^m \leq V_i \leq V^M \\ W_{vli} & \cdots\cdots \quad V_i < V^m \\ W_{vhi} & \cdots\cdots \quad V_i > V^M \end{cases} \qquad (2.26)$$

Variation of W_{vi} with the voltage is shown in fig. 2.7 which is expressed as:

$$W_{vli} = (S^m - V_i)^2$$

$$W_{vhi} = (V_i - S^M)^2 \qquad (2.27)$$

The probability of the occurence of the contingency is then multiplied with this weighting factor to get VSI for the ith bus.

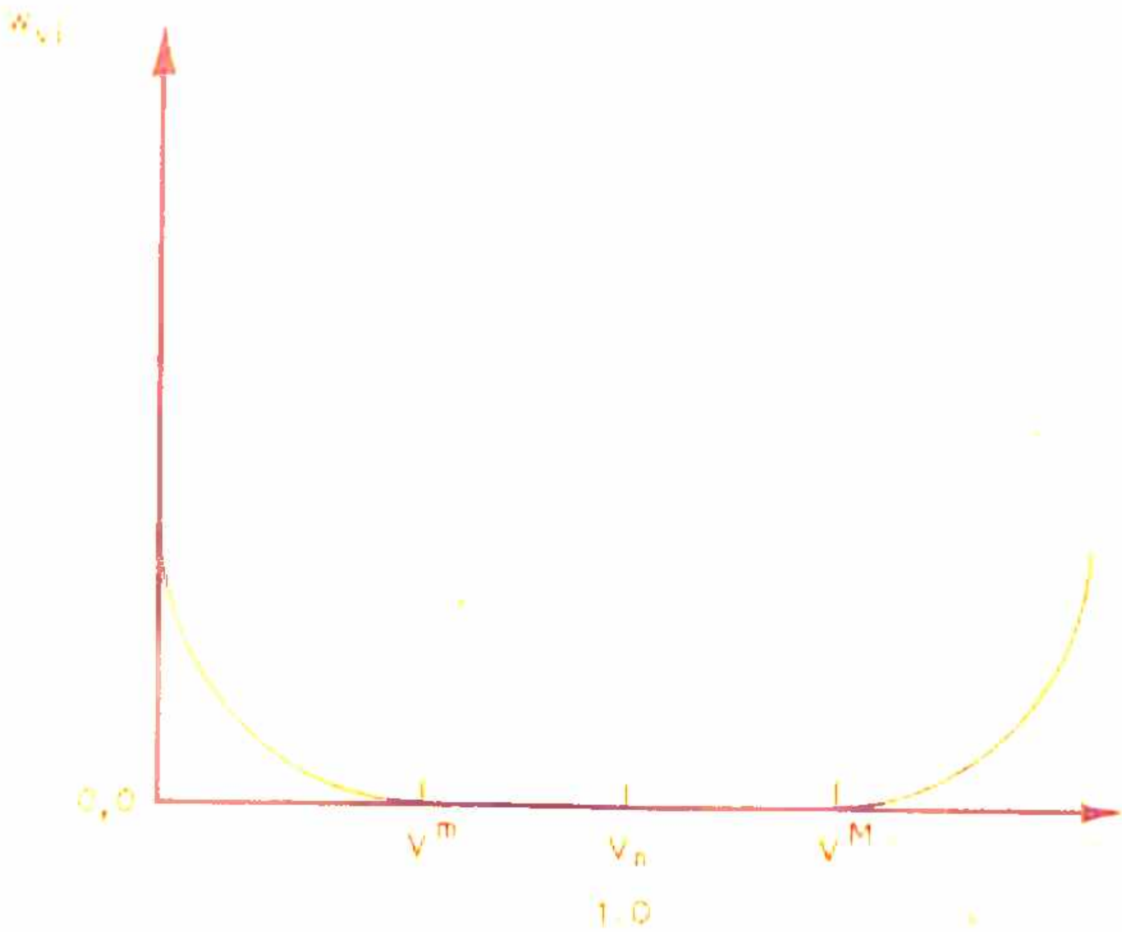


FIG. 2.7 VARIATION OF W_{vi} WITH BUS VOLTAGE

$$S_{vi} = \sum_J P(B_J).\ W_{vi} \qquad (2.28)$$

where:

B_J = System state correspond to the Jth contingency which has resulted in either a voltage dip or rise.

$P(B_J)$= Corresponding state probability.

Application Of These Models:

Local and global LSIs apart from being used to give a guide line to the operator for operational purposes have also been used here as a reliability criteria for the expansion of an already existing system. Power system planning is an widely discussed (51,69,102,105,113) topic. In many of the above mentioned literature the planners made use of some analytical techniques such as economic dispatch based on loss formula and mathematical programming. To the best knowledge of the author, Billinton (51) applied some reliability criteria for the first time in 1971 for transmission planning. Nothing, however, was mentioned about the addition of new generating capacities. A composite power system planner has to answer the following questions, for short range planning.

1. What should be the criteria of adding new generators ?
2. What should be the best location of this additional generation ? Can it be a new bus altogether ?

3. Where to add new transmission lines ?

Most of the above questions can be answered through some economical model. In reality reliability aspect must be considered along with economic one. In the present work only the reliability angle of planning is discussed. It has been found that the global LSI is more sensitive to generation contingency whereas the Local LSI is sensitive to line contingencies which brings in relief to overloaded lines. These properties have been exploited in this thesis for a suitable expansion pattern.

Computer Logic:

Fig. 2.8 gives a functional flow chart on which the entire logic of the evaluation of the security indices are based. This flow chart has been further extended to show how these indices are used for a short range planning problem. Some of the salient points are written below:

1. Compute unit commitment table for all load levels on economic basis.
2. Simulate first generator outages, then line outages and finally a combination of generator and line outages, calculating their respective probability of occurrence.
3. Calculate load flows and check for any overloading of generator at the slack bus for each contingency.

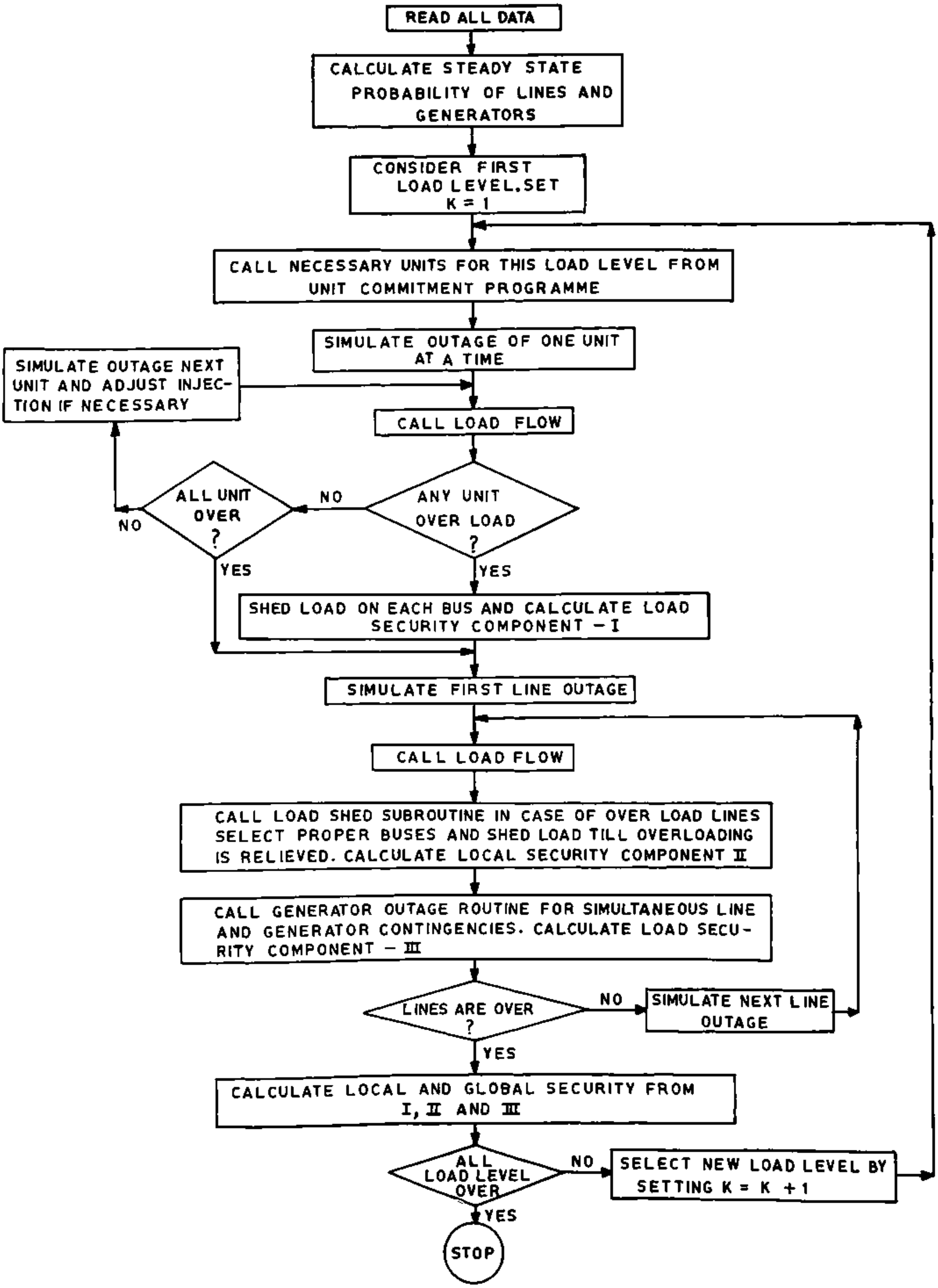


FIG. 2.8 FLOW CHART FOR SECURITY INDEX EVALUTION

4. Adjust generation on other buses to relieve overloading in step 3.
5. If overloading is not relieved shed small portion of load in all buses. Calculate load flow to recheck if slack bus overloading is relieved.
6. Repeat load flow and check for any line overloading.
7. In case a line is overloaded, check the direction of power flow in the overloaded line. This helps to locate the bus where load shedding will relieve the overloading of the line.
8. Calculate local and global LSIs.
9. If global value of LSI exceeds the maximum limit, new generator is added to the existing generating buses one at a time to select the proper bus which results in minimum global LSI.
10. Local value of LSI is checked to see if line addition is required. Addition of proper line will make the local value of LSI minimum.
11. Check system voltage. If any bus voltage is higher than the limiting value reduce the reference voltage to bring this bus voltage within limit. Compute VSI. If VSI of any bus exceeds a preselected limit, calculate the kvar needed for the bus using pre-calculated sensitivity matrix, such that VSI is brought back to the tolerable region.

Logic Of Identifying Bus For Load Shedding:

Whenever a generator or a group of generators get overloaded fraction of load is shed at each bus but a selective load shedding is done in case of line overloading. Whenever a contingency is simulated the flow subroutine is called to detect the lines which are overloaded. At this stage the program is directed to find the direction of power flow in the overloaded lines. It is attempted by properly monitoring the phase angles at both the ends of the overloaded lines.

Precisely if line $i-j$ is overloaded, the program sheds a fraction of load at bus j if

$$\delta_j < \delta_i$$

for all $\delta_j, \delta_i < 0$

or for all $\delta_j, \delta_i > 0$

or for all $\delta_j < 0$ given $\delta_i > 0$ (2.29)

the load reduction is repeated until the line flow is within normal. Before the execution of load shedding starts a check is made to verify if any other line terminating at the bus j is also overloaded. In case no such line exists load is finally shed at the bus j. But if in the previous search it is found that a line $j-k$ is also overloaded a similar check is made as given by the inequality (2.29) to identify the direction of power flow in the overloaded line $j-k$. This finally enables one to shed load either at the bus j or at the bus k depending on whether power is flowing from j to k or in the reverse direction respectively.

2.5 SAMPLE STUDY AND RESULTS:

To evaluate and illustrate the application of the various security indices a 6-bus interconnected power system is considered which is shown in fig. 2.9. Requisite system data are displayed in the table 2.3a and 2.3b. Wide range of load is considered at different buses.

TABLE 2.3a GENERATOR DATA

Capacity	100 MW	150 MW	60 MW	100MW
Failure rate-	4×10^{-4}/hr	$2.0\text{x}10^{-4}$/hr	$0.9\text{x}10^{-4}$/hr	$4\text{x}10^{-4}$/hr
	$8\text{x}10^{-4}$/hr	$5\text{x}10^{-4}$/hr	$2.0\text{x}10^{-4}$/hr	$8\text{x}10^{-4}$/hr
Repair rate	$8\text{x}10^{-2}$/hr	$5\text{x}10^{-2}$/hr	$8\text{x}10^{-2}$/hr	$8\text{x}10^{-2}$/hr
Reactive MVA Limit	30	45	20	30

TABLE 2.3b LINE DATA

	1-2	2-6	2-3	3-4	4-5	5-6	1-6
Failure Rate No/hr	$8\text{x}10^{-4}$	$5\text{x}10^{-4}$	$8\text{x}10^{-4}$	$7\text{x}10^{-4}$	$6\text{x}10^{-4}$	$6\text{x}10^{-4}$	$1\text{x}10^{-}$
Repair Rate No/hr	0.25	0.15	0.15	0.15	0.25	0.25	0.25

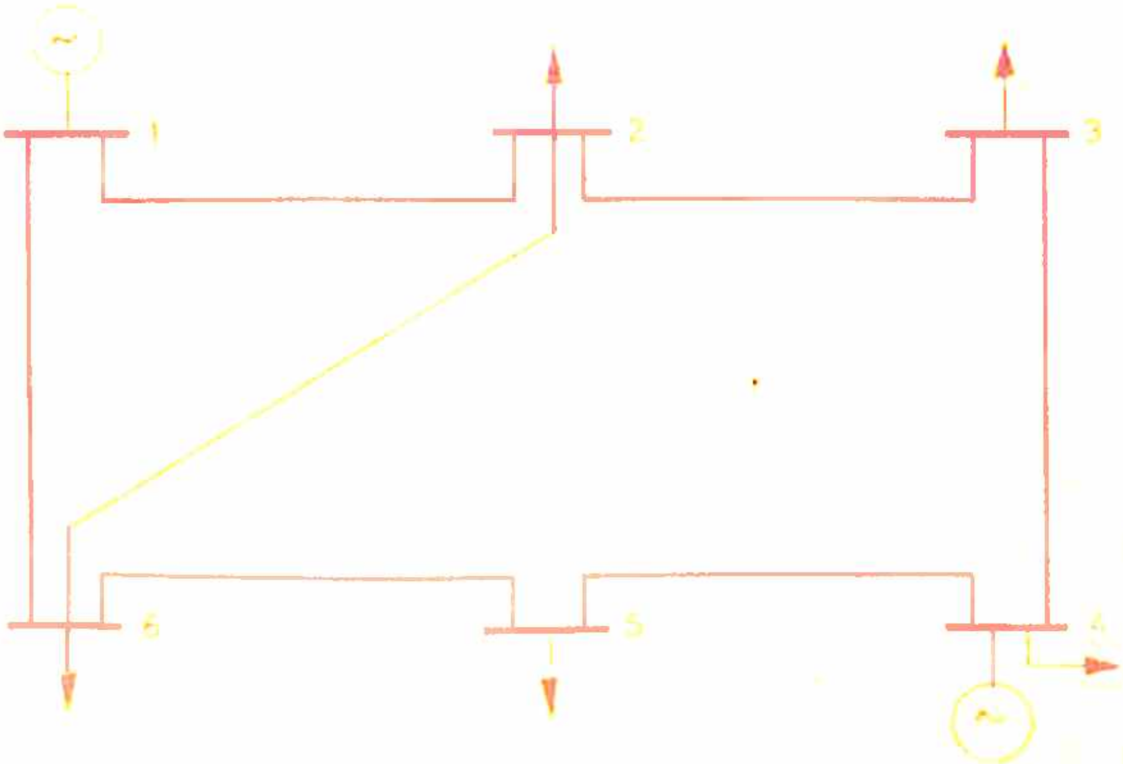


FIG. 2.9 SAMPLE POWER SYSTEM.

Loads are assumed to be estimated before hand and only the expected values of the load levels are considered at each bus. Repeated load flows are carried out for each generator outage, line outage and generator and line outages, for a given load level. All the indices are calculated once in each evaluation cycle, which is defined to be the period from one load level to the other.

Table 2.4 gives the load of the entire system, local and global LSIs. It also indicates the maximum tolerable global LSI. This limit actually may be fixed up considering cost of reliability and to a large extent rests on management's decision. It is observed from this table that the load level beyond and including 280 MW gives rise to the values of global LSI which are higher than the tolerable limit. A 100 MW unit is added to the existing list of generators. For all load level the effect of its addition on the global LSI is studied. It is found that the global LSI is reduced to zero for all considered load levels, when this unit is added to bus 4. This is displayed in the table 2.5. Addition of generator, however, has not much influence on the local values of LSI. In this case also a ceiling has been decided at 1.5×10^{-3}. Lines are added, one at a time, between the bus at which LSI is higher than the upper limit and other. In this case parallel lines are avoided

TABLE 2.4 LOCAL AND GLOBAL LOAD SECURITY INDEX

Total load	Local Load Security Index x 10^{-3}						Global LSI x 10^{-3}
	Bus 1	Bus 2	Bus3	Bus 4	Bus 5	Bus 6	
0.8 + j0.16	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.2 + j0.24	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.6 + j0.32	0.0	0.122	0.122	0.0	0.122	0.122	0.484
1.9 + j0.38	0.0	0.286	0.286	0.0	0.286	0.286	1.144
2.5 + j0.50	0.0	1.653	1.404	0.0	1.404	1.529	5.990
2.8 + j0.56	0.0	1.342	1.560	0.0	1.421	1.530	6.354
3.1 + j0.62	0.0	1.321	1.521	0.0	1.451	1.521	6.414

Maximum tolerable Global LSI = 6.000 x 10^{-3}

TABLE 2.5 EFFECT ON GLOBAL LSI DUE TO ADDITION OF UNIT

Load in p.u.	Global LSI x 10^{-3} Generation: (3.1 + j0.9) p.u.	Global LSI x 10^{-3} Extra Generation (1.0 + j0.25) p.u. at Bus 1.	Global LSI x 10^{-3} Extra Generation shifted to bus 4
0.8 + j0.16	00.000	00.000	00.000
1.2 + j0.24	00.000	00.000	00.000
1.6 + j0.32	00.436	00.000	00.000
1.9 + j0.38	01.144	00.484	00.000
2.0 + j0.40	02.210	00.505	00.000
2.5 + j0.50	05.990	01.380	00.000
2.8 + j0.56	06.354	01.776	00.000
3.1 + j0.62	06.414	01.851	00.000

because it is felt this may change the failure rate of such lines because of proximity effect. Table 2.6 indicates the right choice of line addition. Use of VSI has been made in deciding the quantum of kvar load needed at the desired bus. An estimate of kvar injection necessary is found out with the help of sensitivity analysis. This process is carried out only when there is no scope of improving the system voltage through rescheduling of the kvar load. Table 2.7 shows the VSI at each bus corresponding to some total load levels (MVA). It also points out the higher VSI values in bus 3 and bus 5 indicating the need of extra MVAR load in these buses. These are found to be 33.9 and 25.9 MVAR respectively for the bus 3 and bus 5.

2.6 CONCLUSIONS:

In this chapter new light has been thrown on security of a bulk power system, from both generation and transmission point of view. In the process a new reliability model of standby generator is evolved, and the increased risk of considering starting failure probability in generation security function is established through a suitable example.

A modified security index, which takes into account the corrective action through load shedding, has been developed and is used along with the VSI for judging

TABLE 2.6 EFFECT OF LINE ADDITION ON LOCAL LSI*

System Description	L S I x 10^{-3}						Total load in p.u.
	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	
Original system	00.000	01.653	01.404	00.000	01.404	01.529	
Line 1-3 added	00.000	01.653	01.404	00.000	01.404	01.500	2.5 + j0.50
Line 1-4 added	00.000	01.404	01.404	00.000	01.404	01.404	
Line 1-5 added	00.000	01.585	01.404	00.000	01.404	01.498	
Original System	00.000	01.842	01.560	00.000	01.421	01.530	
Line 1-3 added	00.000	01.842	01.531	00.000	01.421	01.530	2.8 + j0.56
Line 1-4 added	00.000	01.421	01.421	00.000	01.421	01.491	
Line 1-5 added	00.000	01.842	01.560	00.000	01.421	01.512	
Original System	00.000	01.900	01.519	00.000	01.451	01.499	
Line 1-3 added	00.000	01.856	01.500	00.000	01.451	01.499	3.0 + j0.60
Line 1-4 added	00.000	01.451	01.451	00.000	01.451	01.451	
Line 1-5 added	00.000	01.856	01.500	00.000	01.451	01.451	
Original System	00.000	01.921	01.521	00.000	01.451	01.521	
Line 1-3 added	00.000	01.862	01.511	00.000	01.451	01.521	3.1 + j0.62
Line 1-4 added	00.000	01.451	01.451	00.000	01.451	01.451	
Line 1-5 added	00.000	01.870	01.496	00.000	01.451	01.500	

* Any other addition of line increases the value of LSI.
Maximum Local LSI value = 01.500 x 10-3

TABLE 2.7 VOLTAGE SECURITY INDEX:

Sr. No.	V S I x 10^{-7}					
	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
1.	00.000	00.000	00.547	00.000	00.445	00.000
2.	00.000	00.000	01.607	00.000	02.829	00.000
3.	00.000	00.000	04.288	00.000	17.748	00.000
4.	00.000	00.000	05.403	00.000	19.313	00.000
5.	00.000	00.000	59.811	00.000	83.543	00.000

the security of a bulk power system. Repeatative load flows are necessary as it is never apparent at the start what effect the line failures have on system security. Suitable computer logic has been developed for security checking involving load shedding during contingencies and other corrective measures based on VSI. The use of computer logic is illustrated through a power system example in which location of generators and lines to be added have been worked out based on specified maximum value of global and local LSI respectively.

Chapter-III POWER SYSTEM SECURITY THROUGH FAULT TREE ANALYSIS

3.1 INTRODUCTION:

Many practicing engineers in order to evaluate reliability model their systems using probability map(118) reliability diagrams etc. Almost around 1961 the concept of fault tree analysis was originated by H.A. Watson to evaluate safety of the launch control system while it was popularised by D.F. Haasl. Since then this technique has been repeatedly used for safety analysis of systems (1,3,4). Only from 1970, it is applied for calculating system reliability (7,21,22,23,54,62,63,67,76,78). Fault tree analysis is a powerful technique for reliability evaluation of engineering and management system which provides the analysts with quantitative interpretation of failure consequences, trade-off studies, system alterations, etc. Computer aided fault tree analysis (7,63), has made possible for system analysts to venture upon complex system reliability evaluation.

In this chapter this technique has been successfully adopted to evaluate probability that a given load demand at a bus of a power system, cannot be met. Suitable computer algorithm is found to translate the fault tree into a stack of information consisting of operands and operators which is then transformed into a sum of products. Later Bennett's algorithm is suitably modified and adopted for the purpose of final probability evaluation. A radial power system is first considered to illustrate the technique which is later extended to a 3 bus interconnected power system, where load flow problem is a prerequisite to the ultimate probability analysis.

3.2 METHODOLOGY OF FAULT TREE ANALYSIS:

System reliability can be expressed in terms of probability of success or failure through either tie-sets or cut-sets approaches. Reliability diagram, although serving a similar purpose, fails to bring out the richness of logical combination that is available. Besides, there has always been a confusion in the reliability diagram about the meaning of the words, series and parallel. Many people take them in their circuit-information or power flow sense rather than in the logical sense in which they are constructed. In case of the fault tree analysis, the probability of failure is written in terms of element failure modes. Therefore, the system failure is represented as a combination of different failure modes using suitable logic symbols. (Generally digital logic gate symbols are used). The fault tree diagram then, is really a mixture of logical symbols and a flow chart. In particular, fault tree analysis provides flexibilities which ranges from equipment analysis to overall system analysis incorporating all the influencing elements on a total system basis. The deductive approach used in this technique is particularly useful for evaluating design consistency and reliability, for judging alternatives. It readily allows analysts to consider the rate at which failures or events are detected after they occur and the rates at which they are restored to normal.

The methodology developed here critically reviews of some works performed in fault tree analysis. In order to discuss this, some basic definitions must be understood. These are presented below:

1. Event: A previously defined and specified occurrence within the system. It may be defined at the system or component level. Examples: (a) Bus fails as line supplying power is faulty, (b) Bus fails because voltage is low, and (c) Circuit breaker puts a line on. Note: For the present work, the events are defined such that they are binary in nature. An event does not have to cause failure, it can be normal functioning of the system.

Events are further classified into two, as given below:

2. Fault Event: An event in which one of the two states is an abnormal occurrence, resulting in some type of failure.

3. Normal Event: An event in which both states are expected and intended to occur at a specified time. A normal event could possibly become

a fault event with efflux of time. Example: operating and economy shut down states of a generator.

4. Basic Event: An event that occurs at the element level. An element here refers to the smallest subdivision of the analysis of the system. For example: generator outage is a basic event so far as an entire power system is concerned but power interruption at a bus is not a basic event. In short, for any event, if failure and repair rates are available, it can be treated as a basic one.

5. Head Event: The event at the top of a fault tree which is analysed through the remainder of the fault tree. This is generally a resultant failure which removes the system from normal operation.

To understand the procedure, it is helpful to get an overview of the general fault tree approach. The construction of a fault tree originates by a process of synthesis and analysis. This can be observed by the following stepwise outline.

Synthesis:

1. Determine at the most general level, all events that are to be considered as undesirable for the normal

operation of the system under study.

Suppose that the system under consideration is 'operation of an alternator', then a few undesirable events may be:

a. Faulty excitation system.

b. Vacuum in the condenser not proper.

c. Steam ejector is not operating.

d. Pilot exciter terminals open circuited.

e. Generator is getting overheated.

f. Hydrogen cooling system is malfunctioning.

2. Separate these events into mutually exclusive groups, forming groups according to some common relationships.

Among the above listed 6 events it is possible to obtain three mutually exclusive groups each with two related events, such as a,d - b,c - e,f.

3. Utilising the common relationship, establish one event that encompasses all events in each group. This event will form the head event and will be considered by a separate fault tree.

Analysis: Top Down Approach.

1. Select one head event, which is to be prevented.

A system may have more than one head events e.g. more than one load points in a power system.

2. Determine all primary and secondary events that would cause the head event.

3. Determine the relationship between the causal events and the head event in terms of the AND, OR and XOR Boolean operators.

4. Repeat steps 2 and 3 for each causal event that needs to be developed further.

5. Continue to reiterate steps 2,3, and 4 until all events are either in terms of basic events or it is not desirable to develop the event further.

6. Diagram the events using the symbols discussed in the next section.

7. Perform quantitative analysis.

This stepwise procedure may be treated as the basic algorithm to build a fault tree. The common relationship mentioned in synthesis steps 2 and 3 is the key to proper organisation.

3.3 SYMBOLS USED IN FAULT TREE:

Fault tree diagrams are very useful, for both quantitative and qualitative analysis. In order to use the diagrams to their greatest advantages, accepted standard symbols are given in this section. It is, however, noted that not all of these may be present in a single tree.

1. Rectangle: A fault event usually resulting from the combination of more basic faults acting through logic gates.

2. Circle: A basic component of fault.

3. Diamond: A fault event which is not developed further because of insufficient data.

4. Triangle: A connecting or transfer symbol.

5. Up side down triangle: A similarity transfer - the input is similar but not identical to the like identified input.

6. House: An event which is normally expected to occur.

7. AND Gate: Two or more inputs and one output characterise this symbol. In order for the event immediately above the symbol to occur, all the input events must occur.

8. OR Gate: Like AND gate multiple inputs and one output are required. In order for output event to occur, at least one of the input events must occur.

9. Conditional AND or OR Gate: In many situations, strict Boolean AND and OR functions are not appropriate. For example, in some AND situations sequence of event is important. Also, there may be an EXCLUSIVE-OR (XOR) gate where one or the other input would cause the output event, but if both occurs simultaneously the output event does not occur. In the present work, however, these types of gates are not encountered.

All of the above symbols are given in fig. 3.1.

3.4 REVIEW OF EARLIER WORK:

Relevant literature in fault tree is critically reviewed here keeping in mind the computerisation of the method, as it is felt the development of necessary software is the backbone to the furtherence of fault tree application.

Shooman's method (78):

This paper treats the fault tree approach basically in a similar manner as the reliability graph method. It has been shown that the failure probability obtained through fault tree analysis leads to success probability as obtained by the tie-set approach, if one makes use of DeMorgan's theorem at the final stage. While agreeing with this proposition, it can be said that the hallmark of fault tree approach is not fully realised in this paper. Moreover this approach may fail for a large and complex system.

Crausetti's approach (54):

Fault tree has been used here as an effective tool which provides a convenient format for probability evaluation, system analysis and trade-off studies. Simple rules are applied for each logical gate such as probability of the output event of an AND gate is equal to the product of the probability of its input events and the probability of the output event of an OR gate is approximately the sum of the probabilities of occurrence of its input events.

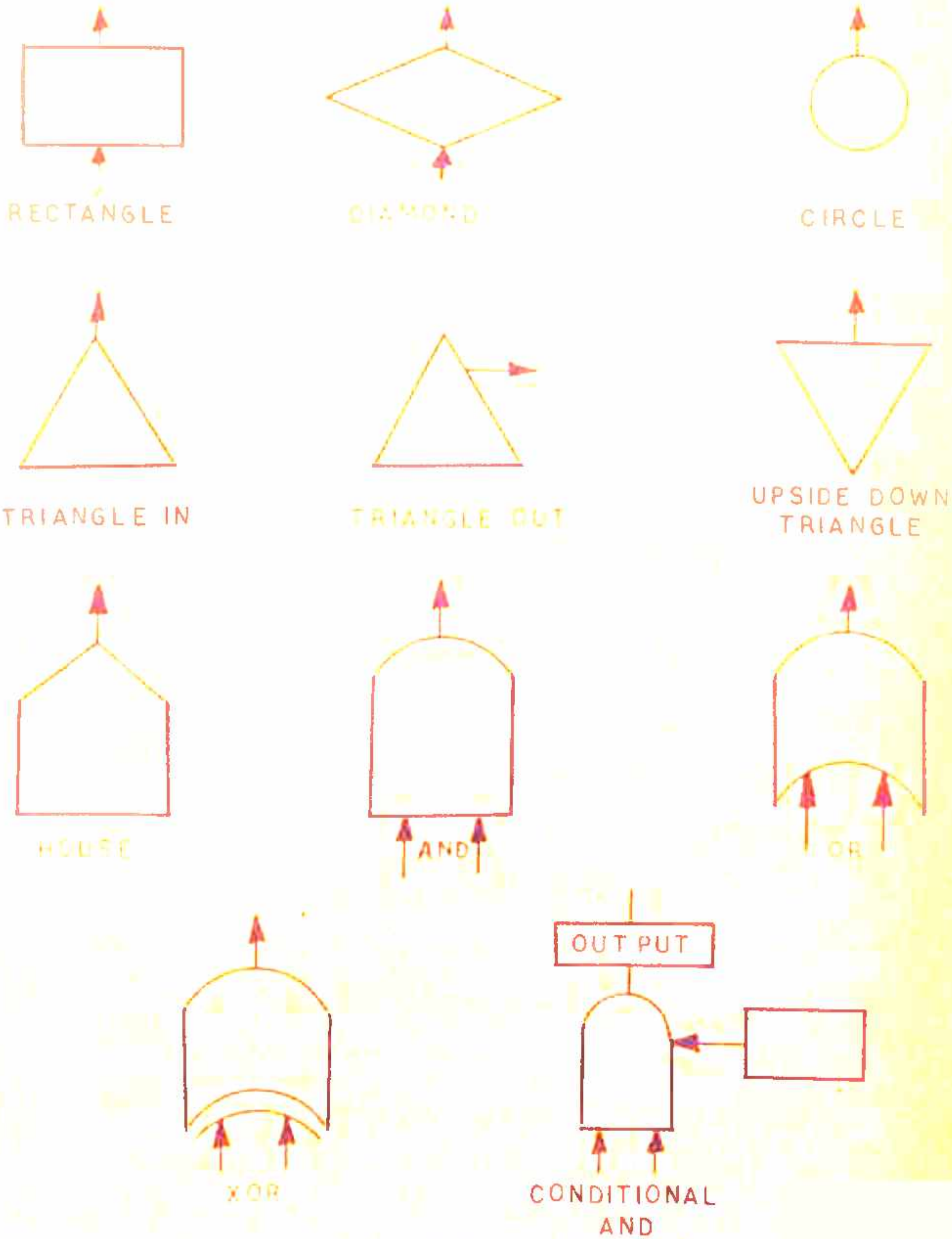


FIG. 3.1 COMMONLY ENCOUNTERED SYMBOLS IN FAULT TREE ANALYSIS

This may lead to substantial error in a cumulative way. Boolean substitution and reduction technique is used to convert a complex tree to a simplified tree consisting of basic events leading to the top event. It only helps in removing redundancy but does not make the logic diagram free of dependence which might creep in for a complex system.

One of the basic purposes, i.e. to determine the dominant path which contributes most to the final failure, is lost because of restructuring of the tree.

Veseley's Method (67):

The analytical technique used here for the probability evaluation is based on Kinetic tree theory. Once the fault tree is drawn this technique can be used to obtain the minimal cut-sets (critical paths) of the tree along with the following statistics:

(a) The probability of no failure to time t.

(b) The probability of being in a failed state at time t.

(c) The expected number of failures to time t.

(d) The failure rate at time t.

The time dependent informations given in the above list, are obtained for each component for minimal cut-set, and finally for the top event for the fault tree. The program written for this purpose can handle upto 2000 gates only. It is not clear how the redundancy of the inputs is accounted for.

ELRAFT Technique (63):

ELRAFT is a fortran program, which formulates the simplest logic expression for each secondary event in a fault tree in terms of its basic events. Each secondary event is expressed as the union of the intersections of basic events. The redundancies are eliminated by insuring that in a particular intersection a basic events appears only once. This fact has been accomplished by exploiting the property of the prime numbers as expressed in the unique factorisation theorem of number theory. The event number in this method has been assigned by numbers such that any new addition to the tree does not alter previous event number. The number of digits of the identification number indicates the level of the fault tree. However, it has two serious limitations: (1) total number of branches going out of any node cannot be more than nine, (2) level of the tree has to be restricted to six for a medium size computer. Furthermore, the author's assumption that the elimination of redundancy (which is mistakenly considered in this paper as dependency) in the secondary events leads to mutually exclusive events is quite doubtful.

Koen and Carnino's Method (23):

This paper applies some form of pattern recognition to solve the fault tree problem. The techniques of pattern recognition follows from the recursive definition of a tree. Any subtree represents a logical connection between its basic events, to which a unique mathematical formula exists relating mathematically the probabilities. It is claimed that these types of subtrees appear frequently in the main tree of any fault tree diagram. The author has listed 14 such patterns along with their respective probability expression. List processing technique is used for this purpose. On application of these known patterns repeatedly, a tree is reduced as far as possible to find the probability of the top event. The method is novel but is subjected to many limitations. Principal amongst them are: (1) a list structure often requires more storage in the computer than an array does, since the pointers as well as the data themselves must be stored, (2) an entry cannot be accessed directly by using a subscript but must be found using appropriate pointer, (3) programming in fortran is not possible as claimed by the author.

Bennett's Approach (7):

Among all approaches considered previously this is the most versatile as it can take care of logic gates like NOR, NAND, NOT, XOR apart from the common AND and OR. Furthermore, with some absorbtion rules the redundancy of the system can be completely eliminated. This is performed at the end of each operation to avoid a global complementation at the end of the final operation.

These exists certain discripancies in one of his algorithms, meant to convert the terms of a sum of products into disjoint events.

The present thesis makes use of the concept of reverse polish expression proposed by Bennett for power system reliability computation. This, being a new approach in the field of power system literature, is discussed at this stage in greater detail.

3.5 ANALYSIS OF FAULT TREE:

Reverse Polish Expression:

The central theme on which this analysis is based is the reverse polish expression (rpe) written for each secondary event as a function of the basic event. This is achieved by establishing a library to maintain the rpe for common type of logic gates. Actually AND and OR gates are sufficient because it is possible to express the output of any gate by either AND or OR through suitable transformation. Table 3.1 shows a suitable library for such purpose for two or three input gates. With the help of DeMorgan's theorem the operator types have been restricted to above mentioned two gates only. This also helps to avoid global complementation which is time consuming. The convention followed for rpe requires some literals followed by an operator and finally an index. This is the rpe of any single gate except for invert. The index immediately following an operator specifies the number of

TABLE 3.1 REVERSE POLISH EXPRESSION FOR SINGLE GATE

2	Input AND	:	$Z = X_1 X_2$ AND(2)
2	Input NAND	:	$Z = \overline{X}_1\ \overline{X}_2$ OR (2)
2	Input OR	:	$Z = X_1\ X_2$ OR(2)
2	Input NOR	:	$Z = \overline{X}_1\ \overline{X}_2$ AND(2)
3	Input AND	:	$Z = X_1\ X_2\ X_3$ AND(3)
3	Input OR	:	$Z = X_1\ X_2\ X_3$ OR(3)

preceeding literals to be operated by that operator. The complete reverse polish expression for the entire tree can be obtained by working back from the top event with successive substitution for secondary event inputs. This process is illustrated with the help of a both end fed power system shown in fig. 3.2. The top event (Z) is the interruption of the load connected to the bus where generator D is connected. Rpe for this is given below:

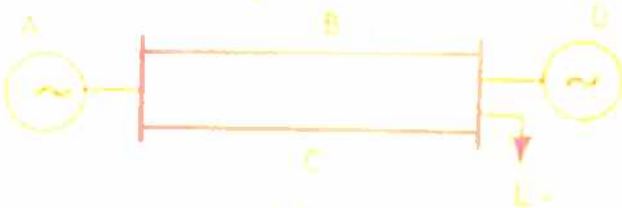
$$Z = \text{DAB OR(2) AND(2) AC OR(2) AND(2)} \qquad (3.1)$$

From eqn. (3.1) final expression of Z can be obtained with the help of suitable algorithm developed afterward. The unpacked expression becomes

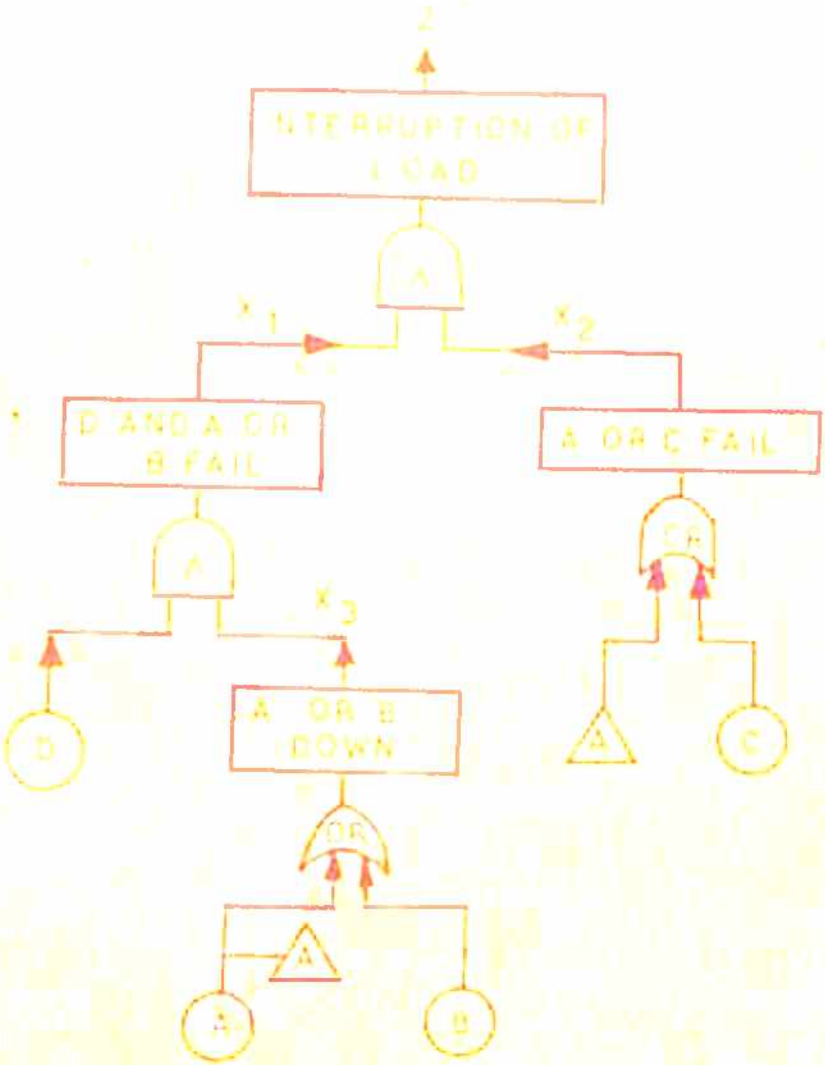
$$Z = AD + BCD \qquad (3.2)$$

Development of a general purpose algorithm is based on the way eqn. (3.1) is transformed into eqn. (3.2) for the above problem. Therefore, the execution detail of this is given here step by step.

The rpe generated for the tree of fig. 3.2 is stored in a stack in left-down-right-up manner. A pointer scans the stack until it comes across an operator with some index i. At this stage preceeding literals or terms (functions of literals) or combination of literals and terms totaling i in number are operated by the operator. An essential feature of the process is that intermediate



(a)



(b)

$Z = X_1 X_2$ AND (2)

$= DX_3$ AND (2) AC OR (2) AND (2)

$=$ DAB OR (2) AND (2) AC OR (2) AND (2)

(c)

FIG. 3.2 (a) PHYSICAL SYSTEM (b) FAULT TREE OF SYSTEM (a), (c) DEVELOPMENT OF RPE FOR ABOVE FAULT TREE results involving the AND operator are always converted into their equivalent union of intersections (UOI) format. Table 3.2 shows the various stages of this process.

TABLE 3.2 STATE OF THE EXPRESSION AFTER EACH OPERATION

Z = DAB OR(2) AND(2) AC OR(2) AND(2)

Stack State Literals	Initial	First OR	First AND	Second OR	Last AND
3	B		C		
2	A	A + B	A	A + C	
1	D	D	AD+BD	AD+BD	AD+BCD

The above table illustrates the operation of OR and AND gates, specifically the UOI at the end of each AND operation resulting in the expressions (AD + BD) and (AD + BCD). Every time an AND or OR operation is carried out, a search is made to remove logical redundancy if present in the resulting UOI, using certain absorption rules outlined below.

$$A.\bar{A} = 0 \quad (3.3a)$$

$$A.A = A \quad (3.3b)$$

$$A + A = A \quad (3.3c)$$

$$AB + A\bar{B} = A \tag{3.3d}$$

$$A + AB = A \tag{3.3e}$$

These identities except for the third one are used exhaustively in the subroutines ANDOP and OROP the structure of which will be discussed later.

Repeated Operators In Rpe:

The derivation of the rpe directly from a structure often leads to an adjacent operator of same type. When this occurs they can be reduced to a single operator with a suitable composite index. In general if n such similar operators exist with indices $i_1, i_2, \ldots, i_n$ a generalised rule has to be evolved. A simpler case is explained here which can be extended to encompass the general case. Consider the first two operators AND (i_1) and AND (i_2), when the preceeding i_1 literals are ANDed they form one composite term which now is one of the operands for the AND (i_2). Consequently the combined action of the above two consecutive AND gates is represented by a single AND gate with an index $(i_1 + i_2 - 1)$. Thus for the n repeated AND gates, the final index is

$$i = \left(\sum_{k=1}^{n} i_k \right) - (n-1) \tag{3.4}$$

The reduction of the repeated gates reduces the computer memory and execution time because the length of the stack reduces and repeated execution of the ANDOP or OROP subroutines are avoided.

Computer Implementation And Data Organisation:

The process which so far has been discussed requires many list construction and item search. One of these lists is dynamic in nature which stores the operands and the current expression at the end of each operation. The word dynamic refers to the fact that the content of this list is variable subjected to increase and decrease during the course of execution. At any stage if the dynamic pointer of this list points zero it implies the completion of the analysis. This is used as a check for terminating the programme.

3.6 COMPUTER ALGORITHM FOR UOI:

The process described earlier for obtaining the Boolean function for a simple tree is converted into a generalised algorithm which can be used to handle trees of any dimension. The overall structure of the algorithm in a flow chart form is given in fig. 3.3. The following subsections is mainly devoted to the various aspects of this flow chart along with other two principal subroutines.

Main Algorithm:

1. The rpe is stored in the POL which is an one dimensional array. The left most item of this occupies the top position of the list. Each item is 'popped out' from the POL and is tested for op rand or operator type. Since the nodes of the tree are given digital values an operand is distinguished from an operator by providing

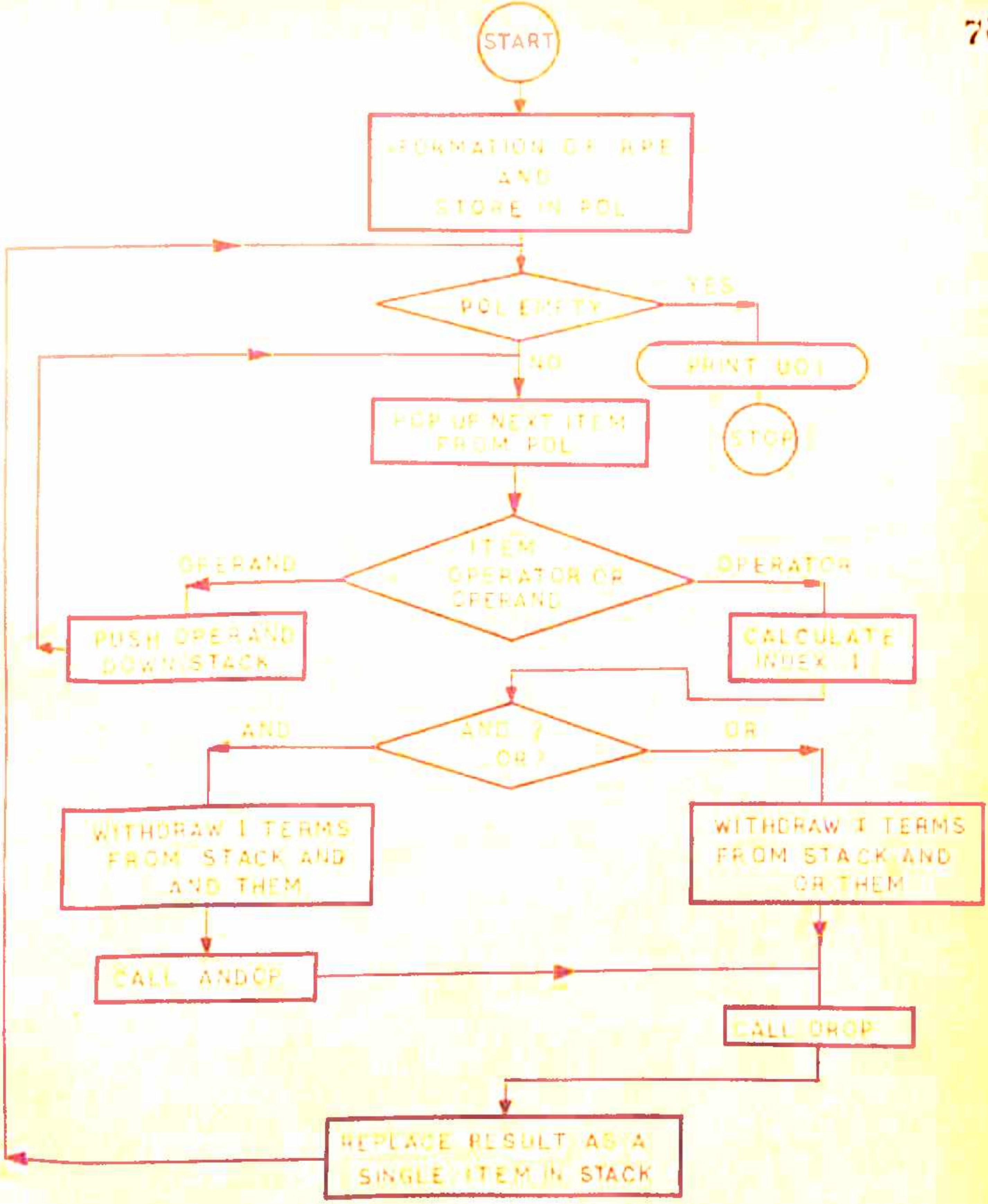


FIG. 3.3 MAIN ALGORITHM FOR UOI

negative sign before the latter. A dynamic array STACK is created which holds the operands and resulting expressions. Pointer of the STACK is initialised to be 1 at which the STACK stores zero. Every time an operand is transferred from the POL to the STACK, the value of the pointer is incremented by the number of operand plus one. At this stage programme makes the current value of the stack to be minus one. After OROP the resulting expression is completely stored in the stack as a single term. In this case the current value of the pointer is incremented by a number which is equal to the number of literals, present in the expression plus one. Value of the stack at this storage location becomes negative of the number of literals present in the expression. For example, let the current value of the pointer be 3 and the Boolean function to be stored is AC + BDE, then the latest value of the pointer will be 3+6+1 = 10. This is because the above Boolean function has six literals including the plus sign. The value of the stack at this stage is -6. The negative values stored in the STACK serves dual purposes:

a. It discriminates two consequtive operands or expressions.

b. It instructs the computer about the number of literals present in the expression immediately below.

2. When an operator is found in the POL, its index is found out. This is a simple task because the last digit of the number assigned to this operator is the value of the index. Likewise the first digit will convey about the type of the operator. The index and the type will decide about the number of operands to be popped out of the STACK for ANDing or ORing. Every time the operands are popped out for the above purposes the pointer is decremented by a suitable amount. A simple way to ensure for correct decrement is to see that the value of the STACK after decrement will be either zero or some negative number.

3. After the AND operation the control is transferred to ANDOP subroutine followed by OROP. In case of OR operator the requisite operation is completed and the result is transferred to OROP subroutine. Final expression from the OROP subroutine is stored in the STACK.

Subroutine ANDOP:

As mentioned previously this subroutine appears in the main programme whenever an AND operator is searched in the POL. Since the index of this operator is variable, provision is made for multiplying only two UOIs at a time within this subroutine. Two UOIs taken out of the STACK are temporarily stored in two arrays. These two along with their respective number of literals (variable) constitute the input to this subroutine. The basic structure of this is shown in fig. 3.4. Two major functions of this routine are discussed below:

1. The plus sign in the Boolean function is represented by blank. A pointer scans TEMP1 or TEMP2 until it comes across the blank. The difference of the value of the pointer from the earli r blank to the present one minus one gives the dimension of the term. To guard against the possible single term present either in TEMP1 or TEMP2 the present value of the pointer is always compared with the maximum dimension of TEMP1 or TEMP2. This is indicated when the pointer attains this without coming across a single blank.

2. When a term of TEMP1 is multiplied with another for from TEMP2, the product may contain logical redundancy. Unless these are weeded out, final probability value becomes erroneous. This function is achieved in the subroutine ARANGE. If a literal and its complement are present in the multiplied term the subroutine shows zero as the output. This is again carried out by searching technique. The subroutine finds the least and the maximum value present in the product term. Then it arranges the terms in the ascending order without repeating any literals, at the same time it continues to scan for a pair of complementary literals. This process while removing logical redundancy helps to establish the terms of the ANDOP output in their ascending order, which becomes useful in the OROP.

In case the index of AND gate is greater than two,

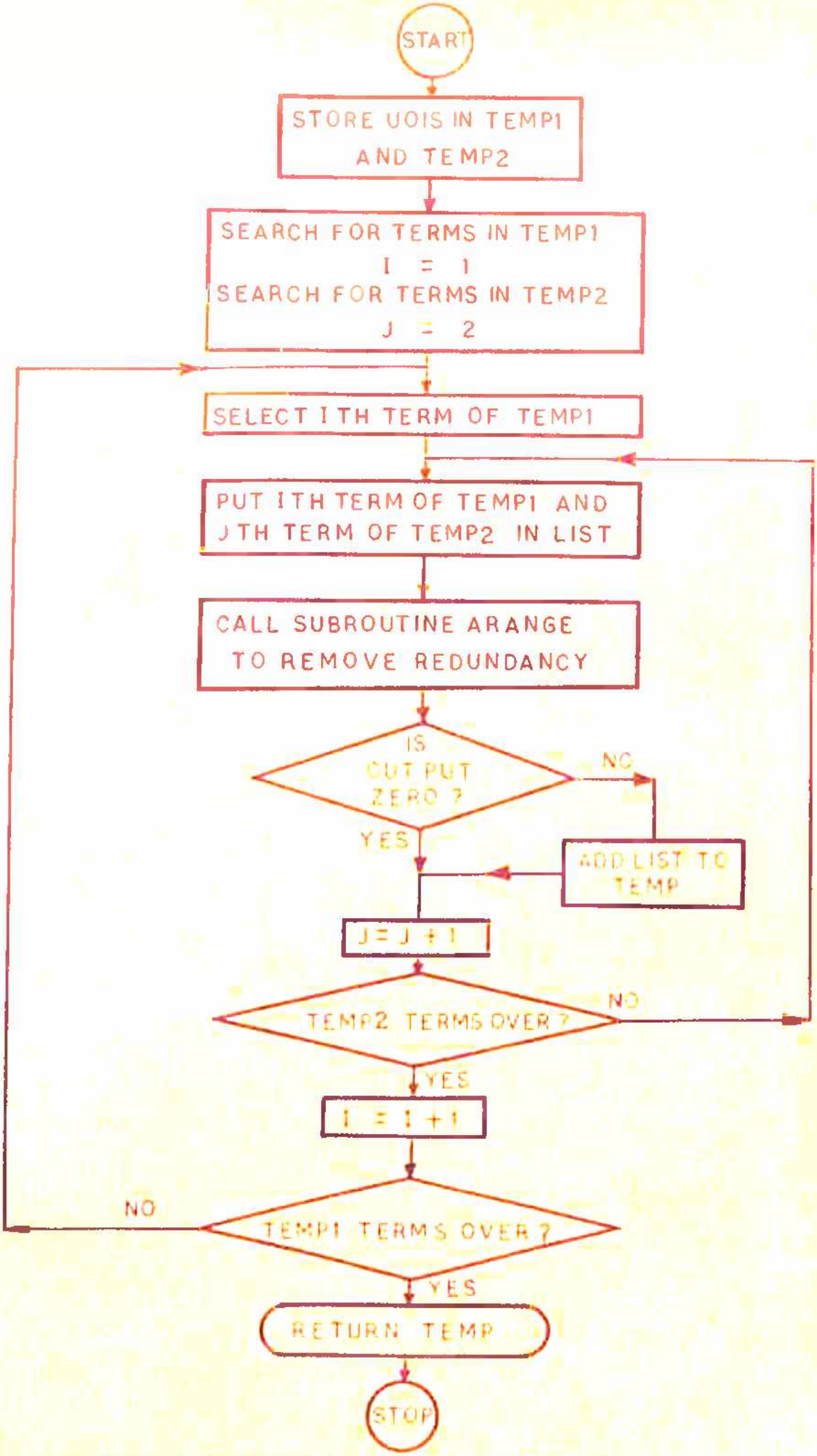


FIG. 3.4 FLOW CHART OF ANDOP

the result of ANDOP i.e. TEMP is transferred into TEMP1 and the next UOI is popped out of the STACK to be stored into TEMP2. These two arrays are again fed to ANDOP. The process is repeated until the value of the index is reached. In case ANDOP results, in a zero value, the POL is searched for OR operator. If no further OR operator exists the programme is terminated and the declared result is zero. This is illustrated in the following equations:

$$(AB\bar{A} + CDB\bar{C} + BD\bar{B}) = 0 \qquad (3.5)$$

This result is maintained irrespective of further AND operators, since:

$$0.(\text{terms after further ANDing}) = 0 \qquad (3.6)$$

Alternatively, non zero result is obtained if even a single OR operator exists, since:

$$0 + (\text{terms after further ORing})$$
$$= (\text{terms resulted in ORing}) \qquad (3.7)$$

OROP Algorithm:

OROP is a straight forward application of three absorption rules given in eqns. (3.3c) to (3.3e). The principal flow chart is shown in the fig. 3.5. The flow chart shows the special ca e of a logical 1. The main features of this subroutine organisation are discussed below:

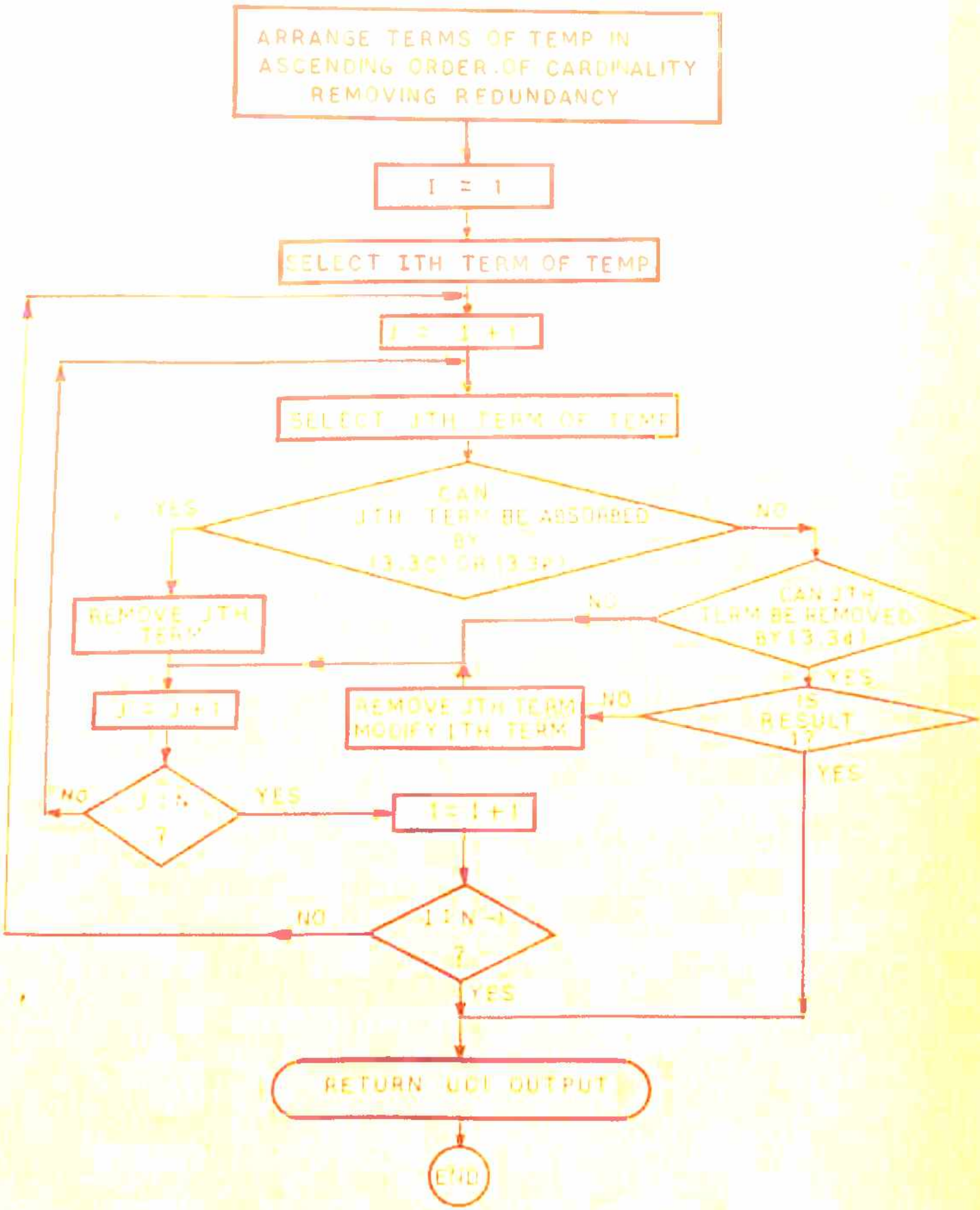


FIG. 3.5 FLOW CHART OF OROP

1. For the efficient implementation of these absorbtion rules it is necessary to arrange the terms contained in a UOI in the ascending order of cardinality. Two arrays are created from the UOI. The first stores the number of literals in each term of the UOI while the second one stores their starting positions. The first array is searched for the minimum number. After obtaining the desired number the least term is lifted from the UOI to a temporary storage, while the highest integer number permissible in the computer is stored in that location of the first array. The process continues till all the location of this array is filled with the highest number.

2. Application of the absorbtion rules are treated in two phases. In the first phase ith and the jth terms are compared on the basis of eqns. (3.3c) and (3.3e). As the terms are arranged in the order of ascending numbers, these comparisons becomes faster. Comparison of the first literal from each term will indicate whether absorbtion is necessary or not.

3. A slight difficultyarises if the answer to eqn. (3.3d) becomes positive, because the result not only removes the jth term but also reduces the ith term by one literal. It is not necessary to readjust the cardinality because this would shift the present ith term to some other space causing a repeat operation almost again from this point.

4. When the result of the OROP becomes 1, the main programme searches for further AND operation in the POL. If no such operator exists the final result becomes one. In case of any further AND operation the result deviates from unity. These are clear from the following equations:

$$A + \bar{A} = 1 \qquad (3.8)$$

$$1 + (\text{terms resulting from ORing}) = 1 \qquad (3.9)$$

$$1.(\text{terms resulting from ANDing}) = \text{terms resulting from ANDing} \qquad (3.10)$$

Expression such as eqn (3.2) represents the logical behaviour of the system input-output relation. The following section presents the interpretation of this as probability relationship.

3.7 PROBABILITY EXPRESSION FROM UOI:

So far the UOI expression has been derived purely from the point of view of logical information flow from source to sink. If probability is to be obtained from this, certain modification may be necessary.

Many published work and algorithms (5,118) exist to convert a Boolean function to a suitable expression to facilitate probability evaluation.

To appreciate the effect of this consider the Boolean expression obtained for the tree of fig. 3.2.

$$Z = AD + BCD$$

This function is plotted on a Karnaugh map in fig. 3.6. This map has been reinterpreted as probability map in the reference (118) where A, B, C, D represent the basic events with individual probabilities of occurrence q_a, q_b, q_c and q_d, while probabilities of nonoccurrence being p_a, p_b, etc. On this basis probability of the top event Z from fig. 3.6 is the probability of the sum of the events E_1 to E_5.

$$P[Z] = P[E_1] + P[E_2] + \ldots + P[E_5] \qquad (3.11)$$

where events E_1 to E_5 from fig. 3.6 becomes

$$E_1 = A.\bar{B}.\bar{C}.D.$$

$$E_2 = A.B.\bar{C}.D.$$

$$E_3 = A.\bar{B}.C.D.$$

$$E_4 = A.B.C.D.$$

$$E_5 = \bar{A}.B.C.D.$$

On substitution of the respective probability value into eqn. (3.11) one obtains

$$P(Z) = q_a p_b p_c q_d + q_a q_b p_c q_d + q_a p_b q_c q_d + q_a q_b q_c q_d + p_a q_b q_c q_d \qquad (3.12)$$

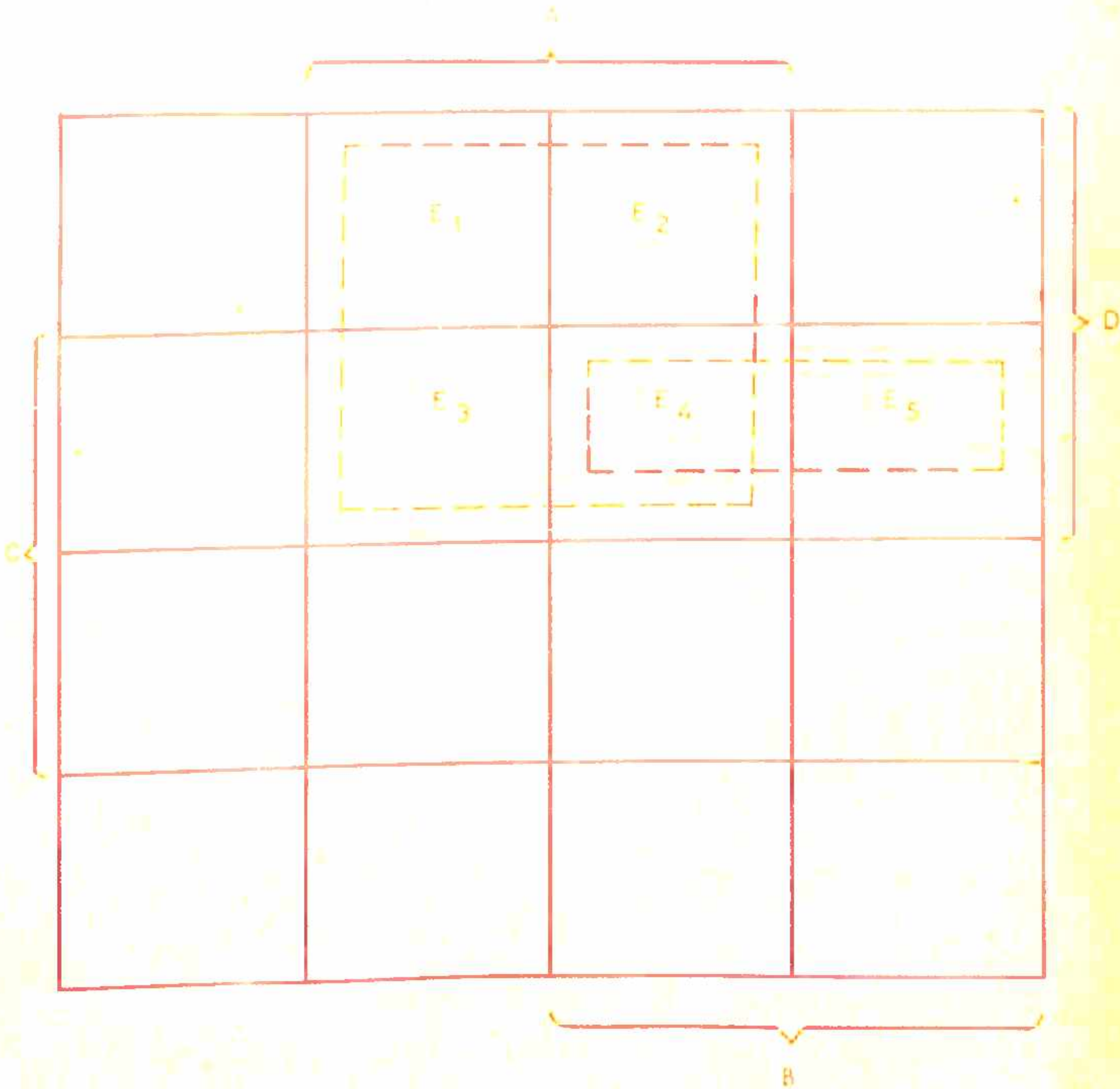


FIG. 3.6 KARNAUGH MAP

Equation (3.12) is the cannonical form of the original Boolean expression of (3.2). Disadvantage of this is that it contains maximum number of disjoint terms and requires more memory. Since all the terms have to be expanded with respect to the other time required for solution will also be high. Graphical technique used by Hurley is limited to a maximum of 8 basic events which is fairly small.

On closer scrutinisation of fig. 3.6 it is noticed that the event E_4 occurs twice in the terms AD and ACD. An alternative approach will be to modify the Boolean terms until they represent a disjoint grouping and yet avoiding either the canonical form or subtraction of the common area. The objective is to achieve this by maximum number of term, and one of the possibilities in this case is to group E_1, E_2, E_3, E_4 and E_5. This would change Z to

AD + ABCD

$$Z = AB + A.\bar{B}.C.D. \qquad (3.13)$$

Equation (3.13) represents a valid alternatives to the full canonical form given by eqn. (3.11).

So far two published work (5,7) are available which have considered the above problems through algorithmic approach. These two algorithms are reviewed critically here which will be followed by the author's modification:

Aggarwal's Method (5):

This method consists of rewriting the Boolean function in an ascending order of cardinality. First term is taken as it is, the second term is expanded about variables which have occured in first but not in second, and thus this term is rewritten such that it is disjoint with the first term. Then the third term is taken to convert into disjoint with respect to all previous terms. (These are already disjoint). The process is repeated till all terms are over.

An example is considered to illustrate term disjointing procedure, consider the Boolean function

$$Z = AB + CD \tag{3.14}$$

Expanding CD over AB

Step 1: $CD(A + \bar{A}) = ACD + \bar{A}CD$

Step 2: Check whether terms of step 1 are disjoint with respect to AB. The term ACD is not disjoint.

Step 3: $ACD(B + \bar{B}) = ABCD + A\bar{B}CD$

Total terms at the end of 3rd step are

$AB + ABCD + A\bar{B}CD + \bar{A}CD$

Step 4: Apply absorption rule.

The term ABCD is absorbed in AB

So the final disjoint terms of Z are

$$Z = AB + \bar{A}CD + A\bar{B}CD \tag{3.15}$$

Author's Comment:

The method is straight forward. If there are n terms in a Boolean function this approach needs a minimum of 1 +...+ n-1 disjointing attempts. Major flaw in this case is the reproduction of a logical redundant term resulting in the application of some absorbtion rule. This needs more time as well as memory.

Bennett's Approach (7):

This approach utilises a theorem and gives a better procedure which can be implemented in the computer to convert terms into disjoint.

The theorem states that any two conjunctive terms T_1 and T_2 will make a disjoint grouping if their exists at least one literal in T_1 whose complement occurs in T_2. A generalised procedure is given below .

Procedure: If T_i and T_j are two terms whose relative complement $T_k = T_i/T_j$ is defined by a nonempty set $(x_1, x_2, \ldots, x_n)$, then the above terms can be converted into a collection of disjoint terms with the help of the following expansion.

$$Z = T_i + T_j$$

$$= T_i + \bar{x}_1 T_j + x_1 \bar{x}_2 T_j + \ldots + x_1 x_2 \ldots \bar{x}_n T_j \qquad (3.16)$$

If the term T_i contains more literals than T_j, it is possible that more terms may be generated through the above process. Therefore, while implementing this procedure it is necessary to check the terms for its cardinality. Equation (3.2) is used to illustrate this

$$Z = BCD + AD$$

$$T_1 = BCD$$

$$T_2 = AD$$

Relative complement i.e. T_1/T_2 is (BC). Applying the above procedure one can get

$$Z = BCD + \bar{B}AD + B\bar{C}AD \qquad (3.17)$$

If terms are interchanged to make:

$$T_1 = AD$$

$$T_2 = BCD$$

relative complement of T_1/T_2 becomes (A). So disjoint terms are,

$$Z = AD + \bar{A}BCD \qquad (3.18)$$

Both the eqns. (3.17) and (3.18) are valid disjoint expression, but eqn. (3.18) is preferrable for least number of operations and memory.

In brief Bennetts algorithm for disjoint terms is given below:

1. Read the given UOI, total number of terms = N
2. I = 1
3. J = I + 1

4. Select Ith term T(I)
5. Select Jth term T(J)
6. Are T(I), T(J) disjoint ? If yes goto 7
   If not goto 8
7. J = J+1. Go to 9.
8. Apply disjoint process, position any additional terms according to the cardinality and up date N. Goto 7.
9. Is J greater than N ? If yes goto 10
   If not goto 5.
10. I = I+1
11. Is I greater than (N-1) ?. If yes print out the terms and stop. If not goto 3.

Author's comment:

The strength of the above algorithm lies on the ease of computerisation to convert the terms of an UOI into mutually exclusive based on the expansion process, which makes the algorithm more useful compared to Aggarwal's. However, this algorithm requires more memory and time as indicated by step 10, because it is possible to increment I by an amount which is equal to the literals present in the complement of T_i and T_j, since all terms created by the above process will be disjoint. After the generation of the additional terms in the step 8, when these are rearranged according to their cardinality, there is a chance that a particular term may be missed

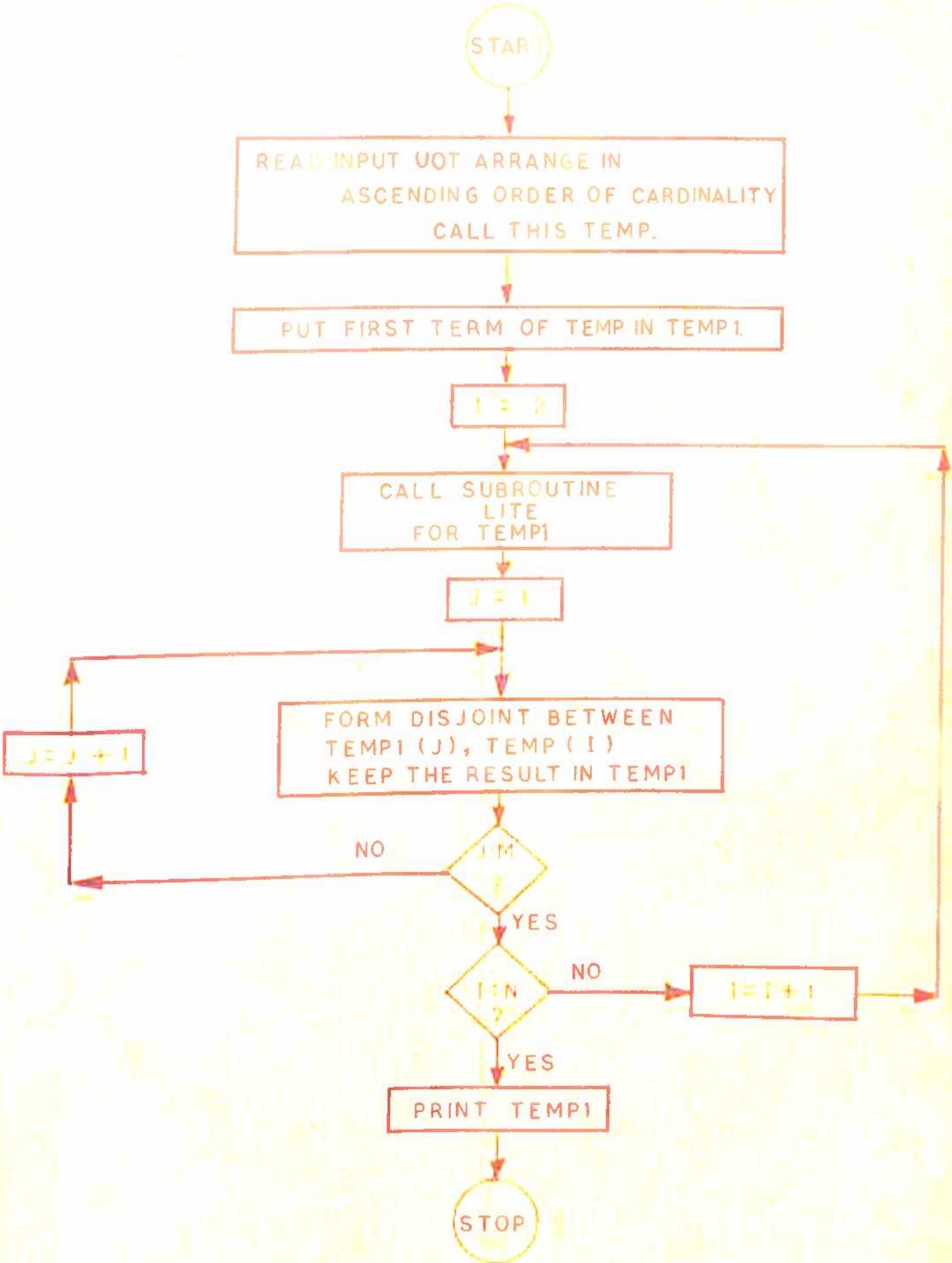


FIG. 3.7 ALGORITHM FOR DISJOINT TERM.

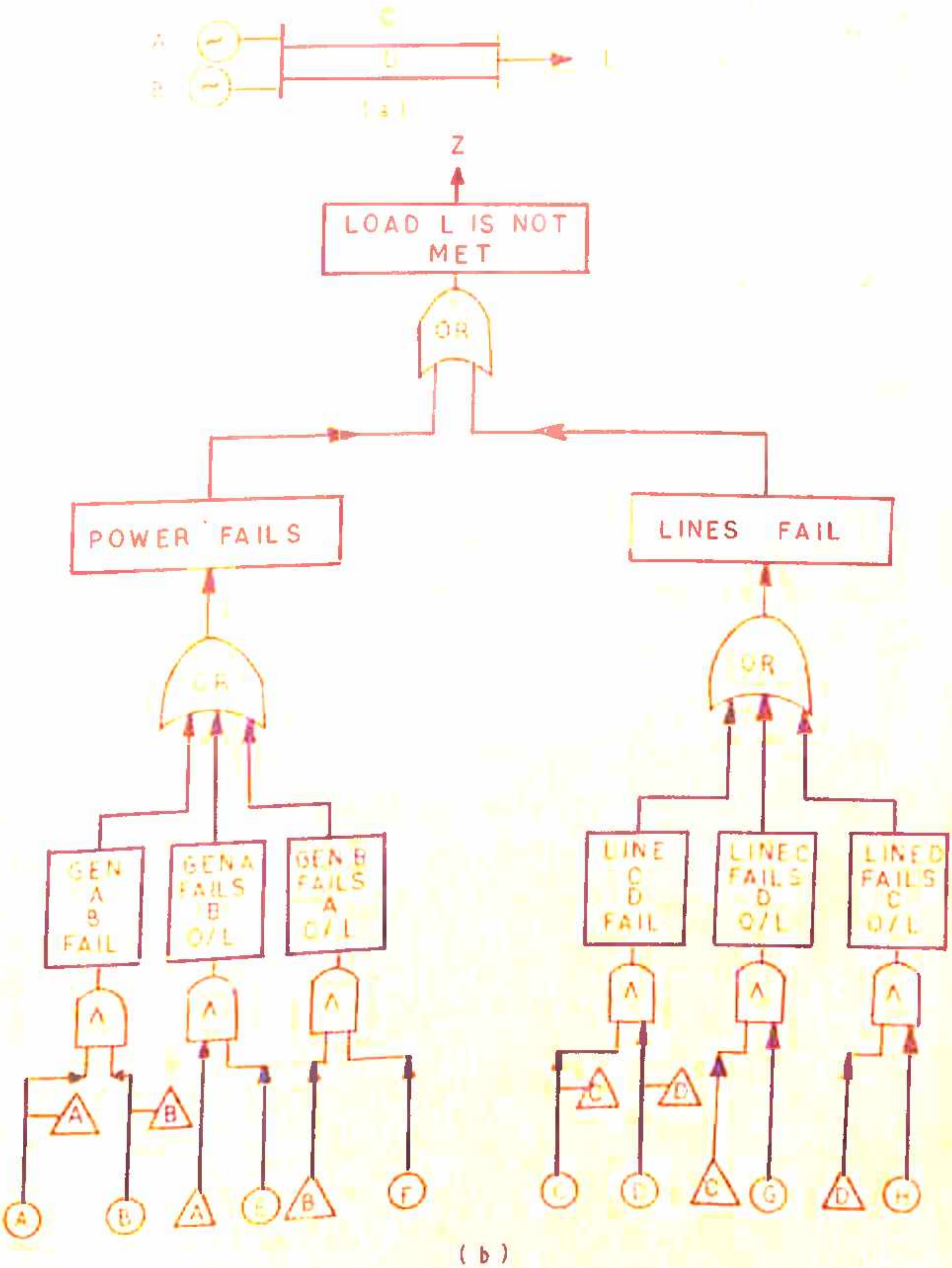


FIG. 3.8 (a) RADIAL SYSTEM

(b) FAULT TREE

where:

a_x = rate of departure to higher load

b_x = rate of departure to lower load

L = variable load

X = given load level.

Fault tree for the system of fig. 3.8a is shown in the fig. 3.8b. Failure to meet the load at bus B has been selected as the top event. The fault tree of the above figure is constructed based on the failure mode of the system. Overload status of either a line or a generator has also been considered here as a failure mode for the given equipment. It is to be noted here that the state of overload of an equipment is assumed to be a random event, though this depends on system load and other equipment state. For example when the load on bus B exceeds certain value, the state of the line may change from normal to overload given the other line is in a state of forced outage. This can be stated mathematically as

P(line 2 gets overloaded | line 3 is out)

$$= P(L > X_1) \qquad (3.20)$$

The tree of fig. 3.8b is read in the computer to give an rpe as

Z = AB AND(2)AE AND(2)BF AND(2)OR(3)CD AND(2)
CG AND(2)DH AND(2) OR(4) (3.21)

Since the system load flow is obvious under contingency, for a given load, some values of the above rpc can be assigned zero after the corresponding UOI is obtained. The resulting UOI from the computer output is

$$Z = AB + AE + BF + CD + CG + DH \tag{3.22}$$

Generator, line and load data for the system of fig. 3.8a is given in the table 3.3. Three load levels are considered as (1) less than 10 MW, (2) between 10 MW and 20 MW, (3) More than 20 MW. From the system configuration it can be seen that overloading of lines and generators are not possible for the case 1 and hence E, F, G and H are made zero in the equation (3.22). Algorithm of disjoint events is then applied to obtain the probability that this load cannot be met. For the case (2) when generator B goes to forced outage state generator A gets overloaded.

TABLE 3.3 SYSTEM DATA

	Generator A	Generator B	Line C	Line D
Failure rate	1×10^{-4}	0.5×10^{-4}	1×10^{-4}	2×10^{-4}
Repair rate	4×10^{-2}	4.5×10^{-2}	0.15	0.2
Capacity	10 MW	20 MW	20 MW	20 MW

Failure and repair rates are expressed per hour.

Except for this no other equipment can get overloaded in this range of load. Therefore, E,G and H will continue to be zero and the probability of event F may be obtained from the eqn. (3.20). Only when load exceeds 20 MW, all of the equipment can go to overload state. Probability values of Z and load are listed in Table 3.4. Final disjointed events are,

TABLE 3.4 PROBABILITY OF TOP EVENT AND LOAD RANGES

Load level	P(L)	P(Z)x10^{-5}
L < 10 MW	0.003	0.3306
10 < L < 20	0.430	47.46998
L > 20	0.567	235.68463

$$
\begin{aligned}
Z = \; & AB + A\bar{B}\bar{E} + \bar{A}BF + \bar{A}.\bar{B}.C.D. + \bar{A}.B.C.D.\bar{F}. + A\bar{B}CD\bar{E} \\
& + \bar{A}.\bar{B}.C.\bar{D}.G. + \bar{A}.B.C.\bar{D}.\bar{F}.G. + A.\bar{B}.C.\bar{D}.\bar{E}.G. + \bar{A}.\bar{B}.\bar{C}.D.H. \\
& + \bar{A}.B.\bar{C}.D.\bar{F}.H. + A.\bar{B}.\bar{C}.D.\bar{E}.H. \qquad (3.23)
\end{aligned}
$$

Three Bus Interconnected Power System:

Logic wise radial and interconnected systems are almost identical, except that for the latter case load flow is not obvious and prior studies of load flows will only reveal some of the additional failure modes. One such mode which is not considered in the previous

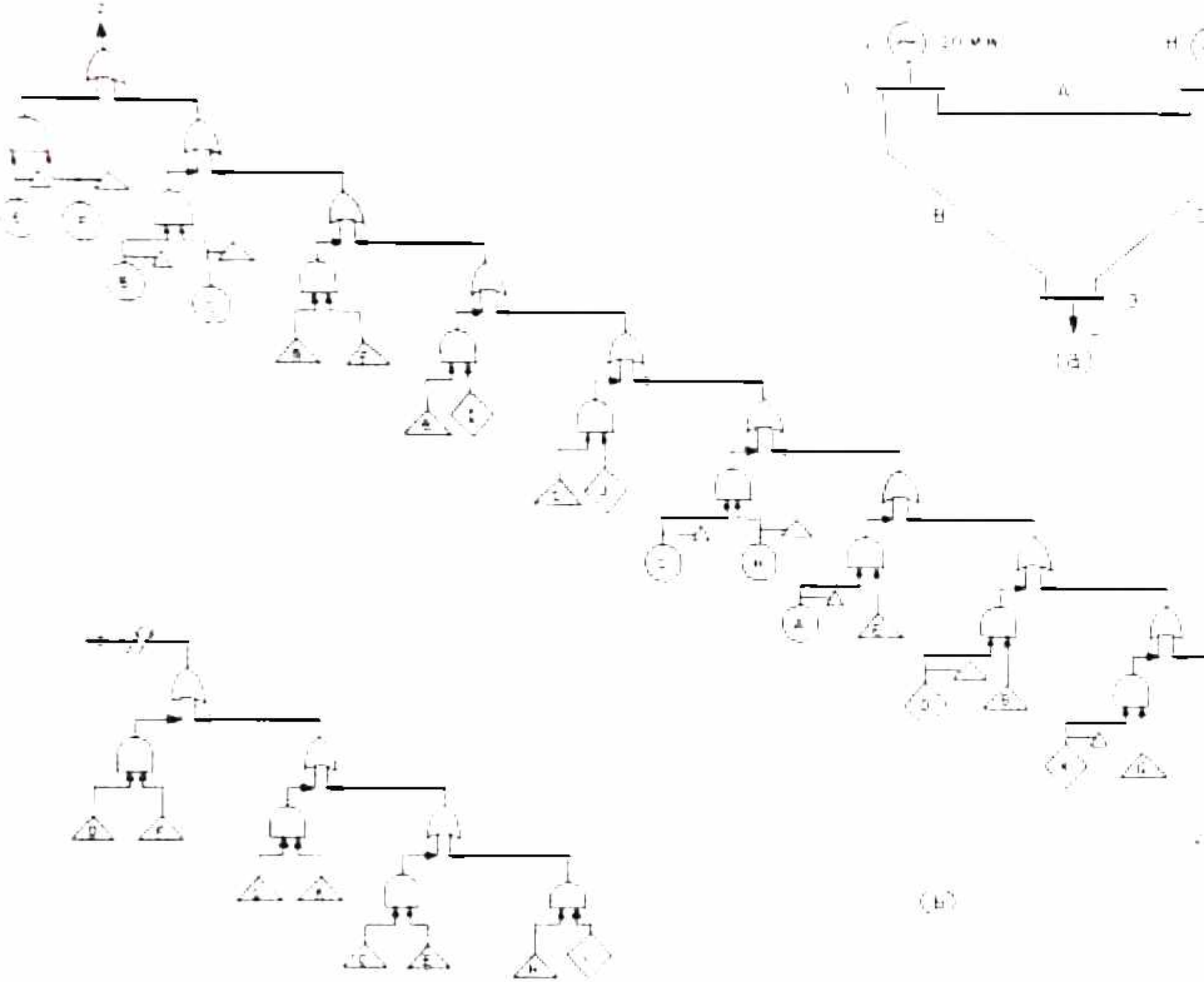
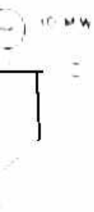


FIG. 3.9 (a) INTER CONNECTED POWERSYSTEM
(b) FAULT TREE



LEGEND

Z = TOP EVENT
A = LINE 1—2 OUT
B = LINE 1—3 OUT
C = LINE 2—3 OUT
D = LINE 1—2 O/L
E = LINE 1—3 O/L
F = LINE 2—3 O/L
G = 25MW GEN OUT
H = 10 MW GEN OUT
I = BUS 3 VOLTAGE OUTSIDE RANGE, GIVEN EVENT B
J = BUS 3 VOLTAGE OUTSIDE RANGE, GIVEN EVENT C
K = 10 MW GEN O/L
L = 20 MW GEN O/L

AND LOGIC

OR LOGIC

TABLE 3.5 LOAD FLOW RESULTS WITH OUTAGES

LOAD LEVEL P.U.	LINE 1-2 OUT						LINE 1-3 OUT						LINE 2-3 OU			
	BUS VOLTAGE P.U.			LINE CURRENT P.U.			BUS VOLTAGE P.U.			LINE CURRENT P.U.			BUS VOLTAGE P.U.			
	1	2	3	1-2	1-3	2-3	1	2	3	1-2	1-3	2-3	1	2	3	1
0.01	1.0	1.028	1.012	-	0.089	0.099	1.0	1.013	1.012	0.09	-	0.010	1.0	1.015	0.998	0.
0.02	1.0	1.026	1.011	-	0.079	0.099	1.0	1.012	1.009	0.08	-	0.020	1.0	1.015	0.996	0.
0.04	1.0	1.023	1.008	-	0.059	0.098	1.0	1.009	1.002	0.06	-	0.040	1.0	1.015	0.993	0.
0.06	1.0	1.020	1.005	-	0.039	0.100	1.0	1.006	0.996	0.04	-	0.061	1.0	1.015	0.990	0.
0.07	1.0	1.019	1.003	-	0.029	0.100	1.0	1.004	0.992	0.029	-	0.070	1.0	1.015	0.988	0.
0.08	1.0	1.017	1.002	-	0.019	0.100	1.0	1.002	0.989	0.019	-	0.082	1.0	1.015	0.986	0.
0.1	1.0	1.014	0.999	-	0.003	0.100	1.0	0.998	0.982	0.003	-	0.108	1.0	1.015	0.983	0.1
0.12	1.0	1.011	0.995	-	0.022	0.100	1.0	0.995	0.974	0.023	-	0.125	1.0	1.015	0.979	0.1
0.14	1.0	1.008	0.992	-	0.042	0.101	1.0	0.991	0.967	0.045	-	0.147	1.0	1.015	0.976	0.1
0.16	1.0	1.004	0.989	-	0.063	0.101	1.0	0.987	0.959	0.067	-	0.171	1.0	1.015	0.972	0.1
0.17	1.0	1.003	0.987	-	0.073	0.101	1.0	0.985	0.955	0.078	-	0.181	1.0	1.015	0.970	0.1
0.18	1.0	1.001	0.985	-	0.084	0.101	1.0	0.982	0.951	0.089	-	0.193	1.0	1.015	0.968	0.1
0.2	1.0	0.997	0.982	-	0.105	0.102	1.0	0.978	0.942*	0.112	-	0.216	1.0	1.015	0.965	0.1
0.22	1.0	0.994	0.978	-	0.126	0.102	1.0	0.973	0.933*	0.136	-	0.24	1.0	1.015	0.961	0.1
0.24	1.0	0.990	0.975	-	0.148	0.102	1.0	0.968	0.924*	0.160	-	0.264*	1.0	1.015	0.957	0.1
0.26	1.0	0.987	0.971	-	0.169	0.103	1.0	0.963	0.914*	0.184	-	0.289*	1.0	1.015	0.953	0.10
0.28	1.0	0.983	0.967	-	0.191	0.103	1.0	0.958	0.904*	0.209	-	0.315*	1.0	1.015	0.949*	0.10
0.29	1.0	0.981	0.965	-	0.202	0.103	1.0	0.955	0.899*	0.224	-	0.328*	1.0	1.015	0.947*	0.10

* The readings with asterik indicate values out side permissible limit.

different load ranges.

TABLE 3.6 PROBABILITY OF TOP EVENT

Load level	Probability of top event x 10^{-3}
$L \leq 10$ MW	0.3306
$10 < L < 20$	49.2685
$L \geq 20$	240.613400

An exhaustive state-probability computations are never attempted to assess power system reliability, since it has been assumed that simultaneous contingency more than two does not contribute significantly to the final probability value. However, for greater accuracy when all the states are considered the memory requirement and computation time becomes prohibitive even for small size power system. In fault tree analysis one needs to find out only the minimal cut-sets and hence computation time and memory requirement are greatly reduced without sacrificing accuracy.

At this stage a mechanised way of forming a fault tree is not possible, which is viewed as a strong point amongst the fault tree analysts, as nonmechanisation in fact leads to an intimate feel about the failure modes of the concerned system. Furthermore, once the fault tree is generated for a system, minor alterations are needed when the system expansion takes place.

3.9 CONCLUSIONS:

The chapter has described a procedure for analysing the fault tree structure, considered to be a combinatorial logic network to produce a corresponding Boolean expression. It has further shown how this expression can be interpreted as a probability relationship after a simple disjointness test. An improved algorithm has been proposed here which requires less memory and is faster. To the author's knowledge this is the first attempt to tackle power system reliability problem through fault tree analysis. It is possible to use this technique to find the probability of not meeting the load at each bus of a multinode power system.

Chapter-IV POWER SYSTEM SECURITY THROUGH PATTERN RECOGNITION TECHNIQUES:

4.1 INTRODUCTION:

Recognition is regarded as a basic attribute of human beings, as well as other living organisms. A pattern may be regarded as a quantitative description of an object. All living bodies perform acts of recognition at every instant of their waking lives. They recognise the objects around them and act in relation to them. Human being is a very sophisticated information processor, partly because it possesses a superior pattern recognition capabilities. Pattern recognition concepts are being increasingly recognised as an important factor in the design of modern computerised information systems. Interest in this area is still growing at a rapid rate, having been a subject of interdisciplinary study and research in the fields of engineering, statistics, physics, linguistics, psychology, medicine, meteorology, etc.

Basically when the human mind perceives a pattern it makes an inductive inference and associates this with some general comets or clues which it has derived from its past experience. Thus problem of pattern recognition may be regarded as one of discriminating the input data, not between individual patterns but between classes via the search for features or invariant attributes among the members of a population.

This chapter deals with the general techniques of the pattern recognition after defining this problem formally through mathematical models. It then goes to review some techniques of generating decision surface and takes up four different methods for comparing their suitability to recognise power system patterns.

4.2 METHODOLOGY OF PATTERN RECOGNITION:

The study of pattern recognition problems is the development of theory and techniques for the design of devices capable of performing a given recognition task for a specific application. The concepts for automatic pattern recognition depend on how the pattern classes are characterised and defined. When a pattern class is characterised by common properties shared by all of its members, the design may be based on the common property concept. In case the pattern class exhibits clustering property, the design may be based on this. Basically a pattern is the description of any system or object and can be treated as a point in Euclidian space.

Common Property Concepts:

Whenever a class of patterns is characterised by some common properties which are shared by the individual patterns, classification can be carried out by processing similar features. These common properties may be stored in the computer. When an unknown pattern is observed by the system its features are extracted and then compared with the stored features. The recognition scheme will classify the new pattern as belonging to the pattern class of similar features.

Clustering Concepts:

In many cases the individual member of pattern class tends to cluster around some point. Depending whether the clusters are distinctly spaced apart in the pattern space or overlapped near the boundary, various techniques can be used to classify the patterns to relative classes. It is evident that the methods used for the former type of clusters are simpler.

The basic design concept of automatic pattern recognition as described above may be implemented through mathematical approach. This is based on classification rules which are formulated making use of common property and clustering concepts. This approach is subdivided into two categories: deterministic and statistical. The former approach is based on a mathematical frame work which does not employ the statistical properties of the concerned pattern classes. Iterative techniques based on minimisation of certain objective function are the example of this type. Whereas the statistical approach is formulated and derived using the statistical properties of the patterns. This is mostly based on the Bayes classification rule. This rule yields an optimum classifier when probability density function (pdf) of each pattern class and probability of its occurrence are known.

Mathematical Formulation Of The Problem:

Let X and Y be N_1 and N_2 number of patterns belonging respectively to classes ω_1 and ω_2 in n-dimensional Euclidian space. The problem of pattern recognition is to device a surface $S(\underline{x})$ which will separate these two classes in some optimal sense. Given an unknown pattern in the same space the surface will be able to categorise it into the proper class. The classification is based on the following logic:

$$S(\underline{x}) \begin{cases} \geq 0 & \underline{x} \text{ belongs to } \omega_1 \\ < 0 & \underline{x} \text{ belongs to } \omega_2 \end{cases} \qquad (4.1)$$

This problem can be extended for multiclass situations by computing surfaces to distinguish class i from class j as given below:

$$S_{ij}(\underline{x}) = S_i(\underline{x}) - S_j(\underline{x}) \qquad (4.2)$$

$$\text{for } j = 1,2,3,\ldots,M$$
$$i \neq j$$

where M is the total number of classes.

Pattern Recognition Process:

From the above formulation it is clear that basically it has two aspects - (1) developing decision surface as evident from eqns. (4.1) or (4.2), (2) using it. The actual recognition occurs in the use of the rule. The pattern is defined in the training process by the labelled samples. In mathematical pattern recognition, a given rule should be able to classify a pattern quickly, although considerable time may be required to derive the decision rule. These stages of the pattern recognition, as described above, can be performed sequencially. Figure 4.1 gives a block diagramatic approach to this problem. From a given physical system patterns are obtained either through measurement by means of certain sensing devices or getting them through computer simulation. This set of raw data is termed as measurement space, that is a pattern sample given by specific values of all the measurements, corresponds to a point in this space. Pattern space may be identical to measurement space or may require some stages of preprocessing or may be a subset of the measurement space.

The above process is called as characterisation problem or feature selection. Given a pattern, before any decision can be made concerning this, it is always convenient and necessary to convert the pattern into a set of features. The features, thus selected, are of lower dimension which contain sufficient information to perform satisfactory classification. These features are usually denoted by real variables $\underline{x}_1, \underline{x}_2, \ldots$ The vector

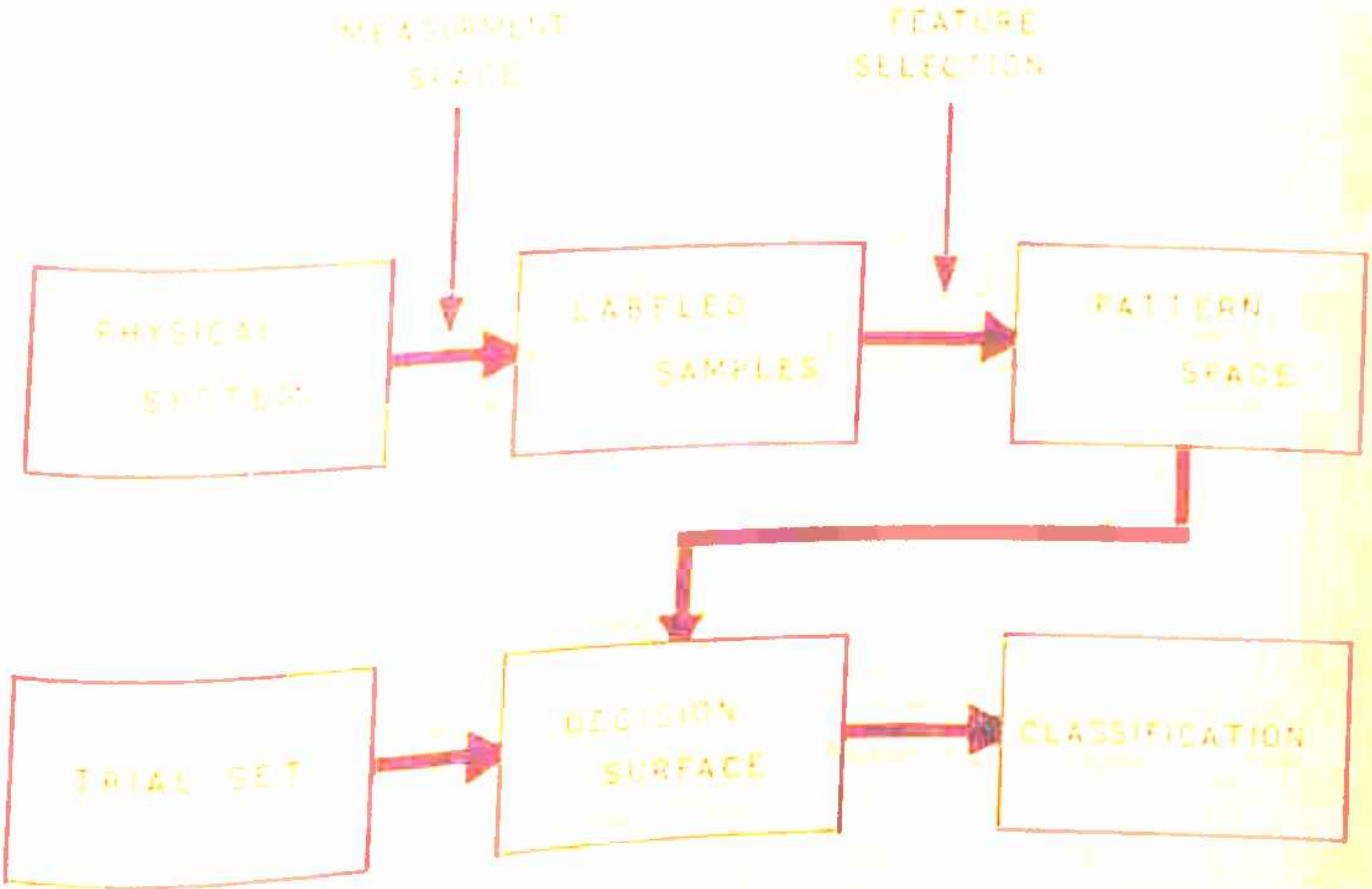


FIG. 4.1 PROCESS OF PATTERN RECOGNITION

$\underline{x}$ is called the pattern vector. Thus the characterisation problem can be stated simply as finding $\underline{x}$ features from $\underline{z}$ which attribute more towards the classification of the pattern. This may also be viewed as a mapping problem from measurement space to feature space with a view to reducing the dimension and helping classification.

In a supervised classification, some patterns termed as labelled samples are selected from each of the known classes. The decision surface i.e. the classifier is trained by these labelled samples. This process is known as abstraction.

Geometrical interpretation of the problem is exceedingly simple but illustrative as shown in figs. 4.2 to 4.5. In case the classes are linearly separable, the decision surface can be linear, otherwise this will be a non-linear surface, or piecewise linear.

Case I:

In this case each class is linearly separable from the other by a single surface as shown in fig. 4.3. For example, if an unknown vector $\underline{x} = (x_1, x_2)^t$ causes $S_1(\underline{x}) < 0$, $S_3(\underline{x}) < 0$ and $S_2(\underline{x}) > 0$ then this belongs to class ω_2.

Case II:

In this case each class is linearly separable from another one. It requires $\frac{M(M-1)}{2}$ (combination of M classes

FIG 4.2 LINEARLY SEPARABLE 2-CLASS PROBLEM
0-TEST PATTERN.

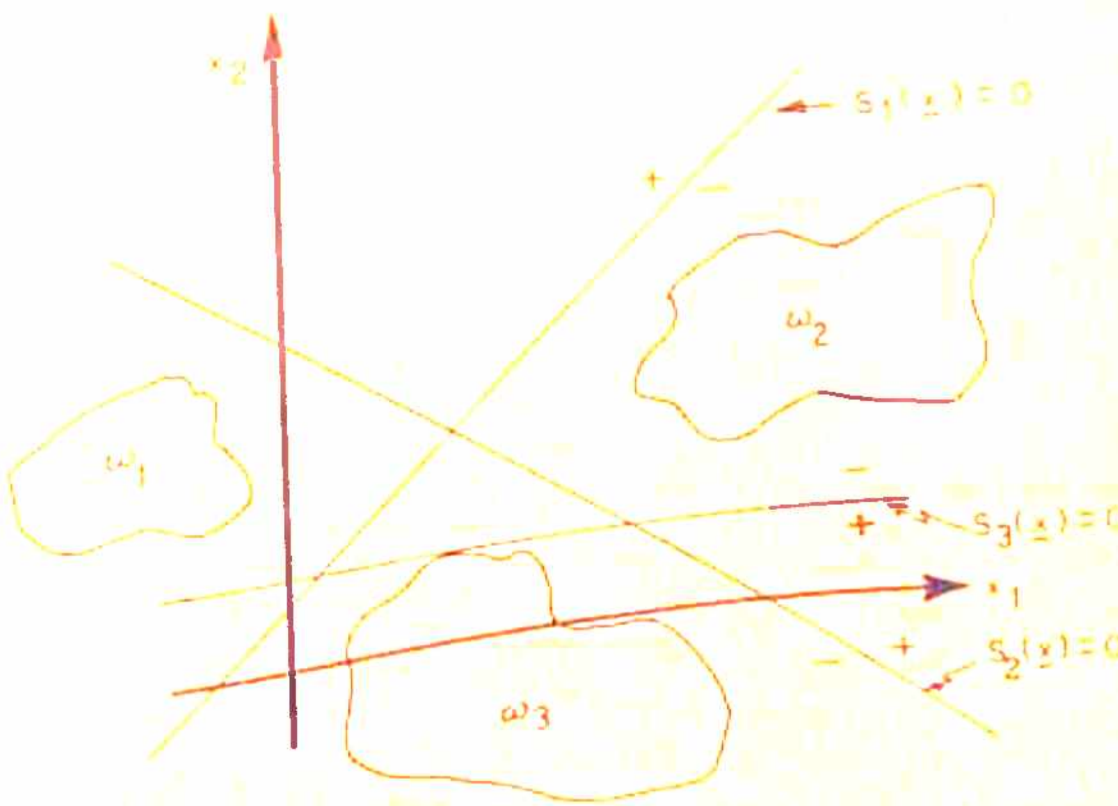


FIG. 4.3 3-CLASS PROBLEM OF CASE I TYPE.

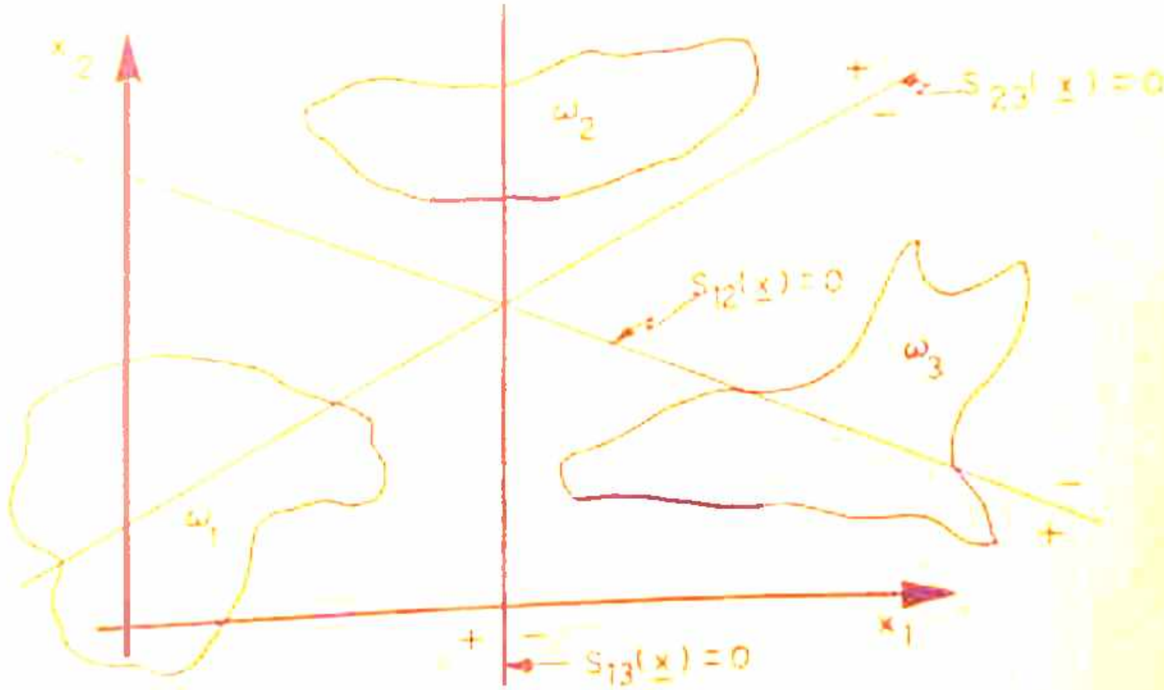


FIG. 4.4 3-CLASS PROBLEM OF CASE II TYPE.

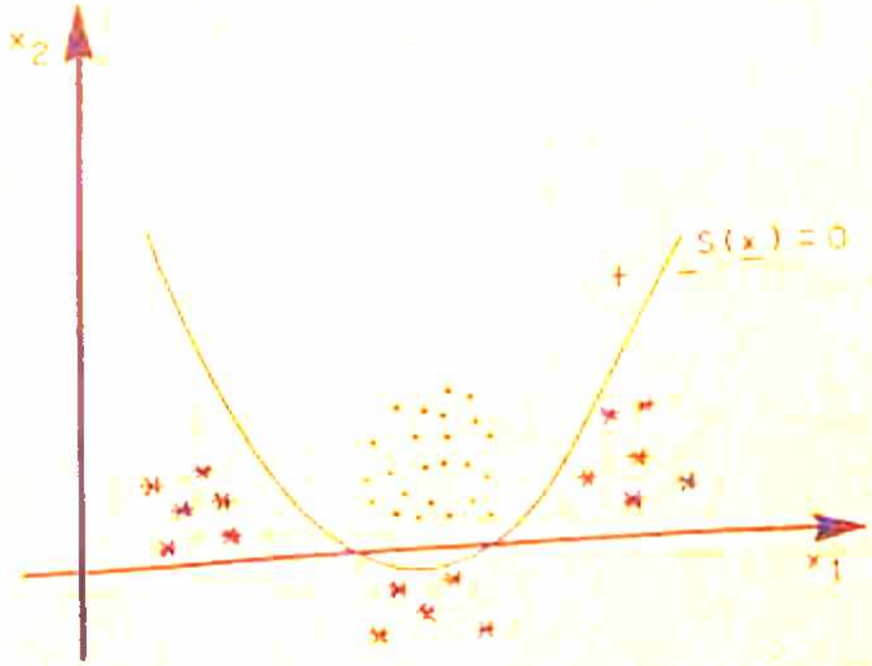


FIG. 4.5 NONLINEAR DECISION SURFACE.

taken any two at a time) decision surfaces. Advantage of this is that indeterminant area is very much reduced from the previous one. Equation (4.2) represents these type of surfaces.

In fig. 4.5 the two classes of patterns are not linearly separable. In such cases the decision surfaces are either nonlinear or piecewise linear. General expression for these decision surfaces are given as

$$S(\underline{x}) = w_{oo} + w_1x_1 + w_2x_2 + \dots + w_nx_n$$
$$= \underline{w}^t\,\underline{x} = 0 \qquad (4.3)$$

or

$$S(\underline{x}) = w_{oo} + \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}\, x_i \cdot x_j = 0 \qquad (4.4)$$

4.3 REVIEW OF PATTERN RECOGNITION TECHNIQUE LITERATURE:

A host of techniques mostly heuristic are available in the pattern recognition literature. Some of these are reviewed critically in the subsequent pages.

Decision Surface by Linear Program (71,84,92,115):

Linear programming methods, guarantee the optimality of the given linear function. This has been applied for static cases (98,115) wherein, only a single set of pattern vectors is given and in dynamic case (71) wherein old pattern vectors are replaced by the current one. The problem is formulated such that simplex algorithm can be used.

$$\text{Minimise} \quad \left| \sum_{i=1}^{n} w_i x_i + w_o \right| \geq b$$

subject to:

$$\sum_{i=o}^{n} (w_i^+ - w_i^-)\, x_i^j \geq b \quad \text{if} \quad x_i^j \text{ belongs to class } \omega_1$$

$$\sum_{i=o}^{n} (w_i^+ - w_i^-)\, x_i^j \leq -b \quad \text{if} \quad x_i^j \text{ belongs to } \omega_2$$

where b is an arbitrary positive number.

Comment:

This technique has been applied successfully for classifying vectors which may not be linearly separable. However, computation time here is much more compared to the other techniques of linear classifiers as the number of pattern vectors are much more than the dimension of the vectors. Furthermore, this technique has to store the simplex tablean requiring thereby additional memory.

Polynomial Discriminant Function (106):

This is a method of determining nonlinear surfaces which is based on Bayes' decision rule. This has avoided storage and large amount of mathematical operations as required by other method using Bayes' rule. However, the estimation of probability density function for the sample vector belonging to certain class is based on an interpolation function which is required to possess a spherical symmetry.

In this thesis, however, the nonlinear surfaces are generated by using certain orthonormal functions which produces the weight vector in much simpler way.

Potential Function Approach (29,37,40,42,72,88,95):

Potential function has been used for linear classifier successfully when the classes are linearly separable. This has also been extended to overlapping classes when used along with statistical approaches. Decision function is made to change as the training proceeds. Principal difficulties are the selection of proper potential function and computational difficulties when applied to a large set of labelled samples.

Statistical Approach (29,37,40,72,90,102,119,120):

In classical pattern recognition problems this has been used extensively. Mostly the decision surfaces are generated by using Bayes', minimax and Nayman-Pearson strategies. It is assumed that probability of occurrence of each class is known, and the conditional pdf of a pattern given a class is either known or estimated. In most of the cases it results in a linear or nonlinear decision surface without going into iterative process. This approach is suitable for overlapping patterns.

Linear Decision Function (73,95,104,110,114,121):

This is a relatively simple approach derived from the pioneering perception algorithm. The various methods belonging to linear decision function differ from the point of view of defining proper performance criteria. Because of the recursive relation of the weight vector this method requires least storage and converging rates of this approach can be controlled through certain parameter. The methods work at their best only for linearly separable classes.

Four powerful techniques have been selected here for detailed study in determining their suitability in recognising power system patterns. The necessary mathematical treatments are given in the following section.

4.4 DETERMINISTIC APPROACH:

If it is possible to obtain a n-dimensional weight vector which will make the eqn. (4.3) greater than zero for a set of vector $\underline{x}$ belonging to ω_1 and less than zero for the other vectors of class ω_2 then the vectors are said to be consistent. In such cases iterative procedure of determining weight vectors are invariably used. In the above case the pattern belonging to class ω_2 may be multiplied by -1 to make

$$\underline{w}^t \underline{x} \geq 0 , \quad \text{for all } \underline{x} \qquad (4.5)$$

where $\underline{w}$ and $\underline{x}$ are weight and pattern vectors respectively. If there are altogether N number of pattern vectors belonging to either of the two classes the eqn.(4.5) may be restated as

$$\sum_{j=0}^{n} w_j x_{ij} \geq 0 \qquad (4.6)$$

for $i = 1, 2, \ldots, N$

where:

w_j = jth element of vector $\underline{W}$

x_{ij} = jth element of ith pattern vector $\underline{X}_i$

Least Mean Square Algorithm:

The perceptron and its variations converge when the classes under consideration are separable by the specified decision surface. In nonseparable situation, however, these algorithms simply oscillate. For a large training set one sometimes wonders whether or not the classes are linearly separable.

The algorithm derived in this section, in addition to being convergent for separable classes, also points out in the course of its operation that the classes under consideration are not linearly separable, if this is indeed the case. This unique feature makes this algorithm a valuable tool for pattern classifier design.

The problem stated in eqn. (4.6) may be written as follows

$$\underline{X}\,\underline{W} = \underline{b} \qquad (4.7)$$

where:

$\underline{X}$ = (N, n+1) dimension matrix whose row corresponds to a pattern vector.

$\underline{b}$ = an N-dimension vector with positive elements only.

$\underline{w}$ = (n+1)-dimension weight vector

Consider the criterion function.

$$J = \tfrac{1}{2} || \underline{X}\,\underline{w} - \underline{b} ||^2 \qquad (4.8)$$

where J indicates the magnitude of the vector $(\underline{Xw} - \underline{b})$. The function achieves its minimum values whenever eqn. (4.7) is satisfied. Criterion function is actually proportional to average or mean of the square error.

The gradient of J with respect to $\underline{w}$ and $\underline{b}$ is

$$\frac{\partial J}{\partial w} = \underline{X}^t (\underline{X}\,\underline{w} - \underline{b}) \qquad (4.9)$$

$$\frac{\partial J}{\partial b} = (\underline{b} - \underline{X}\,\underline{w}) \qquad (4.10)$$

Since $\underline{w}$ is not constrained, minimum of J means

$$\underline{X}^t (\underline{X}\,\underline{w} - \underline{b}) = 0 \qquad (4.11)$$

or $$\underline{w} = \underline{X}^{\#}\,\underline{b} \qquad (4.12)$$

where:

$$\underline{X}^{\#} = (\underline{X}^t\,\underline{X})^{-1}\,\underline{X}^t$$

= generalised inverse of $\underline{X}$

On the otherhand $\underline{b} > 0$ means a descent procedure of the following type, with k denoting iteration count:

$$\underline{b}(k+1) = \underline{b}(k) + \partial\underline{b}(k) \quad (4.13)$$

where ith component of the vector $\partial\underline{b}(k)$ is

$$\partial b_i(k) = \begin{cases} (\underline{X}\,\underline{w}(k) - \underline{b}(k))_i\ 2c & \text{if } (\underline{x}_i^t\,\underline{w}(k) > b_i(k)) \\ 0 & \text{if } (\underline{x}_i^t\,\underline{w}(k) < b_i(k)) \end{cases}$$

(4.14)

The above expression can be compactly written in vector form by

$$\partial\underline{b}(k) = c\,(\underline{X}\,\underline{w}(k) - \underline{b}(k) + |\underline{X}\,\underline{w}(k) - \underline{b}(k)\,|) \quad (4.15)$$

where c is a positive scaler constant.

From eqns. (4.12) and (4.13) one can get

$$\begin{aligned} \underline{w}(k+1) &= \underline{X}^{\#}\ \underline{b}(k+1) \\ &= \underline{X}^{\#}\ (\underline{b}(k) + \partial\underline{b}(k)) \\ &= \underline{X}^{\#}\ \underline{b}(k) + \underline{X}^{\#}\ \partial\underline{b}(k) \\ &= \underline{w}(k) + \underline{X}^{\#}\ \partial\underline{b}(k) \end{aligned} \quad (4.16)$$

(4.17)

Letting $\underline{e}(k) = \underline{X}\,\underline{w}(k) - \underline{b}(k)$

where $\underline{e}(k)$ represents the error at kth iteration.

Following algorithm is then formed which can be used successively to find the final weight vector.

1. Read the augmented pattern vectors belonging to the training set of classes ω_1 and ω_2. Read the elements of the vector $\underline{b}$.

2. Obtain the generalised inverse for the pattern matrix $\underline{X}$.

3. Assume iteration count to be 1 i.e. k = 1.

4. Calculate $\underline{w}(k)$ and $\underline{e}(k)$ from the following expressions

$$\underline{w}(k) = \underline{X}^{\#}\ \underline{b}(k)$$

$$\underline{e}(k) = \underline{X}\ \underline{w}(k) - \underline{b}(k)$$

5. $k = k+1$

6. Up date the weight vector and $\underline{b}$ as in the following expressions

$$\underline{w}(k+1) = \underline{w}(k) + c\ \underline{X}^{\#}\ (\underline{e}(k) + |\underline{e}(k)|)$$

$$\underline{b}(k+1) = \underline{b}(k) + c\ (\underline{e}(k) + |\underline{e}(k)|)$$

7. Check whether all component of error vector are negative. If yes goto 9. If not goto 8.

8. Check whether error vector is within a tolerable limit. If not goto 5. If yes goto 10.

9. Pattern classes are overlapping. Stop the programme.

10. Print weight vector and call exit.

Adaptive Linear Classifier:

The details of the adaption algorithm are best brought to light through introducing the concepts of pattern error and pattern error function. Assume that an observer is presented with a two-category pattern classification problem and for each category ω_i there are N_i labelled samples. The parameters of the classifier must be obtainable through these samples.

As a first step, it might be assumed that a perfectly adapted classifier would give some number b_i as a desired output for each sample in ω_i. The classifier can achieve this only if the set of equation

$$\hat{\underline{X}}^t \, \underline{w} = \underline{b} \tag{4.18}$$

are consistent. Here $\underline{b}$ is a vector whose first N_1 components are $\underline{b}_1$ and next N_2 components are $\underline{b}_2$. The matrix $\underline{X}^t$ is given by

$$\hat{\underline{X}}^t = \left[\begin{array}{c|c} 1 & \\ 1 & \\ 1 & \underline{X}_1 \\ \vdots & \\ \hline 1 & \\ 1 & \\ \vdots & \underline{X}_2 \\ 1 & \end{array}\right] \tag{4.19}$$

where $\underline{X}_i$ is $(N_i \times n)$ matrix whose rows correspond to the pattern vectors from ω_i. Every rows of the matrix $\underline{X}^t$, in fact, represent augmented pattern vectors. If eqn. (4.18) is not consistent, then the pattern error has to be defined. The error of the jth pattern belonging to ω_i is defined here as

$$\underline{e}_j = \underline{x}_j \underline{W} - b_j \tag{4.20}$$

where:

$\underline{x}_j$ = jth row of $\hat{\underline{X}}^t$ belonging to class ω_i

Let $f_{ij}(\underline{e}_j)$ denotes a pattern error function defined for the jth pattern of class ω_i. Then mean error function of the sample patterns may be defined as

$$h(\underline{w}) = \frac{1}{N_1 + N_2} \sum_{i=1}^{2} \sum_{j=1}^{N_i} f_{ij}(\underline{e}_j) \tag{4.21}$$

In order to search for an optimum weight vector the error function of eqn. (4.21) is minimised by gradient method. Moving in the direction of negative gradient of $h(\underline{w})$ one gets

$$\underline{W}(k+1) = \underline{W}(k) - \mu \nabla h(\underline{w}(k)) \tag{4.22}$$

several values of μ are chosen to select upon the best value which accelerate the convergence and stabilise the algorithm. Near the optimum value $\nabla h(w)$ approaches zero.

To ensure the success of this method the function $h(\underline{w})$ must possess the following property:

Given two distinct (n+1) dimensional vectors $\underline{w}_1$ and $\underline{w}_2$ for which

$$\nabla h(\underline{w}_1) = \nabla h(\underline{w}_2) = 0$$

it must be true that

$$h(\underline{w}_1) = h(\underline{w}_2) = \min (h(\underline{w})) \quad \text{for all } \underline{w} \qquad (4.23)$$

Under this condition a vector for which $\nabla h(\underline{w}) = 0$ will minimise h.

To simplify the notation define $h(\underline{w})$ by

$$h(\underline{w}) = \frac{1}{N_1 + N_2} \sum_{j=1}^{N_1 + N_2} f_j(\underline{x}_j \underline{w} - b_j) \qquad (4.24)$$

where $\underline{x}_j$ is a (n+1) dimensional row vector and b_j are real numbers. The above function will possess the property mentioned in eqn. (4.23) if:

(a) all $f_j(\underline{e})$ are real valued function defined for all real $\underline{e}$.

(b) all $f_j(\underline{e})$ are continuously differentiable, for all real $\underline{e}$

(c) $f_j(e)$ is concave upward

the error of the classifier with that pattern as the input. Various values of μ from the range of $0 < \mu < \frac{1}{\max_j \|\underline{x}_j\|^2}$ have been tried to arrive at an optimum.

4.5 STATISTICAL APPROACH:

In the previous article the decision surface considered is a hyperplane. In many realistic situations the pattern classes are overlapping which cause the previous approach to take more trials, and sometimes time requirements are exceedingly high. In contrast to the disadvantage of the deterministic approach in the statistical approach it is not necessary to consider linear separability of the input patterns, yet an optimal recognition can be obtained.

As the name implies, it takes the help of the statistical properties of the patterns in order to arrive at a classification scheme. This is optimal in the sense that on an average basis, it has the lowest probability of committing classification errors.

Once again without loss of generality only two-class problem is considered. The conditional density functions and apriori probabilities of the two classes are assumed to be known.

Bayes Decision Rule:

Let $\underline{x}$ be a pattern vector which is to be classified. A decision rule simply based on probabilities may be written as:

$$p(\omega_1|\underline{x}) \gtrless p(\omega_2|\underline{x}) \longrightarrow \underline{x} \in \begin{cases} \omega_1 \\ \omega_2 \end{cases} \tag{4.28}$$

The aposteriori probabilities $p(\omega_i|\underline{x})$ may be calculated from the apriori probabilities $P(\omega_i)$ and conditional pdf $p(\underline{x}|\omega_i)$, using Bayes' theorem.

$$p(\omega_i|\underline{x}) = \frac{p(\underline{x}|\omega_i)\, P(\omega_i)}{P(\underline{x})} \tag{4.29}$$

Since $P(\underline{x})$ is common to both sides of inequality of (4.28), the above decision rule can be expressed as

$$p(\underline{x}|\omega_1)\, P(\omega_1) \gtrless p(\underline{x}|\omega_2)\, P(\omega_2) \longrightarrow \underline{x} \begin{cases} \omega_1 \\ \omega_2 \end{cases} \tag{4.30}$$

or

$$l(\underline{x}) = \frac{p(\underline{x}|\omega_1)}{p(\underline{x}|\omega_2)} \gtrless \frac{P(\omega_2)}{P(\omega_1)} \longrightarrow \underline{x} \begin{cases} \omega_1 \\ \omega_2 \end{cases} \tag{4.31}$$

The term $l(\underline{x})$ is called the likelyhood ratio and is the basic quantity in hypothesis testing. The term $P(\omega_2)/P(\omega_1)$ is the threshold value of the likelyhood ratio for the decision. Sometime it becomes convenient to express negative logarithm likelyhood ratio rather than as given in eqn. (4.31). In that case the decision rule becomes

$$- \ln l(x) = - \ln p(\underline{x}|\omega_1) + \ln p(\underline{x}|\omega_2) \lessgtr \ln P(\omega_1)/P(\omega_2)$$

$$\longrightarrow \underline{x} \in \begin{cases} \omega_1 \\ \omega_2 \end{cases} \qquad (4.32)$$

The direction of inequality changes because of the negative sign.

It may be noted that the Bayes' decision rule given in eqn. (4.28) is nothing more than the implementation of decision function

$$S_i(\underline{x}) = p(\underline{x}|\omega_i)\, P(\omega_i) \qquad i = 1,2 \qquad (4.33)$$

where a pattern $\underline{x}$ is assigned to class ω_i if for that pattern $S_i(\underline{x}) > S_j(\underline{x})$ for all $j \neq i$. An expression which is equivalent to eqn. (4.33) but does not require explicit knowledge of $p(\underline{x}|\omega_i)$ or $P(\omega_i)$ is obtained upon substitution of the eqn. (4.29) into eqn. (4.33). Thus,

$$S_i(\underline{x}) = p(\omega_i|\underline{x})\, P(\underline{x}) \qquad (4.34)$$

However, since $P(\underline{x})$ does not depend on i, it may be dropped, yielding the decision functions:

$$S_i(\underline{x}) = p(\omega_i|\underline{x}) \qquad (4.35)$$

Both equations (4.33) and (4.35) provide two alternative but equivalent approach to the same problem.

Bayes' Classifier For Normal Patterns:

If it is assumed that the pattern vectors are normally distributed, with the mean $\underline{m}_i$ and covariance matrix $\underline{C}_i$, then the multivariate normal density function becomes

$$p(\underline{x}|\omega_i) = \frac{1}{(2\pi)^{n/2}|C_i|^{1/2}} \exp(-\frac{1}{2}(\underline{x}-\underline{m}_i)^t \underline{C}_i^{-1}(\underline{x}-\underline{m}_i))$$

for $i = 1,2$ (4.36)

where:

$$\underline{m}_i = E_i(\underline{x})$$

$$\underline{C}_i = E((\underline{x}-\underline{m}_i)^t(\underline{x}-\underline{m}_i)) \qquad (4.37)$$

$$|C_i| = \det(\underline{C}_i)$$

From the generated patterns the eqn. (4.37) can be estimated as

$$\underline{m}_i = \frac{1}{N_i}\sum_{j=1}^{N_i} \underline{x}_{ij} \quad \text{for } i=1,2,\ldots,n$$

$$\underline{C}_i = \frac{1}{N_i}\sum_{j=1}^{N_i} \underline{x}_{ij}\,\underline{x}_{ij}^t - \underline{m}_i\,\underline{m}_i^t \qquad (4.38)$$

The covariance matrix is positive semidefinite and symmetric. With known density function from eqn. (4.36), eqn. (4.33) can be used as a classifying criterion. Since eqn. (4.36) involves exponential term, logarithm version is more suitable for the decision function. Thus, the new decision function becomes

$$S_i(\underline{x}) = \ln(p(\underline{x}|\omega_i)\,P(\omega_i)) \qquad (4.39)$$

On substituting eqn. (4.36) in the above equation, one gets

$$S_i(\underline{x}) = \ln P(\omega_i) - \frac{n}{2} \ln 2\pi - \frac{1}{2} \ln |C_i|$$
$$- \frac{1}{2} ((\underline{x} - \underline{m}_i)^t \underline{C}_i^{-1} (\underline{x} - \underline{m}_i))$$
$$\text{for } i = 1,2 \qquad (4.40)$$

It is possible to remove the second term in the above expression without changing the discriminating capacity of the surface and if the covariance matrices of both the classes are identical, eqn. (4.40) may be simplified as

$$S_i(\underline{x}) = \ln P(\omega_i) + \underline{x}^t \underline{C}^{-1} \underline{m}_i - \frac{1}{2} \underline{m}_i^t \underline{C}^{-1} \underline{m}_i \qquad (4.41)$$

The above surface is a hyperplane. For two-class problem decision function $S_{12}(\underline{x})$ is given as

$$S_{12}(\underline{x}) = \ln (A) + \underline{x}^t \underline{C}^{-1} (\underline{m}_1 - \underline{m}_2)$$
$$- \frac{1}{2} \underline{m}_1^t \underline{C}^{-1} \underline{m}_1 + \frac{1}{2} \underline{m}_2^t \underline{C}^{-1} \underline{m}_2 \qquad (4.42)$$

where:

$$A = P(\omega_1)/P(\omega_2)$$

In many real situations, such as power systems, covariance matrices are not identical for all the classes. This brings about a change in the expression of the decision surface. For the classes ω_i and ω_j the decision surface then becomes;

$$S_{ij}(\underline{x}) = \ln \frac{P(\omega_i)}{P(\omega_j)} - \frac{1}{2} \ln \frac{|C_i|}{|C_j|} + \frac{1}{2} (\underline{x} - \underline{m}_j)^t \Sigma_j (\underline{x} - \underline{m}_j)$$

$$- \frac{1}{2} (\underline{x} - \underline{m}_i)^t \Sigma_i (\underline{x} - \underline{m}_i) \qquad (4.43)$$

where:

$\underline{\Sigma}$ = inverse of the covariance matrix $\underline{C}$.

The surface given in the eqn.(4.43) is a hyper-quadratic and may be expressed as a function of pattern vector as given below:

$$S_{ij}(\underline{x}) = w_{oo} + \sum_{k=1}^{n} w_{ko} x_k + \sum_{k=1}^{n} \sum_{l=1}^{n} w_{kl} x_k x_l \qquad (4.44)$$

Ws are the elements of the weight vector in the weight space. These elements can be calculated directly from the labelled patterns' statistics.

$$w_{kk} = \frac{1}{2} (\Sigma^j_{kk} - \Sigma^i_{kk})$$

$$k = 1,2,\ldots,n$$

$$w_{ko} = \sum_{l=1}^{n} (m^i_l (\Sigma^i_{kl} + \Sigma^i_{lk}) \frac{1}{2} - m^j_l (\Sigma^j_{kl} + \Sigma^j_{lk}) \frac{1}{2})$$

$$k = 1,2,\ldots,n.$$

$$w_{kl} = \frac{1}{2}\left((\Sigma^{j}_{kl} + \Sigma^{j}_{lk}) - (\Sigma^{i}_{kl} + \Sigma^{i}_{lk}) \right)$$

$$k = 1,2,\ldots,n$$

$$w_{oo} = \sum_{k=1}^{n} \sum_{l=1}^{n} 2w_{kl} + \ln\left(\frac{A}{B}\right) \qquad (4.45)$$

where:

Σ^{i}_{kl} = element of the matrix Σ belonging to class i and correspond to kth row and lth column.

$A = P(\omega_i)/P(\omega_j)$

$B = (|C_i|/|C_j|)^{1/2}$

Estimation Of Probability Density Function:

In many occassions pdf is not known and needs to be estimated through the pattern vectors. If $\hat{p}(\underline{x}|\omega_i)$ represents the estimation of $p(\underline{x}|\omega_i)$, this must then minimise the mean square error function defined as

$$R = \int_{\underline{x}} u(\underline{x}) \left(p(\underline{x}|\omega) - \hat{p}(\underline{x}|\omega) \right)^2 d\underline{x} \qquad (4.46)$$

where:

$u(\underline{x})$ = weighting function

Expanding the estimate of conditional pdf in a series

$$\hat{p}(\underline{x}|\omega_i) = \sum_{j=1}^{m} C^{i}_{j} \, \phi_j(\underline{x}) \qquad (4.47)$$

where C_j^i are to be determined, and $\phi_j(\underline{x})$ are a set of basis functions. Substitution of eqn. (4.47) in eqn. (4.46) yields

$$R = \int_{\underline{x}} u(\underline{x}) \left(p(\underline{x}|\omega_i) - \sum_{j=1}^{m} C_j^i \phi_j(\underline{x})\right)^2 d\underline{x} \qquad (4.47a)$$

The coefficient C_j^i should be determined such that R is minimised. A necessary condition for this is

$$\frac{\partial R}{\partial C_k} = 0 \qquad (4.48)$$

$$k = 1,2,\ldots,m$$

The result of the partial differentiation becomes

$$\sum_{j=1}^{m} C_j^i \int_{\underline{x}} u(\underline{x})\phi_j(\underline{x})\phi_k(\underline{x})\, d\underline{x}$$

$$= \int_{\underline{x}} u(\underline{x})\, \phi_k(\underline{x})\, p(\underline{x}|\omega)\, d\underline{x} \qquad (4.49)$$

The right hand side of eqn. (4.49) clearly indicates that it is the expected value of the function $u(\underline{x})\phi_k(\underline{x})$ and this may be approximated by the sample average, yielding

$$\int_{\underline{x}} u(\underline{x})\phi_k(\underline{x})\, p(\underline{x}|\ )d\underline{x} \quad \frac{1}{N}\sum_{i=1}^{N} u(\underline{x}_i)\phi_k(\underline{x}_i) \qquad (4.50)$$

Substituting eqn. (4.50) in eqn. (4.49) and knowing that the basis functions are orthogonal with respect to weighting function $u(\underline{x})$ one gets

$$C_k^i = \frac{1}{N\lambda_k} \sum_{i=1}^{N} u(\underline{x}_i)\phi_k(\underline{x}_i) \qquad (4.51)$$

$$k = 1,2,\ldots,m$$

Appendix C brings out the details of orthonormal and orthogonal functions. Further, if the basis functions are chosen to be orthonormal A_k becomes unity for all k. And since $u(\underline{x}_i)$ does not depend on k it can be eliminated without imparing discriminating power of the coefficients. So one gets finally

$$C_k^1 = \frac{1}{N} \sum_{i=1}^{N} \phi_k(\underline{x}_i) \qquad (4.52)$$

$$k = 1,2,..,m$$

The successful application of the pdf and the coefficient C is based on two considerations. Firstly, it should be kept in mind that the quality of approximation, for a chosen set of basis functions, depends on the number m. It is difficult in general to establish apriori the value m. Only through trials one establishes this value, such as increasing the value of m until a satisfactory discrimination is achieved.

Secondly, suitable choice of basis functions are to be made. Since apriori knowledge of the conditional pdf does not exist, the basis functions are purely chosen from the point of view of their simplicity of implementation and remaining orthonormal in the range of the sample patterns. Viewing from this angle it is noted that, Hermite polynomials serve as good orthogonal basis functions as they are particularly easy to apply and their region of orthogonality is the interval $(-\infty, \infty)$. In the one dimensional case these functions are given by the following recursive relation.

$$H_{k+1}(x) - 2x\,H_k(x) + 2k\,H_{k-1}(x) = 0 \qquad (4.53)$$

$$\text{for} \quad k \geq 1$$

with

$$H_0(x) = 1 \quad \text{and} \quad H_1(x) = 2x$$

From a given set of orthonormal functions of single variable i.e. ($\phi_1(x)$, $\phi_2(x)\ldots$) over the interval $(-\infty, \infty)$ a complete system of multivariable orthonormal functions can be easily generated. Typical example for a two-variable case is given below:

$$\varphi_1(x_1,x_2) = \phi_1(x_1)\,\phi_1(x_2)$$

$$\varphi_2(x_1,x_2) = \phi_1(x_1)\,\phi_2(x_2)$$

$$\varphi_3(x_1,x_2) = \phi_2(x_1)\,\phi_1(x_2)$$

$$\varphi_4(x_1,x_2) = \phi_2(x_1)\,\phi_2(x_2)$$

$$\varphi_5(x_1,x_2) = \phi_1(x_1)\,\phi_3(x_2) \qquad (4.54)$$

The extension of the above procedure for n variable case is straight forward. All that is needed, is to multiply together groups of n functions from one variable set after proper substitution of the variables $x_1, x_2, \ldots, x_n$. The resulting n-variable functions $\phi_1, \phi_2, \ldots, \phi_n$ are orthonormal. For example the following five basis functions are given as a function of four variables.

$$\begin{aligned}
\phi_1(\underline{x}) &= 1 &= \quad & H_o(x_1)\, H_o(x_2)\, H_o(x_3)\, H_o(x_4) \\
\phi_2(\underline{x}) &= 2x_4 &= \quad & H_o(x_1)\, H_o(x_2)\, H_o(x_3)\, H_1(x_4) \\
\phi_3(\underline{x}) &= 2x_3 &= \quad & H_o(x_1)\, H_o(x_2)\, H_1(x_3)\, H_o(x_4) \\
\phi_4(\underline{x}) &= 2x_2 &= \quad & H_o(x_1)\, H_1(x_2)\, H_o(x_3)\, H_o(x_4) \\
\phi_5(\underline{x}) &= 2x_1 &= \quad & H_1(x_1)\, H_o(x_2)\, H_o(x_3)\, H_o(x_4)
\end{aligned} \tag{4.55}$$

where:

$$\phi_i(\underline{x}) = \varphi_i(x_1, x_2, x_3, x_4)$$

It should be made clear that there is nothing unique about the order in which the above terms are formed. Any pairwise combination is acceptable for any $\phi(\underline{x})$. Depending on this, terms of eqn. (4.55) maybe made nonlinear also.

Thus the density function for class ω_i can be written as

$$\hat{p}(x|\omega_i) = \sum_{j=1}^{m} \frac{1}{N_i} \sum_{k=1}^{N_i} \phi_j(\underline{x}_k^i)\, \phi_j(\underline{x}) \tag{4.56}$$

where:

$\underline{x}_k^i$ = kth pattern vector belonging to class i

This leads to the decision surface $S_{ij}(\underline{x})$ as

$$P(\omega_i). \sum_{j=1}^{m} \frac{1}{N_i} \sum_{k=1}^{N_i} \phi_j (\underline{x}_k^i). \phi_j(\underline{x}) - P(\omega_j) \sum_{l=1}^{m} \frac{1}{N_j} \sum_{k=1}^{N_j}$$

$$\phi_l(\underline{x}_k^j)\ \phi_l(\underline{x})$$

(4.57)

After substituting the values of the basis functions from eqn.(4.55) the above decision surface may be expressed as a nonlinear function as given below:

$$w_{oo} + \sum_{k=1}^{n} w_{ko}\ x_k + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} w_{ij}\ x_i\ x_j \qquad (4.58)$$

The weight vector $\underline{w} = (w_{oo}, w_{10}, \ldots, w_{no}, w_{12}, w_{13}, \ldots w_{(n-1),n})^t$ is obtained from the following relations:

$$w_{oo} = z_{k1}\ P(\omega_1) - z_{k2}\ P(\omega_2) \qquad (4.58)$$

for $k = 1$

$$w_{io} = 2.0\ (z_{k1}.\ P(\omega_1) - z_{k2}\ .\ P(\omega_2)) \qquad (4.59)$$

for $k = 2, 3, \ldots, n+1$

$i = 1, 2, \ldots, n$

$$w_{ij} = 4.0\ (z_{k1}\ P(\omega_1) - z_{k2}\ P(\omega_2)) \qquad (4.60)$$

for $k = n+2, \ldots \frac{n(n-1)}{2}$

$i = 1,2,.., n-1$

$j = 2,3,..,n$

where:

$$s_{kl} = \frac{1}{N} \sum_{i=1}^{N} \phi(k,i)$$

for $k = 1,2,..,n,.., \frac{1}{2} n(n-1)$

$l = 1,2$ i.e. two classes

N = total patterns

with $\phi(1,i) = 1.0$

$\phi(k,i) = x_{ij}$

for $k = 2,..,n+1$

$i = 1,2,.., N$

$j = 1,2,..,n$

$\phi(k,i) = x_{ij} \cdot x_{i,(j+1)}$

for $k = n+2,.., \frac{1}{2} n(n-1)$

$j = 1,2,.., n-1$

4.6 PATTERN RECOGNITION APPLIED TO POWER SYSTEMS:

The reliability of present day large and interconnected power system is a complex function of uncertainty of load, random equipment failure, cost consideration and completion date of new facilities. In order for the system operator to take reliability conscious operational decision it is necessary to develop effective and fast mean to recognise the current state of power system. Pattern recognition techniques can be effectively adopted for this purpose, since these techniques possess certain attractive features unattainable by the previous methods described in the earlier chapters. Most of the information needed, in this connection, are obtained through numerous off-line studies.

In practice, the operator always attempts to maintain the system in the normal operating state as disturbances might cause the system to go into an undesirable emergency.

In the previous chapter it has been mentioned that security evaluation requires some indicators. The indicator could be represented by one or more decision criteria, same as the decision functions given in eqn. (4.1). These, in the power system literature, have been termed as security functions.

Power system operation is strictly governed by electrical network equations. The flow pattern depends on the load and the generation. Usually line flows, generated power (reactive as well as active) and bus voltages pose definite constraints. It is evident that the larger the set of disturbances more stringent will be the security standard. Thus, a series of security functions, i.e. one for each contingency, can show the type of insecurity, such as low voltage, overloaded lines, overloaded generators, etc. and can be instrumental in deciding the type of security controls.

Some questions which often appears in the mind of system operators and planners are:

1. Is the state of a power system secure ?
2. Does a disturbance result in insecurity ?
3. Is it possible to distinguish a kvar deficient system from a normal one ?

It is clear that each of the above and several other similar questions have two answers. The classifier is designed to provide the two answers. Thus security analysis can be viewed as a two-class pattern recognition problem.

Determination Of Security Function:

In order to obtain the security functions, a training set of various operating conditions must be available. Each operating condition or state is specified by various variables such as injection powers, loads, generation powers, line flows, voltage magnitudes and angles. The variables are determined by computations or measurements. An operating condition is termed as a pattern. All variables describing a given operating condition constitute the component of the pattern vector $\underline{x} = (x_1, x_2, \ldots, x_n)^t$. An ideal training set would include in it all conceivable patterns, which cover the whole spectrum of the system operating conditions. Load flow studies in this case has been made several times under different contingencies and load levels to generate and label the training set.

The number of variables (components) constituting a pattern or a state of a power system can be very large. In pattern recognition it is enough to determine relatively smaller number of variables which will be distinctive for each of the two classes of patterns. Thus the patterns, which essentially are points in Euclidian space, may not be used completely for training the classifier. Some components of these patterns may have all the necessary features for correct classification. Some two dimensional points are shown in the fig. 4.6 giving their projection along x_1 and x_2 axes. It can be seen that the points along x_1 axis are sufficient for classifying these patterns. The information giving by points in x_2 axis do not contribute anything towards classification.

The result of the off-line studies are scanned to decide certain important variables based on engineering judgement. In this thesis a suitable subset of the multidimensional pattern vector has been chosen as the feature vector.

4.7 REVIEW OF POWER SYSTEM LITERATURE USING PATTERN RECOGNITION TECHNIQUE:

So far as the knowledge of the present author goes only a few publications (6,16,24,26,56) have appeared

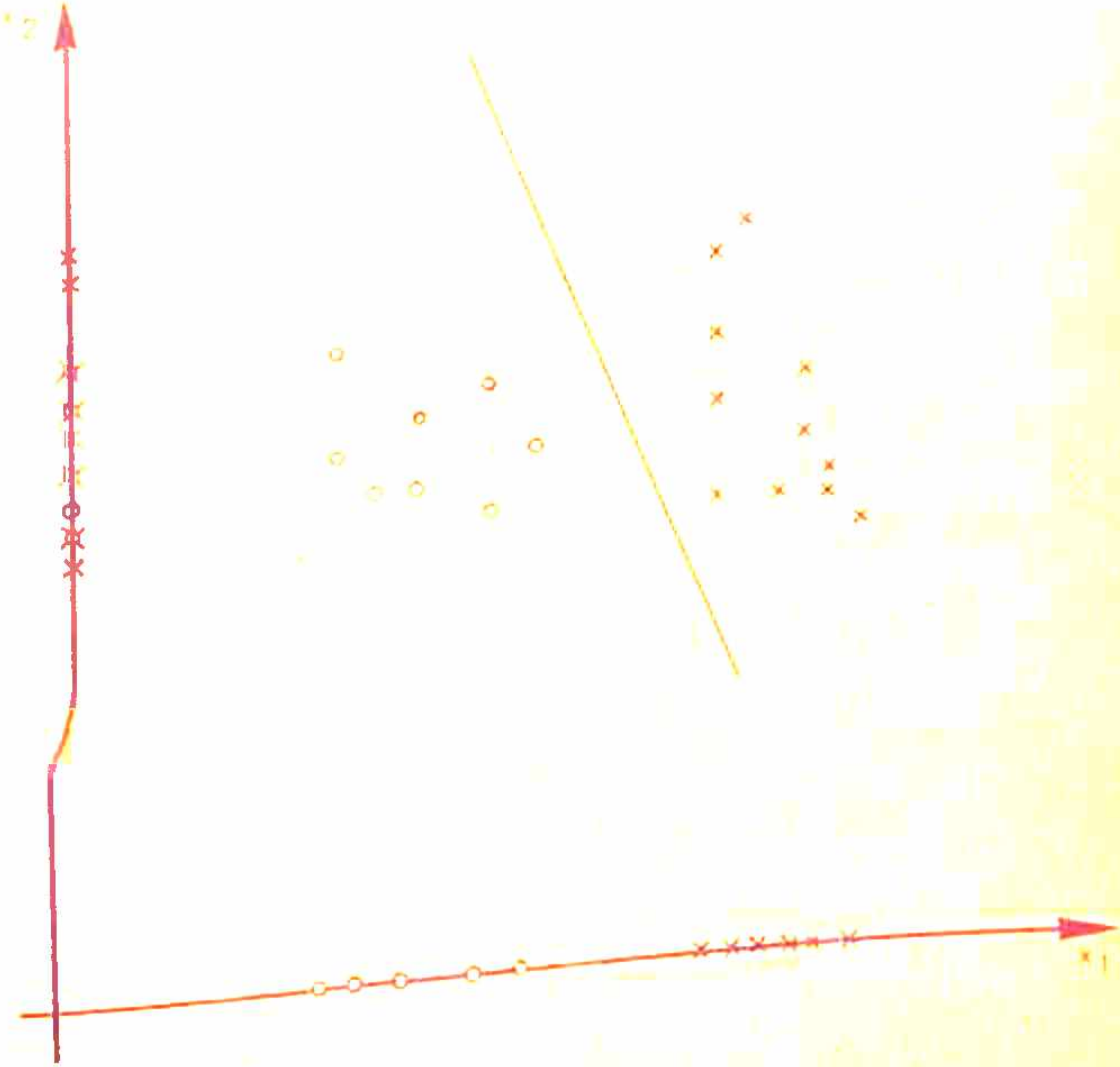


FIG. 4.6 IMPORTANCE OF FEATURE SELECTION

attempting to solve power system security through the methodology of pattern recognition. Out of these, references (16,24,56) deal with the transient security of power systems. In this section these are reviewed critically.

Pang and EL-Abiad's Approach (24):

The main contribution of this paper is to demonstrate the feasibility of applying pattern recognition technique to security monitoring. Furthermore, it ventures into the various applications of security functions in on-line operations. Routine optimal dispatch and fast transient stability calculations have been used herefor pattern generation. Security functions have been calculated by optimal search technique and least square method. While agreeing that optimal search will be better than the least square method, the former takes more time compared to the direct (probabilistic) method proposed in this thesis. The present author does not agree with one of the findings; such as identification of type of contingency by security functions. It is strongly felt that this would require enumerable trials.

Dewey's Approach (56):

Main contribution of this paper is the training of classifier through linear programming. Author's claim of linear discriminant function can be accepted for very limited cases of power system operation. If pattern generations are relatively few in number and both the classes are quite apart from each other, then only linear security function become successful. Furthermore, for these cases more efficient algorithm such as the proposed adaptive linear classifier, is existing. Classification problem becomes truly complex when patterns of either class are generated very close to the security surface. Under such situation it has been found that the classes overlap near the boundary so linear programming becomes useless unless it is being used to generate piecewise linear security function. Same technique has been used in the reference (26).

Tepco's Approach (16):

Basically this paper is devoted to assess fast transient stability studies. Methodologies are essentially same as the above. Security functions in this case are generated by perceptron and least square algorithms. The paper concludes that the perceptron algorithm is superior to the other one, giving 100 percent classification efficiency. This paper along with the previous one have selected a sub set of the main pattern vector as the feature vector.

Main contribution of this paper is the algorithm used for the selection of the samples in the training set. Using this algorithm samples near the boundary can be selected and a good classifier can be obtained.

However, it appears that there is one disadvantage to this iterative procedure of training. One of the requirements of the successful convergence of any iterative training is that the starting point should be sufficiently closer the final point which is being sought. It means initial separating surface between the classes must be closer to the final or the optimum surface. Apparently the paper does not provide with any criterion for selecting the initial training set.

4.8 COMPARATIVE STUDY OF PATTERN RECOGNITION TECHNIQUES AS APPLIED TO POWER SYSTEM:

The 6-bus power system used earlier in the second chapter has been used to illustrate and compare all the four methods outlined above. Six step load levels have been assumed for each load bus. For the worst case analysis further it has been assumed that the peak at each bus occurs simultaneously. In all 6^4 i.e. 1296 load levels have been considered and for each of such load level, 11 equipment outages are taken into consideration. Thus including the normal case load flow for each load level total number of load flow calculations are 15,552. Total computation time is nearly 12.36 hours. Total power demand, reactive generation at each generating bus, active generation at slack bus, active and reactive losses in each line, total active and reactive losses, voltage at each bus, phase angle of each bus, active power reserve, reactive power reserve, for both the generating buses are the componentsof the pattern vector which are evaluated for all of the above mentioned load flow computations. From the above mentioned components of a pattern vector some features have been selected to train, finally, the classifier. The training set for the classifier is shown in the table 4.1. The number of features used in this study is five. It is felt that this number should not be too large and yet large enough to ensure good representation of the patterns. As a rule of thumb, this number is selected to be in the neighbourhood of the number of generating buses. The number could be increased or decreased depending on the system, the nature of the problem and the outcome of the security functions. In this example the features selected are given in the table 4.2.

Using these features decision surfaces are found by all the four methods. Out of total sample patterns generated, 200 samples, which are closer to the decision surface, are selected to train the classifier. It is further to be noted that a system anal st, who knows intimately his system can effectively reduce sample size by discarding states correspond to high load, stringest contingencies and light load, light contingencies. It will considerably reduce the off-line computation time.

TABLE 4.1 FEATURE VECTORS FOR TRAINING SET

PGRA	QGRA	PLOSS	V_2	δ_2
1.941	0.6771	0.1584	1.04	-0.025
1.6937	0.6212	0.2062	1.036	-0.032
1.4349	0.5614	0.2650	1.031	-0.039
1.1648	0.4982	0.3351	1.027	-0.046
0.5892	0.3597	0.5107	1.017	-0.060
0.2830	0.2843	0.6169	1.012	-0.067
0.1251	0.2450	0.6748	1.01	-0.070
1.4316	0.5605	0.2683	1.03	-0.036
1.1665	0.4988	0.3334	1.029	-0.043
0.8900	0.4333	0.4099	1.024	-0.049
0.6016	0.3638	0.4983	1.019	-0.056
0.3010	0.2903	0.5989	1.015	-0.063
0.8788	0.4361	0.4211	1.026	-0.046
0.5956	0.3688	0.5043	1.022	-0.053
0.3004	0.2971	0.5995	1.017	-0.060
0.2786	0.2828	0.6213	1.019	-0.057
0.1288	0.2462	0.6711	1.016	-0.060
2.9269	0.3061	0.0730	1.059	-0.000
2.8225	0.8642	0.0771	1.055	-0.005
2.6073	0.8191	0.0326	1.051	-0.012
2.3818	0.7706	0.1181	1.047	-0.019
2.0242	0.6914	0.1757	1.041	-0.029

Contd..

1.6426	9.6042	0.2573	1.034	-0.039
1.2360	0.5086	0.3639	1.027	-0.049
0.3505	0.4401	0.4494	1.023	-0.056
0.6531	0.3677	0.5468	1.018	-0.063
0.3434	0.2911	0.6565	1.013	-0.070
2.2454	0.7384	0.1545	1.042	-0.020
2.0031	0.6843	0.1968	1.037	-0.027
1.7516	0.6272	0.2483	1.033	-0.034
1.3548	0.5349	0.3451	1.026	-0.044
0.9300	0.4333	0.4699	1.019	-0.054
0.4776	0.3225	0.6223	1.012	-0.065
2.020	0.6900	0.1798	1.040	-0.024
1.7737	0.6345	0.2262	1.035	-0. 031
1.3833	0.5444	0.3166	1.028	-0.041
0.9670	0.4456	0.4329	1.022	-0.051
0.3695	0.2998	0.6304	1.012	-0065
0.050	0.2202	0.7493	1.004	-0.072
1.6519	0.6073	0.2480	1.035	-0.031
0.8436	0.4178	0.4563	1.021	-0.051
0.0878	0.2717	0.7121	1.009	-0.069
0.9857	0.4519	0.4142	1.026	-0.045
0.7040	0.3846	0.4959	1.021	-0.052
0.1043	0.2381	0.6556	1.01	-0.066
0.5477	0.3459	0.5522	1.021	-0.052

Contd..

0.4019	0.3106	0.598	1.019	-0.055
0.2531	0.2743	0.6486	1.016	-0.062
0.1011	0.2370	0.6938	1.014	-0.062
2.6863	0.8321	0.1136	1.053	-0.008
2.5782	0.8094	0.1217	1.051	-0.011
2.4676	0.7858	0.1323	1.049	-0.0147
1.7501	0.6267	0.2498	1.03	-0.034
1.2177	0.5025	0.3822	1.028	-0.048
0.1734	0.2478	0.7265	1.012	-0.072
0.0117	0.2072	0.7882	1.003	-0.076
2.1976	0.7225	0.2023	1.041	-0.019
1.5773	0.5824	0.3226	1.030	-0.036
0.7385	0.3828	0.5614	1.016	-0.057
0.1165	0.2288	0.7834	1.006	-0.071
1.8473	0.6457	0.2526	1.037	-0.026
1.0598	0.4632	0.4401	1.023	-0.047
0.4759	0.3219	0.6240	1.014	-0.061
0.0038	0.2046	0.7361	1.006	-0.071
1.2070	0.4930	0.3296	1-028	-0.040
0.6462	0.3654	0.5537	1.019	-0.054
0.0350	0.2150	0.7649	1.009	-0.068
0.6470	0.3656	0.5529	1.021	-0.051
0.0482	0.2194	0.7517	1.011	-0.065
02.4775	0.7891	0.1224	1.05	-0.011

contd..

0.0805	0.2301	0.7194	1.012	-0.072
2.5440	0.7980	0.1559	1.048	-0.010
1.4501	0.5533	0.3498	1.028	-0.040
0.1206	0.2302	0.7793	1.006	-0.071
2.5281	0.7927	0.1718	1.048	-0.009
0.1091	0.2263	0.7908	1.006	-0.071
2.0654	0.6918	0.2345	1.038	-0.024
0.0856	0.2185	0.8143	1.005	-0.072
-2.2552	-0.5484	3.0552	0.836	-0.261
-0.1874	0.1408	0.9874	1.003	-0.084
-0.1398	0.1700	0.8398	1.0115	-0.076
-0.2553	0.1448	0.8553	1.005	-0.083
-0.9439	-0.0846	1.5439	0.964	-0.138
-0.1132	0.0178	0.8132	1.004	-0.076
-0.2981	0.1172	0.9981	0.987	-0.084
-0.2143	0.1584	0.8143	1.007	-0.081
-0.2688	0.1403	0.8688	1.01	-0.076
-0.3826	0.1157	0.8826	1.004	-0.085
-1.1915	-0.1538	1.6915	0.959	-0.144
-2.332	-0.5608	3.032	0.839	-0.26
-0.0742	0.1919	0.7742	1.007	-0.073
-0.3680	0.1073	0.9680	0.982	-0.090
-0.5687	0.0537	1.0687	1.001	-0.087
-0.5339	0.0766	0.9399	1.003	-0.086

contd..

-0.0535	0.1988	0.7535	1.009	-0.069
-2.5833	-0.6177	3.0833	0.843	-0.260
-0.5637	0.0687	0.6937	1.009	-0.078
-0.7491	0.0202	1.0491	1.008	-0.080
-0.7314	0.0261	1.0314	1.001	-0.088
-01.8120	-0.3340	2.112	0.947	-0.157
-0.5386	0.0771	0.9386	1.004	-0.077
-0.5875	0.0608	0.9875	0.989	-0.084
-0.8479	-0.0126	1.1479	1.0	-0.087
-2.199	-0.4496	2.399	0.939	-0.164
-0.0121	0.2126	0.7121	1.01	-0.07
-0.1735	0.1721	0.7735	1.007	-0.074
-0.3383	0.1305	0.8383	1.005	-0.078
-2.5578	-0.6092	3.0578	0.844	-0.264
-0.5131	0.0856	0.9131	1.008	-0.079
-0.5082	0.0872	0.9082	1.009	-0.079
-1.4626	-0.2308	1.8626	0.954	-0.150
-0.3275	0.1411	0.8275	1.007	-0.074
-0.4926	0.0994	0.8326	1.005	-0.078
-2.7158	-0.6416	3.1158	0.845	-0.264
-0.779	0.0173	1.079	1.009	-0.078
-0.6808	0.0500	0.9808	1.009	-0.079
-1.8187	-0.3292	2.1187	0.947	-0.156
-0.1799	0.1700	0.7799	1.011	-0.067

contd..

-0.5015	0.0894	0.9015	1.007	-0.075
-2.9279	-0.7059	3.2279	0.844	-0.265
-1.003	-0.0634	1.3003	1.01	-0.074
-0.8763	-0.0087	1.0763	1.008	-0.079
-2.2427	-0.4642	2.4427	0.938	-0.163
0.0209	0.2103	0.7790	1.009	-0.077
-1.9557	-0.4485	2.7557	0.869	-0.254
-0.2209	0.1296	1.0209	0.991	-0.102
-0.2819	0.1093	1.0819	1.0	-0.088
-0.1939	0.1520	0.8939	1.008	-0.080
-0.7347	-0.0282	1.434	0.968	-0.132
-0.0047	0.2017	0.8047	1.004	-0.076
-0.0732	0.1922	0.7732	1.008	-0.079
-2.1280	-0.4926	2.828	0.866	-0.261
-0.2946	0.1184	0.9946	0.991	-0.103
-0.1386	0.1704	0.8386	1.005	-0.084
-0.2785	0.1238	0.9785	1.001	-0.087
-0.1001	0.1832	0.8001	1.009	-0.079
-0.0860	0.1879	0.7860	1.007	-0.081
-0.6558	-0.0019	1.3558	0.970	-0.131
-0.0805	0.1898	0.7805	1.005	-0.077
-2.3262	-0.5587	3.0262	0.839	-0.264
-0.2976	0.1174	0.9976	0.978	-0.097
-0.038	0.2037	0.7386	1.009	-0.078

contd..

-0.1993	0.1502	0.899	1.004	-0.084
-0.2172	0.1575	0.8172	1.009	-0.079
-0.0537	0.1987	0.7537	1.011	-0.075
-0.2080	0.1606	0.8080	1.006	-0.082
-0.8843	-0.064	1.484	0.965	-0.137
-0.2004	0.1631	0.8004	1.007	-0.074
-2.4242	-0.578	3.024	0.842	-0.263
-0.3590	0.1103	0.959	0.982	-0.094
-0.3263	0.1345	0.8263	1.007	-0.081
-0.1610	0.1763	0.7610	1.01	-0.077
-0.4820	0.0826	0.9820	1.001	-0.087
-0.3531	0.1256	0.8531	1.009	-0.079
-0.3614	0.1228	0.8614	1.004	-0.084
-1.1517	-0.1405	1.6517	0.96	-0.143
-0.1530	0.1656	0.8530	1.007	-0.079
-0.5615	0.0294	1.2615	0.997	-0.091
-0.1619	0.1626	0.8619	1.007	-0.081
-0.8106	-0.0535	1.5106	0.967	-0.133
-0.0468	0.1877	0.8468	1.004	-0.075
-2.278	-0.5563	3.078	0.836	-0.258
-0.1413	0.1695	0.8413	1.007	-0.081
-0.2663	0.1412	0.8663	1.006	-0.082
-0.1597	0.1634	0.8597	1.004	-0.075

contd..

-0.5115	0.0728	1.0115	1.010	-0.078
-1.2883	-0.1861	1.7883	0.957	-0.145
-0.2892	0.1335	0.8892	1.004	-0.075
-2.4871	-0.5330	3.0871	0.841	-0.257
-0.6791	0.0169	1.1791	1.000	-0.088
-0.4360	0.0979	0.9360	1.004	-0.075
-0.8081	0.0006	1.1081	1.007	-0.081
-0.3549	0.0850	1.1549	1.001	-0.086
-0.2914	0.1328	0.8914	1.005	-0.084
-1.0364	-0.1154	1.6364	0.962	-0.139
-0.2653	0.1415	0.8653	1.007	-0.081
-0.0541	0.1852	0.8541	1.004	-0.074
-1.0175	-0.1091	1.6175	0.963	-0.139
-0.3907	0.0997	0.9907	1.009	-0.078
-0.4277	0.1007	0.9277	1.004	-0.085
-0.2446	0.1484	0.8446	1.008	-0.079
2.7545	0.8548	0.045	1.054	-0.008
2.8597	0.8766	0.040	1.056	-0.005
2.6469	0.8323	0.053	1.052	-0.011
2.536	0.8089	0.0631	1.050	-0.014
2.4241	0.7847	0.0758	1.048	-0.018
2.3089	0.7596	0.091	1.046	-0.021
2.1912	0.7337	0.1088	1.044	-0.024

contd..

2.070	0.7069	0.1291	1.042	-0.027
1.9478	0.6792	0.1521	1.04	-0.030
1.8221	0.6507	0.1778	1.038	-0.034
1.6937	0.6212	0.2062	1.035	-0.037
1.5625	0.5908	0.2374	1.033	-0.041
1.4286	0.5595	0.2713	1.031	-0.044
0.2518	0.2739	0.648	1.013	-0.072
0.09	0.233	0.7090	1.01	-0.075
2.410	0.7800	0.0898	1.046	-0.0156
2.295	0.7552	0.1041	1.044	-0.018
2.1788	0.7296	0.1211	1.042	-0.022
2.0592	0.7030	0.1407	1.040	-0.025
1.9369	0.6756	0.1630	1.038	-0.028
1.8111	0.6473	0.188	1.036	-0.032
1.4187	0.5562	0.2812	1.029	-0.042
1.0025	0.4575	0.3974	1.022	-0.052
0.7091	0.3863	0.4908	1.017	-0.059
0.2456	0.2718	0.6543	1.010	-0.070
0.0847	0.2315	0.7152	1.007	-0.073

TABLE 4.2 FEATURES SELECTED:

Mixed Contingency	PGRA,	QGRA,	PLOSS,	V_2,	∂_2
Line 1-6 out	PGRA,	PLOSS,	∂_2,	∂_{23},	∂_{26}
Line 5-6 out	PGRA,	PLOSS,	∂_2,	∂_{23},	∂_6
Line 2-3 out	PGRA,	PLOSS,	∂_2,	∂_{56},	∂_6
Line 3-4 out	PGRA,	PLOSS,	∂_2,	∂_{23},	∂_6
Line 1-2 out	PGRA,	PLOSS,	∂_{26},	∂_{56},	∂_6
Line 2-6 out	PGRA,	PLOSS,	∂_2,	∂_{23},	∂_6
Line 4-5 out	PGRA,	PLOSS,	∂_2,	∂_{23},	∂_6
kvar Difficiency	QGRA,	PLOSS,	∂_2,	V_3,	V_5

PGRA = Active generation reserve at slack bus.

QGRA = Reactive generation reserve at slack bus.

PLOSS= Total active power transmission loss.

V_i = ith bus voltage.

∂_i = ith bus phase angle.

∂_{ij} = $\partial_i - \partial_j$

Finally, a test set of patterns is generated to determine the performance of the classifiers. It is seen how much of misclassifications are made by the classifiers. It is to be noted that misclassification of secure pattern to insecure is not as much dangerous as insecure being classified as secure. Table 4.3 brings out all these for different methods.

TABLE 4.3 RESULT OF CLASSIFIERS:

Training Method		1	2	3	4
No. of mis-classified Patterns out of 200 samples	Insecure	18	4	27	6
	Secure	24	12	17	15
	Total	42	15	44	21
Percent correct		79	92	78	89.5

It is clearly noted in all the methods except No. 3 secure class is more misclassified than the insecure. This is because in method 3 the pattern vectors are assumed to be distributed normally which may not be a correct proposition. Table 4.3 also indicates the superiority of methods 2 and 4 over others from the point of view of overall percentage correction and least percentage of insecure misclassification. The above methods are also compared on the basis of computer storage, computation time, classification efficiency, etc. The result being indicated in table 4.4 which confirms the finding of table 4.3. In power system it is expected that the pattern classes would overlap near the boundary. This fact is confirmed by the study. Therefore method 4 is the best for a power system.

It takes only a fraction of a second to classify any unknown state by the decision surface. Thus the present technique can conveniently be used on-line at a definite interval to adjudge the real time security of the power system and thereby aiding the operator to take the operating decision.

Table 4.4 PERFORMANCE COMPARISON OF FOUR METHODS:

		Method 1	Method 2	Method 3	Method 4
1.	Type	Iterative	Iterative	Direct	Direct
2.	Time to compute decision function for 200 training samples	5.8 mts	3.9 mts	5 mts	2.4 mts
3.	Computer Storage	2500	1300	3000	1450
4.	Classification efficiency for nonoverlapping samples	79 percent.	92 percent	78 percent	89.5 percent
5.	Classification efficiency for overlapping classes	Does not converge	Does not converge	68 percent	85 percent.

4.9 APPLICATION OF THE DECISION FUNCTION:

As mentioned earlier on-line use of pattern recognition technique to assess security of power system is already established (16,24) wherein it is confirmed that off-line computation needs more time, which can be offset to a large extent if the generated decision surface is used to carry out some specific off-line planning study. In this section it has been used to sense kvar deficiency and, for the first time, an attempt is made to combine probability of contingency and decision surface to give a global security of any power system.

Local kvar Injection:

During the operating history of power systems several occassions arise when kvar deficiency becomes very much prominent. This is brought about in terms of wide ranging voltage fluctuation for several buses. This problem has been attempted in the past by Paris (12) and very recently by Savulescu (2). In this thesis it has been shown in Chapter II how VSI can be used in attempting to solve the same problem.

Paris generated certain index which is proportional to energy curtailment in the event of low voltage experienced by any bus under certain contingencies. This index is found out for all buses and finally, depending on the values of this index new kvar injection is found out. As it is clear from the above this method needs to solve many load flow problems for all probable contingencies and for each contingency the same is repeated for various partial load levels. Thus total computation work including the final capacitor evaluation becomes almost prohibitive. As against this the decis on surface already generated for other purposes, can be used to calculate kvar requirement at some specific buses, thus sharing the consumption of off-line time amongst them.

For illustrating t is hypothesis previously utilised 6-bus power system has been considered again. The decision surface obtained by the method 4 is applied to tackle this problem. Following steps briefly describes the computational logic:

1. Store the decision surface generated by the method 4 i.e. $S(\underline{x})$.
2. Solve load flow problem under the given operating condition.
3. Check the value of $S(x)$. If it is positive stop. If the value comes out to be negative goto step 4.
4. Using sensitivity matrix find approximately the requirement of reactive reschèduling or local reactive injection goto step 2.

This algorithm brings out the requirement, if necessary, of local reactive power injection for different probable system conditions. From this the best value is chosen for the required bus. This analysis, like the one presented in the chapter II of this thesis, confirms the same buses (No. 3 and No. 5) requiring local reactive power injection. The required values to be switched on to the bus 3 and bus 5 are 10.5 MVAR and 25.0 MVAR respectively. These values are quite comparable with the figure already obtained in Chapter II.

Global Security Index:

Security of power system has been assessed both from the point of view of indices and pattern recognition technique. The quantity Q used in Patton's security function (43) has already been modified by this author to calculate local security index, which after suitable combination gives the global security index. The criteria used to compute security index are line and generator overloading voltage being used separately for VSI. Thus Patton's model or weighting factor proposed by the present author cannot sense the system security in totality. True picture of global security index can emerge if the earlier proposed security function replaces the breach of security criterion, because the security function can sense the total health of the system. With the help of security function it is possible to classify the state of power systems in a global sense. Thus the global security index is formulated as

$$G.S.I. = \sum_{i} P_i . S(\underline{x}) \qquad (4.61)$$

where:

$S(\underline{x})$ = Security function

P_i = ith state probability.

A simplified flow chart is presented in fig. 4.7 for security assessment. Principal feature of this proposition is that it avoids the use of multiple indices to assess power system security, and unlike other indices method, it requires less computation time as number of load flow calculation is carried out only once in outer loop. The global security index as obtained by this method is shown in table 4.5. The lower value of security figure of column 2 as compared to that of table 2.5 is due to probability of a contingency appeare once in the present formulation unlike the security.

TABLE 4.5 GLOBAL SECURITY INDEX:

Total load level in p.u.	Global Security index x 10^{-3}	
	Total generation (3.1+j0.9) p.u.	Extra (1.0+j0.25)p.u added to bus 4.
0.8+j0.16	0.0	0.0
1.2+j0.24	0.0	0.0
1.6+j0.32	0.243	0.0
1.9+j0.38	0.286	0.0
2.0+j0.40	0.421	0.0
2.5+j0.50	1.602	0.009
2.8+j0.56	1.739	0.009
3.1+j0.62	1.751	0.009

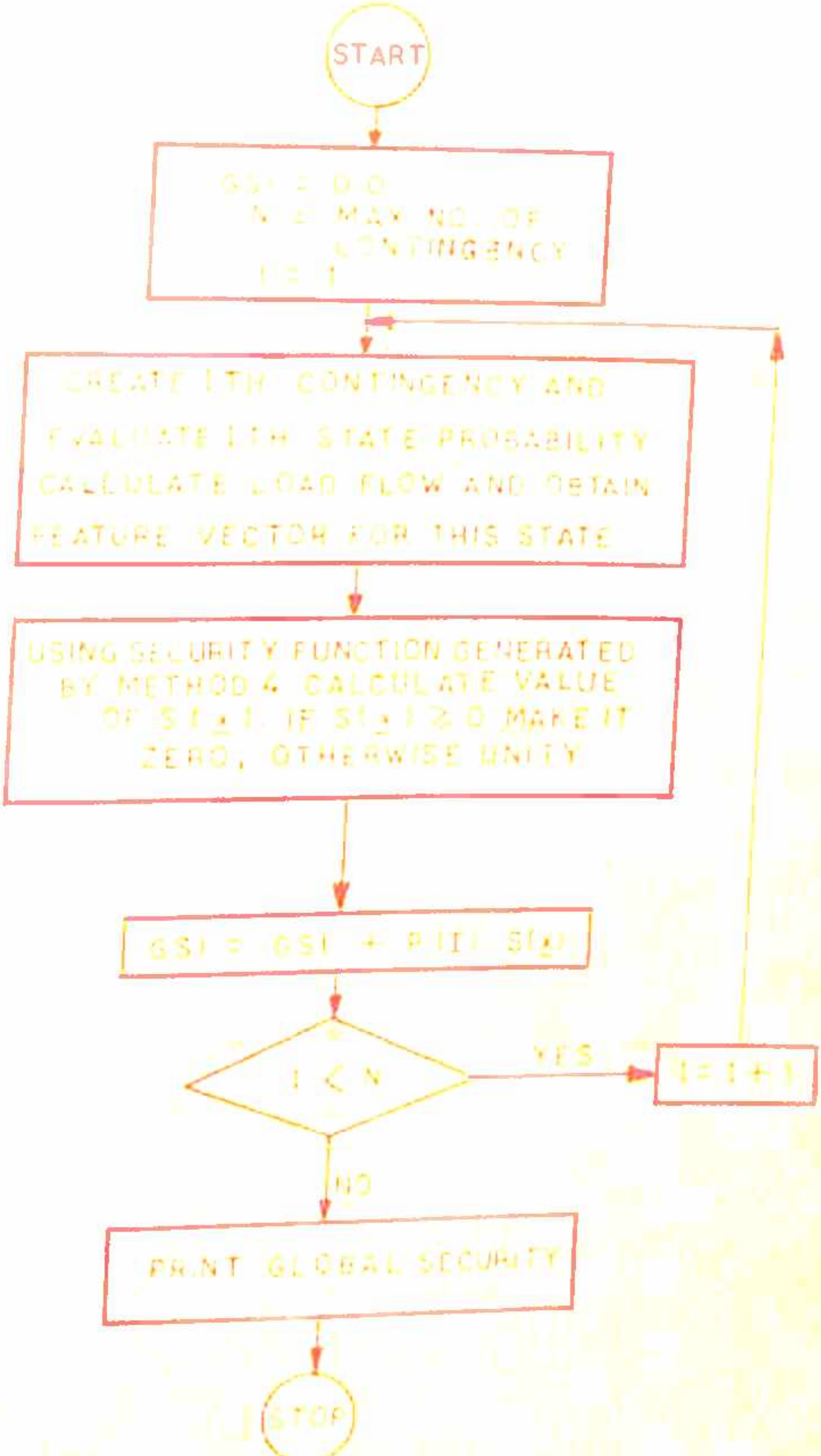


FIG. 4.7 FLOW CHART FOR COMBINED PATTERN RECOGNITION AND SECURITY INDEX METHOD.

where it appears more than once during summation of local security. Last column of both the tables are identical except the last three entries in table 4.5. This may be due to reduction in bus voltage which is not accounted for in the security index model.

4.10 CONCLUSION:

Deterministic and statistical approaches to pattern recognition techniques are studied in detail and their performances based on their power to recognise power system patterns are compared. Statistical technique based on Bayes' risk with estimated pdf is found to be the most suitable for power systems. The decision surface can be used both for on-line security assessment as well as off-line planning problems thereby offsetting the off-line computation time.

The decision function based on the above approach is used to identify the quantum and location of kvar injection requirement for a kvar deficient power system. Finally, a modified formulation of a global security index is worked out which for the first time links indices and pattern recognition approaches.

CHAPTER-V CONCLUSIONS

5.1 CONCLUSIONS:

This thesis has critically examined, compared and developed three approaches to power system security assessment viz. security indices through Markovian approach, fault tree analysis and pattern recognition technique.

For use in system reliability studies a 3-state reliability model is developed which takes into account the risk that a standby generator may fail to start.

Two security indices, LSI and VSI which are a distinct improvement over Patton's security index have been developed in this thesis - LSI based on criterion of meeting the load demand and VSI on requirement of voltage level. LSI can account for both local and global security with due corrective action through load shedding under contingency. The global LSI is infact a linearly related combination of local LSIs. VSI is to be evaluated after LSI and is found to be meaningful only from the local point of view.

Evaluation of above indices requires repeated load flow studies under various contingencies and load shedding wherever necessary. Sensitivity metrix is adopted for rescheduling of reactive power to improve voltage profile under contingency. Latest technique of decoupled load flows are employed to cope with the large number of studies necessary; the required sensitivity matrix is evaluated through direct experimentation. Suitable computer logic has been developed for load shedding and reactive rescheduling.

The use of above indices and techniques for operation and planning studies interms of expansion of lines, addition of new generating units and reactive sources is illustrated through a 6-bus system. It has been found that local LSI is more sensitive to line contingencies while global LSI is more sensitive to generation contingencies. These facts can be usefully exploited in planning studies as has been demonstrated through sample system study.

Present day security literature mainly uses Markovian approach wherein higher level failure states are neglected being assumed less probable. To this author's knowledge this thesis is the first attempt to obtain the probability of not meeting load at a given bus by fault tree analysis, wherein no such approximation is necessary.

Suitable computer simulation of tree has been made to arrive at reverse polish expression of any top event, which has further been translated into Boolean expression. A modified algorithm has been evolved which converts the terms in UOI into mutually exclusive ones. This needs less computation and storage compared to the Bennett's approach.

Fault tree has to be generated manually through an intimate knowledge of a system. This, however, is not a serious drawback as once a fault tree is ready for an existing system only minor modifications are needed to account for future expansion. The entire technique has been demonstrated through a radial network not requiring load flows which then is extended to a 3-bus system requiring load flow solutions to determine failure modes under contingency.

In search for alternative this thesis has thoroughly explored pattern recognition technique for their effective deployment in assessing the security of power system in form of a binary answer. By a careful study of the upto date techniques available four of these were selected and examined from this point of view. Two of these techniques are deterministic and two statistical. The statistical technique wherein conditional pdf of pattern vector given secure or insecure class is estimated has been found to be the most suitable. It takes least computation time with minimum misclassification.

The pattern recognition technique can be used both for on-line and off-line studies while most of the computational work can be carried out off-line. The use of this technique has been demonstrated through a planning study wherein it has been gainfully employed in determining quantum and location of kvar injection in kvar deficient system.

As compared to the indices approach the decision surface of the pattern recognition technique utilises more complete data regarding the system state. This fact has been utilised in proposing a new global security index in which the weighting factors are obtained by means of the decision surface, thereby linking the security index and pattern recognition approaches.

While evaluation of security indices through Markovian approach is a powerful method, fault tree and pattern recognition do offer future possibilities. In particular the pattern recognition technique offers promising prospect for security assessment and for aiding the operator in taking quick security conscious decision as most of the tedious computation work can be done off-line. Furthermore, while the first two methods are limited to load and voltage security assessment only the pattern recognition technique can easily sense the total health of the system at any time.

5.2 SCOPE FOR FURTHER WORK:

On the lines of chapter II time dependent security indices can be evolved which can then be used for on-line security constrained optimal load flow.

It would be a worthy exercise to attempt to mechanise the fault tree formulation of a power system.

As mentioned earlier pattern recognition has wider scope for security assessment. Work carried out in this thesis can be extended in the direction of evolving suitable decision surfaces to identify the type of fault apart from system security. Furthermore, work can be done for modification of decision surfaces as the power system expands and new hardware is commissioned.

APPENDIX-A FAST LOAD FLOW

A.1 D.C.LOAD FLOW:

Basically, the a.c. load flow tackles simultaneously active and reactive power flows. This thesis adopts a simplified load flow model because it is felt that these problems could be examined separately thus minimising the computation time. In a power system with a high reactance to resistance ratio, real and reactive power flows are practically independent of each other. Real power flow in a line is a function of the difference in phase angles of the buses connected by the given line, while reactive power flow through it mainly depends on the difference of the voltages of the same buses.

In essence the real power flow between any two terminals i and j is

$$P_{ij} = \frac{V_i V_j}{X_{ij}} \sin \delta_{ij} \qquad (A.1)$$

This formula is a simplification of a more complex relationship and disregards the resistive component. It can be further simplified by recognising that bus voltages in a power system are approximately 1.0 p.u. Equation (A.1) becomes

$$P_{ij} = B_{ij} \sin \delta_{ij} \qquad (A.2)$$

where:

B_{ij} = susceptance of the line joining buses i and j.

Since sum of the real power flow at a bus is always zero, the injected power of bus k becomes

$$PI_k = \sum_{i \in \alpha_m} B_{ki} \sin \delta_{ki} \qquad (A.3)$$

$k = 2,3,\ldots,n$ $\quad \alpha_m$ = set of nodes connected node k

So long angle δ_{ki} is within 30^0 $\sin \delta_{ki}$ can be further approximated by δ_{ki} expressed in radian.

$$\delta_{ki} = \delta_k - \delta_i \qquad (A.4)$$

Expanding and distributing the summation sign

$$PI_k = \sum_{i \in \alpha_m} B_{ki} \delta_k - \sum_{i \in \alpha_m} B_{ki} \delta_i \qquad (A.5)$$

Rearranging terms in the above equation one gets

$$\delta_k = \frac{PI_k + \sum_{i \in \alpha_m} B_{ki} \delta_i}{\sum_{i \in \alpha_m} B_{ki}} \qquad (A.6)$$

for $k = 2,3,\ldots,n$.

Equation (A.6) is the final form of simplified active power flow model. In all there will be (n-1) equations with as much unknown which can be solved by any standard numerical method.

Along with the real power flow, a linear reactive power flow model has been used while computing bus voltages or reactive rescheduling. The simplifying assumptions made to develop this model are listed below:

1. Small difference between the voltage phase angle between two adjoining buses.
2. Smaller variation in voltage compared to a nominal voltage of 1.0 p.u.

Reactive power injected in any bus is equal to the sum of outgoing reactive power. Thus

$$- QI_k = \sum_{i \in \alpha_m} B_{ki} \left(V_k^2 - V_k . V_i \text{ Cos } (\delta_k - \delta_i) \right) \qquad (A.7)$$

for $k = 2, 3, \ldots, n$

Approximating Cos $(\delta_k - \delta_i)$ by $1 - \frac{1}{2} (\delta_k - \delta_i)^2$ eqn. (A.7) becomes

$$- QI_k = V_k \sum_i B_{ki} \left(V_k - V_i \left(1 - \frac{1}{2} (\delta_k - \delta_i)^2 \right) \right)$$

$$= V_k \sum_i B_{ki} \left(V_k - V_i + \frac{V_i}{2} (\delta_k - \delta_i)^2 \right) \qquad (A.8)$$

Expressing any bus voltage in terms of the nominal bus voltage one gets:

$$V_k = V_n (1 + \xi_k) \qquad (A.9)$$

where ζ_k is a small fraction assuming both positive and negative values.

Recognising the approximated real power in the line k-i as

$$p_{ki} = V_k V_i (\delta_k - \delta_i) B_{ki} \tag{A.10}$$

Equation (A.8) may be expressed as

$$-QI_k = \sum_i B_{ki}(\zeta_k - \zeta_i) + \sum_i \frac{1}{2V_k V_i} \cdot \frac{(p_{ki})^2}{B_{ki}} \tag{A.11}$$

If V_k and V_i in the second term of eqn. (A.11) are approximated each by V_o then this term represents a constant quantity which can be approximately recognised as summation of half of reative loss in all lines connected to bus k. Taking this factor on left hand side a linear relation in reactive power and voltage is resulted.

$$QI_k - \frac{1}{2} q_k = \sum_i B_{ki} (\zeta_i - \zeta_k) \tag{A.12}$$

Thus ζ_k the unknown quantity becomes

$$\zeta_k = \frac{-QI'_k + \sum_i B_{ki} \zeta_i}{\sum_i B_{ki}} \tag{A.13}$$

for $k = 2, 3, \ldots, n$.

where:

$QI'_k = QI_k - \frac{1}{2} q_k$ = modified bus reactive power injection.

Equation (A.13) can be used in a convenient way to solve for the voltage variation. Out of the total n equations in (A.13) only n-1 are linearly independent since summation of reactive power injection for entire power system is zero.

A.2 DETERMINATION OF SENSITIVITY MATRIX:

Theoretically one can compute sensitivity matrix with help of Jacobian as

$$S_x = - J_x^{-1} J_u \quad \text{where } J_x = \text{Jacobian} \tag{A.14}$$

This would mean inversion of matrix and hence quite time consuming. In this thesis as an alternative, direct experimentation on the system has been performed to evaluate the elements of the sensitivity matrix. Using the model of eqn. (A.13) variation of voltages in all buses are computed for a differential change in reactive power injection at a particular bus with a view to compute change in voltage to reactive power ratios. These constitute one row of the sensitivity matrix. It is repeated to compute the elements of other rows.

APPENDIX-B

TWO-STATE LOAD MODEL:

Typical load for reliability planning studies can be modeled if following statistics are indicated:

1. how long the load exceeds a given level
2. the time between those periods.

The upper portion of fig. B.1 shows a plot of a typical load variation over a period. The value X represents a load level at which a particular contingency load exceeds a line capability. As shown in the lower portion of the same figure, one can represent the fluctuation above and below X as a two-state renewal process. The rate of departure of a state and its average duration can be estimated from any hourly load data of a system. For each value of X in fig. B.1 in percent of peak load two counts are made which are:

n_T : no. of hour for which $L(t) < X$ and $L(t+1) \geq X$. Where $L(t)$ is the load for hour t, $t = 1,2,\ldots, 8760$. In other words, the number of transitions from 'less than' to greater than X is counted.

n_L : no. of hours that $L(t) > X$.

From n_T and n_L one can estimate the rate at which loads greater than X occur and average duration

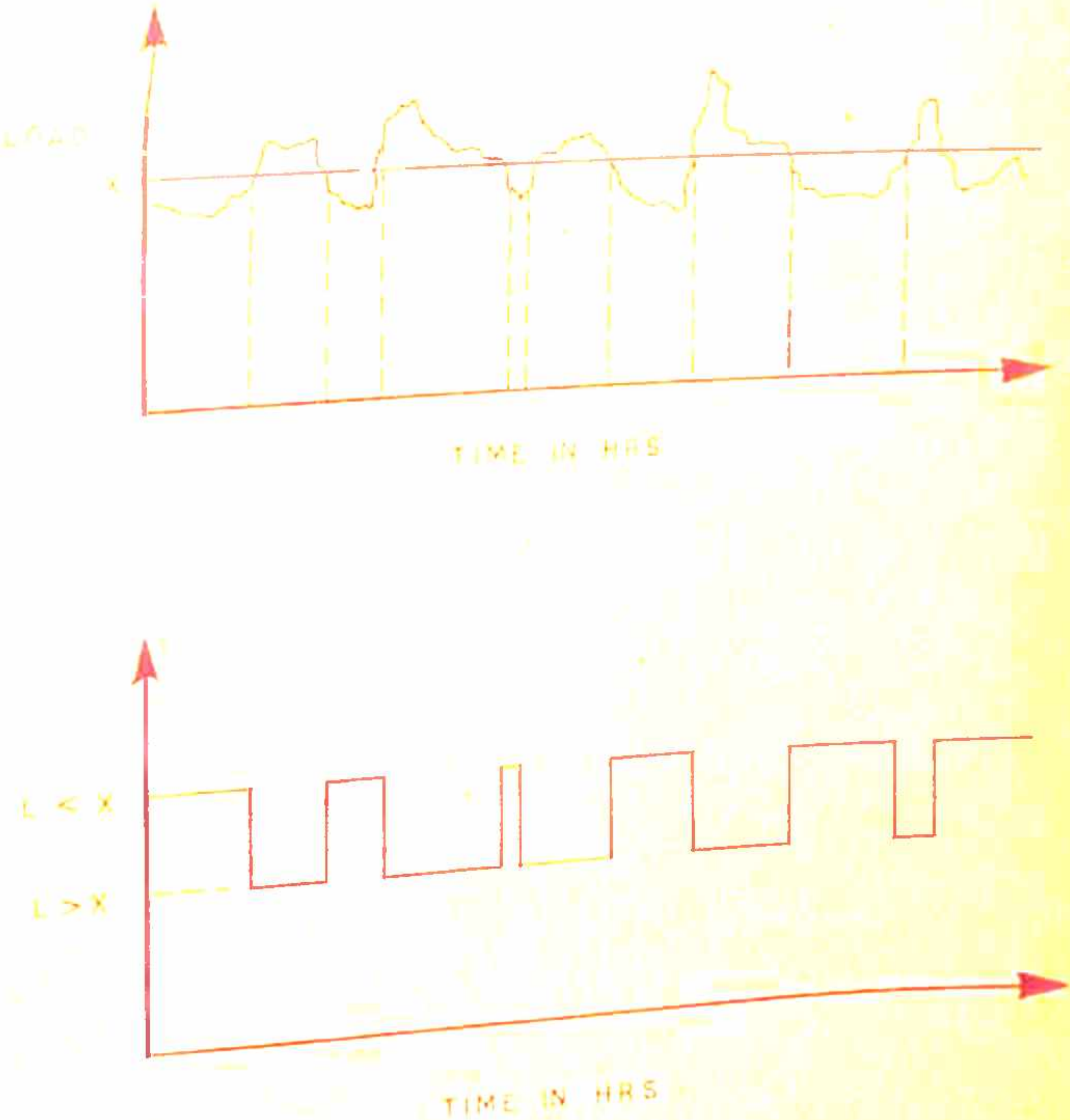


FIG.B1 DEVELOPMENT OF LOAD MODEL FOR A LOAD LEVEL X.

of the high load period. It should be noted that when durations are high, the rate of occurrence should be interpreted as the reciprocal of the mean time between high loads, rather than number of occurrence per year. For example, Table B.1 shows the rate for 60 percent of peak to be 1080. This value does not mean 1080 transitions occur per year. But rather per year of time the load is less than X. A better interpretation still may be the average duration of a period over which the load remains less than 60 percent of peak is 1/1080 year or 8.1 hours. The average pattern, therefore, is an 8-hour period of load less than 60 percent followed by a 17-hour duration of load greater than 60 percent.

The letters a_x and b_x will be used here to represent the rates of high and low load respectively. In Table B.1 the column labelled 'Average duration' represents $1/b_x$ and last column represents the availability, i.e. $P(L(t) > X)$. Since

$$P(L(t) > X) = a_x/(a_x + b_x)$$

$$= n_L/8760 \qquad \text{(B.1)}$$

and

$$\frac{1}{a_x} + \frac{1}{b_x} = \frac{1}{n_T} \qquad \text{(B.2)}$$

it follows that

$$b_x = 8760.\, n_T/n_L \qquad \text{(B.3)}$$

$$a_x = n_T/(1-n_L/8760) \qquad \text{(B.4)}$$

TABLE B.1 PARAMETERS OF LOAD MODEL

Load level in percent of peak	Rate no./yr.	Average Duration-Hrs.	Percent Availability
40	-	-	100.0
42	3406.5	1248.85	99.7
44	2398.6	377.21	99.0
46	2000.7	232.37	98.1
48	1975.3	112.52	96.5
50	1856.7	70.25	93.7
52	1905.6	38.98	89.5
54	1664.6	26.71	83.5
56	1439.2	21.03	77.6
58	1253.5	18.40	72.5
60	1080.6	17.10	67.8
62	993.9	15.51	63.8
64	894.0	14.74	60.1
66	823.6	13.90	56.7
68	729.6	13.53	53.0
70	646.8	13.50	50.0
72	606.6	12.93	47.2
74	582.9	11.93	44.2
76	578.7	10.33	40.5
78	547.9	9.03	36.1
80	500.6	7.45	29.9
82	436.9	6.10	23.3
84	316.0	5.47	16.5
86	252.2	4.37	11.2
88	152.3	4.19	6.8
90	111.5	3.30	4.0
92	60.2	3.01	2.0
94	39.4	2.23	0.1
96	21.1	1.76	0.004
98	3.0	1.67	0.0005
100	1.0	1.00	0.0001

APPENDIX-C.

FUNCTIONS OF SEVERAL VARIABLES:

Multivariate functions play a central role in the study and design of pattern recognition systems. The purpose of this section is to provide a brief treatment of the theoretical foundation and construction of these functions. The following discussion is first limited to functions of one variable. The resulting concepts are then extended to the multivariate case.

Two functions $f(x)$ and $g(x)$ are orthogonal with respect to weighting function $u(x)$ in the interval (a,b) if

$$\int_a^b u(x)f(x)g(x)\,dx = 0 \qquad (C.1)$$

A system of functions $\phi_1(x), \phi_2(x), \ldots,$ any two of which are orthogonal in (a,b), is called orthogonal system. For such a system of functions, the familiar orthogonality condition is

$$\int_a^b u(x)\phi_i(x)\,\phi_j(x)dx = A_{ij}\ \delta_{ij} \qquad (C.2)$$

where:

$$\delta_{ij} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}$$

and A_{ij} is a factor dependent on i and j. Since the right hand side of eqn. (C.2) is zero except when $i = j$, it is common practice to express A_{ij} simply as A_i or A_j. If $A_i = 1$ for all i, the system of functions is called an orthonormal system where the orthonormal condition is

$$\int_a^b u(x)\phi_i(x)\,\phi_j(x)\,dx = \delta_{ij} \qquad (C.3)$$

Generally u(x) is absorbed in the orthonormal functions. If a system of functions $\phi_1^*(x), \phi_2^*(x)\ldots$ is orthogonal in the interval (a,b) an orthonormal system in the same interval may be obtained by means of the relation

$$\phi_i(x) = \sqrt{\frac{u(x)}{A_i}}\;\phi_i^*(x) \qquad (C.4)$$

where:

$$A_i \quad \int_a^b u(x)\phi_i^{*2}(x)\,dx \qquad (C.5)$$

It is easy to show the functions $(\phi_i(x))$ are orthonormal since

$$\int_a^b \phi_i(x)\,\phi_j(x)\,dx = \frac{1}{A_i}\int_a^b u(x)\phi_i^*(x)\,\phi_j^*(x)dx$$

$$= \frac{1}{A_i}\,(A_i\delta_{ij}) = \delta_{ij} \qquad (C.6)$$

It has been shown previously how to obtain orthonormal functions of several variable from the same function of one variable. In such cases orthonormality condition is always expressed in vector form as follows:

$$\int_{\underline{x}} u(\underline{x})\,\phi_i(\underline{x})\,\phi_j(\underline{x})\,d\underline{x} = \delta_{ij} \qquad (C.7)$$

where:

$$u(\underline{x}) = u(x_1, x_2, \ldots, x_n)$$

$$\phi_i(\underline{x}) = \phi_i(x_1, x_2, \ldots, x_n)$$

$$\int_{\underline{x}} d\underline{x} = \int_{x_1=a}^{b} \int_{x_2=a}^{b} \cdots \int_{x_n=a}^{b} dx_1 dx_2 \ldots dx_n$$

Attention now is focused on orthogonal and orthonormal polynomial functions. The motivation for using these functions in pattern recognition is two fold. First, they are easy to generate. Second, they satisfy the Weier-strass approximation theorem, which states that any function which is continuous in a closed interval $a \leq x \leq b$ can be uniformly approximated within any prescribed tolerance over this interval by some polynomial.

Legendre, Laguerre and Hermite polynomials exhibit orthogonal property. Whereas the first two polynomials remain orthogonal in the closed intervals of $[-1, 1]$ and $[0, \infty]$ respectively, Hermite polynomials remain orthogonal in the interval $-\infty < x < \infty$ with respect to

$u(x) = \exp(-x^2)$. Because of the wider interval Hermite polynomials have been selected in this thesis. These polynomials are generated by means of the recursive relation

$$H_{k+1}(x) - 2x\, H_k(x) + 2k\, H_{k-1}(x) = 0 \qquad (C.8)$$

$$k \geq 1$$

The first few polynomials are:

$$H_0(x) = 1$$

$$H_1(x) = 2x$$

$$H_2(x) = 4x^2 - 2$$

$$H_3(x) = 8x^3 - 12x.$$

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(ii) I.J. Nagrath and B.K. Dasgupta., 'Power System reliability assessment through modified security indices'. Accepted by the Institution of Engineers to be presented at the annual technical paper meeting.

(iii) I.J. Nagrath and B.K. Dasgupta., 'Pattern recognition techniques applied to power system',

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