REVIEW OF SOFTWARE FOR POWER SYSTEM SIMULATION AND OPTIMIZATION

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Abstract

A review of the software for power system simulation and optimization developed in the Simulation Optimization Systems Research Laboratory is given in this report. Data bases, routines for data reading and preprocessing, packages for load flow analysis, contingency analysis and gradient analysis and methods of power system optimization are reviewed. Appropriate references to original documents are given. The programs and packages listed in this document have been prepared in Fortran IV for use on the CDC 170/730 system with the NOS 1.4 operating system and on the CDC 170/815 with the NOS 2.1 operating system.

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I. INTRODUCTION

This document is a review of the software for power system simulation and optimization developed in the Simulation Optimization Systems Research Laboratory, Department of Electrical and Computer Engineering, McMaster University.

Power system control and design require computationally intense simulations and optimization, involving large data bases with an easy two-way communication. The software discussed in this document has been prepared to meet these requirements.

The tendency to consider different power system optimization problems in the context of optimal load flow has been observed [1,2]. An optimal power flow solution is defined as the determination of the complete state of a power system corresponding to the best operation, while recognizing limitations on the system equipment. Best operation usually means least production cost. Recently, security requirements have also been incorporated into optimal power flows. It is required that the system operates both under normal and emergency conditions, i.e., when one or several elements of the system suddenly trip. Typically, the outage of one transmission line or of one generator at a time is allowed. However, security demands may sometimes be very sophisticated. Consequently, the number of optimization problems considered within optimal power flows may increase and their sizes may become huge.

The programs and packages listed in this document have been prepared in Fortran IV for use on the CDC 170/730 system with the NOS 1.4 operating system or the CDC 170/815 with the NOS 2.1 operating system. The programs and packages are reviewed and references to the original documents are provided.

II. THE SOFTWARE CAPABILITY

The capability of the software prepared in the Simulation Optimization Systems Research Laboratory is illustrated in Fig. 1. The general approach to solving various problems arising in the power system simulation and optimization can be divided into a few logical steps.

The data bases are permanent files storing the numbers describing appropriate power system models. Data files may be created by the user by calling the specific subroutines after processing original data.

Data reading and preprocessing subroutines create a link between the data bases and a group of subroutines for load flow analysis, contingency analysis and gradient analysis. The load flow problems can be solved with the aid of direct methods, i.e., the fast decoupled method [3], the Newton complex method [4], the Newton real method [5,6], the Tellegen theorem method [7], or with the use of system reduction [8,9] or decomposition and one of the direct methods. Gradient analysis is performed using the Tellegen theorem method [10] or the complex Lagrange multiplier approach [11].

Available subroutines for solving load flow problems, contingency analysis and sensitivity analysis used in conjunction with general optimization packages enable the user to solve any relevant problem in power system optimization. A qualitative representation of the software systems developed is displayed in Fig. 2.

III. AVAILABLE REPORTS AND DOCUMENTS

Available documents describing the software for power system simulation and optimization summarized in Tables I-III are discussed below.

1. Formatted data files [12]. This document presents formatted data files describing test power systems, i.e., 3-bus, 6-bus, 23-bus, 26-bus and the IEEE 118-bus power systems.

2. PWRDD [13] is a package of subroutines for reading unformatted data describing power systems.

3. PWRDS [14] is a package of subroutines for reading and preprocessing unformatted data for power system analysis.

4. DDATA [15] is a package of data handling routines used in packages PWRDD and PWRDS.

5. LFLFD [16] is a package that implements the fast decoupled method for solving load flow problems and uses unformatted data files.

6. LFLNR [17] is a package that implements the Newton-Raphson method in the real mode for solving load flow problems and uses unformatted data files.

7. XLF3 [18] is a package that implements the Newton complex method for solving load flow problems and uses formatted data files. XLF3 also determines function gradients with the use of Lagrange multipliers [11].

8. TTM1 [19] is a package that contains a group of subroutines for reading and preprocessing formatted data, a group of subroutines for solving load flow problems using the fast decoupled method and the Tellegen theorem method, and a group of subroutines for sensitivity calculations using the adjoint network.

9. DECNCM [20] is a package of subroutines for solving load flow problems using system decomposition and the Newton complex method.

10. WARDEQ [21] is a package that determines the Ward type power equivalents and prepares data describing a reduced system for load flow analysis and contingency analysis.

11. CTTM1 [22] is a package for power system contingency analysis.

12. CNTL [23] is a package that processes the results of contingency analysis.

13. GTTM1 [24] is a general package for power system gradient analysis using the Tellegen theorem method.

IV. POWER SYSTEM MODEL

For simulation and optimization purposes, a power system can be modelled as shown in Fig. 3.

The source branches are: load branches for which the complex power is specified, generator branches for which active power and voltage magnitude are specified and one slack generator for which voltage magnitude and argument are specified. An additional branch connecting the bus and the ground node represents the bus static load.

A power transmission network constitutes the bus static loads and transmission elements. The model of a transmission element is shown in Fig. 4. Admittances $G_i + jB_i$ and $G_o + jB_o$ represent input and output line shunt admittances; $R_t + jX_t$ and a_t represent impedance and turns ratio, respectively.

V. DATA BASES

Data describing power systems may be unformatted or formatted. Unformatted data files are designated by the first letter as D and formatted files by the first letter as B. These data files have been summarized in Table IV.

Different data items are identified in D-files by descriptors. The structure of these files is open in the sense that new descriptors can be included and more data can be added. For example, the IEEE 118-bus data file contains not only data describing the system model but also the upper and lower bounds on system variables and the coefficients for solving an economic dispatch problem.

B-files [12] are formatted data files containing, in the present version, only a power system model description. It is assumed in both D-files and B-files that the transformer ratio is a real number. However, there are also available modified B-files with complex transformer ratios [18].

The following permanent data D-files and B-files are available for the user on the CDC system.

D6 6-bus power system [25,26] with bus voltages under the assumption of flat voltage profile.

D23 23-bus power system [26,27] with bus voltages under the assumption of flat voltage profile.

D26 26-bus power system [26,28] with bus voltages under the assumption of flat voltage profile.

D118 the IEEE 118-bus power system [29] with bus voltages under the assumption of flat voltage profile.

D118OP the IEEE 118-bus optimized power system [30] with bus voltages under the assumption of flat voltage profile.

B003FVA 3-bus power system with bus voltages under the assumption of flat voltage profile [12].

B003SVA 3-bus power system with bus voltages at the operating point [12].

B006FVA 6-bus power system with bus voltages under the assumption of flat voltage profile [12,25,26].

B006SVA 6-bus power system with bus voltages at the operating point [12,25,26].

B023FVA 23-bus power system with bus voltages under the assumption of flat voltage profile [12,26,27]

B023SVA 23-bus power system with bus voltages at the operating point [12,26,27]

B026FVA 26-bus power system with bus voltages under the assumption of flat voltage profile [12,26,28].

B026SVA 26-bus power system with bus voltages at the operating point [12,26,28].

B118FVA the IEEE 118-bus power system with bus voltages under the assumption of flat voltage profile [12,29].

B118SVA the IEEE 118-bus power system with bus voltages at the operating point [12,29].

B118FVB the IEEE 118-bus optimized power system with bus voltages under the assumption of flat voltage profile [12,30].

B118SVB the IEEE 118-bus optimized power system with bus voltages at the operating point [12,30].

VI. DATA READING AND PREPROCESSING

The possible modes of reading and preprocessing of data describing power systems are shown in Fig. 5.

PWRDD [13] is a package of subroutines to read data from D-files. The group of subroutines PWRDS [14] reads data from D-files and forms the bus admittance matrix of the system in a sparse form. Both packages PWRDD and PWRDS use subroutines of the package DDATA [15] of data handling routines.

Subroutine READDT of the package TTM1 reads data from the D-files using the package DDATA and preprocesses data into the form required by the B-files. A fresh B-file may be created by calling subroutine FORMDTF of the package TTM1. Data from the B-files is read using subroutine RDAT. The sparse bus admittance matrix and the vector of bus control variables are created in subroutines FORMYT and FORMU, respectively. Subroutine FORMPR is a higher level subroutine which reads data and forms the sparse bus admittance matrix and the vector of bus control variables. There are also available modifications of the subroutines for data reading from modified B-files admitting complex values of transformer ratio [18].

The non-direct methods of power system analysis (e.g., methods applying system decomposition [20] or reduction [21]) require more data (i.e., data defining the system decomposition or reduction) and the packages implementing these methods use the standard B-files. Additional data is supplied within appropriate packages.

VII. LOAD FLOW ANALYSIS

There are two major groups of procedures for load flow analysis as shown in Table I. The first group uses direct methods for solving the load flow equations.

1. Subroutine LFLFD1 of the package LFLFD [16] uses data from the D-files and applies the fast decoupled method [3] for solving load flow equations.
2. Subroutine LFLNR1 of the package LFLNR [17] uses data from the D-files and applies the Newton real method [5,6].
3. Subroutine LFNCM of the package XLF3 [18] uses data from the B-files (modified) and applies the complex Newton method [4].
4. Subroutine LFLFD1M of the package TTM1 [19] uses data from the B-files [12] and applies the fast decoupled method [3].
5. Subroutine LFTTM of the package TTM1 [19] uses data from the B-files [12] and applies the Tellegen theorem method [7].

The aforementioned group of subroutines uses iterative algorithms for solving the nonlinear load flow equations. In each iteration the system of linearized equations is solved with the aid of a sparse matrix technique. Subroutines MA28A, MA28B and MA28C of the package MA28 [31,32] are used for solving the real linear equations. Subroutines ME28A, ME28B and ME28C of the package ME28 [33] are used for solving the complex linear equations.

The second group of subroutines implements indirect methods for solving load flow equations.

1. Subroutine LFNCM of the package DECNCM [20] uses the complex Newton method in conjunction with system decomposition. It calls subroutine CSDSLE1 of the package CSDSLE [34] for solving sparse decomposed systems of complex linear equations. Data from the B-files together with data defining the system decomposition is used as input information.
2. Subroutine EQWARD of the package WARDEQ [21] reduces a power system by determining Ward external equivalences [8,9] and also prepares the description of the reduced system in the form acceptable by the package TTM1 [19]. Data from the B-files together with data defining the system reduction is used as input information.

VIII. CONTINGENCY ANALYSIS

There are two groups of subroutines available for power system congingency analysis as displayed in Table II. In both groups, outages of transmission lines are simulated one at a time. After obtaining the results of contingency analysis, the original data is restored.

The package CTTM1 [22] implements the fast decoupled method for solving the load flow equations of the perturbed system (call to subroutine LFLFD1M of the package TTM1). The selection of the starting point for the iterative procedure of solving the load flow equations is optional. The package CTTM1 has two entries, namely, non-interactive and interactive. The interactive entry allows multiple contingency analysis with an interactive mode of work.

Subroutine EQCONTI of the package WARDEQ [21] performs contingency analysis of the reduced system with the external Ward type equivalents. Call to EQCONTI should be preceded by the call to subroutine EQWARD of the package WARDEQ. EQCONTI solves load flow equations of a reduced, perturbed system using the fast decoupled method (call to subroutine LFLFD1M of the package TTM1).

Subroutine CONTI is an entry subroutine of the package CNTL [23]. This package processes the results of contingency analysis. The results are given in the form of the vector of bus voltages. Subroutine CONTI investigates the line power flows and losses under normal and emergency conditions, and compares the moduli and arguments of bus voltages under normal and emergency conditions.

IX. GRADIENT ANALYSIS

The aim of gradient analysis is to determine gradients of a network function with respect to different control variables. The two methods applied for gradient calculations are the Tellegen theorem method and the Lagrange multiplier method as shown in Table III.

The package TTM1 [19] has subroutine SENSIT for sensitivity calculation using the Tellegen theorem method. It formulates and solves adjoint equations and determines sensitivities assuming that the user supplies the right hand side vector of the adjoint equations. The package GTTM1 [24] determines the values and the gradients with respect to control variables of the most frequently used functions in power system optimization problems. Subroutine SENSIT is used by the package GTTM1, however, information needed for the adjoint analysis is supplied automatically by the package GTTM1.

The subroutine DERIVX of the package XLF3 [18] determines gradients of a function of interest using the method of complex Lagrange multipliers. It is assumed that the user supplies information about the function considered (i.e., the right hand side vector of the perturbed equations).

From the user point of view, the main difference between these two packages is that Tellegen's method provides gradients with respect to real variables, while the Lagrange multiplier method gives gradients with respect to complex control variables. Also, the phase-shifting transformer control variables are included in the subroutine DERIVX. The package XLF3 provides in one call the value of a gradient of a single function with respect to a single complex control variable, while the package GTTM1 provides the vector of gradients of a single function with respect to a vector of control variables.

X. POWER SYSTEM OPTIMIZATION

Most of the common optimization packages require that a part of the information needed to perform one step of an optimization procedure must be provided by the user supplied subroutine. Normally, the user's subroutine determines the values of the objective and the constraint functions and their gradients with respect to optimization variables. The function evaluation should be performed at the system operating point corresponding to the current vector of optimization variables under the normal and/or emergency conditions. Typically, the user supplied subroutine performs a number of load flow analyses and each load flow analysis is followed by the gradient analysis to determine the required gradients.

Different problems of power system optimization have been solved using the software reviewed and general optimization packages, e.g., the minimum-loss problem, economic dispatch, line overloading minimization and optimal load shedding [18,19,24]. The general optimization packages used were MFNC [35-37] - a package for nonlinear optimization with general constraints, MMLC [38,39] - a package for linearly constrained minimax optimization and MINOS [40,41] - a general purpose nonlinear programming system.

XI. REFERENCES

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TABLE I

PACKAGES FOR LOAD FLOW ANALYSIS

Package	Status	Data Base Used	Technique Implemented for Load Flow Solution	Subroutine for Solving the Problem
LFLFD [16]	Direct method	D-files	Fast decoupled version of Newton's method [3]	LFLFD1
LFLNR [17]	Direct method	D-files	Newton's method in real mode [6]	LFLNR1
XLF3 [18]	Direct method	B-files	Newton's method in complex mode [4]	LFNCM
TTM1 [19]	Direct method	D-files and/or B-files	Fast decoupled approach [3] Tellegen theorem method [7]	LFLFD1M LFTTM
*DECNCM [20]	*Indirect method	B-files and data for system decomposition	Newton's method in complex mode [4]	LFNCM
*WARDEQ [21]	*Indirect method	B-files and data for system reduction	Basic Ward-type equivalency methods [8,9]	EQWARD

*Utilize a package for the solution of sparse decomposed systems of linear equations [34].

TABLE II

PACKAGES FOR CONTINGENCY ANALYSIS

Package	Technique for Solving the Perturbed System	Subroutines for Solving the Perturbed System	Comments
WARDEQ [21]	Ward-type power network equivalents [8,9]	EQWARD EQCONTI (LFLFD1M)	
CTTM1 [22]	Fast decoupled version of Newton's method [3]	LFLFD1M	
CNTL [23]			Investigates the pre- and post-contingency states of a power system, namely, bus voltages (in polar mode), line power flows and line losses

TABLE III

PACKAGES FOR GRADIENT EVALUATION OF NETWORK FUNCTIONS

Package	Technique for Gradient Evaluation	Status of the Power Network	Control Variables
XLF3 [18]	Complex Lagrangian method	Reciprocal and/or nonreciprocal	Bus control variables, transmission line control variables, phase shifter control variables
TTM1 [19]	Tellegen theorem method	Reciprocal	Bus control variables, transmission line control variables
GTTM1 [24]	Tellegen theorem method	Recpirocal	Bus control variables, transmission line control variables

TABLE IV

A REPRESENTATIVE SAMPLING OF DATA BASES FOR THE AVAILABLE SOFTWARE

Power System	Transmission Elements	D-file	B-file
3-bus	3		B003FVA B003SVA
6-bus	8	D6	B006FVA B006SVA
23-bus	30	D23	B023FVA B023SVA
26-bus	32	D26	B026FVA B026SVA
118-bus	179	D118 D118OP	B118FVA B118FVB B118SVA B118SVB

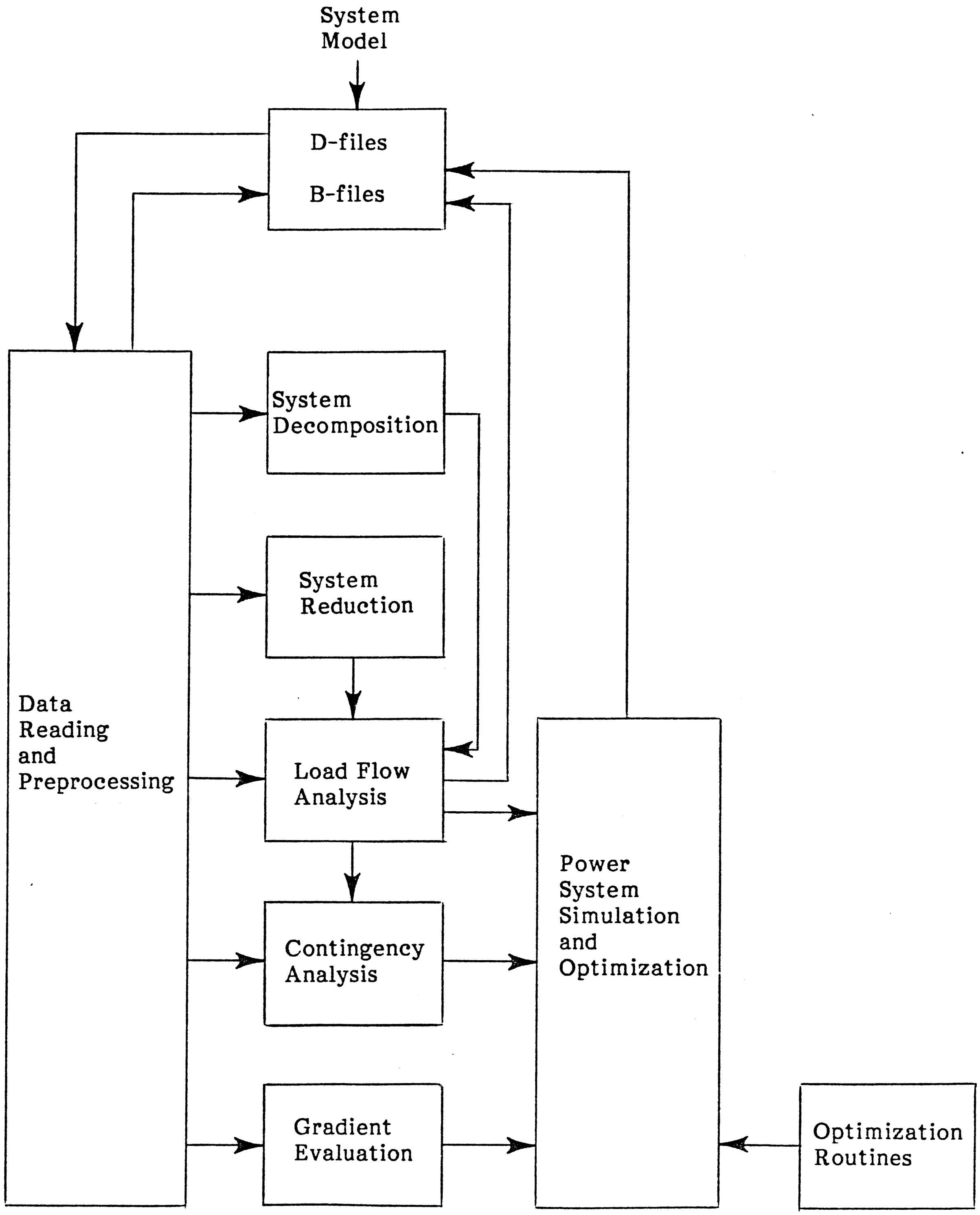


Fig. 1 Power system simulation and optimization software and its capabilities.

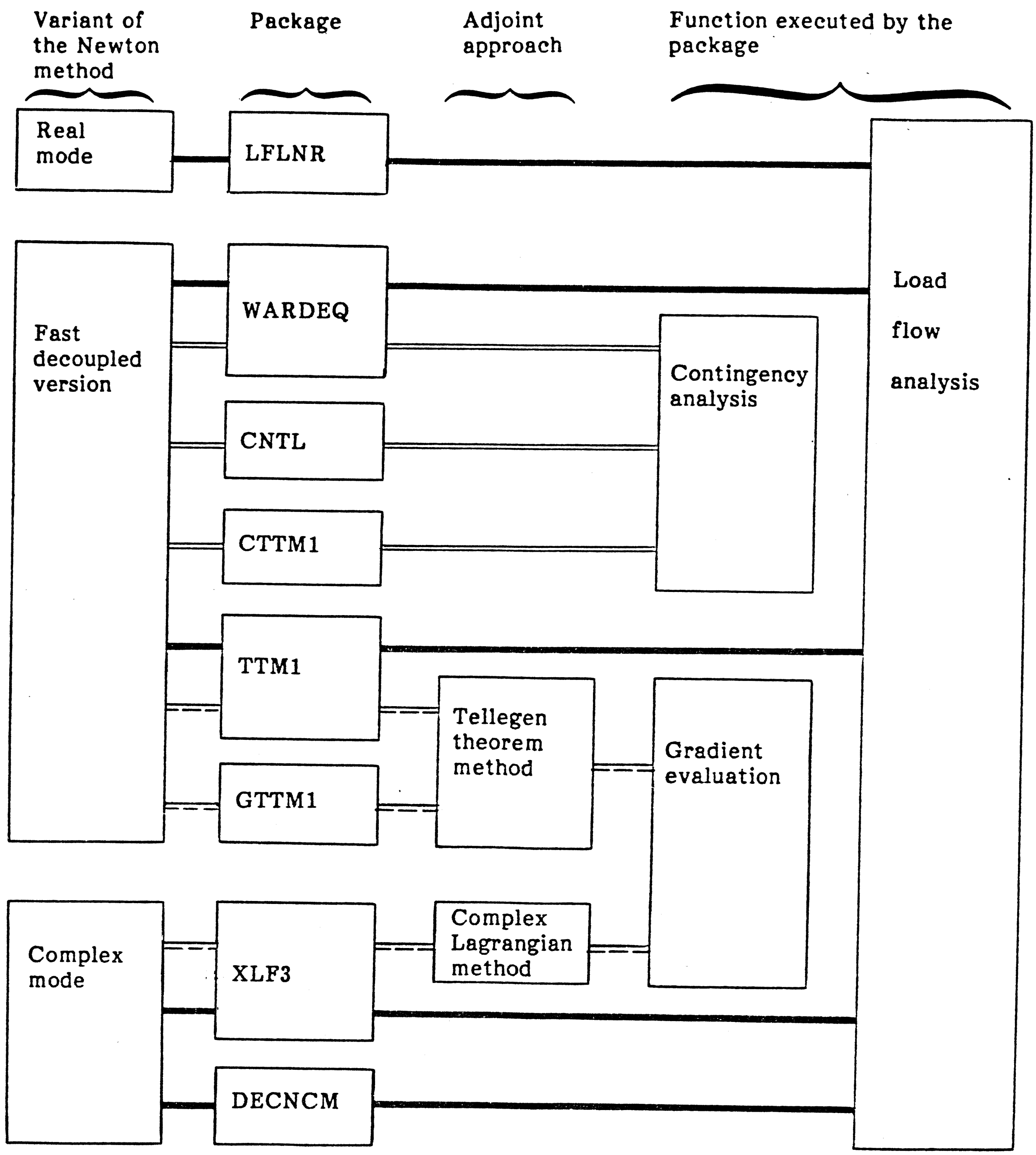


Fig. 2 Detailed representation of the simulation software systems developed.

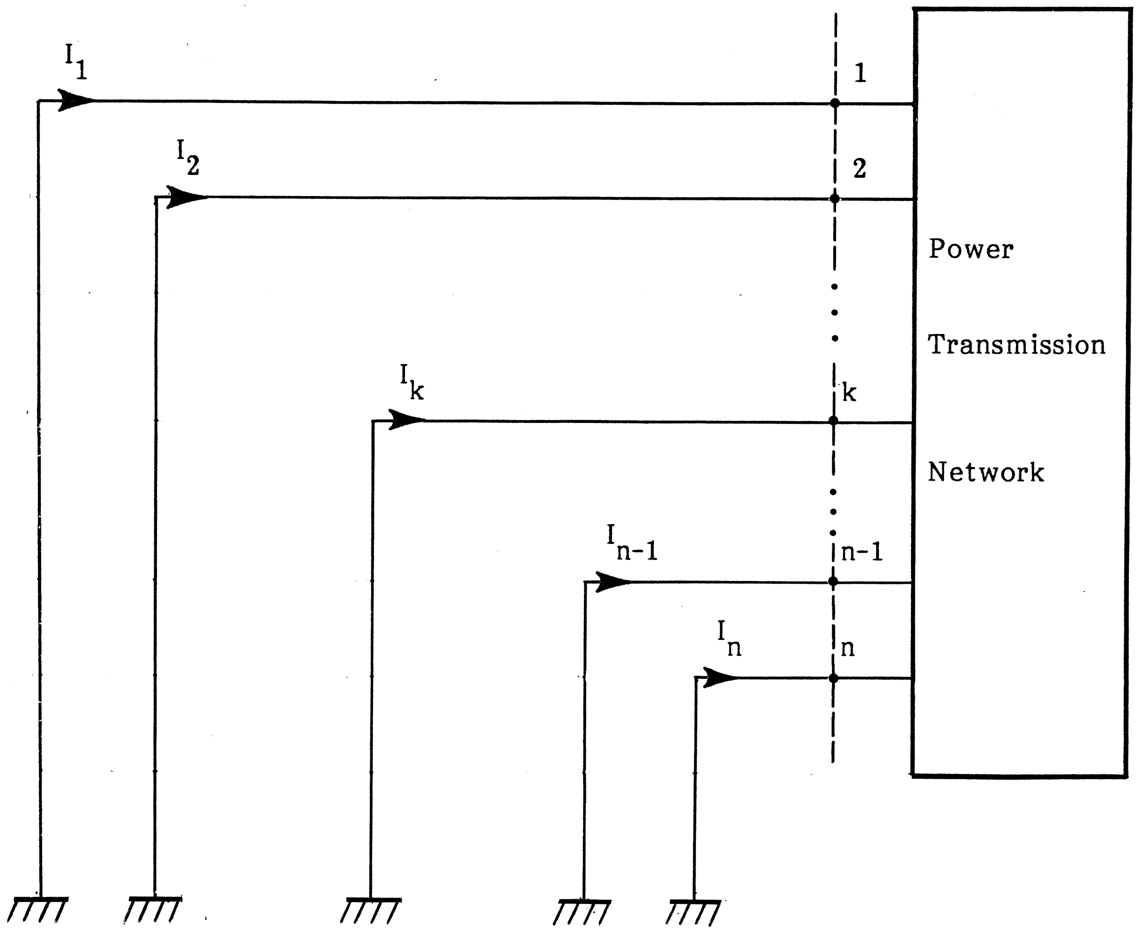


Fig. 3 Model of an n-node power system.

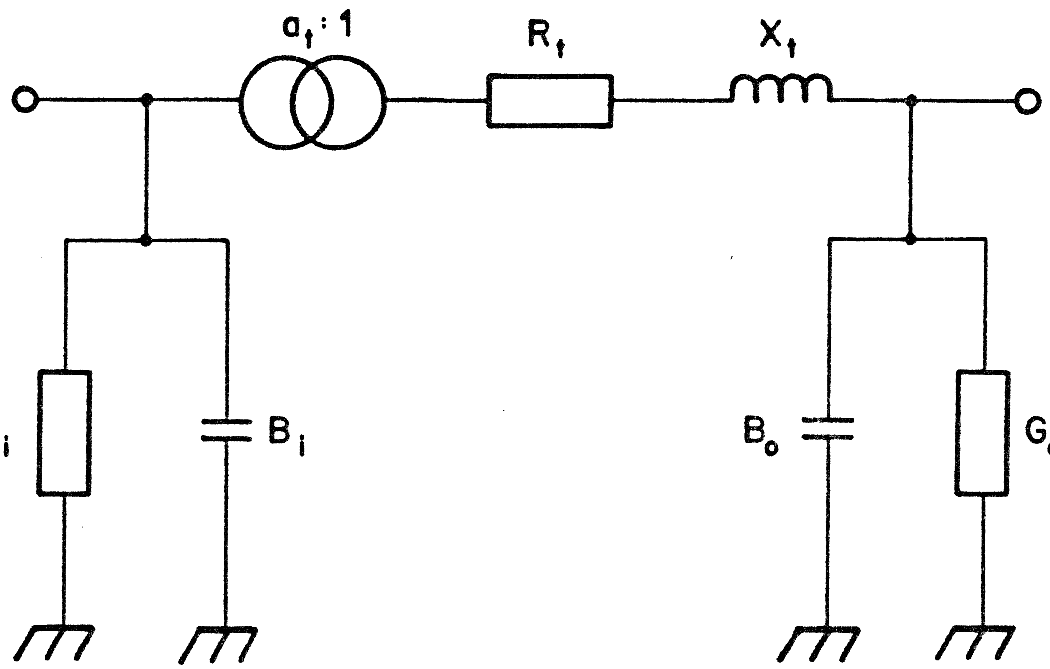
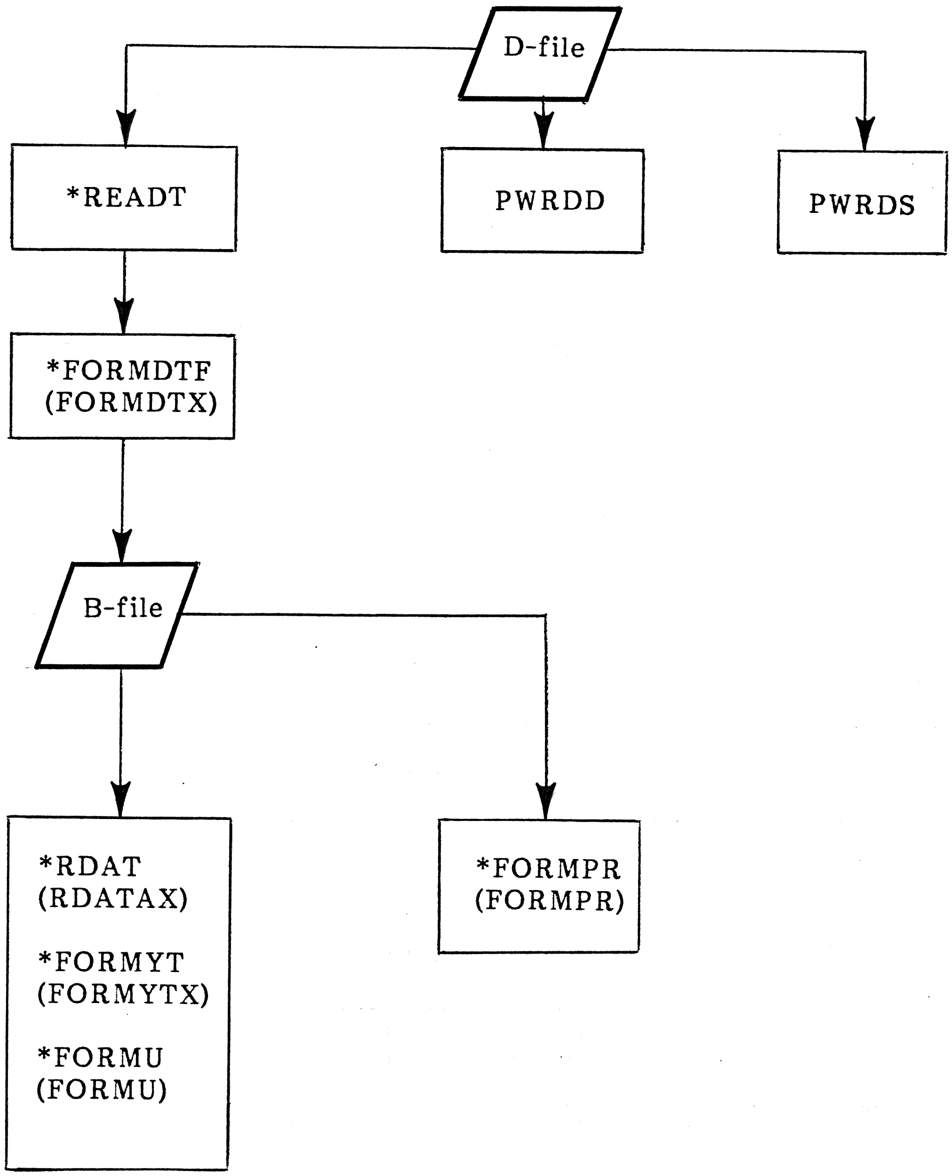


Fig. 4 Model of a transmission element.



*Subroutines associated with package TTM1 (XLF3)

Fig. 5 Possible modes of data reading and preprocessing.