ADAPTIVE OPTIMAL COORDINATION OF DIRECTIONAL OVERCURRENT RELAYS OF LARGE SCALE POWER SYSTEMS

A THESIS

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NASEER AHMAD LAWAY

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE-247 667 (INDIA)

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"ADAPTIVE COORDINATION OF DIRECTIONAL OVERCURRENT RELAYS OF LARGE SCALE POWER SYSTEMS"** in fulfilment of the requirement for the award of the Degree of Doctor of Philosophy and submitted in the Department of Electrical Engineering of the University is an authentic record of my own work carried out during a period from *March 1992* to *May 1994* under the supervision of **Dr. H. O. Gupta, Professor**, Department of Electrical Engineering, University of Roorkee, Roorkee, INDIA.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other University.

(Naseer Ahmad Laway)
Signature of the Candidate

Dated : May 16, 1994

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

(Dr. H. O. Gupta)
Signature of Supervisor

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Signature of Supervisor

Signature of H.O.D.
Professor & Head
Electrical Engineering Department
University of Roorkee, Roorkee
U.P. (India)

D P Kothari
Signature of External Examiner

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SYNOPSIS

Adaptive protection of electric power systems is a new and a revolutionary idea. It is still in its conceptual development stage. At present, research work is going on to develop it as a protection philosophy and to identify its vital components. A few research papers are available in the protection literature on the subject, which highlight the importance and the implementability of this protection philosophy. All the researchers stress the need for this concept as it has much to offer in terms of reliability, dependability, security, efficiency, innovation and economy.

Since the concept of adaptive protection is new, it is appropriate to give it a definition as visualized by some authors. Some of the definitions are :

(A) The adaptive protection is an on-line activity that modifies the preferred protective response to a change in system conditions or requirements. It is usually automatic, but can include timely human intervention.

(B) The adaptive protection is a protection philosophy which permits and seeks to make adjustments to various protection functions in order to make them attuned to prevailing power system conditions.

(C) The adaptive protection refers to the ability of the protection system to automatically alter its operating parameters in response to changing network conditions to maintain optimal performance.

The key concept is to change something in a protection system in response to changes in power system caused by operational or structural disturbances.

The need for the development of adaptive protection arose because of certain weaknesses and shortcomings in the existing protection philosophy. Researchers have been realizing these shortcomings for some time now and have boldly proposed a new way of thinking to tackle the problems of protection. One way of thinking is, why not to make the protection relays adaptable to the system changes so that the relay would respond to new operating states in a self-adaptive manner, thereby reducing the intervention of the operators to a minimum and increasing the efficacy of the protection functions.

One of the most laborious and time-consuming tasks for a protection engineer is to set and coordinate protective relays in an interconnected power system. Ideally these settings are reviewed whenever loads or other system conditions change enough to appreciably alter the fault currents. Settings are also reviewed prior to temporarily taking a line out of service and as a part of post-fault analysis. However, even a review of settings is a troublesome task. Hence settings are not changed as often as conditions warrant and protection system performance is degraded.

This problem was tackled by using computer aided approach in an off-line mode. Based on certain coordination criteria, the settings of relays are computed. In this way the system responds to faults and abnormal conditions in a pre-determined manner. It is not only difficult to identify and analyze all the operating conditions in advance, it is also impossible to determine relay settings that would be optimum for all abnormal and normal operating conditions.

There could be a better and efficient method to set and coordinate the protective relays. The method is " **Adaptive Coordination of Protective Relays**". In this method the relays could respond to the changing system conditions and adapt according to the new conditions. The changing conditions could be operational or structural. The requirements for such a scheme to be implemented include the right kind of efficient algorithms, appropriate digital relays and communication channels. The biggest advantage of this scheme would be to liberate the protection engineer from the most tedious and time-consuming task of setting and coordinating protective relays.

This dissertation aims at the development of the concept and the philosophy of the adaptive coordination of relays in the general framework of adaptive protection.

The adaptive coordination philosophy is implemented using the concept of overcurrent relaying. The directional overcurrent relays in an interconnected power system are suitable relays to be exploited for the introduction of the adaptive concepts.

There are two coordination philosophies available for the coordination of directional overcurrent relays. One is based on the automation of the traditional interactive algorithms and the other is based on the use of parameter optimization techniques. The former technique is the result of traditional relay coordination philosophy implemented with the help of computers. The protection engineer interacts with the computer and tries to find out the solution to the coordination problem. His experience and knowledge influences the coordination results. Whereas, in the later method a performance function is optimized subject to certain coordination criteria. The coordinated relay settings obtained are the optimal relay settings which satisfy a wide variety of conditions which arise due to different system conditions. The performance function chosen reflects the desired operation of the relays.

In the work reported in this dissertation, coordination problem is formulated as a parameter optimization problem with a different characterization which is suitable for adaptive coordination. The solution methods employed efficiently fit in the overall coordination philosophy.

The traditional coordination algorithms need break point set. This requires elaborate schemes for topological analysis of the network. The break point set is needed to decrease the number of iterations in the coordination process. It is established, in the dissertation, that if the optimization techniques are used for relay coordination, this removes the need of determining break points of the network. Thus eliminating the use of elaborate topological analysis programs.

A simple but efficient method is proposed to determine the backup/primary relay pairs by using the linked-list type of data structure known as **LINKNET**. The backup/primary relay pairs are automatically generated for the close-in as well as the far-bus fault currents.

Two integrated software packages **OPCORD** and **OPCON** have been developed for coordinating the directional overcurrent relays of an interconnected power system. Different software packages like load flow analysis, fault analysis, determination of backup/primary relay pairs, main coordination program, etc. have been integrated. The programs could be run as interactive packages or as off-line **'batch'** processing packages, depending on the choice of the user. The information needed for the coordination is stored and used by the software. No data base management packages are needed to manage huge data generated by the program. An efficient method has been developed to generate, store and retrieve the data as per the requirements of the coordination. Data generation, updating, retrieval and use are all combined in the same program.

The problem of sympathy trips of relays in an interconnected power system has been studied in detail. A sympathy trip of a relay is the tendency to operate for a fault which is otherwise of no concern to this relay. The various reasons which give rise to the sympathy trip tendency of a relay have been classified into different categories. It is concluded that the use of adaptive coordination would remove the sympathy trip tendency of certain relays which are caused due to a change in the system conditions.

A full system adaptive optimal coordination algorithm has been developed and tested successfully for different test power transmission systems. The program continuously monitors the system for any disturbance, structural or operational. If a disturbance is detected, the program is invoked immediately. Nothing is assumed apriori. The algorithm calculates everything according to the present conditions of the network. No assumed contingencies are considered.

The determination of the pickup current settings and the time multiplier settings are the essence of any overcurrent coordination process. The pickup current value is normally fixed before the coordination is attempted. This procedure does not ensure correct setting of the relays. Therefore, it is proposed to dynamically vary it as the load current varies. This step would make the relays more sensitive to the system changes. Therefore, an expression for pickup current setting has been developed which dynamically incorporates any change in load current into the new value of pickup current.

Due to large number of interconnections and ever growing demand, the size and complexity of the present day power systems, have increased tremendously. Therefore, it is becoming difficult and time consuming to solve the coordination problem of large and complex power networks. Hence there is a need for an efficient decomposition technique for solving the coordination problem of large power networks. Thus an efficient decomposition technique for the optimal coordination of directional overcurrent relays of large power networks has been developed and successfully implemented. The large power network is decomposed into number of sub-networks called blocks by identifying boundary buses, branches and relays. The blocks are analyzed sequentially and the boundary data table is updated during the solution process. All the components of the software are fully integrated. It is observed that the larger the number of blocks, lesser is the overall execution time for the solution of the coordination problem.

An adaptive optimal coordination algorithm has been developed which is based upon the decomposition approach. The relay settings are determined in an adaptive manner, block-wise. Considerable execution time and the memory requirements are saved if the decomposition approach is used for the coordination process.

A new concept of local optimal coordination has been developed and reported in this dissertation. A local disturbed region is identified along with all the backup/primary relay pairs in response to a structural change or an operational change in the power transmission system. The coordination problem is solved only for this local region using local optimization. The methods developed do not employ any data base management packages or any elaborate topological analysis programs.

The concept of local optimal coordination has been used to develop an adaptive coordination philosophy. This method is an ideal method to solve the coordination problem of the affected part of the network only, in an on-line manner. Only a small portion of the power network is identified and its coordination problem is solved efficiently. The time taken for execution is negligible in comparison with the full system coordination method. The memory requirements are also drastically reduced as a small portion of the network is dealt with.

During the progress of the present work, it was realized that the concepts of control theory can be easily applied to the problem of relay coordination. In future coordinated control and protection schemes are sure to be developed and implemented. Therefore, we have formulated the classical coordination problem as an adaptive control systems engineering problem. It is made clear that this is a closed-loop, non-linear, multidimensional control system with variable parameters and intermittent control. The concept of adaptive relay coordination control system is presented and discussed. The structure of the main component of this control system, i.e., the adaptive relay coordination controller has been given. Other components of the control system are also presented and discussed.

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Naseer Ahmad Laway

TABLE OF CONTENTS

NOMENCLATURE

The nomenclature used in the thesis are listed below. Any minor departure from this nomenclature and specially used symbols are explained in the text itself.

Principal Symbols

CTI	:	Coordination time interval
F	:	Performance or objective function
f	:	Function
I	:	Current seen by a relay
I_l	:	Load current
I_s	:	Instantaneous current setting
I_m	:	Maximum current seen by a relay for a fault at the far-bus
I_{max}	:	Anticipated maximum current at a relay location
I_p	:	Pickup current setting
$I_{p_i}^{max}$	:	Upper limit of I_p for relay i
$I_{p_i}^{min}$	:	Lower limit of I_p for relay i
k_1, k_2, k_3	:	Constants of the relay to be simulated
M	:	Multiple of pickup current setting = $\frac{I}{I_p}$
m_k	:	Number of internal buses in block k
N	:	Total number of relays in the system
N_c	:	Number of relays responding to close-in faults
N_f	:	Number of relays responding to far-bus faults

NBL : Number of blocks in which network is decomposed

N^k : Subnetwork of original network N^o

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

$N^k_{m_k}$, $N^k_{m_{k-1}}$, $N^k_{m_k-b_k}$: Boundary buses in block k

N_B : Number of relays in a block

N_R : Number of relays in the identified local region

T : Operating time of the delay unit of a relay

T_i^{max} : Maximum time of operation allowed for relay i

T_i^{min} : Minimum time of operation allowed for relay i

$T_{p_{c_i}}$: Time of operation of the primary relay i responding to a close-in fault

$T_{p_{f_j}}$: Time of operation of the primary relay j responding to a far-bus fault

T_{b_c} : Time of operation of a backup relay responding to a close-in fault

T_{b_f} : Time of operation of a backup relay responding to a far-bus fault

TOLIP : Tolerance for I_p

TOLBR : Tolerance for TMS of the boundary relays

T^k : Set of boundary lines connecting block k with other blocks

TMS : Time multiplier setting

TMS_i^{max} : Upper limit of TMS for relay i

TMS_i^{min} : Lower limit of TMS for relay i

x	:	Load carrying factor (for phase protection)
	:	tolerance imbalance factor (for ground protection)
X_{max}	:	Upper limit of x
X_{min}	:	Lower limit of x
Δx	:	Variation in the value of x

INTRODUCTION

1.1 OVERVIEW

Protective Relaying is a vital part of any electric power system. Its main function is to cause the prompt removal from service of any element of a power system when it starts to operate in any abnormal fashion that might cause damage or otherwise interfere with the effective operation of the rest of the system [52]. Hence it is quite unnecessary during normal operation, but very important during trouble, faults and abnormal disturbances. The relaying equipment is aided in its task by circuit breakers that are capable of disconnecting the faulty element when they are called upon to do so by the relaying equipment.

Proper application of protective relaying is very crucial for power systems. The system reliability and integrity depends upon the manner in which the protective relays are applied. The relays not only protect the power system equipment against faults but also protect the integrity of the whole system. Protection systems minimize the amount of service lost during abnormal conditions and preclude the long-term outage by preventing equipment damage. Thus the ultimate purpose of protection is to provide power system operational reliability [23].

Protective relays are placed strategically throughout the power system. They are dedicated stand-alone devices and operate in a coordinated manner. The coordinated or the selective operation of the relays is a function of power system topology, relay characteristics and protection philosophy.

It has always been very difficult to coordinate the protective relays on the transmission lines of power networks. Each relay must be set so that it not only recognizes a fault in its zone of protection, known as the primary protection zone, and acts very quickly, but also operates discriminately in a proper time sequence with the relays on the neighbouring lines. By discrimination it means the ability of a relay to recognize a fault outside its intended zone of protection and acts sufficiently slower than the other relays which are meant to provide primary protection for this fault. Therefore, the operating time for each relay of the system must be calculated and compared under various fault conditions. If necessary, new settings must be computed to obtain proper coordination with the relays on the neighbouring lines. Frequently changing a single relay setting or adding another line to the existing system may affect the settings of a large number of neighbouring relays in the system. Repeated setting modifications and coordination checks throughout the system are then required.

Earlier, the relay setting calculations were performed manually. This used to be a huge burden on protection engineers, consuming their precious time and effort on long, routine and laborious calculations. Recently, time-consuming relay setting and coordination calculations have been handed over to computers.

The lack of computer tool for assisting the protection engineer also results in degraded performance of the protective systems. Presently, at a typical utility company, the settings which control the relay operation are changed infrequently, at most a few times a year. Even some utilities do not review the settings for years [23]. This practice is due to the enormous amount of effort required for a manual review of the present relay settings. The settings are arrived by taking into consideration all possible network contingencies and system loading which may be reasonably expected up to the next anticipated change in settings. The resulting settings are very conservative with large "safety" margins thus substantially limiting the relay sensitivity and operating range. The introduction of computers has alleviated this problem since more frequent system studies are now easily carried out and has also increased the operational performance.

Traditionally, the protective relays have consisted of electromechanical or solid-state relays which are analog type devices. Recently the digital equivalent of these relays have been developed. The development of these digital relays and the capability of inter-processor communication have opened ways for the introduction of new concepts, schemes and algorithms, which would not have been possible to conceive and to implement earlier in the important field of electrical power system protection. One such new revolutionary concept is the "adaptive protection".

One of the most important drawbacks in the conventional protection philosophy is the concept of pre-determinism. All the faults, abnormal operating conditions and system contingencies are pre-determined in order to set and coordinate protective relays in an electric power transmission system. The relays respond to these pre-determined conditions in a satisfactory manner. But if a condition arises which has not been included in the analysis earlier, the response of the relays would not be satisfactory and the security, the reliability and the integrity of the power system as far as the protection is concerned is jeopardized. Furthermore, it is not only difficult to identify and analyze all the operating conditions of concern in advance, it is also impossible to determine relay settings which would be optimum for all normal and abnormal operating conditions.

The effectiveness of power system protection is improved and system security enhanced by following the adaptive protection philosophy.

Adaptive protection is a new idea and is still in its embryonic stage. Research is going on to develop it as a potent protection philosophy and to identify its vital components.

The work which is presented in this dissertation deals with one important aspect of adaptive protection i.e. the adaptive coordination of relays. The main objective of providing adaptive coordination is to allow the protective relays to respond to actual conditions of the power system and to calculate the coordinated relay settings in an on-line manner. Moreover, the burden of coordination is shifted from the protection engineer to the on-line computers, thus bringing tremendous relief to the whole protection engineering fraternity.

Lines are protected by overcurrent, distance, or pilot relaying systems, depending on the requirements. Overcurrent relaying is the simplest, the most difficult to apply and the quickest to need readjustment as a system changes. It is generally used for phase and ground-fault protection for distribution circuits. It is used for primary ground-fault protection on most transmission lines where distance relays are used for phase faults, and for ground back-up protection on most lines having pilot relaying for primary protection [52].

The adaptive coordination schemes may not be applied to distance relaying because the settings of the distance relays are independent of load and fault levels over a wide range and the zone 1 and zone 2 settings are independent of any structural disturbances. Hence we have used directional overcurrent relays for exploiting and developing the concept of adaptive coordination. Moreover, the directional overcurrent relays are most suitable for introducing the on-line relay coordination methods. Thus the necessary concepts, schemes, algorithms, etc. have been developed for implementing the adaptive coordination for directional overcurrent relays of large scale power systems.

1.2 LITERATURE SURVEY

The first attempt to use computers in solving the coordination problem dates back to early sixties. Since then continuous research has been conducted in this area to develop automatic methods which could alleviate this problem for protection engineers. All the methods developed tried to implement the traditional coordination philosophy with the help of computers. In a way, these are the computer versions of the same methods which have been used by protection engineers for many years. The evolution of the development of computer methods for implementing coordination philosophy, traditional as well as adaptive, is traced in this literature survey.

One of the initial efforts was due to Albrecht et al. [2] where a relay coordination program using a "batch" off-line approach was introduced. A case study applying this program to a utility's transmission system is reported in [70]. A subsequent study by Begian et al. [7]

followed a similar batch approach detailing various coordination criteria to be adopted. In all these batch approaches, the protection engineer does not interact with the computer during the coordination process. Hence, effective use of the engineer's expertise end knowledge about the system is not utilized. Gastineau et al. [21] have suggested an interactive approach to solve the coordination problem. Oura et al. [48] have outlined an interactive package for coordination of distance relays on EHV systems and also included a simulation facility. However, all the above mentioned approaches started the coordination process from arbitrary relays and proceeded with other relays one by one until all the relays were properly coordinated. But the inherent loop structures found in typical transmission network necessitate a large number of iterative calculations to be performed by proceeding around the loops. The absence of a systematic procedure and efficient ordering of relays for coordination will result in repeated iterations through all the system relays and yet not necessarily converge to the final system solution. This problem prompted Knable [35] to suggest a heuristic scheme wherein relays were arranged in a sequence before they were considered for coordination. Dwarakanath and Nowitz [18] proceeded along this line of thought to obtain optimum starting points and an optimal relay sequence using graph theory concepts. These two approaches provided the basic ground-work for systematically analyzing the topology of the system, but did not include any of the relay coordination procedures.

The determination of the optimum starting points, which are also known as break points, is considered to be very important in solving the coordination problem. The break points are used to decrease the number of iterations in a coordination process. A number of papers deal with the determination of the break point set, specifically. Bapeswara Rao and Sankara Rao [6] reported the development of a method for determining the minimum set of break points. This method has been improved by Prasad et al. [57] and a better method is reported in Prasad et al. [58], in which only the fundamental circuits of the system graph are used.

Extending the concepts introduced by Dwarkanath and Nowitz [18], Damborg et al. [16] and Ramaswami et al. [61,62] have proposed systematic algorithms for determining a relative sequence matrix (RSM) and a corresponding set of sequential pairs (SSP). They have also proposed actual coordination algorithms for overcurrent and distance relays using the RSM and SSP for the given transmission network.

In the conventional coordination methods developed by Damborg et al. [16] and Ramaswami et al. [61,62], a lot of data is generated. They have carried out fault analysis of the power networks separately and stored the fault data in a data-base. The fault analysis program is not integrated with the relay coordination program. To effectively manage the huge data generated, they have used data base management packages like RIM (Relational Information Management) in their coordination programs.

Specific areas of the protection problem, like coordination of relays in radial distribution lines and industrial power systems have been considered by a number of researchers [34,78]. Mathematical modelling of overcurrent relays to get computer representation has also been attempted [13,29].

Urdaneta et al. [76] have proposed a method which uses parameter optimization technique to coordinate the directional overcurrent relays in an interconnected power system. They have formulated the problem as an extended minimax problem with fixed network configuration and with multiple network configurations.

The papers which first highlighted the concept of adaptive protection came in the later part of the year 1988. Horowitz et al. [27] defined the adaptive protection in general terms and highlighted specific applications which could be implemented using the newly developed protection philosophy. The treatment of the paper is purely conceptual. They have mentioned the adaptive relay setting as a possible application for implementing the coordination philosophy in the general framework of adaptive protection. At the same time Rockefeller et al. [65] also presented their ideas about the adaptive relaying. Their treatment of the subject is also conceptual and general. One of the main differences between the two papers is that the later paper recognizes the timely human intervention as part of the overall adaptive protection philosophy. Rocekefeller et al. [65] suggested the adaptive relay checks rather than actually resetting the relays on-line. At about the same time, Shah et al. [71] conducted a feasibility study for adaptive distribution protection system using computer overcurrent relaying concept. They showed that if adaptive distribution protection concepts are implemented, the benefits obtained would be numerous.

Jampala et al. [32] have described some software aspects of the adaptive transmission protection. They suggest to use the already existing software in adaptive protective philosophy. Some implementation results are also given.

As is evident from the literature survey, the concept of adaptive protection is still in its infancy. Any new contributions in this thrust area are welcome. It can therefore be concluded that the present state-of-art in analyzing the protection systems can be substantially improved by developing new analytical tools to make the system-wide coordination process feasible and efficient and to develop new concepts, methods and algorithms to effectively implement the new adaptive coordination philosophy in realistic power transmission systems. This dissertation will address techniques to achieve these objectives.

1.3 AUTHOR'S CONTRIBUTION

The objective of this research work is to develop concepts, algorithms and methods for adaptive coordination of directional overcurrent relays in the general framework of adaptive protection.

The author's contribution in this area of research is summarized as follows :

* In the work reported in this dissertation, coordination problem is formulated as a parameter optimization problem with a different characterization than reported in [76]. This characterization is suitable for solving coordination problem in an adaptive manner.
* It is established, in the dissertation, that if the optimization techniques are used to solve the coordination problem, there is no need to determine the break point set. Thus eliminating the use of elaborate and complex topological analysis programs. This step simplifies the coordination philosophy a great deal.
* A simple but efficient method is proposed to determine the backup/primary (B/P) relay pairs by using the linked-list type of data structure known as **LINKNET**. The B/P relay pairs are automatically generated for the close-in as well as the far-bus

fault currents. This step totally eliminates the use of topological analysis programs.

* Two integrated software packages called **OPCORD** and **OPCON** have been developed for coordinating the directional overcurrent relays for full systems. Different software packages like load flow analysis, fault analysis, determination of B/P relay pairs and main coordination program, etc. have been integrated.

* An efficient method has been developed to generate, store, retrieve and use the data as per the requirements of the coordination. No data base management packages are needed. Even a data base itself is not required. Data generation, updating, retrieval and use are all combined in the same program.

* Interactive versions of **OPCORD** and **OPCON** programs have been developed for off-line use of the protection engineers. These interactive versions of the programs incorporate the "feel" of the protection engineer in solving the coordination problem.

* An expression has been developed which allows the pickup current setting of the directional overcurrent relays to vary dynamically as the load current varies. This expression reflects any change in load current in the pickup current settings. Earlier, the pickup current setting used to be kept fixed before coordination was attempted. This step would make the relays more sensitive to the system changes.

* Sympathy trips are the incorrect trips during faults. These are caused by the inappropriate relay settings. The sympathy trip tendencies of directional overcurrent relays in an interconnected

power system have been classified into different categories. It is shown that some of the sympathy trip tendency of relays are removed by following the adaptive coordination method.

* The concept of adaptive coordination of directional overcurrent relays in an interconnected power system is presented and its various vital component are identified.
* A method for full system adaptive optimal coordination has been developed and tested successfully for different test power transmission systems. The algorithm continuously monitors the system for any disturbance, structural or operational. If a disturbance is detected, the program is invoked immediately. Nothing is assumed apriori. The algorithm calculates everything according to the present conditions of the network. No assumed contingencies are considered. The above developed efficient algorithms are all included in the adaptive coordination algorithm.
* A program has been developed to determine the performance evaluation of all the coordinated relays. A fault is simulated at random at any location of the power system, and the performance of the relays is obtained. This procedure gives an idea how the relays would behave in case of a disturbance.
* To solve the coordination problem of large power transmission systems, a newly developed efficient network decomposition method is used. In this decomposition method, the large power network is decomposed into a number of sub-networks called blocks by identifying boundary buses, branches and relays. The blocks are

analyzed sequentially and the boundary data table is updated during the solution process. All the components of the software are integrated. It is observed that the larger the number of blocks, lesser is the overall execution time needed to solve the problem. This method of coordination is very efficient as far as the speed and memory requirements are concerned.

* An adaptive optimal coordination algorithm has been developed which is based upon the above mentioned decomposition approach. The relay settings are obtained in an adaptive manner, region or area-wise. The possibility of using parallel processing is surveyed and the findings reported. The use of parallel processing in solving coordination problems will make the coordination algorithms very efficient.

* A new concept of local optimal coordination has been developed and is reported in this dissertation. This method of coordination is used under changed system conditions. A local disturbed region is identified in response to a structural or an operational change in the power transmission system. The coordination problem is solved only for this local disturbed region using the concept of local optimization. No data base management packages are needed and all the components of the software are integrated. The program does not use elaborate and complex topological analysis programs. Two algorithms have been developed for identifying the local disturbed region. Based upon which identifying algorithm is used, two local optimal coordination methods have been developed. The methods have been applied successfully to solve the coordination

problem of the disturbed region, which is created by simulating a disturbance, of various standard test power transmission systems. The results obtained are highly encouraging.

* An ideal method is developed for adaptive coordination of interconnected power systems, under changed system conditions, using the concept of local optimal coordination. This method is most suitable for adopting adaptive coordination philosophy, since only a small portion of the network is to be considered after a disturbance has occurred. The time taken to solve the local optimal coordination problem is negligible in comparison to full system adaptive coordination method and the decomposed system adaptive coordination method. The memory requirements are also less. The software is integrated and self-contained.
* The protective relay coordination problem is formulated as an adaptive control system engineering problem. The system concepts are used to highlight the nature of the coordination problem. The concept of adaptive relay coordination control system is presented and the structure of the adaptive relay coordination controller is given. The philosophy behind this presentation is reported and discussed.

1.4 ORGANIZATION OF THE THESIS

The integrated software for the optimal coordination of directional overcurrent relays in an interconnected power system is presented in *Chapter 2*. The problem of relay coordination is formulated as a parameter optimization problem and different solution methods are suggested with inherent advantages of each method. The algorithms developed during the research on optimal coordination are presented at the appropriate places. Two interactive coordination programs OPCORD and OPCON which have been developed are presented and discussed.

Chapter 3 is devoted to describing the full system adaptive coordination. The concept of adaptive optimal coordination along with the vital components of the algorithm are presented. The algorithms developed are self-consistent and self-contained in their applications. The details about the individual components which make up the adaptive algorithm are given.

Chapter 4 deals with the adaptive optimal coordination of directional overcurrent relays using the newly developed network decomposition approach. The network decomposition approach is presented to solve the coordination problem of large electric power systems in block- or region- or area-wise. The large power networks are decomposed into a number of sub-networks by identifying the boundary buses, branches and relays. The sub-networks are solved sequentially. This way of solving coordination problem saves considerable execution time and the memory requirements. The use of the concept of parallel processing is also surveyed in this Chapter. Its importance is highlighted.

The subject of adaptive coordination using the concept of newly developed local optimization is covered in *Chapter 5*. To solve the coordination problem of large interconnected power systems under the changed system conditions on-line, the method of local optimal coordination is an ideal one. The need to use this method is highlighted in this Chapter. It is known that at the occurrence of a disturbance, operational or structural, in a large power system, only a small portion of the network gets affected. The disturbance produces ripples in the relay settings which die down after travelling some distance away from the disturbance. Methods have been proposed and presented which identify this local disturbed region in an on-line fashion. Methods which have been developed to coordinate the relays of this identified local region are also covered in this Chapter.

The algorithms developed and presented in this thesis have been applied to solve the coordination problems of the following test systems :

* 6-bus test system
* IEEE 14-bus test system
* SPC 26-bus test system
* IEEE 57-bus test power transmission system
* 64-bus power system of North-Western India
* IEEE 118-bus test power system

The results obtained are encouraging.

Some rethinking has been done in *Chapter 6*. The amalgamation of the ideas from different fields are applied to solve the coordination problem of power systems in a new way. The difference between the adaptive protection and control, in future, will become blurred. The classical control concepts will creep in slowly into the fold of adaptive protection. We have formulated the classical coordination problem as an adaptive control systems engineering problem. It is made clear that this is a closed-loop, non-linear, multidimensional control system with variable parameters and intermittent control. The structure of the vital component of the adaptive control system, the adaptive relay coordination controller, is presented and discussed in this Chapter.

Chapter 7 provides some concluding remarks along with suggestions for future work in this newly emerged field of protection engineering.

OPTIMAL SYSTEM COORDINATION

2.1 INTRODUCTION

The use of optimization techniques in solving relay coordination problem of interconnected power transmission systems is a revolutionary step. It has greatly simplified the relay coordination philosophy. It is shown, in this Chapter, that the elaborate and highly complex topological analysis programs are rendered redundant by this new coordination philosophy.

Literature survey which was conducted on the subject revealed that only Urdaneta et al. [76] have exploited the parameter optimization technique in solving the coordination problem before. They have formulated the coordination problem as an extended minimax optimization problem and suggested possible solution methods which could solve the problem in an effective way. Their treatment of the subject is fairly general. Both cases involving the fixed network configurations with several perturbations and the multiple network configurations with several perturbations have been studied by them. Different decomposition techniques have also been presented by them to speed-up and simplify the solution techniques.

In this Chapter, a different characterization of the coordination problem is presented which is suitable for the adaptive coordination of relays. Solution methods are also presented which are commensurate with the problem formulation.

It is demonstrated, in this Chapter, that there is no need to employ data base management packages for managing huge data which is required for the solution of the coordination problem. A simple but efficient method has been developed to generate, store, retrieve and use data as per the requirements of the coordination. Data generation, updating, retrieval and use are all combined in the same program.

A method is also presented which determines the backup/primary relay pairs and the associated fault current pairs for the system by using the linked-list type of data structure known as **LINKNET**.

An integrated approach has been adopted in developing a software package for solving the coordination problem of interconnected and complex power networks. Different software packages like load flow analysis, fault analysis, determination of backup/primary relay pairs and main coordination program are integrated. The integrated software package **OPCORD** uses the Simplex method [17] of linear programming to determine the time multiplier settings of the directional overcurrent relays. Another integrated software package **OPCON** is also developed which utilizes the Charalombous least pth algorithm [11] for determining the time multiplier settings of the relays. The utilization of this algorithm decreases the computational effort considerably.

Interactive versions of the programs **OPCORD** and **OPCON** are also presented and discussed. More important coordination issues are allowed to be decided by the user so that his expertise and "**feel**" about the system influences the coordination results in a better way.

The problem of sympathy trips of directional overcurrent relays has been studied in detail. The reasons have been identified which cause the sympathy trip tendency of certain relays in an interconnected power system. A case study has been conducted which has helped us to classify the sympathy trips into different categories. It is concluded that the use of adaptive coordination would remove the sympathy trip tendency of certain relays which would have otherwise arose due to the system changes.

2.2 DIRECTIONAL OVERCURRENT RELAYS

Protective devices like directional overcurrent relays are placed strategically throughout the power system. They are stand-alone devices and operate in a coordinated manner i.e. their operating settings are coordinated so as to achieve desired operations whenever a fault or an abnormal condition occurs. The art of protective device coordination is a highly developed and a specialized field of protection engineering.

The directional overcurrent relays detect any fault in the system through the amount of excess current flowing through them in a specified direction. These relays are placed on both ends of a transmission line and provide primary as well as backup protection against faults which may occur anywhere in the system. A directional overcurrent relay mainly consists of :

- an instantaneous unit
- a time delay unit

The instantaneous unit is set to operate without any intentional time delay. When a current is above a certain limit called the threshold value, this unit operates the relay. This threshold value of the current is known as the instantaneous current setting. This setting of the relay provides the primary protection of the lines i.e. the relay operates when a fault occurs in its primary protection zone and does not operate for faults outside this zone. Therefore, the coordination issues of the power transmission network does not concern the instantaneous current settings of the relays. Coordination of the directional overcurrent relays is a system-wide phenomenon and involves all the relays in the power transmission system.

The instantaneous current setting is selected in such a way that the relay provides protection for as large portion of the line as possible and does not operate for faults which may occur elsewhere in the system. This setting is calculated as :

$$I_s = 1.3 \times I_m \tag{2.1}$$

where I_m is the maximum current for a fault at the far bus under normal conditions.

The second unit of the directional overcurrent relay is the time delay unit. This unit operates at the occurrence of a fault with an intentional time delay. The time delay is adjustable and depends upon the coordination philosophy adopted. This unit is used for currents which are below the instantaneous current setting but exceed the normal flow due to a fault. Two settings are associated with this unit. These are :

- the pickup current setting (I_p)
- the time multiplier setting (TMS)

The pickup current setting is the minimum current for which the relay operates. The time multiplier setting adjusts the time of operation of a relay and is like a scale factor for the operating time. The operating time of the time delay unit of a directional overcurrent relay is a non-linear function of the relay settings and the current seen by the relay, i.e.,

$$T = f(I, I_p, \text{TMS}) \tag{2.2}$$

This equation is normally given in the form of inverse characteristic curves of the concerned relays for different values of TMS. The curves are provided by the relay manufacturers. For simulating the relays mathematically, these curves are suitably modelled and the mathematical models are discussed in detail in [29]. The type of mathematical model selected depends upon the inverseness of the relays.

As mentioned before, TMS is the scale factor for the operating time of the relays. Since the operating time of directional overcurrent relay increases with the increase in TMS, the lower the TMS, the faster is the relay operation. TMS should ensure not only the fastest operation possible for primary protection but also properly coordinated action when backing up the relays on the adjacent lines.

2.3 RELAY COORDINATION

The relay coordination is a system-wide phenomenon and involves all the relays in the system. A relay operates as a primary relay to a fault in its primary protection zone and the same relay operates as a backup to some other primary relays in the system. Since there are many interconnections in a realistic power system, therefore, there are many backup/primary (B/P) relationships between different relays. The determination of B/P relay pairs is a very important feature of all coordination programs. The time lag between the operations of a primary and its backup relays is known as the coordination time interval.

The process of determining the relay settings in such a way that all the B/P relay pairs operate as planned is known as the relay coordination. The calculated relay settings have to remain within their respective limits. Therefore, the coordination of directional overcurrent relays involves the determination of :

- I_p
- TMS

for all the relays of the power system.

2.4 OPTIMAL COORDINATION OF DIRECTIONAL OVERCURRENT RELAYS

2.4.1 STATEMENT OF THE PROBLEM

The optimal coordination problem can be stated so as to minimize a performance function subject to certain coordination criteria and limit on problem variables.

2.4.2 PERFORMANCE FUNCTION

The performance function chosen must reflect the desired operation of the overcurrent relays. The desired operation in the coordination context, means selecting the suitable settings of the relays such that their fundamental protective function is met under the requirements of sensitivity, selectivity, reliability and speed.

A performance function ,F, which describes these features is the summation of the primary operating times of the relays which would respond to the close-in fault currents plus the summation of the primary operating times of the relays which would respond to the far-bus fault currents. It is given by :

$$F = \sum_{i=1}^{N_c} T_{p_{c_i}} + \sum_{j=1}^{N_f} T_{p_{f_j}} \qquad (2.3)$$

The minimization of the objective function, F, would yield a faster response and greater sensitivity as far as the protection function is concerned. The selectivity would be achieved by minimizing F with the following constraints :

2.4.3 CONSTRAINTS

(i) Coordination Criteria

The coordination of overcurrent relays in an interconnected power system is done according to certain coordination criteria. The most important coordination criterion is the time lag in operation between a primary relay and its backup relay. This time lag, as already mentioned, is known as the coordination time interval or the coordination margin and depends upon many factors such as the time of operation of circuit beakers, relay overtravel time and factor of safety.

The coordination criterion is written as :

$$T_{backup} - T_{primary} \geq CTI \tag{2.4}$$

This criterion is broken into two criteria

$$T_{b_c} - T_{p_c} \geq CTI \tag{2.5}$$

and

$$T_{b_f} - T_{p_f} \geq CTI \tag{2.6}$$

where (T_{b_c} , T_{p_c}) are the time of operations of a backup relay and its corresponding primary relay for a close-in fault and (T_{b_f} ,

T_{p_f}) are the time of operations of a backup relay and its corresponding primary relay for a far-bus fault. A fault near a relay is its close-in fault and this will generate its own B/P relay pairs and the associated current pairs. Similarly the same fault is a far-bus fault for the relay which is on the opposite side of the line. This will also generate its own B/P relay pairs and the associated fault current pairs.

(ii) Bounds on Relay Settings

The range of relay settings is always fixed. The pickup current setting has its own lower limit and the upper limit, similarly TMS has also the lower limit and the upper limit. The relay settings are to be selected between these extreme values. The bounds on the relay settings are supplied as the constraints :

$$TMS_i^{min} \leq TMS_i \leq TMS_i^{max} \quad (2.7)$$

$$I_{p_i}^{min} \leq I_{p_i} \leq I_{p_i}^{max} \quad (2.8)$$

where $i = 1, \ldots, N$

(iii) Bounds on Operation Times

In addition to satisfying the above mentioned coordination criteria and bounds on relay settings, it is also to be assured that the relays operate within a time range which is supplied by the user. For example, the primary protection is to be accomplished with a maximum time delay of 1 second for all faults and the minimum time of operation is around 0.05 seconds.

$$T_i^{min} \leq T_i \leq T_i^{max} \quad (2.9)$$

2.5 OPTIMIZATION METHODS

The overall relay coordination problem is divided into two sub-problems, viz, the optimal selection of TMS and the optimal selection of I_p for all the relays. This division of the coordination problem into two sub-problems is possible if the relay characteristics are modelled by the equations which give natural partition between TMS and I_p. To keep this in mind, we heve selected the mathematical model of the relays as :

$$T = \frac{k_1 \text{ (TMS)}}{(M)^{k_2} + k_3} \tag{2.10}$$

Where k_1, k_2 and k_3 are the constants and depend upon the specific device being simulated.

Eq. (2.10) gives a natural partition between TMS and I_p and this partition facilitates the solution of the coordination problem.

The solution of the coordination problem of an interconnected power system involves minimizing the objective function given in Eq. (2.3) subject to the constraints given in Eqs. (2.5), (2.6), (2.7), (2.8) and (2.9). The overall solution of the problem involves an iterative procedure i.e. TMS of relays are computed for known values of I_p and vice versa, until convergence is achieved. It is the essence of coordination to find the solution for these two variables. The procedure (which is based upon the Gauss-Seidel Method) adopted is :

(1) An initial value of I_p is selected for all relays

(2) For optimal selection of TMS,
Minimize [F]
subject to the constraints given in Eqs. (2.5), (2.6), (2.7) and (2.9).

(3) For this value of TMS, to get I_p,
Minimize [F]
subject to the constraints given in Eq. (2.8)

(4) Go to step 2 with new values of I_p settings, until convergence is achieved.

2.5.1 OPTIMAL COORDINATION OF TMS

The relay characteristic given in Eq. (2.10) is rewritten as :

$$T = \frac{k_1 \text{ (TMS)}}{\left(\frac{I}{I_p}\right)^{k_2} + k_3} \tag{2.11}$$

For a known value of I_p, Eq. (2.11) is written as

$$T = k \text{ (TMS)} \tag{2.12}$$

where
$$k = \frac{k_1}{\left(\frac{I}{I_p}\right)^{k_2} + k_3} \tag{2.13}$$

Therefore Eq. (2.3) is written as

$$F = \sum_{i=1}^{N_c} k_i \text{ (TMS}_i) + \sum_{j=1}^{N_f} k_j \text{ (TMS}_j) \tag{2.14}$$

Observation of Eq. (2.14) reveals that it is a linear function in terms of TMS. Hence this problem is solved as a linear optimization problem [17], subject to the linear constraints. The constraints are derived from Eqs. (2.5), (2.6), (2.7) and (2.9).

For a close-in fault, the primary relay i will see a current I_i, therefore its time of operation is given by

$$T_{p_{c_i}} = \frac{k_1 \, (TMS_i)}{\left[\frac{I_i}{I_{p_i}}\right]^{k_2} + k_3} = k_{c_i} \, (TMS_i) \tag{2.15}$$

Similarly its corresponding backup relay j will also see a corresponding current I_j, therefore its time of operation is given by

$$T_{b_{c_j}} = \frac{k_1 \, (TMS_j)}{\left[\frac{I_j}{I_{p_j}}\right]^{k_2} + k_3} = k_{c_j} \, (TMS_j) \tag{2.16}$$

Therefore the constraints given by Eq. (2.5) are written as :

$$k_{c_j} \, (TMS_j) \; - \; k_{c_i} \, (TMS_i) \; \geq \; CTI \tag{2.17}$$

Where i refers to the primary relay and j refers to the corresponding backup relays.

Similarly for far-bus faults, the constraints given by Eq. (2.6) are written as :

$$k_{f_j} \, (TMS_j) \; - \; k_{f_i} \, (TMS_i) \; \geq \; CTI \tag{2.18}$$

Since the objective function is a linear function and the constraints are also linear, the Simplex Method of linear programming is used for the solution of this problem.

2.5.2 *OPTIMAL COORDINATION OF I_p*

For a given TMS, the relay characteristics from Eq. (2.11) is written as :

$$T = \frac{k_1 \,[TMS]\, (I_p)^{k_2}}{(I)^{k_2} + (I_p)^{k_2} . k_3} \tag{2.19}$$

Therefore in this context, Eq. (2.3) is written as

$$F = \sum_{i=1}^{N_c} \left[\frac{k_1 \,[TMS_i](I_{p_i})^{k_2}}{(I_i)^{k_2} + (I_{p_i})^{k_2} . k_3} \right] + \sum_{j=1}^{N_f} \left[\frac{k_1 \,[TMS_j](I_{p_j})^{k_2}}{(I_j)^{k_2} + (I_{p_j})^{k_2} . k_3} \right] \tag{2.20}$$

TMS for all relays is fixed in this expression.

Observation of Eq. (2.20) reveals that the performance function in this case is a non-linear one and is in terms of the variable I_p. This performance function is to be minimized subject to linear constraints given by Eq. (2.8). Rosenbrock-Hillclimb method [39] is used to determine the optimal pickup current settings for the given values of TMS. This method is used because of its low storage requirements and the nature of the constraints. The constraints are only the upper and the lower limits of I_p for each relay. This method is a sequential search technique which has proven effective in solving problems where the variables are constrained [39].

The final values of I_p and TMS are determined iteratively. The complete algorithm for the optimal coordination of directional overcurrent relays is presented in Sec.2.9.

2.6 COORDINATION OF RELAYS WITHOUT USING TOPOLOGICAL ANALYSIS

As mentioned previously, there are two approaches to solve a coordination problem. One is based on the conventional or the traditional coordination philosophy and the other is based on the use of parameter optimization techniques. The conventional coordination method is simply the computer version of the same procedure which has been used for many years. The latest improvements in this coordination philosophy include much sophistications. Elaborate and complex topological analysis programs have been included to determine the break point set, the relative sequence matrix (RSM), the set of selection pairs (SSP), etc. and the facility for data base management is also provided [16,62]. The other coordination method, which is based on the optimization theory, is also gaining considerable importance [41,76]. In this method an objective function is optimized subject to certain coordination criteria. The coordination criteria is precisely identified and implemented. There are certain inherent advantages in this coordination procedure. One of the main advantages is that, there is no need to determine the break point set and hence no need to employ elaborate and complex topological analysis programs. The other equally important advantage is that the settings obtained are optimal settings, whereas in the conventional method the settings obtained are not optimal.

Coordination of directional relays on radial systems is an established and orderly procedure. However, in interconnected and multiloop power systems, it is very difficult to set and coordinate the settings. The main difficulty in setting the relays arises when one sets the last relay in a sequence which closes a loop- it must coordinate with the one set initially in that loop. If it does not, one must proceed around the loop again. Of course, a given relay usually participates in more than one loop

[16]. The order in which the relays are considered for setting decides how fast the system-wide coordination is achieved. If an arbitrary order is assumed, it is very likely that changing the parameters of one relay for obtaining coordination for all the relevant primary/backup fault current pairs can disturb the proper coordination of some of the relay pairs already checked. Hence, after a series of changes in settings, one can effectively remain at the beginning of the process with all the pairs yet to be checked with respect to the current settings.

Thus, identification of an efficient sequence in which relays are to be considered for coordination is a must for ensuring fast and reliable convergence of the system coordination process. Therefore, most of the conventional relay coordination programs use topological analysis algorithms based on graph theory to obtain an efficient relay setting sequence which will ensure fast convergence of the coordination process.

After the break point set is determined, the topological analysis programs find RSM to set all other relays. The RSM is an ordered sequence of all the relays in the system. The next step involves determination of the SSP, which is an ordered sequence of all the primary/backup relay pairs in the system.

Formulation of the coordination problem as an optimization problem suggests that the coordination criteria is supplied in the form of a constraint list (Eq. (2.17) and Eq. (2.18)). The generation of this constraint list depends upon the list of the B/P relay pairs and the corresponding fault current pairs for every fault location simulated. The B/P relay pairs are generated in any manner one likes. There is no need to have a specific order in which these could be generated. We can start from anywhere and there is no need to have a list of the starting relays. The reason is that, the coordination of the directional relays in an interconnected power system is achieved by simultaneously satisfying all the constraints. When all the constraints are treated simultaneously, the idea to go from one relay to other relay in order to coordinate them becomes unnecessary. Thus the shortcomings of coordinating the relays in an interconnected power system are removed, and the elaborate and complex topological analysis programs are not required. But we still have to generate B/P relay pairs. We have used the linked-list type of data structure LINKNET [60] to determine the relay pairs. Appendix-C gives the algorithm which is used to develop the LINKNET structure for an interconnected power system.

2.7 DETERMINATION OF B/P RELAY PAIRS

The LINKNET is used to scan the power system network. The scanning is performed to determine the B/P relay pairs for each fault location considered. The LINKNET has three main one-dimensional vectors. The vectors are described as below :

(a) Bus links : LIST is a vector which stores all the bus links. For any given bus, the element LIST(BUS) points to the first directional relay incident at this bus. The order of this vector is equal to the number of buses in the network.

(b) Directional Relay links : NEXT is a vector which is used to store the links between directional relays incident at a given bus. For any given RELAY, the element NEXT(RELAY) points to the next directional relay incident at this bus. The last relay on the list for each bus is indicated when NEXT(RELAY) assumes a zero value.

The order of this vector is given by the number of relays in the system.

(c) Remote Relay Links : FAR is a vector which is used to link any directional relay with its remote bus . For any given RELAY, the element FAR(RELAY) points to the remote bus at the end of the line on which RELAY is located. The order of this vector is also given by the number of relays in the system.

The LIST and NEXT vectors facilitate finding the directional relays at any bus. The FAR vector aids in systematically travelling from one bus to another in the power network. Thus these vectors enable various network scanning operations to be performed very efficiently. In the proposed method, the B/P relay pairs are determined for a fault which may occur at any location.

The algorithm for determining the B/P relay pairs for a fault at each relay location is depicted in Fig.2.1.

2.7.1 ALGORTIHM FOR DETERMINING B/P RELAY PARIS

The power network topology is stored using the data structure LINKNET. The relays are assigned numbers by LINKNET commensurate with the bus numbers which are assigned by the user. The main steps of the algorithm for determining the B/P relay pairs are listed below [Fig.2.1] :

1. A relay, '*RELAY*', is visited.
2. The relay which is on the other side of the transmission line is also determined.
3. IFLT gives the bus number near which the relay under consideration is located.

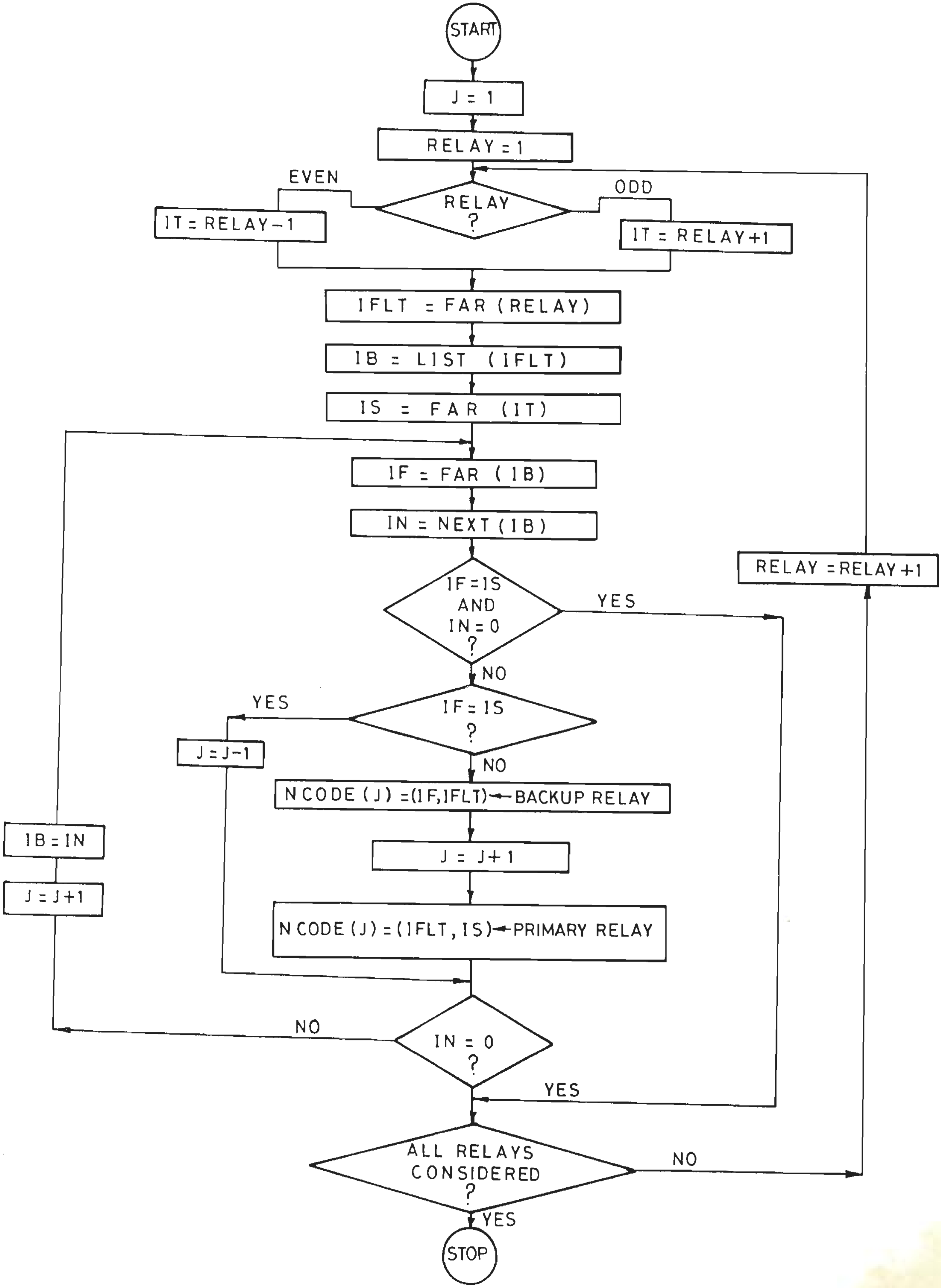


FIG. 2·1 — DETERMINATION OF B/P RELAY PAIRS

4. IB points to the first directional relay incident at this bus.

5. For the given *'RELAY'*, IS points to the remote bus at the end of the line on which *'RELAY'* is located.

6. IF points to the bus near which the backup relay to the relay under consideration, *'RELAY'*, is located.

7. For the given *'RELAY'*, IN points to the next directional relay incident at bus IFLT.

8. If IF = IS and IN = 0, all the B/P relay pairs for a fault at *'RELAY'* have been determined. The next relay is visited. If this condition is not met, go to step 9.

9. If IF = IS, adjust the vector counter and go to step 12; otherwise go to the next step.

10. The vector NCODE(J) collects the backup relay, which is the relay given by (IF, IFLT).

11. The same vector NCODE(J) stores the primary relay also, which is the relay given by (IFLT, IS). The vector count for NCODE i.e. J is adjusted accordingly.

12. IN is checked at this stage. If IN = 0, all the B/P relay pairs for this fault simulated have been determined and next relay is visited. If IN ≠ 0, there are still more B/P relay pairs to be determined. Put IB = IN, adjust J and go to step 6.

13. Put *RELAY = RELAY + 1* and go to step 1 i.e. the next relay is visited.

The B/P relay pairs are stored in the vector NCODE (J) in a sequence in which they are determined by the algorithm. Two sets of B/P relay pairs are generated for each fault simulated. One set of B/P relay pairs is generated for a close-in fault and the other set is generated for a far-bus fault. A fault is a close-in fault for one relay and a far-bus fault for the other relay which is just on the opposite end of the same line.

The vector NCODE(J) contains all the B/P relay pairs. The counter J gives the total number of all the backup and primary relays involved in the coordination process and J/2 gives the total number of B/P relay pairs to be coordinated.

2.8 EFFICIENT METHOD FOR GENERATION, STORAGE AND RETRIEVAL OF DATA FOR THE COORDINATION OF DIRECTIONAL RELAYS

The computerization of the coordination process has relieved the protection engineer from the tedious and laborious task of manual calculations of the relay settings. In the presently used computer methods, all possible system contingencies are considered beforehand, the relay coordination is attempted off-line, and the relays are set manually. This generates a lot of data and thus data management techniques are used. Such techniques are not suitable for on-line coordination of directional protective relays such as adaptive coordination. The reason is that, by using data base management systems (DBMS) such as RIM (relational information management) [62], we require interaction with DBMS for retrieving and updating the data. After updating the data, the data files are to be reindexed for efficient retrieval of the data. Thus the use of DBMS in solving the relay coordination problem on-line is a cumbersome process. Moreover, the index files also require a large amount of memory.

Thus a method is proposed which integrates the load flow program, the fault analysis program, the program for the determination of the B/P relay pairs and the main relay coordination program. The technique developed does not require a data base management system. Data generation, updating, retrieval and use are all combined in the same program. This method has allowed us to develop fully integrated software package for optimal coordination of directional overcurrent relays in interconnected power transmission systems.

2.8.1 THE PROPOSED METHOD

The integration of different software packages has been made possible by LINKNET. The three vectors which are used to store the vital information about the network are LIST(BUS), NEXT(RELAY) and FAR(RELAY). A fault (three-phase or single-phase-to-ground as the case may be) is simulated at each relay location. The scanning operations determine the B/P relay pairs and also the associated fault current pairs. These currents are the fault currents to be seen at the occurrence of fault and relay settings are determined on the basis of these simulated fault levels. These fault currents are stored in a vector in a sequence in which the B/P relay pair occurs. This vector of the current pairs is used to determine the list of constraints .

The algorithm and the flowchart [Fig 2.2] demonstrates the methodology adopted.

2.8.2 ALGORITHM FOR INTEGRATING DIFFERENT SOFTWARE PACKAGES

The algorithm consists of the following main steps :

1. The buses are numbered manually and the relays are numbered by the computer.

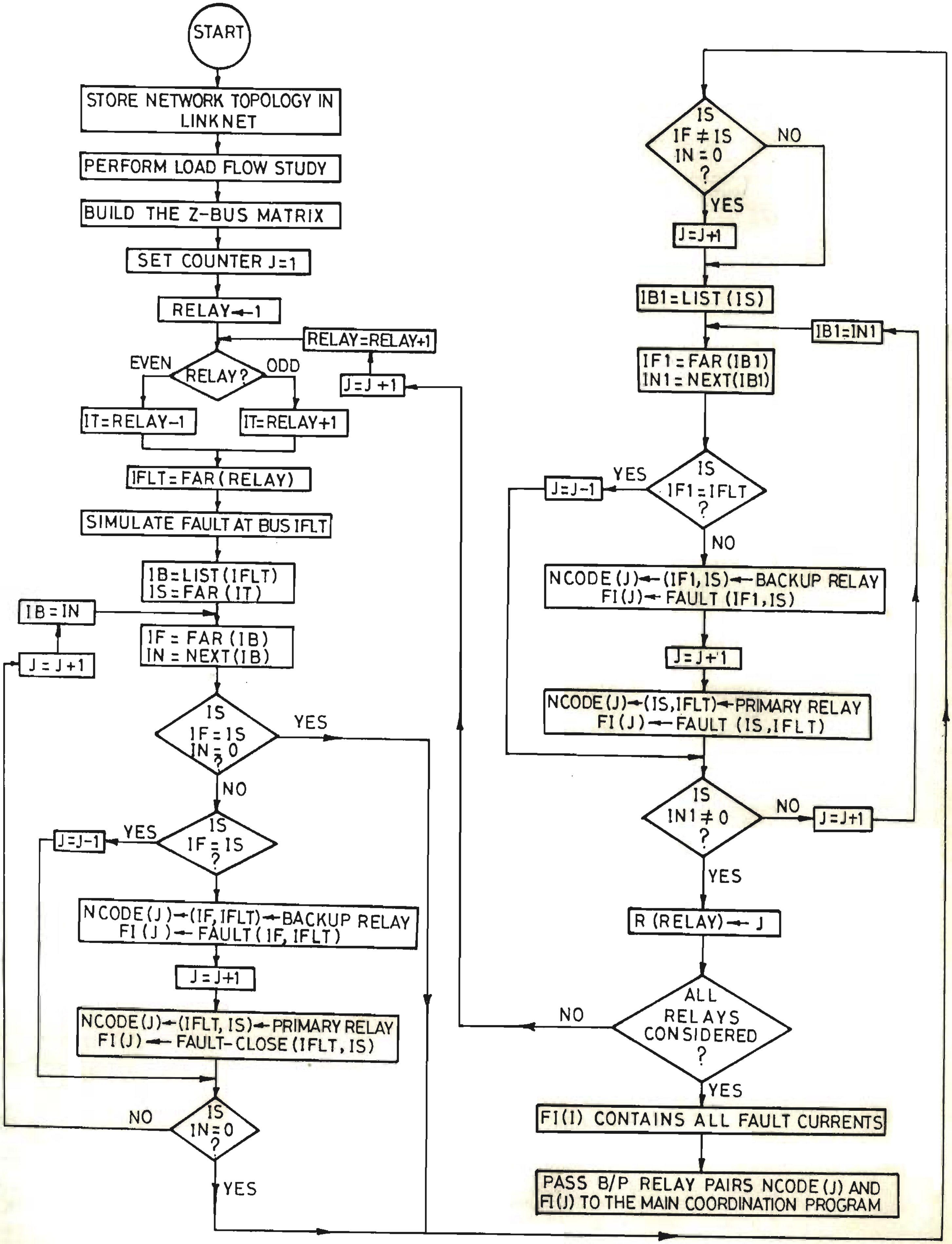


FIG. 2·2 – FLOWCHART FOR INTEGRATING FAULT ANALYSIS PROGRAM AND DETERMINING B/P RELAY PAIRS

2. The information about the power network topology is stored in the computer using LINKNET.

3. The load flow analysis is performed to get the bus voltages and the line currents. The line currents are used to determine the pickup current settings of the relays.

4. The Z-bus matrix is built up for calulating the fault currents.

5. A relay is visited and the bus is found near which this particular relay is located.

6. A fault is simulated near the relay.

7. This fault is a close-in fault for the relay under consideration.

8. The B/P relay pairs are determined for this close-in fault and the fault currents seen by each relay are stored in the vector FI(J). The B/P relay pairs are also stored in the vector NCODE(J) separately.

9. The relay on the opposite bus is determined. The fault just simulated is a far-bus fault for this relay.

10. The B/P relay pairs are determined for this far-bus fault and the fault currents seen by these relays are stored in the vector FI(J). The B/P relay pairs are stored in the vector NCODE(J).

11. All relays are visited in the same manner.

12. The vector FI(J) contains all the fault current pairs and the vector NCODE(J) contains all the B/P relay pairs.

13. The vectors FI(J) and NCODE(J) are passed on to the main relay coordination program.

2.8.3 RETRIEVAL OF DATA

The data stored in different vectors is easily retrieved in the proposed method. Whatever information is needed for any other purpose is available to the user. The B/P relay pairs and the associated fault currents are retrieved for a fault at any location. Fig.2.3 depicts an algorithm which gives the B/P relay pairs and the associated fault current pairs for a fault near relay '*RELAY*'. Fig 2.4 depicts an algorithm which gives the backup relays for any given primary relay and the currents seen by the backup relays.

2.9 INTEGRATED ALGORITHM FOR OPTIMAL SYSTEM COORDINATION (OPCORD)

The integrated algorithm for the optimal coordination of directional overcurrent relays OPCORD is presented in this section and is depicted in the flowchart of Fig. 2.5. The main steps involved are :

1. LINKNET is used to store the topology of the power network.
2. The load flow analysis is performed to determine the line currents and the bus voltages.
3. The Z-bus matrix is built for the entire network.
4. Visit a relay and simulate a fault near it on the line side.
5. Determine the B/P relay pairs and the associated fault current pairs for this close-in fault.
6. The same fault is a far-bus fault to the relay which is on the opposite end of the same line. Determine the B/P relay pairs and the associated fault current pairs for the far-bus fault.
7. All relays considered, if no go to step 4, otherwise go to the next step.
8. The initial value of the pickup current setting is assigned to each relay by :

$$I_p = x\, I_l \qquad (2.21)$$

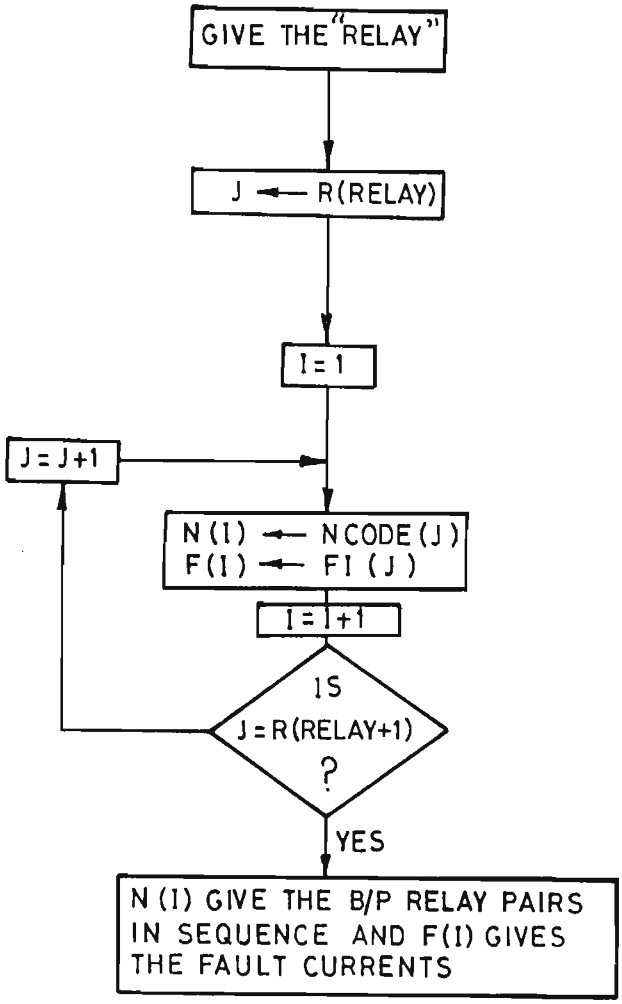


FIG. 2·3—RETRIEVAL OF B/P RELAY INFORMATION AND THE ASSOCIATED CURRENTS

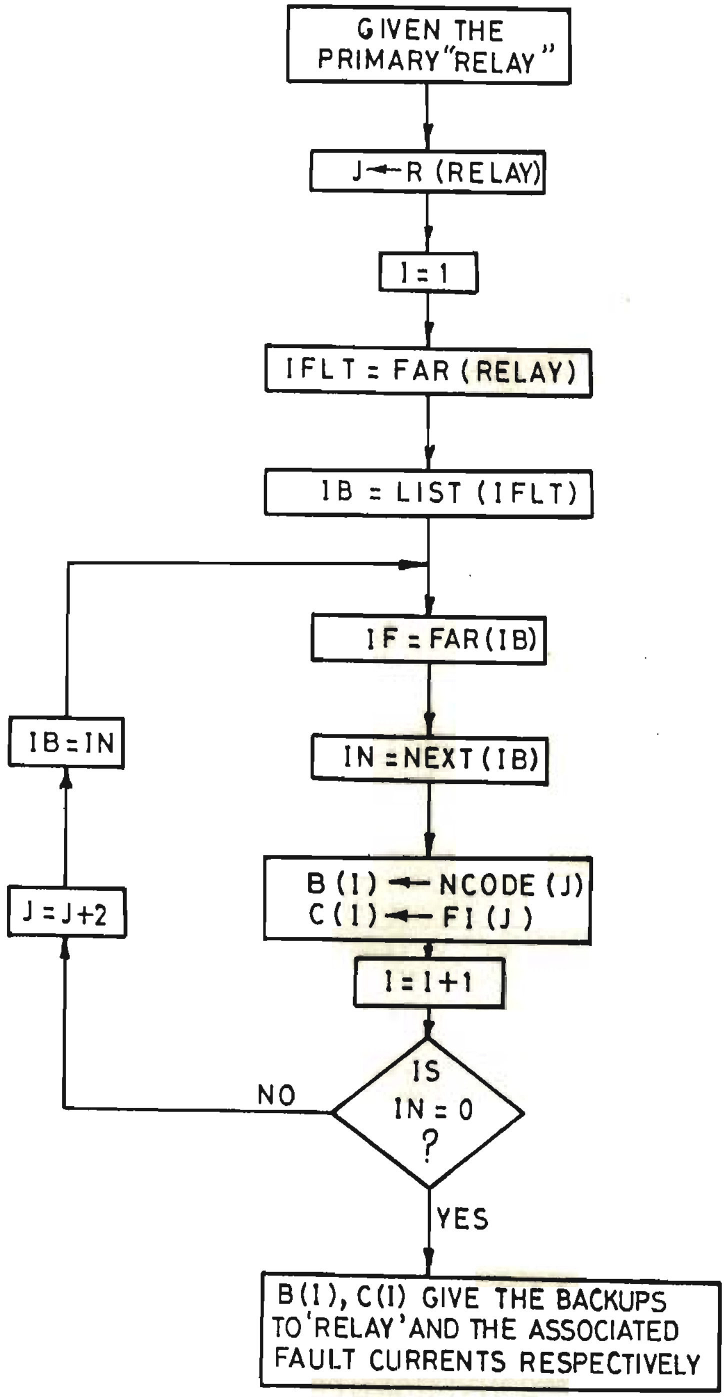


FIG. 2·4–RETRIEVAL OF THE BACKUP RELAY INFORMATION AND THE ASSOCIATED FAULT CURRENTS FOR A PRIMARY RELAY "RELAY"

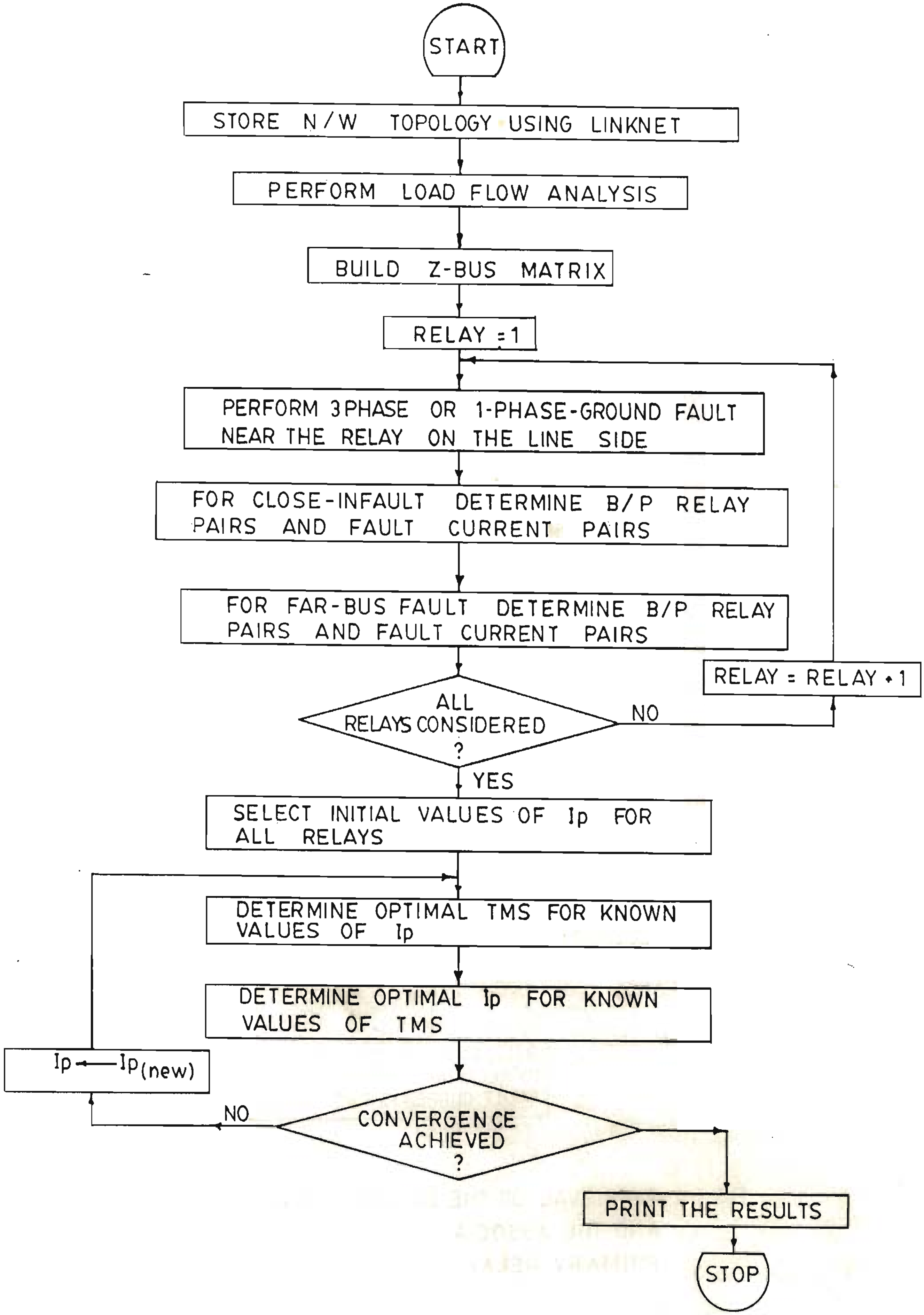


FIG. 2·5 INTEGRATED FLOW-CHART FOR OPTIMAL SYSTEM COORDINATION (OPCORD)

In case of phase protection, x is known as the load carrying factor and its value varies from 1.25 to 1.50. For ground protection, x is made to vary from 0.05 to 1.0 and is known as the tolerance imbalance factor.

For the relays which do not see any load current during the normal operation of the system, they are assigned the minimum available pickup current setting. The directional overcurrent relays see currents only in the specified direction. The minimum pickup current setting available on the relays is 0.5. In certain situations, the load current which is seen by a relay is too low for the setting of I_p. In such cases also, the minimum pickup current setting is assigned to the concerned relays.

An expression for x has been developed which allows dynamic variations in the value of x and hence in the value of I_p according to the variations in the load current. The expression is presented in *Chapter 3*.

9. Determine the optimal values of TMS, keeping the values of I_p fixed. The Simplex method is used for this purpose.

10. Determine the optimal values of I_p, keeping the just calculated values of TMS fixed. The Rosenbrock-Hilclimb method is used for the purpose.

11. The new refined values of I_p obtained are compared with the previous values. If the difference is within the tolerable limits (TOLIP), the algorithm stops and the final optimal values of I_p and TMS are obtained, otherwise the procedure is repeated from step 9. The final optimal values of I_p are converted to the nearest discrete values. I_p has only discrete values available on a relay whereas TMS can be varied continuously.

2.10 SYSTEM STUDIES

The method developed was applied to solve the coordination problem of directional overcurrent relays of the following interconnected power transmission systems :

- the 6-bus test system.
- the IEEE 14-bus test system.
- the SPC (Saskatchewan Power Corporation) 26-bus transmission system.
- the IEEE 57-bus test system.

Since the calculations were performed on Intel's 80486 based personal computer, it was not possible to solve the coordination problem for the 64-bus North-Western power system of India (NWI) and the 118-bus IEEE system. For these two systems, the time taken by the program was prohibitively large. Even after five hours of execution time, the solution for the 64-bus NWI system had not been reached. For these large systems, efficient decomposition methods have been developed which solve their coordination problems in a lesser period of time. These methods are discussed in *Chapter 4* and *Chapter 5*.

System data and single-line diagrams of all the power systems studied are presented in Appendix-B.

2.10.1 B/P RELAY PAIRS

The program generated 60, 184, 254, 680, 900 and 2036 B/P relay pairs for the 6-bus, the IEEE 14-bus, the SPC 26-bus, the IEEE 57-bus, the NWI 64-bus and the IEEE 118-bus power systems respectively. The B/P relay pairs are generated for the close-in as well as the far-bus fault currents.

One of the most important features of the program is that it mentions those B/P relay pairs for which the coordination has not been achieved. Such a condition arises out of two reasons :

(a) Some relays do not see any fault current due to their directional nature. Such a condition arises when the fault current is not seen by a relay which is backup to a primary relay. This is sometimes the case for a backup relay when responding to a far-bus fault which has occurred two buses ahead. Actually such conditions are recognized at the beginning, even before the actual coordination program starts.

(b) Some relays do not even pickup for fault currents seen by them. This is because the chosen pickup current setting is more than the fault current seen by the relay. This condition is also detected early in the analysis. Therefore, in case of the 6-bus power system, only 47 B/P relay pairs were considered for coordination. The remaining 13 pairs were not coordinated. Out of these 13 B/P relay pairs, 8 were not coordinated because the backup relays did not see any fault current and 5 were not coordinated because the pickup current settings chosen for the respective relays were more than the anticipated fault currents seen by them. Let us take another example. The program generated 254 B/P relay pairs for the SPC 26-bus power system. Out of the 254 relay pairs, 36 relay pairs could not be coordinated properly. Out of these 36 pairs, 17 failed to coordinate because one of the relays of the pair did not see the fault current because its direction was opposite to the relay directionality and 19 could not be coordinated because the pickup current came out to be more than the fault current seen by one of the relays of the pairs.

Table 2.1 gives in detail the number of relays, the number of B/P relay pairs generated, the number of pairs actually coordinated, and the number of total constraints generated for the optimal selection of TMS and I_p for all the test systems studied.

2.10.2 CONSTRAINT RELAXATION

Since the coordination criterion i.e. the time lag between the operation of a primary relay and its backup relay, is supplied in the form of constraints, those constraints are relaxed for which the algorithm anticipates miscoordination. The miscoordinations for certain B/P relay pairs are anticipated on the strength of the fault level profiles generated by different fault conditions. These constraints are removed from the original constraint list which is prepared by the algorithm. Thus the constraint relaxation is a very important feature of the proposed optimal coordination algorithm.

2.10.3 DATA GENERATION AND STORAGE

As already mentioned, there is no need for data base management packages to manage huge data generated in the coordination process. The program itself generates, updates, retrieves and uses the data whenever necessary. Table 2.2, Table 2.3 and Table 2.4 give some of the B/P relay pairs and the associated fault currents seen by the relays for the 6-bus, the IEEE 14-bus and the SPC 26-bus power systems respectively (for figures refer to Appendix-B).

The frequent data retrieval and manipulations are made efficient by the program.

TABLE 2.1 *B/P RELAY PAIRS OF THE SYSTEMS STUDIED*

	POWER SYSTEMS STUDIED					
	6-bus	IEEE 14-bus	SPC 26-bus	IEEE 57-bus	NWI 64-bus	IEEE 118-bus
No. of relays	16	40	64	156	176	358
Total No. of B/P relay pairs	60	184	254	680	900	2036
Actual B/P pairs to be coordinated	47	149	218	593	800	1812
Constraints for optimal determin-ation of TMS	79	229	346	905	1152	2528
Constraints for optimal selection of I_P	32	80	128	312	352	716

TABLE 2.2 *SOME OF THE RESULTS FOR 6-BUS POWER SYSTEM*

FAULT LOCA-TION	TYPE OF FAULT	BACKUP			PRIMARY		
		Relay No.	Line No.	Fault current (A)	Relay No.	Line No.	Fault current (A)
A	Close-in	3	2	2576.99	2	1	2268.68
	Far-bus	14	7	21.22	1	1	1535.68
		8	4	50.97	1	1	1535.68
P	Close-in	11	6	2616.31	6	3	4704.92
		9	5	1541.66	6	3	4704.92
		7	4	809.35	6	3	4704.92
	Far-bus	15	8	425.48	5	3	331.0
		13	7	318.90	5	3	331.0

TABLE 2.3 *SOME OF THE RESULTS FOR IEEE 14-BUS POWER SYSTEM*

FAULT LOCATION	TYPE OF FAULT	BACKUP			PRIMARY		
		Relay No.	Line No.	Fault current (A)	Relay No.	Line No.	Fault current (A)
A	Close-in	17	9	378.65	22	11	5246.72
		13	7	2176.15	22	11	5246.72
		12	6	1449.90	22	11	5246.72
		6	3	1243.57	22	11	5246.72
	Far-bus	33	17	218.46	21	11	203.06
		25	13	362.48	21	11	203.06
		24	12	0.0	21	11	203.06

TABLE 2.4 *SOME OF THE RESULTS FOR SPC 26-BUS POWER SYSTEM*

FAULT LOCATION	TYPE OF FAULT	BACKUP			PRIMARY		
		Relay No.	Line No.	Fault current (A)	Relay No.	Line No.	Fault current (A)
A	Close-in	57	29	1507.84	47	24	3234.95
		51	26	1212.41	47	24	3234.95
		41	21	559.82	47	24	3234.95
	Far-bus	53	27	3392.54	48	24	3264.05
B	Close-in	24	12	1163.12	5	3	8635.64
		22	11	1126.59	5	3	8635.64
		16	8	239.24	5	3	8635.64
		7	4	470.32	5	3	8635.64
		4	2	906.45	5	3	8635.64
	Far-bus	50	25	1744.89	6	3	1722.97

2.10.4 COORDINATION RESULTS

The detailed coordination results are presented for the 6-bus and the IEEE 14-bus power systems in Table 2.5 and Table 2.6 respectively. The results were obtained for CTI = 0.4 seconds. The coordination results were also obtained for CTI = 0.2 sec. and CTI = 0.3 sec. The coordinated settings are presented in the form of TMS and I_p (expressed in terms of plug settings).

2.10.5 PERFORMANCE EVALUATION

Detailed performance evaluation has been obtained in case of the 6-bus power system. For each fault simulated, the operating time of all the B/P relay pairs is obtained and the results are given in Table 2.7. From the table, it is clear that for which B/P relay pairs miscoordination is obtained. The same performance evaluation has been done for all the systems studied.

2.10.6 COORDINATION CURVES

From the results obtained, it is also possible to draw the coordination curves i.e. the time-current characteristics for all the B/P relay pairs.

The time-current characteristics (TCC) are given for the cases when a fault occurs at location C and J (6-bus system). Fig.2.6 depicts the TCC of the B/P relay pair (3,10) responding to a close-in fault at location C. Similarly Fig. 2.7 depicts the TCC of the B/P relay pair (1,4) responding to a far-bus fault at location C.

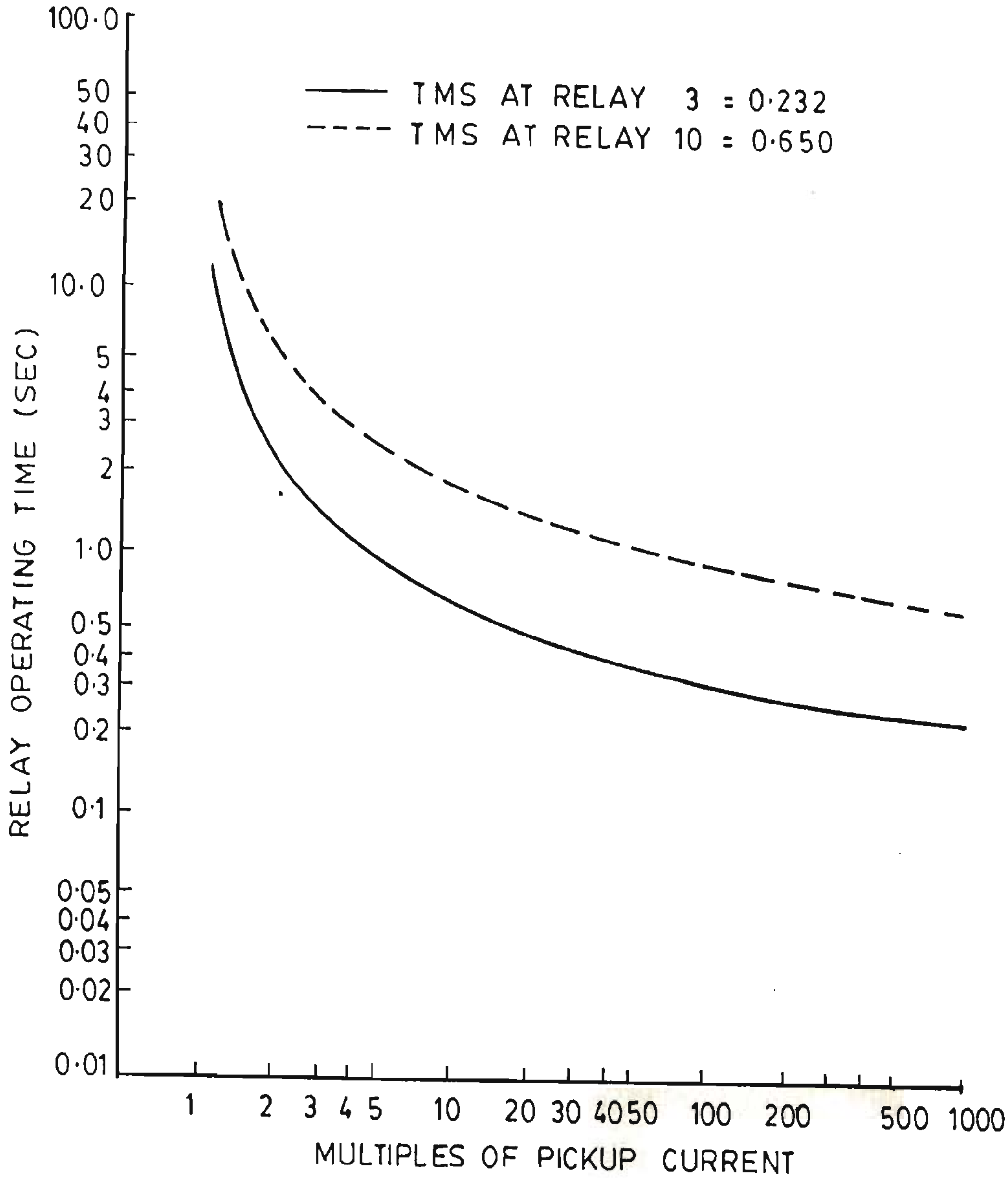


FIG. 2·6-TIME CURRENT CHARACTERISTICS OF THE RELAYS 3 , 10 WHEN RESPONDING TO A CLOSE IN FAULT CURRENT AT LOCATION C FOR 6-BUS TEST SYSTEM

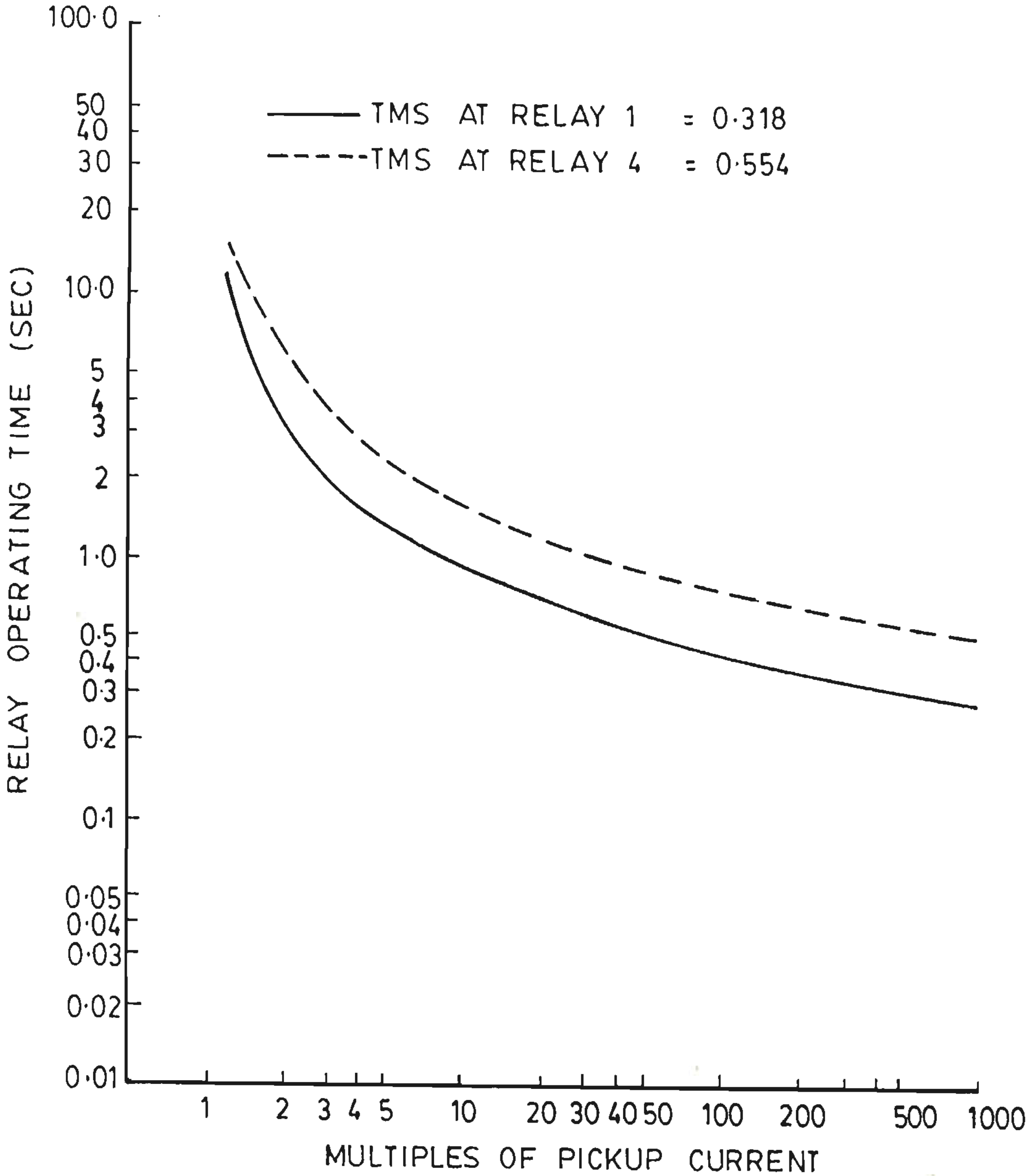


FIG. 2·7 - TIME - CURRENT CHARACTERISTICS OF RELAYS 1 , 4 WHEN RESPONDING TO A FAR - BUS FAULT AT LOCATION C FOR 6-BUS TEST SYSTEM

TABLE 2.5 *OPTIMAL COORDINATED SETTINGS OF THE RELAYS FOR 6-BUS SYSTEM*

Relay	Instt. setting (4.0 - 16.0)	Plug setting (0.5 - 2.0)	Time multiplier setting (0.05 - 1.10)
1	8.0	1.25	0.318
2	16.0	0.50	0.552
3	6.0	1.25	0.232
4	16.0	0.50	0.554
5	9.0	0.50	0.483
6	16.0	1.25	0.414
7	6.0	0.75	0.334
8	16.0	0.50	0.558
9	8.0	1.25	0.287
10	16.0	0.50	0.650
11	7.0	1.25	0.268
12	16.0	0.50	0.557
13	4.0	0.75	0.355
14	10.0	0.50	0.461
15	5.0	1.00	0.217
16	8.0	0.50	0.477

TABLE 2.6 *OPTIMAL COORDINATED SETTINGS OF THE RELAYS FOR IEEE 14-BUS POWER SYSTEM*

Relay	Instt. setting (4.0 - 16.0	Plug setting (0.5 - 2.0)	Time multiplier setting (0.05 - 1.10)
1	16.0	0.50	1.000
2	4.0	1.25	0.050
3	16.0	0.50	0.899
4	4.0	1.00	0.318
5	16.0	0.50	0.753
6	4.0	0.75	0.351
7	16.0	0.50	0.765
8	4.0	1.25	0.176
9	16.0	0.50	0.778
10	7.0	1.00	0.470
11	9.0	0.75	0.486
12	16.0	0.50	1.100
13	10.0	1.25	0.464
14	16.0	0.50	0.935
15	16.0	0.50	1.094
16	5.0	1.00	0.392
17	10.0	0.50	0.669
18	14.0	1.25	0.668
19	4.0	1.25	0.050
20	16.0	0.50	0.379
21	5.0	0.50	0.514
22	6.0	0.75	0.541
23	16.0	0.50	0.870
24	5.0	0.75	0.523
25	16.0	0.50	0.876
26	16.0	0.50	1.019
27	7.0	0.50	0.636
28	16.0	1.00	0.968
29	4.0	0.50	0.050
30	16.0	0.50	0.820
31	4.0	0.50	0.387
32	16.0	1.00	0.765
33	10.0	0.50	0.836
34	16.0	0.75	0.752
35	16.0	1.00	0.881
36	16.0	0.50	0.824
37	16.0	0.50	0.249
38	11.0	0.50	0.758
39	9.0	0.50	0.724
40	10.0	0.50	0.845

TABLE 2.7 *PERFORMANCE EVALUATION OF THE RELAYS OF 6-BUS POWER SYSTEM FOR FAULTS AT DIFFERENT LOCATIONS*

Fault Location	Type of Fault	Primary Relay		Backup Relay		Remarks
		Relay	Operating time (sec.)	Relay	Operating time (sec.)	
A	Close-in fault	2	0.819	3	1.216	Relay 14 does not operate because $I_{fault} < I_p$
	Far-bus fault	1 1	1.357 1.357	8 14	5.444 --	
B	Close-in fault	4	0.957	1	1.357	All operate
	Far-bus fault	3	1.216	10	1.680	
C	Close-in fault	3	0.729	10	1.131	All operate
	Far-bus fault	4	1.073	1	1.655	
D	Close-in fault	9	0.672	4	1.073	All operate
	Far-bus fault	10 10 10	1.131 1.131 1.131	11 7 5	2.631 7.474 3.029	
E	Close-in fault	10 10 10	0.876 0.876 0.876	11 7 5	1.273 1.275 1.275	Relay 4 does not operate because of directional restraint
	Far-bus fault	9	1.240	4	---	
F	Close-in fault	12 12 12	0.843 0.843 0.843	9 7 5	1.240 1.275 1.275	Relay 16 does not operate because of directional restraint
	Far-bus fault	11	1.273	16	--	
G	Close-in fault	11	0.848	16	1.248	Relay 5 does not operate because $I_{fault} < I_p$
	Far-bus fault	12 12 12	0.979 0.979 0.979	9 7 5	1.484 1.554 --	
H	Close-in fault	15	0.579	12	0.979	All operate
	Far-bus fault	16 16	1.447 1.447	6 13	4.069 1.848	

Table 2.7 Continued

Fault Location	Type of Fault	Primary Relay		Backup Relay		Remarks
		Relay	Operating time (sec.)	Relay	Operating time (sec.)	
I	Close-in fault	16 16	0.899 0.899	6 18	1.299 1.599	Relay 12 does not operate because of directional restraint
	Far-bus fault	15	1.108	12	--	
J	Close-in fault	5 5	0.727 0.727	15 13	1.108 1.599	Relay 14 does not operate because $I_{fault} < I_p$
	Far-bus fault	6 6 6	1.299 1.299 1.299	11 9 7	-- 3.260 4.345	
K	Close-in fault	14 14	0.688 0.688	6 15	1.299 1.108	Relays 8 and 2 do not operate because of directional restraint
	Far-bus fault	13 13	1.599 1.599	8 2	-- --	
L	Close-in fault	13 13	0.618 0.618	8 2	1.137 1.017	All operate
	Far-bus fault	14 14	1.138 1.38	6 15	10.540 4.367	
M	Close-in fault	7 7	0.591 0.591	2 14	1.017 1.138	Relay 5 does not operate because of directional restraint and relay 9 does not operate because $I_{fault} < I_p$
	Far-bus fault	8 8 8	1.137 1.137 1.137	9 11 5	-- 5.417 --	
N	Close-in fault	1 1	0.738 0.738	8 14	1.137 1.138	All operate
	Far-bus fault	2	1.017	3	2.536	

Table 2.7 Continued

Fault Location	Type of Fault	Primary Relay		Backup Relay		Remarks
		Relay	Operating time (sec.)	Relay	Operating time (sec.)	
O	Close-in fault	8 8 8	0.722 0.722 0.722	9 11 5	1.240 1.273 1.275	Relay 2 and 14 do not operate because of directional restraint
	Far-bus fault	7 7	1.275 1.275	2 14	-- --	
P	Close-in fault	6 6 6	0.676 0.676 0.676	7 9 11	1.275 1.240 1.273	Relay 15 does not operate $I_{fault} < I_p$
	Far-bus fault	5 5	1.275 1.275	13 15	2.788 --	

When a fault occurs at J, for the close-in fault the B/P relay pairs are (15, 5) and (13, 5). The TCC's are shown in Fig.2.8 for this case. The same fault produces the B/P relay pairs which are (11,6), (9,6) and (7,6). They respond to the far-bus fault at location J. The TCC's are given in Fig. 2.9.

Only four cases have been taken for the construction of TCC for the concerned relays. Likewise the TCC for all the cases given in Table 2.7 are drawn. The TCC clearly shows the results of optiomal coordination.

2.11 OPTIMAL SELECTION OF TMS USING CHARALAMBOUS LEAST PTH ALGORITHM

It has been observed that a major portion of the computational effort in solving the coordination problem of directional overcurrent relays of power networks is consumed by the optimal selection of TMS. The optimal values of TMS are calculated by solving the linear programming problem using the Simplex method. However, we have also solved the problem

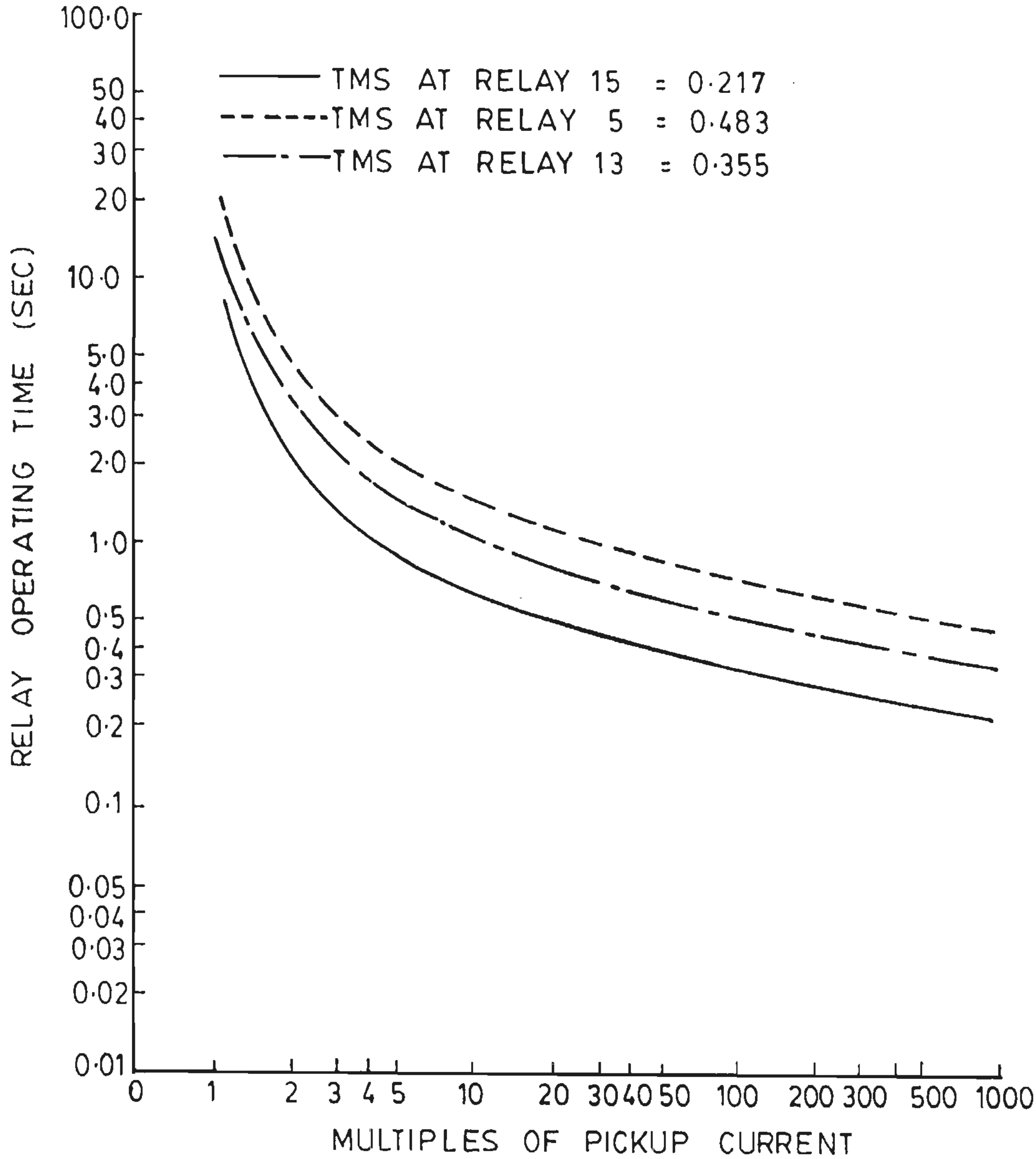


FIG. 2·8-TIME CURRENT CHARACTERISTICS OF RELAYS 15, 5, 13 WHEN RESPONDING TO A CLOSE-IN FAULT AT LOCATION J FOR 6-BUS TEST SYSTEM

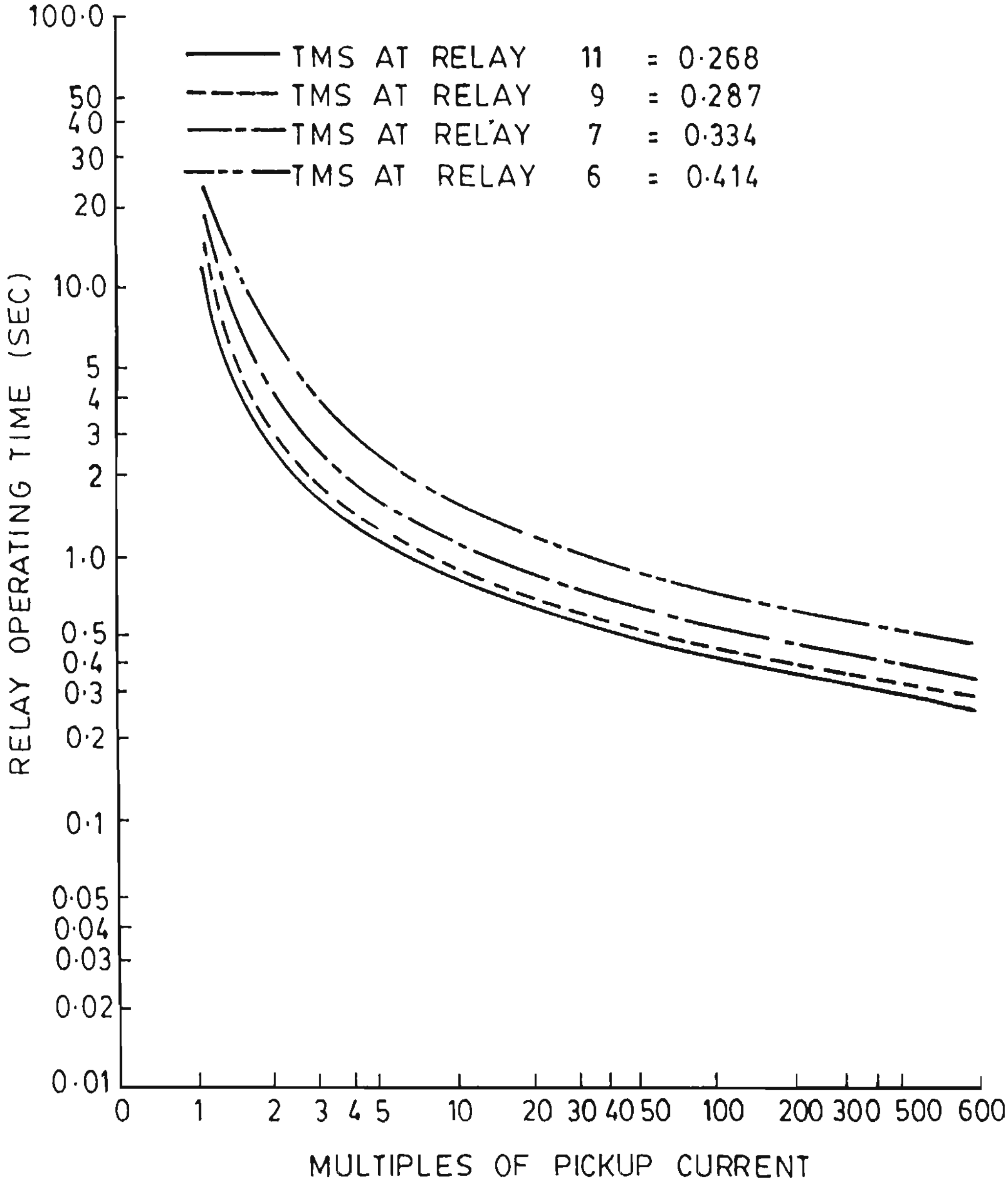


FIG. 2·9 TIME - CURRENT CHARACTERISTICS OF RELAYS 11, 9, 7, 6 WHEN RESPONDING TO A FAR-BUS FAULT AT LOCATION J FOR 6-BUS TEST SYSTEM.

of determining optimal values of TMS by using the Charalambous least pth algorithm. Basically Charalambous least pth algorithm is a part of the software package FLOPT5 which has been developed by Bandler and Sinha [5]. FLOPT5 was developed to solve the minimax optimization problems using the accelerated least pth algorithm. The main features of FLOPT5 include Fletcher's quasi-Newton algorithm, a least pth objective formulation algorithm and the charalambous least pth algorithm. With appropriate utilization of these features, the program can solve a wide variety of optimization problems. These may range from unconstrained problems, problems subject to inequality/equality constraints to minimax problems in general. We have utilized the same package in solving the linear programming problem for determining the optimal values of TMS.

The overall organization of the FLOPT5 software package is depicted in Appendix-A [Fig.A.2.1] . In order to use the FLOPT5 package, the user has to provide the main program and a subroutine called FUNCT5. The main program contains the necessary initialization and calls to subroutine FLOPT5. The number of times FLOPT5 is called depends upon the number of desired iterations. Subroutine FUNCT5 contains the user's definition of the problem to be solved. Subroutine LEASTP5 evaluates least pth objective function and the gradient vector. Subroutine QUASI5 performs the unconstrained minimization using the Fletcher's quasi-Newton method.

2.11.1 INTEGRATED SOFTWARE PACKAGE OPCON FOR SOLVING COORDINATION PROBLEM

The integrated software package OPCON has been developed for solving the coordination problem of directional overcurrent relays of power networks. The only difference between OPCORD and OPCON is that in the former package the optimal values of TMS are determined by using the Simplex method of linear programming and in the later package these values are determined by using the Charalambous least pth algorithm of non-linear programming. The software description of OPCON is given in Appendix-A [Fig.A.2.2].

2.11.2 APPLICATION AND RESULTS

OPCON was used to solve the coordination problem of the following systems :

- IEEE 14-bus power system
- SPC 26-bus power system
- IEEE 57-bus power system

Table 2.8 gives the comparison between the execution times of OPCORD and OPCON for the above mentioned systems. It is clear from the table that OPCON is 3.14, 3.00 and 4.30 times faster than OPCORD for the IEEE 14-bus, the SPC 26-bus and the IEEE 57-bus power systems respectively.

TABLE 2.8 *COMPARISON OF EXECUTION TIMES BETWEEN OPCORD AND OPCON*

System	OPCORD Exe. Time (sec.)	OPCON Exe. Time (sec.)	Saving in Exe. Time
IEEE 14-bus	136.6	43.5	68.15 %
SPC 26-bus	502.1	167.3	66.67 %
IEEE 57-bus	10452.7	2428.63	76.76 %

Table 2.9 gives the TMS values of some of the relays of the IEEE 57-bus power system obtained by using OPCORD and OPCON software packages.

2.12 INTERACTIVE VERSIONS OF OPCORD AND OPCON

The fully integrated software packages OPCORD and OPCON are also made interactive. Most of the time, the protection engineer wants to decide the most important coordination issues himself so that his expertise and the *"feel"* about the system are utilized in determining the best coordinated results for the protective relays. This section discusses some of the most important features of the interactive version of OPCORD and OPCON programs.

2.12.1 FEATURES OF OPCORD AND OPCON PROGRAMS

The system parameter data is kept in a file for easy editing. In this file, information is contained regarding the system connectivity, generation/load, type of bus and system component values. Other relevant data are supplied interactively. The values supplied in the interactive mode are :

1. The coordination margin or the CTI. The CTI for electro-mechanical relays may vary from 0.3 to 0.5 seconds. For solid state relays and computer-based relays, it can go up to 0.2 seconds. Actually this value depends upon the response of the circuit breaker and the relay over-travel time. In short, any value may be supplied.
2. We can keep the CTI the same for all B/P relay pairs or different values for different B/P relay pairs. This option is also available. The experienced engineer will decide this important variable.

TABLE 2.9 *TMS VALUES FOR SOME OF THE RELAYS OF IEEE 57-BUS POWER SYSTEM OBTAINED BY USING OPCORD AND OPCON*

Relay	OPCORD (0.05 - 1.1)	OPCON (0.05 - 1.1)
1	0.724	0.737
2	0.188	0.190
3	0.733	0.749
4	0.242	0.244
5	0.785	0.790
6	0.406	0.411
7	0.741	0.745
8	0.529	0.538
9	0.810	0.819
10	0.480	0.486
11	0.485	0.488
12	0.910	0.922
13	0.329	0.334
14	0.639	0.649
15	0.827	0.843
16	0.220	0.222
17	0.611	0.619
18	0.523	0.529
19	0.664	0.670
20	0.704	0.709
21	0.609	0.617
22	0.495	0.500
23	0.664	0.673
24	1.016	1.022
25	0.351	0.357
26	1.040	1.044
27	0.349	0.357
28	0.685	0.697
29	0.608	0.618
30	0.151	0.154
31	0.504	0.512
32	0.208	0.211
33	0.496	0.504
34	0.202	0.206
35	0.733	0.743
36	0.523	0.526
37	0.883	0.889

3. The maximum and the minimum range of the relays used is supplied next. For a typical directional overcurrent relay, the range for TMS is from 0.05 to 1.1 and for I_p is from 50% to 200% expressed in terms of plug setting.

4. k_1, k_2, k_3 are the constants of the relay to be simulated . The user supplies these values. The choice depends upon the inverseness desired for a particular application. For example for a solid state IDMT relay, $k_1 = 0.14$, $k_2 = 0.02$, $k_3 = -1.0$ [22].

5. Some relays take a lot of time to operate. This is particularly true when a relay is acting as a backup. We can fix the maximum time of such a relay. This is also chosen by the engineer. He must have a *'feel'* of the system and must know which of the relays are not operating properly or are not faster. He can determine the relays having operating times above certain tolerable limits by making a trial run of the program. After this trial run, he can fix the maximum value of the operating time.

6. Similarly the minimum time can also be fixed.

The interactive versions of OPCORD and OPCON programs inform the user which of the B/P relay pairs will not be coordinated. This decision is taken after studying the fault level profiles for all the faults simulated. The coordination is not performed for such B/P relay pairs. The programs plot the TCC or the coordination curves for any B/P relay pair on demand. We have run the program for many cases and all gave good results. No infeasible solution was noted because those constraints are relaxed in the beginning which might give such a condition. Some of the relay setting values for SPC 26-bus power system are given in Table 2.8. Faults simulated

TABLE 2.8 *SOME OF THE RESULTS OF COORDINATION OF SPC 26-BUS POWER SYSTEM*

FAULT LOCATION "A", CLOSE-IN FAULT FOR RELAY 47							
PRIMARY RELAY				BACKUP RELAY			
Relay No.	T.M.S.	P.S. (%)	Operating time (sec.)	Relay	T.M.S.	P.S. (%)	Operating time (sec.)
47	0.856	50.0	1.172	51	0.849	50.0	1.472
47	0.856	50.0	1.172	41	0.469	125.0	1.472
47	0.856	50.0	1.172	57	0.899	50.0	1.472
FAULT LOCATION "A", FAR-BUS FAULT FOR RELAY 48							
48	0.180	125.0	1.283	53	0.225	125.0	1.606
FAULT LOCATION "B", CLOSE-IN FAULT FOR RELAY 42							
42	0.815	50.0	0.983	51	0.849	50.0	1.472
42	0.815	50.0	0.983	48	0.180	125.0	1.283
42	0.815	50.0	0.983	57	0.899	50.0	1.472
FAULT LOCATION "B", FAR-BUS FAULT FOR RELAY 41							
41	0.469	125.0	1.472	43	0.296	100.0	2.65
		AND SO ON					
FAULT LOCATION "X", CLOSE - IN FAULT FOR RELAY 44							
44	0.589	50.0	1.045	42	0.815	50.0	1.400
FAULT LOCATION "X", FAR-BUS FAULT FOR RELAY 43							
43	0.296	100.0	1.335	46	0.264	75.0	--
43	0.296	100.0	1.335	62	0.475	100.0	--
43	0.296	100.0	1.335	40	0.741	50.0	--
43	0.296	100.0	1.335	38	0.600	50.0	--

at locations A and B give excellent coordination results. All relays involved are coordinated properly, even the backup to the far-end relay operates satisfactorily. At fault location X, relay coordination is not satisfactory. For a close-in fault, relay 44 along with its backup relay operate satisfactorily. For far-bus faults, relay 43 operates as per the overall coordination scheme. Its backup relays 46, 62, 40 and 38 do not operate at all. Relays 46, 40 and 38 do not see any fault current for this fault location and relay 62 has a pickup current value more than the fault current seen by it. For these results CTI is fixed at 0.3 second for all the relays and three-phase faults are considered for the coordination purposes.

2.13 PROBLEM OF SYMPATHY TRIPS

There are many problems associated with the operation of interconnected power systems, sympathy tripping is one of them. Sympathy trips one defined as those incorrect trips which occur during faults [65]. A relay and its associated circuit breaker trip unnecessarily for faults for which they are not supposed to trip at all. The sympathy trips represent a major source of concern to the planner and operator, since they remove additional circuits along with the loss of the faulted line. The unnecessary tripping of lines puts serious obstacles to optimum system performance.

2.13.1 CAUSES OF SYMPATHY TRIPS

Sympathy trips are often caused by a sound relay whose settings are inappropriate for the prevailing system conditions. Normally, the coordinated relay settings are determined by considering reasonable excursions in generation/load levels and the possible anticipated system contingencies. It is not possible to anticipate all the future changes which may occur in the system. Hence the relay settings would be inappropriate for some system condition, which had not been included in the analysis earlier. These system conditions give rise to the nuisance tripping known as the sympathy tripping.

2.13.2 CLASSIFICATION OF SYMPATHY TRIPS

After studying the sympathy trip tendencies of relays in interconnected power systems for different system conditions, we have classified the sympathy trips in the following categories :

1. Primary relay does not trip because it does not see the fault current. The fault current direction is opposite to that of the relay directionality.
2. Primary relay does not trip because the fault current seen by it is less than the pickup current setting of the relay.
3. Before the primary relay has a chance to trip, its backup relay operates first.
4. Before the operation of a primary relay and its backup relays, some other relays operate first.

All the aforementioned cases cause sympathy trips and disconnect other lines unnecessarily.

2.13.3 CASE STUDY

The IEEE 57-bus power transmission system [Appendix-B] has been taken for detailed study of the sympathy trip tendencies of relays. This system is complex and has many loops in it. As mentioned before, it has 156 directional overcurrent relays and 680 B/P relay pairs.

The study which is conducted is reported below :

1. The system was studied for the cases when the primary relays do not operate for faults which occur in their primary zone of protection. Such a case was detected for a fault which occurs at the location of relay 79. Relay 80 is the primary relay for the far-bus fault which occurs at relay 79. Relay 80 does not see a fault current and hence does not operate for this fault. Instead of relay 80, relay 74 operates and this is a clear case of sympathy tripping. Lines 39, 76, 37 and 38 are unnecessarily put out of service.
2. Another case has also been studied when primary relay does not operate for a fault, because the pickup current setting chosen is more than the fault current seen by the relay. Such a case has been detected for a fault at relay 77. Relay 78 does not operate for far-bus fault which has occurred at relay location 77. The pickup current selected for relay 78 is 25.0A, but the fault current seen is only 13.15A. It is also a clear case of sympathy tripping. Similar case were detected for relay 78 when fault occurs at relay 78, for relay 80 when fault occurs at relay 79 and for relay 80 when fault occurs at relay 80.
3. No sympathy trip was detected due to reason 3 as given in the Sec.2.13.2 under normal generation/load levels. But when the generation/load level was increased by 1% and the settings of

the relays kept the same, we could detect one sympathy trip. The sympathy trip tendency was shown by the relay 69 which is acting as backup to the primary relay 147. The backup operates before the primary relay operates. The increase of 1% in the generation / load levels also caused the coordination criterion violation for five B/P relay pairs. The effective value of CTI decreased for these relay pairs. The sympathy trip tendencies were also detected for some relays when generation/load levels were increased by 2% and 5%. In the same way, when generation/load levels were decreased by 1%, 2% and 5%, for some faults backup relays operated before their respective primary relays had a chance to operate. Thus giving rise to sympathy trips.

4. The cases were also studied when a relay operates before the scheduled operation of a primary and its backup relay for a particular fault. This is the most important reason for causing sympathy trips of the relays. This kind of sympathy tripping was caused for certain relays when generation/load levels were decreased by 5%. For a fault at relay 78, relay 70 operates first which does not belong to the B/P relay pair of the fault. Thus extra lines 35, 36, 37, 38 and 76 are put out of service. For a fault at 78, relay 83 also trips in sympathy of the fault. Thus causing sympathy tripping of the lines 40, 41 and 42.

The first two types of sympathy trips are difficult to treat. The conditions which give rise to such situations can easily be detected but the sympathy trips cannot be avoided. For such cases the autoreclosing of the circuit breakers is the answer.

For the last two types of sympathy trips, the use of adaptive coordination would remove any such tendency of the relays which would cause unnecessary tripping of the concerned relays. The adaptive coordination would always coordinate the relays based upon the present conditions of the power system. Any change in generation/load level or any structural change would initiate the recoordination procedure. The adaptive coordination mathed is presented in *chapter 3*.

2.14 CONCLUSIONS

The problem of directional overcurrent relay coordination in an interconnected power system has been formulated as a parameter optimization problem. Different solution techniques which are commensurate with the problem formulation have been presented and implemented in this Chapter.

Two inherent advantages of using optimization techniques in solving coordination problem have been identified. These advantages are :

1. There is no need to determine the break point set of the relays of the interconnected power system. This removes the need of using the elaborate and complex topological analysis programs. This discovery simplifies the coordination philosophy a great deal.
2. The coordinated settings of the relays obtained are optimal settings which give fastest operation of the relays with proper selectivity.

A simple method has been presented which determines the B/P relay pairs for all faults simulated.

A method has also been developed and presented which generates, updates, retrieves and uses the data as per the requirements of the coordination procedure. The use of DBMS has been rendered unnecessary.

Two fully integrated software packages OPCORD and OPCON for the optimal coordination of directional overcurrent relays of interconnected power systems have been developed and presented in this Chapter. In OPCORD program, optimal values of TMS are calculated by using the Simplex method of linear programming, whereas in OPCON program, these values are calculated by using the Charalambous least pth algorithm. The programs have been applied to solve the relay coordination problem of different test power systems. The results obtained are satisfactory.

Easy-to-use interactive versions of the programs OPCORD and OPCON have also been developed and presented. The main features of the programs have also been discussed.

The problem of sympathy trip tendency of certain relays in an interconnected power system has been defined in this Chapter. The various reasons which cause sympathy tripping of relays have been classified into different categories. It is concluded that the use of adaptive coordination would remove the sympathy trip tendency of certain relays under changed system canditions.

ADAPTIVE COORDINATION

3.1 INTRODUCTION

The adaptive protection of electric power systems is a new idea. It is being developed conceptually at present. The inspiration to develop this protection philosophy came from the implementation of the microprocessor-based relays for the protection purposes. The presently available microprocessor-based relays are simply the computer versions of the electromechanical and the solid state relays with limited capability. But the computer technology has much to offer, more than the simple copying of the traditional protection equipment, in terms of processing ability, ability to take decisions , monitoring, self-diagnostic ability, etc. The necessary technology at present is available to take a bold step into revolutionizing the overall protection philosophy. But what is lacking , is the conceptual development of the schemes and the right kind of algorithms. The adaptive features could be made inbuilt in such algorithms.

Research work on this line started in the later part of 1988. Rockefeller and his co-workers [65] presented the adaptive concepts for transmission relaying. The work presented by them is purely conceptual. They presented many adaptive features which could be implemented in future Some of them are :

- Adaptive system impedance model
- Adaptive multiterminal relay coverage
- Adaptive reclosing

- Adaptive Zone 1 ground distance relaying
- Adaptive last resort islanding
- Adaptive internal logic monitoring
- Variable breaker failure timing

Some of the expected benefits are : improved relaying reliability, improved zone 1 and 2 settings of distance relays, greater sensitivity to high impedance faults, faster restoration following incorrect trips, etc. Implementation of these concepts will improve the performance of transmission line protective relaying and thus the reliability of power system operation.

Horowitz et al. [27, 55] have proposed adaptive relaying concepts for improving power system control. By implementing these concepts in a hierarchical integrated protection and control system, they foresee that the power system control functions like detection and control of instability , load shedding and restoration, out-of-step relaying, etc., can be enhanced. They have also described the implementation of adaptive techniques for multiterminal transmission line protection, automatic reclosing as well as to enhance the security and dependability of relays.

Jampala et al. [32] have concentrated on the software aspects of the adaptive transmission protection. They have presented efficient enhancements to off-line algorithms for relay coordination. They have also proposed multi-processing and super-computing approaches in order to develop a fast, on-line tool for computing relay settings in real time. But they have used the traditional algorithms for adaptive protection purposes.

In summary, all the adaptive relaying concepts aim to adjust the various relay characteristics or functions in tune with the changing power system conditions or requirements.

In this Chapter, the concept of adaptive coordination of directional overcurrent relays in an interconnected power system is presented. The adaptive coordination is defined in the framework of adaptive protection. An algorithm has been developed which could be implemented to coordinate the relays in a self-adaptive manner. The developed method has been applied to a numbar of standard test systems with encouraging results.

3.2 CONCEPT OF ADAPTIVE RELAY COORDINATION

The concept of adaptive relay coordination is defined as a part of overall adaptive protection scheme of an electrical power system [27, 32, 65]. The adaptive protection has been given different definitions by different authors, but the adaptive relay coordination itself lacks a proper definition.

3.2.1 DEFINITION

The adaptive relay coordination is defined as a coordination philosophy, implemented with the help of digital relays, which in response to operational or structural changes of the power system, automatically alters or changes the operating parameters of the relays to maintain coordination between them. By relay coordination the auther means the process of determining the relay settings in such a way that, whenever a disturbance occurs in the power system, all the B/P relay pairs operate as planned.

3.2.2 NEED FOR ADAPTIVE RELAY COORDINATION

There are many reasons which compel us to develop the adaptive relay coordination philosophy into an on-line relay coordination tool. Some of them are discussed as below :

1. Earlier the coordinated relay settings were calculated manually and this used to be a big burden on a protection engineer. Any change, operational or structural, warrants a complete review of the relay settings. Thus the burden of routine calculations was perpetual. Recently the relay coordination philosophy has been computerized. This computerized coordination philosophy has relieved protection engineers from the routine and huge calculations. The next step in this direction of relay coordination is naturally the on-line coordination of the relays, where the role of protection engineers is taken by the computers. Thus protection engineers are relieved from this highly routine job so that they can concentrate on other topics of interest.
2. As has already been mentioned elsewhere, the presently followed relay coordination philosophy uses the concept of pre-determinism. In this, contingencies which may occur in the system in future are anticipated and the relay settings are determined which satisfies all the pre-determined conditions. The relay response may be satisfactory if any such contingency arises. But this procedure does not take into account the unforeseen system changes which may occur in the system. The relay settings which were calculated on the basis of certain assumed conditions may not apply to the new system conditions. Thus jeopardizing the system

security and the integrity of the whole system. In actual practice, the settings are not even reviewed for years [23]. This tendency also gives large safety margins to the relay settings. Thus the effectiveness of the relay protection system is also decreased. In adaptive relay coordination, the relay settings are determined on the basis of present conditions of the power systems. Whenever there is a change, operational or structural, which warrants a coordination review, the new relay coordination strategy immediately invokes the right kind of algorithms and the new relay settings are available and are transmitted to the respective relays.

3. The distinction between the concepts of protection and control is fast disappearing. Normally, the equipments for protection and control functions are physically segregated. Thus there is a lot of duplication in the equipments, wiring, space, etc. New coordinated protection and control schemes could be developed which will remove much of the redundancy producing functions in these spheres. Adaptive coordination could be a very important step in this direction.

3.2.3 ASSUMPTIONS

Before proceeding to present a scheme for adaptive relay coordination, certain assumptions are made which are commensurate with the developed concepts. The assumptions are :

1. The relays are of digital type.
2. There are communication channels between the processing computers and these relays.

3. No line-out contingencies are considered. This is an important assumption. Actually there is no need for such type of contingencies in adaptive coordination. The existing conditions are taken into account for the relay coordination, not the assumed conditions.

4. The whole spectrum of line protection is considered by simulating a fault at every relay location. A fault is a close-in fault for the relay near which the fault has occurred and the same fault is a far-bus fault for the relay which is on the opposite side of the line. Thus two sets of B/P pairs and the associated current pairs are generated, one set for the close-in fault and the other set for the far-bus fault.

3.3 ADAPTIVE SELECTION OF PICKUP CURRENT SETTING

As mentioned earlier, the determination of I_p and TMS are the essence of relay coordination process. The value of I_p is normally fixed before the coordination is attempted. This procedure does not ensure correct settings of the relays. Therefore, it is proposed to dynamically vary it as the load current varies. This step would make the relays more sensitive to the system changes.

The pickup current is given by

$$I_p = x\ I_l \tag{3.1}$$

where

$$x = X_{min} + \Delta x \tag{3.2}$$

Δx is the variation in the load carrying factor x. It is given by the expression :

$$\Delta x = \left(\frac{X_{max} - X_{min}}{I_{max}} \right) I_l \tag{3.3}$$

Eqs. (3.2) , (3.3) always keep the value of x between X_{max} and X_{min}. If there is any change in I_l, Δx is accordingly changed and this varies x in proportion to the change in Δx. I_{max} is the anticipated maximum current to be expected at the relay location for which x is determined. If the load current is less or is equal to zero, I_p is assigned the minimum value available on the relay.

Thus the expression given in Eq. (3.1) adaptively selects the I_p values for the relays which see load currents and the I_p value is set to the minimum value for a relay which does not see a load current.

3.4 ALGORITHM FOR ADAPTIVE COORDINATION

Fig. 3.1 depicts the flowchart of the algorithm for the adaptive coordination of directional overcurrent relays. The main steps of the algorithm are given below :

1. *Topology Processor* : The topology processor tracks the network topology over time [59]. The circuit breaker status information is the main input to this subroutine. Whenever there is a structural change in the power network, the topology processor determines the latest topology of the network.
2. *Storing of Topology* : The latest information obtained about the power network by the topology processor is stored using the LINKNET subroutine.
3. *Load Flow Analysis* : The next step is to perform the load flow analysis of the entire network. This analysis determines the bus voltages and the line currents. Gauss-Seidel method has been employed for this purpose.

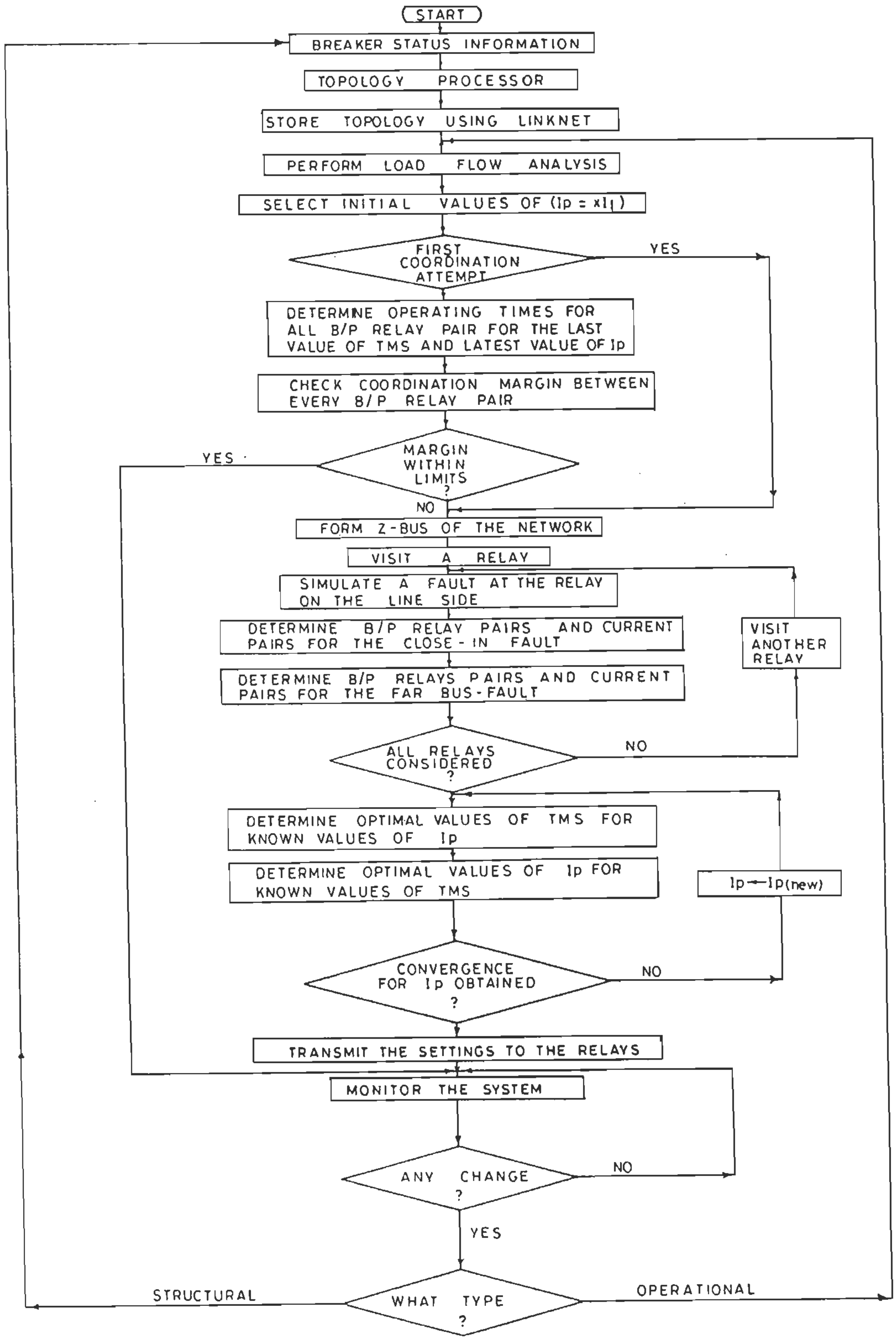


FIG. 3·1 ADAPTIVE COORDINATION OF DIRECTIONAL OVER-CURRENT RELAYS

4. *Adaptive Selection of Initial Pickup Current* : As mentioned earlier, it is advantageous to select the initial value of the pickup currents according to the actual currents seen by the relays. This step will make the relays more sensitive in their operations.

5. *Check For Coordination Criterion* : If it is not a first coordination attempt, the coordination criterion is checked whether it has been violated or not. If the coordination criterion is violated (i.e. the coordination margin is not within the limits) the recoordination procedure starts, otherwise the recoordination is not performed. If it is the first coordination attempt, the coordination criterion is not checked.

6. *Formation of Z-bus Matrix* : Z-bus matrix is built to simulate faults at different relay locations. This matrix is used to calculate the fault currents which are seen by each relay of the power system.

7. *B/P Relay Pairs and Associated Fault current Pairs* : The next step is to determine the B/P relay pairs and the associated fault current pairs for each fault simulated.

8. *Optimal Selection of TMS* : The optimal values of TMS are determined, keeping the values of I_p fixed.

9. *Optimal Selection of I_p* : The optimal values of I_p are determined, keeping the values of TMS fixed.

10. *Convergence Criterion* : If the value of I_p has converged, the coordinated settings have been obtained , otherwise with the new values of I_p, the control is shifted to step 8.

11. *Communication of the Settings to the Relays* : The final coordinated relay settings calculated are transmitted to the respective relays. Fibre optic channels could be used for the purpose.

12. *Monitoring* : The power transmission network is continuously monitored for any changes, operational or structural. If a change is detected , the adaptive algorithm is immediately invoked and the new relay settings are calculated and transmitted to the relays. If the change is an operational one, the computer will restart the coordination process from step 3 and if the change is a structural one i.e. the topology of the network is disturbed, the coordination process is restarted from step 1.

3.5 APPLICATION AND RESULTS

The developed methodology was applied successfully to solve the coordination problem of the following test systems in an adaptive manner :

- 6-bus test system
- 14-bus IEEE system
- 26-bus SPC system
- 57-bus IEEE system

Many contingencies were created and the adaptive algorithm responded favourably. The adaptive algorithm responded to the operational as well as to the structural changes and recalculated the coordinated relay settings based upon the existing network conditions.

3.5.1 RESPONSE OF THE ADAPTIVE ALGORITHM TO THE VARIATION IN GENERATION/LOAD LEVELS

Table 3.1 and Table 3.2 give the coordinated relay settings for different generation/load levels for the 6-bus power system. The settings are the final optimal values determined by the algorithm. The pickup current settings are given in terms of currents for which the relays would pickup. The value of x is also given. It is to be noted that it gets adaptively set according to the existing loading pattern of the power system. Table 3.4 gives the coordinated settings for some of the relays of the IEEE 57-bus power transmission system for a particular generation / load level.

TABLE 3.1 *RELAY COORDINATED SETTING FOR A PARTICULAR GENERATION/LOAD LEVEL (6-BUS POWER SYSTEM)*

Relay	Load current (A)	x	I_p (A)	TMS
1	327.45	1.262	413.30	0.114
2	--	--	25.00	0.242
3	746.45	1.312	979.73	0.076
4	--	--	25.00	0.248
5	--	--	25.00	0.225
6	86.18	1.250	107.73	0.141
7	139.19	1.299	180.92	0.127
8	--	--	25.00	0.247
9	322.30	1.311	422.60	0.106
10	--	--	25.00	0.294
11	671.83	1.286	864.00	0.092
12	--	--	25.00	0.257
13	141.66	1.306	185.09	0.105
14	--	--	25.00	0.203
15	549.32	1.270	697.92	0.075
16	--	--	25.00	0.183

TABLE 3.2 : *RELAY COORDINATED SETTINGS FOR A DIFFERENT GENERATION/LOAD LEVEL (6-BUS POWER SYSTEM)*

Relay	Load current (A)	x	I_p (A)	TMS
1	241.04	1.252	301.34	0.152
2	--	--	25.00	0.265
3	551.89	1.275	703.72	0.106
4	--	--	25.00	0.280
5	--	--	25.00	0.243
6	61.78	1.258	77.74	0.190
7	106.75	1.271	135.73	0.157
8	--	--	25.00	0.277
9	245.90	1.297	319.04	0.138
10	--	--	25.00	0.317
11	486.85	1.267	616.85	0.124
12	--	--	25.00	0.289
13	105.47	1.313	138.52	0.142
14	--	--	25.00	0.231
15	397.97	1.321	526.04	0.103
16	--	--	25.00	0.228

Fig. 3.2 depicts the adaptive shifting of the TCC for relay 16 of the 6-bus power system and *Fig*.3.3 depict it for relay 120 of the IEEE 57-bus power system, as the conditions of the respective systems change. The TCC of the relays adapt to the latest conditions of the network. Thus the effective operation of the relays is assured. In all the cases studied, the value of CTI is taken as 0.2 sec.

3.5.2 RESPONSE OF THE ALGORITHM TO A STRUCTURAL CHANGE

The response of the adaptive algorithm to structural changes was also studied. Many structural changes were created and the algorithm responded favourably with the calculation of new coordinated relay settings. Table 3.3 and Table 3.4 give some of the coordinated relay settings for the 6-bus power system and the IEEE 57-bus power system. In each case a line was put out of service. The shifting of the TCC is shown

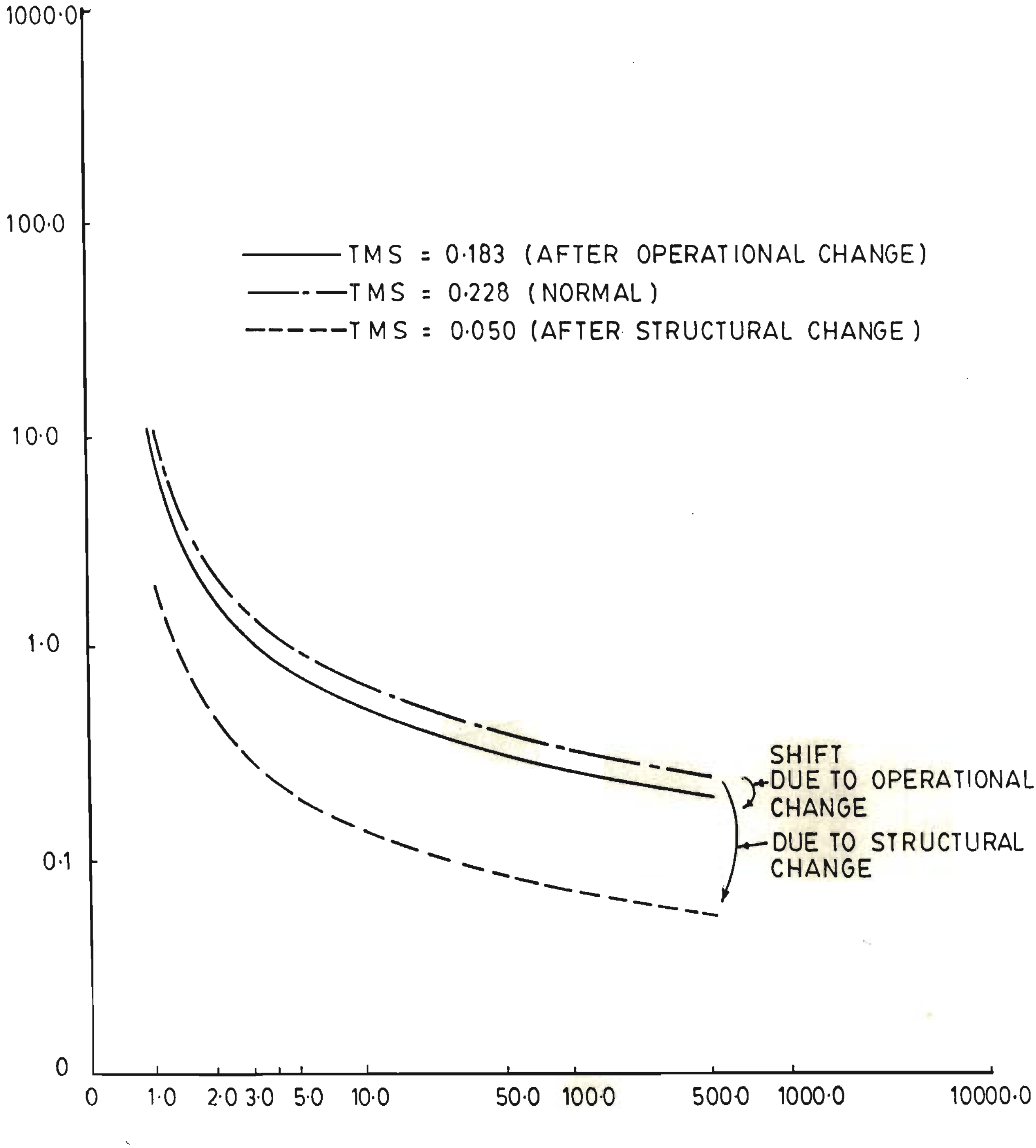


FIG. 3·2 ADAPTIVE SHIFTING OF TCC OF RELAY 16 FOR DIFFRENT CONDITIONS (6-BUS POWER SYSTEM)

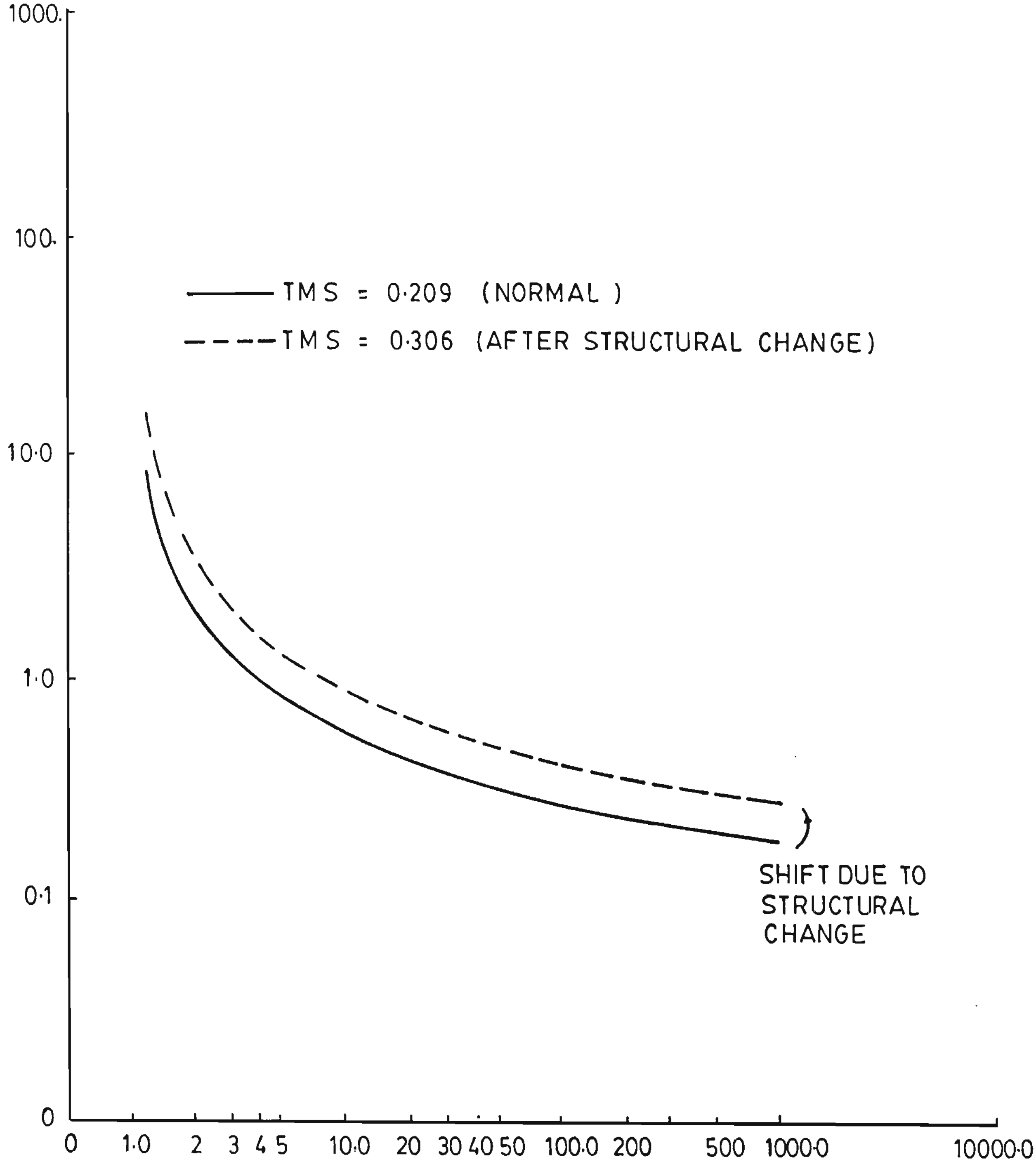


FIG. 3·3 ADAPTIVE SHIFTING OF TCC OF RELAY NO.120 WHEN LINE NO. 59 IS TAKEN OUT (IEEE 57-BUS SYSTEM) in Figs. 3.2 and 3.3.

3.6 RELAXATION OF CONVERGENCE CRITERION FOR I_p

In adaptive coordination, there is a limitation of time. All the calculations have to be done as quickly as possible. In the adaptive algorithm presented, most of the execution time is consumed by the optimal calculation of the TMS. We suggest to relax the convergence criterion for I_p and to calculate optimal values of TMS and I_p only in one iteration. This will greatly reduce the execution time. It is observed that the execution time is reduced to almost half in all cases studied.

TABLE 3.3 *RELAY COORDINATED SETTINGS WHEN LINE NO. 7 IS OUT (I.E. RELAYS 13 AND 14 ARE OUT) (6-BUS POWER SYSTEM)*

Relay	Load current (A)	x	I_p (A)	TMS
1	287.13	1.283	368.42	0.128
2	--	--	25.00	0.252
3	508.52	1.268	644.83	0.109
4	--	--	25.00	0.264
5	--	--	25.00	0.213
6	96.73	1.271	123.02	0.079
7	164.18	1.250	205.23	0.122
8	--	--	25.00	0.270
9	290.80	1.309	380.71	0.118
10	--	--	25.00	0.313
11	432.38	1.332	576.04	0.132
12	--	--	25.00	0.267
13	--	--	--	--
14	--	--	--	--
15	472.04	1.260	595.00	0.087
16	--	--	25.00	0.050

TABLE 3.4 *SOME OF THE COORDINATED RELAY SETTINGS OF THE IEEE 57-BUS POWER SYSTEM*

Relay	WHEN NO LINE IS TAKEN OUT			WHEN LINE NO.59. IS TAKEN OUT		
	x	I_p (A)	TMS	x	I_p (A)	TMS
110	1.287	89.21	0.362	1.277	88.19	0.364
111	1.299	52.11	0.502	1.291	52.06	0.503
112	--	25.00	0.463	--	25.00	0.467
113	1.273	76.13	0.494	1.261	75.72	0.495
114	--	25.0	0.380	--	25.00	0.383
115	1.282	251.41	0.368	1.272	254.42	0.365
116	--	25.00	0.520	--	25.00	0.514
117	1.288	44.90	0.255	**RELAY 117 OUT OF SERVICE**		
118	--	25.00	0.193	**RELAY 118 OUT OF SERVICE**		
119	1.299	16.94	0.431	1.277	44.40	0.306
120	--	25.00	0.209	--	25.00	0.306
121	1.271	24.45	0.402	1.293	17.72	0.398
122	--	25.00	0.257	--	25.00	0.250
123	1.299	52.14	0.601	1.296	56.06	0.586
124	--	25.00	0.644	--	25.00	0.642
125	1.309	121.10	0.581	1.306	129.70	0.567
126	--	25.00	0.751	--	25.70	0.746
127	--	25.00	0.088	--	25.00	0.086
128	1.333	193.32	0.267	1.328	193.37	0.262
129	--	25.00	0.465	--	25.00	0.469
130	1.312	385.28	0.410	1.305	385.17	0.412
131	--	25.00	0.287	--	25.00	0.289
132	1.310	123.22	0.521	1.302	122.80	0.523
133	--	25.00	0.543	--	25.00	0.546
134	1.262	204.94	0.430	1.250	204.90	0.429

TABLE 3.5 *SOME OF THE PICKUP VALUES FOR THE RELAYS OF IEEE 14-BUS POWER SYSTEM*

Relay	First Iteration I_{p_1}	Second iteration I_{p_2}	$\lvert I_{p_2} - I_{p_1} \rvert$
26	28.90	28.89	0.01
25	25.00	25.00	0.00
30	46.71	46.72	0.01
29	25.00	25.00	0.00
34	48.96	48.96	0.00
33	25.00	25.00	0.00
2	845.14	845.52	0.38
1	25.00	25.00	0.00

Table 3.5 gives some of the coordinated relay settings for the IEEE 14-bus power system when the convergence criterion for I_p (TOLIP) is relaxed. The same table also compares the values of the settings before the relaxation and after the relaxation is done. Thus, it is noted that the iterative procedure is not needed for the coordination of directional overcurrent relays. Hence the adaptive coordination algorithm also becomes simpler.

3.7 REMOVAL OF SYMPATHY TRIP TENDENCY OF RELAYS

The problem of sympathy trips of relays in an interconnectd power system has been presented in *Chapter 2*. It has been noted that the sympathy trips of certain relays are caused by the inappropriate settings of the relays. The classification of sympathy trips suggested that some sympathy trips are caused because of the nature of the interconnected power systems and some are caused by not responding to the system changes which occur quite often in the power systems. The sympathy trips which are caused by the inherent nature of directional overcurrent relays in an interconnected power system are difficult to treat but the sympathy trips which are caused by the system changes are easily removed by the adoption of adaptive coordination. The TCC of relays are adaptively changed in accordance with the change in system conditions. The violation of coordination criterion for even a single B/P relay pair is enough to invoke the adaptive coordination algorithm. Thus the nuisance tripping of sympathy trips are removed considerably.

3.8 CONCLUSIONS

The concept of adaptive coordination of directional overcurrent relays is defined and its importance highlighted in this chapter. An algorithm has been presented which recoordinates the relays of a system adaptively, responding to the changing conditions of the system. The developed adaptive coordination algorithm has been applied to many cases and all gave good results. It is also shown that the use of adaptive coordination removes the sympathy trip tendency of relays by responding to the latest changes in the system conditions.

ADAPTIVE COORDINATION USING NETWORK DECOMPOSITION APPROACH

4.1 INTRODUCTION

In recent years, with the increase in demand, the size and complexity of power network has grown tremendously. It is difficult and time consuming to analyze such networks as a whole, particularly for coordinating the relays of the power network. Hence there is a need to develop a decomposition method which would be helpful in determining the coordinated relay settings. In the decomposition method, the power network is divided into a number of areas. The need for subdivision into areas arises due to the complexity and computational difficulty associated with a single large power network, geographical disposition of generating sources, heavy load centers and interconnections, ownerships and political boundaries and overall considerations of reliability.

If the network area is very large, then the area may further be divided into sub-areas. The subdivision should be made such that each sub-area is as self-sufficient as possible, in generating capacity and in interconnection support. This criteria would be a sound principle for control and reliability. Thus, it is preferred to decompose the power network at structural level.

In this Chapter, a network decomposition method is presented which determines the coordinated relay settings of the power network area-wise or region-wise. The method utilizes optimization techniques to solve the coordination problem of the directional overcurrent relays.

The idea of network decomposition or network tearing is not new. It has been used for conducting the load flow studies on large power systems for many years. Kron [38] was the pioneer to develop the idea of network tearing into sub-networks. Other researchers like Happ [24], Andretich et al. [4], Dy Liacco [19], Sasson [69], Happ et al. [25], Roy [67], Kasturi et al. [36], Alvardo et al. [3] and Agnihotri et al. [1] also developed methods to solve the load flow problems of large power networks. In all these methods, a power network is decomposed into several sub-network and the sub-networks are solved in turn, one by one. These methods are efficient as far as the speed of execution and the memory requirements are concerned.

In the network decomposition optimal coordination method developed, the large power network is decomposed into number of sub-networks called blocks by identifying boundary buses, branches and relays. The blocks are analyzed sequentially and the boundary data table is updated during the solution process. The method reported is distinctly superior to the full system optimal coordination method from the point of view of speed and memory requirements. The results are discussed for the various standard test systems.

An adaptive technique for coordinating the directional overcurrent relays in an interconnected power system has been developed and implemented successfully using this newly developed network decomposition method.

The possible use of the concept of parallel processing in block-wise coordination of the relays has been surveyed and the findings reported.

4.2 DECOMPOSITION METHOD FOR COORDINATION

Assume that a large power network N^o is decomposed into sub-networks N^1, N^2 and N^3 as shown in Fig 4.1. These sub-networks are called blocks.

The blocks are connected with each other with the help of boundary lines. There may be one or more than one boundary lines between different blocks. In case of Fig. 4.1, there are two boundary lines between blocks N^1 and N^2, two boundary lines between blocks N^1 and N^3, and one boundary line between blocks N^2 and N^3. The boundary lines are connected to the boundary buses of each block. Each boundary line has two boundary relays installed at its two ends. These boundary relays are classified as the external boundary relays and the internal boundary relays, depending upon which block is being currently analyzed. Consider block N^1 of Fig 4.1, the internal boundary relays are R1, R4, R5 and R8. The external boundary relays are R2, R3 (which are a part of internal boundary relays of block N^2) and R6, R7 (which are a part of internal boundary relays of block N^3). Similarlv R2, R3 and R9 are the internal boundary relays of block N^2 and the relays which are installed on the other end of the boundary lines connected to this block are the external boundary relays. Therefore, a boundary relay belongs to its own block as an internal boundary relay and it also belongs to the adjacent blocks as an external boundary relay.

Now, if a fault has occurred near bus $N^1_{m_1}$ at location (A) [Fig. 4.1], the directional overcurrent relay R1 will act as a primary relay for the close-in fault and other appropriate relays of block N^1 will act as the backup relays. The same fault is a far-bus fault for the relay R2 which

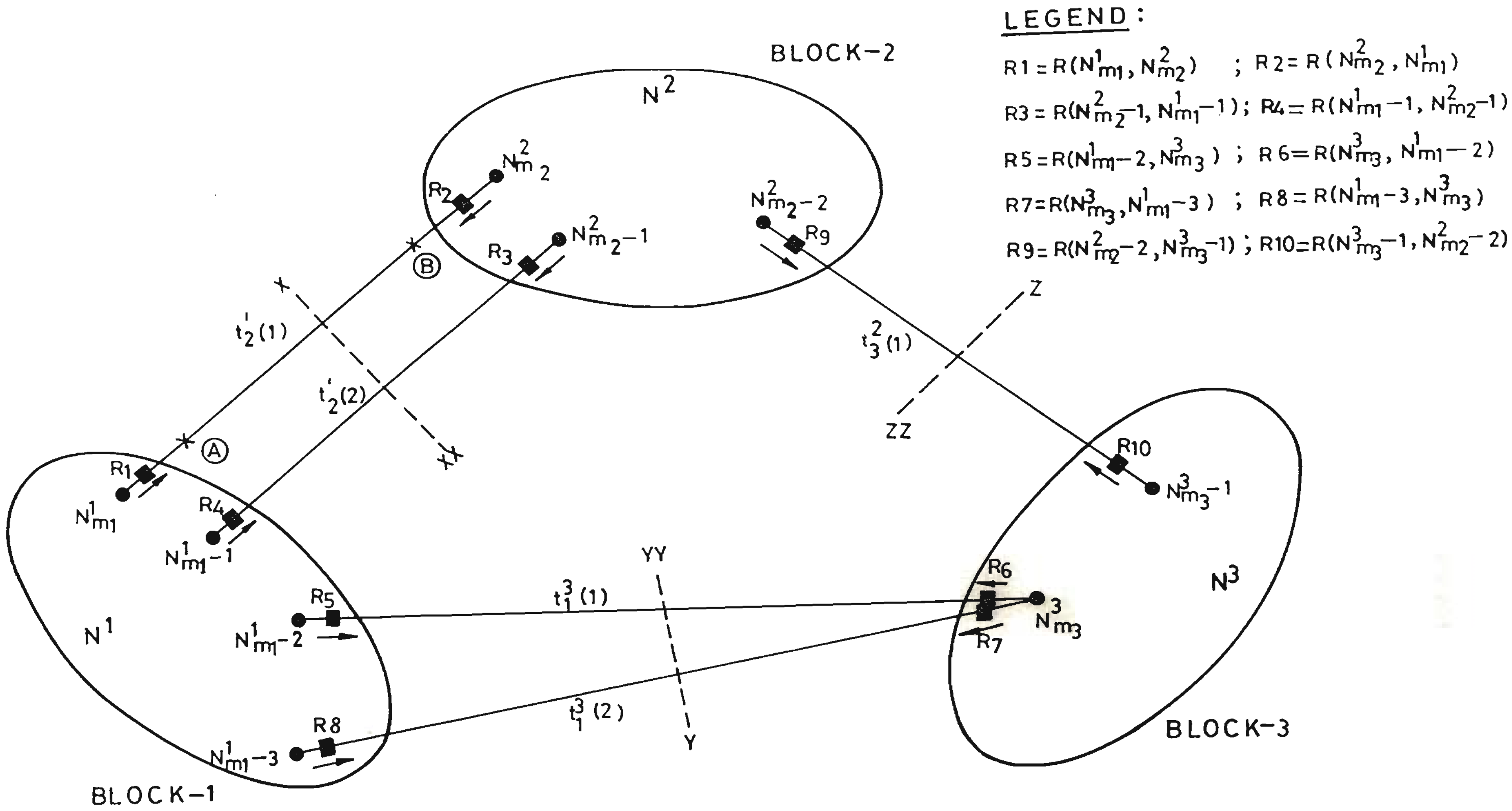


FIG. 4·1 — INTERCONNECTION OF BLOCKS

falls under the jurisdiction of block N^2. Thus, the relay R2 will operate as a primary relay to a fault in block N^1 alongwith its appropriate backup relays which are a part of block N^2. Moreover, the relay R1 acts as a backup relay which falls under block N^2 and similarly R2 acts as a backup relay to other primary relays which fall under block N^1.

For the sake of decomposing the network into blocks and making them independent or disassociated from each other for individual analysis along with their boundary relays, the close-in faults and the far-bus faults are not considered for external boundary relays. As an example, for block N^1 fault at location A is a far-bus fault for relay R2 and fault at location B is a close-in fault for the same relay. These faults are not considered for relay R2 as far as the analysis of block N^1 is concerned. This step limits the role of the external boundary relays to that of backup relays only. Similar is the case when block N^2 is analyzed. For relay R1, no close-in and far-bus faults are considered. It behaves as a backup relay to the primary relays in block N^2. This step helps in delinking the various blocks and making them independent for individual analysis. To summarise, the external boundary relays appear only as the backup relays to the primary relays of the block under consideration. The boundary relays belong to their own blocks as well as to other blocks simultaneously. This special feature of interdependence is utilized in the proposed decomposition method which greatly enhances the efficiency of the coordination solution algorithm. This feature of interdependence is exploited in the manner as explained below :

Each directional overcurrent relay has three settings to be determined; I_s, I_p and TMS. In order to ensure the selective operation of the relays, proper coordinated values of TMS have to be determined. For each block, an objective function or a performance function is minimized subject to the coordination criteria and the limits on the relay settings. The objective function chosen must reflect the desired operation of the relays. The coordination problem of each block is formulated as a parameter optimization problem.

$$\text{Minimize } F = \sum_{i=1}^{N_B} T_{p_i} \tag{4.1}$$

Subject to

$$T_{b_c} - T_{p_c} \geq CTI \tag{4.2}$$

$$T_{b_f} - T_{p_f} \geq CTI \tag{4.3}$$

$$TMS_i^{min} \leq TMS_i \leq TMS_i^{max} \tag{4.4}$$

$$I_{p_i}^{min} \leq I_{p_i} \leq I_{p_i}^{max} \tag{4.5}$$

where $i = 1, 2, \ldots, N_B$

$$TMS_j = TMS_{IBR} \tag{4.6}$$

where F is the summation of the primary operating times (T_P) of all the relays of a block, including that of the boundary relays. Two types of the primary relays are considered ; one type which responds to close-in faults and the other which responds to far-bus faults. TMS_j are the time multiplier settings of the internal boundary relays (IBR) of each block which are kept fixed during the analysis of the block.

Consider Fig.4.1, to begin with, the coordination problem of block N^1 is solved. The TMS for the internal boundary relays are not kept fixed at this stage because there are no previous TMS results available. The TMS of the external boundary relays of block N^1 are preserved. These become the TMS of the internal boundary relays of block N^2 (only those relays which are connected with block N^1). Now, block N^2 is analyzed, keeping the TMS of its internal boundary relays fixed (not for those relays which are connected to block N^3). The TMS of the external boundary relays of block N^2 are preserved. These are now the internal boundary relays of blocks N^3 and N^1. Next, block N^3 is analyzed, keeping the TMS of its internal boundary relays fixed. Then again block N^1 is analyzed and so on. Thus the analysis of the blocks continue till the convergence is achieved. The convergence criterion selected depends upon the TMS of the boundary relays. After each iteration (i.e. when all the blocks are analyzed) the TMS of the boundary relays is checked. If there is no change in the TMS values, the algorithm stops, otherwise another iteration is taken.

4.3 ALGORITHM FOR OPTIMAL DECOMPOSITION COORDINATION

The decomposition method described is used to decompose the power network into blocks. All the blocks are solved sequentially and the solutions are coordinated simultaneously to get the overall optimal settings of all the directional overcurrent relays.

The main steps of the algorithm are [Fig 4.2] :

1. The linked-list data structure LINKNET is used to store the topology of the complete network.
2. The load flow analysis is performed for the whole system to determine the bus voltages and the line currents. Gauss-Seidel method is utilized for the purpose.
3. Z-Bus matrix is built for the complete system. This matrix is put to use to perform the fault analysis of the power system.
4. The next step is to decompose the power network into blocks. Blocks are formed in any convenient manner one may like. Normally blocks are formed with minimum number of boundary relays between them. At this stage data is read about the relays of each block and the external and the internal boundary relays of each block.
5. ITER <—— 1
6. I <——— 1
7. A fault (for which relay coordination is sought) is simulated at every relay location of block I. The B/P relay pairs and the associated fault currents are determined and stored. The LINKNET is used to determine the B/P relay pairs.
8. The coordination problem is solved, by using the methods already presented in *Chapter 2*, for block I. For first iteration, if block I is analyzed, TMS values are not kept fixed for the internal boundary relays,but for the subsequent iterations these are kept fixed.
9. The TMS values of all the boundary relays are updated for block I.

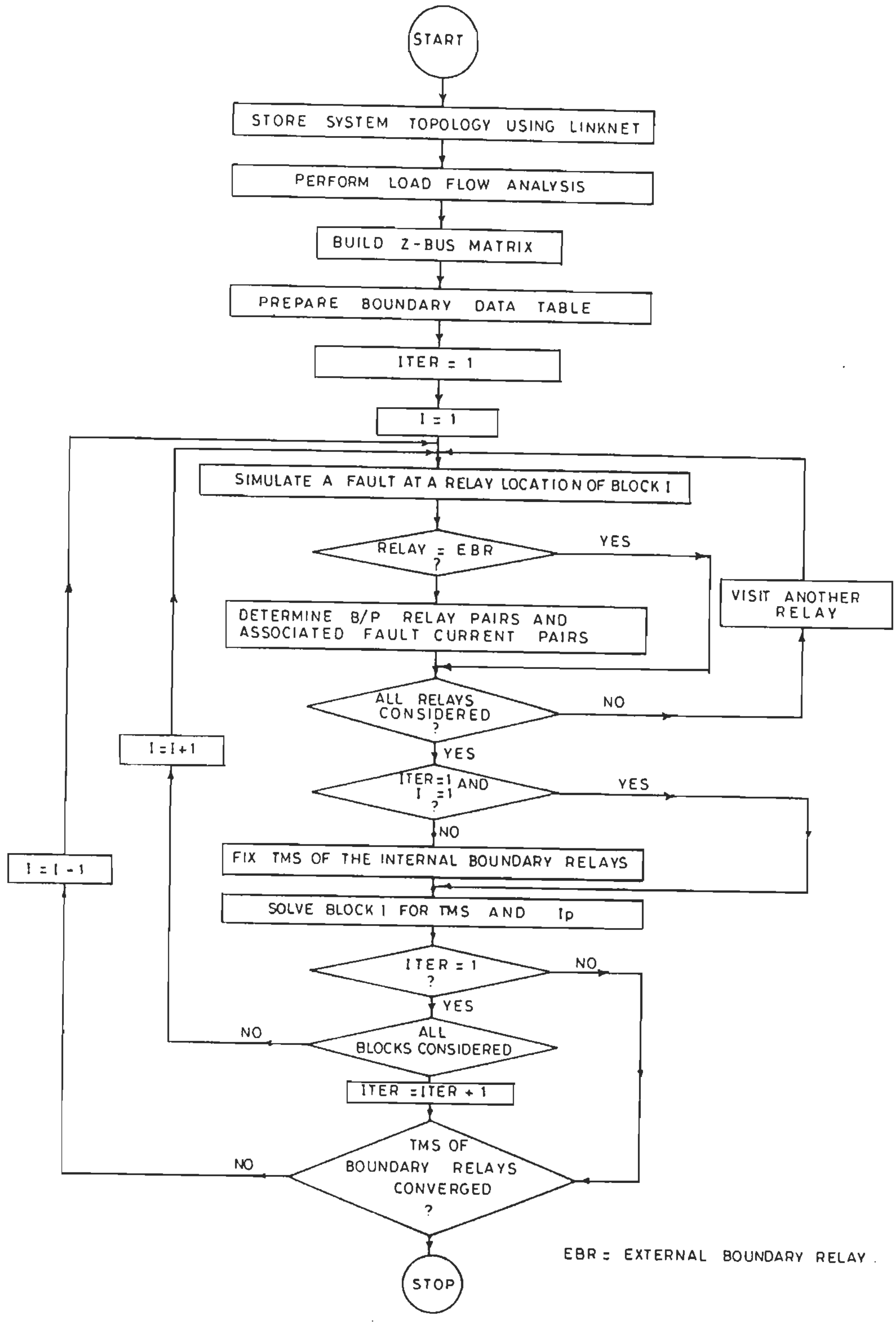


FIG. 4.2 FLOW CHART FOR OPTIMAL DECOMPOSITION COORDINATION ALGORITHM

10. If it is the first iteration and all blocks have not been considered, set I = I+1 and go to step 7; otherwise go to step 12.

11. Set ITER = ITER + 1

12. If convergence of the TMS of the boundary relays is not achieved, set I = I - 1 and go to step 7 ; otherwise stop.

4.4 APPLICATION TO SAMPLE POWER SYSTEMS AND RESULTS

Computer software implementing the proposed algorithm is prepared and tested on Intel's 80486 based personal computer. All the components of the software are fully integrated. The method has been successfully tested for the following test systems :

- the IEEE 14-bus power system
- the SPC 26-bus power system
- the IEEE 57-bus power system
- the NWI 64-bus power system
- the IEEE 118-bus power system

Except the IEEE 118-bus power system, all other systems are solved as 2-block decomposed networks. The IEEE 57-bus, the NWI 64-bus and the IEEE 118-bus power systems are also solved as 3-block and 4-block decomposed networks. The results are discussed in detail for the 2-block decomposed network of the SPC 26-bus, 3-block decomposed network of the IEEE 57-bus, 4-block decomposed network of the NWI 64-bus and the 7-block decomposed network of the IEEE 118-bus power systems. All the results obtained are encouraging. The CTI is chosen to be 0.2 sec. for all examples and the convergence criterion for TMS is chosen to be 0.1.

Example 1

The SPC 26-bus model transmission network is solved by the developed decomposition method as shown in Fig.4.3. Line X-XX divides the network into two blocks, block 1 and block 2. Relays numbered 20 and 52 are the internal boundary relays of block 1 and the external boundary relays of block 2. Similarly the relays 19 and 51 are the internal and the external boundary relays of block 2 and block 1 respectively. First block 1 is solved, no relay has fixed value of TMS at this stage. The TMS values of the relays 19 and 51 are stored. After block 1 is solved, the algorithm solves the coordination problem of block 2, keeping the TMS of relays 19 and 51 fixed. The TMS values of relays 20 and 52 are preserved. Then again block 1 is solved, but this time the TMS values of the relays 20 and 52 are kept fixed and the TMS values of 19 and 51 are preserved. Block 2 is again solved, keeping the TMS of 19 and 51 fixed. It is observed that there is no improvement in the TMS values for the boundary relays beyond this stage. In fact, there is no need to solve block 2 in the second iteration. The improvement in the TMS values for the boundary relays at this stage is less than 0.1, which is the convergence criterion. Thus the decomposition algorithm completely solves the coordination problem in the following manner (for 2-block decomposed networks) :

Block 1 ——> Block 2 ——> Block 1

with appropriate boundary relays having fixed values of TMS.

Table 4.1 gives the comparison of CPU time when the power network is solved as an intact system and when it is solved as a 2-block decomposed network. It is seen that the latter method is 3.23 times faster than the complete system coordination method.

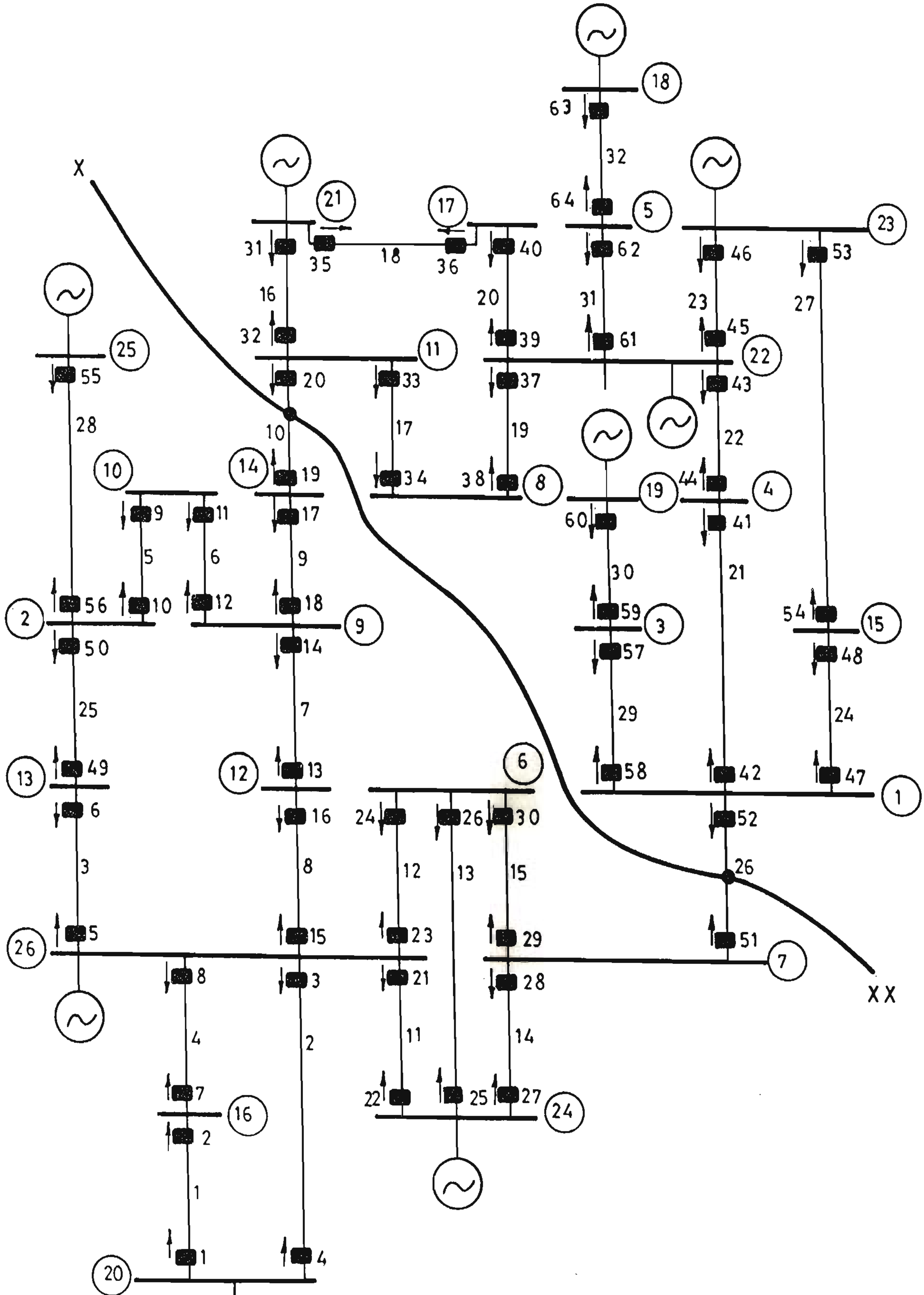


FIG. 4·3 : 26-BUS (SPC) SYSTEM

Example 2

The IEEE 57-bus test power transmission system is decomposed into three blocks for solving its coordination problem. The lines X-XX and Y-YY decompose the network into three blocks [Fig.4.4]. The blocks are solved sequentially, till the convergence criterion is satisfied.

Table 4.1 shows the CPU time for the solution of the system when it is solved as an intact system and when it is solved as a 3-block decomposed network. It is seen that the proposed method is 5.78 times faster than the full system optimal coordination method.

Example 3

The 64-bus power system of North-Western India is shown in Fig 4.5. The proposed method is applied to solve its coordination problem. The network is decomposed into four blocks by the lines X-XX, Y-YY and Z-ZZ. The procedure is similar to Example 2 but there is an extra block in it.

Example 4

The IEEE 118-bus power system is solved by decomposing it into seven blocks. The lines A-AA, B-BB, C-CC, D-DD, E-EE, and F-FF decompose it into seven blocks as shown in Fig 4.6. The coordination problem is solved successfully by the proposed method.

4.5 ADAPTIVE COORDINATION USING NETWORK DECOMPOSITION APPROACH

The proposed network decomposition method for coordinating the directional overcurrent relays in a large interconnected power system is employed to develop a method for adaptive coordination. In the adaptive

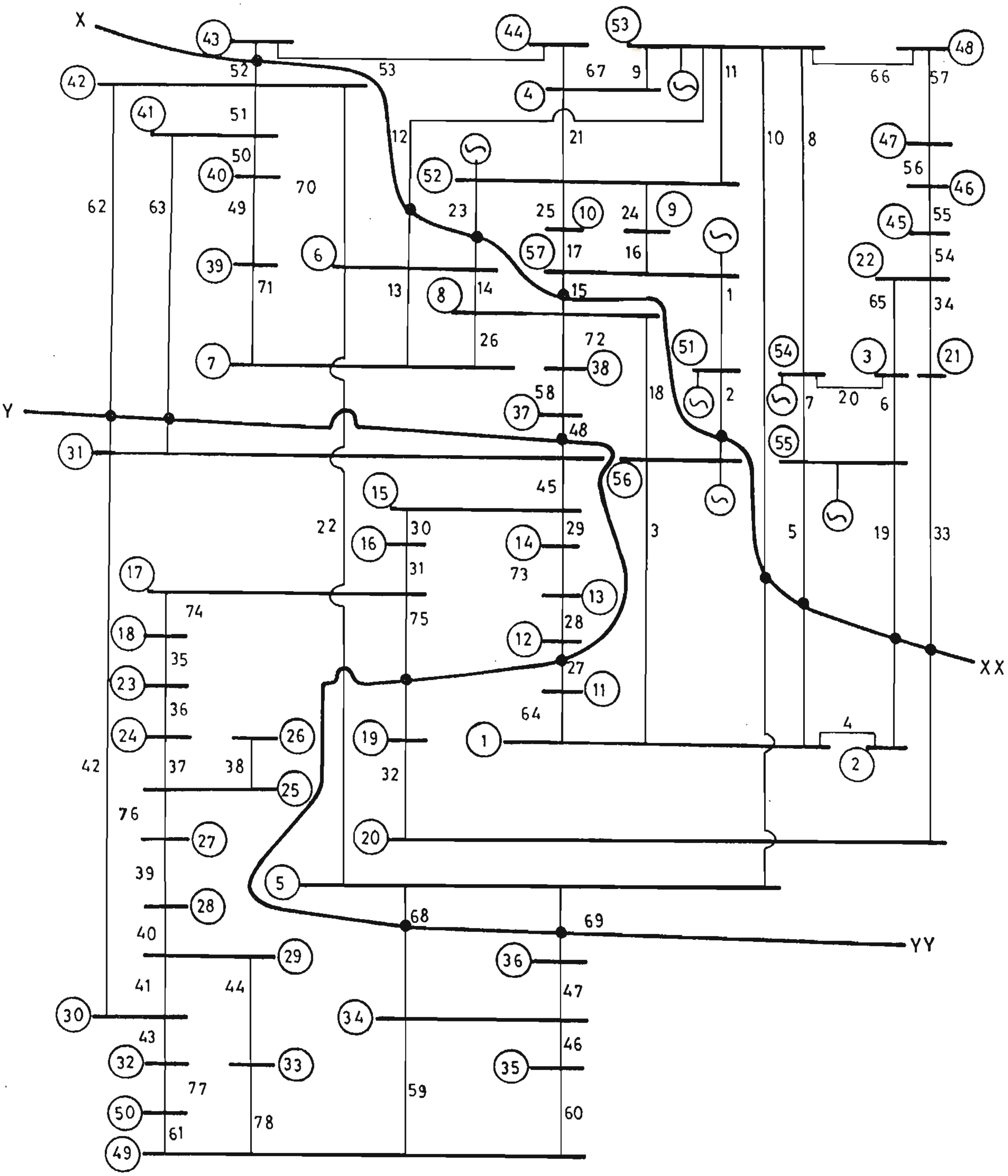


FIG. 4·4 : 57-BUS IEEE TEST SYSTEM

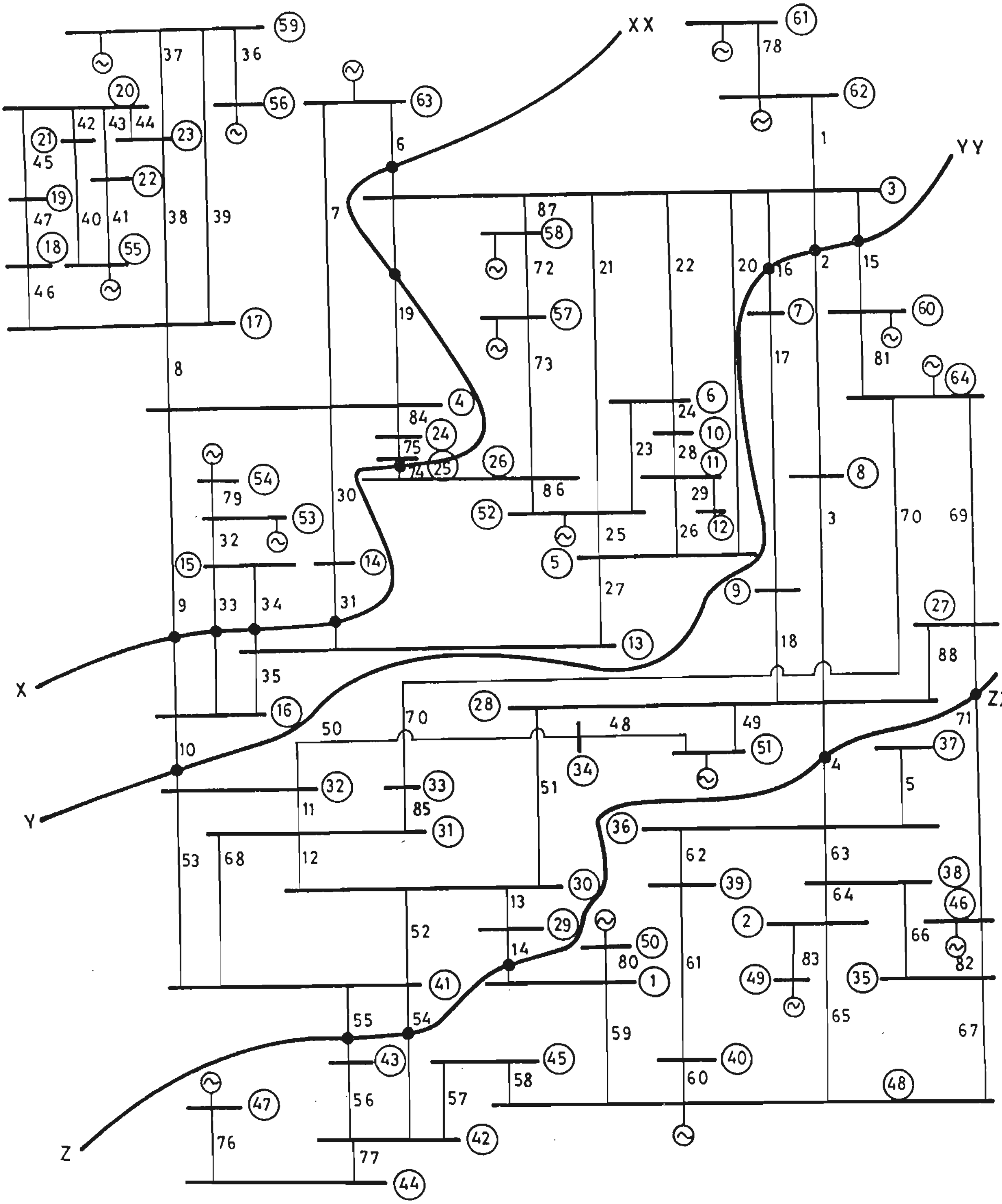


FIGURE 4·5 : 64-BUS NETWORK OF NORTH WEST POWER SYSTEM OF INDIA

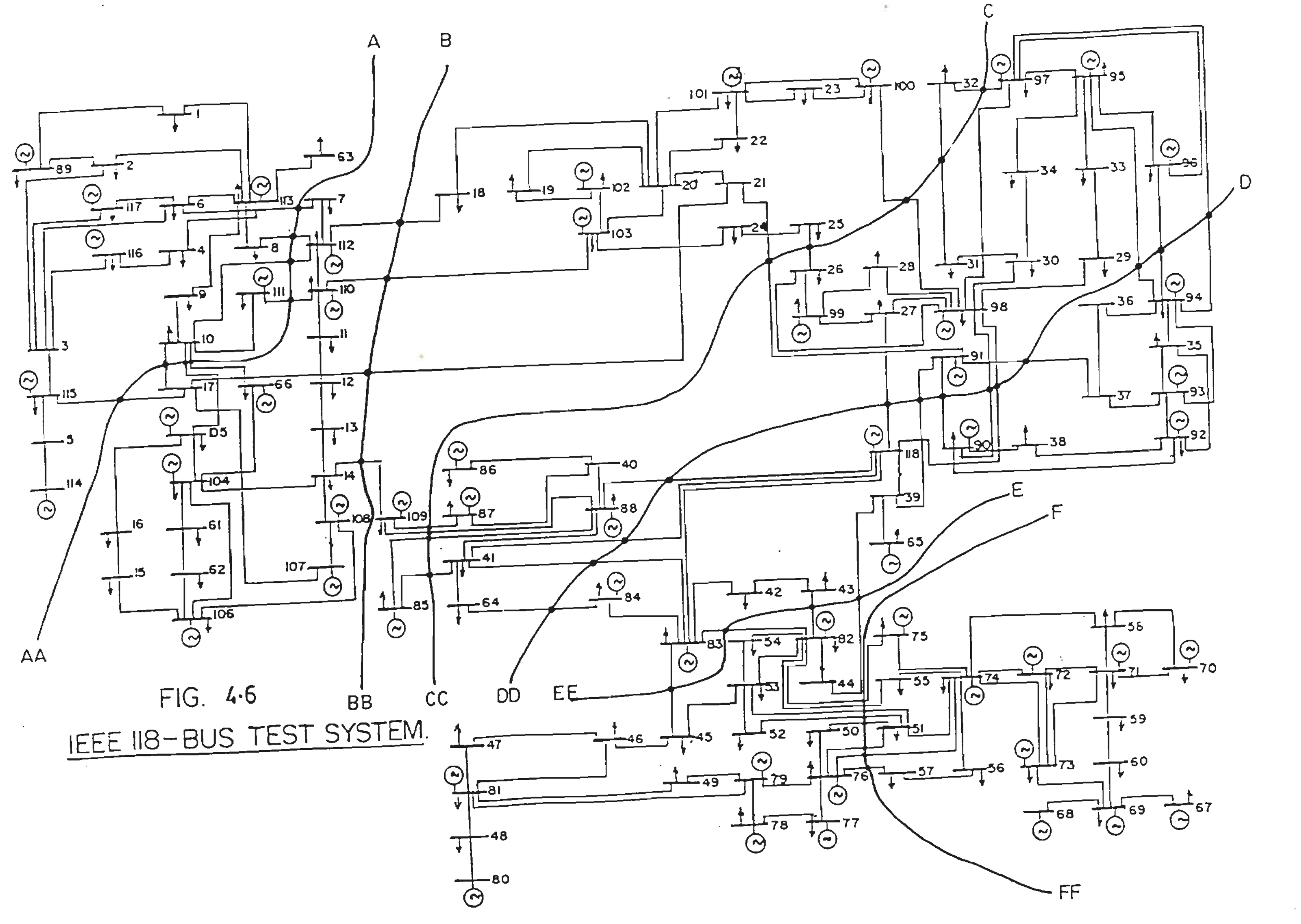


FIG. 4·6

IEEE 118-BUS TEST SYSTEM.

TABLE 4.4 *COMPARISON OF COMPUTATIONAL TIME*

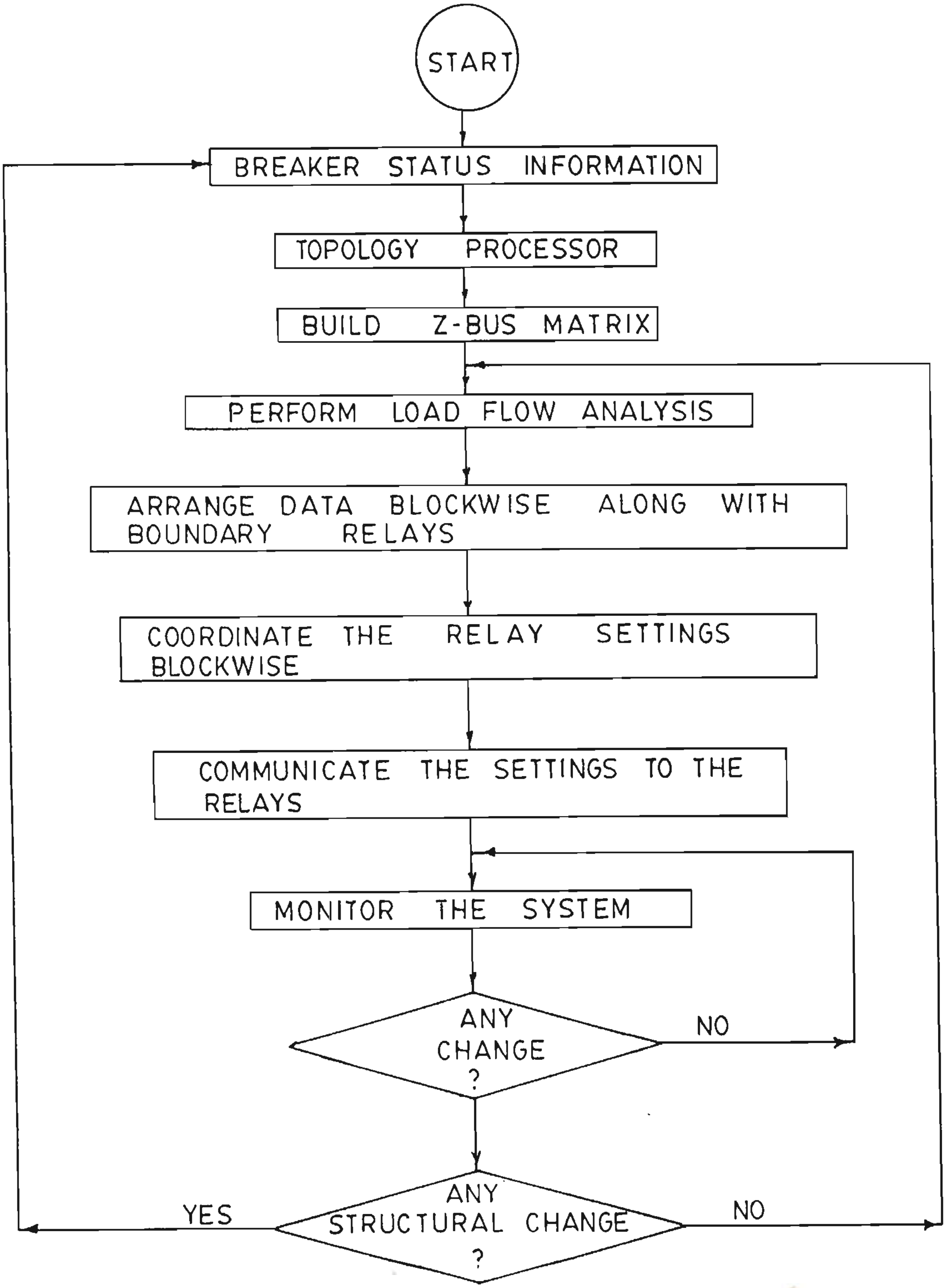
Test System	Power Network As a whole CPU Time (sec.)	Decomposed Power Network		Saving in CPU Time
		No. of Blocks	CPU Time (sec.)	
SPC 26-bus System	501.50	2	155.0	69.81 %
IEEE 57-bus System	10452.7	3	1807.20	82.7 %
NWI 64-bus System	---	4	2465.80	--
IEEE 118-bus system	---	7	9713.40	--

TABLE 4.2 *SOME VITAL INFORMATION ABOUT THE SYSTEM AND THEIR BLOCKS (FOR THE OPTIMAL CACULATION OF TMS)*

Test System	Vital Information	Complete system	Decomposed system							No. of Blocks
			BLOCK 1	2	3	4	5	6	7	
SPC 26-bus system	No. of Relays	64	32	36	--	--	--	--	--	2
	No. of Const-raints	342	154	196	--	--	--	--	--	
	No. of B/P relay pairs	252	108	144	--	--	--	--	--	
IEEE 57-bus system	No. of Relays	152	60	64	64	--	--	--	--	3
	No. of Const-raints	905	321	347	310	--	--	--	--	
	No. of B/P relay pairs	680	236	240	204	--	--	--	--	
NWI 64-bus system	No. of Relays	176	52	52	54	46	--	--	--	4
	No. of Const-raints	1152	273	373	317	239	--	--	--	
	No. of B/P relay pairs	900	184	306	228	160	--	--	--	
IEEE 118-bus system	No. of Relays	358	56	64	54	86	68	64	57	7
	No. of Const-raints	2528	354	359	280	548	431	396	368	
	No. of B/P relay pairs	2036	268	240	180	418	320	308	292	

coordination method, the coordinated settings of the relays are computed according to the present condition of the power system.. No apriori knowledge is assumed. No contingencies like the line-out conditions are taken into account. The developed algorithm monitors the system for any disturbance, structural or operational. When a disturbance is detected, the appropriate elements of the adaptive algorithm are invoked and the new settings are calculated and transmitted to the respective relays. The algorithm is also invoked if a coordination review is done for the present relay settings. The main steps of the adaptive algorithm are [Fig. 4.7].

1. The topology processor tracks the network topology over time. The circuit breaker status information is the main input to the subroutine. The topology processor feeds the network information to the load flow study and the fault analysis programs.
2. Perform the load flow analysis for the complete system.
3. Build Z-bus matrix for the complete system.
4. Decompose the network into blocks.
5. Solve the coordination problem of all the blocks and coordinate the results simultaneously, as explained earlier.
6. The settings obtained are transmitted to the respective relays. In the adaptive coordination, it is assumed that all relays are of digital type and there is a communication channel between them and the processing computers. The power system is continuously monitored for any changes, operational or structural. If the change detected is an operational one , the algorithm will start from step 2 and if it is due to a structural change, the procedure is restarted from the topology processor.



G. 4·7 ADAPTIVE OPTIMAL COORDINATION OF DIRECTIONAL OVER-CURRENT RELAYS USING N/W DECOMPOSITION METHOD

4.6 APPLICATION TO SAMPLE POWER SYSTEMS

The developed adaptive coordination method is applied to the systems under study. Many contingencies were created and the algorithm responded favourably. The algorithm responded to the major load changes and the structural changes and the new relay settings were calculated according to the present state of the power system. Table 4.2 gives some of the coordinated relay settings of the SPC 26-bus power system under normal conditions, and when a structural disturbance is detected. It is clear from the table that all relays do not get involved whenever a disturbance is entertained. But in the present method all the relay settings are recalculated, even for those relays which were not affected by the disturbance. An ideal method would be a method which would recoordinate only those relays which have been affected by a disturbance. Such a method has been developed and is discussed in the next Chapter.

4.7 APPLICATION OF PARALLEL PROCESSING

The adaptive coordination using the network decomposition approach is an ideal problem to be solved using the concept of parallel processing. There is a natural parallelism in the problem formulation. The parallel processing is used to speed up the coordination process. The application of the distributed computing is gainning much importance these days. The computing is done region-wise or area-wise. The region would be a geographical one or determined on the basis of the operating strategy of a utility company.

Consider the SPC 26-bus model transmission network. Line X-XX shows the network decomposition into two blocks. Normally, according to the method presented in the previous sections, block 1 and block 2 are solved sequentially to get the overall solution of the coordination problem. We suggest, now, that block 1 and block 2 be solved simultaneously. Same computer with two processors can do the job very easily. If we have more than two blocks, we can use a computer having the number of processors equal to the number of blocks. We can also use computers which are independent of each other. They share information after every iteration. In first iteration, all the blocks are solved simultaneously without keeping the TMS of the internal boundary relays fixed. In the second iteration, the blocks are solved simultaneously but have TMS values of their internal boundary relays fixed. This information about the TMS of the boundary relays is interchanged between the processors. Same technique of parallel processing is applied to the other systems with more than two blocks.

The time needed to calculate the optimal coordinated settings would correspond to the time taken by the largest block of the network.

If the concept of parallel processing is applied, there will be a percentage saving of 54.33 % and 50.19 % in execution time in cases of the SPC 26-bus and the IEEE 57-bus power systems respectively. The comparison is made between the uniprocessing of the block-wise system coordination and the parallel processing of the block-wise system coordination (BWSC). If the comparison is made between the full system coordination and the BWSC using parallel processing, the percentage saving in execution time would be 85.88 % and 91.38 % in case of the SPC 26-bus and the IEEE 57-bus power systems respectively. This corresponds to a speed-up of 7.08 and 11.61 in the respective cases.

TABLE 4.2 : *SOME OF THE RESULTS OF RELAY COORDINATION FOR THE SPC 26-BUS POWER SYSTEM*

RELAY	COMPLETE SYSTEM			SYSTEM WITHOUT LINE NO. 13		
	TMS (0.05-1.1)	I_p (=XI_1)	x (1.25-1.50)	TMS (0.05-1.1)	T_p (=XI_1)	x (1.25-1.50)
19	0.376	46.54	1.280	0.373	47.39	1.288
20	0.561	25.00	--	0.562	25.00	--
21	0.468	25.00	--	0.365	25.00	--
22	0.238	213.01	1.252	0.140	502.85	1.324
23	0.516	25.00	--	0.348	178.65	1.304
24	0.296	154.43	1.288	0.447	25.00	--
25	0.237	475.60	1.317	--	--	--
26	0.411	25.00	--	--	--	--
27	0.267	170.50	1.296	0.178	316.94	1.295
28	0.380	25.00	--	0.301	25.00	--
29	0.409	25.00	--	0.315	106.97	1.265
30	0.320	114.29	1.261	0.535	25.00	--
31	0.594	30.33	1.282	0.589	30.48	1.250
32	0.471	25.00	--	0.470	25.00	--
33	0.513	25.00	--	0.511	25.00	--
34	0.137	242.29	1.274	0.136	244.78	1.280
35	0.614	25.00	--	0.612	25.00	--

4.8 CONCLUSION

The concept of coordinating the directional overcurrent relays of large scale power transmission systems area-wise or block-wise has been presented and discussed in this Chapter. The algorithm developed has been applied to a number of standard test systems with good and encouraging results. It is observed that, more the number of blocks or sub-networks to be analyzed for a particular system, less will be the execution time needed for solving the coordination problem completely.

An adaptive coordination algorithm has been developed around the presented concept of piecewise solution of the coordination problem of large power systems. There exists a natural parallelism in the network decomposition approach developed. Hence the possibility of using parallel processing or distributed processing in adaptive coordination, has been surveyed and the benefits expected are presented and discussed.

LOCAL OPTIMAL COORDINATION BASED ADAPTIVE COORDINATION

5.1 INTRODUCTION

The main thrust of developing the relay coordination algorithms has been towards the *"system-wide"* coordination of the interconnected power systems. Many interactive [16, 42, 61, 62, 78] and non-interactive [2, 7, 34, 41] types of algorithms were reported. Such algorithms are time consuming especially for analyzing large multiloop power networks. The system-wide coordination methods need huge data-bases and a lot of computer memory and are inherently computationally intensive because of many interconnections present in realistic power transmission systems [16, 61, 62].

A change, structural or operational, in the power network warrants a new complete system-wide coordination study. The structural changes are like addition or removal of lines or of generators and the operational changes are the significant changes in system loading conditions. The structural changes may be temporary due to maintenance, or permanent because of network reconfiguration For a large power network, it may not be possible to carry out the coordination study whenever such a disturbance is entertained. Coordination of the complete system may be expensive in terms of manual and computer effort involved in obtaining new settings for the relays.

A disturbance, operational or structural, produces effects which are localized in an electric power system. For example, if a line is out due to a fault or otherwise, the fault levels change in the immediate vicinity of this line. The change produces ripples in the settings of the relays. The ripples travel in the direction in which the disturbance has travelled. The disturbance dies after travelling some distance. Thus a small portion of the power system is affected. Hence only the relays,which fall in this small area termed as the local disturbed region or simply the local region, need to be reset for proper coordination. Thus it is appropriate to develop a method which would recoordinate only those relays of the network which fall in this disturbed local region.

The initial effort in this direction is reported in [63]. The method reported has many shortcomings like the fault analysis program is not integrated with the coordination program, a huge data-base is maintained, elaborate topological analysis programs are required and moreover the calculated settings are not optimal.

Two new algorithms called the Local Optimal Coordination (LOC) algorithms are proposed in this Chapter. In the event of a change, structural or operational , these algorithms automatically identify a local disturbed region around the place of disturbance. Two methods are proposed for identifying the local region. One is based on checking the value of the time multiplier setting (TMS) of the external boundary relays and the other is based on checking the pickup current setting (I_p) of all the relays. Those relays whose I_p have changed appreciably, are included in the local region.

The LOC algorithms are based on the concept of local optimization. The coordination problem is formulated only for the local disturbed region and the problem is solved by using the solution methods which are discussed in *Chapter 2*.

LINKNET data structure is used to integrate the fault analysis program and to determine the backup/primary relationships for the relays of the disturbed region.

The elaborate topological analysis programs and the data-base management packages are not used. The programs developed generate, retrieve, update and use the data whenever it is needed.

It is appropriate and logical to use the concept of local optimal coordination in coordinating the directional overcurrent relays of large electric power transmission networks in an on-line or self-adaptive manner. This has made us to develop a new adaptive coordination philosophy which is based upon the local optimal coordination. This new adaptive coordination philosophy is termed as the Adaptive Local Optimal Coordination (ALOC). This chapter also presents the concepts and the vital components of this newly emerged fascinating area. An algorithm known as the adaptive local optimal coordination algorithm (ALOCA) is presented and discussed. The developed algorithm automatically identifies the local disturbed region in response to a structural change or an operational change in a power system and re-coordinates only the settings of the relays which fall inside this identified local region , in an on-line manner. The scheme is highly efficient as it deals with a small portion of the network. Thus the execution time and the memory requirement are greatly reduced. The schemes developed are applied to a number of test power transmission systems including the SPC 26-bus, the IEEE 57-bus, the NWI 64-bus and the IEEE 118-bus systems with highly encouraging results.

5.2 LOCAL OPTIMAL COORDINATION

It has been well established that, on the occurrence of a disturbance, structural or operational, in a power transmission network, ripples are produced in the settings of the relays which die down after travelling some distance away from the place of disturbance. How far the disturbance propagates depends upon the severity of the disturbance and hence on the profile of the fault levels produced in the vicinity of the place. The region which covers all those relays whose settings have been changed is termed as the local disturbed region. The settings of the relays which fall outside this local region remain unchanged and the region outside the local region is termed as the external undisturbed region or simply the external region.

Fig. 5.1 depicts the local region N of a power transmission network. The region has K boundary lines. Each boundary line has two directional overcurrent boundary relays installed at its two ends. The boundary relays are classified as the internal boundary relays and the external boundary relays. The external boundary relays [$R(N_E^1, N_I^1)$, ..., $R(N_E^k, N_I^k)$] act as backups to the relays which are inside the local region. Their settings do not change in the event of a fault occurring in the local region. No close-in fault is considered for these relays, only the far-bus fault currents are taken into account. This step de-links or disassociates the local region from the external region for separate analysis.

The settings of the internal boundary relays [$R(N_I^1, N_E^1)$,....., $R(N_I^k, N_E^k)$] are kept fixed while calculating the settings of the relays in the local region . This step couples the settings of the relays of the

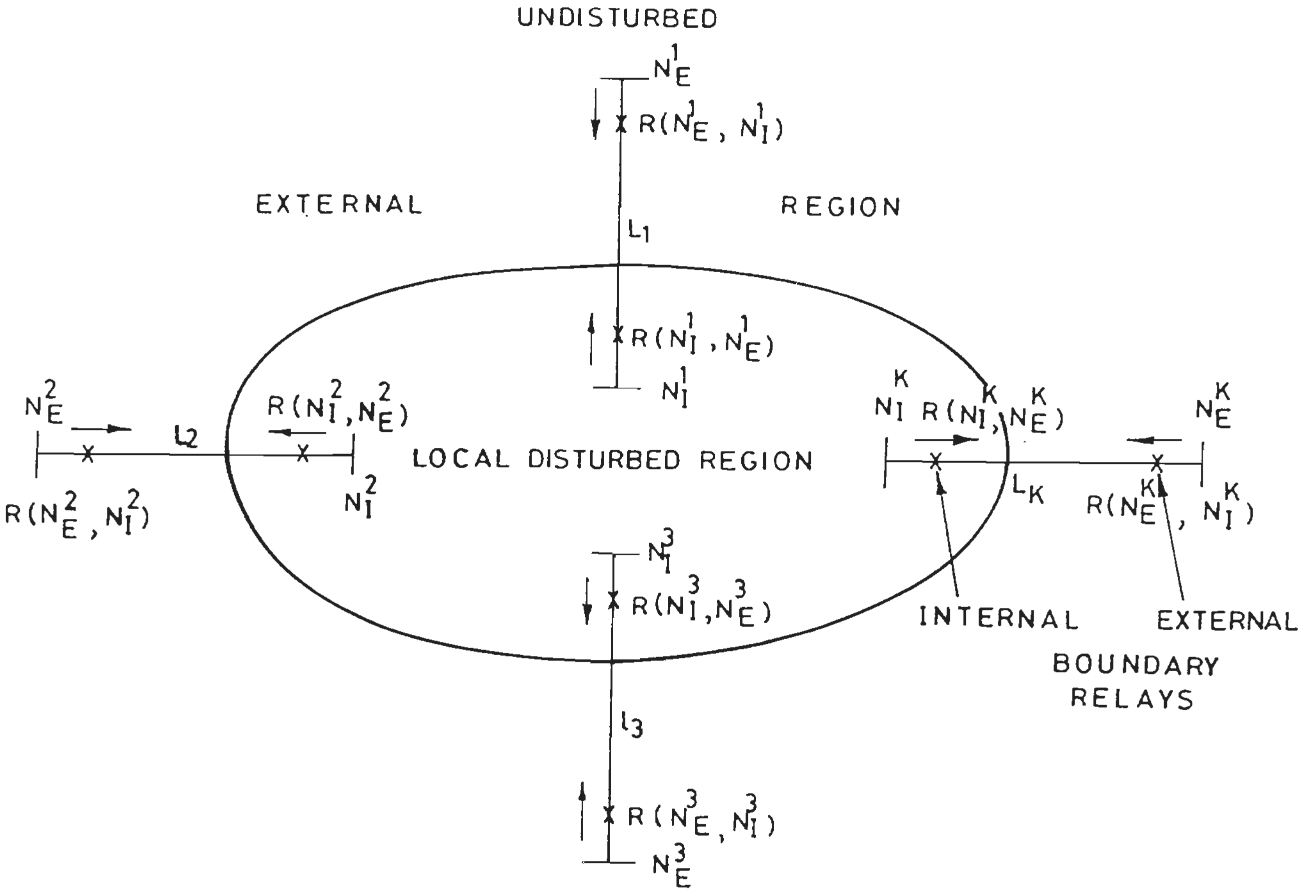


FIG. 5·1–LOCAL REGION

local region with the settings of the relays in the external region. No far-bus fault is considered for the internal boundary relays. These relays constrain the backup operation of the relays in the local region.

5.2.1 PROBLEM FORMULATION

The local optimal coordination problem is formulated as an optimization problem of the type :

$$\text{Minimize } F = \sum_{i=1}^{N_R} T_{p_i} \tag{5.1}$$

Subject to

$$T_{b_c} - T_{p_c} \geq CTI \tag{5.2}$$

$$T_{b_f} - T_{p_f} \geq CTI \tag{5.3}$$

$$TMS_i^{min} \leq TMS_i \leq TMS_i^{max} \tag{5.4}$$

$$I_{p_i}^{min} \leq I_{p_i} \leq I_{p_i}^{max} \tag{5.5}$$

where $i = 1, 2, \ldots, N_R$

$$TMS_j = TMS_{(IBR)_j} \tag{5.6}$$

where the objective function, F, is the summation of the time of operation of all the relays of the local region which act as primary relays. (T_{b_c},

T_{p_c}) are the time of operations of B/P relay pairs which are generated for close-in fault currents. Similarly (T_{b_f}, T_{p_f}) are the time of operations of B/P relay pairs for far-bus fault currents. CTI, as already mentioned, is the coordination margin between the operation of a primary and its backup relay. The lower and the upper limits of the relay settings are also provided as the constraints. $(IBR)_j$ is the internal boundary relay j of the local region and TMS of these relays are kept fixed.

The solution of the above problem gives the coordinated optimal TMS and I_p for all the relays of the local region. Same techniques are adopted for solution as has been described in *Chapter 2.*

5.3 LOCAL REGION IDENTIFICATION

The first step in the local optimal coordination involves the identification of the local disturbed region. Two methods are proposed for the identification of the local region. A brief description of the methods is as given below.

5.3.1 FIRST METHOD

In this method the number of disturbed buses are specified. The algorithm developed finds all the buses which are connected to these disturbed buses. The algorithm depicted in Fig. 5.2 determines all the buses around the disturbance. These buses constitute the initial local region. The initial local region is determined by the powerful scanning ability of the linked-list type of data structure known as LINKNET [60]. The vector LBUS (LBS) contains all the buses of the initial local region.

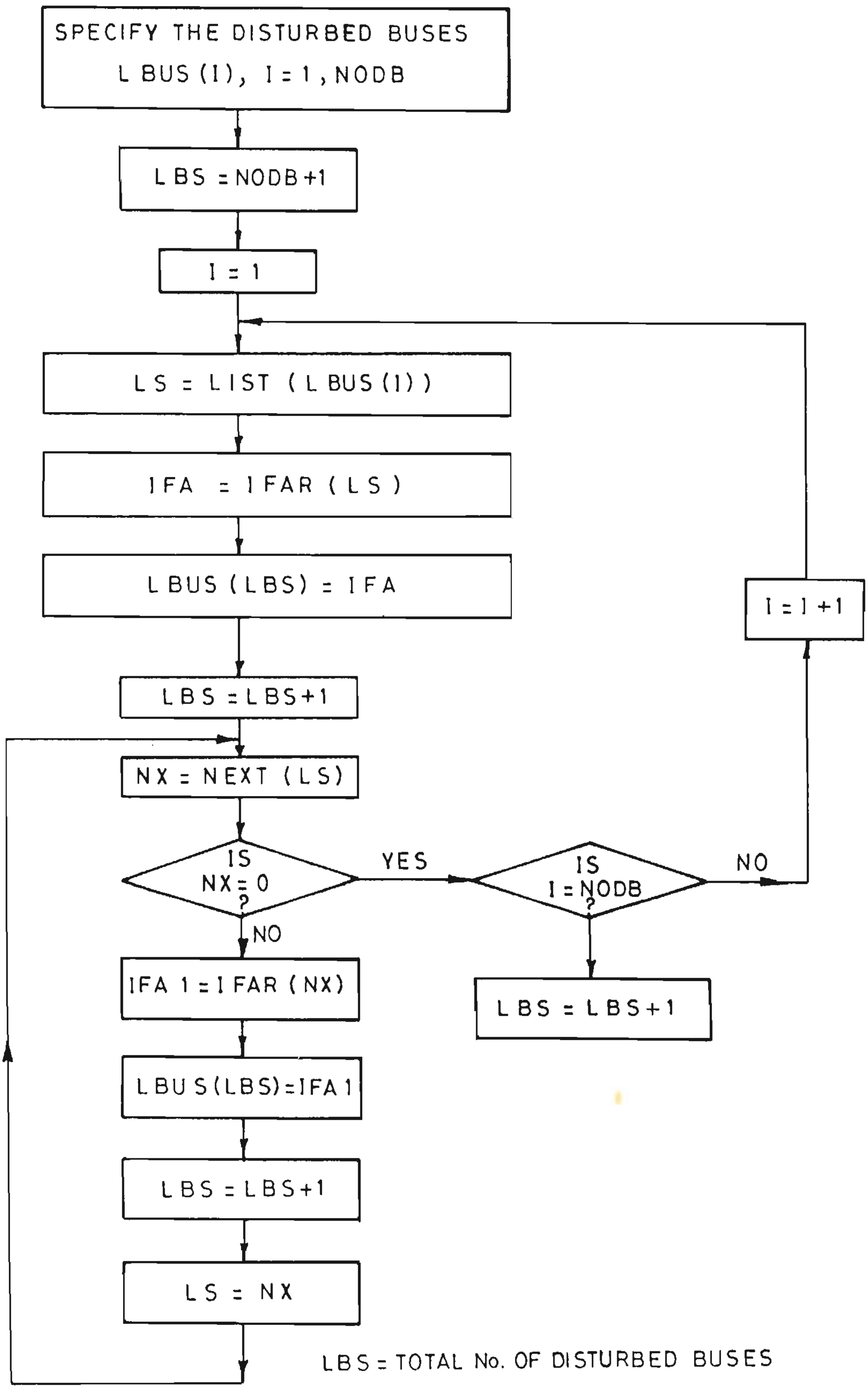


FIG. 5·2—BUSES OF THE INITIAL LOCAL REGION

The next step is to determine all the relays contained in this local region, The flowchart depicted in Fig. 5.3 gives the algorithm which is utilized to determine the relays. The relays are collected in the vector LRG(IL). The steps of Figs.5.2 and 5.3 are self-explanatory. The internal as well as the external boundary relays of the local region are determined, next, by using the algorithm depicted in the flowchart of Fig.5.4. The vectors LBRC(NBR) and LBRF(NBR) contain the external and the internal boundary relays of the local region respectively.

The B/P relay pairs and the associated fault current pairs are determined with the help of the algorithm depicted in Fig.5.5. The close-in fault is not considered for the external boundary relays, therefore, the B/P relay pairs and the associated current pairs are also not considered. Similarly, the far-bus fault is not considered for the internal boundary relays and hence the B/P relay pairs and the associated current pairs are also not taken. This is clearly demonstrated in the flowchart. The same flowchart of Fig.5.5 is also used to integrate the fault analysis program with the main coordination program. The vector NCODE(J) contains all the B/P relay pairs in a sequence in which they are generated by the program and the vector FI(I) contains all the corresponding fault currents seen by the relays. These two vectors are passed on to the main coordination program.

Now, all the relevant data for the solution of the coordination problem has been determined. Before actually solving the problem, me must reorder the number of relays of the local region. As is seen from Fig.5.9, the number of relays of the local region are not in a proper order. The algorithm depicted in Fig. 5.6, reorders the number of relays sequentially

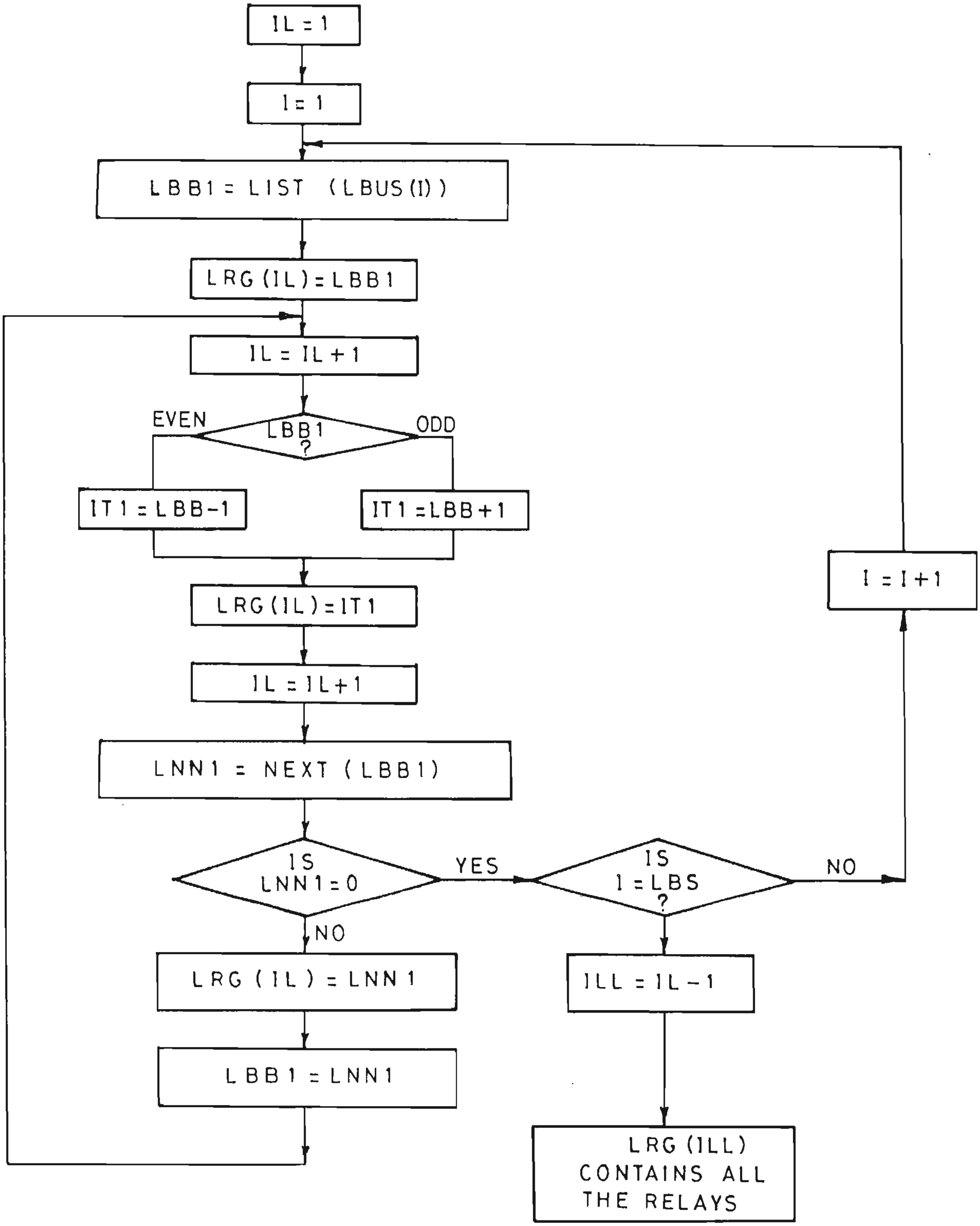


FIG.5·3—DETERMINATION OF THE RELAYS OF THE LOCAL REGION

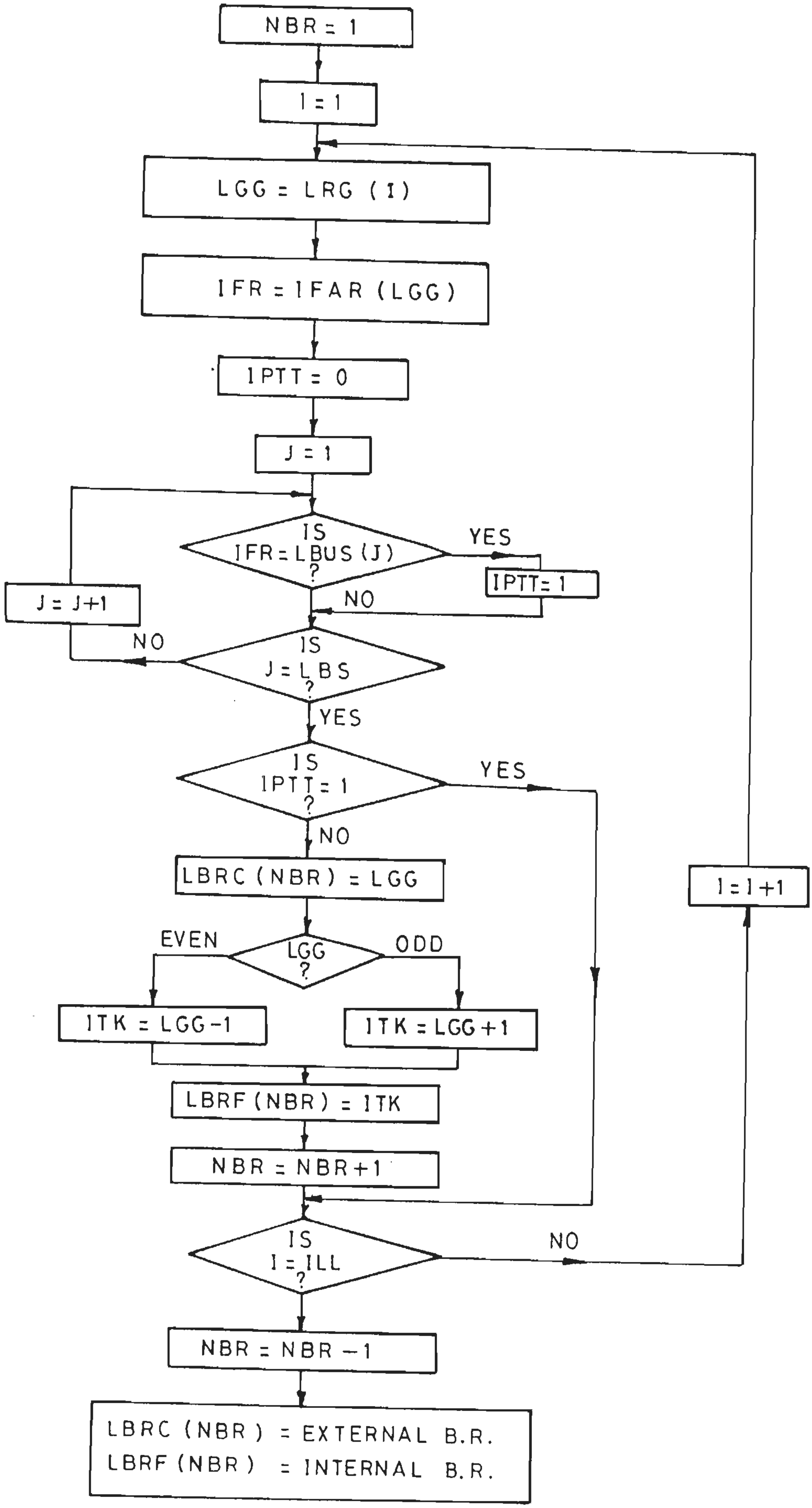


FIG. 5·4—DETERMINATION OF THE EXTERNAL AND INTERNAL BOUNDARY RELAYS

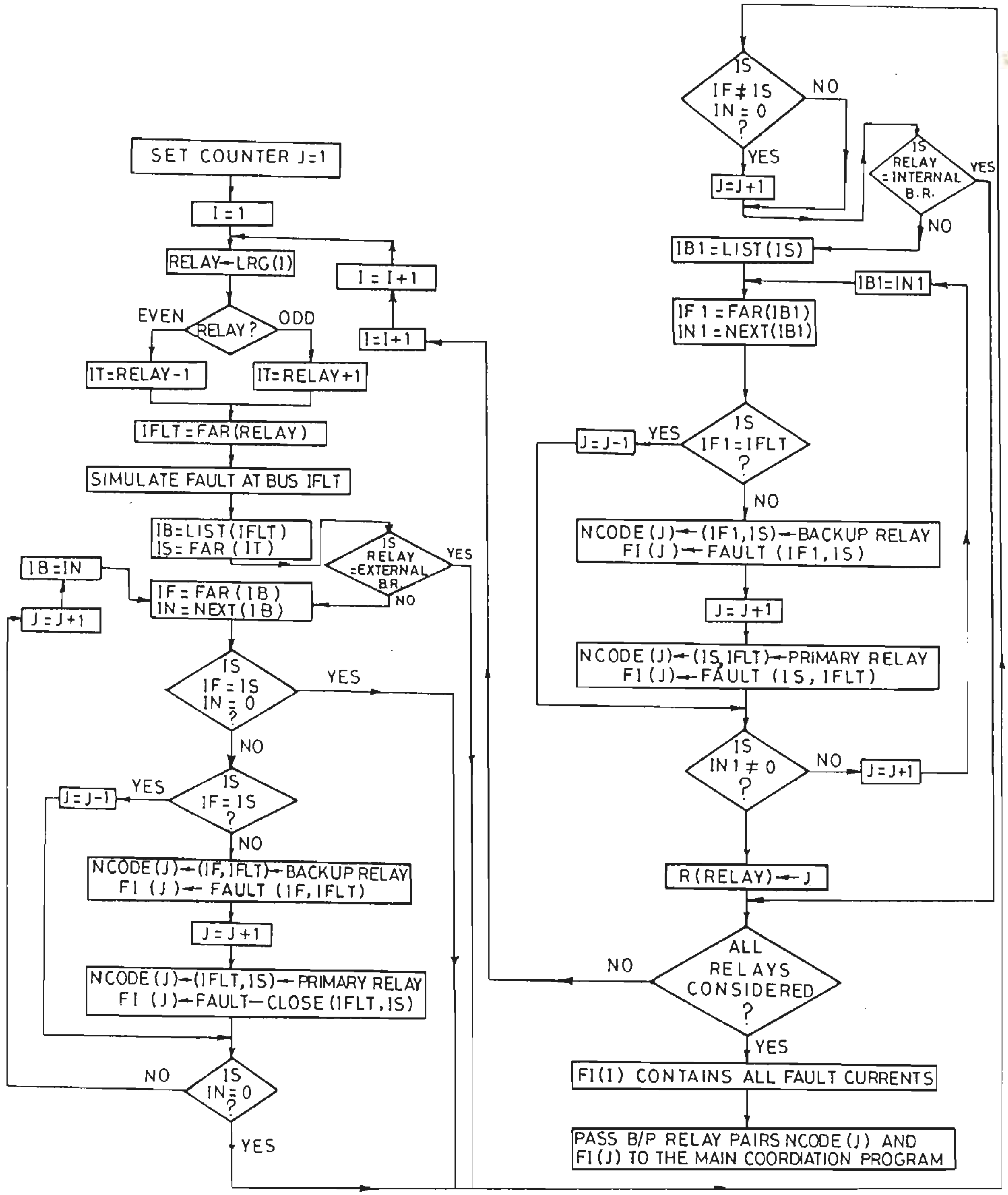


FIG. 5·5—FLOWCHART FOR INTEGRATING FAULT ANALYSIS PROGRAM AND DETERMINING B/P RELAY PAIRS OF THE LOCAL REGION

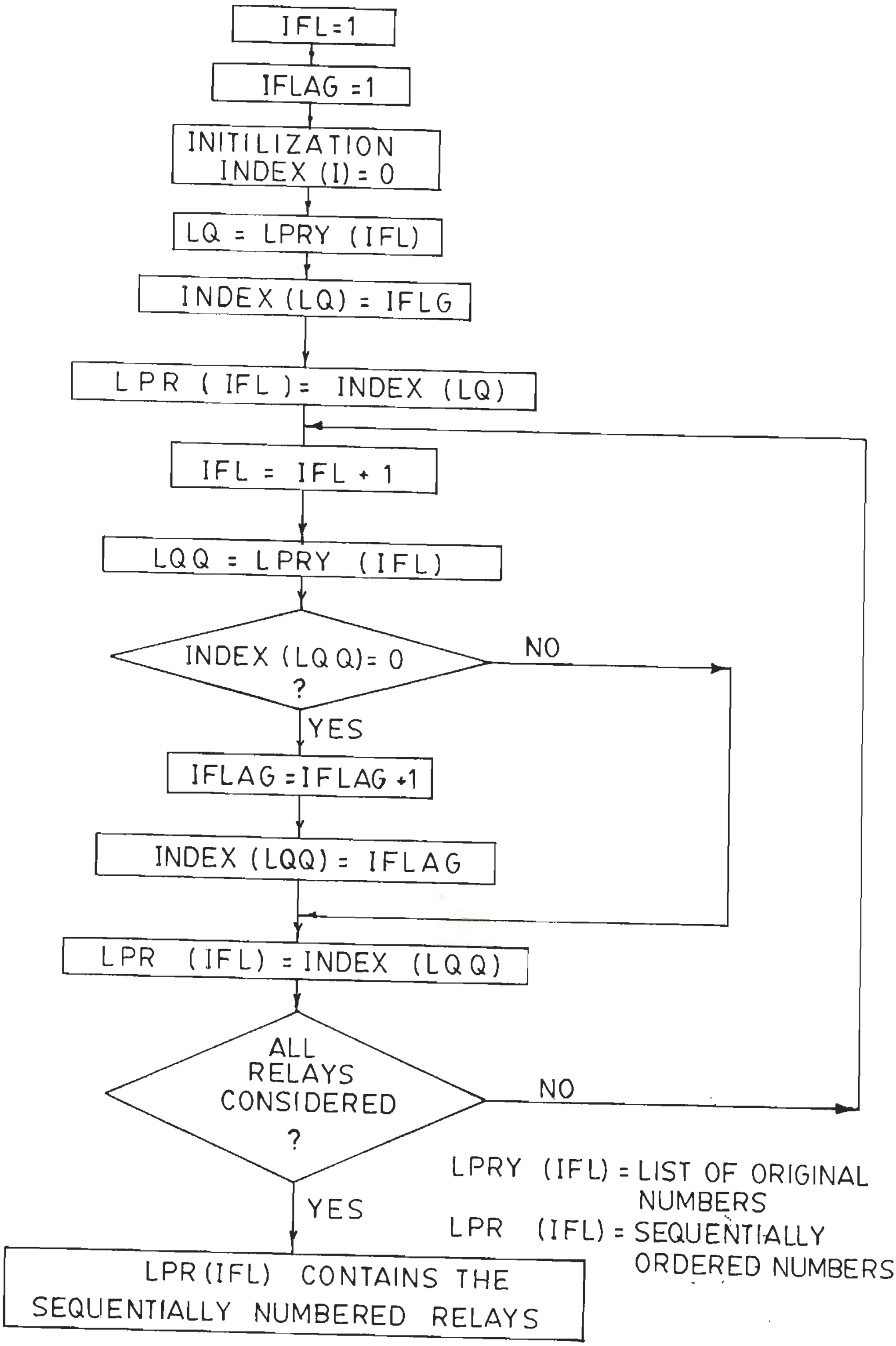


FIG. 5·6 SEQUENTIAL ORDERING OF RELAYS OF THE IDENTIFIED LOCAL REGION so that the solution methods could be applied properly. The original number of each relay of the local region is preserved.

Simplex method of linear programming is employed to determine the TMS of all the relays of the initial local region, keeping the TMS of the internal boundary relays fixed.

The TMS of the external boundary relays is checked. If the TMS of these relays do not change appreciably, the program moves on to calculate I_p for the relays of the local region, otherwise those relays are included into the local region whose settings have changed. Thus the local region is expanded and the expansion occurs in the direction in which the disturbance has travelled, and the procedure is repeated.

5.3.2 SECOND METHOD

In this method the number of disturbed buses are not specified. The pickup current settings (I_p) of all the relays of the complete system after the disturbance is entertained i.e. after the change, structural or operational, has occurred, are determined by the expression (base case) :

$$I_p = x \; I_l \qquad (5.7)$$

where I_p is the load current seen by the relay and x is the load carrying factor. The value of x is dynamically made to vary from 1.25 to 1.50 by the expression :

$$x = X_{max} - \Delta x \qquad (5.8)$$

where $\Delta x = \left[\frac{X_{max} - X_{min}}{I_{max}} \right] I_l$ (5.9)

These calculated pickup current settings are compared with the pickup current setting of the relays of the system before the occurrence of the disturbances. Same base case is considered. Those relays which show significant difference in their I_p values are included in the local region.

The optimal TMS of the relays of the local region are determined, keeping the TMS of the internal boundary relays fixed. There is no need to check the settings of the external boundary relays as the expansion of the local region is not required. After the TMS are calculated, the optimal I_p are calculated by using the Rosenbrock-Hillclimb procedure of the nonlinear programming method for the relays of the local region.

5.4 LOCAL OPTIMAL COORDINATION ALGORITHMS

Based upon the methods used for identifying the local region, two local optimal coordination algorithms are presented in this Chapter :

5.4.1 LOC ALGORITHM-1

The flowchart depicting the salient features of this algorithm is given in Fig.5.7. The steps involved are :

(1) The network topology is stored using the linked-list data structure LINKNET.

(2) Load flow analysis is performed for the complete system after the disturbance, structural or operational, is entertained. This analysis determines the bus voltages and the load currents seen by the relays. Gauss-Seidel method is utilized for the purpose.

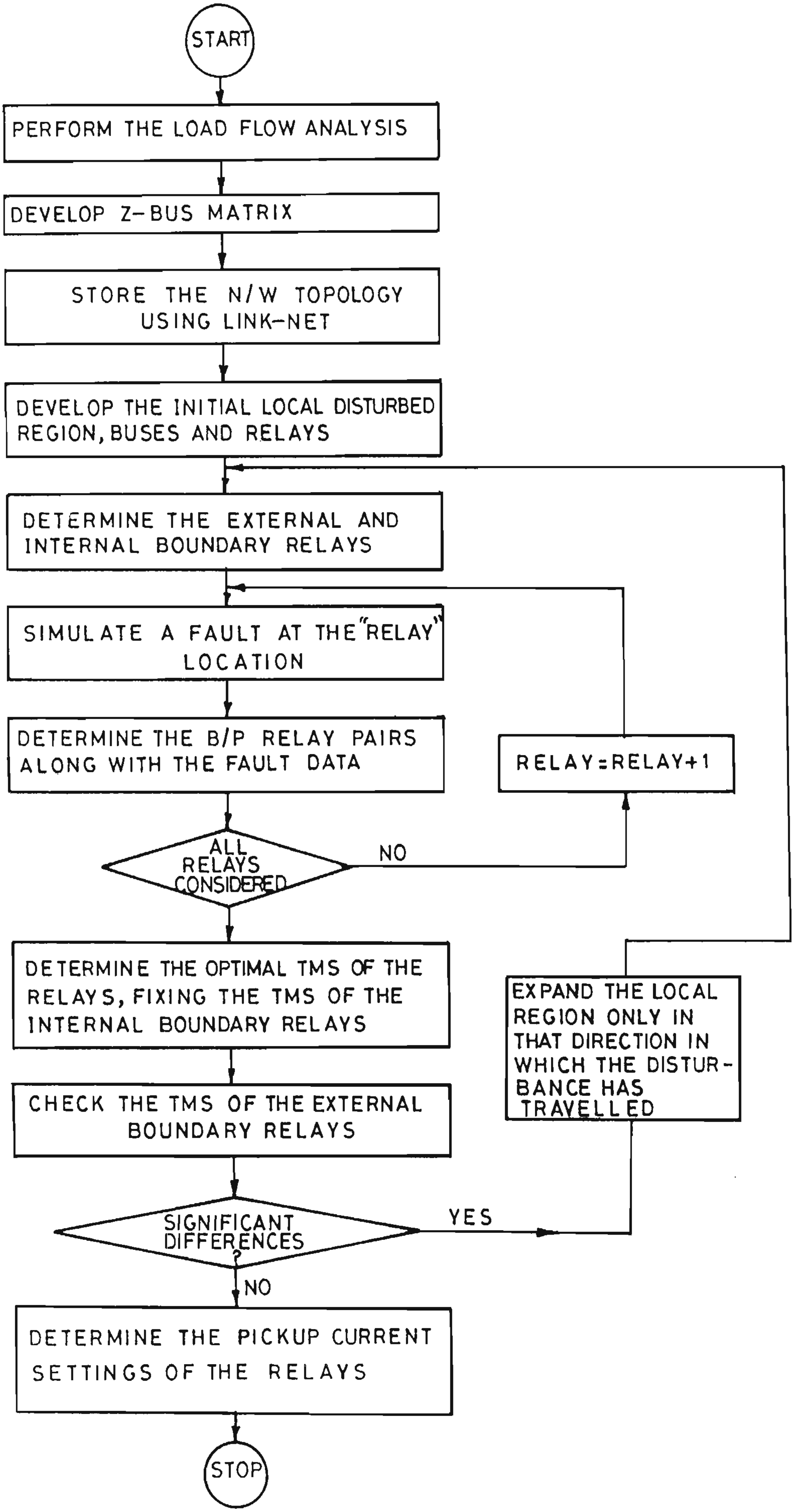


FIG. 5·7 – LOCAL OPTIMAL COORDINATION ALGORITHM – 1

(3) Z-bus matrix is built for the whole power system. It is used for simulating the faults at different relay locations of the identified local region later in the program.

(4) Next step is to develop the initial local disturbed region. This initial region is developed around the specified disturbed buses and is identified by using the algorithm depicted in Fig. 5.2.

(5) The algorithm which is given in Fig. 5.3 is used to find out all the directional overcurrent relays of the local disturbed region.

(6) The external and the internal boundary relays of the local disturbed area are determined by using the algorithm of Fig. 5.4.

(7) Till now, all the relays including the external and the internal boundary relays of the local region have been determined. The relays are not in a serial order. In order to frame a proper coordination problem, the relays are numbered properly in a sequential order. The original numbers of the relays are preserved. The final results are presented using the original number of the relays. The algorithm of Fig 5.6 is utilized for reordering the numbers of relays.

(8) A fault is simulated at every location of a relay in the identified local region (a three-phase dead short circuit for phase relaying and a single-to-ground fault for ground relaying are simulated). Two types of fault currents are considered. One is due to a close-in fault and the other is due to a far-bus fault. These fault currents are discussed fully in *Chapter 2*. No line-out contingencies are assumed. Since two types of fault currents have been considered, therefore two sets of B/P relay

pairs are generated. The consideration of close-in fault gives rise to one set of B/P relay pairs and the consideration of far-bus fault gives rise to another set of B/P relay pairs. The corresponding fault current pairs are also determined. The algorithm of Fig. 5.5 determines these B/P relay pairs and the associated fault current pairs and also integrates the fault analysis algorithm with the main coordination program.

(9) The next step involves the determination of the optimal TMS of the relays of the local region, keeping the TMS of the internal boundary relays fixed. Simplex method of linear programming is employed for the purpose.

(10) The calculated values of TMS of the relays of the local region are compared with previous coordinated values of TMS, which have been stored earlier.

(11) If the differences between the previous and the newly calculated values of TMS of the relays of the local region are significant, the local region is expanded and the expansion occurs in the direction in which the disturbance has travelled. Expansion is fixed by the "Level of remote backup" desired. Generally one level of remote backup is used. The procedure is repeated from step 6.

(12) If the difference is not significant, the algorithm moves on to determine the optimal pickup current settings of the relays of the identified disturbed region. Rosenbrock-Hillclimb method of non-linear programming is used for the purpose.

5.4.2 LOC ALGORITHM-2

This local optimal coordination algorithm uses the second method of local region identification. The flowchart depicting the salient features of the algorithm is given in Fig.5.8. The main steps involved are :

(1) The network topology is stored using LINKNET.

(2) Load flow analysis is performed for the power network after the changed system conditions are taken into account.

(3) Z-bus matrix is built.

(4) Determine I_p ($= xI_1$) for all the relays of the full system after the disturbance is entertained.

(5) Compare these values with the values of I_p of the relays obtained before the disturbance has occurred.

(6) The relays which show a significant change in the value of I_p are included in the local region.

(7) Determine the external and the internal boundary relays of the local region using algorithm as depicted in Fig.5.4.

(8) The numbering of the relays of the local region are changed and the numbers are assigned sequentially. The previous numbers of the relays are preserved.

(9) Faults are simulated at each relay location, and the B/P relay pairs along with the associated fault current pairs are determined for the local region only. The algorithm is depicted in Fig.5.5.

(10) Determine the optimal TMS for the relays of the local region, keeping the TMS of the internal boundary relays fixed.

(11) Determine the optimal I_p for all the relays of the local region.

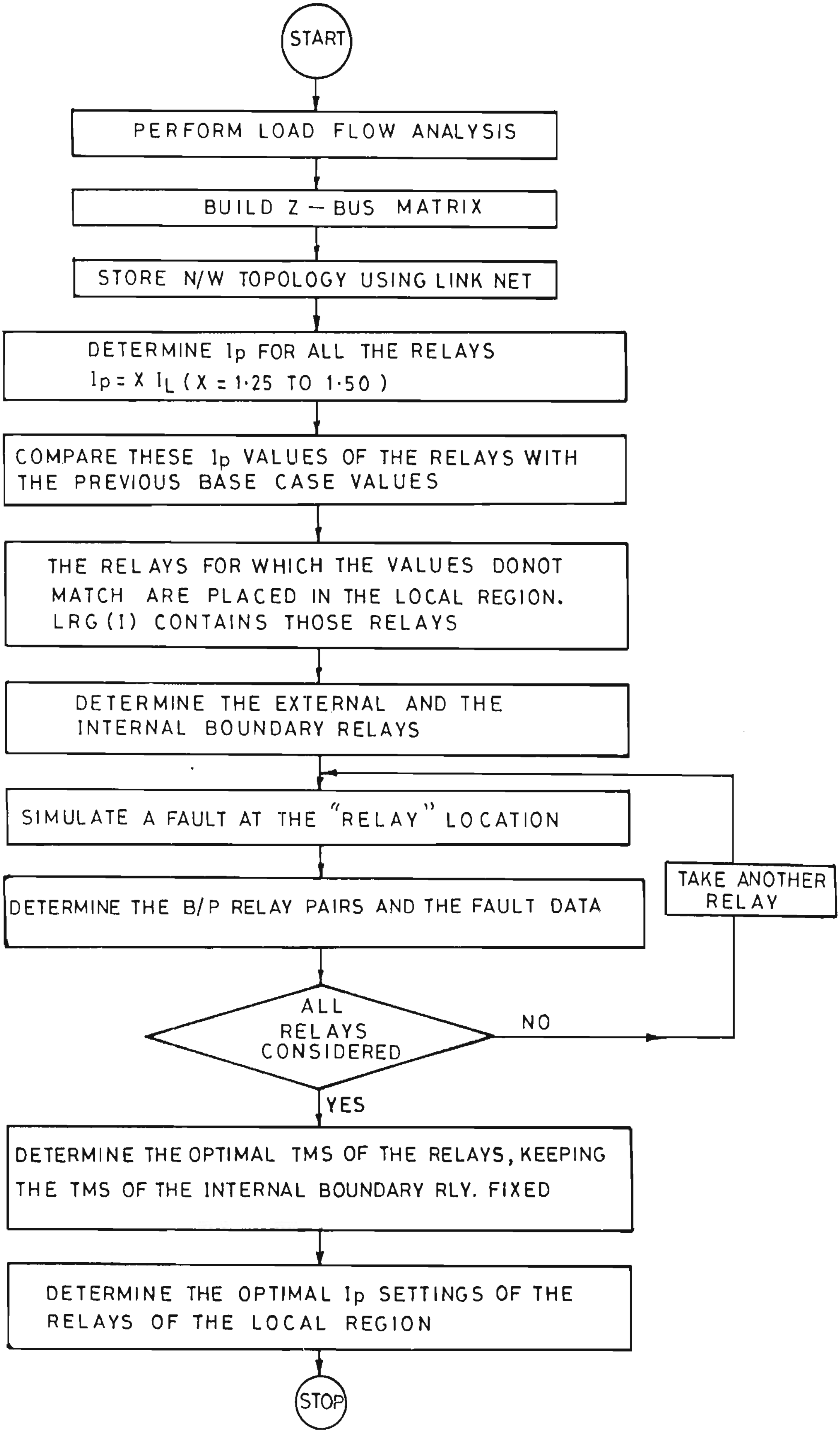


FIG. 5·8—LOCAL OPTIMAL COORDINATION USING ALGORITHM—2

5.5 EXAMPLE AND RESULTS

5.5.1 LOC ALGORITHM - 1

The local optimal coordination algorithm-1 developed is applied to the SPC 26-bus, the IEEE 57-bus, the NWI 64-bus and the IEEE 118-bus power transmission systems.

Example 1

For the SPC 26-bus [Fig.5.9] test power system, line number 13 is removed. It is a structural disturbance. The line number 13 is connected between the buses 24 and 6. Thus the buses 24 and 6 are the input to the program using LOC Algorithm-1. The initial local region determined consists of the buses 24, 6, 26, 7 and the relays in this region are 21, 22, 23, 24, 27, 28, 29, 30, 51, 52, 5, 6, 15, 16, 7, 8, 3 and 4. The internal boundary relays determined are 5, 15, 8, 3, 51 and the external boundary relay are 6, 16, 7, 4, 52. This local region generated 80 B/P relay pairs and 103 constraints and has 18 relays in it. The optimal TMS are calculated for the relays of this local region. These TMS are compared with the previous calculated values. Two cases are studied, when TOLBR (tolerance over TMS of the external boundary relays) is taken as 0.1 and when it is taken as 0.01. For TOLBR = 0.1, no expansion of the local region is observed, but for TOLBR = 0.01, expansion in the direction of bus 1 is observed. Thus the additional relays which are included in the local region are now 57, 58, 41, 42, 47 and 48. The external and the internal boundary relays are now 6, 16, 7, 4, 57, 41, 48 and 5, 15, 8, 3, 58, 42, 47 respectively. This expanded local region has 24 relays and generated 104 B/P relay pairs along with 140 constraints. The optimal TMS for the relays are determined,

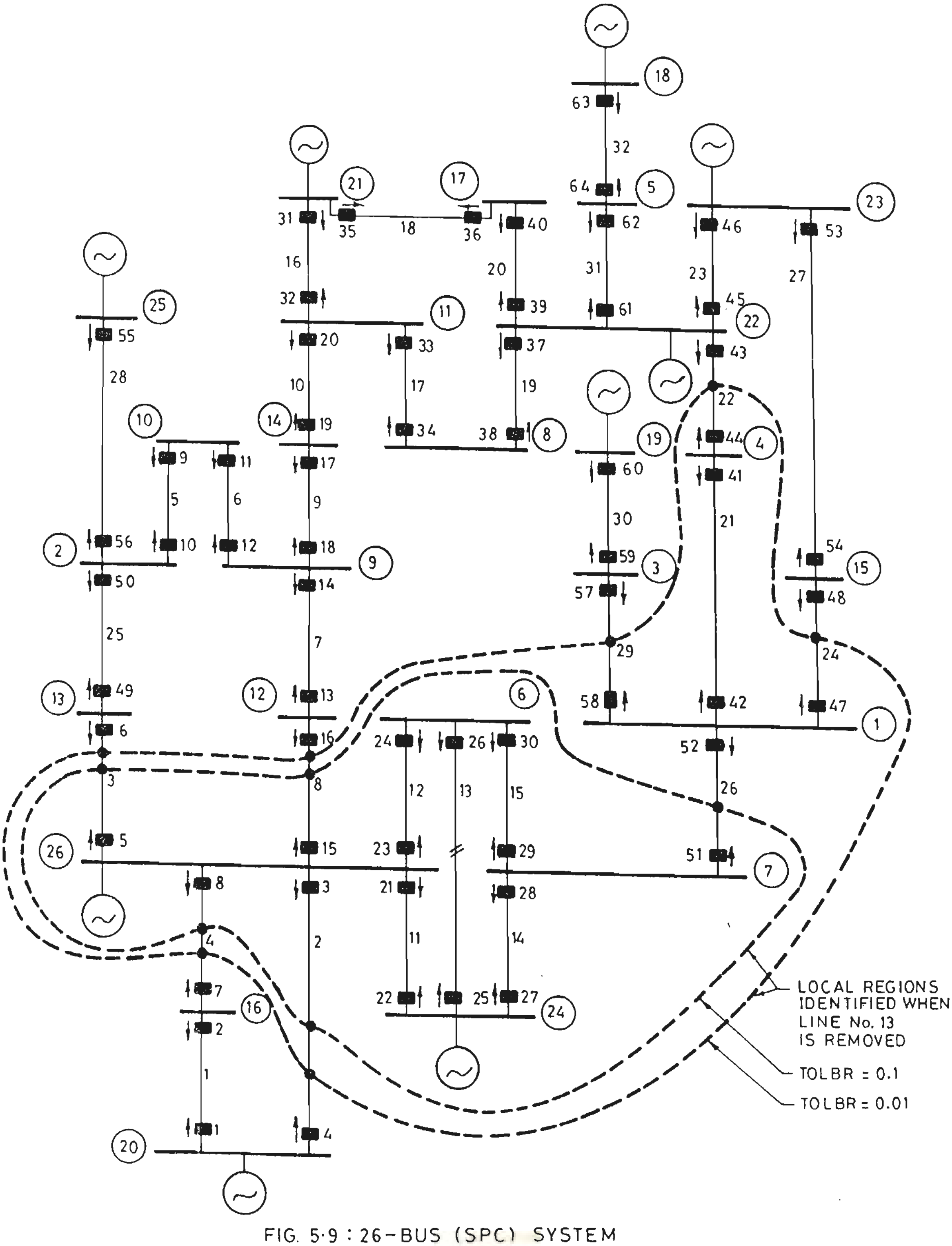


FIG. 5·9 : 26-BUS (SPC) SYSTEM

keeping the TMS of the internal boundary relays fixed. The TMS of the external boundary relays is checked with the previous values. It is observed that the local region gets expanded further in the direction of bus 4. Thus the additional relays to be included in the local region are 43 and 44. This local region generated 108 B/P relay pairs along with 148 constraints and has 26 relays in it. No further expansion occurred after finding out the TMS of the relays of this region and comparing them with the previous calculated values.

The comparison between the execution times of the LOC Algorithm-1 and that of the complete system for TOLBR = 0.1 and TOLBR = 0.01 is depicted in Table 5.1. It is evident from the table that the proposed method is 25.02 times faster when TOLBR = 0.1 and 5.01 times faster when TOLBR = 0.01 and needs considerably less memory as only a small portion of the system is dealt with.

Example 2

Line number 59 is removed from the IEEE 57-bus power transmission system [Fig.5.10]. It creates a structural disturbance. The local regions identified for TOLBR = 0.1 and TOLBR = 0.03 are shown in the figure with the help of dashed lines. For TOLBR = 0.1, there is no expansion in the local region, but for TOLBR = 0.03, the expansion is observed. The expansions occur through the buses 29, 32 in the first pass, 28, 30 in the second pass, 27 in the third pass and 53, 25 in the fourth pass.

The execution times are shown in Table 5.1 for various cases. In case of TOLBR = 0.1, the proposed method is 505.0 times faster and in case of TOLBR = 0.03, the method is 46.0 times faster than the complete system coordination method.

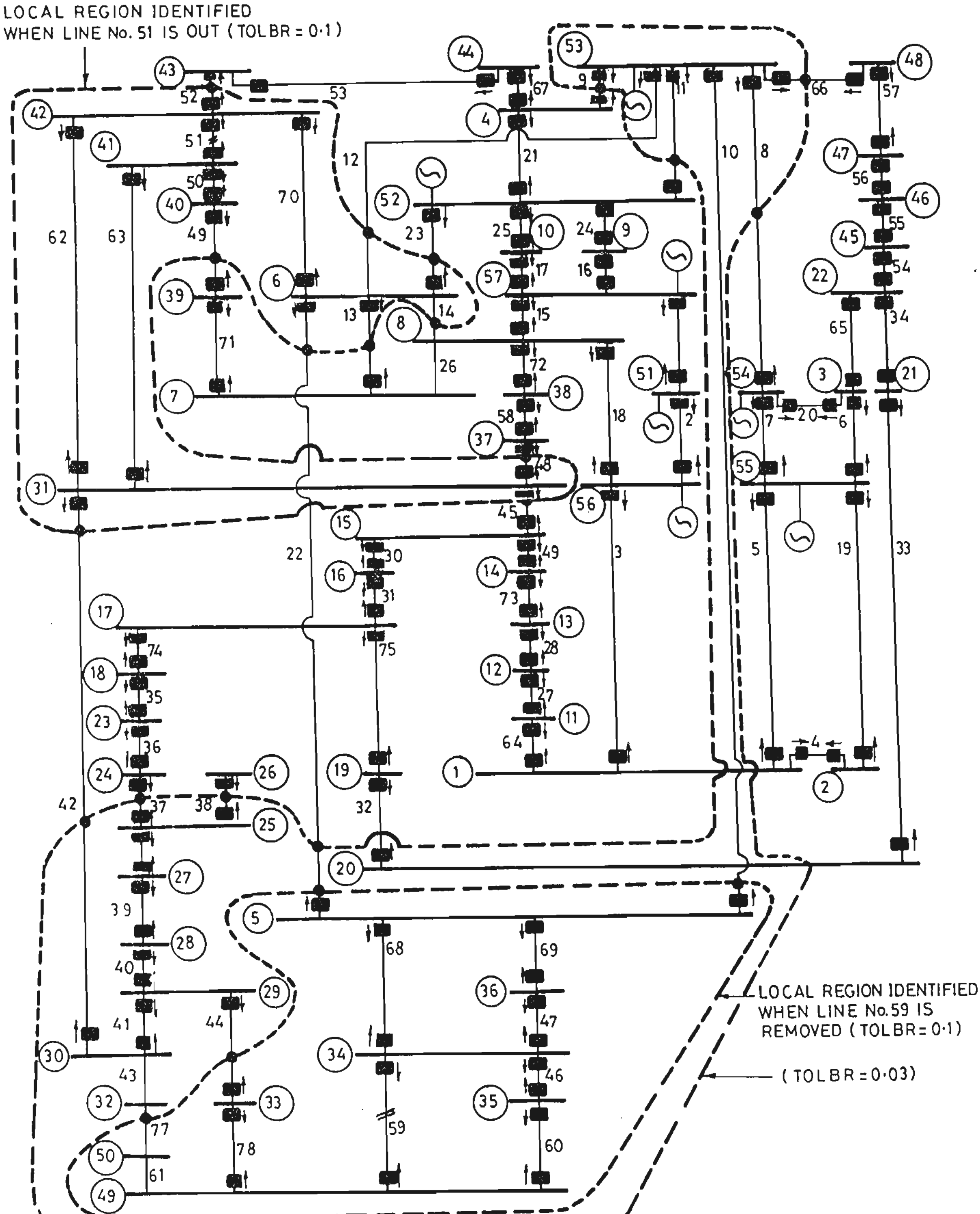


FIG.5.10: 57-BUS IEEE TEST SYSTEM

Line number 51 is also removed. The algorithm responded favourably and recalculated the coordinated settings of the identified local region.

Example 3

The problem of relay coordination of the 64-bus power system of North-Western India [Fig 5.11] is also solved by using the LOC Algorithm-1 under the changed system conditions. Two contingencies are created separately. Line number 12 is removed and the coordination problem is solved only for the identified local region. The expansions of local region occurred through buses 43, 42, 34, 1 in the first pass and through buses 16, 44, 45, 51, 58 in the second pass. For this case TOLBR is taken as 0.1. Another structural disturbance is created when line number 44 is removed from the system. The local region is identified only after one expansion and the expansion occurs through buses 18 and 4. For this case TOLBR is also taken as 0.1.

The execution times are shown in Table 5.1 for both the cases studied.

Example 4

Finally, LOC Algorithm-1 is also applied to solve the coordination problem of the IEEE 118-bus power transmission system [Fig.5.12] under the changed system conditions. Three cases are studied separately. For all the cases studied TOLBR is taken as 0.1. Line numbers 7, 93 and 161 are removed and in each case the coordination problem is solved for the identified local region only. Table 5.1 depicts the execution times for each case studied.

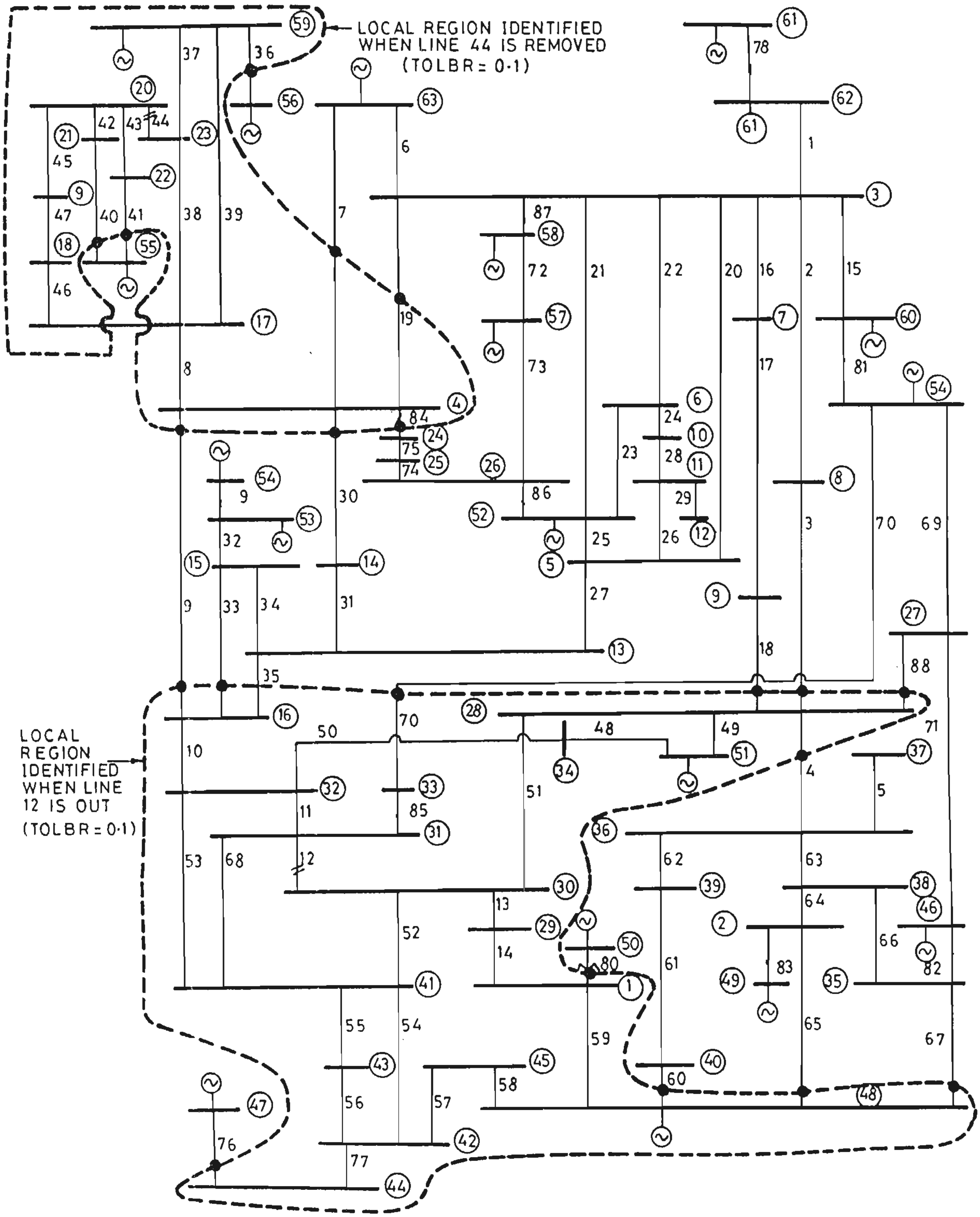


FIGURE 5·11 : 64–BUS NETWORK OF NORTH–WEST POWER SYSTEM OF INDIA

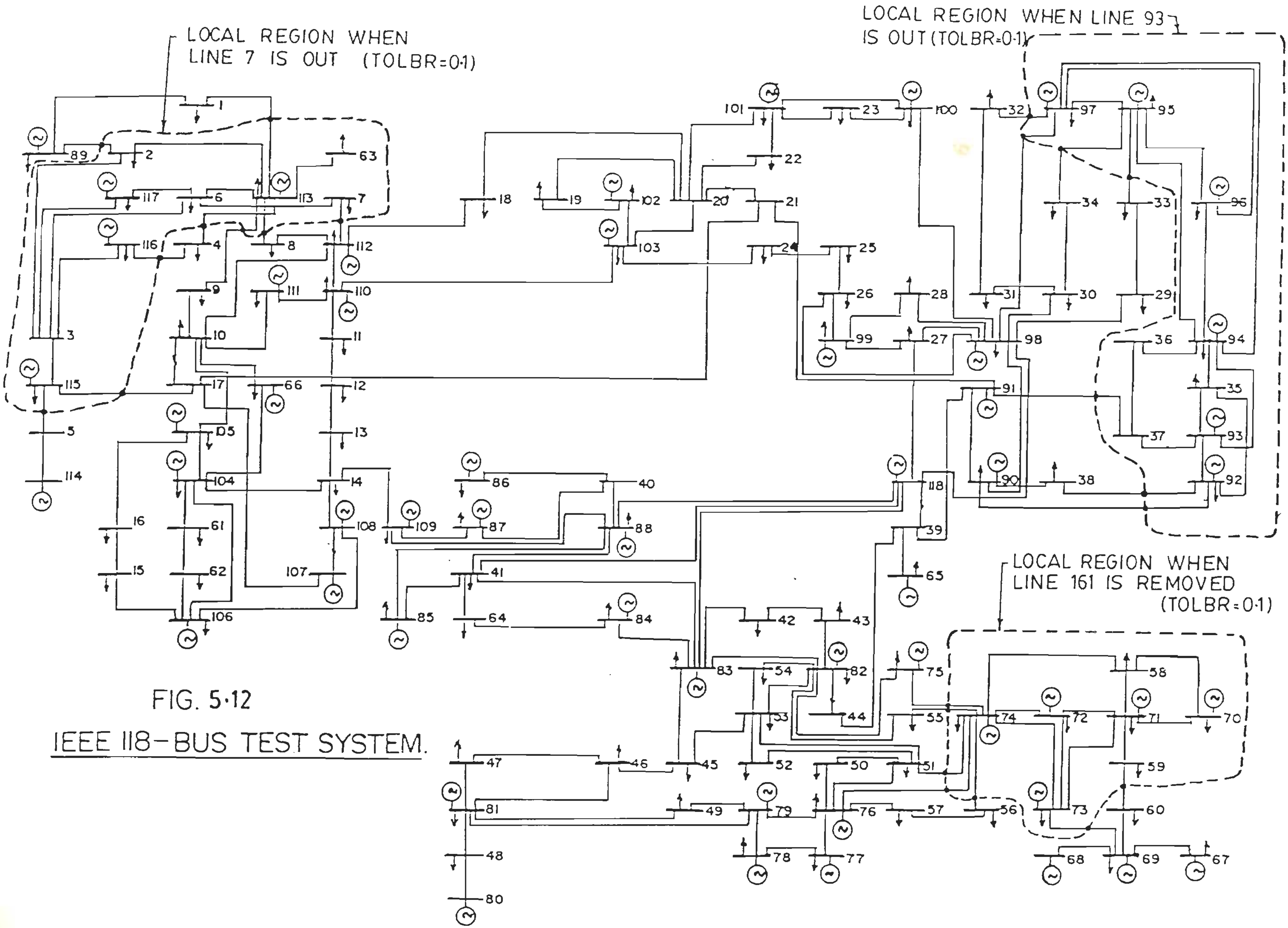


FIG. 5·12

IEEE 118-BUS TEST SYSTEM.

TABLE 5.1 *COMPARISON OF EXECUTION TIMES (LOC ALGORITHM-1)*

Test system	Line out	Complete system coordination Exe. Time (sec.)	Local optimal coordination algorithm-1 TOLBR	EXe.Time (sec.)	Percentage saving in exection time
SPC 26-bus system	13	352.9	0.1	14.1	96.00
	13	352.9	0.01	70.4	80.05
IEEE 57-bus system	59	10101.4	0.1	20.0	99.80
	59	10101.4	0.03	219.6	97.82
	51	10131.3	0.1	65.0	99.35
NWI 64-bus system	12	---	0.1	784.5	---
	44	---	0.1	81.3	---
IEEE 118-bus system	7	---	0.1	301.5	---
	93	---	0.1	263.3	---
	161	---	0.1	190.5	---

5.5.2 LOC ALGORITHM-2

LOC Algorithm-2 is also applied to solve the coordination problem of all the systems under changed system conditions. Only one example is discussed here, that's of IEEE 118-bus power transmission system. The structural disturbances created are the same as are created when LOC Algorithm -1 is used. LOC Algorithm-2 identified slightly different local regions in all the cases. The local regions identified are depicted in Fig.5.13. But the results obtained are almost the same. Table 5.2 gives the TMS of the relays of the local region when line number 7 is removed for the cases when LOC algorithm-1 and LOC Algorithm-2 are used. It is evident from the Table that there is not much variation in the results obtained by the two methods. Table 5.3 gives the execution times for each contingency created.

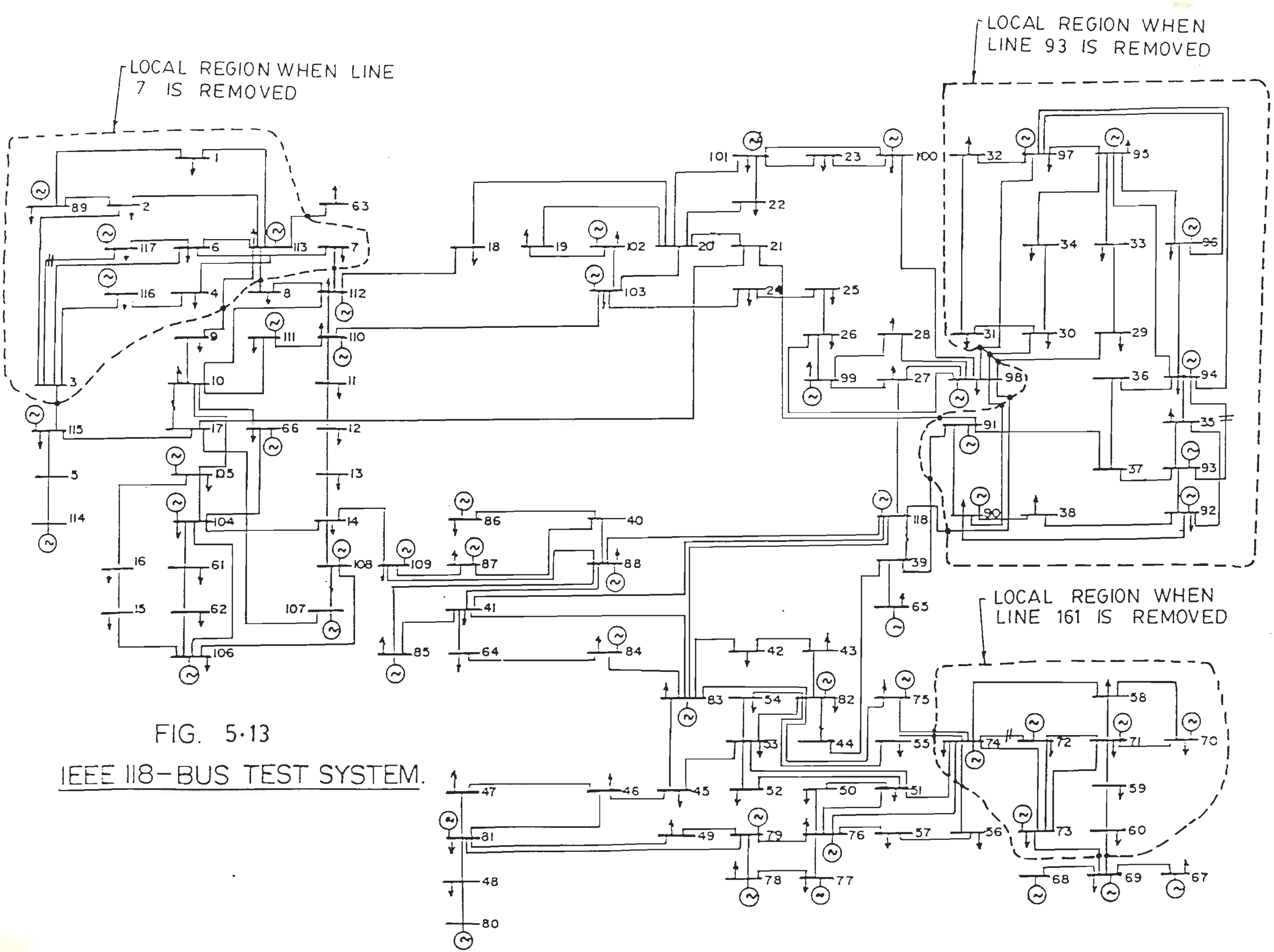


FIG. 5·13

IEEE 118-BUS TEST SYSTEM.

TABLE 5.2 *COMPARISON OF LOC ALGORITHM-1 AND LOC ALGORITHM-2 (FOR CALCULATING TMS OF THE RELAYS)*

Relay	LOC Algorithm-1 TMS	LOC Algorithm-2 TMS
11	0.050	0.050
342	0.284	0.269
341	0.903	0.927
17	0.904	0.924
18	0.456	0.423
15	0.882	0.902
16	0.407	0.425
8	0.781	0.799
7	0.366	0.365
32	0.538	0.538
30	0.477	0.499
20	0.690	0.633
9	0.661	0.659
10	0.741	0.776
3	0.466	0.465
38	0.838	0.837
36	0.050	0.050
34	0.780	0.781
21	0.741	0.776
40	0.645	0.645
19	0.949	0.969
12	0.378	0.393
4	0.873	0.890
39	0.573	0.592
37	0.717	0.751
33	0.414	0.433
22	0.642	0.652
6	0.770	0.806

TABLE 5.3 *COMPARISON OF EXECUTION TIMES FOR LOC ALGORITHM-1 AND LOC ALGORITHM-2*

Test system	Line out	LOC Algorithm-1 Exe. Time (sec.)	LOC Algorithm-2 Exec. Time (sec.)
IEEE 118-bus system	7	301.5	174.4
	93	263.3	702.6
	161	190.5	207.1

5.6 LOCAL OPTIMAL COORDINATION BASED ADAPTIVE COORDINATION

The developed local optimal coordination algorithms are better suited for on-line or adaptive implementation of coordination philosophy for directional overcurrent relays of large interconnected realistic power transmission systems. The adaptive coordination demands prompt response to any change which may occur in the power system. As has been clearly demonstrated in the previous sections, the local optimal coordination algorithms consume only a fraction of the execution time of the complete system optimal coordination method. The LOC methods developed do not use elaborate and complex topological analysis programs, do not require a huge data base and have fully integrated software packages. The data generation, updating, retrieval and use are all combined in the same program.

In this section, the concept of adaptive local optimal coordination is presented. A method developed is reported and discussed which coordinates the settings of the relays of the identified local region only, in an adaptive manner. The vital components of the software are also identified and presented so that the adaptive coordination algorithms become self-contained and self-consistent.

5.6.1 CONCEPT OF ADAPTIVE LOCAL OPTIMAL COORDINATION

The adaptive relay coordination is defined as a coordination philosophy, implemented with the help of digital relays, which automatically alters or changes the operating parameters of the relays in response to operational or structural changes of the power system to maintain coordination between them. This definition, which has already been presented in *Chapter 3*, is applicable to the complete systems. For the local area, the adaptive coordination is defined as the coordination philosophy,implemented with the help of digital relays, which identifies a local disturbed region around the place of disturbance and alters or changes the operating parameters of the relays of the local region only in order to maintain the overall coordination of the relays of the whole system. The identification of the local region is a vital part of the adaptive local coordination philosophy. Thus this coordination philosophy deals with the relays of a small portion only, under the changed system conditions. It assumed in this coordination philosophy that the system was fully coordinated before the disturbance occurred.

5.7 ADAPTIVE LOCAL OPTIMAL COORDINATION ALGORITHM (ALOCA)

To develop the adaptive local optimal coordination algorithm, the LOC algorithm-1 is used. The main steps involved are [Fig 5.14] :

1. To keep a track of the structural changes in the system, the topology processor is used for the purpose [59]. The topology processor tracks the network topology over time. It detects which line has been removed from or added to the system.The circuit breaker status information is the main input to this subroutine.

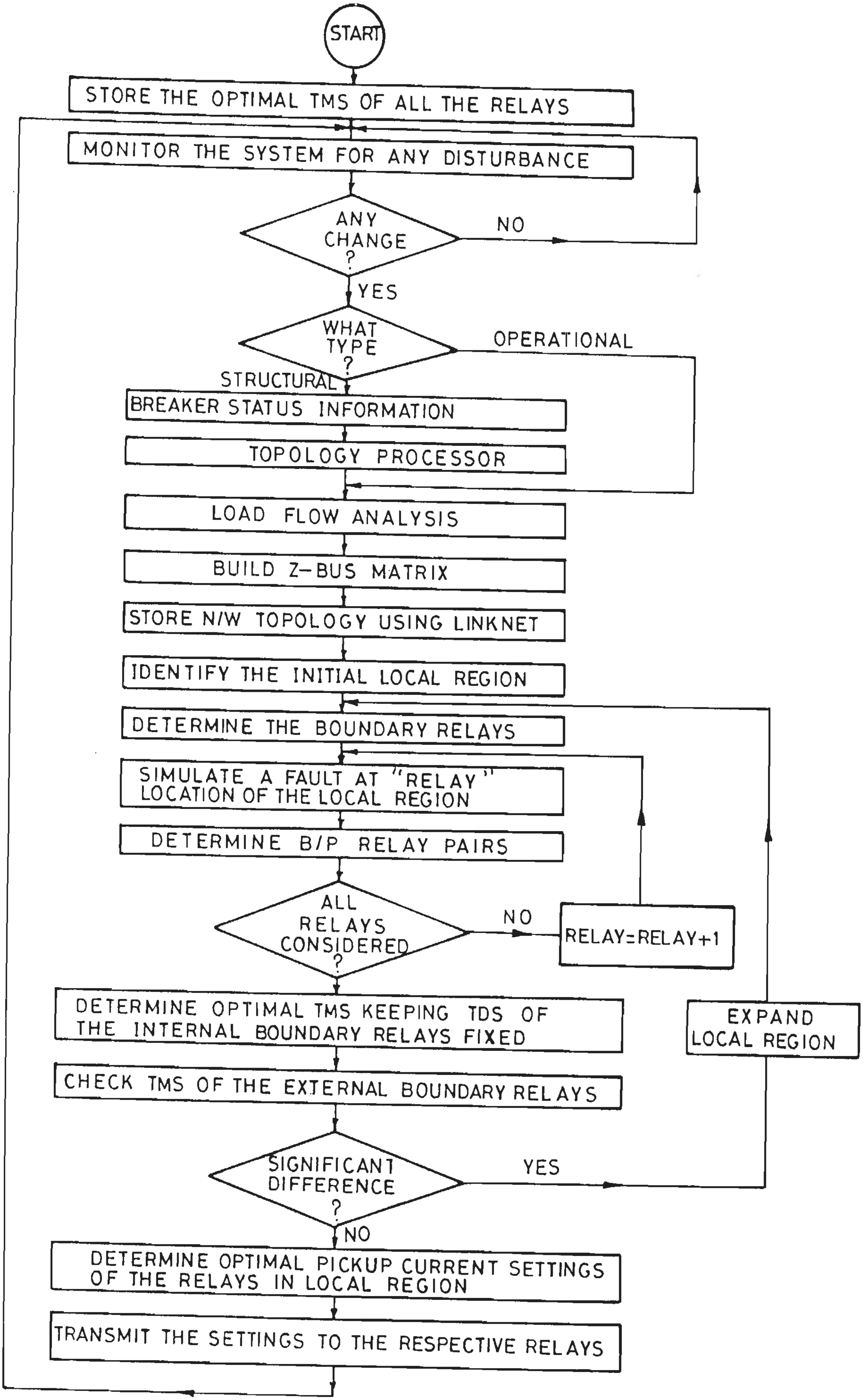


FIG. 5·14 — ADATIVE LOCAL OPTIMAL COORDINATION ALGORITHM

The topology processor feeds the latest power network information to the load flow study and the fault study programs.

2. The load flow study is performed for the whole system.
3. Z-bus matrix is built for the whole system.
4. The latest topology information of the network is stored using the LINKNET for easy network scanning operations.
5. The initial local region is developed around the place of disturbance.
6. The relay of the local region are determined along with the external and the internal boundary relays.
7. A fault (three phase or single-line-to-ground fault, as the case may be) is simulated at every relay location of the local area.
8. B/P relay pairs along with the associated fault currents are determined for the local region.
9. TMS of the relays of the local region are determined , keeping the TMS of the internal boundary relays fixed.
10. If the TMS of the external boundary relays do not change appreciably from the values of the previous coordinated results, the optimal I_p are calculated. If the change is appreciable, those relays are included in the local region which exhibit this difference. Hence the local region is expanded and the algorithm shifts the control to step no.6.
11. The situation of the power system is continuously monitored for a change, operational or structural. The calculated optimal settings are transmitted to the respective relays of the local region.

The newly developed adaptive local optimal coordination algorithm is applied to solve the coordination problem of the SPC 26-bus, the IEEE 57-bus, the NWI 64-bus and the IEEE 118-bus power transmission systems. Different system contingencies were created and the algorithm responded favourably.

5.8 CONCLUSIONS

Two efficient algorithms have been presented in this Chapter for the optimal coordination of directional overcurrent relays of large electrical power systems. These algorithms automatically identify the local region which is affected by the system change and carries out the coordination process to ensure correct relay operation under the new system conditions. The usefulness of the algorithms are demonstrated through the system studies which are carried out on standard test power transmission systems. The algorithms are very fast and their memory requirements are also less in comparison to the full system optimal coordination algorithm.

The adaptive local coordination algorithm is also developed around the LOC algorithm-1. It is shown that the local coordination procedure is better suited for the on-line or adaptive coordination of the relays under the changed system conditions.

CHAPTER 6

FORMULATION OF COORDINATION PROBLEM AS A CONTROL SYSTEMS ENGINEERING PROBLEM

6.1 INTRODUCTION

During the course of the present research on adaptive protection, it has been realized that the concepts of protection and control could be fused together to develop an integrated protection philosophy. The induction of the classical control system concepts would effectively enhance the power system protection and thus the integrity and the security could be improved.

Hence some rethinking has been done in this Chapter. It is made clear that the system coordination is a system-wide phenomenon and the classical system concepts are applied to suggest a line of attack for its solution.

Relay coordination problem is formulated as an adaptive control systems engineering problem. It is demonstrated that this is a closed-loop non-linear, multidimensional control system with variable parameters and intermittent control. Based upon the new formulation of the coordination problem, the concept of adaptive relay coordination control system (ARCCS) is presented in this Chapter. An adaptive relay coordination controller (ARCC), which is a vital component of ARCCS, is presented and its structure is given.

6.2 SYSTEM CONCEPTS IN RELAY COORDINATION

Directional overcurrent relays are strategically placed throughout a power system. These relays protect the system whenever a fault or an abnormal condition occurs. Since there are many interconnections in a realistic power system, there are many backup/primary relationships between its relays. The multiplicity of the relationships depend upon the network topology and the coordination philosophy adopted. A relay gives primary protection to its immediate zone of protection which is known as the primary zone of protection and the same relay has to operate as a backup for faults on the neighbouring lines. Extending the concept of backup protection will involve all the relays in intricate and complex relationships. Whenever the relays are set, all these relationships are to be satisfied. Therefore,we can say that the primary protection is a local problem and the relay coordination is a system problem. The use of system concepts in relay coordination will help us to understand the solution strategy in a better way. The first and the most important advantage is that it will help us in tackling the coordination problem in an analytical way.

6.3 RELAY COORDINATION - AN ADAPTIVE CONTROL SYSTEM PROBLEM

As has been mentioned in the previous section, the relay coordination is a system condition and must be accomplished on a system-wide basis. The relay coordination must have a system-wide, systematic and analytic solution.

It is proposed to define the system-wide coordination problem as the relay coordination control system (RCCS) problem. Fig 6.1 depicts the essential parts of this automatic control system composed of a relay coordination controller and the power transmission system as the controlled system. This is a closed-loop, non-linear, multidimensional control system with variable parameters and intermittent control. Coordination parameters are a set of parameters which determine the coordination of the relays. These parameters include the coordination time interval, the setting ranges of each relay, the maximum/minimum time of the relays. The control signals operate on tripping or closing the breaker of the lines. State outputs are current/voltage signals from the system. The perturbations are input to the system which expresses the fault states of the system. The relay coordination controller determines the new relay settings whenever the system undergoes a change (structural or operational).

The perturbations are quite random in nature. The relay settings are determined by considering a particular set of perturbations (i.e. faults) and these fault levels are considered in advance. The variation of the fault levels caused by structural or operational change of the power system are unpredictable interference in the operation of the coordination controller. Such interference sometimes makes the states of the protected power system vary so widely that it is difficult to treat them only by the main loop of the control system. Therefore, it is reasonable to make some control rules of coordination automatically adaptable to the changes in the system states caused by the interference. Some adaptive loops may be added to the control system shown in Fig 6.1. The result is the Adaptive Relay Coordination Control System (ARCCS) as depicted in Fig 6.2. In this control system, the output states of the power system are continuously monitored for any significant changes. The changes are caused by the perturbations

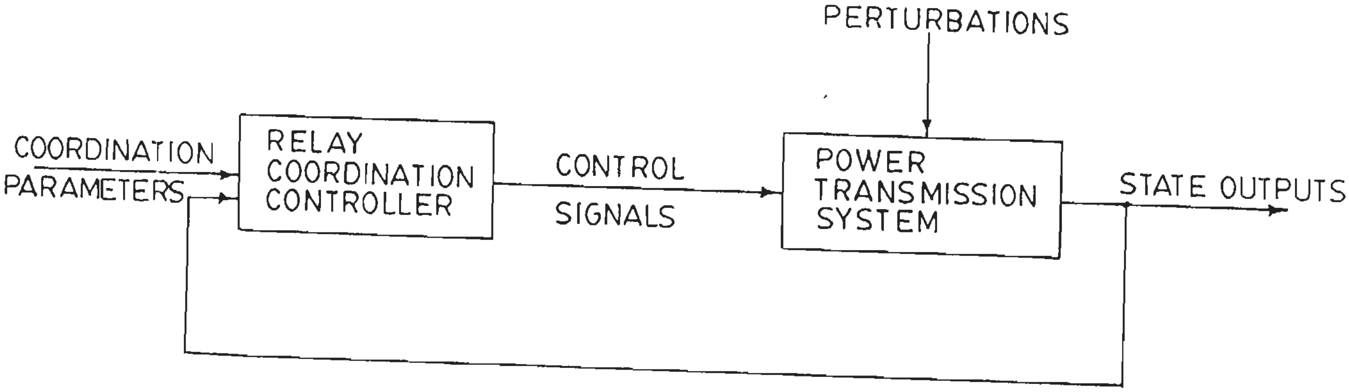


FIG. 6·1 RELAY COORDINATION CONTROL SYSTEM (RCCS)

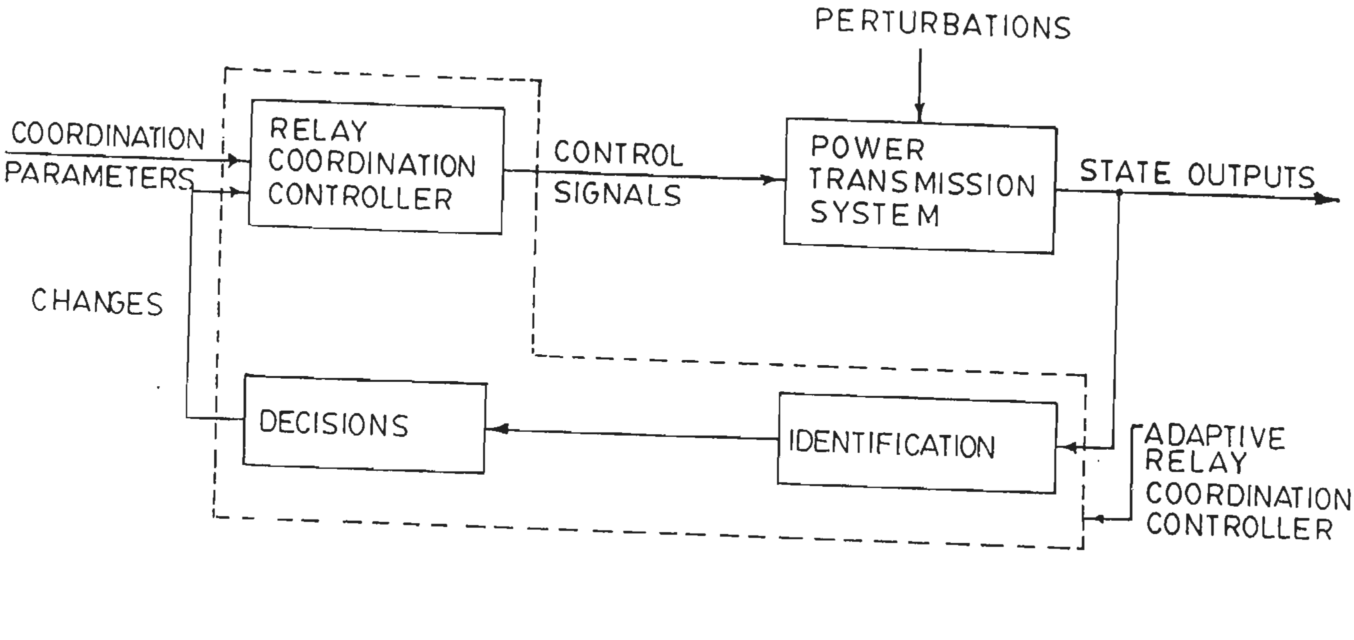


FIG. 6·2 ADAPTIVE RELAY COORDINATION CONTROL SYSTEM (ARCCS) which are introduced into the power system which is to be protected. The adaptive relay coordination controller, which is a vital part of the control system, senses any change (structural or operational) in the system to be protected and invokes the necessary elements of the coordination program and finds out the settings in an on-line manner. The settings obtained are transmitted to the respective relays.

6.4 ADAPTIVE RELAY COORDINATION CONTROLLER

The adaptive relay coordination controller consists of three main blocks :

(a) Identification Block

(b) Decision Block

(c) Relay Coordination Controller Block

6.4.1 IDENTIFICATION BLOCK

The power transmission system is continuously monitored for any changes (operational or structural) by the identification block. It is the identification block which recognizes or identifies the new system states. The previous states are always stored in it. If there is a structural change, the new Y-bus matrix of the system is developed by this block. The Y-bus matrix is developed by the program segment known as the topology processor. This processor tracks the topology of the network over time. The Y-bus is used for the load flow analysis. Topology processor also develops the new Z-bus matrix. It is used for performing the fault analysis of the system.

The identification block also determines the new B/P relationships of all the relays in the interconnected power system. The constraint list is also generated by the same block. The constraints are the coordination criteria on which the relay coordination philosophy is based.

6.4.2 DECISION BLOCK

The decision block is a very important feature of the adaptive loop added to the control system. All the vital decisions are taken by it. Its role is that of a protection engineer. The main decision taken by this block is whether the relay coordination controller should be made active or not. For example, if the coordination criterion is violated for any B/P relay pair (*Chapter 3*), then the new relay settings are calculated. If the coordination criterion is not violated i.e. the coordination margin is within limits then there is no need to invoke the coordination controller. The coordination criterion for each B/P relay pair is determined by this block. The error signal which will invoke the relay coordination controller is also generated by the decision block.

6.4.3 RELAY COORDINATION CONTROLLER BLOCK

This is the heart of the adaptive relay coordination control system. Once a positive decision is taken by the decision block, this controller starts functioning. Actually this controller implements the relay coordination philosophy. New settings are calculated and transmitted to the respective relays. The coordination parameters are very important input parameters. They modify the coordination process and influence the results obtained.

6.5 STRUCTURE OF RELAY COORDINATION CONTROLLER

The relay coordination controller implements the relay coordination philosophy. Its function is to determine the new coordinated relay settings. We could use the full-system optimal coordination philosophy or the local optimal coordination philosophy. It is appropriate and logical to design the relay coordination controllers around the local optimal coordination strategy. The coordination process would remain confined to a particular area and the response of the controller would be faster. We suggest a change in the local optimal coordination which has been presented in *Chapter 5.* We need not to determine the optimal values of the pickup current settings of the relays of the local region. The pickup current settings are made to vary dynamically as the load current varies. We can forego this sophistication in our coordination strategy for the sake of quick response on the the part of relay coordination controller. Its effect has been studied and there is little difference between the initial selected values and the optimal values of the pickup current settings. The only effect would be that the sensitivity of the relays would slightly decrease. The main steps of the algorithm which is now implemented by the coordination controller is given below :

1. Determine the pickup current settings of all the relays of the local region. The pickup current settings are dynamically varied as the load current seen by the relays vary.

$$I_p = x \cdot I_l \tag{6.1}$$

The expression for x is given in *Chapter 3.*

2. Solve the linear programming problem :

$$\text{Min} \sum_{i=1}^{N_R} T_{Pi} \tag{6.2}$$

Subject to

$$T_{backup} - T_{primary} \geq CTI \qquad (6.3)$$

$$TMS_i^{min} \leq TMS_i \leq TMS_i^{max} \qquad (6.4)$$

$$TMS_j = TMS_{(IBR)_j} \qquad (6.5)$$

$$T_i^{min} \leq T_i \leq T_i^{max} \qquad (6.6)$$

The problem is solved only for the relays of the local region.

The coordination parameters, which are inputs to the controller, are CTI, TMS_i^{min}, TMS_i^{max} , T_i^{min} and T_i^{max}. These factors control the coordination results. The identification of the local region is done by the identification block. The constraint list is generated by the decision block. Thus the structure of the coordination controller becomes very simple and straight forward.

6.6 CONCLUSIONS

Relay coordination is a system-wide phenomenon and needs an analytical tool for its solution. Keeping in mind the system nature of the relay coordination, it has been formulated as an adaptive relay coordination control system problem. The necessary elements of the control system have been identified. The structure of the relay coordination controller has been given.

CONCLUSIONS AND SCOPE FOR FUTURE WORK

7.1 CONCLUSIONS

The aim of this investigation has been to develop concepts, algorithms and methods for adaptive coordination of directional overcurrent relays. The details of the developed concepts, algorithms and the software implementation for the adaptive coordination have been presented in this dissertation and have also been published during the course of this work [40 - 50]. In this Chapter, some concluding remarks and suggestions for future work are provided.

The parameter optimization method has been studied in detail for solving the relay coordination problem of interconnected power systems. During the investigation it was noted that there is no need to determine the break point set of the relays of the system if the coordination problem is solved by using the optimization methods. This realization has eliminated the use of elaborate and complex topological analysis programs and has simplified the coordination philosophy a great deal.

Since the topological analysis programs have been eliminated , we have developed a simple but efficient method to determine the B/P relay pairs for all the faults simulated in the power network. This method exploits the network scanning ability of the LINKNET.

Two integrated software packages OPCORD and OPCON have been developed for the coordination of directional overcurrent relays of interconnected power systems. The OPCORD package uses the Simplex method for determining the optimal values of TMS and the OPCON package uses the Charalambous least pth algorithm for the determination of the optimal values of TMS. The OPCON package is faster than the OPCORD package. It has been observed that OPCON is 3.14, 3.00 and 4.30 times faster than OPCORD for the IEEE 14-bus, the SPC 26-bus and the IEEE 57-bus power systems respectively.

Different software packages like load flow analysis, fault analysis, determination of the B/P relay pairs and the main coordination program have been integrated. The integration of these software packages have been made possible by the LINKNET subroutine.

The relay coordination software was developed keeping in view the adaptive coordination of the relays of large interconnected power systems. The relay coordination procedure generates huge data and thus data management packages are needed. These data management packages like RIM cannot be used for adaptive coordination . Thus we have developed an efficient method which generates, stores, retrieves and uses the data as per the requirements of the coordination. In this method no DBMS packages are needed. Even a data base itself is not required. Data generation , updating, retrieval and use are all combined in the same program. This procedure makes the coordination software a self-contained package.

The interactive versions of OPCORD and OPCON programs have also been developed for off-line use. One important advantage of these packages is that they inform the user about the possible miscoordination of particular B/P relay pairs. The miscoordination is anticipated even before the relay coordination solution is attempted.

A valuable addition to the directional overcurrent coordination process is the performance review capability. This review process can be used to check the performance of the existing set of relay settings or to compare alternate settings.

The problem of sympathy trips of relays has been studied in detail. The sympathy trips have been classified into different categories. The classification is based on the causes which produce the tendency in the relays to trip for a fault for which they are not supposed to trip. It has been established that the use of adaptive coordination eliminates the tendency of some of the relays to trip in sympathy for faults.

The concept of on-line or adaptive coordination of directional overcurrent relays has been presented. A method has been developed and successfully tested for the coordination of relays in an adaptive manner. The algorithm continuously monitors the state of the power system . If a disturbance is detected, the algorithm is invoked and recalculates the coordinated relay settings. The recalculations are started on the basis of coordination criterion. If the coordination criterion is violated for any B/P relay pair, the adaptive algorithm is invoked. For small changes in line currents, the algorithm is not invoked. The algorithm absorbs the small disturbances or small excursions in line currents.

To make the response of the relays more sensitive, it has been suggested to vary the pickup current setting of the relays according to the changes in currents seen by the relays. Thus an expression has been developed which allows dynamic variation in I_p according to the changes in current.

It has been established during the investigation that the relay coordination procedure need not be an iterative procedure. There is no need to iteratively solve the coordination problem for I_p and TMS. The subsequent iterations do not improve the values of I_p and TMS appreciably. This makes the coordination procedure faster as only one iteration is required for the complete solution of the coordination problem.

The decomposition method has been presented, which decomposes the large size power network into number of blocks. A block or group of blocks may represent a zone/area and constraints associated with a particular area can easily be included. The blocks with boundary relays are solved in a sequence iteratively for the coordinated relay settings using optimization methods.

The suggested decomposition method requires memory to accommodate the largest sized block data plus the boundary data table. Coordination matrix is not required, since the TMS of the boundary relays are updated after solving each block. Therefore a considerable saving in memory and CPU time has been achieved. It has been observed that the saving in CPU time and memory increases with the increase in the size of the network. Hence this method is a suitable method for solving the relay coordination problems of large size networks.

The developed decomposition method has been applied to a number of standard test power transmission systems such as the SPC 26-bus, the IEEE 57-bus, the NWI 64-bus and the IEEE 118-bus systems. All case gave good results.

An adaptive coordination scheme has been developed around the decomposition method .Such a scheme is good for distributed computing.

A new concept of local optimal coordination has been developed and presented in this dissertation. Two local optimal coordination algorithms which will efficiently compute the relay settings for a part of a large system in response to changes in system conditions in that part have been developed. The local optimal coordination procedure automatically identifies the local disturbed region which is affected by the system change and carries out the coordination process to ensure correct relay operation under the new system conditions. These algorithms have been successfully impelemented and tested on standard power transmission systems. The test results have been verified to agree with those obtained when the modified system is coordinated as a single entity using the full system method. A significant advantage of local coordination approach is the reduction in computation time required when compared to the full system method. For example, in case of IEEE 57-bus power system the local optimal coordination algorithm proved to be 505 times faster than the full system optimal coordination algorithm, when line number 59 is removed and TOLBR is taken as 0.1.

It has been shown that the local optimal coordination algorithms are best suited for the on-line or adaptive coordination of relays. Thus an adaptive coordination scheme based upon the local optimal coordination has been developed. This algorithm will continuously monitor the state of the system. If a disturbance, operational or structural, is detected the adaptive coordination algorithm is invoked and the relay settings are recalculated.

Some rethinking has been done about the relay coordination problem in this dissertation. The relay coordination problem has been formulated as an adaptive control system engineering problem. It is demonstrated that this is a closed-loop, non-linear, multidimensional control system with variable parameters and intermittent control. The structure of the vital components of the adaptive control system have been defined.

7.2 SUGGESTIONS FOR FURTHER WORK

The suggestions for further work in this filed are summarized below :

Transmission systems at only one voltage level have been considered in this work. It is desirable to accommodate multiple voltage levels since this feature is very common in a typical utility. This addition requires including transformers and possible modifications in the coordination criteria in the existing algorithms.

To reduce the execution time it is suggested to use an interior point method like Karmakar's algorithm for solving the optimal selection problem of TMS. In the literature , it has been reported that Karmakar's algorithm is mouch faster than the Simplex method.

To simplify the coordination philosophy further and to reduce the execution time, we suggest to remove the problem of optimal selection of I_p from the coordination algorithm. The value of I_p is selected initially and then the optimal values of I_p are calculated. Little differences have been observed between the initial values of I_p selected and the optimal values of I_p. The removal of the optimal selection of I_p problem will only slightly decrease the sensitivity of the relays. Thus the relay coordination problem will be reduced to initial selection of I_p values and the solution of linear programming problem for the optimal selection of TMS.

The interactive versions of OPCORD and OPCON programs can be improved further. One of the immediate future goals is to develop a prototype "production grade" versions of the programs. These versions should incorporate a number of desirable user interface features through a hierarchy of menus, facilitate the data entry and provide for user interaction through computer graphics. We believe that a more detailed interface will be developed during the prototype stage when greater effort can be expended on displays and on experimentation and trials with actual users.

It is suggested to use the concept of parallel processing in solving the relay coordination problem of large size power networks by using the decomposition method. We have presented the ideas in this thesis but have not actually implemented the parallel processing. The use of this concept will greatly reduce the actual execution time of the coordination program.

In the decomposed method, the load flow analysis is performed for the entire system. It is suggested to solve the load flow problem also on the basis of the decomposed network. Such a work has already been done [1] but it will be a novel method to combine the load flow analysis and the relay coordination together for each block.

It is suggested to actually implement the adaptive coordination of directional overcurrent relays for large networks using the decomposition method in the field. The relay coordination problem would be solved region-wise. The implementation will require extensive communication network. Present day supervisory control and data acquisition (SCADA) and energy management systems uses similar communication networks and these networks can be expanded as needed to inculde adaptive protection function.

It is also suggested to implement the adaptive local optimal coordination method for on-line coordination of directional overcurrent relays of large scale power systems. The local optimal coordination is an ideal method to be actually implemented in the field. It would recoordinate the relays of the affected part of the network only, after entertaining the network disturbance, operational or structural.

Initial ideas about the adaptive relay coordination control system have been presented in this dissertation. It is suggested to conceptually expand such ideas and develop a potent control theory for the relay coordination problem of interconnected power systems.

SOFTWARE DESCRIPTION IN BRIEF

A.1 OPCORD

The software package called OPCORD implements the integrated procedure for coordinating the directional overcurrent relays of interconnected power systems. This program uses Simplex method of linear programming for the optimal selection of TMS. Fig. A.1, with arrows emanating from calling program and leading to called subroutines, highlights the overall organization of the program. Brief description of different abbreviated program names are given below.

OPCORD : It calls various subroutines and solves the relay coordination problem.

DATA : This subroutine reads the data of the system.

LINK : Scans the network and stores the information about the network topology.

FORMY : This subroutine determines and stores the elements of Y-matrix.

FLOW : Performs load flow analysis using Gauss-Seidel method.

LINEC : This subroutine determines the line currents seen by each relay and calculates the initial value of I_p for all relays.

FORMZ : This subroutine develops the Z-Bus matrix for the system.

BPRP : This subroutine determines the backup/primary relay pairs and the associated fault current pairs of the system. The B/P relay pairs and the current pairs are stored in different vectors.

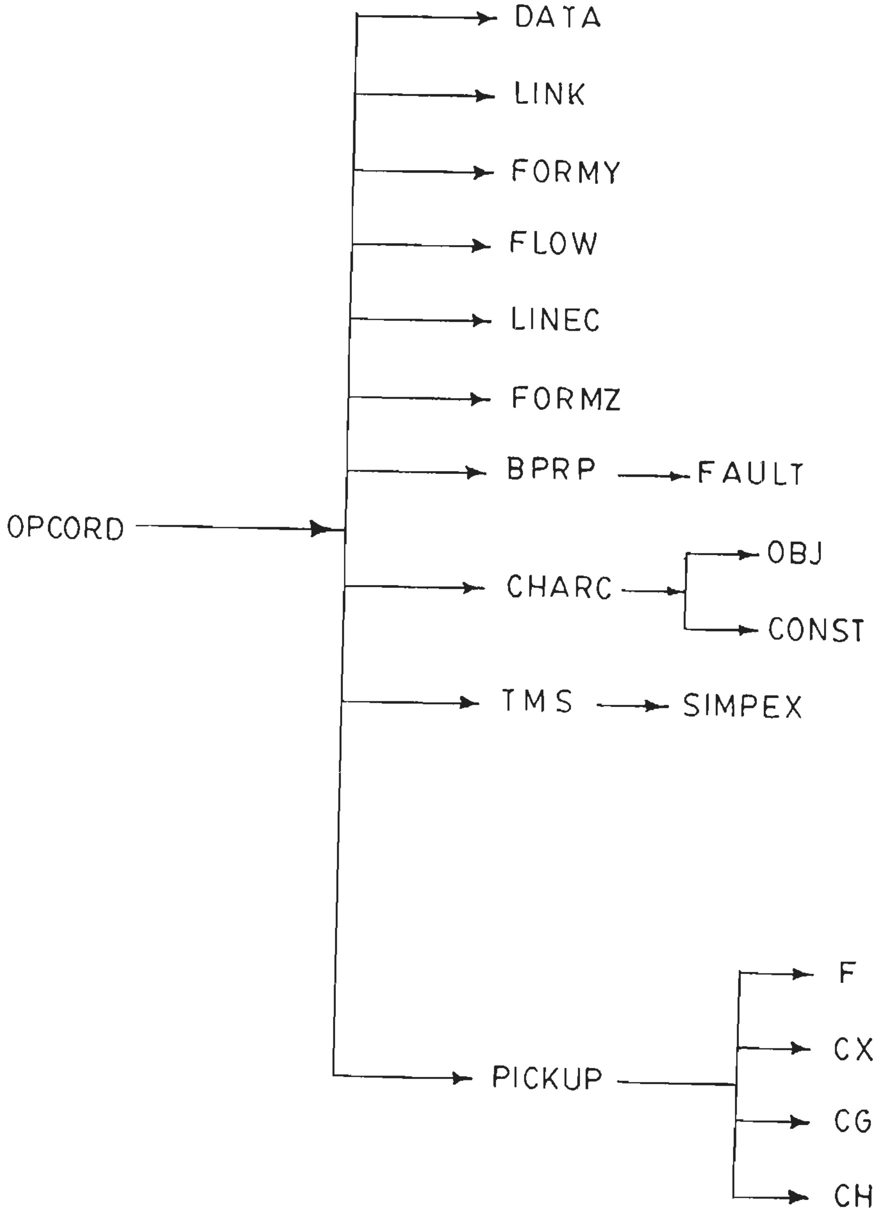


FIG. A-1 OVERALL ORGANIZATION OF THE PACKAGE 'OPCORD'

FAULT : Performs the fault analysis of the network.

CHARC : This subroutine simulates the operation of directional overcurrent relays by using the relevant mathematical models of the relays.

OBJ : Determines the objective function or the performance function.

CONST : Generates the constraint list according to the coordination criteria implemented.

TMS : Prepares the data as required by the subroutine SIMPEX.

SIMPEX : Solves the linear programming problem for TMS.

PICKUP : Determines the optimal I_p values by using the Rosenbrock-Hillclimb procedure.

F : This is a function which determines the objective function to be used by the Rosenbrock-Hillclimb method.

CX : Determines the initial values of the variables.

CG : Supplies the lower limit of the variable.

CH : Supplies the upper limit of the variable.

A.2 OPCON :

The software package called OPCON also implements the integrated procedure for coordinating the directional overcurrent relays of interconnected power systems. This program uses Charalambous least pth algorithm for optimal selection of TMS. The overall organization of the FLOPT5 software package is depicted in Fig.A.2.1. Fig. A.2.2, with arrows emanating from calling programs and leading to called subroutines, highlights the overall organization of the program. Brief description of

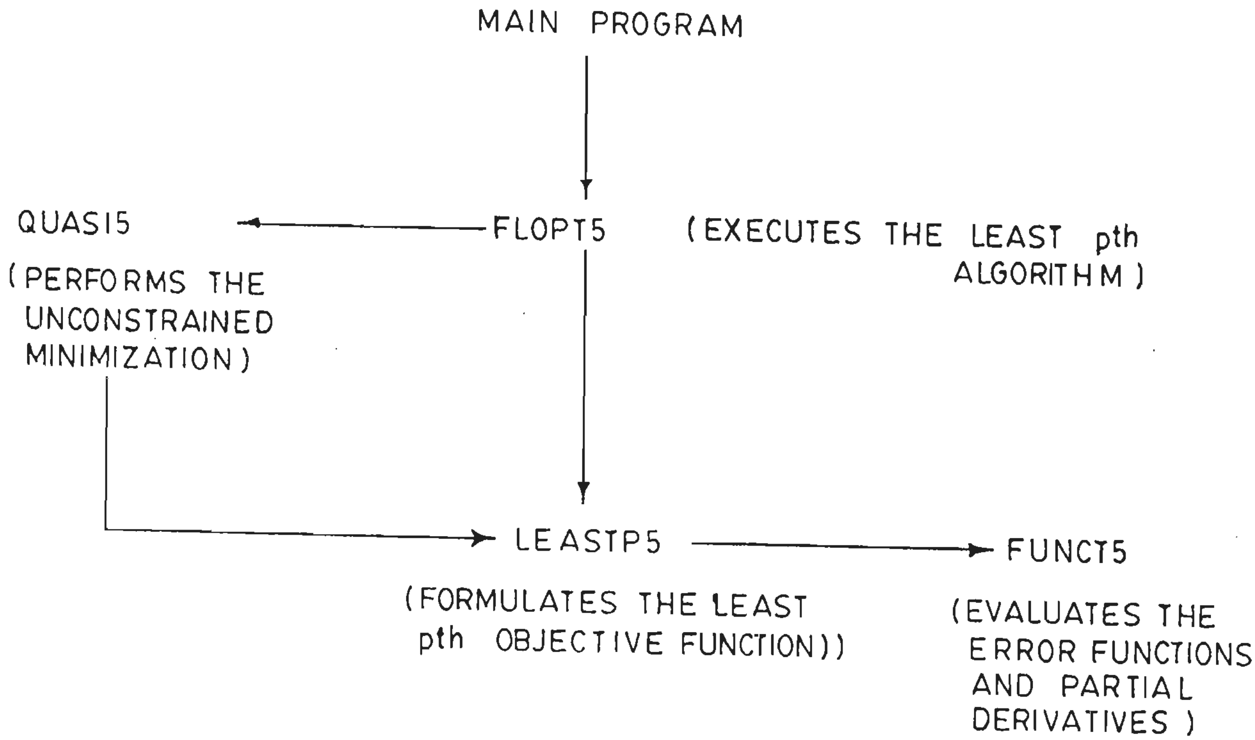


FIG. A-2-1 OVERALL ORGANIZATION OF FLOPT5 SOFTWARE PACKAGE

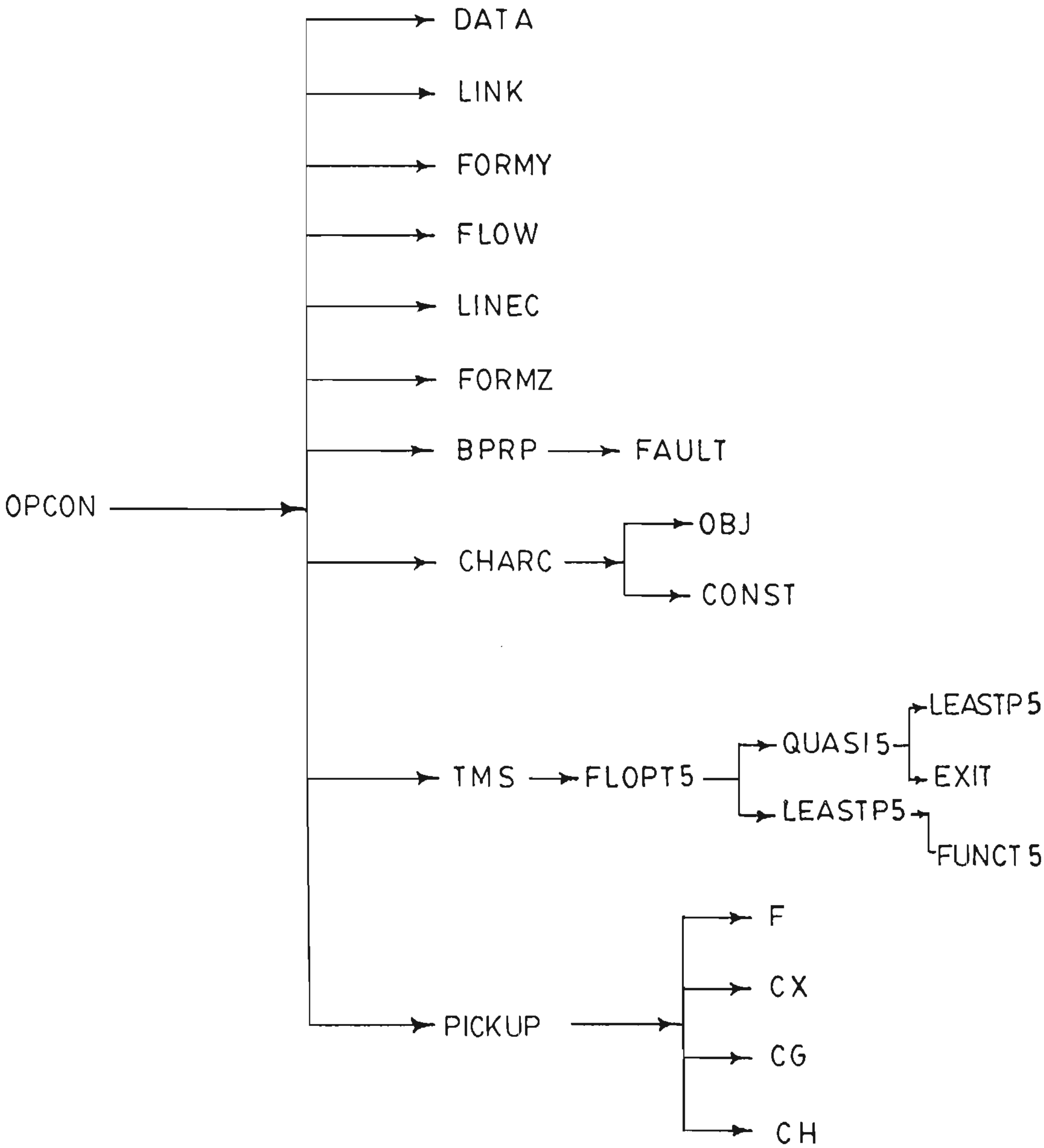


FIG. A-2-2 OVERALL ORGANIZATION OF THE PACKAGE 'OPCON' different abbreviated program names are given below :

OPCON : It calls various subroutines and solves the relay coordination problem.

LINK : Stores the information of network topology and scans the network.

FORMY : Forms Y-BUS matrix of the network.

FLOW : Performs load flow analysis.

LINEC : Calculates line currents and determines the initial values of I_p.

FORMZ : Forms Z-Bus matrix of the network.

BPRP : This subroutine determines the backup/primary relay pairs and the associated fault currents of the system.

FAULT : Performs the fault analysis of the network.

CHARC : Simulates the operation of directional overcurrent relays by using the mathematical models of the relays.

OBJ : Determines the performance function.

CONST : Generates the constraint list according to the coordination criteria.

TMS : Solves the optimal selection problem of TMS.

FLOPT5 : Calls various subroutines and performs an iterations of the charalambous algorithm.

FUNCT5 : This subroutine evaluates the error functions and partial derivatives.

QUASI5 : This subroutine performs the unconstrained optimization using Fletcher's quasi-Newton method.

LEASTP5: This subroutine formulates the least pth objective function.

EXIT : This subroutine exits the program.

PICKUP : Determines the optimal values of I_p by using the Rosenbrock-Hillclimb procedure.

F : Determines the objective function for the Roseubrock-Hillclimb method.

CX : Determines the initial values of I_p .

CG : Supplies the lower limit of I_p.

CH : Supplies the upper limit of I_p.

A.3 BLOCK :

The software named BLOCK implements the developed decomposition technique presented in *Chapter 4*. This package is particularly efficient in solving large size power networks with smaller computers for coordinating directional overcurrent relays. Fig A.3, with arrows emanating from calling program and leading to called subroutines, shows the overall organization of the program. Brief description of the different abbreviated program names are given below :

BLOCK : It calls various subroutines and solves the relay coordination problem, using the proposed decomposition technique.

DATA : Reads the data of the system.

LINK : Store and scans the network topology.

FORMY : Forms the Y-matrix.

FLOW : Performs the load flow program.

LINEC : Calculates line currents and determines I_p values of therelays.

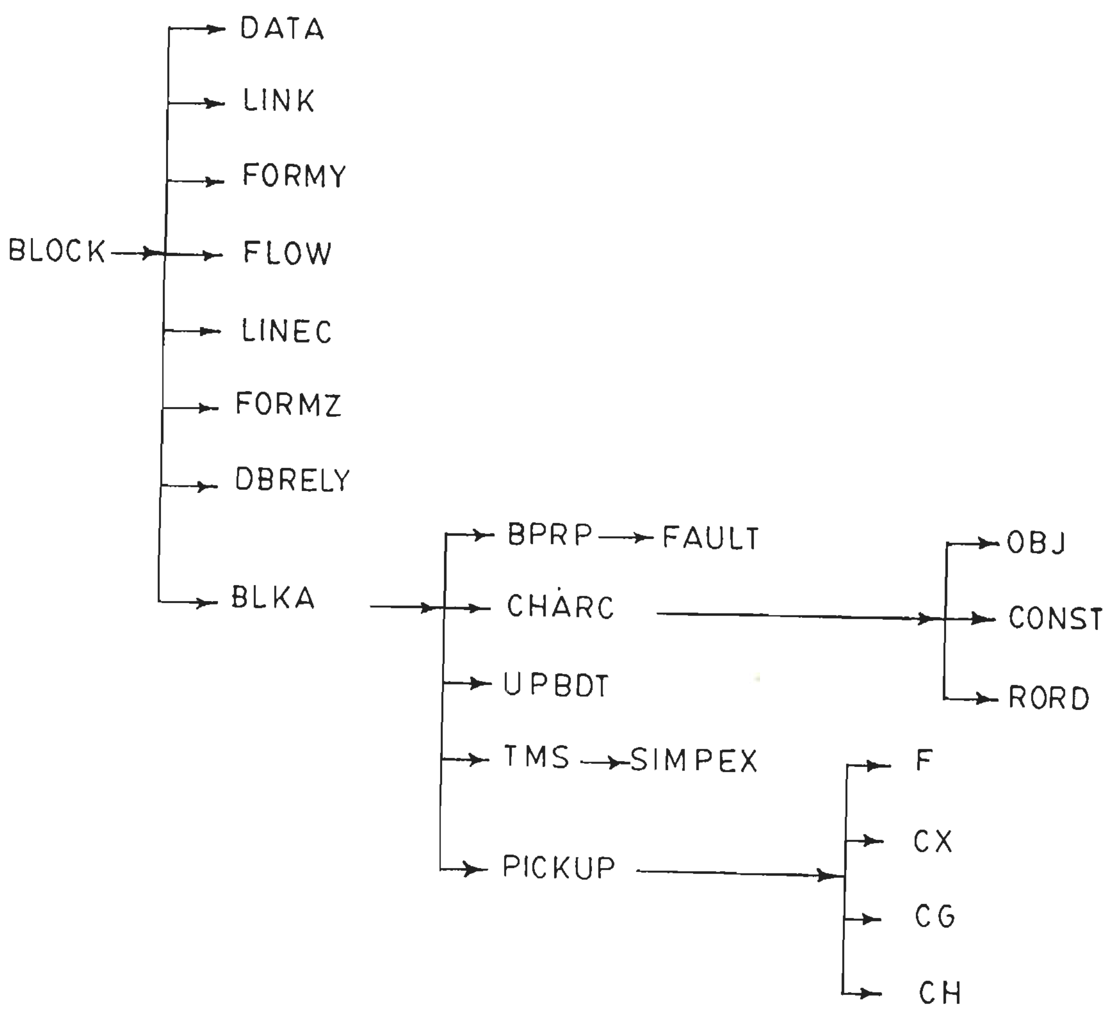


FIG. A-3 OVERALL ORGANIZATION OF THE PACKAGE 'BLOCK'

FORMZ : Forms the Z-matrix for the entire network.

DBRELY : It prepares the boundary data table block-wise. The data of each block are stored in different files.

BLKA : solves the coordination problem of the blocks sequentially.

BRPR : Determines the B/P relay pairs and the associated fault current pairs.

FAULT : Perform the fault analysis.

CHARC : Simulates operation of the relay.

OBJ : Prepares the performance function.

CONST : Generates the constraint list.

RORD : Performs the re-ordering of the relays.

UPBDT : Updates the boundary data table.

TMS : Prepares the data as required by the subroutine SIMPEX.

SIMPEX : Solves the linear programming for TMS.

PICKUP : Determines optimal values of I_p.

F : Prepares the objective function for PICKUP.

CX : Determines the initial values of I_p.

CG : Supplies lower limit of I_p.

CH : Supplies upper limit of I_p.

A.4 LOCORD :

The software called LOCORD implements the developed local optimal coordination of directional overcurrent relays presented in *Chapter* 5. This package is highly efficient for solving the coordination problem of large power network under changed system conditions. A system change effects only a small area of the network. Hence this package identifies this disturb region and coordinates the settings of the of relays which fall in this local region. By assigning a proper value to LOC variable, we may invoke LOC Algorithm-1 or LOC Algorithm-2.

LOC = 1 : Solve local relay coordination problem using LOC Algorithm-1

= 2 : Solve local relay coordination problem using LOC Algorithm-2

Figs. A.4.1 and A.4.2 with arrows emanating from calling program and leading to called subroutines, shows the overall organization of the programs. Brief description of different abbreviated program names are given below :

LOCORD : Solves the coordination problem of local region using the concept of local optimization.

DATA : Reads the data of the entire system.

LINK : Stores the topology of the network and performs the scanning operation of the network.

FORMY : Forms Y-matrix for the entire system.

FLOW : Performs the load flow analysis for the entire system.

LINEC : Calculates the line currents and determines the initial value of I_p for all the relays.

FORMZ : Formulates the Z-BUS matrix for the entire system.

LRID : Identifies the disturbed region around the disturbance.

LRB : Determines all the buses of the local region.

LRR : Determines all the relays of the local region.

RDUP : Removes the duplication of the relays.

BRELY : Determines the internal as well as the external boundary relays.

LCRA : Solves the coordination problem of the local region.

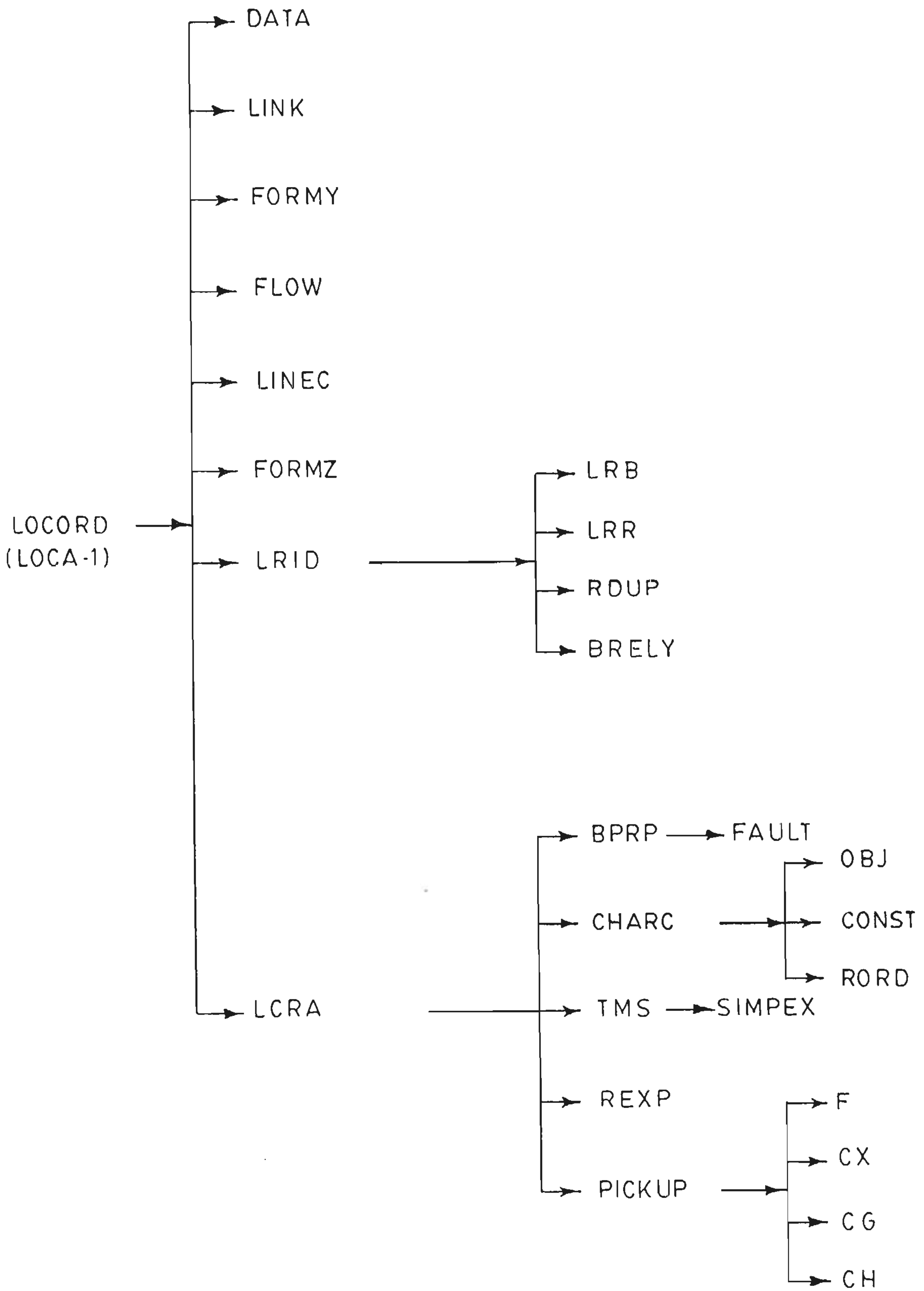


FIG. A-4-1 OVERALL ORGANIZATION OF THE PACKAGE 'LOCORD' USING LOC ALGORITHM-1

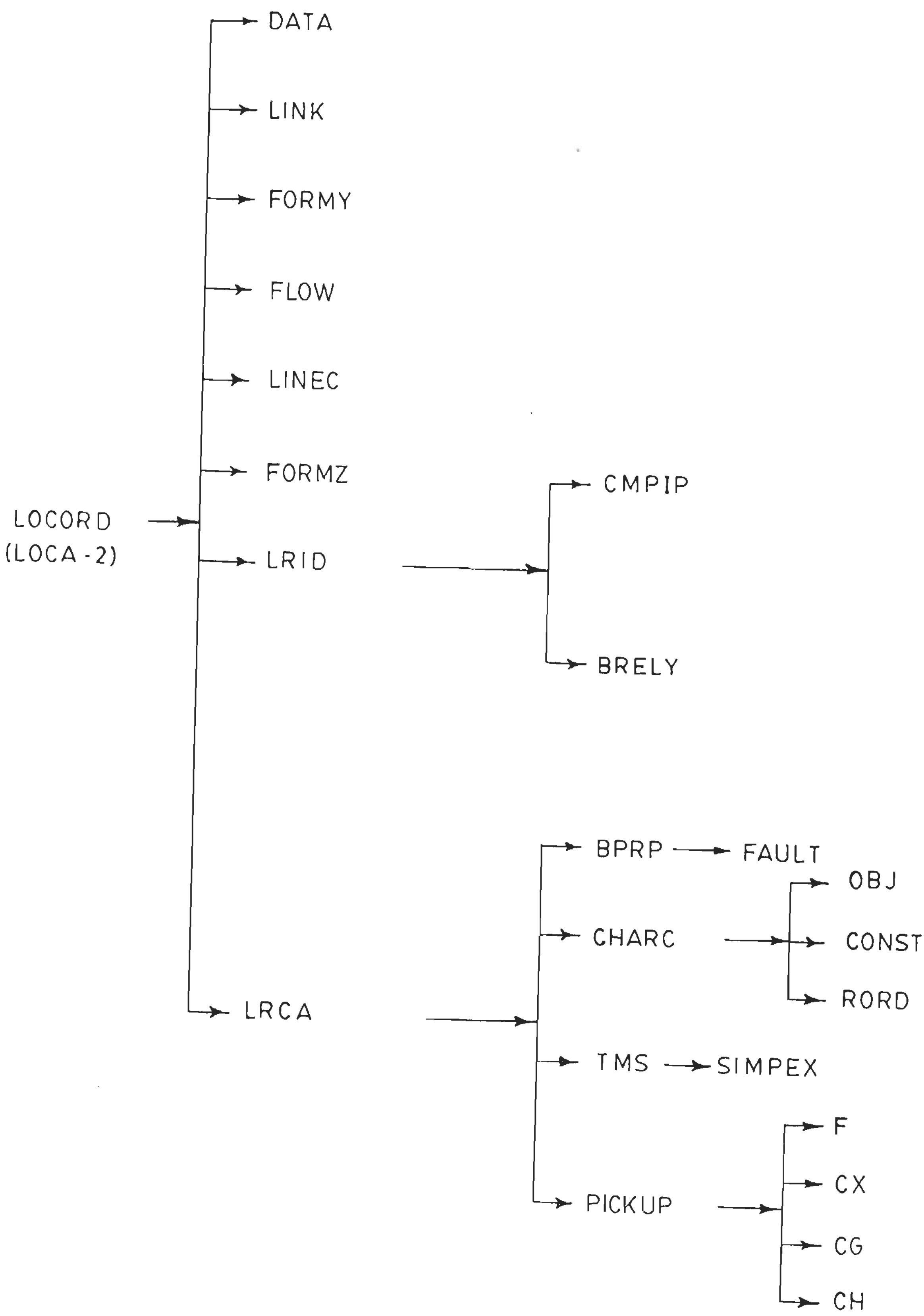


FIG. A-4-2 OVERALL ORGANIZATION OF THE PACKAGE 'LOCORD' USING LOC ALGORITHM-2.

BPRP : Determines the B/P relay pairs and the associated current pairs.

FAULT : Performs the fault analysis.

CHARC : Models the characteristis of the relays.

OBJ : Determines the objection function.

CONST : Prepares the constraint list.

RORD : Re-orders the relays of the local region.

TMS : Prepares the data as required by the subroutine SIMPEX.

SIMPEX : Solves the linear programming problem for I_p.

REXP : Checks whether the expansion of the local region should occur or not.

PICKUP : Determines the optimal values of I_p.

F : Prepares the performance function for PICKUP.

CX : Determines the initial values of I_p.

CG : Supplies the lower limit of I_p.

CH : Supplies the upper limit of I_p.

Important Note : For the adaptive version of the programs, one more subroutine is included. The subroutine is TOPP.

TOPP : Determines the latest topology of the network.

For LOCA-2

CMIP : Compares the values of I_p for all the relays and determines the relays of the local region.

TEST SYSTEM DATA

In this appendix system data for the following power transmission networks are given :

* 6-bus test power system
* 14-bus IEEE test system
* 26-bus model of SPC transmission system
* 57-bus IEEE test system
* 64-bus model of North-West power system of India
* 118-bus model of IEEE test system

The data are presented in the following manner :

- Bus data
- Line data

In the bus data, bus type o indicates a load bus, bus type 2 indicates generator bus and bus type 3 means the reference bus. In the line data, line type 1 indicates an ordinary line, line type 2 indicates a tie line and line type 3 means a transformer line.

TABLE : *B.1.1*

6 BUS SYSTEM : BUS DATA

BUS NO.	BUS TYPE	BUS VOLTAGE MAGNITUDE (P.U.)	BUS VOLTAGE ANGLE (RADIANS)	GENERATION ACTIVE (MW)	GENERATION REACTIVE (MVAR)	LOAD ACTIVE (MW)	LOAD REACTIVE (MVAR)	REACTOR/ CAPACITOR SUSCEPT. (P.U.)
1	2	3	4	5	6	7	8	9
1	0	0.9795	-0.6602	0.000	0.000	2.400	0.000	0.000
2	0	0.9941	-0.2976	0.000	0.000	2.400	0.000	0.000
3	0	0.9355	-0.3036	0.000	0.000	1.600	0.400	0.000
4	2	1.0200	-0.5566	1.900	0.270	0.500	0.100	0.000
5	2	1.0400	-0.4740	3.00	0.631	0.500	0.200	0.000
6	3	1.0400	0.0000	2.760	0.840	0.000	0.000	0.000

TABLE : *B.1.2*

6 BUS SYSTEM : LINE DATA

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	LINE IMPEDANCE REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)
1	2	3	4	5	6	7
1	1	1	4	0.0500	0.2000	0.00
2	1	1	5	0.0250	0.1000	0.00
3	1	2	3	0.1000	0.4000	0.00
4	1	2	4	0.1000	0.4000	0.00
5	1	2	5	0.0500	0.2000	0.00
6	1	2	6	0.1875	0.0750	0.00
7	1	3	4	0.1500	0.6000	0.00
8	1	3	6	0.0375	0.1500	0.00

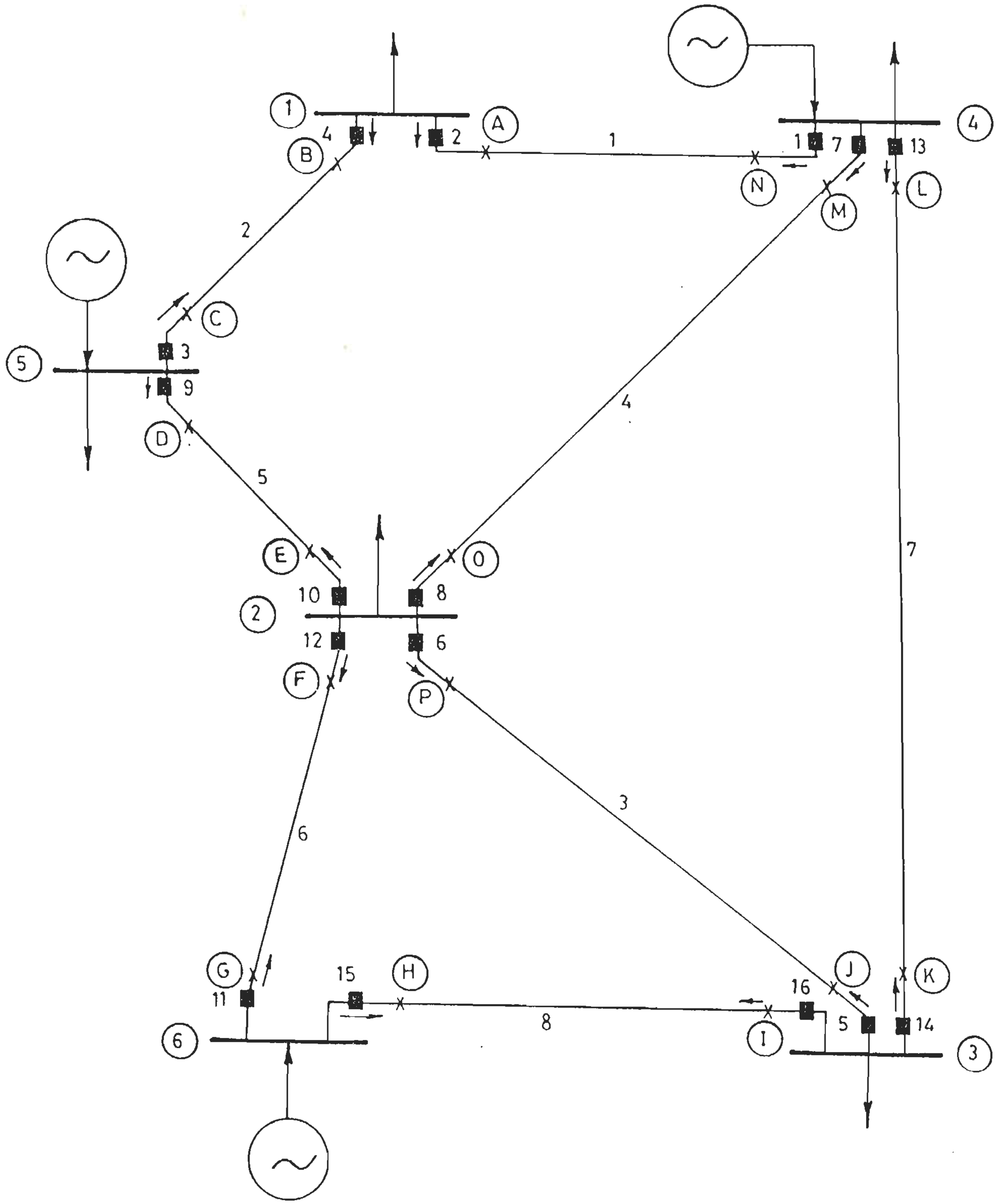


FIG.B.1 : 6-BUS SAMPLE POWER SYSTEM

TABLE : *B.2.1*

14 BUS SYSTEM : BUS DATA

BUS NO.	BUS TYPE	BUS VOLTAGE MAGNITUDE (P.U.)	BUS VOLTAGE ANGLE (RADIANS)	GENERATION ACTIVE (MW)	GENERATION REACTIVE (MVAR)	LOAD ACTIVE (MW)	LOAD REACTIVE (MVAR)	REACTOR/ CAPACITOR SUSCEPT. (P.U.)
1	2	3	4	5	6	7	8	9
1	0	1.0078	-0.1774	0.000	0.000	47.800	3.900	0.000
2	0	1.0114	-0.1512	0.000	0.000	7.600	1.600	0.000
3	0	1.0370	-0.2323	0.000	0.000	0.000	0.000	0.000
4	0	1.0335	-0.2612	0.000	0.000	29.500	16.600	0.190
5	0	1.0288	-0.2642	0.000	0.000	9.000	5.800	0.000
6	0	1.0357	-0.2587	0.000	0.000	3.500	1.800	0.000
7	0	1.0347	-0.2643	0.000	0.000	6.100	1.600	0.000
8	0	1.0297	-0.2657	0.000	0.000	13.500	5.800	0.000
9	0	1.0134	-0.2814	0.000	0.000	14.900	5.000	0.000
10	2	1.0500	-0.2323	0.000	17.400	0.000	0.000	0.000
11	2	1.0500	-0.2488	0.000	12.200	11.200	7.500	0.000
12	2	1.0100	-0.2219	0.000	23.400	94.200	19.000	0.000
13	2	1.0450	-0.0866	40.000	42.400	21.700	12.700	0.000
14	3	1.0600	0.0000	231.136	-12.590	0.000	0.000	0.000

TABLE : *B.2.2*

14 BUS SYSTEM : LINE DATA

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	LINE IMPEDANCE REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
1	1	14	13	0.0194	0.0592	0.0264	250.0000
2	1	13	12	0.0470	0.1980	0.0219	125.0000
3	1	13	1	0.0581	0.1763	0.0187	100.0000
4	1	14	2	0.0540	0.2230	0.0246	125.0000
5	1	13	2	0.0570	0.1739	0.0170	75.0000
6	1	12	1	0.0670	0.1710	0.0173	50.0000
7	1	1	2	0.0134	0.0421	0.0064	100.0000
8	3	2	11	0.0000	0.2520	0.0000	75.0000
9	3	1	3	0.0000	0.2091	0.0000	50.0000
10	1	3	10	0.0000	0.1761	0.0000	25.0000
11	3	1	4	0.0000	0.5562	0.0000	30.0000
12	1	3	4	0.0000	0.1100	0.0000	50.0000
13	1	4	5	0.0318	0.0845	0.0000	25.0000
14	1	11	6	0.0950	0.1989	0.0000	25.0000
15	1	11	7	0.1229	0.2558	0.0000	25.0000
16	1	11	8	0.0662	0.1303	0.0000	25.0000
17	1	4	9	0.1271	0.2704	0.0000	25.0000
18	1	5	6	0.0821	0.1921	0.0000	25.0000
19	1	7	8	0.2209	0.1999	0.0000	25.0000
20	1	8	9	0.1709	0.3480	0.0000	25.0000

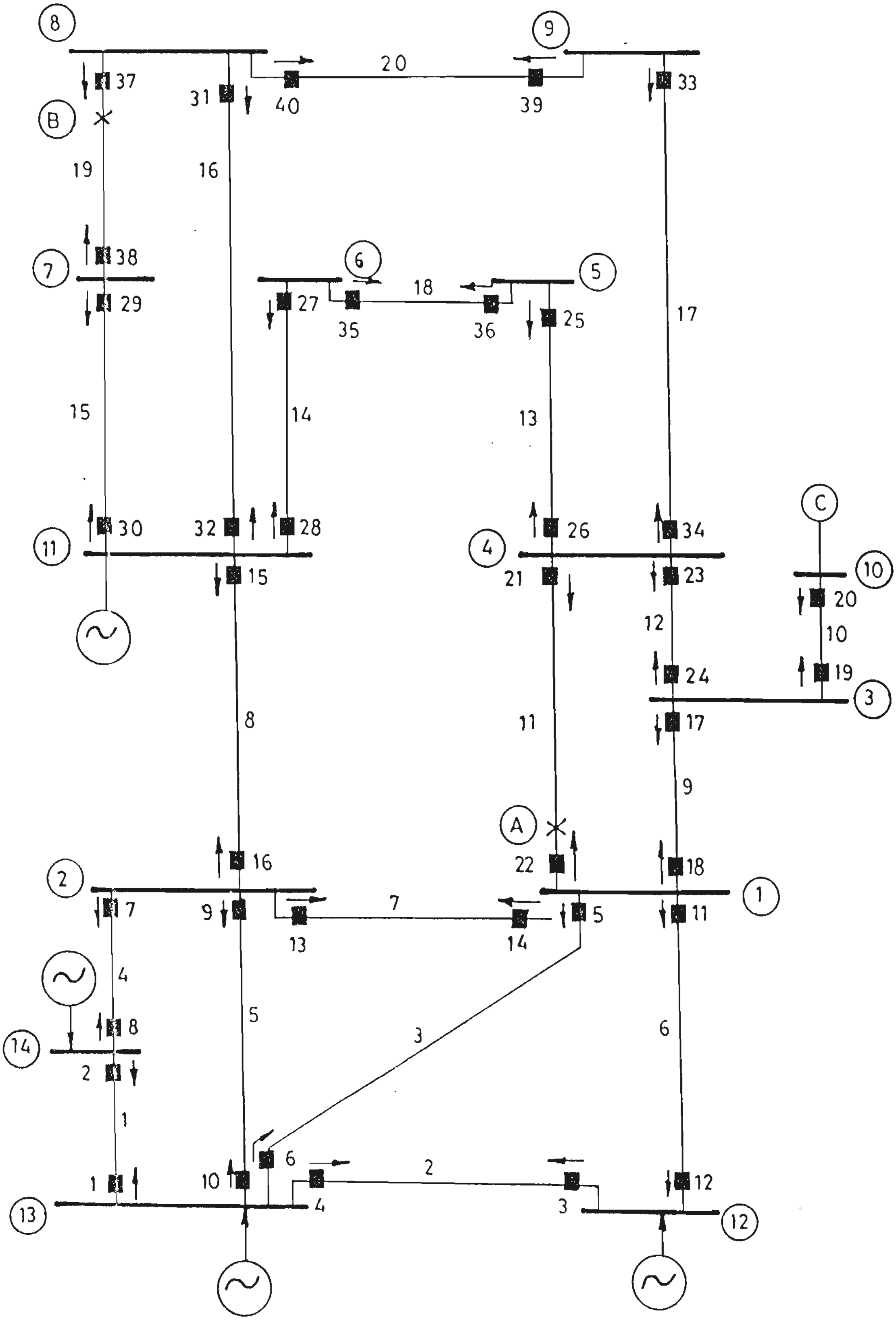


FIG.B.2: 14-BUS IEEE TEST SYSTEM

TABLE : *B.3.1*

26 BUS SYSTEM : BUS DATA

BUS NO.	BUS TYPE	BUS VOLTAGE MAGNITUDE (P.U.)	BUS VOLTAGE ANGLE (RADIANS)	GENERATION ACTIVE (MW)	GENERATION REACTIVE (MVAR)	LOAD ACTIVE (MW)	LOAD REACTIVE (MVAR)	REACTOR/ CAPACITOR SUSCEPT. (P.U.)
1	2	3	4	5	6	7	8	9
1	0	1.0618	0.0683	0.000	0.000	82.000	21.000	0.000
2	0	1.1159	0.0755	0.000	0.000	0.000	0.000	0.000
3	0	1.0649	0.0472	0.000	0.000	57.000	17.000	0.000
4	0	1.0123	0.0912	0.000	0.000	48.000	21.000	0.000
5	0	1.0081	0.2540	0.000	0.000	43.000	11.000	0.000
6	0	1.0400	0.0524	0.000	0.000	40.000	10.000	0.000
7	0	1.0410	0.0137	0.000	0.000	111.000	27.000	0.000
8	0	0.9800	0.0296	0.000	0.000	23.000	6.000	0.000
9	0	1.0712	-0.1354	0.000	0.000	67.000	21.000	0.000
10	0	1.0947	0.0550	0.000	0.000	102.000	27.000	0.000
11	0	0.9516	-0.1185	0.000	0.000	43.000	14.000	0.000
12	0	1.0189	-0.0884	0.000	0.000	43.000	12.000	0.000
13	0	1.0582	0.0140	0.000	0.000	0.000	0.000	0.000
14	0	1.0313	-0.1322	0.000	0.000	0.000	0.000	0.000
15	0	0.9563	0.0966	0.000	0.000	0.000	0.000	0.000
16	0	1.0363	-0.0455	0.000	0.000	131.000	30.000	0.000
17	0	0.9396	0.0266	0.000	0.000	3.000	1.000	0.000
18	2	1.0000	0.3533	63.000	0.000	0.000	0.000	0.000
19	2	1.0000	0.0405	0.000	0.000	5.000	0.000	0.000
20	2	1.0000	-0.0266	0.000	0.000	4.000	0.000	0.000
21	2	0.8900	-0.0986	0.000	0.000	56.000	0.000	0.000
22	2	1.0200	0.2203	110.000	0.000	0.000	0.000	0.000
23	2	1.0000	0.2365	280.000	0.000	0.000	0.000	0.000
24	2	1.0500	0.0921	145.000	0.000	0.000	0.000	0.000
25	2	1.0700	0.2244	280.000	0.000	0.000	0.000	0.000
26	3	1.0100	0.0000	15.978	-141.952	0.000	0.000	0.000

TABLE : *B.3.2*

26 BUS SYSTEM : LINE DATA

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	LINE IMPEDANCE REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
1	1	16	20	0.0000	0.4320	0.0000	25.0000
2	1	20	26	0.0000	0.3140	0.0000	25.0000
3	3	13	26	0.0000	0.0131	0.0000	225.0000
4	3	26	16	0.0000	0.0392	0.0000	165.0000
5	3	2	10	0.0000	0.0150	0.0000	237.5000
6	1	9	10	0.1494	0.3392	0.8240	81.2500
7	1	9	12	0.0658	0.1494	0.0364	27.5000
8	1	12	26	0.0533	0.1210	0.0294	81.2500
9	1	9	14	0.0618	0.2397	0.0638	25.0000
10	1	11	14	0.0676	0.2620	0.0698	25.0000
11	1	24	26	0.0610	0.2521	0.0590	52.5000
12	1	6	26	0.0513	0.1986	0.0530	40.0000
13	1	6	24	0.0129	0.0532	0.0148	110.0000
14	1	7	24	0.0906	0.3742	0.0874	30.0000
15	1	6	7	0.0921	0.3569	0.0950	25.0000
16	1	11	21	0.0513	0.2118	0.0496	25.0000
17	1	8	11	0.0865	0.3355	0.0894	50.0000
18	1	17	21	0.0281	0.1869	0.0474	67.5000
19	1	8	22	0.0735	0.2847	0.0758	81.2500
20	1	17	22	0.0459	0.3055	0.0774	78.7500
21	1	1	4	0.0619	0.2401	0.0638	25.0000
22	1	4	22	0.0610	0.2365	0.0630	65.0000
23	3	23	22	0.0000	0.0305	0.0000	75.0000
24	3	15	1	0.0000	0.0147	0.0000	250.0000
25	1	2	13	0.0086	0.0707	0.6034	156.2500
26	1	1	7	0.0199	0.0785	0.0808	105.0000
27	1	15	23	0.0107	0.0617	0.8942	270.0000
28	1	2	25	0.0074	0.0608	0.5186	350.0000
29	3	1	3	0.0000	0.0392	0.0000	82.5000
30	3	19	3	0.0000	0.1450	0.0000	25.0000
31	3	5	22	0.0000	0.1750	0.0000	25.0000
32	3	5	18	0.0000	0.1540	0.0000	67.5000

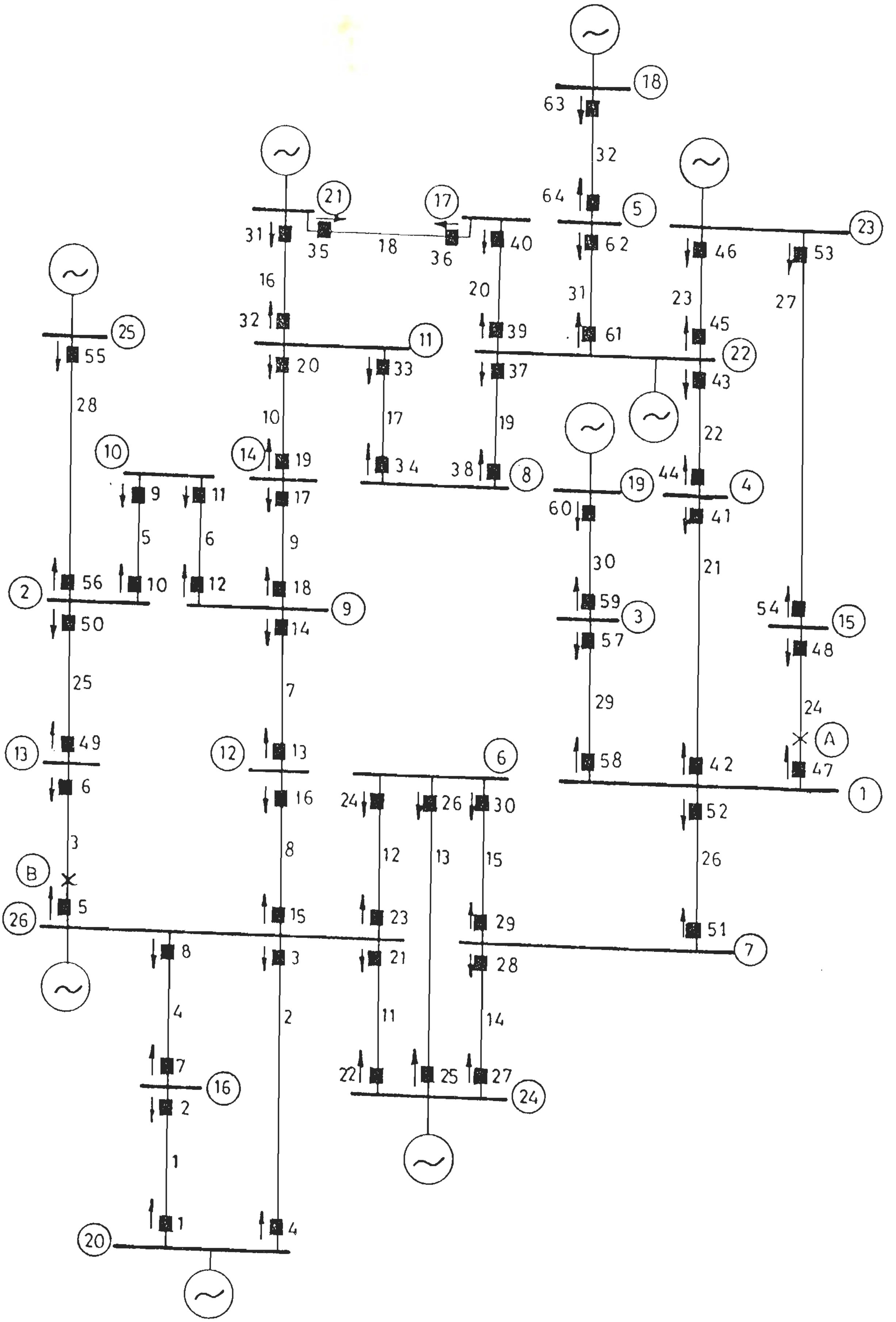


FIG.B.3: 26-BUS (SPC) SYSTEM

TABLE : *B.4.1*

57 BUS SYSTEM : BUS DATA

BUS NO.	BUS TYPE	BUS VOLTAGE MAGNITUDE (P.U.)	BUS VOLTAGE ANGLE (RADIANS)	GENERATION ACTIVE (MW)	GENERATION REACTIVE (MVAR)	LOAD ACTIVE (MW)	LOAD REACTIVE (MVAR)	REACTOR/ CAPACITOR SUSCEPT. (P.U.)
1	2	3	4	5	6	7	8	9
1	0	0.9799	-0.1261	0.000	0.000	0.000	0.000	0.000
2	0	0.9762	-0.1474	0.000	0.000	13.000	4.000	0.000
3	0	0.9853	-0.1307	0.000	0.000	0.000	0.000	0.000
4	0	0.9825	-0.2031	0.000	0.000	5.000	2.000	0.000
5	0	0.9719	-0.1799	0.000	0.000	0.000	0.000	0.000
6	0	0.9800	-0.1729	0.000	0.000	18.000	2.300	0.000
7	0	0.9708	-0.1646	0.000	0.000	10.500	5.300	0.000
8	0	0.9854	-0.1263	0.000	0.000	22.000	5.000	0.000
9	0	1.0133	-0.1559	0.000	0.000	43.000	3.000	0.000
10	0	1.0174	-0.0949	0.000	0.000	42.000	8.000	0.000
11	0	0.9301	-0.3035	0.000	0.000	27.200	9.800	0.100
12	0	0.9106	-0.3048	0.000	0.000	3.300	0.600	0.000
13	0	0.9116	-0.2907	0.000	0.000	2.300	1.000	0.000
14	0	0.9000	-0.2494	0.000	0.000	0.000	0.000	0.000
15	0	0.9036	-0.2433	0.000	0.000	0.000	0.000	0.000
16	0	0.9012	-0.2442	0.000	0.000	6.300	2.100	0.000
17	0	0.8770	-0.2431	0.000	0.000	0.000	0.000	0.000
18	0	0.7794	-0.4448	0.000	0.000	6.300	3.200	0.059
19	0	0.8733	-0.2379	0.000	0.000	0.000	0.000	0.000
20	0	0.8899	-0.2094	0.000	0.000	9.300	0.500	0.000
21	0	0.9034	-0.1885	0.000	0.000	4.600	2.300	0.000
22	0	0.9164	-0.1740	0.000	0.000	17.000	2.600	0.000
23	0	0.7603	-0.4538	0.000	0.000	3.600	1.800	0.000
24	0	0.7409	-0.4571	0.000	0.000	5.800	2.900	0.000
25	0	0.7807	-0.4134	0.000	0.000	1.600	0.800	0.000
26	0	0.7779	-0.4144	0.000	0.000	3.800	1.900	0.000

TABLE : *B.4.1 CONT...*

BUS NO.	BUS TYPE	BUS VOLTAGE MAGNITUDE (P.U.)	BUS VOLTAGE ANGLE (RADIANS)	GENERATION ACTIVE (MW)	GENERATION REACTIVE (MVAR)	LOAD ACTIVE (MW)	LOAD REACTIVE (MVAR)	REACTOR/ CAPACITOR SUSCEPT. (P.U.)
1	2	3	4	5	6	7	8	9
27	0	0.8461	-0.2783	0.000	0.000	0.000	0.000	0.000
28	0	0.8574	-0.2714	0.000	0.000	6.000	3.000	0.000
29	0	0.8708	-0.2645	0.000	0.000	0.000	0.000	0.000
30	0	0.8808	-0.2590	0.000	0.000	0.000	0.000	0.000
31	0	0.9093	-0.2401	0.000	0.000	14.000	7.000	0.000
32	0	0.8793	-0.2600	0.000	0.000	0.000	0.000	0.000
33	0	0.8698	-0.2658	0.000	0.000	0.000	0.000	0.000
34	0	0.9200	-0.2657	0.000	0.000	6.300	3.000	0.000
35	0	0.8769	-0.2938	0.000	0.000	7.100	4.000	0.000
36	0	0.9504	-0.2049	0.000	0.000	2.000	1.000	0.000
37	0	0.9239	-0.2229	0.000	0.000	12.000	1.800	0.000
38	0	0.9670	-0.1729	0.000	0.000	0.000	0.000	0.000
39	0	0.9521	-0.2016	0.000	0.000	0.000	0.000	0.000
40	0	0.9263	-0.2319	0.000	0.000	29.700	11.600	0.000
41	0	0.9212	-0.2348	0.000	0.000	0.000	0.000	0.000
42	0	0.9279	-0.2378	0.000	0.000	18.000	8.500	0.000
43	0	0.9208	-0.2474	0.000	0.000	21.000	10.500	0.000
44	0	0.9656	-0.2277	0.000	0.000	18.000	5.300	0.000
45	0	0.8859	-0.2091	0.000	0.000	4.900	2.200	0.000
46	0	0.8768	-0.2244	0.000	0.000	20.000	10.000	0.063
47	0	0.9111	-0.2137	0.000	0.000	4.100	1.400	0.000
48	0	0.9551	-0.1953	0.000	0.000	6.800	3.400	0.000
49	0	0.8668	-0.3017	0.000	0.000	7.600	2.200	0.000
50	0	0.8573	-0.3130	0.000	0.000	6.700	2.000	0.000
51	2	1.0100	-0.0207	0.000	0.000	3.000	88.000	0.000
52	2	1.0150	-0.1845	310.000	128.500	377.000	24.000	0.000
53	2	0.9800	-0.1689	0.000	2.200	121.000	26.000	0.000
54	2	1.0050	-0.0780	450.000	62.100	150.000	22.000	0.000
55	2	0.9800	-0.1497	0.000	0.800	75.000	2.000	0.000
56	2	0.9850	-0.1042	40.000	-1.000	41.000	21.000	0.000
57	3	1.0400	0.0000	480.931	131.722	55.000	17.000	0.000

TABLE : *B.4.2*

57 BUS SYSTEM : LINE DATA

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
1	1	57	51	0.0083	0.0280	0.0645	150.0000
2	1	51	56	0.0298	0.0850	0.0409	130.0000
3	1	56	1	0.0112	0.0366	0.0190	75.0000
4	1	1	2	0.0625	0.1320	0.0129	25.0000
5	1	1	55	0.0430	0.1480	0.0174	25.0000
6	1	55	3	0.0200	0.1020	0.0138	25.0000
7	1	55	54	0.0339	0.1730	0.0235	50.0000
8	1	54	53	0.0099	0.0505	0.0274	230.0000
9	1	53	4	0.0369	0.1679	0.0220	25.0000
10	1	53	5	0.0258	0.0848	0.0109	25.0000
11	1	53	52	0.0648	0.2950	0.0386	25.0000
12	1	53	6	0.0481	0.1580	0.0203	25.0000
13	1	6	7	0.0132	0.0434	0.0055	25.0000
14	1	6	8	0.0269	0.0869	0.0115	62.5000
15	1	57	8	0.0178	0.0910	0.0494	200.0000
16	1	57	9	0.0454	0.2060	0.0273	100.0000
17	1	57	10	0.0238	0.1080	0.0143	125.0000
18	1	56	8	0.0162	0.0530	0.0272	50.0000
19	1	2	55	0.0302	0.0641	0.0062	25.0000
20	1	3	54	0.0139	0.0712	0.0097	100.0000
21	1	4	52	0.0277	0.1262	0.0164	25.0000
22	1	5	6	0.0223	0.0732	0.0094	25.0000
23	1	52	6	0.0178	0.0580	0.0302	25.0000
24	1	52	9	0.0180	0.0813	0.0108	50.0000
25	1	52	10	0.0397	0.1790	0.0238	62.5000
26	1	7	8	0.0171	0.0547	0.0074	100.0000

TABLE : *B.4.2 CONTD...*

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
27	1	11	12	0.4610	0.6850	0.0000	25.0000
28	1	12	13	0.2830	0.4340	0.0000	25.0000
29	1	14	15	0.0736	0.1170	0.0000	25.0000
30	1	15	16	0.0099	0.0152	0.0000	25.0000
31	1	16	17	0.1660	0.2560	0.0042	25.0000
32	1	19	20	0.1650	0.2540	0.0000	25.0000
33	1	20	21	0.0618	0.0954	0.0000	25.0000
34	1	21	22	0.0418	0.0587	0.0000	25.0000
35	1	18	23	0.1350	0.2020	0.0000	25.0000
36	1	23	24	0.3260	0.4970	0.0000	25.0000
37	1	24	25	0.5070	0.7550	0.0000	25.0000
38	1	25	26	0.0392	0.0360	0.0000	25.0000
39	1	27	28	0.0520	0.0780	0.0016	25.0000
40	1	28	29	0.0430	0.0537	0.0008	25.0000
41	1	29	30	0.0290	0.0366	0.0000	25.0000
42	1	30	31	0.0651	0.1009	0.0010	30.0000
43	1	30	32	0.0239	0.0379	0.0000	25.0000
44	1	29	33	0.0300	0.0466	0.0000	25.0000
45	1	15	31	0.0192	0.0295	0.0000	25.0000
46	1	34	35	0.2070	0.3520	0.0000	25.0000
47	1	34	36	0.0000	0.4120	0.0000	25.0000
48	1	31	37	0.0289	0.0585	0.0010	50.0000
49	1	39	40	0.0230	0.0680	0.0016	62.5000
50	1	40	41	0.0182	0.0233	0.0000	25.0000
51	1	41	42	0.0834	0.1290	0.0024	25.0000
52	1	42	43	0.0801	0.1280	0.0000	25.0000
53	1	43	44	0.1386	0.2200	0.0000	25.0000
54	1	22	45	0.1442	0.1870	0.0000	25.0000
55	1	45	46	0.0762	0.0984	0.0000	25.0000
56	1	46	47	0.1878	0.2320	0.0000	25.0000
57	1	47	48	0.1732	0.2265	0.0000	25.0000
58	1	37	38	0.0624	0.1242	0.0020	62.5000
59	1	49	34	0.5530	0.5490	0.0000	25.0000

TABLE : *B.4.2 CONTD...*

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
60	1	49	35	0.2125	0.3540	0.0000	25.0000
61	1	50	49	0.1740	0.2600	0.0000	25.0000
62	1	31	42	0.1150	0.1770	0.0030	25.0000
63	1	31	41	0.0312	0.0482	0.0000	25.0000
64	3	1	11	0.0000	0.5550	0.0000	50.0000
65	3	3	22	0.0000	0.0648	0.0000	75.0000
66	3	53	48	0.0000	0.1205	0.0000	25.0000
67	3	4	44	0.0000	0.0712	0.0000	50.0000
68	3	5	34	0.0000	0.7490	0.0000	25.0000
69	3	5	36	0.0000	0.1530	0.0000	25.0000
70	3	6	42	0.0000	0.1910	0.0000	50.0000
71	3	7	39	0.0000	0.0735	0.0000	62.5000
72	3	8	38	0.0000	0.1042	0.0000	50.0000
73	3	13	14	0.0000	0.7767	0.0000	25.0000
74	3	17	18	0.0000	1.1820	0.0000	25.0000
75	3	17	19	0.0000	0.0473	0.0000	25.0000
76	3	25	27	0.0000	0.9530	0.0000	25.0000
77	3	32	50	0.0000	1.3550	0.0000	25.0000
78	3	33	49	0.0000	1.1950	0.0000	25.0000

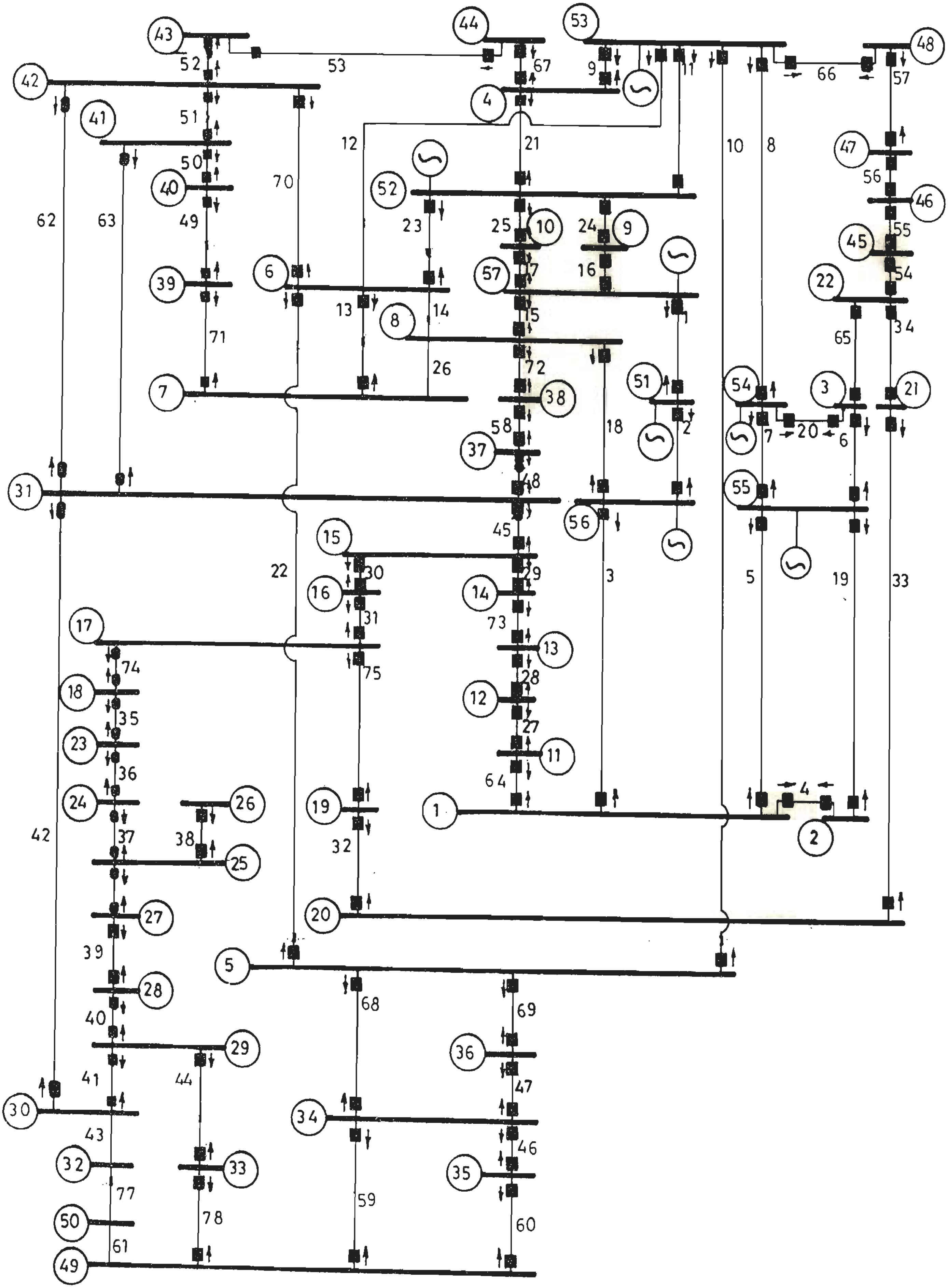


FIG.B.4-57-BUS IEEE TEST SYSTEM

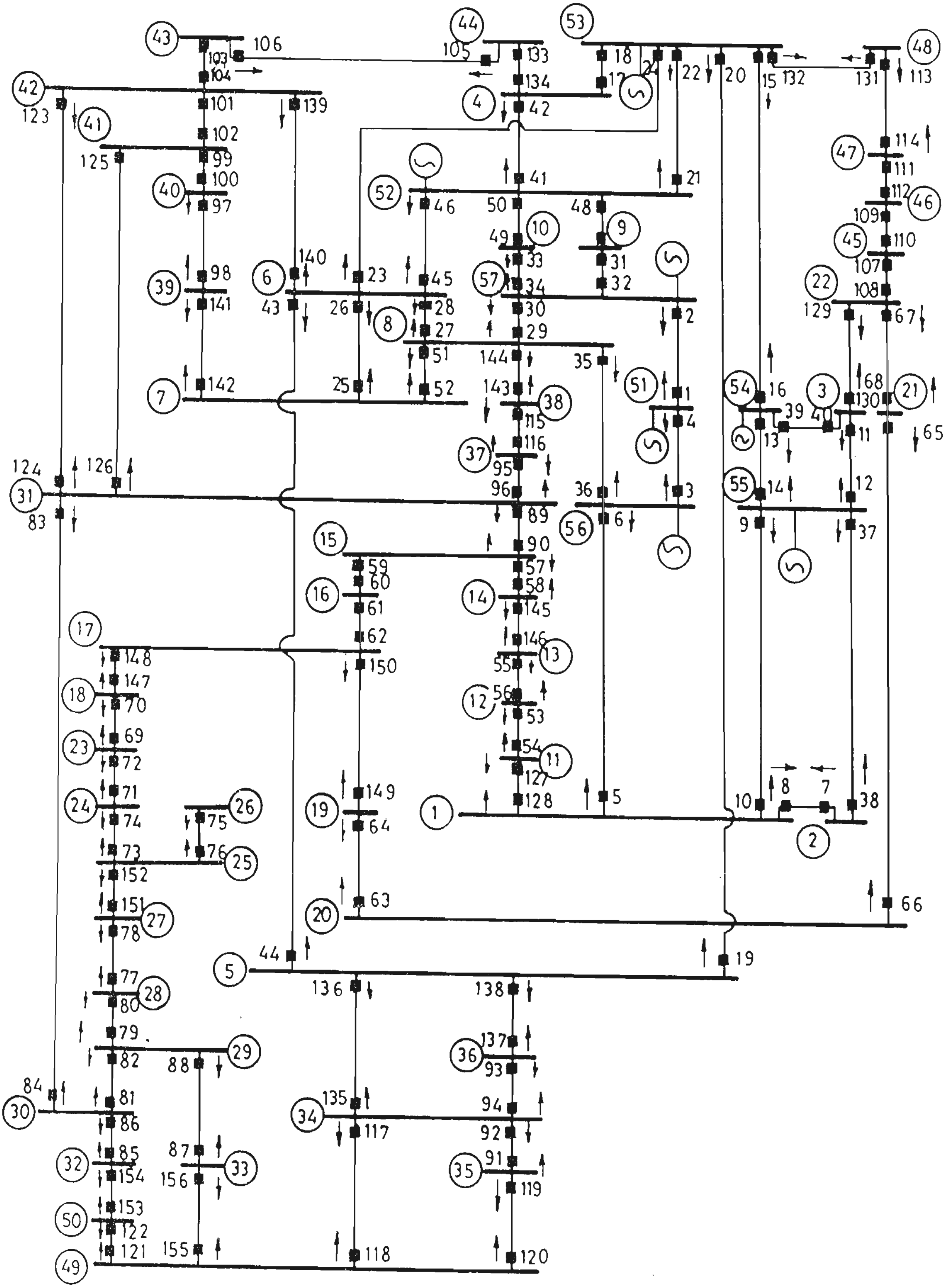


FIG. B.4.1 : 57-BUS IEEE TEST SYSTEM

TABLE : *B.5.1*

64 BUS SYSTEM : BUS DATA

BUS NO.	BUS TYPE	BUS VOLTAGE MAGNITUDE (P.U.)	ANGLE (RADIANS)	GENERATION ACTIVE (MW)	GENERATION REACTIVE (MVAR)	LOAD ACTIVE (MW)	LOAD REACTIVE (MVAR)	REACTOR/ CAPACITOR SUSCEPT. (P.U.)
1	2	3	4	5	6	7	8	9
1	0	0.9869	-0.3088	0.000	0.000	250.000	155.000	0.700
2	0	0.9949	-0.2829	0.000	0.600	100.000	62.000	0.350
3	0	0.9976	-0.0298	0.000	0.000	0.000	0.000	0.000
4	0	0.9625	-0.1072	0.000	0.000	260.000	161.100	0.000
5	0	0.9896	-0.1050	0.000	0.000	50.000	31.000	0.300
6	0	0.9915	-0.0902	0.000	0.000	100.000	62.000	0.500
7	0	0.9753	-0.2197	0.000	0.000	80.000	49.600	0.250
8	0	0.9983	-0.1601	0.000	0.000	89.000	50.200	0.450
9	0	0.9805	-0.2436	0.000	0.000	50.000	31.000	0.100
10	0	0.9866	-0.1130	0.000	0.000	45.000	27.900	0.300
11	0	0.9826	-0.1224	0.000	0.000	100.000	62.000	0.300
12	0	0.9717	-0.1429	0.000	0.000	50.000	31.000	0.100
13	0	0.9774	-0.1558	0.000	0.000	50.000	31.000	0.100
14	0	0.9632	-0.1260	0.000	0.000	65.000	40.300	0.200
15	0	0.9872	-0.1734	0.000	0.000	30.000	18.600	0.000
16	0	0.9765	-0.1841	0.000	0.000	90.300	55.800	0.250
17	0	0.9544	-0.0785	0.000	0.000	350.000	217.000	0.600
18	0	0.9357	-0.1110	0.000	0.000	90.000	55.800	0.300
19	0	0.9406	-0.0924	0.000	0.000	80.000	49.600	0.200
20	0	0.9679	-0.0274	0.000	0.000	80.000	49.000	0.200
21	0	0.9703	-0.0248	0.000	0.000	100.000	62.000	0.300
22	0	0.9936	-0.0992	0.000	0.000	54.000	33.500	0.150
23	0	0.9771	-0.0223	0.000	0.000	0.000	0.000	0.000
24	0	0.9713	-0.1265	0.000	0.000	50.000	31.000	0.000
25	0	0.9644	-0.1203	0.000	0.000	50.000	31.000	0.150
26	0	0.9752	-0.0882	0.000	0.000	115.000	71.300	0.350

TABLE : *B.5.1 CONTD...*

BUS NO.	BUS TYPE	BUS VOLTAGE MAGNITUDE (P.U.)	ANGLE (RADIANS)	GENERATION ACTIVE (MW)	REACTIVE (MVAR)	LOAD ACTIVE (MW)	REACTIVE (MVAR)	REACTOR/ CAPACITOR SUSCEPT. (P.U.)
1	2	3	4	5	6	7	8	9
27	0	1.0062	-0.1438	0.000	0.000	0.000	0.000	-0.650
28	0	0.9981	-0.2487	0.000	0.000	180.000	111.600	0.500
29	0	0.9868	-0.3302	0.000	0.000	65.000	40.300	0.150
30	0	0.9913	-0.3500	0.000	0.000	200.000	124.000	0.700
31	0	0.9922	-0.3420	0.000	0.000	35.000	21.700	0.000
32	0	0.9884	-0.3386	0.000	0.000	110.000	68.200	0.300
33	0	1.0523	-0.1568	0.000	0.000	10.000	0.000	-1.000
34	0	0.9764	-0.3346	0.000	0.000	205.000	127.000	0.700
35	0	0.9963	-0.2661	0.000	0.000	0.000	0.000	0.000
36	0	0.9875	-0.2980	0.000	0.000	200.000	124.000	0.800
37	0	0.9823	-0.3080	0.000	0.000	115.000	71.300	0.400
38	0	0.9944	-0.2826	0.000	0.000	95.000	58.900	0.550
39	0	0.9876	-0.3070	0.000	0.000	110.000	68.200	0.400
40	0	0.9916	-0.3022	0.000	0.000	215.000	133.200	0.800
41	0	1.0345	-0.4502	0.000	0.000	95.000	58.900	0.600
42	0	1.0460	-0.5012	0.000	0.000	170.000	105.400	1.000
43	0	1.0481	-0.4971	0.000	0.000	60.000	37.200	0.500
44	0	1.0033	-0.4745	0.000	0.000	174.000	107.800	0.500
45	0	1.0306	-0.4436	0.000	0.000	70.000	43.400	0.400
46	2	1.0000	-0.1275	351.000	0.000	0.000	0.000	0.000
47	2	1.0000	-0.4494	220.000	0.000	20.000	12.400	0.000
48	2	1.0000	-0.2853	600.000	0.000	15.500	9.600	0.000
49	2	1.0000	-0.0722	274.000	0.000	168.000	104.400	0.000
50	2	1.0000	-0.1197	135.000	0.000	14.000	8.700	0.000
51	2	1.0000	-0.2468	290.000	0.000	22.000	13.600	0.000
52	2	1.0000	-0.0607	220.000	0.000	22.000	13.600	0.600
53	2	1.0000	-0.1689	150.000	0.000	11.000	6.800	0.000
54	2	1.0000	-0.2456	110.000	0.000	221.000	136.800	0.700
55	2	1.0000	0.1296	345.000	0.000	4.000	2.500	0.000
56	2	1.0000	0,1073	180.000	0.000	2.000	1.200	0.000
57	2	1.0000	-0.0405	77.000	0.000	1.000	0.600	0.000
58	2	1.0000	-0.0301	77.000	0.000	1.000	0.600	0.000
59	2	1.0000	0.0271	360.000	0.000	7.000	4.300	0.000

TABLE : *B.5.1 CONTD...*

BUS NO.	BUS TYPE	BUS VOLTAGE MAGNITUDE (P.U.)	BUS VOLTAGE ANGLE (RADIANS)	GENERATION ACTIVE (MW)	GENERATION REACTIVE (MVAR)	LOAD ACTIVE (MW)	LOAD REACTIVE (MVAR)	REACTOR/ CAPACITOR SUSCEPT. (P.U.)
1	2	3	4	5	6	7	8	9
60	2	1.0000	0.0313	330.000	0.000	38.000	22.000	0.000
61	2	1.0000	0.0987	216.000	0.000	101.000	48.900	0.000
62	2	1.0000	0.0008	324.000	0.000	2.000	1.900	0.000
63	2	1.0000	0.0006	593.000	0.000	7.000	4.300	0.000
64	3	1.0000	0.0000	414.071	-418.991	7.000	4.300	0.000

TABLE : *B.5.2*

64 BUS SYSTEM : LINE DATA

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	LINE IMPEDANCE REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
1	1	62	3	0.0017	0.0067	0.0950	700.0000
2	1	3	8	0.0120	0.0476	0.2890	500.0000
3	1	8	28	0.0130	0.0518	0.3160	300.0000
4	1	28	36	0.0042	0.0182	0.2545	500.0000
5	1	36	37	0.0023	0.0090	0.0550	150.0000
6	1	63	3	0.0021	0.0104	0.0668	825.0000
7	1	63	4	0.0071	0.0359	0.2310	825.0000
8	1	4	17	0.0051	0.0261	0.1660	125.0000
9	1	4	16	0.0085	0.0339	0.2060	250.0000
10	1	16	32	0.0151	0.0602	0.3660	300.0000
11	1	32	31	0.0060	0.0238	0.1455	50.0000
12	1	31	30	0.0014	0.0064	0.1584	175.0000
13	1	30	29	0.0083	0.0332	0.2022	75.0000
14	1	29	1	0.0042	0.0168	0.1050	175.0000
15	1	60	3	0.0042	0.0263	0.1720	425.0000
16	1	3	7	0.0265	0.1336	0.2150	200.0000
17	1	7	9	0.0079	0.0399	0.0645	100.0000
18	1	9	28	0.0116	0.0584	0.0932	50.0000
19	1	3	4	0.0064	0.0323	0.2076	500.0000
20	1	3	5	0.0138	0.0706	0.1126	500.0000
21	1	3	52	0.0052	0.0265	0.0422	500.0000
22	1	3	6	0.0132	0.0668	0.1070	200.0000
23	1	6	52	0.0056	0.0290	0.0462	150.0000
24	1	6	10	0.0048	0.0250	0.0398	150.0000
25	1	52	5	0.0047	0.0243	0.1548	250.0000
26	1	5	11	0.0032	0.0166	0.1064	150.0000

TABLE : *B.5.2 CONTD...*

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	LINE IMPEDANCE REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
27	1	5	13	0.0077	0.0390	0.0622	200.0000
28	1	11	10	0.0042	0.0216	0.0348	100.0000
29	1	11	12	0.0082	0.0415	0.0666	100.0000
30	1	4	14	0.0026	0.0133	0.0204	200.0000
31	1	14	13	0.0080	0.0406	0.0596	100.0000
32	1	53	15	0.0048	0.0240	0.1540	425.0000
33	1	15	16	0.0070	0.0354	0.0544	425.0000
34	1	15	13	0.0080	0.0406	0.0596	425.0000
35	1	13	16	0.0051	0.0262	0.0420	200.0000
36	1	56	59	0.0087	0.0436	0.2804	225.0000
37	1	59	23	0.0068	0.0350	0.0560	450.0000
38	1	23	17	0.0092	0.0466	0.0744	200.0000
39	1	59	17	0.0064	0.0279	0.3886	450.0000
40	1	55	21	0.0123	0.0623	0.0996	450.0000
41	1	55	22	0.0034	0.0175	0.1120	450.0000
42	1	21	20	0.0147	0.0747	0.1202	100.0000
43	1	22	20	0.0204	0.1040	0.1658	150.0000
44	1	20	23	0.0048	0.0241	0.1544	50.0000
45	1	20	19	0.0098	0.0499	0.0798	200.0000
46	1	18	17	0.0131	0.0664	0.0532	100.0000
47	1	18	19	0.0075	0.0385	0.0612	100.0000
48	1	51	34	0.0082	0.0415	0.2672	425.0000
49	1	51	26	0.0008	0.0039	0.0561	425.0000
50	1	34	32	0.0118	0.0598	0.0964	50.0000
51	1	28	30	0.0180	0.0913	0.1470	200.0000
52	1	30	41	0.0229	0.1152	0.1768	100.0000
53	1	32	41	0.0190	0.0960	0.1520	150.0000
54	1	41	42	0.0118	0.0599	0.3840	125.0000
55	1	41	43	0.0132	0.0668	0.1070	100.0000
56	1	43	42	0.0107	0.0542	0.0868	50.0000
57	1	45	42	0.0211	0.1065	0.1710	75.0000
58	1	48	45	0.0237	0.1198	0.1920	200.0000
59	1	48	1	0.0020	0.0100	0.0640	400.0000

TABLE : *B.5.2 CONTD...*

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
60	1	48	40	0.0013	0.0067	0.0430	400.0000
61	1	40	39	0.0021	0.0106	0.0660	200.0000
62	1	39	36	0.0027	0.0138	0.0880	100.0000
63	1	36	38	0.0028	0.0142	0.0908	150.0000
64	1	38	2	0.0003	0.0017	0.0053	50.0000
65	1	2	48	0.0012	0.0063	0.0390	200.0000
66	1	35	38	0.0015	0.0072	0.1560	450.0000
67	1	35	48	0.0106	0.0500	0.0866	200.0000
68	1	31	41	0.0282	0.1418	0.2176	100.0000
69	1	64	27	0.0050	0.0577	1.5380	500.0000
70	1	64	33	0.0063	0.0720	1.8212	500.0000
71	1	27	46	0.0015	0.0170	0.4930	200.0000
72	1	58	57	0.0055	0.0107	0.0086	200.0000
73	1	57	26	0.0149	0.0315	0.0570	200.0000
74	1	26	25	0.0263	0.0512	0.0406	100.0000
75	1	25	24	0.0210	0.0400	0.0310	50.0000
76	1	47	44	0.0023	0.0119	0.1722	275.0000
77	1	44	42	0.0150	0.0770	0.4860	100.0000
78	3	61	62	0.0000	0.0833	0.0000	275.0000
79	3	53	54	0.0000	0.0690	0.0000	150.0000
80	3	1	50	0.0000	0.1460	0.0000	175.0000
81	3	64	60	0.0000	0.0495	0.0000	425.0000
82	3	35	46	0.0000	0.0520	0.0000	450.0000
83	3	2	49	0.0000	0.1870	0.0000	350.0000
84	3	4	24	0.0000	0.0385	0.0000	100.0000
85	3	31	33	0.0000	0.0800	0.0000	300.0000
86	3	26	52	0.0000	0.1250	0.0000	275.0000
87	3	3	58	0.0000	0.0385	0.0000	200.0000
88	3	28	27	0.0000	0.0311	0.0000	500.0000

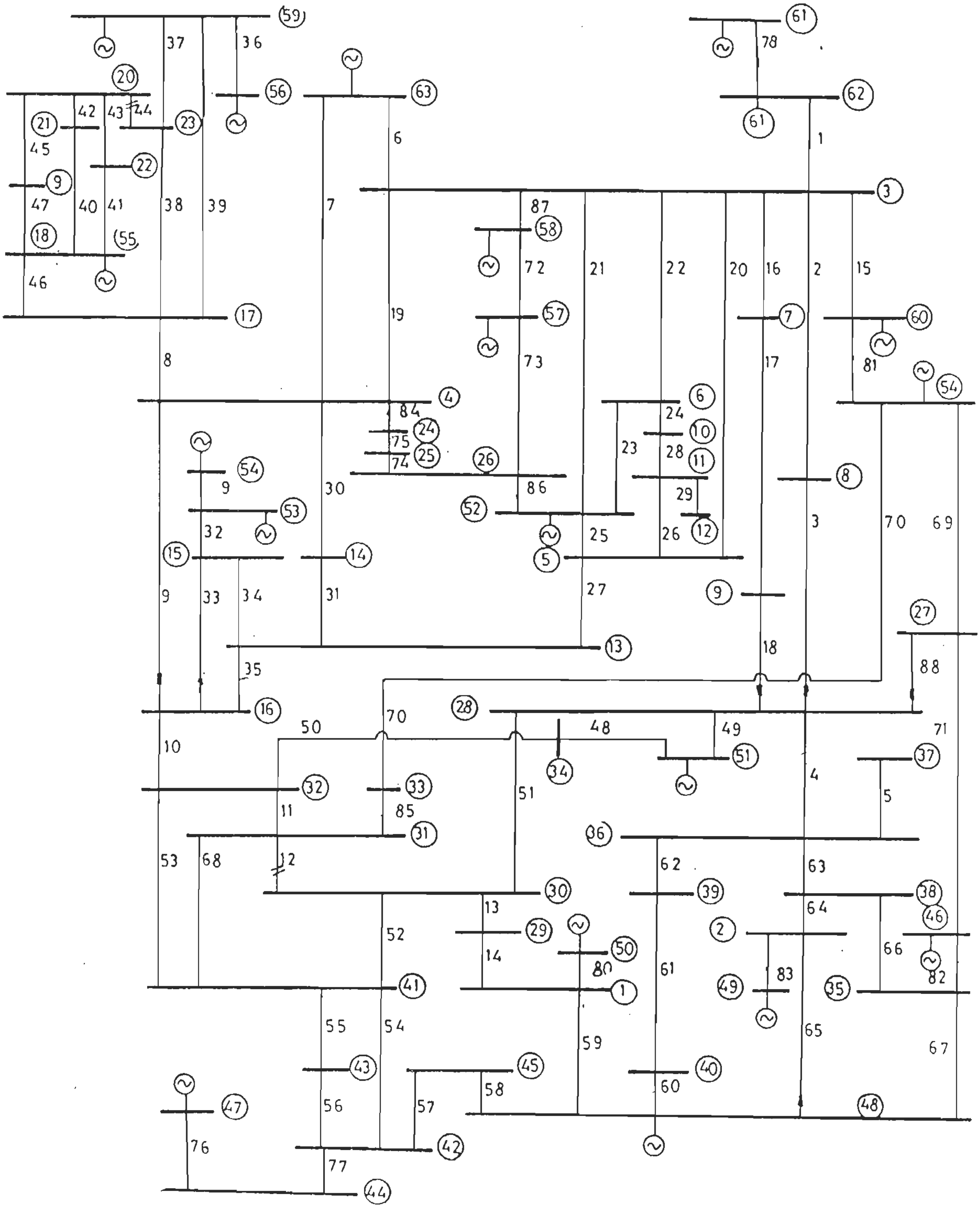


FIG.B.5 : 64–BUS NETWORK OF NORTH–WEST POWER SYSTEM OF INDIA

TABLE : *B.6.1*

118 BUS SYSTEM : BUS DATA

BUS NO.	BUS TYPE	BUS VOLTAGE MAGNITUDE (P.U.)	BUS VOLTAGE ANGLE (RADIANS)	GENERATION ACTIVE (MW)	GENERATION REACTIVE (MVAR)	LOAD ACTIVE (MW)	LOAD REACTIVE (MVAR)	REACTOR/ CAPACITOR SUSCEPT. (P.U.)
1	2	3	4	5	6	7	8	9
1	0	1.0639	-0.1638	0.000	0.000	20.000	9.000	0.000
2	0	1.0634	-0.1611	0.000	0.000	39.000	10.000	0.000
3	0	1.1001	-0.1045	0.000	0.000	0.000	0.000	-0.400
4	0	1.0825	-0.1451	0.000	0.000	19.000	2.000	0.000
5	0	1.0867	-0.0330	0.000	0.000	0.000	0.000	0.000
6	0	1.0793	-0.1405	0.000	0.000	70.000	23.000	0.000
7	0	1.0626	-0.1480	0.000	0.000	34.000	16.000	0.000
8	0	1.0737	-0.1446	0.000	0.000	14.000	1.000	0.000
9	0	1.0740	-0.1313	0.000	0.000	25.000	10.000	0.000
10	0	1.0883	-0.0585	0.000	0.000	11.000	3.000	0.000
11	0	1.0480	-0.0717	0.000	0.000	18.000	3.000	0.000
12	0	1.0449	-0.0328	0.000	0.000	14.000	8.000	0.000
13	0	1.0530	-0.0224	0.000	0.000	10.000	5.000	0.000
14	0	1.0825	-0.1230	0.000	0.000	7.000	3.000	0.000
15	0	1.0913	-0.0450	0.000	0.000	17.000	7.000	0.000
16	0	1.0956	-0.0296	0.000	0.000	24.000	4.000	0.000
17	0	0.9988	-0.0294	0.000	0.000	0.000	0.000	0.000
18	0	1.0475	-0.1314	0.000	0.000	23.000	9.000	0.000
19	0	1.0411	-0.1441	0.000	0.000	33.000	9.000	0.000
20	0	1.0492	-0.1309	0.000	0.000	0.000	0.000	-0.250
21	0	0.9838	-0.0845	0.000	0.000	0.000	0.000	0.000
22	0	0.9884	-0.1290	0.000	0.000	27.000	11.000	0.000
23	0	0.9681	-0.1290	0.000	0.000	37.000	10.000	0.000
24	0	1.0415	-0.1708	0.000	0.000	18.000	7.000	0.000
25	0	1.0517	-0.1793	0.000	0.000	16.000	8.000	0.100
26	0	1.0543	-0.1683	0.000	0.000	53.000	22.000	0.100

TABLE : *B.6.1 CONTD...*

BUS NO.	BUS TYPE	BUS VOLTAGE		GENERATION		LOAD		REACTOR/ CAPACITOR SUSCEPT. (P.U.)
		MAGNITUDE (P.U.)	ANGLE (RADIANS)	ACTIVE (MW)	REACTIVE (MVAR)	ACTIVE (MW)	REACTIVE (MVAR)	
1	2	3	4	5	6	7	8	9
27	0	1.0569	-0.1274	0.000	0.000	34.000	0.000	0.000
28	0	1.0775	-0.1427	0.000	0.000	20.000	11.000	0.150
29	0	1.0744	-0.1709	0.000	0.000	17.000	4.000	0.000
30	0	1.0687	-0.2074	0.000	0.000	17.000	8.000	0.000
31	0	1.0665	-0.2206	0.000	0.000	18.000	5.000	0.000
32	0	1.0764	-0.2319	0.000	0.000	23.000	11.000	0.000
33	0	1.0820	-0.2053	0.000	0.000	12.000	3.000	0.000
34	0	1.0767	-0.2170	0.000	0.000	12.000	3.000	0.000
35	0	1.0040	-0.1127	0.000	0.000	78.000	3.000	0.000
36	0	1.0267	-0.1249	0.000	0.000	0.000	0.000	0.000
37	0	1.0588	-0.0967	0.000	0.000	0.000	0.000	0.000
38	0	1.0307	-0.1140	0.000	0.000	28.000	7.000	0.000
39	0	1.0556	-0.0220	0.000	0.000	0.000	0.000	0.000
40	0	0.9063	0.1188	0.000	0.000	0.000	0.000	0.000
41	0	0.9089	-0.0341	0.000	0.000	47.000	11.000	0.000
42	0	0.9760	0.0046	0.000	0.000	71.000	26.000	0.000
43	0	0.9837	0.0050	0.000	0.000	39.000	32.000	0.200
44	0	1.0036	0.0005	0.000	0.000	0.000	0.000	0.000
45	0	0.9798	0.1257	0.000	0.000	54.000	27.000	0.200
46	0	0.9801	0.1872	0.000	0.000	20.000	10.000	0.100
47	0	0.9946	0.2933	0.000	0.000	11.000	7.000	0.000
48	0	1.0339	0.4668	0.000	0.000	21.000	10.000	0.000
49	0	1.0313	0.3899	0.000	0.000	48.000	10.000	0.000
50	0	1.0324	0.2829	0.000	0.000	12.000	7.000	0.000
51	0	1.0296	0.2212	0.000	0.000	30.000	16.000	0.000
52	0	1.0031	0.1759	0.000	0.000	42.000	31.000	0.000
53	0	0.9951	0.1347	0.000	0.000	38.000	15.000	0.000
54	0	1.0015	0.0778	0.000	0.000	15.000	9.000	0.000
55	0	1.0358	0.0962	0.000	0.000	34.000	8.000	0.000
56	0	1.0635	0.2818	0.000	0.000	22.000	15.000	0.000
57	0	1.0520	0.3329	0.000	0.000	5.000	3.000	0.000
58	0	1.0777	0.2824	0.000	0.000	43.000	16.000	0.000
59	0	1.0781	0.3206	0.000	0.000	2.000	1.000	0.000

TABLE : *B.6.1 CONTD...*

BUS NO.	BUS TYPE	BUS VOLTAGE MAGNITUDE (P.U.)	ANGLE (RADIANS)	GENERATION ACTIVE (MW)	REACTIVE (MVAR)	LOAD ACTIVE (MW)	REACTIVE (MVAR)	REACTOR/ CAPACITOR SUSCEPT. (P.U.)
1	2	3	4	5	6	7	8	9
60	0	1.0782	0.3327	0.000	0.000	8.000	3.000	0.000
61	0	1.0868	0.0492	0.000	0.000	8.000	3.000	0.000
62	0	1.0869	0.0502	0.000	0.000	22.000	7.000	0.000
63	0	1.0643	-0.1711	0.000	0.000	20.000	8.000	0.000
64	0	0.8976	-0.0590	0.000	0.000	33.000	15.000	0.000
65	2	1.0620	-0.0201	250.000	115.000	184.000	0.000	0.000
66	2	1.1000	-0.0258	100.000	6.000	6.000	0.000	0.000
67	2	1.1000	0.3941	118.100	13.000	68.000	13.000	0.000
68	2	1.1000	0.4330	100.000	-8.000	0.000	0.000	0.000
69	2	1.0830	0.3694	0.000	0.000	39.000	30.000	0.060
70	2	1.1000	0.3397	120.100	0.000	50.000	12.000	0.060
71	2	1.0790	0.2922	20.000	-5.000	31.000	26.000	0.200
72	2	1.0790	0.2804	20.000	5.000	38.000	25.000	0.000
73	2	1.0910	0.2775	18.700	11.000	23.000	16.000	0.000
74	2	1.1000	0.2473	100.000	300.000	37.000	18.000	0.000
75	2	1.0710	0.2339	124.900	-23.000	42.000	0.000	0.000
76	2	1.0490	0.3611	10.000	0.000	65.000	10.000	0.000
77	2	1.0746	0.4678	125.600	-19.000	10.000	0.000	0.000
78	2	1.0740	0.4504	150.700	60.000	163.000	42.000	0.000
79	2	1.0590	0.4480	400.000	-5.000	0.000	0.000	0.000
80	2	1.1000	0.6873	124.200	32.000	0.000	0.000	0.000
81	2	1.0130	0.3482	10.000	3.000	24.000	15.000	0.000
82	2	1.0210	0.0316	100.000	-31.000	130.000	26.000	0.000
83	2	0.9780	0.0129	30.700	38.000	61.000	28.000	0.000
84	2	0.9000	-0.0681	0.000	8.000	68.000	36.000	0.000
85	2	0.9000	-0.0375	5.000	0.000	68.000	27.000	0.120
86	2	0.9000	0.1741	100.000	-27.000	6.000	0.000	0.000
87	2	0.9000	0.2584	100.000	-100.000	12.000	0.000	0.000
88	2	0.9150	0.0486	10.000	0.000	66.000	20.000	0.000
89	2	1.0510	-0.1732	0.000	0.000	51.000	27.000	0.000
90	2	1.0640	-0.0891	100.000	-28.000	39.000	18.000	0.000
91	2	1.0680	-0.0537	100.000	114.000	0.000	0.000	0.000
92	2	1.0060	-0.1142	10.000	2.000	77.000	14.000	0.000

TABLE : *B.6.1 CONTD...*

BUS NO.	BUS TYPE	BUS VOLTAGE MAGNITUDE (P.U.)	ANGLE (RADIANS)	GENERATION ACTIVE (MW)	REACTIVE (MVAR)	LOAD ACTIVE (MW)	REACTIVE (MVAR)	REACTOR/ CAPACITOR SUSCEPT. (P.U.)
1	2	3	4	5	6	7	8	9
93	2	0.9980	-0.0956	205.000	-46.000	0.000	0.000	0.000
94	2	1.0900	-0.1763	120.100	74.000	277.000	113.000	0.000
95	2	1.0930	-0.2201	7.200	-5.000	84.000	16.000	0.000
96	2	1.0910	-0.2217	15.000	5.000	63.000	22.000	0.000
97	2	1.1000	-0.2181	109.400	148.000	113.000	32.000	0.000
98	2	1.0770	-0.1410	100.000	139.000	87.000	30.000	0.000
99	2	1.0770	-0.1120	111.100	-6.000	28.000	10.000	0.000
100	2	1.0050	-0.1253	106.600	9.000	96.000	23.000	0.100
101	2	0.9650	-0.1125	101.700	-100.000	66.000	23.000	0.000
102	2	1.0410	-0.1439	5.000	-5.000	31.000	17.000	0.000
103	2	1.0490	-0.1389	5.000	15.000	59.000	26.000	0.000
104	2	1.0890	0.0473	5.000	12.000	59.000	23.000	0.140
105	2	1.1000	0.0305	100.000	37.000	43.000	27.000	0.000
106	2	1.0950	0.0701	100.000	9.000	71.000	13.000	0.000
107	2	0.9760	0.1914	300.000	-118.000	0.000	0.000	0.000
108	2	1.1000	0.1742	100.000	33.000	0.000	0.000	0.000
109	2	1.0800	0.1575	100.000	91.000	13.000	0.000	0.000
110	2	1.0600	-0.1060	5.000	14.000	45.000	25.000	0.000
111	2	1.0680	-0.0936	5.000	23.000	60.000	34.000	0.000
112	2	1.0630	-0.1085	5.000	5.000	90.000	30.000	0.000
113	2	1.0800	-0.1488	30.000	75.000	47.000	10.000	0.000
114	2	1.1000	-0.0069	100.000	-71.000	0.000	0.000	0.000
115	2	1.0550	-0.0573	100.000	-8.000	28.000	0.000	0.000
116	2	1.0850	-0.1395	5.000	18.000	52.000	22.000	0.000
117	2	1.1000	-0.1048	100.000	14.000	39.000	12.000	0.000
118	3	0.9500	0.0000	105.831	-88.270	0.000	0.000	0.000

TABLE : *B.6.2*

118 BUS SYSTEM : LINE DATA

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
1	1	89	1	0.0303	0.0999	0.0063	130.0000
2	1	89	2	0.0129	0.0424	0.0027	130.0000
3	1	1	113	0.0187	0.0616	0.0039	130.0000
4	1	2	3	0.0241	0.1080	0.0071	325.0000
5	1	2	113	0.0484	0.1600	0.0101	130.0000
6	1	117	6	0.0209	0.0688	0.0043	130.0000
7	1	117	3	0.0018	0.0080	0.0005	280.0000
8	1	3	6	0.0203	0.0682	0.0043	130.0000
9	1	3	116	0.0119	0.0540	0.0035	157.5000
10	1	116	4	0.0045	0.0208	0.0013	157.5000
11	1	4	113	0.0086	0.0340	0.0021	144.0000
12	1	115	17	0.0043	0.0504	0.1285	700.0000
13	1	115	5	0.0024	0.0305	0.2905	1395.0000
14	1	5	114	0.0026	0.0322	0.3075	1395.0000
15	1	6	113	0.0059	0.0196	0.0012	130.0000
16	1	6	7	0.0222	0.0731	0.0047	130.0000
17	1	113	9	0.0212	0.0834	0.0053	144.0000
18	1	113	63	0.0329	0.1400	0.0089	144.0000
19	1	113	6	0.0215	0.0707	0.0045	130.0000
20	1	7	112	0.0744	0.2444	0.0156	130.0000
21	1	8	112	0.0595	0.1950	0.0125	130.0000
22	1	112	10	0.0132	0.0437	0.0111	260.0000
23	1	112	110	0.0120	0.0394	0.0025	130.0000
24	1	112	18	0.0380	0.1244	0.0080	130.0000
25	1	9	10	0.0454	0.1801	0.0116	144.0000
26	1	10	66	0.0091	0.0301	0.0019	280.0000

TABLE : *B.6.2 CONTED...*

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE		HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
				RESISTANCE (P.U.)	REACTANCE (P.U.)		
1	2	3	4	5	6	7	8
27	1	10	111	0.0123	0.0505	0.0032	325.0000
28	1	10	105	0.0474	0.1563	0.0100	130.0000
29	1	111	110	0.0111	0.0493	0.0028	263.0000
30	1	110	11	0.0252	0.1170	0.0074	157.5000
31	1	110	103	0.0752	0.2470	0.0158	130.0000
32	1	11	12	0.0183	0.0849	0.0054	157.5000
33	1	12	13	0.0209	0.0970	0.0061	157.5000
34	1	13	14	0.0342	0.1590	0.0101	157.5000
35	1	14	104	0.0317	0.1153	0.0293	260.0000
36	1	14	109	0.0135	0.0492	0.0124	288.4000
37	1	14	108	0.0156	0.0800	0.0216	168.3000
38	1	109	88	0.1022	0.4115	0.0255	144.0000
39	1	109	87	0.0488	0.1960	0.0122	144.0000
40	1	108	106	0.0318	0.1630	0.0441	336.4000
41	1	107	17	0.0079	0.0860	0.2270	645.3000
42	1	106	104	0.0229	0.0755	0.0048	130.0000
43	1	106	62	0.0164	0.0741	0.0049	130.0000
44	1	106	15	0.0191	0.0855	0.0054	157.5000
45	1	15	16	0.0237	0.0943	0.0059	157.5000
46	1	16	105	0.0108	0.0331	0.0020	130.0000
47	1	17	21	0.0046	0.0540	0.1055	645.3000
48	1	105	104	0.0298	0.0985	0.0062	130.0000
49	1	104	66	0.0615	0.2030	0.0129	280.0000
50	1	104	61	0.0135	0.0612	0.0040	157.5000
51	1	18	20	0.0415	0.1420	0.0091	130.0000
52	1	103	102	0.0087	0.0268	0.0014	157.5000
53	1	103	20	0.0026	0.0094	0.0024	284.4000
54	1	103	24	0.0413	0.1681	0.0105	144.0000
55	1	19	102	0.0022	0.0102	0.0006	144.0000
56	1	19	20	0.0110	0.0497	0.0033	157.5000
57	1	20	22	0.0321	0.1060	0.0067	130.0000
58	1	20	101	0.0593	0.1680	0.0105	284.4000
59	1	21	91	0.0090	0.0986	0.2615	645.3000

TABLE : *B.6.2 CONTED...*

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	LINE IMPEDANCE REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
60	1	22	101	0.0184	0.0605	0.0038	130.0000
61	1	101	23	0.0145	0.0487	0.0030	130.0000
62	1	101	100	0.0555	0.1830	0.0116	130.0000
63	1	23	100	0.0410	0.1350	0.0086	130.0000
64	1	100	98	0.0358	0.1610	0.0430	297.0000
65	1	24	25	0.0608	0.2454	0.0151	144.0000
66	1	25	26	0.0224	0.0901	0.0056	144.0000
67	1	26	99	0.0400	0.1356	0.0083	130.0000
68	1	26	98	0.0684	0.1860	0.0111	157.5000
69	1	99	27	0.0380	0.1270	0.0079	130.0000
70	1	99	28	0.0601	0.1890	0.0118	130.0000
71	1	27	98	0.0191	0.0625	0.0040	130.0000
72	1	27	118	0.0844	0.2778	0.0177	130.0000
73	1	28	98	0.0179	0.0505	0.0031	130.0000
74	1	98	29	0.0267	0.0752	0.0046	284.4000
75	1	98	30	0.0486	0.1370	0.0085	284.4000
76	1	98	90	0.0090	0.0459	0.0124	838.8000
77	1	98	118	0.0985	0.3240	0.0207	130.0000
78	1	98	97	0.0398	0.1410	0.0367	288.4000
79	1	29	33	0.0474	0.1340	0.0083	284.4000
80	1	30	31	0.0203	0.0588	0.0035	284.4000
81	1	30	34	0.0255	0.0719	0.0044	284.4000
82	1	31	32	0.0405	0.1635	0.0101	144.0000
83	1	32	97	0.0263	0.1220	0.0077	157.5000
84	1	97	96	0.0169	0.0707	0.0050	325.0000
85	1	97	95	0.0027	0.0095	0.0018	234.0000
86	1	97	94	0.0503	0.2293	0.0149	462.6000
87	1	96	95	0.0048	0.0151	0.0009	130.0000
88	1	96	94	0.0473	0.2158	0.0141	157.5000
89	1	95	33	0.0343	0.0966	0.0060	284.4000
90	1	95	34	0.0343	0.0966	0.0060	284.4000
91	1	95	94	0.0407	0.1200	0.0276	207.0000
92	1	94	35	0.0317	0.1450	0.0094	157.5000

TABLE : *B.6.2 CONTED...*

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	LINE IMPEDANCE REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
93	1	94	93	0.0328	0.1500	0.0097	157.5000
94	1	35	93	0.0026	0.0135	0.0036	168.3000
95	1	35	92	0.0123	0.0561	0.0036	157.5000
96	1	93	92	0.0082	0.0376	0.0024	157.5000
97	1	92	90	0.0482	0.2180	0.0144	157.5000
98	1	92	38	0.0258	0.1170	0.0077	157.5000
99	1	36	37	0.0017	0.0200	0.0540	700.0000
100	1	37	91	0.0027	0.0302	0.0950	700.0000
101	1	91	39	0.0014	0.0160	0.1595	1343.7000
102	1	90	38	0.0224	0.1015	0.0067	157.5000
103	1	39	65	0.0003	0.0040	0.0410	700.0000
104	1	39	44	0.0017	0.0202	0.2020	645.3000
105	1	118	41	0.0405	0.1220	0.0310	130.0000
106	1	118	83	0.0309	0.1010	0.0259	130.0000
107	1	118	88	0.0300	0.1270	0.0305	144.0000
108	1	88	40	0.0088	0.0355	0.0021	144.0000
109	1	88	85	0.0401	0.1323	0.0084	130.0000
110	1	88	41	0.0428	0.1410	0.0090	130.0000
111	1	40	87	0.0446	0.1800	0.0111	144.0000
112	1	40	86	0.0087	0.0454	0.0029	168.3000
113	1	85	41	0.0123	0.0406	0.0025	130.0000
114	1	41	64	0.0145	0.0481	0.0029	130.0000
115	1	41	83	0.0601	0.1999	0.0124	130.0000
116	1	84	64	0.0164	0.0544	0.0034	130.0000
117	1	84	83	0.0444	0.1480	0.0092	130.0000
118	1	83	42	0.0037	0.0124	0.0031	130.0000
119	1	83	82	0.0108	0.0331	0.0175	228.6000
120	1	83	45	0.0298	0.0853	0.0204	114.3000
121	1	42	43	0.0054	0.0244	0.0016	157.5000
122	1	43	82	0.0156	0.0704	0.0046	157.5000
123	1	82	53	0.0356	0.1820	0.0123	168.3000
124	1	82	54	0.0183	0.0934	0.0063	168.3000
125	1	82	55	0.0238	0.1080	0.0071	157.5000

TABLE : *B.6.2 CONTED...*

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
126	1	82	75	0.0454	0.2060	0.0136	157.5000
127	1	45	53	0.0162	0.0530	0.0136	260.0000
128	1	45	46	0.0112	0.0366	0.0095	130.0000
129	1	46	47	0.0625	0.1320	0.0064	182.7000
130	1	46	81	0.0430	0.1480	0.0087	130.0000
131	1	47	81	0.0302	0.0641	0.0030	168.3000
132	1	81	48	0.0350	0.1230	0.0069	130.0000
133	1	81	49	0.0200	0.1020	0.0069	168.3000
134	1	81	79	0.0239	0.1730	0.0117	168.3000
135	1	48	80	0.0282	0.2074	0.0111	180.9000
136	1	49	79	0.0139	0.0712	0.0048	168.3000
137	1	79	78	0.0158	0.0653	0.0397	673.2000
138	1	79	76	0.0079	0.0380	0.0240	336.6000
139	1	78	77	0.0254	0.0836	0.0053	130.0000
140	1	77	76	0.0387	0.1272	0.0081	130.0000
141	1	76	50	0.0258	0.0848	0.0054	130.0000
142	1	76	51	0.0481	0.1580	0.0101	130.0000
143	1	76	74	0.0648	0.2950	0.0193	157.5000
144	1	76	57	0.0123	0.0559	0.0036	157.5000
145	1	50	51	0.0223	0.0732	0.0047	130.0000
146	1	51	52	0.0132	0.0434	0.0027	130.0000
147	1	51	53	0.0269	0.0869	0.0057	130.0000
148	1	51	74	0.0178	0.0580	0.0151	260.0000
149	1	52	53	0.0171	0.0547	0.0037	130.0000
150	1	53	54	0.0173	0.0885	0.0060	168.3000
151	1	55	74	0.0397	0.1790	0.0119	157.5000
152	1	75	74	0.0180	0.0813	0.0054	157.5000
153	1	74	56	0.0277	0.1262	0.0082	157.5000
154	1	74	73	0.0160	0.0525	0.0134	130.0000
155	1	74	72	0.0451	0.2040	0.0135	157.5000
156	1	74	58	0.0605	0.2290	0.0155	157.5000
157	1	56	57	0.0246	0.1120	0.0073	157.5000
158	1	73	69	0.0391	0.1813	0.0115	157.5000

TABLE : *B.6.2 CONTED...*

LINE NO.	LINE TYPE	FROM BUS	TO BUS	LINE IMPEDANCE RESISTANCE (P.U.)	LINE IMPEDANCE REACTANCE (P.U.)	HALF LINE CHARGING SUSCEPTANCE (P.U.)	LINE RATING (MW)
1	2	3	4	5	6	7	8
159	1	73	72	0.0466	0.1584	0.0101	130.0000
160	1	73	71	0.0535	0.1625	0.0102	130.0000
161	1	72	71	0.0099	0.0378	0.0024	130.0000
162	1	71	58	0.0140	0.0547	0.0036	130.0000
163	1	71	70	0.0530	0.1830	0.0118	130.0000
164	1	71	59	0.0261	0.0703	0.0046	114.3000
165	1	58	70	0.0530	0.1830	0.0118	130.0000
166	1	59	60	0.0105	0.0288	0.0019	114.3000
167	1	60	69	0.0278	0.0762	0.0050	114.3000
168	1	69	68	0.0220	0.0755	0.0050	130.0000
169	1	69	67	0.0247	0.0640	0.0155	114.3000
170	1	61	62	0.0023	0.0104	0.0007	157.5000
171	3	115	3	0.0000	0.0267	0.0000	1800.0000
172	3	107	108	0.0000	0.0382	0.0000	1800.0000
173	3	17	10	0.0000	0.0388	0.0000	1800.0000
174	3	21	20	0.0000	0.0375	0.0000	1800.0000
175	3	36	94	0.0000	0.0386	0.0000	1800.0000
176	3	37	93	0.0000	0.0268	0.0000	1800.0000
177	3	91	90	0.0000	0.0370	0.0000	1800.0000
178	3	39	118	0.0000	0.0370	0.0000	1800.0000
179	3	44	82	0.0000	0.0370	0.0000	1800.0000

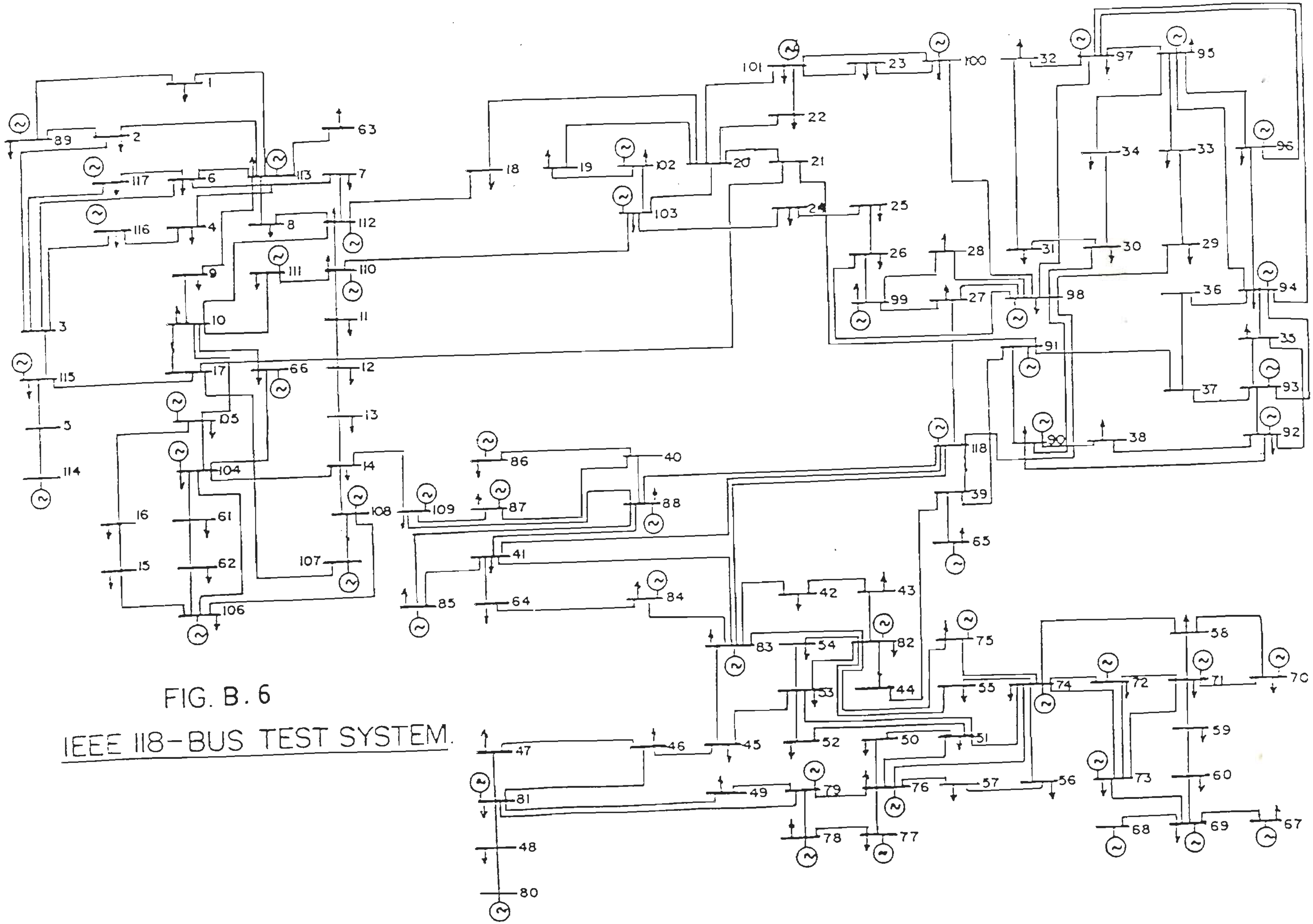


FIG. B. 6

IEEE 118-BUS TEST SYSTEM.

LINKNET STRUCTURE

In the development of any algorithm which deals with a network, the programmer has to decide on how the information of the network should be stored in computer memory. It is important for the large sparse storage network analysis of power system.

The LINKNET structure [60] is a general purpose structure for representing networks in a computer. It incorporates each of the desirable features. The node numbering is done manually but branch numbering is left to the computer. The properties of the network are node properties, branch properties and topological properties. For each node or branch property a one dimensional array is allocated and each position in the array is identified with the node or branch having the corresponding number.

The topological properties are represented by specifying the connections between the nodes and the branches, assuming that the ends of each branch are numbered as follows : ends of branch 1 are numbered 1 and 2, ends of branch 2 are numbered 3 and 4 etc. Thus the branch end numbers may be derived from a branch number as -

$$\text{END} = f\ (\text{BRANCH})$$

$$= 2.\text{BRANCH}-1$$

and

$$\text{END} = g\ (\text{BRANCH})$$

$$= 2.\text{BRANCH}$$

Conversely a branch number may be derived from either of its ends numbers using, BRANCH = h(END)

= (END+1)/2

In this relationship the integer round off is used to obtain the two to one mapping between branch ends and branches. The topology of the network can be defined by constructing a linked-list of the branch ends which are connected to each node.

LIST(NODE) = The first branch end on the list from node. For each branch a pointer is defined, NEXT(END)= The next branch end on the list after END. The last branch end on the list for each node is indicated when NEXT(END)=0. The LIST(NODE) and NEXT(END) are sufficient to define the network topology. The branches connected to any node can be obtained by using the procedure.

Initialize, END = LIST(NODE)

then set BRANCH= h(END)

and END = NEXT(END) Until NEXT(END) = 0

To find out the nodes which are connected to a given node, an additional pointer for each branch is defined.

FAR(END) = The node at the far or opposite end of the branch. The nodes connected to any given node can be obtained using the procedure.

Initialize, END = LIST(NODE)

Set NODE B = FAR(END)

and END = NEXT(END) Until NEXT(END) = 0

The successive values of NODE B will be the nodes which are connected to NODE A. It may also be required to get the nodes at the ends of a given branch, which can be obtained as follows :

END A = f(BRANCH)

END B = g(BRANCH)

NODEA = FAR(ENDB)

NODEB = FAR(ENDA)

Fig C.1,a flow chart illustrates how the LINKNET structure can be built simply by adding each branch to the network.

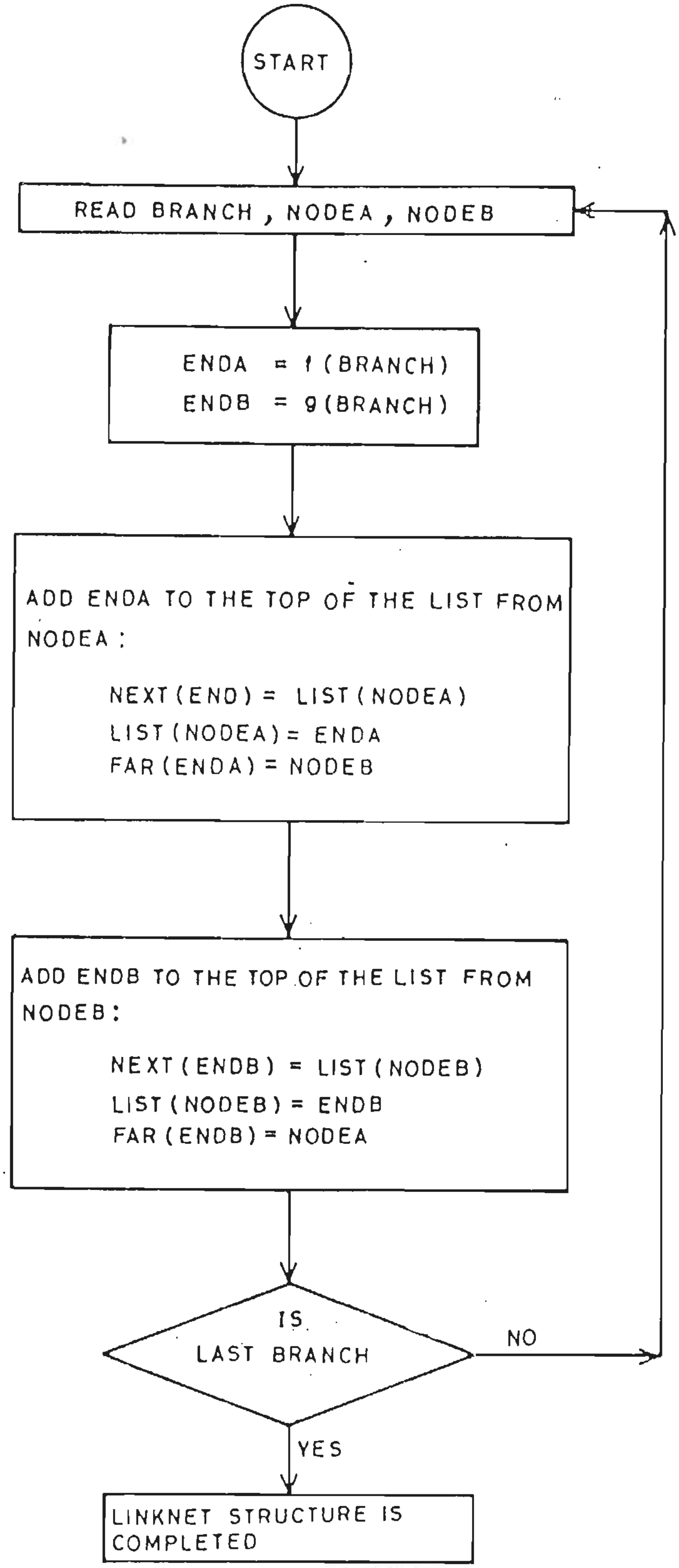


FIG. C.1 FLOW CHART FOR CONSTRUCTION OF THE LINKET STRUCTURE.

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LIST OF PUBLICATIONS BY THE AUTHOR

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