TTM1 - A FORTRAN IMPLEMENTATION OF THE TELLEGEN THEOREM METHOD TO POWER SYSTEM SIMULATION AND DESIGN

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Abstract

TTM1 is a package of twenty-five Fortran subroutines which have been designed to solve various problems arising in simulation and optimization of power systems. The Tellegen theorem method has been implemented in various subroutines for sensitivity calculation and some subroutines for solving the load flow equations. Subroutines for reading and preprocessing data describing a power system and subroutines for solving the load flow problem using the fast decoupled method are also included. The Harwell package MA28 is employed to represent and to solve appropriate sets of sparse linear equations. The package and user-oriented documentation have been developed for the CDC 170/730 system with the NOS 1.4 level 552 operating system and the Fortran Extended (FTN) version 4.8 compiler. Several numerical examples illustrate the use of TTM1 in load flow and contingency analysis. Optimization examples demonstrate how TTM1 is linked with minimax and nonlinear programming packages. We consider a 3-bus, 6-bus, 23-bus, 26-bus and the IEEE 118-bus systems.

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1 INTRODUCTION AND DESCRIPTION OF CONTENTS

This report gives a user-oriented description of the package TTM1 of Fortran subroutines to solve various problems arising in simulation and optimization of power systems (e.g., load flow, contingency analysis, load shedding, sensitivity calculation, etc.) using the Tellegen theorem method. The package and documentation have been prepared for the CDC 170/730 system with the NOS 1.4 level 552 operating system, and the Fortran Extended (FTN) version 4.8 compiler.

In Chapter 2 of this report general information concerning the implementation of the Tellegen theorem method is given. It is assumed that the user is familiar with the Tellegen theorem method and only a brief description of the method to introduce the necessary symbols and formulas is given here. A detailed description of the method was presented by Bandler and El-Kady [1-3].

The TTM1 package has been modularized into 25 subroutines which may be called from the user's program in any sequence to solve a specific problem. The hierarchy of subroutines and the functional organization of the package are discussed in Chapter 3.

In Chapter 4 information on how to access the TTM1 package on the CDC 170/730 system at McMaster University is given.

The aim of Chapter 5 is to familiarize the user informally with the package through examples, and to indicate possible applications. The most commonly used variables and vectors of the package are explained. How to create a standard data file, the formulation of the load flow equations, the determination of the solution of the load flow problem, contingency analysis and sensitivity calculation are discussed together with illustrative examples. The application of the sensitivity calculations in power system optimization is also described.

The full, formal description of all package subroutines is given in Chapter 6. A sparse matrix approach is used throughout the whole package. The sparse matrix technique, namely, the Harwell package MA28 [4], must be provided by the user. The complete listing of TTM1 is presented in [5].

2 GENERAL INFORMATION

Many problems appearing in power systems are solved using gradient-type iterative methods. Using the Tellegen theorem method we may provide all gradients needed by such methods.

The real form of the extended perturbed Tellegen sum has been applied to obtain consistent adjoint network modelling for any real function f of power network state and control variables, i.e.,

$$\sum_b (\hat{I}_b \,\delta V_b + \hat{I}_b^* \,\delta V_b^* - \hat{V}_b \,\delta I_b - \hat{V}_b^* \,\delta I_b^*) = 0 \,, \tag{2.1}$$

where

V_b, I_b are the complex voltage and current, respectively, associated with branch b of the original power network,

$\hat{V}_b$, $\hat{I}_b$ are the complex voltage and current, respectively, associated with branch b of the adjoint network,

$*$ denotes the complex conjugate.

As a consequence of (2.1), we obtain the system of real adjoint equations [2]

$$\hat{\underset{\sim}{T}} \, \hat{\underset{\sim}{x}}_i = \hat{\underset{\sim}{b}}_i \,. \tag{2.2}$$

Adjoint matrix $\hat{\underset{\sim}{T}}$ is determined by the nodal admittance matrix of the power system and bus voltages at the operating point, while the right-hand side vector $\hat{\underset{\sim}{b}}_i$ depends also on the function f_i being considered. The vector of unknown variables $\hat{\underset{\sim}{x}}_i$ is a vector of adjoint bus voltages.

The gradient of a real function $f(\underset{\sim}{x},\underset{\sim}{u})$ of the power system state and control variables with respect to a control variable u is obtained as

$$\frac{df}{du} = \frac{\partial f}{\partial u} - \hat{\eta}_u . \tag{2.3}$$

It has been shown [1,3] that the sensitivity $\hat{\eta}_u$ of a function f with respect to any control variable can be expressed in terms of currents and voltages of the adjoint network.

If we apply the Tellegen theorem method in conjunction with gradient-type iterative algorithms, the adjoint matrix $\hat{\underset{\sim}{T}}$ may be formulated and decomposed into LU factors only once per iteration. Then the set (2.2) is solved repeatedly using only forward and backward substitutions for different functions f_i. Consequently, the computational effort per solution is reduced, especially when the number of functions f_i is large.

The foregoing method has been implemented as a package of computer programs. This package is called TTM1. The main goal of the package is to provide sensitivities needed by gradient-type methods. However, to make the package more general, several other subroutines have been included as well, e.g., subroutines to read and preprocess data describing a power system, subroutines for solving the load flow problem using the Tellegen theorem method [2] and the fast decoupled method [6]. The package uses a sparse representation of the bus admittance matrix as well as of the adjoint matrix.

3 STRUCTURE OF THE PACKAGE

The whole package has been modularized into 25 Fortran subroutines and arranged in a hierarchical structure. The overall structure of the package is shown in Fig. 3.1, 3.2 and 3.3. There are two other packages associated with TTM1. Package PWRDD [7,8] is to simplify the reading of descripted data of the power system. Package MA28 [4] is for solving a set of linear equations using a sparse matrix technique.

There is no one general entry to the package TTM1. The user, in his program, may call any of the package subroutines, after making the package accessible for his program. A sequence of call statements should be arranged in the main program appropriately to the user's problem.

The lower level subroutines of the TTM1 package solve such problems as: reading and preprocessing of input data describing a power system, creating an updated data file after processing the original data, formulation of the power system nodal admittance matrix and the vector of bus control variables, formulation of the adjoint matrix, formulation of the right-hand side vector of adjoint equations for the load flow purposes, sensitivity calculations, etc. These subroutines enable the user to prepare his own program to solve a very specific problem.

The highest level subroutines are dedicated to deal with more general problems: formulation of the load flow equations (subroutine FORMPR), solution of the load flow problem (subroutines LFTTM and LFLFD1M), general sensitivity calculation for optimization purposes (subroutine SENSIT). For the user's convenience, the highest level subroutines, except SENSIT, have all internal vectors comprised into one

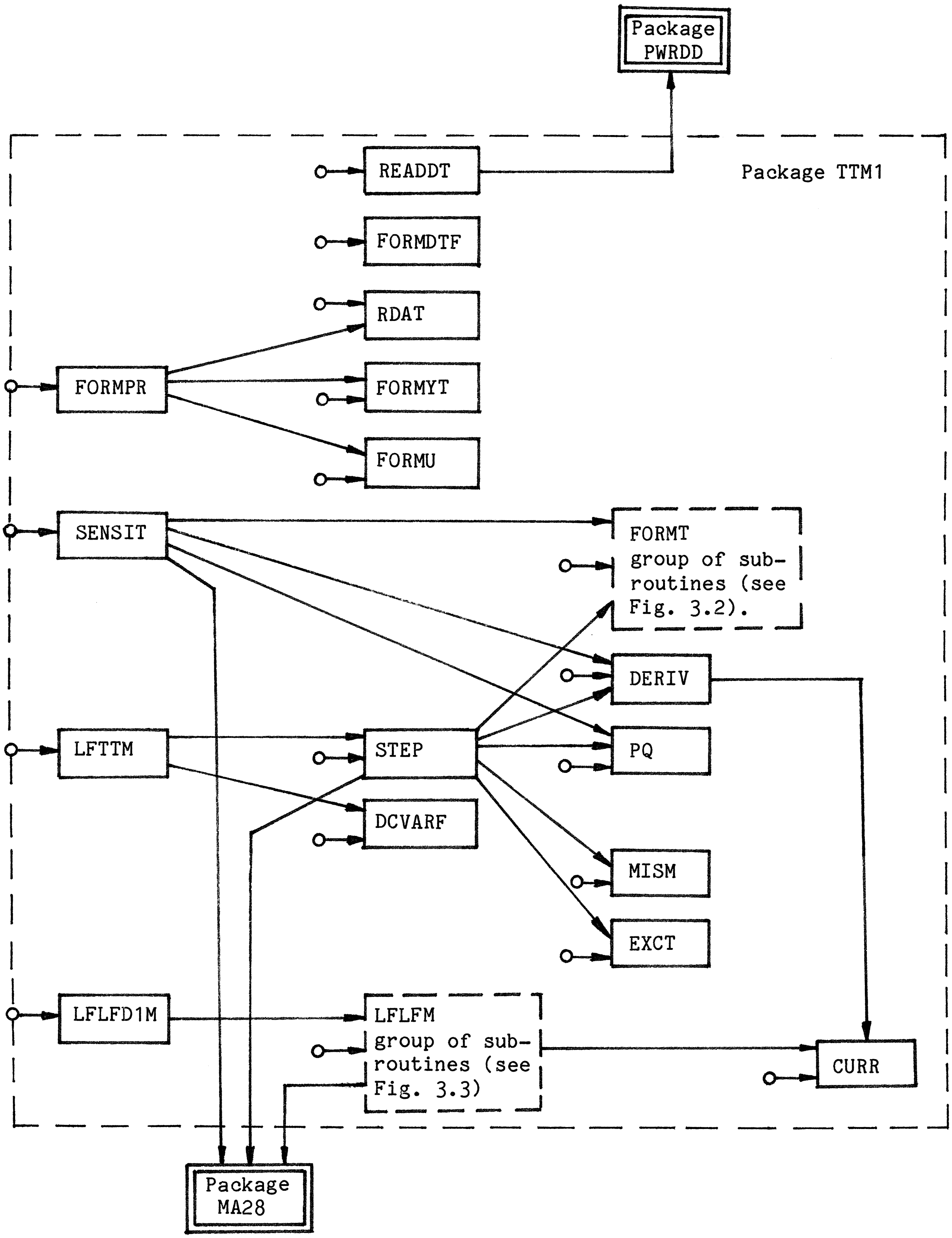

Fig. 3.1 Overall structure of the TTM1 package.

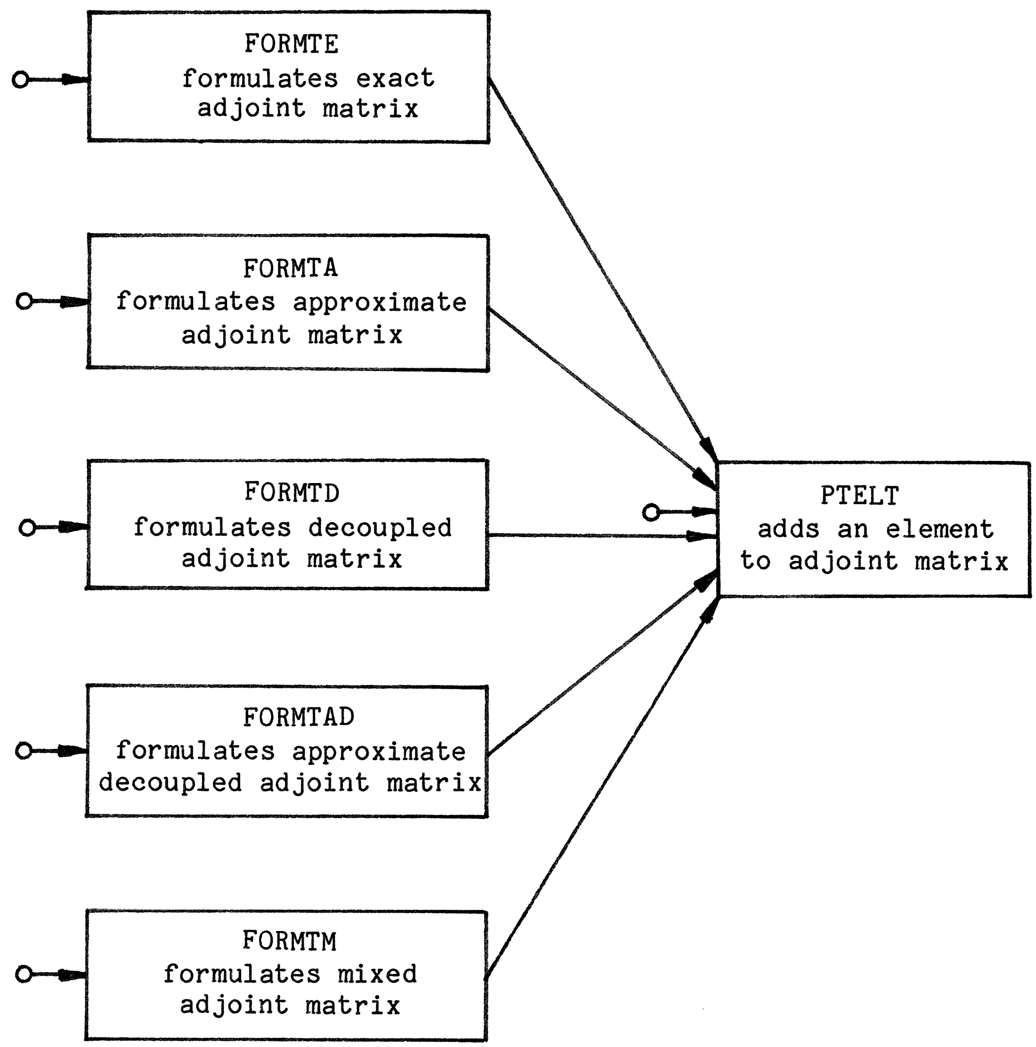

Fig. 3.2 FORMT - a group of subroutines for formulation of adjoint matrix of power system.

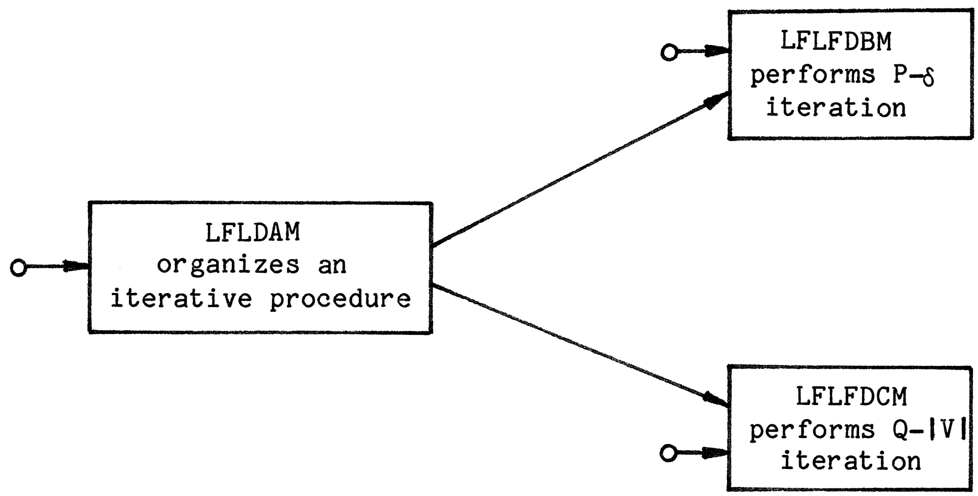

Fig. 3.3 LFLFM - a group of subroutines implementing the fast decoupled method.

workspace vector. The user, in his program, must provide a sufficient workspace. Distribution of this workspace is done automatically by the subroutine, and the location of any internal vector appearing in the workspace vector is available through the appropriate COMMON block.

It is usually possible to prepare the user's program using the highest level subroutines without reference to subroutines called by them, to solve most of typical problems arising in simulation and optimization of power systems.

The subroutines of the package can be divided into four categories: subroutines for data handling, subroutines for load flow problem formulation, subroutines for sensitivity calculation and subroutines for load flow solution. These groups of subroutines are shown in Figures 3.4 to 3.8, respectively.

There are three lower level subroutines for data manipulation (Fig. 3.4) READDT, FORMDTF and RDAT. It is assumed that the data file describing the power system is a formatted one, with the standard structure acceptable by TTM1. Subroutine RDAT is to read data from such a file. However, the existing power system data group files are in most cases unformatted [9], with different data identified by descriptors. Subroutine READDT is to read data from such a file. It is done with the aid of package PWRDD [7,8]. Only the data needed by the package TTM1 is retrived from the unformatted file. Subroutine FORMDTF is to create a standard data file from the data acquired by the subroutine READDT or from the data obtained after processing of the original data. The use of subroutine READDT is illustrated in Example 5.2, subroutine FORMDTF in Examples 5.2 and 5.4, and subroutine RDAT in Example 5.6.

There are two lower level subroutines to form the load flow

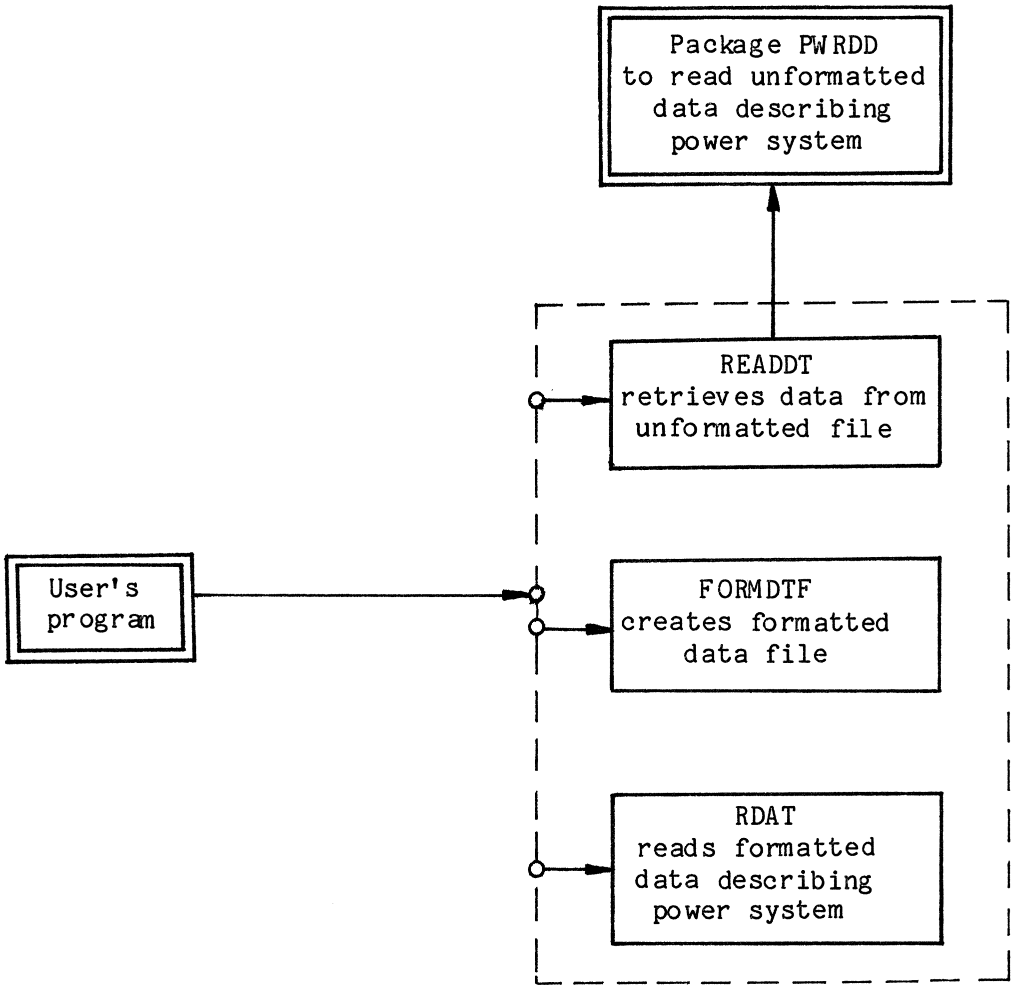

Fig. 3.4 Data handling routines.

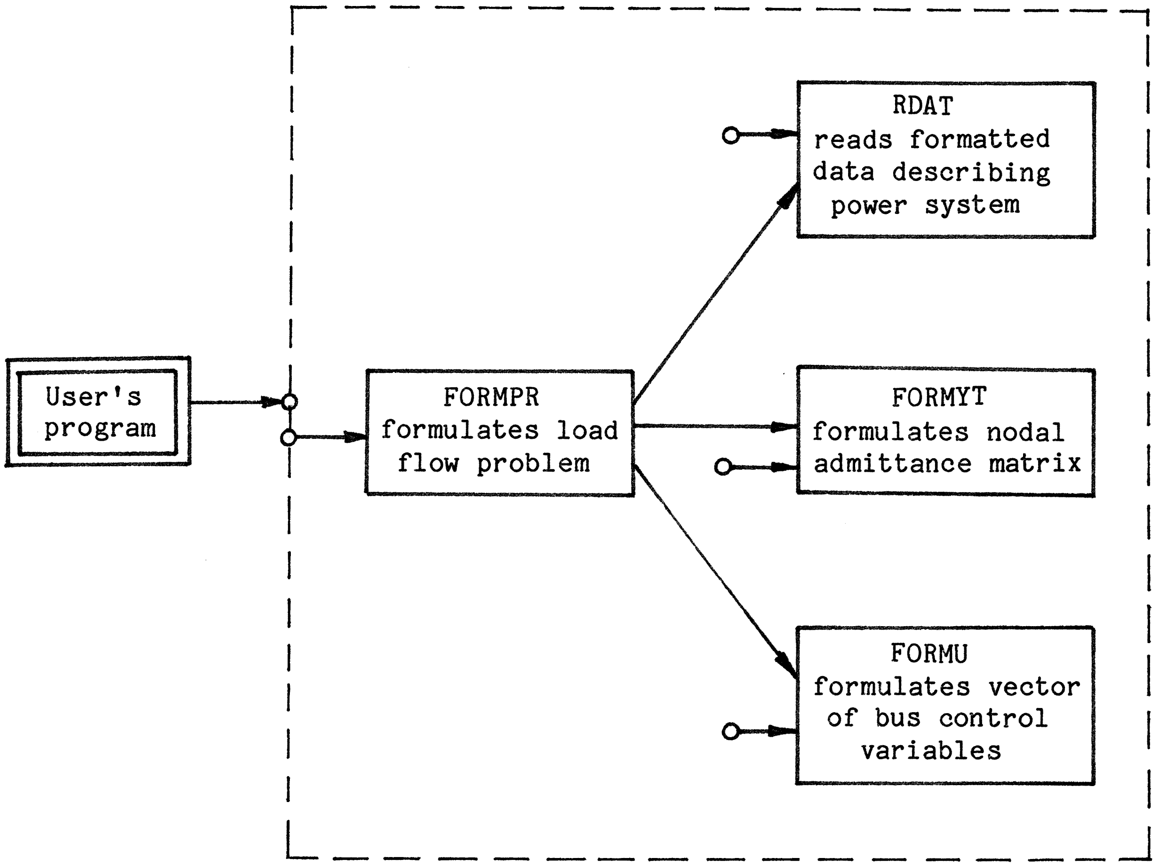

Fig. 3.5 A group of subroutines for the load flow problem formulation.

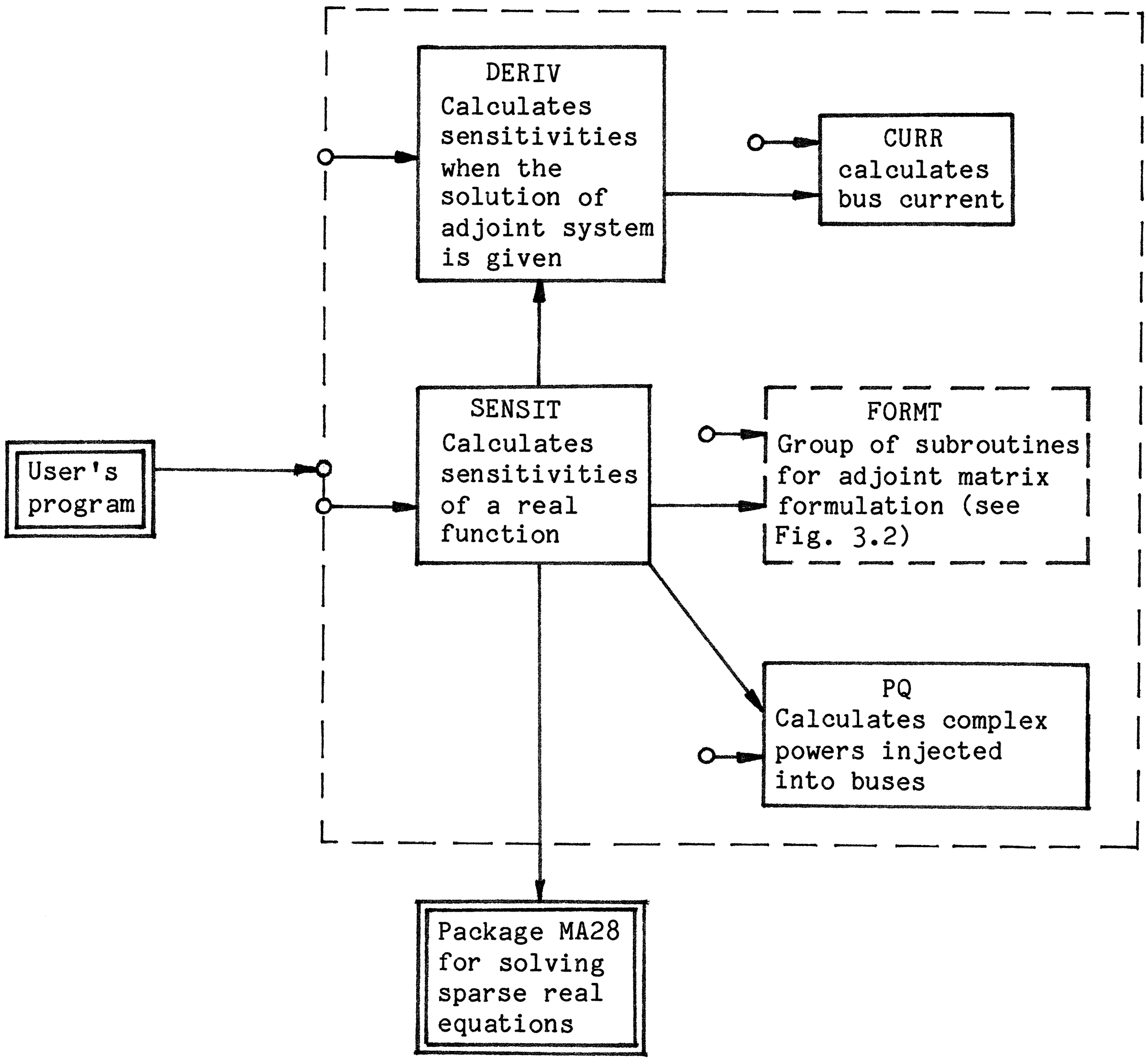

Fig. 3.6 A group of subroutines for sensitivity calculation.

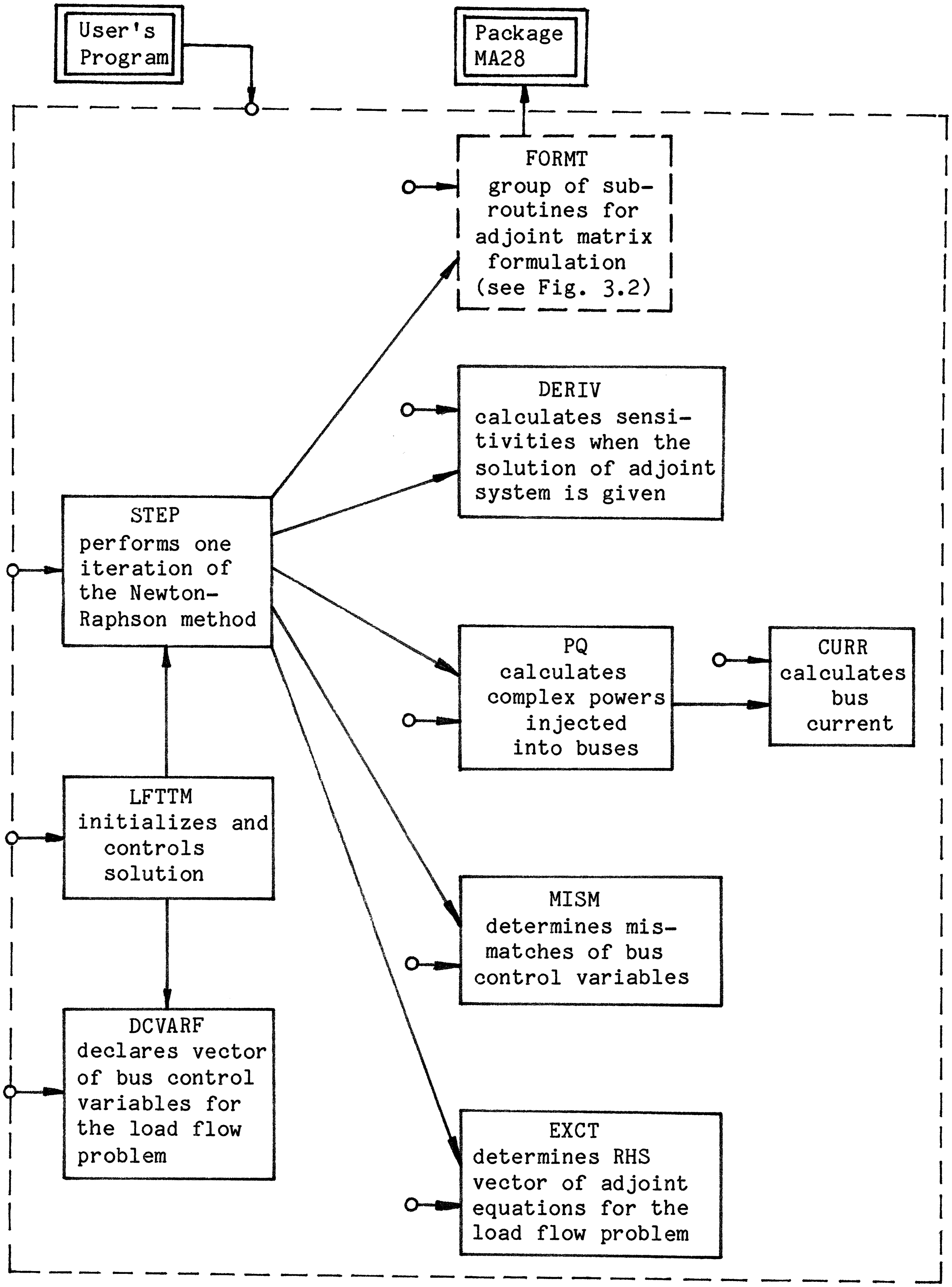

Fig. 3.7 A group of subroutines for solving the load flow problem using the Tellegen theorem method.

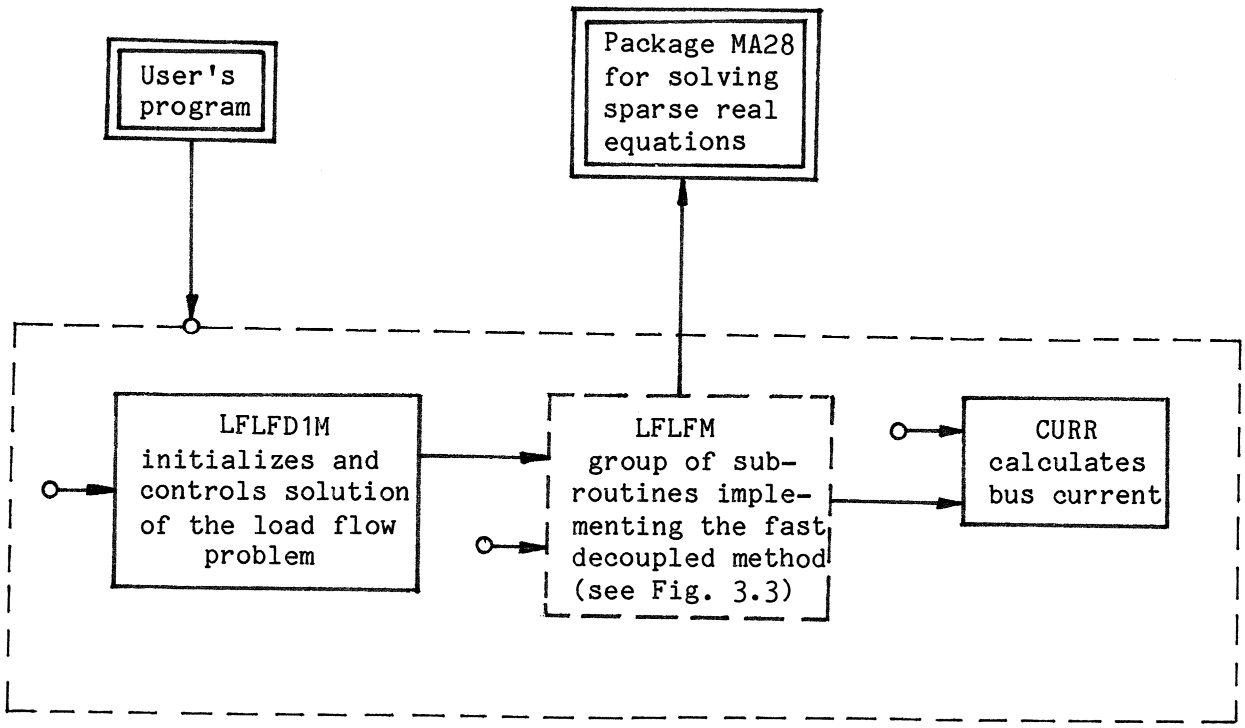

Fig. 3.8 A group of subroutines for solving the load flow problem using the fast decoupled method.

equations (Fig. 3.5). Subroutine FORMYT creates the nodal admittance matrix of a power system in a sparse form. Subroutine FORMU forms the vector of bus control variables, i.e., the right-hand side vector of the power flow equations. Both subroutines and subroutine RDAT are called by the higher level subroutine FORMPR. This subroutine reads standard input data, forms the load flow equations and the vector of initial bus voltages. The use of subroutine FORMYT is shown in Example 5.6, and of subroutine FORMPR in Examples 5.3, 5.4, 5.5, 5.7 and 5.8.

There is a family of subroutines to create different versions of the adjoint matrix of a power system (Fig. 3.2). The exact, decoupled, approximate, approximate decoupled [2] or mixed versions of the adjoint matrix are formed by subroutines FORMTE, FORMTD, FORMTA, FORMTAD or FORMTM, respectively. With this family of subroutines is associated an auxiliary subroutine PTELT. Sparse representation of the adjoint matrix is used.

Subroutine DERIV (Fig. 3.6) calculates sensitivities of a real function of the power system state and control variables with respect to control variables, when the solution of adjoint equations is given. This subroutine is called by the higher level subroutine SENSIT. It is assumed that the right-hand side vector of the adjoint equations is supplied by the user. Subroutine SENSIT is intended to evaluate sensitivities for optimization purposes. The use of this subroutine is illustrated in Examples 5.7 and 5.8. There are several subroutines addressed to solve the load flow problem using the Tellegen theorem method (Fig. 3.7). Subroutine DCVARF declares the set of control variables. Subroutine EXCT calculates the right-hand side vector of the adjoint equations for a state variable of the load flow problem. Both subroutines, and some others are called by the subroutine STEP which performs one iteration at a time of the solution of the power flow equations. The highest level subroutine is LFTTM, which organizes the solution of the load flow problem with possible different options using the Tellegen theorem method. The use of subroutine LFTTM is shown in Examples 5.4, 5.6 and 5.8.

The package contains also a set of subroutines for solving the load flow problem using the fast decoupled method (Fig. 3.3 and 3.8). The highest level subroutine LFLFD1M solves the equations with different possible options. The whole problem is decomposed into a few sub-problems solved by subroutines LFLFDAM, LFLFDBM, LFLFDCM. The use of subroutine LFLFD1M is shown in Examples 5.5 and 5.7.

Some general purpose subroutines are also included in the package. Subroutine CURR calculates the current injected into a bus, subroutine PQ calculates complex powers injected into buses, and subroutine MISM calculates mismatches of bus control variables.

All subroutines of the TTM1 package are listed in alphabetical order in Table 3.1.

TABLE 3.1

LIST OF SUBROUTINES OF THE TTM1 PACKAGE

	Subroutine	Number of lines (source text)	Number of words (compiled code)	Description (page)	Listing (page of [5])
1	CURR	20	50	90	5
2	DCVARF	36	64	92	6
3	DERIV	91	604	94	7
4	EXCT	78	273	101	9
5	FORMDTF	39	422	103	11
6	FORMPR	59	441	106	12
7	FORMTA	87	512	110	13
8	FORMTAD	80	413	113	15
9	FORMTD	89	472	115	17
10	FORMTE	99	624	117	19
11	FORMTM	100	606	120	21
12	FORMU	45	203	123	23
13	FORMYT	63	315	126	24
14	LFLFD1M	93	274	130	25
15	LFLFDAM	192	1473	134	27
16	LFLFDBM	42	203	141	30
17	LFLFDCM	46	213	144	31
18	LFTTM	157	721	147	32
19	MISM	47	253	152	35
20	PQ	31	210	154	36
21	PTELT	19	34	156	37
22	RDAT	84	720	158	38
23	READDT	76	564	162	40
24	SENSIT	77	635	167	42
25	STEP	166	1270	173	44

4 HOW TO USE THE PACKAGE

The package is available at McMaster University at CDC 170/730 system as a permanent indirect group file LIBTTM1 under the charge RJWBAND. It exists as a library of binary relocatable subroutines.

As was mentioned in Chapter 3, some of the package subroutines call some subroutines of the packages PWRDD [8] and MA28 [4]. These packages are also available as permanent indirect group files LIBSPWR and LIBRHSM, respectively, under the charge RJWBAND. Both packages are in the form of a library of binary relocatable subroutines.

The general sequence of NOS commands to use the TTM1 package may be as follows:

/GET LIBTTM1, LIB/GR. - fetch the libraries,

/LIBRARY LIBTTM1, LIB. - indicate the libraries to the loader,

where

LIB is the name of some other library required by the user's program (e.g., LIBSPWR or LIBRHSM).

The user's program may call any of the package subroutines. However, the user's program should at least declare all arguments appearing in the call statement and to initialize required variables.

The user may supply his own data describing the power system. However, it is recommended to use one of the existing data group files. Data describing the power system may be retrieved from an unformatted data file using subroutine READDT and the package PWRDD or from a formatted data file with the use of subroutine RDAT. A list of available unformatted data group files is given in [9]. The formatted data files are listed in Chapter 5.

5 MORE INFORMATION AND EXAMPLES

The aim of this chapter is to familiarize the user informally with the package through examples.

The full, formal description of all package subroutines is given in Chapter 6. Here, we discuss how to solve some typical problems of power system simulation and optimization applying the TTM1 package.

5.1 The Most Commonly Used Variables and Vectors

Essentially one class of method is used throughout the whole package, hence the memory distribution is uniform in most of the subroutines. Here, in Example 5.1, we give an explanation of the most commonly used variables and vectors.

5.1.1 Example 5.1 Description of the 3-Bus Power System

Let us consider a 3-bus power system, which is shown in Fig. 5.1. It has 3 transmission lines, one load bus, one generator, and one slack bus. The slack bus must have the highest index. In the package, the number of buses is denoted by NB, the number of load buses by NLB, and the number of transmission lines by NTL, e.g., NB = 3, NLB = 1, NTL = 3.

The system topology is stored by two integer vectors LBINP and LBOUT. LBINP(i) and LBOUT(i) store indices of the terminal buses of the ith transmission line. Values of line resistances and reactances are stored in vectors LR and LX.

In the example considered we have

$$\text{LBINP} = \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix}, \quad \text{LBOUT} = \begin{bmatrix} 2 \\ 3 \\ 3 \end{bmatrix},$$

$$\text{LR} = \begin{bmatrix} 0.050 \\ 0.025 \\ 0.100 \end{bmatrix}, \quad \text{LX} = \begin{bmatrix} 0.200 \\ 0.100 \\ 0.250 \end{bmatrix}.$$

The nodal admittance matrix of the power system is stored in a sparse form using the three vectors YT, JRYT, ICYT. Complex vector YT stores row by row all nonzero elements of the nodal admittance matrix. It is assumed that each row begins with the diagonal element. Vector JRYT stores indices of such elements. Vector ICYT contains column indices of the elements stored in YT. The number of nonzero elements of the nodal admittance matrix is denoted by NYT.

In our example, the nodal admittance matrix $\underset{\sim}{Y}_T$ is

$$\underset{\sim}{Y}_T = \begin{bmatrix} 3.53 - j14.1 & -1.18 + j4.71 & -2.35 + j9.41 \\ -1.18 + j4.71 & 2.55 - j8.15 & -1.38 + j3.45 \\ -2.35 + j9.41 & -1.38 + j3.45 & 3.73 - j12.9 \end{bmatrix}.$$

It is stored as

YT = [(3.53, -14.1), (-1.18, 4.71), (-2.35, 9.41), (2.55, -8.15), (-1.18, 4.71), (-1.38, 3.45), (3.73, -12.9), (-2.35, 9.41), (-1.38, 3.45)],

JRYT = [1, 4, 7, 10],

ICYT = [1, 2, 3, 2, 1, 3, 3, 1, 2].

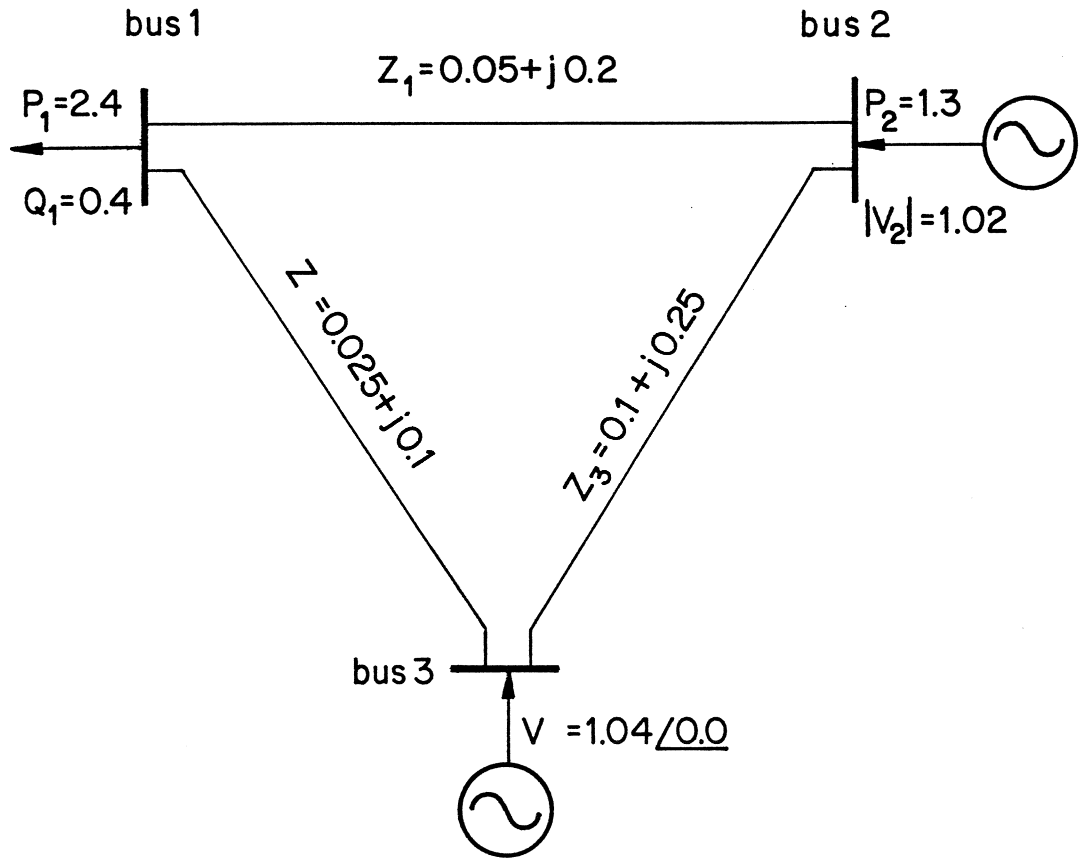

Fig. 5.2 3-bus power system.

There are several vectors associated with buses. Vector BTYP stores bus types, i.e., 0 for a load bus, 1 for a generator and 2 for the slack bus. Vector BCV stores control variables associated with buses. It is a real vector of dimension twice the number of buses. In our example, we have

$$\text{BTYP} = \begin{bmatrix} 0 \\ 1 \\ 2 \end{bmatrix}, \quad \text{BCV} = \begin{bmatrix} -2.40 \\ -0.40 \\ 1.30 \\ 1.02 \\ 1.04 \\ 0.00 \end{bmatrix}.$$

Values of bus voltages are retained throughout the package in the complex vector V. Let us assume that the current values of bus voltages of the 3-bus system are

$$V = \begin{bmatrix} (1.00,\ 0.0) \\ (1.02,\ 0.0) \\ (1.04,\ 0.0) \end{bmatrix}.$$

Vector BCS stores values of complex powers injected into buses for the values of bus voltages stored in vector V

$$\text{BCS} = \begin{bmatrix} (-0.1180,\ -0.4710) \\ (-.00414,\ \ 0.0257) \\ (\ 0.2220,\ \ 0.8750) \end{bmatrix}.$$

The adjoint matrix of the power system is stored in a sparse form using vectors T, IRT and ICT. T is a real vector which contains all nonzero elements of the adjoint matrix. Vectors IRT and ICT store the row and the column indices of nonzero elements stored in T.

There are five different formulations of the adjoint matrix. Parameter IVT is to select a proper version. In the example considered, selecting the exact version (IVT = 1), for the given vector of bus voltages V, we obtain the adjoint matrix

$$\hat{\underset{\sim}{T}} = \begin{bmatrix} 3.41 & 13.60 & -1.18 & -4.71 \\ -14.60 & 3.65 & 4.71 & 1.18 \\ 4.80 & -1.20 & -8.29 & 2.61 \\ 0.00 & 0.00 & 0.00 & 1.02 \end{bmatrix}.$$

It is stored as

T = [3.41, -14.6, 13.6, 3.65, -1.18, 4.71, -4.71, 1.18, -8.29, 2.61, 4.8, -1.2, 0.0, 1.02],

IRT = [1, 2, 1, 2, 1, 2, 1, 2, 3, 3, 3, 3, 4, 4],

ICT = [1, 1, 2, 2, 3, 3, 4, 4, 3, 4, 1, 2, 3, 4].

Two vectors CCV and ICV are designated to define a set of control variables with respect to which sensitivities are to be calculated. CCV(i) contains the code number of the ith control variable, while ICV(i) stores the index of the bus or transmission line associated with this variable. Code numbers of control variables are given in Chapter 6 in the description of subroutine DERIV. It is left to the user to define vectors CCV and ICV in his program. However, there is a special subroutine DCVARF to declare these vectors for load flow purposes.

Let us assume that we want to calculate sensitivities of a function $f = |V_1|$ with respect to P_1, Q_1, $|V_2|$. Vectors CCV and ICV must be defined as

$$CCV = \begin{bmatrix} 7 \\ 8 \\ 9 \end{bmatrix}, \quad ICV = \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix}.$$

The required sensitivities are

$$\hat{\eta}_{P1} = -\ 0.0172, \quad \hat{\eta}_{Q1} = -0.0690, \quad \hat{\eta}_{|V2|} = -0.3448.$$

Results of sensitivity analysis are stored in vector SENS. In the example considered, we obtain

$$SENS = \begin{bmatrix} -0.0172 \\ -0.0690 \\ -0.3448 \end{bmatrix}.$$

A few variables which are associated rather with the package itself than with the method implemented are used throughout the package. Integer variables INPT, OTPT must be set in the user's program to the number of the input and output units, respectively. Integer variable IWRITE controls printed output. There are five possible levels of printouts. The detailed explanation of this parameter is given in Chapter 6 in the description of each subroutine. Generally, the larger the value of IWRITE the more details are printed out. If IWRITE is less than or equal to zero, all printouts are suppressed.

5.2 How to Create a Standard Data File

It is very simple to create a standard formatted data file from the unformatted one with data identified by descriptors. We illustrate this with the aid of an example.

5.2.1 Example 5.2 A Standard Data File for the 26-Bus Power System

In this example the standard, formatted data file describing the 26-bus power system [10,11] is created from the unformatted data group file D26 [9]. Two subroutines, READDT and FORMDTF of the package TTM1 are designated to solve such a problem. The listing of the user's program DTHND26 is shown on page 27. This program uses also the package PWRDD [7,8] to simplify the reading of descripted data. This package exists as a library of compiled subroutines under the name LIBSPWR. To make the both libraries LIBTTM1 and LIBSPWR available to the user's program the following NOS commands were used:

```
/GET, LIBTTM1, LIBSPWR/GR.
/LIBRARY,LIBTTM1,LIBSPWR.
```

To make available the input data file containing unformatted data of the system considered the following command was used:

```
/GET, D26/GR.
```

After execution the data file created exists as a local file under the name B026. The contents of this file are printed out on pages 28-29. The diagram of the 26-bus power system is shown in Fig. 5.2.

The available unformatted data group files are listed in [9]. However, for the user's convenience, standard formatted data files have been created and stored as group files for the following power systems

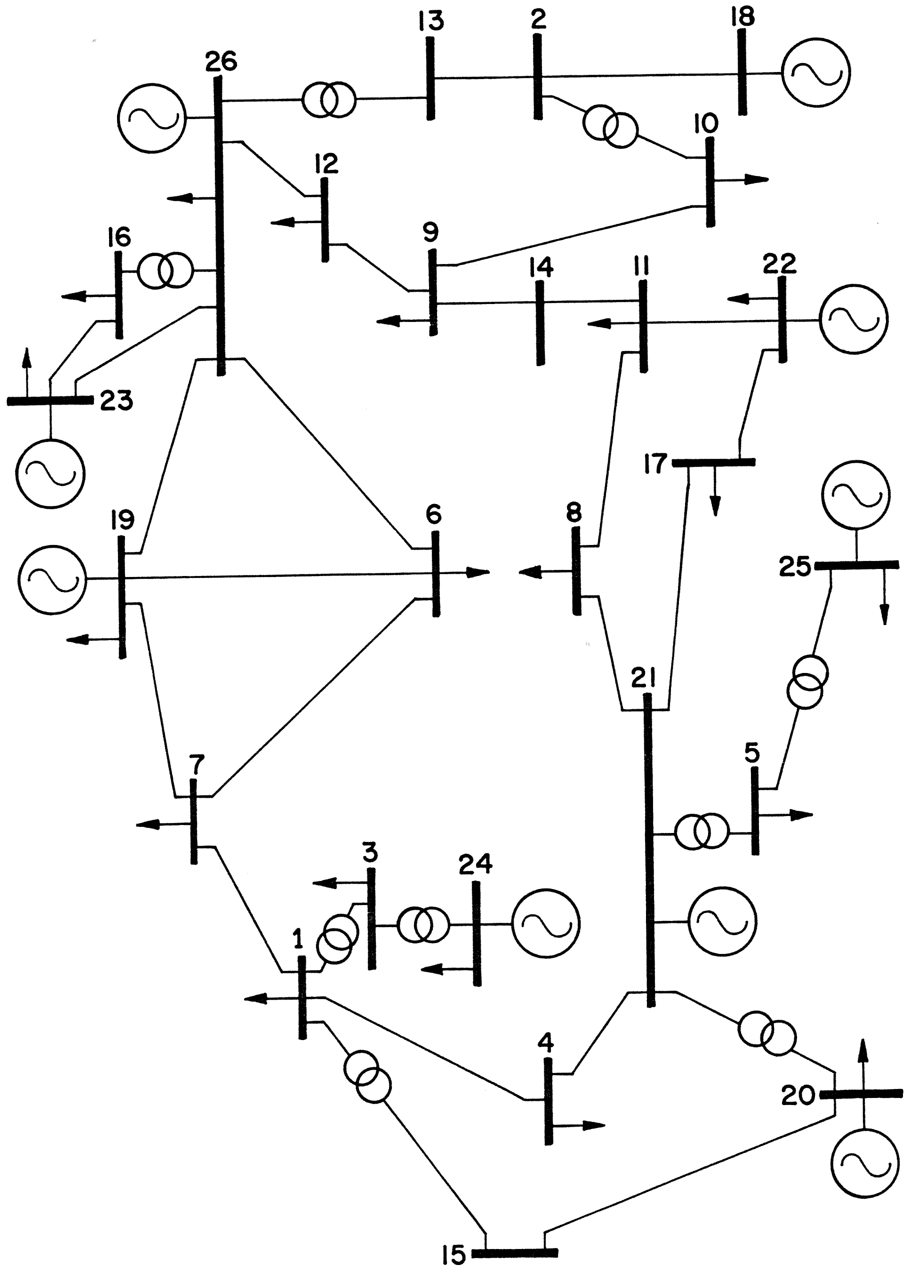

Fig. 5.2 26-bus power system.

```
C
C
C
      PROGRAM DTHND26(D26,B026,TAPE3=D26,TAPE4=B026)
C
C     THIS IS THE MAIN PROGRAM TO CREATE A STANDARD, FORMATTED
C     DATA FILE OF 26-BUS POWER SYSTEM FROM AN UNFORMATTED ONE
C
      INTEGER LBINP(32),LBOUT(32),BNR(26),BTYP(26),OTPT
      REAL LINPG(32),LINPB(32),LR(32),LX(32),LOUTG(32),LOUTB(32),LTAP(32
     1),BVMOD(26),BVARG(26),BGP(26),BLP(26),BLQ(26),BSTL(26),HDLN(8)
      DATA HDLN/"FVA        ",7*"  "/
      INPT=3
      OTPT=4
      CALL READDT (LBINP,LBOUT,LINPG,LINPB,LR,LX,LOUTG,LOUTB,LTAP,BNR,BT
     1YP,BVMOD,BVARG,BGP,BLP,BLQ,BSTL,NB,NTL,INPT)
      CALL FORMDTF (LBINP,LBOUT,LINPG,LINPB,LR,LX,LOUTG,LOUTB,LTAP,BNR,B
     1TYP,BVMOD,BVARG,BGP,BLP,BLQ,BSTL,HDLN,NB,NTL,OTPT)
      REWIND OTPT
      STOP
      END
```

B026FVA

NB = 026, NTL = 032

LINE DATA

LBINP	LBOUT	LINPG	LINPB	LR	LX	LOUTG	LOUTB	LTAP
13	26	0.	0.	0.	.1310000E-01	0.	0.	.1030000E+01
26	16	0.	0.	0.	.3920000E-01	0.	0.	.9600000E+00
16	23	0.	0.	0.	.4320000E+00	0.	0.	.1000000E+01
23	26	0.	0.	0.	.3140000E+00	0.	0.	.1000000E+01
2	10	0.	0.	0.	.1500000E-01	0.	0.	.1030000E+01
9	10	0.	.4120000E+00	.1494000E+00	.3392000E+00	0.	.4120000E+00	.1000000E+01
9	12	0.	.1820000E-01	.6580000E-01	.1494000E+00	0.	.1820000E-01	.1000000E+01
12	26	0.	.1470000E-01	.5330000E-01	.1210000E+00	0.	.1470000E-01	.1000000E+01
9	14	0.	.3190000E-01	.6180000E-01	.2397000E+00	0.	.3190000E-01	.1000000E+01
11	14	0.	.3490000E-01	.6760000E-01	.2620000E+00	0.	.3490000E-01	.1000000E+01
19	26	0.	.2950000E-01	.6100000E-01	.2521000E+00	0.	.2950000E-01	.1000000E+01
6	26	0.	.2650000E-01	.5130000E-01	.1986000E+00	0.	.2650000E-01	.1000000E+01
6	19	0.	.7400000E-02	.1290000E-01	.5320000E-01	0.	.7400000E-02	.1000000E+01
7	19	0.	.4370000E-01	.9060000E-01	.3742000E+00	0.	.4370000E-01	.1000000E+01
6	7	0.	.4750000E-01	.9210000E-01	.3569000E+00	0.	.4750000E-01	.1000000E+01
11	22	0.	.2480000E-01	.5130000E-01	.2118000E+00	0.	.2480000E-01	.1000000E+01
8	11	0.	.4470000E-01	.8650000E-01	.3355000E+00	0.	.4470000E-01	.1000000E+01
17	22	0.	.2370000E-01	.2810000E-01	.1869000E+00	0.	.2370000E-01	.1000000E+01
8	21	0.	.3790000E-01	.7350000E-01	.2847000E+00	0.	.3790000E-01	.1000000E+01
17	21	0.	.3870000E-01	.4590000E-01	.3055000E+00	0.	.3870000E-01	.1000000E+01
1	4	0.	.3190000E-01	.6190000E-01	.2401000E+00	0.	.3190000E-01	.1000000E+01
4	21	0.	.3150000E-01	.6100000E-01	.2365000E+00	0.	.3150000E-01	.1000000E+01
20	21	0.	0.	0.	.3050000E-01	0.	0.	.9700000E+00
15	1	0.	0.	0.	.1470000E-01	0.	0.	.8900000E+00
2	13	0.	.3017000E+00	.8600000E-02	.7070000E-01	0.	.3017000E+00	.1000000E+01
1	7	0.	.4040000E-01	.1990000E-01	.7850000E-01	0.	.4040000E-01	.1000000E+01
15	20	0.	.4471000E+00	.1070000E-01	.6170000E-01	0.	.4471000E+00	.1000000E+01
2	18	0.	.2593000E+00	.7400000E-02	.6080000E-01	0.	.2593000E+00	.1000000E+01
1	3	0.	0.	0.	.3920000E-01	0.	0.	.9800000E+00
24	3	0.	0.	0.	.1450000E+00	0.	0.	.9800000E+00
5	21	0.	0.	0.	.1750000E+00	0.	0.	.9900000E+00
5	25	0.	0.	0.	.1540000E+00	0.	0.	.1030000E+01

BUS DATA

BNR	BTYPE	BVMOD	BVARG	BGP	BLP	BLQ	BSTL
1	0	.1000000E+01	0.	0.	.8200000E+00	.2100000E+00	0.
2	0	.1000000E+01	0.	0.	0.	0.	0.
3	0	.1000000E+01	0.	0.	.5700000E+00	.1700000E+00	0.
4	0	.1000000E+01	0.	0.	.4800000E+00	.2100000E+00	0.
5	0	.1000000E+01	0.	0.	.4300000E+00	.1100000E+00	0.
6	0	.1000000E+01	0.	0.	.4000000E+00	.1000000E+00	0.
7	0	.1000000E+01	0.	0.	.1110000E+01	.2700000E+00	0.
8	0	.1000000E+01	0.	0.	.2300000E+00	.6000000E-01	0.
9	0	.1000000E+01	0.	0.	.6700000E+00	.2100000E+00	0.
10	0	.1000000E+01	0.	0.	.1020000E+01	.2700000E+00	0.
11	0	.1000000E+01	0.	0.	.4300000E+00	.1400000E+00	0.
12	0	.1000000E+01	0.	0.	.4300000E+00	.1200000E+00	0.
13	0	.1000000E+01	0.	0.	0.	0.	0.
14	0	.1000000E+01	0.	0.	0.	0.	0.
15	0	.1000000E+01	0.	0.	0.	0.	0.
16	0	.1000000E+01	0.	0.	.1310000E+01	.3000000E+00	0.
17	0	.1000000E+01	0.	0.	.3000000E-01	.1000000E-01	0.
18	1	.1070000E+01	0.	.2800000E+01	0.	0.	0.
19	1	.1050000E+01	0.	.1450000E+01	0.	0.	0.
20	1	.1000000E+01	0.	.2800000E+01	0.	0.	0.
21	1	.1020000E+01	0.	.1100000E+01	0.	0.	0.
22	1	.8900000E+00	0.	-.5600000E+00	0.	0.	0.
23	1	.1000000E+01	0.	-.4000000E-01	0.	0.	0.
24	1	.1000000E+01	0.	-.5000000E-01	0.	0.	0.
25	1	.1000000E+01	0.	.6300000E+00	0.	0.	0.
26	2	.1010000E+01	0.	0.	0.	0.	0.

3-bus power system (Fig. 5.1)

- B003FVA with bus voltages consistent with a flat voltage profile,
- B003SVA with bus voltages at the corresponding solution point;

6-bus power system [11,12] (Fig. 5.3)

- B006FVA with bus voltages consistent with a flat voltage profile,
- B006SVA with bus voltages at the corresponding solution point;

23-bus power system [11,13]

- B023FVA with bus voltages consistent with a flat voltage profile,
- B023SVA with bus voltages at the corresponding solution point;

26-bus power system [10,11] (Fig. 5.2)

- B026FVA with bus voltages consistent with a flat voltage profile,
- B026SVA with bus voltages at the corresponding solution point;

118-bus power system [14,15]

- B118FVA unoptimized, with bus voltages consistent with a flat voltage profile,
- B118SVA unoptimized, with bus voltages at the corresponding solution point,
- B118FVB optimized, with bus voltages consistent with a flat voltage profile,
- B118SVB optimized, with bus voltages at the corresponding solution point.

5.3 How to Formulate the Load Flow Equations

Here, we describe how to prepare a program which formulates the load flow equations. The highest level subroutine FORMPR is designated to read input data describing the power system and to formulate the load flow problem, i.e., the nodal admittance matrix, the right-hand side vector and the vector of initial bus voltages. It is assumed that data is read from a standard formatted file.

Before calling subroutine FORMPR the user must initialize the variables LWS, NB, NTL, IP, INPT, OTPT and IWRITE. LWS is the length of the workspace vector WS. Parameter IP should be set to 1 if on return from FORMPR vector V of initial bus voltages is required in polar coordinates. If IP is set to any integer different from 1, then on return from FORMPR vector V is in rectangular coordinates. The user should initialize variables NB and NTL to values at least as large as the number of buses and the number of transmission lines, respectively. On return from FORMPR, NB and NTL are the number of buses and the number of transmission lines of the power system considered. The load flow formulation is provided on return from the subroutines by vectors YT, JRYT, ICYT, BCV, V and BTYP.

5.3.1 Example 5.3 Formulation of the Load Flow Equations for the 26-Bus Power System

In this example, the load flow problem for the 26-bus power system (Fig. 5.2) is formulated using TTM1. The listing of the main program LFPR026 is given on page 32. Data describing the power system is read from the formatted data file which was created in Example 5.2 and then stored as a permanent indirect file under the name B026FVA.

```
C
C
C
      PROGRAM LFPR026(B026,OUTPUT,TAPE3=B026,TAPE6=OUTPUT)
C
C     THIS IS THE MAIN PROGRAM FOR THE LOAD FLOW PROBLEM FORMULATION
C     OF 26-BUS POWER SYSTEM
C
      INTEGER LBINP(32),LBOUT(32),BTYP(26),JRYT(27),ICYT(116),OTPT
      REAL BCV(52),WS(410)
      COMPLEX YT(90),V(26)
      LWS=410
      INPT=3
      OTPT=6
      IP=1
      IWRITE=3
      NB=26
      NTL=32
      WRITE(OTPT,40)
      CALL FORMPR (LBINP,LBOUT,BTYP,YT,JRYT,ICYT,BCV,V,WS,LWS,NB,NTL,NLB
     1,IP,INPT,OTPT,IFLAG,IWRITE)
      IF (IFLAG.LT.0) WRITE (6,10) IFLAG
      WRITE (6,20)
      WRITE (6,30) (I,V(I),I=1,NB)
      STOP
   10 FORMAT (///" RETURN FLAG FROM FORMPR:",I2)
   20 FORMAT (///" VECTOR OF THE INITIAL BUS VOLTAGES"/)
   30 FORMAT (3(3X,I3,":",2(1X,E13.7)))
   40 FORMAT (//" LOAD FLOW PROBLEM FORMULATION FOR 26-BUS POWER SYSTEM"
     1)
      END
```

LOAD FLOW PROBLEM FORMULATION FOR 26-BUS POWER SYSTEM

B026FVA

NB = 026,   NTL = 032

LINE DATA

LBINP	LBOUT	LINPG	LINPB	LR	LX	LOUTG	LOUTB	LTAP
13	26	0.	0.	0.	.1310000E-01	0.	0.	.1030000E+01
26	16	0.	0.	0.	.3920000E-01	0.	0.	.9600000E+00
16	23	0.	0.	0.	.4320000E+00	0.	0.	.1000000E+01
23	26	0.	0.	0.	.3140000E+00	0.	0.	.1000000E+01
2	10	0.	0.	0.	.1500000E-01	0.	0.	.1030000E+01
9	10	0.	.4120000E+00	.1494000E+00	.3392000E+00	0.	.4120000E+00	.1000000E+01
9	12	0.	.1820000E-01	.6580000E-01	.1494000E+00	0.	.1820000E-01	.1000000E+01
12	26	0.	.1470000E-01	.5330000E-01	.1210000E+00	0.	.1470000E-01	.1000000E+01
9	14	0.	.3190000E-01	.6180000E-01	.2397000E+00	0.	.3190000E-01	.1000000E+01
11	14	0.	.3490000E-01	.6760000E-01	.2620000E+00	0.	.3490000E-01	.1000000E+01
19	26	0.	.2950000E-01	.6100000E-01	.2521000E+00	0.	.2950000E-01	.1000000E+01
6	26	0.	.2650000E-01	.5130000E-01	.1986000E+00	0.	.2650000E-01	.1000000E+01
6	19	0.	.7400000E-02	.1290000E-01	.5320000E-01	0.	.7400000E-02	.1000000E+01
7	19	0.	.4370000E-01	.9060000E-01	.3742000E+00	0.	.4370000E-01	.1000000E+01
6	7	0.	.4750000E-01	.9210000E-01	.3569000E+00	0.	.4750000E-01	.1000000E+01
11	22	0.	.2480000E-01	.5130000E-01	.2118000E+00	0.	.2480000E-01	.1000000E+01
8	11	0.	.4470000E-01	.8650000E-01	.3355000E+00	0.	.4470000E-01	.1000000E+01
17	22	0.	.2370000E-01	.2810000E-01	.1869000E+00	0.	.2370000E-01	.1000000E+01
8	21	0.	.3790000E-01	.7350000E-01	.2847000E+00	0.	.3790000E-01	.1000000E+01
17	21	0.	.3870000E-01	.4590000E-01	.3055000E+00	0.	.3870000E-01	.1000000E+01
1	4	0.	.3190000E-01	.6190000E-01	.2401000E+00	0.	.3190000E-01	.1000000E+01
4	21	0.	.3150000E-01	.6100000E-01	.2365000E+00	0.	.3150000E-01	.1000000E+01
20	21	0.	0.	0.	.3050000E-01	0.	0.	.9700000E+00
15	1	0.	0.	0.	.1470000E-01	0.	0.	.8900000E+00
2	13	0.	.3017000E+00	.8600000E-02	.7070000E-01	0.	.3017000E+00	.1000000E+01
1	7	0.	.4040000E-01	.1990000E-01	.7850000E-01	0.	.4040000E-01	.1000000E+01
15	20	0.	.4471000E+00	.1070000E-01	.6170000E-01	0.	.4471000E+00	.1000000E+01
2	18	0.	.2593000E+00	.7400000E-02	.6080000E-01	0.	.2593000E+00	.1000000E+01
1	3	0.	0.	0.	.3920000E-01	0.	0.	.9800000E+00
24	3	0.	0.	0.	.1450000E+00	0.	0.	.9800000E+00
5	21	0.	0.	0.	.1750000E+00	0.	0.	.9900000E+00
5	25	0.	0.	0.	.1540000E+00	0.	0.	.1030000E+01

BUS DATA

BNR	BTYPE	BVMOD	BVARG	BGP	BLP	BLQ	BSTL
1	0	.1000000E+01	0.	0.	.8200000E+00	.2100000E+00	0.
2	0	.1000000E+01	0.	0.	0.	0.	0.
3	0	.1000000E+01	0.	0.	.5700000E+00	.1700000E+00	0.
4	0	.1000000E+01	0.	0.	.4800000E+00	.2100000E+00	0.
5	0	.1000000E+01	0.	0.	.4300000E+00	.1100000E+00	0.
6	0	.1000000E+01	0.	0.	.4000000E+00	.1000000E+00	0.
7	0	.1000000E+01	0.	0.	.1110000E+01	.2700000E+00	0.
8	0	.1000000E+01	0.	0.	.2300000E+00	.6000000E-01	0.
9	0	.1000000E+01	0.	0.	.6700000E+00	.2100000E+00	0.
10	0	.1000000E+01	0.	0.	.1020000E+01	.2700000E+00	0.
11	0	.1000000E+01	0.	0.	.4300000E+00	.1400000E+00	0.
12	0	.1000000E+01	0.	0.	.4300000E+00	.1200000E+00	0.
13	0	.1000000E+01	0.	0.	0.	0.	0.
14	0	.1000000E+01	0.	0.	0.	0.	0.
15	0	.1000000E+01	0.	0.	0.	0.	0.
16	0	.1000000E+01	0.	0.	.1310000E+01	.3000000E+00	0.
17	0	.1000000E+01	0.	0.	.3000000E-01	.1000000E-01	0.
18	1	.1070000E+01	0.	.2800000E+01	0.	0.	0.
19	1	.1050000E+01	0.	.1450000E+01	0.	0.	0.
20	1	.1000000E+01	0.	.2800000E+01	0.	0.	0.
21	1	.1020000E+01	0.	.1100000E+01	0.	0.	0.
22	1	.8900000E+00	0.	-.5600000E+00	0.	0.	0.
23	1	.1000000E+01	0.	-.4000000E-01	0.	0.	0.
24	1	.1000000E+01	0.	-.5000000E-01	0.	0.	0.
25	1	.1000000E+01	0.	.6300000E+00	0.	0.	0.
26	2	.1010000E+01	0.	0.	0.	0.	0.

```
BUS ADMITTANCE MATRIX YT
IN EACH ROW DATA IS IN SEQUENCE: COLUMN NUMBER,REAL(YT),IMAG(YT)

BUS NO.  1
    1:  .4041179E+01 -.1103920E+03    4: -.1006838E+01  .3905359E+01   15: 0.             .7643507E+02
    7: -.3034341E+01  .1196964E+02    3: 0.             .2603082E+02

BUS NO.  2
    2:  .3668030E+01 -.9242405E+02   10: 0.             .6472492E+02   13: -.1695433E+01  .1393804E+02
   18: -.1972597E+01  .1620728E+02

BUS NO.  3
    3: 0.            -.3240676E+02    1: 0.             .2603082E+02   24: 0.             .7037298E+01

BUS NO.  4
    4:  .2029414E+01 -.7806538E+01    1: -.1006838E+01  .3905359E+01   21: -.1022576E+01  .3964579E+01

BUS NO.  5
    5: 0.            -.1195106E+02   21: 0.             .5772006E+01   25: 0.             .6304375E+01

BUS NO.  6
    6:  .6202001E+01 -.2501902E+02   26: -.1219290E+01  .4720294E+01   19: -.4304807E+01  .1775316E+02
    7: -.6779036E+00  .2626969E+01

BUS NO.  7
    7:  .4323441E+01 -.1698939E+02   19: -.6111958E+00  .2524387E+01    6: -.6779036E+00  .2626969E+01
    1: -.3034341E+01  .1196964E+02

BUS NO.  8
    8:  .1570718E+01 -.6005235E+01   11: -.7205781E+00  .2794843E+01   21: -.8501401E+00  .3292992E+01

BUS NO.  9
    9:  .4565124E+01 -.1152487E+02   10: -.1087518E+01  .2469118E+01   12: -.2469043E+01  .5606004E+01
   14: -.1008562E+01  .3911852E+01

BUS NO. 10
   10:  .1087518E+01 -.6872378E+02    2: 0.             .6472492E+02    9: -.1087518E+01  .2469118E+01

BUS NO. 11
   11:  .2724108E+01 -.1072880E+02   14: -.9233237E+00  .3578562E+01   22: -.1080206E+01  .4459799E+01
    8: -.7205781E+00  .2794843E+01

BUS NO. 12
   12:  .5517913E+01 -.1249455E+02    9: -.2469043E+01  .5606004E+01   26: -.3048869E+01  .6921448E+01

BUS NO. 13
   13:  .1695433E+01 -.8559022E+02   26: 0.             .7411250E+02    2: -.1695433E+01  .1393804E+02
```

```
BUS NO. 14
   14:   .1931886E+01 -.7423614E+01    9: -.1008562E+01  .3911852E+01   11: -.9233237E+00  .3578562E+01

BUS NO. 15
   15:   .2728631E+01 -.1011693E+03    1: 0.             .7643507E+02   20: -.2728631E+01  .1573426E+02

BUS NO. 16
   16: 0.             -.2782502E+02   26: 0.             .2657313E+02   23: 0.             .2314815E+01

BUS NO. 17
   17:   .1267593E+01 -.8370847E+01   22: -.7866473E+00  .5232184E+01   21: -.4809452E+00  .3201063E+01

BUS NO. 18
   18:   .1972597E+01 -.1594798E+02    2: -.1972597E+01  .1620728E+02

BUS NO. 19
   19:   .5822723E+01 -.2394423E+02   26: -.9067206E+00  .3747283E+01    6: -.4304807E+01  .1775316E+02
    7: -.6111958E+00   .2524387E+01

BUS NO. 20
   20:   .2728631E+01 -.5013346E+02   21: 0.             .3380091E+02   15: -.2728631E+01  .1573426E+02

BUS NO. 21
   21:   .2353662E+01 -.4885170E+02    8: -.8501401E+00  .3292992E+01   17: -.4809452E+00  .3201063E+01
    4: -.1022576E+01   .3964579E+01   20: 0.             .3380091E+02    5: 0.             .5772006E+01

BUS NO. 22
   22:   .1866854E+01 -.9643483E+01   11: -.1080206E+01  .4459799E+01   17: -.7866473E+00  .5232184E+01

BUS NO. 23
   23: 0.             -.5499528E+01   16: 0.             .2314815E+01   26: 0.             .3184713E+01

BUS NO. 24
   24: 0.             -.7180916E+01    3: 0.             .7037298E+01

BUS NO. 25
   25: 0.             -.6493506E+01    5: 0.             .6304375E+01

BUS NO. 26
   26:   .5174880E+01 -.1225193E+03   13: 0.             .7411250E+02   16: 0.             .2657313E+02
   23: 0.              .3184713E+01   12: -.3048869E+01  .6921448E+01   19: -.9067206E+00  .3747283E+01
    6: -.1219290E+01   .4720294E+01
```

```
RHS VECTOR BCV OF POWER FLOW EQUATIONS
VALUE OF AN ELEMENT IS PRECEDED BY THE NUMBER OF BUS

 1: -.8200000E+00 -.2100000E+00    2: 0.             0.               3: -.5700000E+00 -.1700000E+00
 4: -.4800000E+00 -.2100000E+00    5: -.4300000E+00 -.1100000E+00    6: -.4000000E+00 -.1000000E+00
 7: -.1110000E+01 -.2700000E+00    8: -.2300000E+00 -.6000000E-01    9: -.6700000E+00 -.2100000E+00
10: -.1020000E+01 -.2700000E+00   11: -.4300000E+00 -.1400000E+00   12: -.4300000E+00 -.1200000E+00
13: 0.             0.             14: 0.             0.             15: 0.             0.
16: -.1310000E+01 -.3000000E+00   17: -.3000000E-01 -.1000000E-01   18:  .2800000E+01  .1070000E+01
19:  .1450000E+01  .1050000E+01   20:  .2800000E+01  .1000000E+01   21:  .1100000E+01  .1020000E+01
22: -.5600000E+00  .8900000E+00   23: -.4000000E-01  .1000000E+01   24: -.5000000E-01  .1000000E+01
25:  .6300000E+00  .1000000E+01   26:  .1010000E+01 0.


VECTOR OF THE INITIAL BUS VOLTAGES

 1:  .1000000E+01 0.               2:  .1000000E+01 0.               3:  .1000000E+01 0.
 4:  .1000000E+01 0.               5:  .1000000E+01 0.               6:  .1000000E+01 0.
 7:  .1000000E+01 0.               8:  .1000000E+01 0.               9:  .1000000E+01 0.
10:  .1000000E+01 0.              11:  .1000000E+01 0.              12:  .1000000E+01 0.
13:  .1000000E+01 0.              14:  .1000000E+01 0.              15:  .1000000E+01 0.
16:  .1000000E+01 0.              17:  .1000000E+01 0.              18:  .1070000E+01 0.
19:  .1050000E+01 0.              20:  .1000000E+01 0.              21:  .1020000E+01 0.
22:  .8900000E+00 0.              23:  .1000000E+01 0.              24:  .1000000E+01 0.
25:  .1000000E+01 0.              26:  .1010000E+01 0.
```

Printed output is controlled by the parameter IWRITE=3. This means that, by calling subroutine FORMPR the data describing the power system, the nodal admittance matrix and the vector of bus control variables will be printed out. These results are shown on pages 33-37. Since parameter IP is set to 1 the vector V of initial bus voltages is in polar coordinates.

5.4 How to Determine the Load Flow Solution

There are two highest level subroutines to determine the load flow solution: LFTTM and LFLFD1M. The first solves the flow equations using the Tellegen theorem method [2], the other one implements the fast decoupled method [6].

Both subroutines assume that the load flow problem has been formulated earlier, i.e., vectors YT, JRYT and ICYT storing the nodal admittance matrix, and vectors BTYP, BCV and V of bus types, of bus control variables and of initial bus voltages, respectively, are given, e.g., due to an earlier call to subroutine FORMPR.

(a) To use subroutine LFTTM the user should also initialize the following parameters: NB, NTL, LW, IVT, IP, ITEL, VEPS, TIMEL, MODE, OTPT and IWRITE.

If the value of IP is 1, then the polar formulation of load flow equations is used. On entry to LFTTM vector V must be given in polar coordinates and on return, it contains the values of bus voltages at the solution in polar coordinates as well. If IP $\neq$ 1, then the rectangular formulation of load flow equations is used.

On entry to LFTTM vector V must be given in rectangular coordinates, and on return it contains the values of bus voltages at the solution point also in rectangular coordinates.

(b) To use subroutine LFLFD1M to solve the load flow problem the user should also initialize the parameters: NB, NLB, NYT, LW, ITEL, VEPS, TIMEL, MODE, OTPT and IWRITE. On return from the subroutine, vector V contains the values of bus voltages in rectangular coordinates.

5.4.1 Example 5.4 Load Flow Solution of the 26-Bus Power System

In this example the load flow solution of the 26-bus power system (Fig. 5.2) is determined using the Tellegen theorem method and, after obtaining the solution, an updated data file is also created. The listing of the user's program LFTM26 is shown on pages 40-41. Program LFTM26 uses the package of subroutines MA28 [4] to solve the system of sparse, real equations.

The load flow problem is formulated in the program by a call to subroutine FORMPR. The power flow equations are solved using subroutine LFTTM. Demanded accuracy of the solution is TOLV=10^{-6}. At least one call to subroutine LFTTM has been allowed. In the first call the number of iterations is limited to 3 (ITEL=3), and the execution time is limited to 3.0 seconds (T=3.0). The exact version of the adjoint matrix is used (IVT=1). If the demanded accuracy is not attained then subroutine LFTTM is called again with parameter MODE=3. The adjoint matrix is kept constant from the previous call to the subroutine and is not updated in consecutive iterations.

The results of the analysis are reported on pages 42-43. After the

```
C
C
C
      PROGRAM LFTM26(B26FVA,B26SVA,OUTPUT,TAPE3=B26FVA,TAPE4=B26SVA,TAPE
     16=OUTPUT)
C
C     THIS IS THE MAIN PROGRAM FOR THE LOAD FLOW PROBLEM SOLUTION
C     OF 26-BUS  POWER SYSTEM  USING  THE TELLEGEN THEOREM METHOD
C
      INTEGER BTYP(26),JRYT(27),ICYT(120),LBINP(32),LBOUT(32),OTPT
      REAL WST(3800),WSP(420),BCV(52),HDLN(8),D(2)
      COMPLEX YT(90),V(26),Z
      COMMON /MDFRMPR/ JINPG,JINPB,JLG,JLB,JOUTG,JOUTB,JTAP,JNR,JVM,JVA,
     1JGP,JLP,JLQ,JSTL,JMAX
      DATA D/"    EXACT","CONSTANT"/,HDLN/"SVA        ",7*" "/
      IWRITE=0
      INPT=3
      OTPT=6
      LWSP=420
      LWST=3800
      NB=26
      NTL=32
      WRITE (OTPT,80)
      IP=1
C
C     SUBROUTINE FORMPR FORMULATES THE LOAD FLOW PROBLEM
C
      CALL FORMPR (LBINP,LBOUT,BTYP,YT,JRYT,ICYT,BCV,V,WSP,LWSP,NB,NTL,N
     1LB,IP,INPT,OTPT,IFLAG,IWRITE)
      IF (IFLAG.GE.0) GO TO 10
      WRITE (6,90) IFLAG
      STOP
   10 IWRITE=1
      IVT=1
      TOLV=1.E-6
      T=3.0
      MODE=1
      ITEL=3
   20 VEPS=TOLV
      TIMEL=T
      WRITE (OTPT,100) (VEPS,TIMEL,ITEL,MODE,D(IVT))
C
C     SUBROUTINE LFTTM SOLVES THE LOAD FLOW EQUATIONS USING
C     THE TELLEGEN THEOREM METHOD
C
      CALL LFTTM (NB,NTL,JRYT,ICYT,BTYP,YT,V,BCV,WST,LWST,IVT,IP,ITEL,VE
     1PS,TIMEL,MODE,IFLAG,OTPT,IWRITE)
      IF (IFLAG.GE.0) GO TO 30
      WRITE (6,70) IFLAG
      STOP
   30 IF (MODE.EQ.3) GO TO 40
      IF (IFLAG.EQ.0) GO TO 40
      ITEL=4
      MODE=3
      IVT=2
      GO TO 20
C
C     DATA IS PREPARED TO CREATE AN UPDATED DATA FILE
C
   40 J1=JVM-1
      J2=JVA-1
      DO 50 I=1,NB
      Z=V(I)
      WSP(J1+I)=REAL(Z)
      WSP(J2+I)=AIMAG(Z)
```

```
   50 CONTINUE
      J1=JLG-1
      J2=JLB-1
      DO 60 I=1,NTL
      J3=J1+I
      J4=J2+I
      Z=1./CMPLX(WSP(J3),WSP(J4))
      WSP(J3)=REAL(Z)
      WSP(J4)=AIMAG(Z)
   60 CONTINUE
      OTPT=4
C
C     SUBROUTINE FORMDTF CREATES AN UPDATED DATA FILE
C
      CALL FORMDTF (LBINP,LBOUT,WSP(JINPG),WSP(JINPB),WSP(JLG),WSP(JLB),
     1WSP(JOUTG),WSP(JOUTB),WSP(JTAP),WSP(JNR),BTYP,WSP(JVM),WSP(JVA),WS
     2P(JGP),WSP(JLP),WSP(JLQ),WSP(JSTL),HDLN,NB,NTL,OTPT)
      REWIND OTPT
      STOP
   70 FORMAT (///" RETURN FLAG FROM LFTTM :",I3)
   80 FORMAT (//" LOAD FLOW ANALYSIS OF 26-BUS POWER SYSTEM")
   90 FORMAT (///" RETURN FLAG FROM FORMPR :",I3)
  100 FORMAT (///" SUBROUTINE LFTTM WAS CALLED WITH PARAMETERS"//" DEMAN
     1DED ACCURACY:",2X,E10.4/" LIMIT OF TIME:",11X,F5.2/" LIMIT OF ITER
     2ATIONS:",7X,I3/" MODE OF ITERATION:",10X,I2/" ADJOINT MATRIX:",7X,
     3A8)
      END
```

LOAD FLOW ANALYSIS OF 26-BUS POWER SYSTEM

SUBROUTINE LFTTM WAS CALLED WITH PARAMETERS

DEMANDED ACCURACY: .1000E-05
LIMIT OF TIME: 3.00
LIMIT OF ITERATIONS: 3
MODE OF ITERATION: 1
ADJOINT MATRIX: EXACT

LOAD FLOW SOLUTION OF 26-BUS SYSTEM USING THE TELLEGEN THEOREM METHOD

IT = 1 EPS = .3995E+00 ITERATION TIME .742 TOTAL TIME .742

IT = 2 EPS = .6318E-01 ITERATION TIME .656 TOTAL TIME 1.398

IT = 3 EPS = .4856E-02 ITERATION TIME .658 TOTAL TIME 2.056

RESULTS OF ANALYSIS

NUMBER OF ITERATIONS: 3
RETURN FLAG: 1
ACCURACY OBTAINED: .4856E-02
ANALYSIS TIME: 2.056 SECONDS

VECTOR OF BUS VOLTAGES

BUS	RECTANGULAR COORDINATES		POLAR COORDINATES	
1	.1032765E+01	.7730712E-01	.1035655E+01	.7471516E-01
2	.1064367E+01	.9434005E-01	.1068540E+01	.8840387E-01
3	.1042367E+01	.5496294E-01	.1043815E+01	.5268017E-01
4	.9859070E+00	.9788492E-01	.9907543E+00	.9895982E-01
5	.9740793E+00	.2598296E+00	.1008138E+01	.2606744E+00
6	.1032446E+01	.5542083E-01	.1033932E+01	.5362770E-01
7	.1013191E+01	.1806840E-01	.1013352E+01	.1783127E-01
8	.9441199E+00	.4027987E-01	.9449787E+00	.4263808E-01
9	.9613780E+00	-.1087670E+00	.9675112E+00	-.1126575E+00
10	.1036971E+01	.6924534E-01	.1039281E+01	.6667754E-01
11	.8982234E+00	-.9920556E-01	.9036852E+00	-.1100006E+00
12	.9670459E+00	-.7406401E-01	.9698779E+00	-.7643867E-01
13	.1046329E+01	.1572018E-01	.1046447E+01	.1502300E-01
14	.9388251E+00	-.1071221E+00	.9449168E+00	-.1136110E+00
15	.9273417E+00	.9702367E-01	.9324034E+00	.1042463E+00
16	.1035263E+01	-.4711813E-01	.1036334E+01	-.4548182E-01
17	.9317612E+00	.2782013E-01	.9321764E+00	.2984871E-01
18	.1039703E+01	.2528190E+00	.1070000E+01	.2385350E+00
19	.1045549E+01	.9658191E-01	.1050000E+01	.9211298E-01
20	.9705745E+00	.2408012E+00	.1000000E+01	.2431913E+00
21	.9938394E+00	.2295284E+00	.1020000E+01	.2269716E+00
22	.8855917E+00	-.8847271E-01	.8900000E+00	-.9957199E-01
23	.9996475E+00	-.2655108E-01	.1000000E+01	-.2655420E-01

24	.9989480E+00	.4585728E-01	.1000000E+01	.4587336E-01
25	.9359104E+00	.3522381E+00	.1000000E+01	.3599614E+00
26	.1010000E+01	0.	.1010000E+01	0.

SUBROUTINE LFTTM WAS CALLED WITH PARAMETERS

DEMANDED ACCURACY:	.1000E-05
LIMIT OF TIME:	3.00
LIMIT OF ITERATIONS:	4
MODE OF ITERATION:	3
ADJOINT MATRIX:	CONSTANT

LOAD FLOW SOLUTION OF 26-BUS SYSTEM USING THE TELLEGEN THEOREM METHOD

IT = 1 EPS = .1896E-04 ITERATION TIME .568 TOTAL TIME .568

IT = 2 EPS = .2891E-06 ITERATION TIME .571 TOTAL TIME 1.139

RESULTS OF ANALYSIS

NUMBER OF ITERATIONS:	2
RETURN FLAG:	0
ACCURACY OBTAINED:	.2891E-06
ANALYSIS TIME:	1.139 SECONDS

VECTOR OF BUS VOLTAGES

BUS	RECTANGULAR COORDINATES		POLAR COORDINATES	
1	.1032758E+01	.7728919E-01	.1035646E+01	.7469839E-01
2	.1064366E+01	.9433929E-01	.1068539E+01	.8840321E-01
3	.1042361E+01	.5494543E-01	.1043809E+01	.5266371E-01
4	.9859041E+00	.9786664E-01	.9907496E+00	.9894175E-01
5	.9740839E+00	.2598125E+00	.1008138E+01	.2606568E+00
6	.1032445E+01	.5541752E-01	.1033931E+01	.5362455E-01
7	.1013184E+01	.1805726E-01	.1013345E+01	.1782041E-01
8	.9441193E+00	.4026454E-01	.9449775E+00	.4262190E-01
9	.9613740E+00	-.1087696E+00	.9675075E+00	-.1126607E+00
10	.1036971E+01	.6924455E-01	.1039280E+01	.6667683E-01
11	.8982194E+00	-.9921886E-01	.9036827E+00	-.1100157E+00
12	.9670438E+00	-.7406484E-01	.9698760E+00	-.7643969E-01
13	.1046329E+01	.1572009E-01	.1046447E+01	.1502292E-01
14	.9388198E+00	-.1071300E+00	.9449124E+00	-.1136199E+00
15	.9273368E+00	.9700728E-01	.9323969E+00	.1042294E+00
16	.1035263E+01	-.4711813E-01	.1036334E+01	-.4548182E-01
17	.9317616E+00	.2780420E-01	.9321764E+00	.2983161E-01
18	.1039703E+01	.2528182E+00	.1070000E+01	.2385343E+00
19	.1045549E+01	.9657833E-01	.1050000E+01	.9210955E-01
20	.9705787E+00	.2407841E+00	.1000000E+01	.2431736E+00
21	.9938434E+00	.2295109E+00	.1020000E+01	.2269540E+00
22	.8855902E+00	-.8848754E-01	.8900000E+00	-.9958874E-01
23	.9996475E+00	-.2655108E-01	.1000000E+01	-.2655420E-01
24	.9989488E+00	.4584079E-01	.1000000E+01	.4585686E-01
25	.9359166E+00	.3522216E+00	.1000000E+01	.3599438E+00
26	.1010000E+01	0.	.1010000E+01	0.

B026SVA

NB = 026,   NTL = 032

LINE DATA

LBINP	LBOUT	LINPG	LINPB	LR	LX	LOUTG	LOUTB	LTAP
13	26	0.	0.	0.	.1310000E-01	0.	0.	.1030000E+01
26	16	0.	0.	0.	.3920000E-01	0.	0.	.9600000E+00
16	23	0.	0.	0.	.4320000E+00	0.	0.	.1000000E+01
23	26	0.	0.	0.	.3140000E+00	0.	0.	.1000000E+01
2	10	0.	0.	0.	.1500000E-01	0.	0.	.1030000E+01
9	10	0.	.4120000E+00	.1494000E+00	.3392000E+00	0.	.4120000E+00	.1000000E+01
9	12	0.	.1820000E-01	.6580000E-01	.1494000E+00	0.	.1820000E-01	.1000000E+01
12	26	0.	.1470000E-01	.5330000E-01	.1210000E+00	0.	.1470000E-01	.1000000E+01
9	14	0.	.3190000E-01	.6180000E-01	.2397000E+00	0.	.3190000E-01	.1000000E+01
11	14	0.	.3490000E-01	.6760000E-01	.2620000E+00	0.	.3490000E-01	.1000000E+01
19	26	0.	.2950000E-01	.6100000E-01	.2521000E+00	0.	.2950000E-01	.1000000E+01
6	26	0.	.2650000E-01	.5130000E-01	.1986000E+00	0.	.2650000E-01	.1000000E+01
6	19	0.	.7400000E-02	.1290000E-01	.5320000E-01	0.	.7400000E-02	.1000000E+01
7	19	0.	.4370000E-01	.9060000E-01	.3742000E+00	0.	.4370000E-01	.1000000E+01
6	7	0.	.4750000E-01	.9210000E-01	.3569000E+00	0.	.4750000E-01	.1000000E+01
11	22	0.	.2480000E-01	.5130000E-01	.2118000E+00	0.	.2480000E-01	.1000000E+01
8	11	0.	.4470000E-01	.8650000E-01	.3355000E+00	0.	.4470000E-01	.1000000E+01
17	22	0.	.2370000E-01	.2810000E-01	.1869000E+00	0.	.2370000E-01	.1000000E+01
8	21	0.	.3790000E-01	.7350000E-01	.2847000E+00	0.	.3790000E-01	.1000000E+01
17	21	0.	.3870000E-01	.4590000E-01	.3055000E+00	0.	.3870000E-01	.1000000E+01
1	4	0.	.3190000E-01	.6190000E-01	.2401000E+00	0.	.3190000E-01	.1000000E+01
4	21	0.	.3150000E-01	.6100000E-01	.2365000E+00	0.	.3150000E-01	.1000000E+01
20	21	0.	0.	0.	.3050000E-01	0.	0.	.9700000E+00
15	1	0.	0.	0.	.1470000E-01	0.	0.	.8900000E+00
2	13	0.	.3017000E+00	.8600000E-02	.7070000E-01	0.	.3017000E+00	.1000000E+01
1	7	0.	.4040000E-01	.1990000E-01	.7850000E-01	0.	.4040000E-01	.1000000E+01
15	20	0.	.4471000E+00	.1070000E-01	.6170000E-01	0.	.4471000E+00	.1000000E+01
2	18	0.	.2593000E+00	.7400000E-02	.6080000E-01	0.	.2593000E+00	.1000000E+01
1	3	0.	0.	0.	.3920000E-01	0.	0.	.9800000E+00
24	3	0.	0.	0.	.1450000E+00	0.	0.	.9800000E+00
5	21	0.	0.	0.	.1750000E+00	0.	0.	.9900000E+00
5	25	0.	0.	0.	.1540000E+00	0.	0.	.1030000E+01

BUS DATA

BNR	BTYPE	BVMOD	BVARG	BGP	BLP	BLQ	BSTL
1	0	.1035646E+01	.7469839E-01	0.	.8200000E+00	.2100000E+00	0.
2	0	.1068539E+01	.8840321E-01	0.	0.	0.	0.
3	0	.1043809E+01	.5266371E-01	0.	.5700000E+00	.1700000E+00	0.
4	0	.9907496E+00	.9894175E-01	0.	.4800000E+00	.2100000E+00	0.
5	0	.1008138E+01	.2606568E+00	0.	.4300000E+00	.1100000E+00	0.
6	0	.1033931E+01	.5362455E-01	0.	.4000000E+00	.1000000E+00	0.
7	0	.1013345E+01	.1782041E-01	0.	.1110000E+01	.2700000E+00	0.
8	0	.9449775E+00	.4262190E-01	0.	.2300000E+00	.6000000E-01	0.
9	0	.9675075E+00	-.1126607E+00	0.	.6700000E+00	.2100000E+00	0.
10	0	.1039280E+01	.6667683E-01	0.	.1020000E+01	.2700000E+00	0.
11	0	.9036827E+00	-.1100157E+00	0.	.4300000E+00	.1400000E+00	0.
12	0	.9693760E+00	-.7643969E-01	0.	.4300000E+00	.1200000E+00	0.
13	0	.1046447E+01	.1502292E-01	0.	0.	0.	0.
14	0	.9449124E+00	-.1136199E+00	0.	0.	0.	0.
15	0	.9323969E+00	.1042294E+00	0.	0.	0.	0.
16	0	.1036334E+01	-.4548182E-01	0.	.1310000E+01	.3000000E+00	0.
17	0	.9321764E+00	.2983161E-01	0.	.3000000E-01	.1000000E-01	0.
18	1	.1070000E+01	.2385343E+00	.2800000E+01	0.	0.	0.
19	1	.1050000E+01	.9210955E-01	.1450000E+01	0.	0.	0.
20	1	.1000000E+01	.2431736E+00	.2800000E+01	0.	0.	0.
21	1	.1020000E+01	.2269540E+00	.1100000E+01	0.	0.	0.
22	1	.8900000E+00	-.9958874E-01	-.5600000E+00	0.	0.	0.
23	1	.1000000E+01	-.2655420E-01	-.4000000E-01	0.	0.	0.
24	1	.1000000E+01	.4585686E-01	-.5000000E-01	0.	0.	0.
25	1	.1000000E+01	.3599438E+00	.6300000E+00	0.	0.	0.
26	2	.1010000E+01	0.	0.	0.	0.	0.

first three iterations an accuracy of 0.49×10^{-2} was achieved, and two more iterations with constant adjoint matrix were needed to obtain the demanded accuracy.

After solving the equations the program LFTM26 calls the subroutine FORMDTF to create an updated data file. In this file all original power system data is preserved except for the moduli and the arguments of bus voltages, which are set to the values at the solution. After the program execution the updated data file exists as a local file under the name B26SVA. The contents of this file are printed out on pages 44-45. The first non-empty data record is the file identifier which is B026SVA due to appropriate initialization of vector HDLN in the program LFTM26.

5.4.2 Example 5.5 Load Flow Solution of the 118-Bus Power System

In this example the load flow solution of the General Electric optimized 118-bus power system [15] is determined using the fast decoupled method [6].

The listing of the user's program LFFD118 is shown on page 47. In this example the load flow problem is formulated using subroutine FORMPR and the power flow equations are solved with the aid of subroutine LFLFD1M. Because IP=0 then on return from FORMPR vector V of the initial bus voltages is in rectangular coordinates, as required by LFLFD1M. The demanded accuracy of the solution is $VEPS=10^{-3}$.

The input data, brief information concerning the iterations and the load flow solution are printed out (IWRITE = 2). These results are reported on pages 48-58. On entry to subroutine LFLFD1M the number of iterations was limited to 20 and the execution time was limited to 2.0

```
C
C
C
      PROGRAM LFFD118(B118,OUTPUT,TAPE4=B118,TAPE6=OUTPUT)
C
C     THIS IS THE MAIN PROGRAM FOR THE LOAD FLOW PROBLEM SOLUTION
C     OF 118-BUS POWER SYSTEM USING THE FAST DECOUPLED METHOD
C
      INTEGER BTYP(120),JRYT(120),ICYT(600),OTPT
      REAL BCV(236),W(10000)
      COMPLEX YT(480),V(118),Z
      INPT=4
      OTPT=6
      LWS=2100
      LW=10000
      NB=118
      NTL=179
      WRITE (OTPT,40)
      JBINP=1
      JBOUT=JBINP+NTL
      JWS=JBOUT+NTL
      IP=0
      IWRITE=2
C
C     SUBROUTINE FORMPR FORMULATES THE LOAD FLOW PROBLEM
C
      CALL FORMPR (W(JBINP),W(JBOUT),BTYP,YT,JRYT,ICYT,BCV,V,W(JWS),LWS,
     1NB,NTL,NLB,IP,INPT,OTPT,IFLAG,IWRITE)
      IF (IFLAG.GE.0) GO TO 10
      WRITE (OTPT,30) IFLAG
      STOP
   10 NYT=NB+2*NTL
      VEPS=1.E-3
      ITEL=20
      TIMEL=2.0
      MODE=0
      IWRITE=2
C
C     SUBROUTINE LFLFD1M SOLVES THE LOAD FLOW EQUATIONS USING
C     THE FAST DECOUPLED METHOD
C
      CALL LFLFD1M (NB,NLB,NYT,JRYT,ICYT,BTYP,YT,V,BCV,W,LW,ITEL,VEPS,TI
     1MEL,MODE,IFLAG,OTPT,IWRITE)
      IF (IFLAG.GE.0) STOP
      WRITE (OTPT,20) IFLAG
      STOP
   20 FORMAT (///10X,"RETURN FLAG FROM LFLFD1M:",I3)
   30 FORMAT (///10X,"RETURN FLAG FROM FORMPR:",I3)
   40 FORMAT (//1X,"LOAD FLOW ANALYSIS OF 118-BUS POWER SYSTEM")
      END
```

LOAD FLOW ANALYSIS OF 118-BUS POWER SYSTEM

B118FVB

NB = 118, NTL = 179

LINE DATA

LBINP	LBOUT	LINPG	LINPB	LR	LX	LOUTG	LOUTB	LTAP
1	2	0.	.1270000E-01	.3030000E-01	.9900000E-01	0.	.1270000E-01	.1000000E+01
1	3	0.	.5150000E-02	.1290000E-01	.4240000E-01	0.	.5150000E-02	.1000000E+01
4	5	0.	.1050000E-02	.2180000E-01	.5800000E-01	0.	.1050000E-02	.1000000E+01
3	5	0.	.1420000E-01	.2410000E-01	.1080000E+00	0.	.1420000E-01	.1000000E+01
5	6	0.	.7150000E-02	.1190000E-01	.5400000E-01	0.	.7150000E-02	.1000000E+01
6	7	0.	.2750000E-02	.4600000E-02	.2080000E-01	0.	.2750000E-02	.1000000E+01
8	9	0.	.5810000E+00	.2400000E-02	.3050000E-01	0.	.5810000E+00	.1000000E+01
8	5	0.	0.	0.	.2670000E-01	0.	0.	.1020000E+01
9	10	0.	.6150000E+00	.2600000E-02	.3220000E-01	0.	.6150000E+00	.1000000E+01
4	11	0.	.8750000E-02	.2090000E-01	.6880000E-01	0.	.8750000E-02	.1000000E+01
5	11	0.	.8700000E-02	.2030000E-01	.6820000E-01	0.	.8700000E-02	.1000000E+01
11	12	0.	.2500000E-02	.6000000E-02	.1960000E-01	0.	.2500000E-02	.1000000E+01
2	12	0.	.7850000E-02	.1870000E-01	.6160000E-01	0.	.7850000E-02	.1000000E+01
3	12	0.	.2030000E-01	.4840000E-01	.1600000E+00	0.	.2030000E-01	.1000000E+01
7	12	0.	.4350000E-02	.8600000E-02	.3400000E-01	0.	.4350000E-02	.1000000E+01
11	13	0.	.9400000E-02	.2230000E-01	.7310000E-01	0.	.9400000E-02	.1000000E+01
12	14	0.	.9100000E-02	.2150000E-01	.7070000E-01	0.	.9100000E-02	.1000000E+01
13	15	0.	.3135000E-01	.7440000E-01	.2444000E+00	0.	.3135000E-01	.1000000E+01
14	15	0.	.2510000E-01	.5950000E-01	.1950000E+00	0.	.2510000E-01	.1000000E+01
12	16	0.	.1070000E-01	.2120000E-01	.3840000E-01	0.	.1070000E-01	.1000000E+01
15	17	0.	.2220000E-01	.1320000E-01	.4370000E-01	0.	.2220000E-01	.1000000E+01
16	17	0.	.2330000E-01	.4540000E-01	.1801000E+00	0.	.2330000E-01	.1000000E+01
17	18	0.	.6500000E-02	.1230000E-01	.5050000E-01	0.	.6500000E-02	.1000000E+01
18	19	0.	.5700000E-02	.1190000E-01	.4930000E-01	0.	.5700000E-02	.1000000E+01
19	20	0.	.1490000E-01	.2520000E-01	.1170000E+00	0.	.1490000E-01	.1000000E+01
15	19	0.	.5050000E-02	.1200000E-01	.3940000E-01	0.	.5050000E-02	.1000000E+01
20	21	0.	.1080000E-01	.1830000E-01	.8490000E-01	0.	.1080000E-01	.1000000E+01
21	22	0.	.1230000E-01	.2090000E-01	.9700000E-01	0.	.1230000E-01	.1000000E+01
22	23	0.	.2020000E-01	.3420000E-01	.1590000E+00	0.	.2020000E-01	.1000000E+01
23	24	0.	.2490000E-01	.1350000E-01	.4920000E-01	0.	.2490000E-01	.1000000E+01
23	25	0.	.4320000E-01	.1560000E-01	.8000000E-01	0.	.4320000E-01	.1000000E+01
26	25	0.	0.	0.	.3820000E-01	0.	0.	.1040000E+01
25	27	0.	.8800000E-01	.3180000E-01	.1630000E+00	0.	.8800000E-01	.1000000E+01
27	28	0.	.1080000E-01	.1910000E-01	.8550000E-01	0.	.1080000E-01	.1000000E+01
28	29	0.	.1190000E-01	.2730000E-01	.9430000E-01	0.	.1190000E-01	.1000000E+01
30	17	0.	0.	0.	.3880000E-01	0.	0.	.1040000E+01
8	30	0.	.2570000E+00	.4300000E-02	.5040000E-01	0.	.2570000E+00	.1000000E+01

26	30	0.	.4540000E+00	.8000000E-02	.8600000E-01	0.	.4540000E+00	.1000000E+01
17	31	0.	.1995000E-01	.4740000E-01	.1563000E+00	0.	.1995000E-01	.1000000E+01
29	31	0.	.4150000E-02	.1080000E-01	.3310000E-01	0.	.4150000E-02	.1000000E+01
23	32	0.	.5865000E-01	.3170000E-01	.1153000E+00	0.	.5865000E-01	.1000000E+01
31	32	0.	.1255000E-01	.2980000E-01	.9580000E-01	0.	.1255000E-01	.1000000E+01
27	32	0.	.9650000E-02	.2290000E-01	.7550000E-01	0.	.9650000E-02	.1000000E+01
15	33	0.	.1595000E-01	.3800000E-01	.1244000E+00	0.	.1595000E-01	.1000000E+01
19	34	0.	.3160000E-01	.7520000E-01	.2470000E+00	0.	.3160000E-01	.1000000E+01
35	36	0.	.1350000E-02	.2200000E-02	.1020000E-01	0.	.1350000E-02	.1000000E+01
35	37	0.	.6600000E-02	.1100000E-01	.4970000E-01	0.	.6600000E-02	.1000000E+01
33	37	0.	.1830000E-01	.4150000E-01	.1420000E+00	0.	.1830000E-01	.1000000E+01
34	36	0.	.2850000E-02	.8700000E-02	.2680000E-01	0.	.2850000E-02	.1000000E+01
34	37	0.	.4900000E-02	.2260000E-01	.5940000E-01	0.	.4900000E-02	.1000000E+01
38	37	0.	0.	0.	.3750000E-01	0.	0.	.1070000E+01
37	39	0.	.1350000E-01	.3210000E-01	.1060000E+00	0.	.1350000E-01	.1000000E+01
37	40	0.	.2100000E-01	.5930000E-01	.1680000E+00	0.	.2100000E-01	.1000000E+01
30	38	0.	.2110000E+00	.4600000E-02	.5400000E-01	0.	.2110000E+00	.1000000E+01
39	40	0.	.7750000E-02	.1840000E-01	.6050000E-01	0.	.7750000E-02	.1000000E+01
40	41	0.	.6100000E-02	.1450000E-01	.4780000E-01	0.	.6100000E-02	.1000000E+01
40	42	0.	.2330000E-01	.5550000E-01	.1830000E+00	0.	.2330000E-01	.1000000E+01
41	42	0.	.1720000E-01	.4100000E-01	.1350000E+00	0.	.1720000E-01	.1000000E+01
43	44	0.	.3035000E-01	.6080000E-01	.2454000E+00	0.	.3035000E-01	.1000000E+01
34	43	0.	.2115000E-01	.4130000E-01	.1681000E+00	0.	.2115000E-01	.1000000E+01
44	45	0.	.1120000E-01	.2240000E-01	.9010000E-01	0.	.1120000E-01	.1000000E+01
45	46	0.	.1160000E-01	.4000000E-01	.1356000E+00	0.	.1160000E-01	.1000000E+01
46	47	0.	.1580000E-01	.3800000E-01	.1270000E+00	0.	.1580000E-01	.1000000E+01
46	48	0.	.2360000E-01	.6010000E-01	.1890000E+00	0.	.2360000E-01	.1000000E+01
47	49	0.	.8000000E-02	.1910000E-01	.6250000E-01	0.	.8000000E-02	.1000000E+01
42	49	0.	.8600000E-01	.3580000E-01	.1615000E+00	0.	.8600000E-01	.1000000E+01
76	69	0.	.4300000E-01	.6140000E-01	.5440000E-01	0.	.4300000E-01	.1000000E+01
45	49	0.	.2220000E-01	.6840000E-01	.1860000E+00	0.	.2220000E-01	.1000000E+01
48	49	0.	.6300000E-02	.1790000E-01	.5050000E-01	0.	.6300000E-02	.1000000E+01
49	50	0.	.9350000E-02	.2670000E-01	.7520000E-01	0.	.9350000E-02	.1000000E+01
49	51	0.	.1710000E-01	.4860000E-01	.1370000E+00	0.	.1710000E-01	.1000000E+01
51	52	0.	.7000000E-02	.2030000E-01	.5880000E-01	0.	.7000000E-02	.1000000E+01
52	53	0.	.2030000E-01	.4050000E-01	.1635000E+00	0.	.2030000E-01	.1000000E+01
53	54	0.	.1550000E-01	.2630000E-01	.1220000E+00	0.	.1550000E-01	.1000000E+01
49	54	0.	.7340000E-01	.3990000E-01	.1451000E+00	0.	.7340000E-01	.1000000E+01
75	69	0.	.3650000E-01	.1450000E-01	.4810000E-01	0.	.3650000E-01	.1000000E+01
54	55	0.	.1010000E-01	.1690000E-01	.7070000E-01	0.	.1010000E-01	.1000000E+01
54	56	0.	.3650000E-02	.2280000E-01	.5950000E-01	0.	.3650000E-02	.1000000E+01
55	56	0.	.1850000E-02	.2490000E-01	.5510000E-01	0.	.1850000E-02	.1000000E+01
56	57	0.	.1210000E-01	.3430000E-01	.9660000E-01	0.	.1210000E-01	.1000000E+01
50	57	0.	.1660000E-01	.4740000E-01	.1340000E+00	0.	.1660000E-01	.1000000E+01
56	58	0.	.1210000E-01	.3430000E-01	.9660000E-01	0.	.1210000E-01	.1000000E+01
51	58	0.	.8950000E-02	.2550000E-01	.7190000E-01	0.	.8950000E-02	.1000000E+01
54	59	0.	.2990000E-01	.5030000E-01	.2293000E+00	0.	.2990000E-01	.1000000E+01
56	59	0.	.5525000E-01	.4070000E-01	.1224000E+00	0.	.5525000E-01	.1000000E+01
12	117	0.	.2680000E-01	.3290000E-01	.1400000E+00	0.	.2680000E-01	.1000000E+01
55	59	0.	.2825000E-01	.4740000E-01	.2158000E+00	0.	.2825000E-01	.1000000E+01

59	60	0.	.1880000E-01	.3170000E-01	.1450000E+00	0.	.1880000E-01	.1000000E+01
59	61	0.	.1940000E-01	.3280000E-01	.1500000E+00	0.	.1940000E-01	.1000000E+01
60	61	0.	.7300000E-02	.2260000E-01	.5350000E-01	0.	.7300000E-02	.1000000E+01
60	62	0.	.7350000E-02	.1230000E-01	.5600000E-01	0.	.7350000E-02	.1000000E+01
61	62	0.	.4900000E-02	.8200000E-02	.3760000E-01	0.	.4900000E-02	.1000000E+01
63	59	0.	0.	0.	.3860000E-01	0.	0.	.1040000E+01
63	64	0.	.1080000E+00	.1700000E-02	.2000000E-01	0.	.1080000E+00	.1000000E+01
64	61	0.	0.	0.	.2680000E-01	0.	0.	.1020000E+01
38	65	0.	.5230000E+00	.9000000E-02	.9860000E-01	0.	.5230000E+00	.1000000E+01
64	65	0.	.1900000E+00	.2700000E-02	.3020000E-01	0.	.1900000E+00	.1000000E+01
49	66	0.	.2480000E-01	.9000000E-02	.4590000E-01	0.	.2480000E-01	.1000000E+01
68	116	0.	.1240000E-01	.2030000E-01	.5410000E-01	0.	.1240000E-01	.1000000E+01
62	66	0.	.2890000E-01	.4820000E-01	.2180000E+00	0.	.2890000E-01	.1000000E+01
62	67	0.	.1550000E-01	.2580000E-01	.1170000E+00	0.	.1550000E-01	.1000000E+01
66	65	0.	0.	0.	.3700000E-01	0.	0.	.9400000E+00
66	67	0.	.1340000E-01	.2240000E-01	.1015000E+00	0.	.1340000E-01	.1000000E+01
65	68	0.	.3190000E+00	.2140000E-01	.5600000E-01	0.	.3190000E+00	.1000000E+01
47	118	0.	.3545000E-01	.8440000E-01	.2778000E+00	0.	.3545000E-01	.1000000E+01
49	118	0.	.4140000E-01	.9850000E-01	.3240000E+00	0.	.4140000E-01	.1000000E+01
118	68	0.	0.	0.	.3700000E-01	0.	0.	.9900000E+00
118	70	0.	.6100000E-01	.3000000E-01	.1270000E+00	0.	.6100000E-01	.1000000E+01
24	70	0.	.5100000E-01	.1022000E+00	.4115000E+00	0.	.5100000E-01	.1000000E+01
70	71	0.	.4400000E-02	.8800000E-02	.3550000E-01	0.	.4400000E-02	.1000000E+01
24	72	0.	.2440000E-01	.4880000E-01	.1960000E+00	0.	.2440000E-01	.1000000E+01
71	72	0.	.2220000E-01	.4460000E-01	.1800000E+00	0.	.2220000E-01	.1000000E+01
71	73	0.	.5900000E-02	.8600000E-02	.4540000E-01	0.	.5900000E-02	.1000000E+01
70	74	0.	.1685000E-01	.4010000E-01	.1323000E+00	0.	.1685000E-01	.1000000E+01
70	75	0.	.1800000E-01	.4280000E-01	.1410000E+00	0.	.1800000E-01	.1000000E+01
118	75	0.	.6200000E-01	.4050000E-01	.1220000E+00	0.	.6200000E-01	.1000000E+01
74	75	0.	.5150000E-02	.1230000E-01	.4060000E-01	0.	.5150000E-02	.1000000E+01
76	77	0.	.1840000E-01	.4440000E-01	.1480000E+00	0.	.1840000E-01	.1000000E+01
118	77	0.	.5190000E-01	.3090000E-01	.1010000E+00	0.	.5190000E-01	.1000000E+01
75	77	0.	.2490000E-01	.6010000E-01	.1999000E+00	0.	.2490000E-01	.1000000E+01
77	78	0.	.6300000E-02	.2380000E-01	.5240000E-01	0.	.6300000E-02	.1000000E+01
78	79	0.	.3250000E-02	.5500000E-02	.2440000E-01	0.	.3250000E-02	.1000000E+01
77	80	0.	.3500000E-01	.1090000E-01	.3320000E-01	0.	.3500000E-01	.1000000E+01
114	115	0.	.1140000E-01	.2300000E-02	.1040000E+00	0.	.1140000E-01	.1000000E+01
79	80	0.	.9350000E-02	.1560000E-01	.7040000E-01	0.	.9350000E-02	.1000000E+01
68	81	0.	.4040000E+00	.1800000E-02	.2020000E+00	0.	.4040000E+00	.1000000E+01
81	80	0.	0.	0.	.3700000E-01	0.	0.	.9500000E+00
77	82	0.	.4870000E-01	.2980000E-01	.8530000E-01	0.	.4870000E-01	.1000000E+01
82	83	0.	.1900000E-01	.1120000E-01	.3660000E-01	0.	.1900000E-01	.1000000E+01
83	84	0.	.1290000E-01	.6250000E-01	.1320000E+00	0.	.1290000E-01	.1000000E+01
83	85	0.	.1740000E-01	.4300000E-01	.1480000E+00	0.	.1740000E-01	.1000000E+01
84	85	0.	.6150000E-02	.3020000E-01	.6410000E-01	0.	.6150000E-02	.1000000E+01
85	86	0.	.1380000E-01	.3500000E-01	.1230000E+00	0.	.1380000E-01	.1000000E+01
86	87	0.	.2225000E-01	.2830000E-01	.2074000E+00	0.	.2225000E-01	.1000000E+01
85	88	0.	.1380000E-01	.2000000E-01	.1020000E+00	0.	.1380000E-01	.1000000E+01
85	89	0.	.2350000E-01	.2390000E-01	.1730000E+00	0.	.2350000E-01	.1000000E+01
88	89	0.	.9650000E-02	.1390000E-01	.7120000E-01	0.	.9650000E-02	.1000000E+01

89	90	0.	.7940000E-01	.1640000E-01	.6520000E-01	0.	.7940000E-01	.1000000E+01
27	115	0.	.5300000E-01	.1640000E-01	.7410000E-01	0.	.5300000E-01	.1000000E+01
90	91	0.	.1070000E-01	.2540000E-01	.8360000E-01	0.	.1070000E-01	.1000000E+01
89	92	0.	.4810000E-01	.8000000E-02	.3830000E-01	0.	.4810000E-01	.1000000E+01
32	114	0.	.2070000E-01	.1350000E-01	.6120000E-01	0.	.2070000E-01	.1000000E+01
91	92	0.	.1635000E-01	.3870000E-01	.1272000E+00	0.	.1635000E-01	.1000000E+01
92	93	0.	.1090000E-01	.2580000E-01	.8480000E-01	0.	.1090000E-01	.1000000E+01
92	94	0.	.2030000E-01	.4810000E-01	.1580000E+00	0.	.2030000E-01	.1000000E+01
93	94	0.	.9400000E-02	.2230000E-01	.7320000E-01	0.	.9400000E-02	.1000000E+01
94	95	0.	.5550000E-02	.1320000E-01	.4340000E-01	0.	.5550000E-02	.1000000E+01
80	96	0.	.2470000E-01	.3560000E-01	.1820000E+00	0.	.2470000E-01	.1000000E+01
82	96	0.	.2720000E-01	.1620000E-01	.5300000E-01	0.	.2720000E-01	.1000000E+01
94	96	0.	.1150000E-01	.2690000E-01	.8690000E-01	0.	.1150000E-01	.1000000E+01
80	97	0.	.1270000E-01	.1830000E-01	.9340000E-01	0.	.1270000E-01	.1000000E+01
80	98	0.	.1430000E-01	.2380000E-01	.1080000E+00	0.	.1430000E-01	.1000000E+01
80	99	0.	.2730000E-01	.4540000E-01	.2060000E+00	0.	.2730000E-01	.1000000E+01
92	100	0.	.3860000E-01	.6480000E-01	.2950000E+00	0.	.3860000E-01	.1000000E+01
94	100	0.	.3020000E-01	.1780000E-01	.5800000E-01	0.	.3020000E-01	.1000000E+01
95	96	0.	.7350000E-02	.1710000E-01	.5470000E-01	0.	.7350000E-02	.1000000E+01
96	97	0.	.1200000E-01	.1730000E-01	.8850000E-01	0.	.1200000E-01	.1000000E+01
98	100	0.	.2380000E-01	.3970000E-01	.1790000E+00	0.	.2380000E-01	.1000000E+01
99	100	0.	.1080000E-01	.1800000E-01	.5830000E-01	0.	.1080000E-01	.1000000E+01
100	101	0.	.1640000E-01	.2770000E-01	.1262000E+00	0.	.1640000E-01	.1000000E+01
92	102	0.	.7300000E-02	.1230000E-01	.5590000E-01	0.	.7300000E-02	.1000000E+01
101	102	0.	.1470000E-01	.2460000E-01	.1120000E+00	0.	.1470000E-01	.1000000E+01
100	103	0.	.2680000E-01	.1600000E-01	.5250000E-01	0.	.2680000E-01	.1000000E+01
100	104	0.	.2705000E-01	.4150000E-01	.2040000E+00	0.	.2705000E-01	.1000000E+01
103	104	0.	.2035000E-01	.4660000E-01	.1584000E+00	0.	.2035000E-01	.1000000E+01
103	105	0.	.2040000E-01	.5350000E-01	.1625000E+00	0.	.2040000E-01	.1000000E+01
100	106	0.	.3100000E-01	.6050000E-01	.2290000E+00	0.	.3100000E-01	.1000000E+01
104	105	0.	.4950000E-02	.9900000E-02	.3780000E-01	0.	.4950000E-02	.1000000E+01
105	106	0.	.7150000E-02	.1400000E-01	.5470000E-01	0.	.7150000E-02	.1000000E+01
105	107	0.	.2360000E-01	.5300000E-01	.1830000E+00	0.	.2360000E-01	.1000000E+01
105	108	0.	.9200000E-02	.2610000E-01	.7030000E-01	0.	.9200000E-02	.1000000E+01
106	107	0.	.2360000E-01	.5300000E-01	.1830000E+00	0.	.2360000E-01	.1000000E+01
108	109	0.	.3800000E-02	.1050000E-01	.2880000E-01	0.	.3800000E-02	.1000000E+01
103	110	0.	.2305000E-01	.3910000E-01	.1813000E+00	0.	.2305000E-01	.1000000E+01
109	110	0.	.1010000E-01	.2780000E-01	.7620000E-01	0.	.1010000E-01	.1000000E+01
110	111	0.	.1000000E-01	.2200000E-01	.7550000E-01	0.	.1000000E-01	.1000000E+01
110	112	0.	.3100000E-01	.2470000E-01	.6400000E-01	0.	.3100000E-01	.1000000E+01
17	113	0.	.3850000E-02	.9100000E-02	.3010000E-01	0.	.3850000E-02	.1000000E+01
32	113	0.	.2590000E-01	.6150000E-01	.2030000E+00	0.	.2590000E-01	.1000000E+01

BUS DATA

BNR	BTYPE	BVMOD	BVARG	BGP	BLP	BLQ	BSTL
1	1	.1150000E+01	0.	.1000000E+00	.5100000E+00	.2700000E+00	0.
2	0	.1000000E+01	0.	0.	.2000000E+00	.9000000E-01	0.
3	0	.1000000E+01	0.	0.	.3900000E+00	.1000000E+00	0.
4	1	.1100000E+01	0.	.2000000E+00	.9000000E+00	.1200000E+00	0.
5	0	.1000000E+01	0.	0.	0.	0.	-.4000000E+00
6	1	.1052000E+01	0.	.1500000E+00	.5200000E+00	.2200000E+00	0.
7	0	.1000000E+01	0.	0.	.1900000E+00	.2000000E-01	0.
8	1	.1090000E+01	0.	.1000000E+00	.5000000E+00	0.	0.
9	0	.1000000E+01	0.	0.	0.	0.	0.
10	1	.1075000E+01	0.	.4500000E+01	0.	0.	0.
11	0	.1000000E+01	0.	0.	.7000000E+00	.2300000E+00	0.
12	1	.1051000E+01	0.	.8500000E+00	.3700000E+00	.1000000E+00	0.
13	0	.1000000E+01	0.	0.	.3400000E+00	.1600000E+00	0.
14	0	.1000000E+01	0.	0.	.1400000E+00	.1000000E-01	0.
15	1	.9700000E+00	0.	.1200000E+00	.9000000E+00	.3000000E+00	0.
16	0	.1000000E+01	0.	0.	.2500000E+00	.1000000E+00	0.
17	0	.1000000E+01	0.	0.	.1100000E+00	.3000000E-01	0.
18	1	.9700000E+00	0.	.1000000E+00	.6000000E+00	.3400000E+00	0.
19	1	.9600000E+00	0.	.2000000E+00	.4500000E+00	.2500000E+00	0.
20	0	.1000000E+01	0.	0.	.1800000E+00	.3000000E-01	0.
21	0	.1000000E+01	0.	0.	.1400000E+00	.8000000E-01	0.
22	0	.1000000E+01	0.	0.	.1000000E+00	.5000000E-01	0.
23	0	.1000000E+01	0.	0.	.7000000E-01	.3000000E-01	0.
24	1	.9100000E+00	0.	.1500000E+00	.3000000E+00	.2000000E+01	0.
25	1	.9700000E+00	0.	.2200000E+01	0.	.2000000E+01	0.
26	1	.1010000E+01	0.	.3140000E+01	0.	0.	0.
27	1	.8230000E+00	0.	.1200000E+00	.8200000E+00	.1300000E+00	0.
28	0	.1000000E+01	0.	0.	.1700000E+00	.1660000E+01	0.
29	0	.1000000E+01	0.	0.	.2400000E+00	.9900000E+00	0.
30	0	.1000000E+01	0.	0.	0.	0.	0.
31	1	.7830000E+00	0.	.1000000E+00	.4300000E+00	.9900000E+00	0.
32	1	.8720000E+00	0.	.2000000E+00	.5900000E+00	.2300000E+00	0.
33	0	.1000000E+01	0.	0.	.2300000E+00	.9000000E-01	0.
34	1	.9590000E+00	0.	.1500000E+00	.5900000E+00	.2600000E+00	.1400000E+00
35	0	.1000000E+01	0.	0.	.3300000E+00	.9000000E-01	0.
36	1	.9630000E+00	0.	.1000000E+00	.3100000E+00	.1700000E+00	0.
37	0	.1000000E+01	0.	0.	0.	0.	-.2500000E+00
38	0	.1000000E+01	0.	0.	0.	0.	0.
39	0	.1000000E+01	0.	0.	.2700000E+00	.1100000E+00	0.
40	1	.9700000E+00	0.	.1000000E+00	.7600000E+00	.2300000E+00	0.
41	0	.1000000E+01	0.	0.	.3700000E+00	.1000000E+00	0.
42	1	.1100000E+01	0.	.1200000E+00	.1100000E+01	.2300000E+00	0.
43	0	.1000000E+01	0.	0.	.1800000E+00	.7000000E-01	0.
44	0	.1000000E+01	0.	0.	.1600000E+00	.8000000E-01	.1000000E+00
45	0	.1000000E+01	0.	0.	.5300000E+00	.2200000E+00	.1000000E+00

46	1	.1000000E+01	0.	.2000000E+00	.2800000E+00	.1000000E+00	.1000000E+00
47	0	.1000000E+01	0.	0.	.3400000E+00	0.	0.
48	0	.1000000E+01	0.	0.	.2000000E+00	.1100000E+00	.1500000E+00
49	1	.1020000E+01	0.	.2040000E+01	.8700000E+00	.3000000E+00	0.
50	0	.1000000E+01	0.	0.	.1700000E+00	.4000000E-01	0.
51	0	.1000000E+01	0.	0.	.1700000E+00	.8000000E-01	0.
52	0	.1000000E+01	0.	0.	.1800000E+00	.5000000E-01	0.
53	0	.1000000E+01	0.	0.	.2300000E+00	.1100000E+00	0.
54	1	.9500000E+00	0.	.4800000E+00	.1300000E+00	.3200000E+00	0.
55	1	.9500000E+00	0.	.1000000E+00	.6300000E+00	.2200000E+00	0.
56	1	.9500000E+00	0.	.1200000E+00	.8400000E+00	.1800000E+00	0.
57	0	.1000000E+01	0.	0.	.1200000E+00	.3000000E-01	0.
58	0	.1000000E+01	0.	0.	.1200000E+00	.3000000E-01	0.
59	1	.9900000E+00	0.	.1550000E+01	.2770000E+01	.1130000E+01	0.
60	0	.1000000E+01	0.	0.	.7800000E+00	.3000000E-01	0.
61	1	.1000000E+01	0.	.1600000E+01	0.	0.	0.
62	1	.1000000E+01	0.	.1500000E+00	.7700000E+00	.1400000E+00	0.
63	0	.1000000E+01	0.	0.	0.	0.	0.
64	0	.1000000E+01	0.	0.	0.	0.	0.
65	1	.1000000E+01	0.	.3910000E+01	0.	0.	0.
66	1	.1051000E+01	0.	.3920000E+01	.3900000E+00	.1800000E+00	0.
67	0	.1000000E+01	0.	0.	.2800000E+00	.7000000E-01	0.
68	0	.1000000E+01	0.	0.	0.	0.	0.
69	0	.1000000E+01	0.	0.	.3300000E+00	.1500000E+00	0.
70	1	.9800000E+00	0.	.5000000E+00	.6600000E+00	.2000000E+00	0.
71	0	.1000000E+01	0.	0.	0.	0.	0.
72	1	.9800000E+00	0.	.2000000E+00	.3200000E+00	0.	0.
73	1	.9900000E+00	0.	.1500000E+00	.2100000E+00	0.	0.
74	1	.9600000E+00	0.	.1000000E+00	.6800000E+00	.2700000E+00	.1200000E+00
75	0	.1000000E+01	0.	0.	.4700000E+00	.1100000E+00	0.
76	1	.9450000E+00	0.	.1000000E+00	.6800000E+00	.3600000E+00	0.
77	1	.1010000E+01	0.	.1200000E+00	.6100000E+00	.2800000E+00	0.
78	0	.1000000E+01	0.	0.	.7100000E+00	.2600000E+00	0.
79	0	.1000000E+01	0.	0.	.3900000E+00	.3200000E+00	.2000000E+00
80	1	.1040000E+01	0.	.4770000E+01	.1300000E+01	.2600000E+00	0.
81	0	.1000000E+01	0.	0.	0.	0.	0.
82	0	.1000000E+01	0.	0.	.5400000E+00	.2700000E+00	.2000000E+00
83	0	.1000000E+01	0.	0.	.2000000E+00	.1000000E+00	.1000000E+00
84	0	.1000000E+01	0.	0.	.1100000E+00	.7000000E-01	0.
85	1	.9900000E+00	0.	.2000000E+00	.2400000E+00	.1500000E+00	0.
86	0	.1000000E+01	0.	0.	.2100000E+00	.1000000E+00	0.
87	1	.1010000E+01	0.	.1500000E+00	0.	0.	0.
88	0	.1000000E+01	0.	0.	.4800000E+00	.1000000E+00	0.
89	1	.1000000E+01	0.	.6070000E+01	0.	0.	0.
90	1	.9900000E+00	0.	.1000000E+00	.1730000E+01	.4200000E+00	0.
91	1	.9800000E+00	0.	.1200000E+00	.2200000E+00	0.	0.
92	1	.9920000E+00	0.	.5000000E+00	.6500000E+00	.1000000E+00	0.
93	0	.1000000E+01	0.	0.	.1200000E+00	.7000000E-01	0.
94	0	.1000000E+01	0.	0.	.3000000E+00	.1600000E+00	0.
95	0	.1000000E+01	0.	0.	.4200000E+00	.3100000E+00	0.

96	0	.1000000E+01	0.	0.	.3800000E+00	.1500000E+00	0.
97	0	.1000000E+01	0.	0.	.1500000E+00	.9000000E-01	0.
98	0	.1000000E+01	0.	0.	.3400000E+00	.8000000E-01	0.
99	1	.1010000E+01	0.	.2000000E+00	.6200000E+00	0.	0.
100	1	.1020000E+01	0.	.2520000E+01	.3700000E+00	.1800000E+00	0.
101	0	.1000000E+01	0.	0.	.2200000E+00	.1500000E+00	0.
102	0	.1000000E+01	0.	0.	.5000000E-01	.3000000E-01	0.
103	1	.1010000E+01	0.	.5000000E+00	.2300000E+00	.1600000E+00	0.
104	1	.9700000E+00	0.	.1000000E+00	.3800000E+00	.2500000E+00	0.
105	1	.9650000E+00	0.	.1000000E+00	.3100000E+00	.2600000E+00	.2000000E+00
106	0	.1000000E+01	0.	0.	.4300000E+00	.1600000E+00	0.
107	1	.9500000E+00	0.	.1200000E+00	.6200000E+00	.1200000E+00	.6000000E-01
108	0	.1000000E+01	0.	0.	.2000000E-01	.1000000E-01	0.
109	0	.1000000E+01	0.	0.	.8000000E-01	.3000000E-01	0.
110	1	.9730000E+00	0.	.1200000E+00	.3900000E+00	.3000000E+00	.6000000E-01
111	1	.9800000E+00	0.	.3600000E+00	0.	0.	0.
112	1	.9800000E+00	0.	.1200000E+00	.8000000E+00	.1300000E+00	0.
113	1	.9900000E+00	0.	.1200000E+00	.1200000E+00	0.	0.
114	0	.1000000E+01	0.	0.	.8000000E-01	.3000000E-01	0.
115	0	.1000000E+01	0.	0.	.2200000E+00	.7000000E-01	0.
116	1	.1000000E+01	0.	.1200000E+00	0.	0.	0.
117	0	.1000000E+01	0.	0.	.2000000E+00	.8000000E-01	0.
118	2	.1030000E+01	0.	.2278000E+01	.3000000E+01	0.	0.

LOAD FLOW SOLUTION OF 118-BUS SYSTEM USING THE FAST DECOUPLED METHOD

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RESULTS OF ITERATION NO.      1
ITERATION TYPE:          P-DELTA
ACCURACY OBTAINED:     .3921E+00
ITERATION TIME:             .448 SECONDS

RESULTS OF ITERATION NO.      2
ITERATION TYPE:              Q-V
ACCURACY OBTAINED:     .3106E+00
ITERATION TIME:             .029 SECONDS

RESULTS OF ITERATION NO.      3
ITERATION TYPE:          P-DELTA
ACCURACY OBTAINED:     .5356E-01
ITERATION TIME:             .065 SECONDS

RESULTS OF ITERATION NO.      4
ITERATION TYPE:              Q-V
ACCURACY OBTAINED:     .3328E-01
ITERATION TIME:             .030 SECONDS

RESULTS OF ITERATION NO.      5
ITERATION TYPE:          P-DELTA
ACCURACY OBTAINED:     .2090E-01
ITERATION TIME:             .066 SECONDS

RESULTS OF ITERATION NO.      6
ITERATION TYPE:              Q-V
ACCURACY OBTAINED:     .2311E-02
ITERATION TIME:             .030 SECONDS

RESULTS OF ITERATION NO.      7
ITERATION TYPE:          P-DELTA
ACCURACY OBTAINED:     .9103E-02
ITERATION TIME:             .062 SECONDS

RESULTS OF ITERATION NO.      8
ITERATION TYPE:          P-DELTA
ACCURACY OBTAINED:     .2177E-02
ITERATION TIME:             .065 SECONDS

RESULTS OF ITERATION NO.      9
ITERATION TYPE:              Q-V
ACCURACY OBTAINED:     .1206E-02
ITERATION TIME:             .031 SECONDS

RESULTS OF ITERATION NO.     10
ITERATION TYPE:          P-DELTA
ACCURACY OBTAINED:     .2611E-03
ITERATION TIME:             .062 SECONDS
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RESULTS OF ITERATION NO. 11
ITERATION TYPE: Q-V
ACCURACY OBTAINED: .2855E-03
ITERATION TIME: .029 SECONDS

RESULTS OF ANALYSIS

NUMBER OF ITERATIONS: 11
RETURN FLAG: 0
ACCURACY OBTAINED: .2855E-03
ANALYSIS TIME: .928 SECONDS

VECTOR OF BUS VOLTAGES

BUS	RECTANGULAR COORDINATES		POLAR COORDINATES	
1	.1131121E+01	-.2075232E+00	.1150000E+01	-.1814490E+00
2	.1070407E+01	-.1727234E+00	.1084253E+01	-.1599834E+00
3	.1099321E+01	-.1747247E+00	.1113120E+01	-.1576203E+00
4	.1089795E+01	-.1494900E+00	.1100000E+01	-.1363218E+00
5	.1072803E+01	-.8352254E-01	.1076049E+01	-.7769778E-01
6	.1044902E+01	-.1219995E+00	.1052000E+01	-.1162306E+00
7	.1042720E+01	-.1318596E+00	.1051024E+01	-.1257897E+00
8	.1089989E+01	.4988192E-02	.1090000E+01	.4576339E-02
9	.1087721E+01	.1293732E+00	.1095388E+01	.1183835E+00
10	.1043304E+01	.2591173E+00	.1075000E+01	.2434367E+00
11	.1044329E+01	-.1419930E+00	.1053938E+01	-.1351371E+00
12	.1041333E+01	-.1422226E+00	.1051000E+01	-.1357377E+00
13	.1010395E+01	-.1555625E+00	.1022300E+01	-.1527625E+00
14	.1017868E+01	-.1481508E+00	.1028593E+01	-.1445352E+00
15	.9602574E+00	-.1371341E+00	.9700000E+00	-.1418506E+00
16	.1024283E+01	-.1374786E+00	.1033468E+01	-.1334220E+00
17	.9766592E+00	-.9897049E-01	.9816610E+00	-.1009910E+00
18	.9610045E+00	-.1317969E+00	.9700000E+00	-.1362947E+00
19	.9501064E+00	-.1374692E+00	.9600000E+00	-.1436910E+00
20	.9260974E+00	-.1268926E+00	.9347503E+00	-.1361707E+00
21	.9150459E+00	-.1037344E+00	.9209071E+00	-.1128833E+00
22	.9134037E+00	-.6506123E-01	.9157180E+00	-.7110933E-01
23	.9195281E+00	.1425081E-01	.9196385E+00	.1549672E-01
24	.9099980E+00	-.1917439E-02	.9100000E+00	-.2107077E-02
25	.9578514E+00	.1530381E+00	.9700000E+00	.1584332E+00
26	.9922492E+00	.1885247E+00	.1010000E+01	.1877594E+00
27	.8209874E+00	-.5752189E-01	.8230000E+00	-.6994997E-01
28	.6540758E+00	-.3804176E-01	.6551812E+00	-.5809564E-01
29	.7104708E+00	-.6312313E-01	.7132694E+00	-.8861422E-01
30	.1048487E+01	-.1373652E-01	.1048577E+01	-.1310053E-01
31	.7788187E+00	-.8081067E-01	.7830000E+00	-.1033906E+00
32	.8686124E+00	-.7678879E-01	.8720000E+00	-.8817475E-01
33	.9500167E+00	-.1441465E+00	.9608902E+00	-.1505819E+00
34	.9472107E+00	-.1499093E+00	.9590000E+00	-.1569621E+00
35	.9509265E+00	-.1498414E+00	.9626597E+00	-.1562891E+00
36	.9509045E+00	-.1521499E+00	.9630000E+00	-.1586606E+00
37	.9615381E+00	-.1239351E+00	.9694923E+00	-.1281858E+00
38	.1040086E+01	-.4413021E-01	.1041022E+01	-.4240396E-01
39	.9436831E+00	-.1867657E+00	.9619871E+00	-.1953865E+00
40	.9470461E+00	-.2097707E+00	.9700000E+00	-.2179806E+00
41	.9697909E+00	-.2321680E+00	.9971943E+00	-.2349776E+00
42	.1069850E+01	-.2557740E+00	.1100000E+01	-.2346698E+00
43	.9444657E+00	-.1571528E+00	.9574510E+00	-.1648827E+00
44	.9648079E+00	-.1264772E+00	.9730625E+00	-.1303473E+00
45	.9730664E+00	-.9912399E-01	.9781021E+00	-.1015175E+00
46	.9982297E+00	-.5947601E-01	.1000000E+01	-.5951113E-01

47	.1013041E+01	-.3384362E-01	.1013606E+01	-.3339553E-01
48	.1015072E+01	-.2680324E-01	.1015425E+01	-.2639914E-01
49	.1019977E+01	-.6850835E-02	.1020000E+01	-.6716556E-02
50	.9966125E+00	-.3009827E-01	.9970669E+00	-.3019140E-01
51	.9624785E+00	-.5485817E-01	.9640406E+00	-.5693517E-01
52	.9520922E+00	-.6357903E-01	.9542127E+00	-.6667923E-01
53	.9400992E+00	-.6070290E-01	.9420570E+00	-.6448123E-01
54	.9494485E+00	-.3236595E-01	.9500000E+00	-.3407601E-01
55	.9484854E+00	-.5362380E-01	.9500000E+00	-.5647612E-01
56	.9485661E+00	-.5217607E-01	.9500000E+00	-.5494983E-01
57	.9657001E+00	-.4969462E-01	.9669779E+00	-.5141433E-01
58	.9539384E+00	-.5857513E-01	.9557351E+00	-.6132647E-01
59	.9899725E+00	-.7384491E-02	.9900000E+00	-.7459151E-02
60	.9904250E+00	.2997123E-01	.9908784E+00	.3025174E-01
61	.9976435E+00	.6861108E-01	.1000000E+01	.6866503E-01
62	.9987502E+00	.4998077E-01	.1000000E+01	.5000161E-01
63	.1019160E+01	.4508467E-01	.1020156E+01	.4420828E-01
64	.1014111E+01	.7087494E-01	.1016584E+01	.6977531E-01
65	.9937815E+00	.1113474E+00	.1000000E+01	.1115788E+00
66	.1044678E+01	.1151021E+00	.1051000E+01	.1097369E+00
67	.1018935E+01	.7008333E-01	.1021343E+01	.6867279E-01
68	.1019399E+01	.4741523E-01	.1020502E+01	.4647940E-01
69	.9491821E+00	-.5496971E-01	.9507725E+00	-.5784809E-01
70	.9790298E+00	-.4359662E-01	.9800000E+00	-.4450104E-01
71	.9833106E+00	-.4743704E-01	.9844542E+00	-.4820480E-01
72	.9788610E+00	-.4723516E-01	.9800000E+00	-.4821782E-01
73	.9886531E+00	-.5162357E-01	.9900000E+00	-.5216868E-01
74	.9578865E+00	-.6366711E-01	.9600000E+00	-.6636862E-01
75	.9678515E+00	-.4863543E-01	.9690727E+00	-.5020869E-01
76	.9443350E+00	-.3544673E-01	.9450000E+00	-.3751856E-01
77	.1008206E+01	.6017638E-01	.1010000E+01	.5961588E-01
78	.9984622E+00	.5184247E-01	.9998072E+00	.5187573E-01
79	.1004229E+01	.6388316E-01	.1006259E+01	.6352850E-01
80	.1032447E+01	.1251143E+00	.1040000E+01	.1205943E+00
81	.9979284E+00	.1100252E+00	.1003975E+01	.1098101E+00
82	.9833058E+00	.1105975E+00	.9895059E+00	.1120045E+00
83	.9743244E+00	.1441701E+00	.9849330E+00	.1469033E+00
84	.9603175E+00	.2083087E+00	.9826506E+00	.2136072E+00
85	.9588709E+00	.2463061E+00	.9900000E+00	.2514349E+00
86	.9601246E+00	.2383979E+00	.9892789E+00	.2433770E+00
87	.9728185E+00	.2715220E+00	.1010000E+01	.2721819E+00
88	.9393564E+00	.3007835E+00	.9863372E+00	.3098859E+00
89	.9272194E+00	.3745186E+00	.1000000E+01	.3838775E+00
90	.9541806E+00	.2638929E+00	.9900000E+00	.2698205E+00
91	.9439226E+00	.2634581E+00	.9800000E+00	.2721831E+00
92	.9528884E+00	.2758038E+00	.9920000E+00	.2817405E+00
93	.9632748E+00	.2101395E+00	.9859295E+00	.2147861E+00
94	.9768623E+00	.1624157E+00	.9902721E+00	.1647556E+00
95	.9709337E+00	.1351858E+00	.9802997E+00	.1383434E+00
96	.9843657E+00	.1222135E+00	.9919234E+00	.1235225E+00
97	.1004271E+01	.1170098E+00	.1011064E+01	.1159892E+00
98	.1017752E+01	.1170942E+00	.1024465E+01	.1145482E+00
99	.1000752E+01	.1363636E+00	.1010000E+01	.1354270E+00
100	.1006792E+01	.1636126E+00	.1020000E+01	.1611005E+00
101	.9743198E+00	.1943436E+00	.9935132E+00	.1968820E+00
102	.9597618E+00	.2467429E+00	.9909716E+00	.2516382E+00
103	.1003708E+01	.1125602E+00	.1010000E+01	.1116778E+00
104	.9673987E+00	.7099153E-01	.9700000E+00	.7325264E-01
105	.9635402E+00	.5305911E-01	.9650000E+00	.5501127E-01
106	.9605824E+00	.4470245E-01	.9616220E+00	.4650326E-01
107	.9500000E+00	.1772137E-03	.9500000E+00	.1865407E-03
108	.9656253E+00	.3617285E-01	.9663026E+00	.3744304E-01
109	.9666486E+00	.2989974E-01	.9671109E+00	.3092149E-01
110	.9728101E+00	.1922459E-01	.9730000E+00	.1975934E-01
111	.9788490E+00	.4748337E-01	.9800000E+00	.4847139E-01

112	.9793620E+00	-.3535562E-01	.9800000E+00	-.3608500E-01
113	.9843848E+00	-.1052925E+00	.9900000E+00	-.1065576E+00
114	.8526086E+00	-.7941889E-01	.8562995E+00	-.9288011E-01
115	.8292888E+00	-.7928630E-01	.8330704E+00	-.9531786E-01
116	.9981260E+00	.6119258E-01	.1000000E+01	.6123083E-01
117	.1024218E+01	-.1651575E+00	.1037448E+01	-.1598761E+00
118	.1030000E+01	0.	.1030000E+01	0.

seconds. Since the return flag from LFLFD1M is zero, none of these bounds was reached during the iterative procedure.

5.5 Contingency Analysis

5.5.1 Example 5.6 Contingency Analysis of the 26-Bus Power System

In this example we discuss a simple, interactive program for the contingency analysis of the 26-bus system (Fig. 5.2) using packages TTM1 and MA28 [4]. The listing of the program CNT26T is shown on pages 60-61.

The solution of the load flow problem of the original system is taken as a starting point for the contingency analysis. An appropriate data file was created in Example 5.4 under the name BO26SVA (see pages 44-45).

The line removal results in the updating of vectors LINPG, LINPB, LG, LB, LOUTG and LOUTB describing the transmission lines. The nodal admittance matrix of the updated system is created (call to FORMYT) and vector V of initial bus voltages is initialized to the values of bus voltages of the original system at the solution point. The load flow equations are solved using subroutine LFTTM. The demanded accuracy of the solution is 10^{-4}. When the contingency analysis is completed, the original data of the system is reconstructed.

The user is supposed to choose in an interactive way the following options:

- to continue contingency analysis with an alternative line or to terminate execution,
- print out level (0, 1, 2, 3 or 4),
- the index of the line which is to be removed,

```
C
C
C
      PROGRAM CNT26T(B026,INPUT,OUTPUT,TAPE3=B026,TAPE4=INPUT,TAPE6=OUTP
     1UT)
C
C     THIS IS THE MAIN PROGRAM FOR CONTINGENCY ANALYSIS OF 26-BUS
C     POWER SYSTEM USING THE TELLEGEN THEOREM METHOD
C
      INTEGER BTYP(26),BNR(26),JRYT(27),ICYT(120),LBINP(32),LBOUT(32),OT
     1PT
      REAL W(3800),LINPG(32),LINPB(32),LG(32),LB(32),LOUTG(32),LOUTB(32)
     1,LTAP(32),BVMOD(26),BVARG(26),BGP(26),BLP(26),BLQ(26),BSTL(26),BCV
     2(52)
      COMPLEX YT(90),VI(26),V(26)
      EQUIVALENCE (VI(1),BGP(1)), (VI(14),BLP(1)), (V(1),BLQ(1)), (V(14)
     1,BNR(1))
      IWRITE=0
      INPT=3
      OTPT=6
      WRITE (OTPT,100)
      IP=1
      LW=3800
      TOLV=1.E-4
      T=3.0
      ITER=8
      CALL RDAT (LBINP,LBOUT,LINPG,LINPB,LG,LB,LOUTG,LOUTB,LTAP,BNR,BTYP
     1,BVMOD,BVARG,BGP,BLP,BLQ,BSTL,JRYT,NB,NTL,NLB,INPT,IWRITE)
      CALL FORMU (BTYP,BVMOD,BVARG,BGP,BLP,BLQ,BCV,NB,OTPT,IWRITE)
      DO 10 I=1,NB
      VI(I)=CMPLX(BVMOD(I),BVARG(I))
   10 CONTINUE
   20 WRITE (6,110)
      READ (4,*) ICONT
      IF (ICONT.EQ."YES") GO TO 30
      IF (ICONT.NE."STOP") GO TO 20
      STOP
   30 WRITE (6,140)
      READ (4,*) IWRITE
   40 WRITE (6,120)
      READ (4,*) LN
      IF (LN.GE.1.AND.LN.LE.NTL) GO TO 50
      WRITE (6,130) NTL
      GO TO 40
C
C     VECTORS DESCRIBING TRANSMISSION LINES ARE UPDATED
C
   50 R1=LINPG(LN)
      R2=LINPB(LN)
      R3=LG(LN)
      R4=LB(LN)
      R5=LOUTG(LN)
      R6=LOUTB(LN)
      LINPG(LN)=0.
      LINPB(LN)=0.
      LG(LN)=0.
      LB(LN)=0.
      LOUTG(LN)=0.
      LOUTB(LN)=0.
C
C     THE NODAL ADDMITTANCE MATRIX OF UPDATED SYSTEM IS FORMULATED
C
      CALL FORMYT (LBINP,LBOUT,LINPG,LINPB,LG,LB,LOUTG,LOUTB,LTAP,BSTL,J
     1RYT,ICYT,YT,NB,NTL,NYT,OTPT,IWRITE)
      WRITE (6,150) LBINP(LN),LBOUT(LN)
```

```
      DO 60 I=1,NB
      V(I)=VI(I)
   60 CONTINUE
   70 WRITE (6,160)
      READ (4,*) IVT
      IF (IVT.LT.1.OR.IVT.GT.5) GO TO 70
      VEPS=TOLV
      TIMEL=T
      ITEL=ITER
      MODE=1
C
C     LOAD FLOW EQUATIONS ARE SOLVED USING THE TELLEGEN THEOREM METHOD
C
      CALL LFTTM (NB,NTL,JRYT,ICYT,BTYP,YT,V,BCV,W,LW,IVT,IP,ITEL,VEPS,T
     1IMEL,MODE,IFLAG,OTPT,IWRITE)
      IF (IFLAG.GE.0) GO TO 80
      WRITE (6,90) IFLAG
      STOP
C
C     THE ORIGINAL DATA IS RECONSTRUCTED
C
   80 LINPG(LN)=R1
      LINPB(LN)=R2
      LG(LN)=R3
      LB(LN)=R4
      LOUTG(LN)=R5
      LOUTB(LN)=R6
      GO TO 20
   90 FORMAT (///" RETURN FLAG FROM LFTTM :",I3)
  100 FORMAT (//" CONTINGENCY ANALYSIS OF 26-BUS POWER SYSTEM")
  110 FORMAT (////1X,53HTYPE "YES" FOR CONTINGENCY ANALYSIS OR "STOP" TO
     1 STOP)
  120 FORMAT (//" ENTER LINE NUMBER")
  130 FORMAT (//" LINE NUMBER MUST BE LESS THAN ",I3)
  140 FORMAT (//" SELECT PRINTOUT LEVEL (0,1,2,3 OR 4)")
  150 FORMAT (//" LINE REMOVED. TERMINAL BUSES:",I3,",",I3)
  160 FORMAT (//" SELECT VERSION OF ADJOINT EQUATIONS (1,2,3,4 OR 5)")
      END
```

CONTINGENCY ANALYSIS OF 26-BUS POWER SYSTEM

TYPE "YES" FOR CONTINGENCY ANALYSIS OR "STOP" TO STOP
INPUT "YES"

SELECT PRINTOUT LEVEL (0,1,2,3 OR 4)
INPUT 1

ENTER LINE NUMBER
INPUT 3

LINE REMOVED. TERMINAL BUSES: 16, 23

SELECT VERSION OF ADJOINT EQUATIONS (1,2,3,4 OR 5)
INPUT 1

LOAD FLOW SOLUTION OF 26-BUS SYSTEM USING THE TELLEGEN THEOREM METHOD

IT = 1 EPS = .1412E-01 ITERATION TIME .756 TOTAL TIME .756

IT = 2 EPS = .1248E-04 ITERATION TIME .645 TOTAL TIME 1.401

RESULTS OF ANALYSIS

NUMBER OF ITERATIONS: 2
RETURN FLAG: 0
ACCURACY OBTAINED: .1248E-04
ANALYSIS TIME: 1.401 SECONDS

VECTOR OF BUS VOLTAGES

BUS	RECTANGULAR COORDINATES		POLAR COORDINATES	
1	.1032758E+01	.7728918E-01	.1035646E+01	.7469838E-01
2	.1064366E+01	.9433929E-01	.1068539E+01	.8840321E-01
3	.1042361E+01	.5494542E-01	.1043809E+01	.5266371E-01
4	.9859041E+00	.9786663E-01	.9907496E+00	.9894174E-01
5	.9740839E+00	.2598124E+00	.1008138E+01	.2606568E+00
6	.1032445E+01	.5541752E-01	.1033931E+01	.5362455E-01
7	.1013184E+01	.1805726E-01	.1013345E+01	.1782040E-01
8	.9441193E+00	.4026454E-01	.9449775E+00	.4262189E-01
9	.9613740E+00	-.1087696E+00	.9675075E+00	-.1126607E+00
10	.1036971E+01	.6924455E-01	.1039280E+01	.6667682E-01

11	.8982194E+00	-.9921886E-01	.9036827E+00	-.1100157E+00
12	.9670438E+00	-.7406484E-01	.9698760E+00	-.7643969E-01
13	.1046329E+01	.1572009E-01	.1046447E+01	.1502292E-01
14	.9388198E+00	-.1071300E+00	.9449124E+00	-.1136199E+00
15	.9273368E+00	.9700728E-01	.9323969E+00	.1042294E+00
16	.1038465E+01	-.4880982E-01	.1039611E+01	-.4696734E-01
17	.9317616E+00	.2780419E-01	.9321764E+00	.2983160E-01
18	.1039703E+01	.2528182E+00	.1070000E+01	.2385343E+00
19	.1045549E+01	.9657833E-01	.1050000E+01	.9210955E-01
20	.9705787E+00	.2407841E+00	.1000000E+01	.2431736E+00
21	.9938434E+00	.2295109E+00	.1020000E+01	.2269540E+00
22	.8855902E+00	-.8848754E-01	.8900000E+00	-.9958874E-01
23	.9999227E+00	-.1243564E-01	.1000000E+01	-.1243596E-01
24	.9989488E+00	.4584078E-01	.1000000E+01	.4585685E-01
25	.9359166E+00	.3522216E+00	.1000000E+01	.3599438E+00
26	.1010000E+01	0.	.1010000E+01	0.

TYPE "YES" FOR CONTINGENCY ANALYSIS OR "STOP" TO STOP
INPUT "YES"

SELECT PRINTOUT LEVEL (0,1,2,3 OR 4)
INPUT 1

ENTER LINE NUMBER
INPUT 3

LINE REMOVED. TERMINAL BUSES: 16, 23

SELECT VERSION OF ADJOINT EQUATIONS (1,2,3,4 OR 5)
INPUT 4

LOAD FLOW SOLUTION OF 26-BUS SYSTEM USING THE TELLEGEN THEOREM METHOD

IT = 1 EPS = .1425E-01 ITERATION TIME .591 TOTAL TIME .591

IT = 2 EPS = .1875E-03 ITERATION TIME .537 TOTAL TIME 1.128

IT = 3 EPS = .9151E-05 ITERATION TIME .572 TOTAL TIME 1.700

RESULTS OF ANALYSIS

NUMBER OF ITERATIONS: 3
RETURN FLAG: 0
ACCURACY OBTAINED: .9151E-05
ANALYSIS TIME: 1.700 SECONDS

VECTOR OF BUS VOLTAGES

BUS	RECTANGULAR COORDINATES		POLAR COORDINATES	
1	.1032758E+01	.7728869E-01	.1035646E+01	.7469791E-01
2	.1064366E+01	.9433926E-01	.1068539E+01	.8840318E-01
3	.1042361E+01	.5494491E-01	.1043809E+01	.5266322E-01
4	.9859041E+00	.9786611E-01	.9907495E+00	.9894122E-01
5	.9740838E+00	.2598119E+00	.1008138E+01	.2606563E+00
6	.1032445E+01	.5541736E-01	.1033931E+01	.5362440E-01
7	.1013184E+01	.1805687E-01	.1013345E+01	.1782001E-01
8	.9441192E+00	.4026404E-01	.9449774E+00	.4262137E-01
9	.9613740E+00	-.1087698E+00	.9675075E+00	-.1126608E+00
10	.1036971E+01	.6924452E-01	.1039280E+01	.6667680E-01
11	.8982194E+00	-.9921928E-01	.9036828E+00	-.1100162E+00
12	.9670439E+00	-.7406490E-01	.9698760E+00	-.7643974E-01
13	.1046329E+01	.1572009E-01	.1046447E+01	.1502291E-01
14	.9388198E+00	-.1071302E+00	.9449124E+00	-.1136201E+00
15	.9273368E+00	.9700682E-01	.9323968E+00	.1042289E+00
16	.1038465E+01	-.4881025E-01	.1039611E+01	-.4696775E-01
17	.9317616E+00	.2780369E-01	.9321763E+00	.2983107E-01
18	.1039703E+01	.2528181E+00	.1070000E+01	.2385342E+00
19	.1045549E+01	.9657816E-01	.1050000E+01	.9210939E-01
20	.9705788E+00	.2407836E+00	.1000000E+01	.2431732E+00
21	.9938435E+00	.2295104E+00	.1020000E+01	.2269535E+00
22	.8855901E+00	-.8848794E-01	.8900000E+00	-.9958920E-01
23	.9999227E+00	-.1243563E-01	.1000000E+01	-.1243595E-01
24	.9989488E+00	.4584028E-01	.1000000E+01	.4585635E-01
25	.9359168E+00	.3522211E+00	.1000000E+01	.3599432E+00
26	.1010000E+01	0.	.1010000E+01	0.

TYPE "YES" FOR CONTINGENCY ANALYSIS OR "STOP" TO STOP
INPUT "YES"

SELECT PRINTOUT LEVEL (0,1,2,3 OR 4)
INPUT 1

ENTER LINE NUMBER
INPUT 3

LINE REMOVED. TERMINAL BUSES: 16, 23

SELECT VERSION OF ADJOINT EQUATIONS (1,2,3,4 OR 5)
INPUT 5

LOAD FLOW SOLUTION OF 26-BUS SYSTEM USING THE TELLEGEN THEOREM METHOD

IT = 1 EPS = .1411E-01 ITERATION TIME .691 TOTAL TIME .691

IT = 2 EPS = .1248E-04 ITERATION TIME .615 TOTAL TIME 1.306

RESULTS OF ANALYSIS

NUMBER OF ITERATIONS: 2
RETURN FLAG: 0
ACCURACY OBTAINED: .1248E-04
ANALYSIS TIME: 1.306 SECONDS

VECTOR OF BUS VOLTAGES

BUS	RECTANGULAR COORDINATES		POLAR COORDINATES	
1	.1032758E+01	.7728917E-01	.1035646E+01	.7469837E-01
2	.1064366E+01	.9433929E-01	.1068539E+01	.8840321E-01
3	.1042361E+01	.5494541E-01	.1043809E+01	.5266370E-01
4	.9859041E+00	.9786662E-01	.9907496E+00	.9894173E-01
5	.9740839E+00	.2598124E+00	.1008138E+01	.2606568E+00
6	.1032445E+01	.5541751E-01	.1033931E+01	.5362454E-01
7	.1013184E+01	.1805725E-01	.1013345E+01	.1782039E-01
8	.9441193E+00	.4026452E-01	.9449775E+00	.4262188E-01
9	.9613740E+00	-.1087696E+00	.9675075E+00	-.1126607E+00
10	.1036971E+01	.6924455E-01	.1039280E+01	.6667682E-01
11	.8982194E+00	-.9921887E-01	.9036827E+00	-.1100157E+00
12	.9670438E+00	-.7406484E-01	.9698760E+00	-.7643969E-01
13	.1046329E+01	.1572009E-01	.1046447E+01	.1502292E-01
14	.9388198E+00	-.1071300E+00	.9449124E+00	-.1136199E+00
15	.9273368E+00	.9700727E-01	.9323969E+00	.1042294E+00
16	.1038465E+01	-.4880982E-01	.1039611E+01	-.4696734E-01
17	.9317616E+00	.2780418E-01	.9321764E+00	.2983159E-01
18	.1039703E+01	.2528182E+00	.1070000E+01	.2385343E+00
19	.1045549E+01	.9657832E-01	.1050000E+01	.9210954E-01
20	.9705787E+00	.2407841E+00	.1000000E+01	.2431736E+00
21	.9938434E+00	.2295109E+00	.1020000E+01	.2269540E+00
22	.8855902E+00	-.8848755E-01	.8900000E+00	-.9958875E-01
23	.9999227E+00	-.1243564E-01	.1000000E+01	-.1243597E-01
24	.9989488E+00	.4584077E-01	.1000000E+01	.4585684E-01
25	.9359166E+00	.3522216E+00	.1000000E+01	.3599438E+00
26	.1010000E+01	0.	.1010000E+01	0.

TYPE "YES" FOR CONTINGENCY ANALYSIS OR "STOP" TO STOP
INPUT "STOP"

- the version of the adjoint equations (1 for the exact, 2 for the decoupled, 3 for the approximate, 4 for the approximate decoupled, and 5 for the mixed version of the adjoint matrix).

As an example, an outage of the third transmission line appearing in the data file was considered. This line connects the 16th and the 23rd buses. The contingency analysis was carried out three times for the same line, with different versions of the adjoint matrix: exact (IVT=1), approximate decoupled (IVT=4) and mixed (IVT=5). The results of the analysis are shown on pages 62-65.

5.6 Sensitivity Calculation

Sensitivity calculations are usually part of a bigger problem, e.g., optimization of power systems.

Two subroutines of the package are dedicated to deal with sensitivity calculation: the lower level subroutine DERIV and the highest level subroutine SENSIT. Subroutine DERIV calculates sensitivities when the solution vector VT of the adjoint equations is given. Subroutine SENSIT forms the adjoint equations, solves them and calculates the required sensitivities by calling the appropriate subroutines. The right-hand side vector of the adjoint equations depends on the function whose sensitivities are to be calculated. Thus, it is left to the user to supply the right-hand side vector RHST.

The total derivative of a real function $f(\underset{\sim}{x},\underset{\sim}{u})$ of the power system state and control variables with respect to a control variable u can be calculated using (2.3). Both subroutines DERIV and SENSIT determine only the term $\hat{\eta}_u$ appearing in this formula. To calculate a total derivative the user must supply in his program a formula for determination of the partial derivative $\partial f/\partial u$.

The function f being considered also influences formulas for the calculation of $\hat{\eta}_u$, i.e., formulas for sensitivity calculation with respect to transmission line parameters: conductance, susceptance, shunt conductance and susceptance and with respect to bus static load. The formal partial derivative of f with respect to the current of an element appears in such formulas. For example, if we want to calculate the sensitivity of a function f with respect to conductance G_t of the tth transmission line, then we apply

$$\hat{\eta}_{Gt} = -\mathrm{Re}\,[V_t \; (\hat{V}_t + \frac{\partial f}{\partial I_{t1}} - j\,\frac{\partial f}{\partial I_{t2}})] \; , \qquad (5.1)$$

where

V_t is the voltage across the tth transmission line,

$I_t = I_{t1} + j\,I_{t2}$ is the current of the tth transmission line,

$\hat{V}_t$ is the adjoint voltage across the tth transmission line.

To calculate $\hat{\eta}_{Gt}$ the value of the formal partial derivative $\partial f/\partial I_t$ must be known. Complex vector PDR appearing on the list of parameters of both subroutines DERIV and SENS stores, multiplied by 2, the values of such derivatives. It is left to the user to initialize this vector.

Control variables with respect to which sensitivities are to be calculated are identified by the two vectors CCV and ICV as explained in Example 5.1. On return from the subroutine, vector SENS stores the required sensitivities.

Next are given two examples of the application of subroutine SENSIT to power system optimization.

5.6.1 Example 5.7 Minimization of Transmission Power Losses in the 6-Bus Power System

In this example transmission power losses in the 6-bus power system are minimized using packages TTM1, MA28 [4] and MFNC [16,17]. The diagram of the analysed system is shown in Fig. 5.3. Input data is taken from the file B006SVA, which describes the 6-bus system at the operating point. The contents of the file B006SVA are shown on page 77.

The package MFNC minimizes the objective function with general constraints using the Han-Powell algorithm [18]. The aim of this example is to determine the optimal values of voltages and active powers of generators such that transmission losses during normal operation are minimized.

We formulate the problem as follows. The total transmission losses are given by

$$F = \sum_{t=1}^{8} |V_t|^2 G_t , \qquad (5.2)$$

where

V_t is the voltage across the tth transmission line,

G_t is the conductance of the tth transmission line.

The control variables are the moduli of bus voltages, $|V_4|$, $|V_5|$ and $|V_6|$, and bus real powers P_4 and P_5. These variables are renamed in the program X(i), i = 1, 2, ..., 5. The constraints assumed on the control variables are [19]

$$0.9 \leq |V_k| \leq 1.1, \quad k = 4, 5, 6,$$

$$-0.3 \leq P_4 \leq 4.0,$$

$$-0.3 \leq P_5 \leq 4.0.$$

The user's program must provide values of total derivatives dF/dX(i), i = 1, 2, ..., 5, required by the package MFNC. This is done using (2.3). The value of a partial derivative $\partial F/\partial X(i)$ appearing in this formula is given by

$$\frac{\partial F}{\partial X(i)} = \sum_{t=1}^{8} \frac{\partial |V_t|^2}{\partial X(i)} G_t, \quad i = 1, 2, \ldots, 5. \tag{5.4}$$

It is obvious that

$$\frac{\partial F}{\partial P_4} = \frac{\partial F}{\partial P_5} = 0. \tag{5.5}$$

Let us assume that the tth transmission line connects buses k and m, and let $V_k = |V_k|e^{j\alpha}$, $V_m = |V_m|e^{j\beta}$. Since

$$|V_t|^2 = |V_k - V_m|^2 \tag{5.6}$$

we obtain

$$\frac{\partial |V_t|^2}{\partial |V_i|} = \begin{cases} 0 & \text{if } i \neq k \text{ and } i \neq m, \\ 2\big(|V_k| - |V_m| \cos(\alpha-\beta)\big) & \text{if } i = k, \\ 2\big(|V_m| - |V_k| \cos(\alpha-\beta)\big) & \text{if } i = m. \end{cases} \tag{5.7}$$

The partial derivative $\partial F/\partial |V_i|$, i=4,5,6, is calculated through (5.4) and (5.7). The listing of the main program OPT6HP and subroutines RHSLT and FDF, as required by MFNC, is given on pages 72-76.

The main program OPT6HP defines and initializes control variables for the optimization and calls subroutine MFNC2A of the package MFNC.

Subroutine FDF supplies information required by the package MFNC. For the given vector X of control variables it calculates the value of the objective function F and its derivatives, vector C of constraint functions and matrix DC of their derivatives. The fast decoupled method (call to subroutine LFLFD1M) is used to solve the power flow equations for the current values of control variables. Sensitivities of the objective function are calculated at the solution point using the

Tellegen theorem method (call to RHSLT and SENSIT) and modified according to (2.3) to obtain the required total derivatives.

In the first call to subroutine SENSIT, parameter MODES is equal to 1, i.e., subroutines MA28A and MA28C of the package MA28 are called to solve the set of adjoint equations. Afterwards SENSIT is called with MODES=2 because the structure of the adjoint matrix is preserved and subroutines MA28B and MA28C are used.

Subroutine RHSLT is an auxiliary subroutine to formulate the right-hand side vector of the adjoint equations, as required by SENSIT.

Elements $\hat{I}_\ell$ and $\hat{I}_g$ of vectors $\hat{\underset{\sim}{I}}_L$ and $\hat{\underset{\sim}{I}}_G$, constituting the right-hand side vector of the adjoint equations, are given by [3]

$$\hat{I}_\ell = - \sum_{t=1}^{8} \lambda_{\ell t} Y_t \left(\frac{\partial F}{\partial I_{t1}} - j \frac{\partial F}{\partial I_{t2}}\right) ,$$

$$\mathrm{Re}\, (\hat{I}_g) = -\mathrm{Im}\, \left(V_g \sum_{t=1}^{8} \lambda_{gt} Y_t \left(\frac{\partial F}{\partial I_{t1}} - j \frac{\partial F}{\partial I_{t2}}\right)\right) , \tag{5.8}$$

$$\mathrm{Im}\, (\hat{I}_g) = 0 ,$$

where

ℓ denotes a load bus,

g denotes a generator bus,

$\lambda_{\ell t}$ is an element of the incidence matrix of the power system,

Y_t is the admittance of the tth transmission line,

$I_t = I_{t1} + j\, I_{t2}$.

However,

$$\left(\frac{\partial F}{\partial I_{t1}} - j \frac{\partial F}{\partial I_{t2}}\right) = 2\, R_t\, I_t^* \tag{5.9}$$

so that

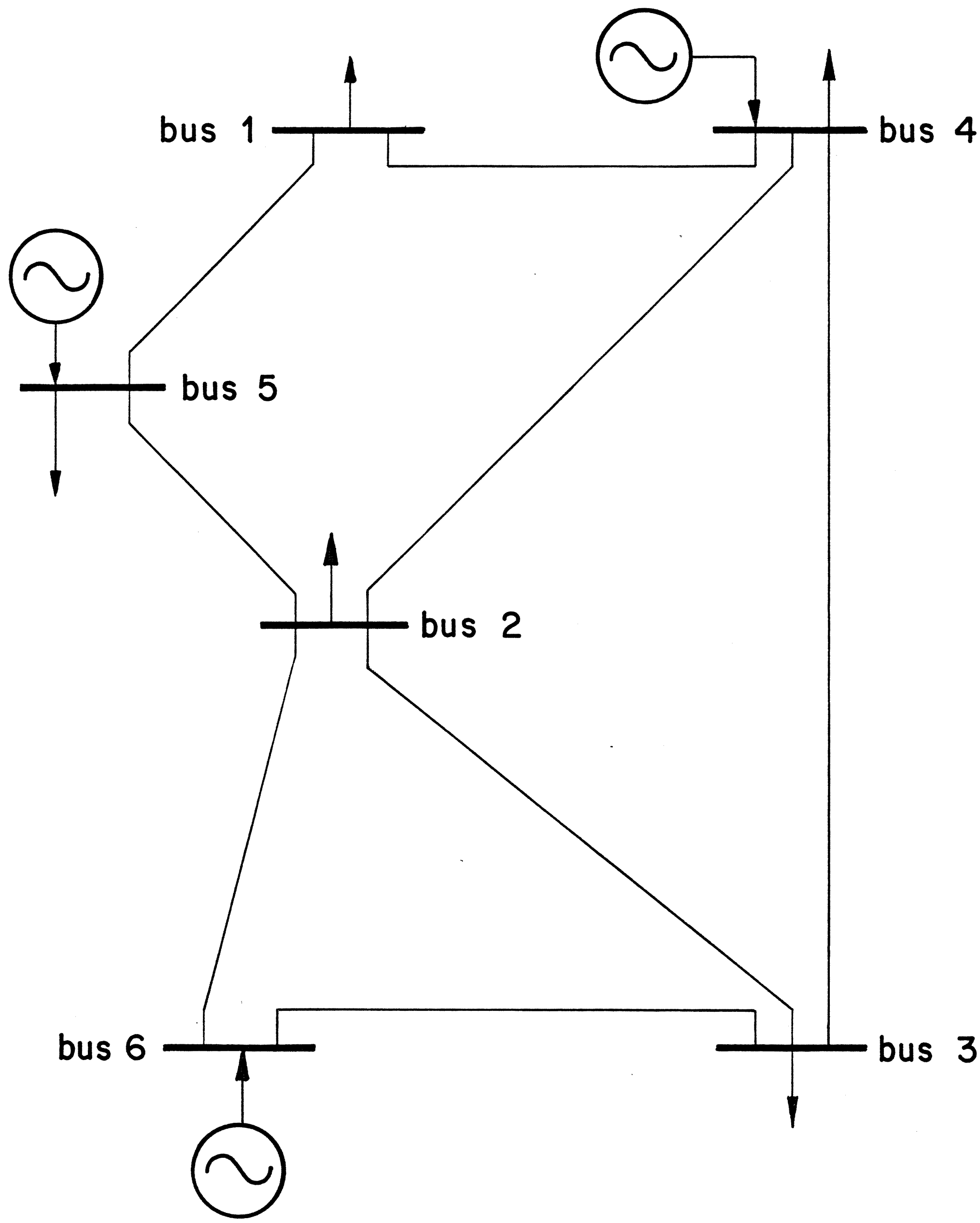

Fig. 5.3 6-bus power system.

```
C
C
C
      PROGRAM OPT6HP(B006,OUTPUT,TAPE4=B006,TAPE6=OUTPUT)
C
C     THIS IS THE MAIN PROGRAM FOR MINIMIZING TRANSMISSION POWER
C     LOSSES IN 6-BUS POWER  SYSTEM USING PACKAGES TTM1 AND MFNC
C
      INTEGER CCV(5),ICV(5)
      REAL X(5),WW(1000)
      COMMON /MNFDF/ NCOUNT,CCV,ICV
      EXTERNAL FDF
C
      NCOUNT=1
      NV=5
      L=10
      LEQ=0
C
C     INITIALIZATION OF CONTROL VARIABLES FOR OPTIMIZATION
C
      X(1)=1.02
      X(2)=1.04
      X(3)=1.04
      X(4)=-0.3
      X(5)=1.25
C
C     DEFINING CONTROL VARIABLES FOR OPTIMIZATION
C
      CCV(1)=9
      ICV(1)=4
      CCV(2)=9
      ICV(2)=5
      CCV(3)=9
      ICV(3)=6
      CCV(4)=7
      ICV(4)=4
      CCV(5)=7
      ICV(5)=5
      EPS=1.0E-6
      MAXF=50
      IWW=1500
      WRITE (6,10)
      CALL SECOND (TM1)
      CALL MFNC2A (FDF,NV,L,LEQ,X,EPS,MAXF,WW,IWW,IFLAG)
      CALL SECOND (TM2)
      CPU=TM2-TM1
      WRITE (6,20) IFLAG,EPS,CPU,MAXF
      WRITE (6,30) (X(I),I=1,NV)
      WRITE (6,40) WW(1)
      STOP
C
   10 FORMAT (///" MINIMIZING OF TRANSMISSION POWER LOSSES IN 6-BUS POWE
     1R SYSTEM")
   20 FORMAT (//" IFLAG:",12X,I2/" ACCURACY:",E11.5/" CPU TIME:",5X,F6.3
     1," SECONDS"/" F.EVAL:",10X,I3)
   30 FORMAT (//" SOLUTION:",9X,3(F13.8,1X),1X,2(1X,F13.8))
   40 FORMAT (/" TOTAL TRANSMISSION POWER LOSSES:",F13.8//)
      END
```

```
C
C
C
      SUBROUTINE RHSLT (YT,JRYT,ICYT,V,BTYP,RHS,NB,IWRITE)
C
C     SUBROUTINE RHSLT FORMULATES RHS VECTOR OF ADJOINT EQUATIONS WHEN
C     THE FUNCTION  REPRESENTS REAL POWER LOSSES  (SEE SOC-258,EQ.25)
C
      INTEGER JRYT(1),ICYT(1),BTYP(1)
      REAL RHS(1)
      COMPLEX YT(1),V(1),Z,C
C
      NR=NB+NB
      N=NB-1
      RHS(NR-1)=0.
      RHS(NR)=0.
      DO 30 I=1,N
      J1=JRYT(I)+1
      J2=JRYT(I+1)-1
      Z=(0.,0.)
      DO 10 J=J1,J2
      C=-YT(J)
      Z=Z+CONJG(V(I)-V(ICYT(J)))*REAL(C)
   10 CONTINUE
      Z=2*Z
      J2=I+I
      J1=J2-1
      IF (BTYP(I).EQ.1) GO TO 20
      RHS(J1)=REAL(Z)
      RHS(J2)=AIMAG(Z)
      GO TO 30
   20 RHS(J1)=AIMAG(V(I)*Z)
      RHS(J2)=0.
   30 CONTINUE
      IF (IWRITE.LT.4) GO TO 40
      WRITE (6,50)
      WRITE (6,60) (I,RHS(I),I=1,NR)
   40 RETURN
   50 FORMAT (//" RHS VECTOR OF ADJOINT EQUATIONS"/)
   60 FORMAT (5(2X,I4,":",E13.7))
      END
```

```
C
C
C
      SUBROUTINE FDF (NV,L,X,F,G,C,DC,KN)
C
C     THIS SUBROUTINE EVALUATES THE OBJECTIVE FUNCTION, CONTSTRAINS
C     AND THEIR DERIVATIVES  W.R.T. V4, V5, V6, P4 AND P5
C
      INTEGER LBINP(8),LBOUT(8),BTYP(6),JRYT(7),ICYT(30),ICV(5),CCV(5),I
     1RT(70),ICT(60),ICN(180),IKEEP(50),IW(80),OTPT
      REAL BCV(12),RHS(12),W(300),X(5),G(10),C(10),DC(KN,10),T(180)
      COMPLEX BCS(6),PDR(1),YT(22),V(6),YL(8),VAS,CC,CURR
      COMMON /MNFDF/ NCOUNT,CCV,ICV/MDLFLF/JA1,JICN1,JIKP1,JA2,JICN2,JIK
     1P2,JVM,JVA,NZ,NZR
C
C     INITIALIZATION OF SOME VARIABLES AND FORMULATION OF THE LOAD
C     FLOW EQUATIONS
C
      IF (NCOUNT.NE.1) GO TO 30
      INPT=4
      OTPT=6
      NB=6
      NTL=8
      LITER=-1
      BTIME=2.
      MODE=0
      LW=300
      TOLV=1.E-6
      IVT=1
      MODES=1
      IWRITE=1
      IP=0
      CALL FORMPR (LBINP,LBOUT,BTYP,YT,JRYT,ICYT,BCV,V,W,LW,NB,NTL,NLB,I
     1P,INPT,OTPT,IFLAG,IWRITE)
      IF (IFLAG.GE.0) GO TO 10
      WRITE (6,130) IFLAG
      STOP
   10 WRITE (OTPT,160)
      IWRITE=0
      J1=NTL+NTL
      J2=J1+NTL
      DO 20 I=1,NTL
      YL(I)=CMPLX(W(J1+I),W(J2+I))
   20 CONTINUE
      NYT=NB+J1
C
C     UPDATING CONTROL VARIABLES AND BUS VOLTAGES
C
   30 WRITE (6,120) NCOUNT,(X(I),I=1,NV)
      R=X(1)
      V(4)=V(4)*(R/BCV(8))
      BCV(8)=R
      R=X(2)
      V(5)=V(5)*(R/BCV(10))
      BCV(10)=R
      R=X(3)
      V(6)=CMPLX(R,0.)
      BCV(11)=R
      BCV(7)=X(4)
      BCV(9)=X(5)
C
C     SOLUTION OF THE LOAD FLOW PROBLEM
C
      VEPS=TOLV
      ITEL=LITER
```

```
      TIMEL=BTIME
      CALL LFLFD1M (NB,NLB,NYT,JRYT,ICYT,BTYP,YT,V,BCV,W,LW,ITEL,VEPS,TI
     1MEL,MODE,IFLAG,OTPT,IWRITE)
      IF (IFLAG.GE.0) GO TO 40
      WRITE (6,140) IFLAG
      STOP
   40 NCOUNT=NCOUNT+1
      MODE=3
C
C     CALCULATION OF SENSITIVITIES OF THE OBJECTIVE FUNCTION
C     W.R.T. V4, V5, V6, P4, P5
C
      CALL RHSLT (YT,JRYT,ICYT,V,BTYP,RHS,NB,IWRITE)
      CALL SENSIT (LBINP,LBOUT,YT,JRYT,ICYT,V,BTYP,BCS,RHS,CCV,ICV,PDR,G
     1,T,IRT,ICT,ICN,IKEEP,IW,NB,NV,IVT,MODES,IFLAG,OTPT,IWRITE)
      IF (IFLAG.GE.0) GO TO 50
      WRITE (6,150) IFLAG
      STOP
   50 MODES=2
C
C     CALCULATION OF THE OBJECTIVE FUNTION AND ITS DERIVATIVES
C
      F=0.
      LVA=JVA-1
      LVM=JVM-1
      DO 90 IL=1,NTL
      L1=LBINP(IL)
      L2=LBOUT(IL)
      CC=YL(IL)
      F=F+((CABS(V(L1)-V(L2)))**2)*REAL(CC)
      R2=W(LVA+L1)-W(LVA+L2)
      DO 80 LV=1,3
      LL=ICV(LV)
      IF (L1.NE.LL.AND.L2.NE.LL) GO TO 80
      IF (L1.EQ.LL) GO TO 60
      R3=W(LVM+L2)
      R4=W(LVM+L1)
      GO TO 70
   60 R3=W(LVM+L1)
      R4=W(LVM+L2)
   70 G(LV)=G(LV)+2.*REAL(CC)*(R3-R4*COS(R2))
   80 CONTINUE
   90 CONTINUE
      IF (IWRITE.GE.1) WRITE (6,170) F
C
C     DETERMINATION OF CONSTRAINTS AND THEIR DERIVATIVES
C
      C(1)=1.1-X(1)
      C(2)=1.1-X(2)
      C(3)=1.1-X(3)
      C(4)=4.0-X(4)
      C(5)=4.0-X(5)
      C(6)=X(1)-0.9
      C(7)=X(2)-0.9
      C(8)=X(3)-0.9
      C(9)=X(4)+0.3
      C(10)=X(5)+0.3
      DO 100 J=1,NV
      DO 100 I=1,L
  100 DC(J,I)=0.
      DO 110 I=1,NV
      DC(I,I)=-1.
      DC(I,I+NV)=1.
  110 CONTINUE
      RETURN
```

```
120 FORMAT (/" ITERATION",I3,":",5X,3(F13.8,1X),1X,2(1X,F13.8))
130 FORMAT (//" RETURN FLAG FROM FORMPR:",I3)
140 FORMAT (//" RETURN FLAG FROM LFLFD1M:",I3)
150 FORMAT (//" RETURN FLAG FROM SENSIT:",I3)
160 FORMAT (//26X,"V4",12X,"V5",12X,"V6",14X,"P4",12X,"P5")
170 FORMAT (" TOTAL TRANSMISSION LOSSES:",F13.8)
    END
```

B006SVA

NE = 006,   NTL = 008

LINE DATA

LBINP	LBOUT	LINPG	LINPB	LR	LX	LOUTG	LOUTB	LTAP
1	4	0.	0.	.5000000E-01	.2000000E+00	0.	0.	.1000000E+01
1	5	0.	0.	.2500000E-01	.1000000E+00	0.	0.	.1000000E+01
2	3	0.	0.	.1000000E+00	.4000000E+00	0.	0.	.1000000E+01
2	4	0.	0.	.1000000E+00	.4000000E+00	0.	0.	.1000000E+01
2	5	0.	0.	.5000000E-01	.2000000E+00	0.	0.	.1000000E+01
2	6	0.	0.	.1875000E-01	.7500000E-01	0.	0.	.1000000E+01
3	4	0.	0.	.1500000E+00	.6000000E+00	0.	0.	.1000000E+01
3	6	0.	0.	.3750000E-01	.1500000E+00	0.	0.	.1000000E+01

BUS DATA

BNR	BTYPE	BVMOD	BVARG	BGP	BLP	BLQ	BSTL
1	0	.9786592E+00	-.6601992E+00	0.	.2400000E+01	0.	0.
2	0	.9632523E+00	-.2978056E+00	0.	.2400000E+01	0.	0.
3	0	.9031892E+00	-.3035574E+00	0.	.1600000E+01	.4000000E+00	0.
4	1	.1020000E+01	-.5565773E+00	-.3000000E+00	0.	0.	0.
5	1	.1040000E+01	-.4740483E+00	.1250000E+01	0.	0.	0.
6	2	.1040000E+01	0.	0.	0.	0.	0.

MINIMIZING OF TRANSMISSION POWER LOSSES IN 6-BUS POWER SYSTEM

B006SVA

NB = 006,   NTL = 008

	V4	V5	V6	P4	P5
ITERATION 1:	1.02000000	1.04000000	1.04000000	-.30000000	1.25000000
ITERATION 2:	1.05735616	1.10000000	1.10000000	.07581153	1.56283770
ITERATION 3:	1.10000000	1.07179732	1.08959147	.77151983	2.13993403
ITERATION 4:	.95093334	1.10000000	1.10000000	1.29936965	2.54975373
ITERATION 5:	1.03615701	1.08387610	1.09404929	.99758989	2.31545358
ITERATION 6:	1.10000000	1.10000000	1.10000000	1.28780476	2.53383233
ITERATION 7:	1.10000000	1.10000000	1.10000000	1.26323721	2.49944822
ITERATION 8:	1.10000000	1.10000000	1.10000000	1.26114629	2.46614620
ITERATION 9:	1.10000000	1.10000000	1.10000000	1.29132674	2.38614365
ITERATION 10:	1.10000000	1.10000000	1.10000000	1.36008230	2.30807640
ITERATION 11:	1.10000000	1.10000000	1.10000000	1.42740503	2.27482305
ITERATION 12:	1.10000000	1.10000000	1.10000000	1.44690024	2.28202327
ITERATION 13:	1.10000000	1.10000000	1.10000000	1.44683835	2.28774927

IFLAG: 0
ACCURACY: .10000E-05
CPU TIME: 1.929 SECONDS
F.EVAL: 13

	V4	V5	V6	P4	P5
SOLUTION:	1.10000000	1.10000000	1.10000000	1.44683835	2.28774927

TOTAL TRANSMISSION POWER LOSSES: .22446119

MINIMIZING OF TRANSMISSION POWER LOSSES IN 6-BUS POWER SYSTEM

B006SVA

NB = 006,   NTL = 008

	V4	V5	V6	P4	P5
ITERATION 1:	1.02000000	1.04000000	1.04000000	-.30000000	1.25000000
ITERATION 2:	1.10000000	1.10000000	1.10000000	-.04698686	1.47506463
ITERATION 3:	1.10000000	1.10000000	1.10000000	.86018269	2.25833279
ITERATION 4:	1.08006261	1.10000000	1.10000000	1.24253757	2.56723517
ITERATION 5:	1.10000000	1.10000000	1.10000000	1.21827905	2.52965755
ITERATION 6:	1.10000000	1.10000000	1.10000000	1.23043447	2.51993521
ITERATION 7:	1.10000000	1.10000000	1.10000000	1.28167136	2.46584175
ITERATION 8:	1.10000000	1.10000000	1.10000000	1.44614116	2.28770173

IFLAG: 0
ACCURACY: .10000E-05
CPU TIME: 1.218 SECONDS
F.EVAL: 8

SOLUTION:	1.10000000	1.10000000	1.10000000	1.44614116	2.28770173

TOTAL TRANSMISSION POWER LOSSES: .22446127

$$\hat{I}_\ell = -2 \sum_{t=1}^{8} \lambda_{\ell t} Y_t R_t I_t^* = -2 \sum_{j \varepsilon J_\ell} G_{\ell j}(V_\ell - V_j)^*,$$

$$\mathrm{Re}(\hat{I}_g) = -\mathrm{Im}\ (V_g \sum_{k \varepsilon J_g} G_{gk}(V_g - V_k)^*), \qquad (5.10)$$

$$\mathrm{Im}(\hat{I}_g) = 0,$$

where

J_m is the set of buses adjacent to the mth bus ($m = \ell$ or $m=g$).

The right hand side vector RHS is created by the subroutine RHSLT as follows:

if $m = \ell$ then

$$\mathrm{RHS}(k) = -\mathrm{Re}\ (\hat{I}_\ell),$$
$$\mathrm{RHS}(n) = -\mathrm{Im}\ (\hat{I}_\ell), \qquad (5.11a)$$

if m=g then

$$\mathrm{RHS}(k) = -\mathrm{Re}\ (\hat{I}_g),$$
$$\mathrm{RHS}(n) = 0\ , \qquad (5.11b)$$

where

$k = 2m-1$, $n = 2m$, $m = 1, 2, .., NB-1$.

The power system discussed was optimized twice using different versions of the adjoint matrix: exact (IVT=1) and mixed (IVT=5). The results of optimization are shown on pages 78 and 79, respectively.

5.6.2 Example 5.8 Minimization of Line Overloading During a Single Line Outage in the 6-Bus Power System

This example deals with the optimization of the 6-bus power system using packages TTM1, MA28 [4] and MMLC [20,21]. The diagram of the analysed system is shown in Fig. 5.3. Input data is taken from the file B006SVA, which describes the 6-bus system at the solution point of the load flow problem (see page 77).

MMLC is a Fortran package for linearly constrained minimax optimization described by Hald and Madsen [22]. The aim of this example is to determine the optimal values of voltages and active powers of generators such that the line overloading is minimal during single line outages. The outages considered are (1,4), (2,3), (2,4), (2,5) and (3,4), i.e., outages of lines labelled in the program by the numbers 1, 3, 4, 5 and 7, respectively.

We formulate the problem as follows. The error functions are

$$f_k = (|I_j^t|) - C_j)/C_j,$$
$$t = 1, 3, 4, 5, 7,$$
$$j = 1, 2, \ldots, 8; \; j \neq t, \tag{5.12}$$
$$k = 1, 2, \ldots, 35,$$

where

C_j is the current carrying capacity of the jth line,

I_j^t is the current flowing in the jth line while the tth line is removed.

The control variable are $|V_4|$, $|V_5|$, $|V_6|$, P_4 and P_5. These variables are renamed in the program X(i), i = 1, 2, ..., 5.

The constraints on the control variables under consideration are

$$0.9 \leq |V_m| \leq 1.1, \quad m = 4, 5, 6,$$
$$-0.3 \leq P_4 \leq 4.0,$$
$$-0.3 \leq P_5 \leq 4.0,$$

where

$|V_m|$ is the modulus of the voltage at the mth bus,

P_m is the active power of the mth bus.

The problem described may be considered as a problem of tuning or alignment in a power system. The tuning variables are $|V_4|$, $|V_5|$, $|V_6|$, P_4 and P_5. The constraint region is determined by the condition that all functions f_k must be non-positive. The aim of optimization is to find the values of the tuning variables such that the operating point is within the constraint region.

The listing of the main program OPT6HM and subroutine RHSL2, as required by MMLC, is given on pages 83-88. Subroutine FDF supplies information required by MMLC. For the given vector X of control variables it calculates vector F of residual functions f_k (k = 1, 2, ..., 35) and matrix DF of their gradients with respect to control variables. In each call to FDF, a contingency analysis for the outages of 5 single lines at a time must be carried out. This is done using the Tellegen theorem method (call to LFTTM). In the first iteration of optimization, as a starting point for contingency analysis, the bus voltages defined in the input data file B006SVA are taken. In the ensuing iterations, as a starting point for each contingency analysis, the bus voltages at the solution to the corresponding contingency problem obtained in the previous step of the optimization procedure are taken except for the moduli of generator voltages, which are updated by the package MMLC. Columns of matrix VI store the initial bus voltages for each contingency analysis.

The results of optimization of the power system under consideration are shown on page 89. All error functions are negative and the system meets the required specification.

```
C
C
C
      PROGRAM OPT6HM(B006,OUTPUT,TAPE4=B006,TAPE6=OUTPUT)
C
C     THIS IS THE MAIN PROGRAM FOR OPTIMIZING 6-BUS POWER SYSTEM
C     CONSIDERING  LINE OVERLOADING  DURING  CONTINGENCIES USING
C     PACKAGES TTM1 AND MMLC
C
      INTEGER CCV(5),ICV(5),LREM(5)
      REAL X(5),DC(10,5),C(10),WW(1500),CL(8)
      COMMON /MNFDF/ NCOUNT,CCV,ICV,LREM,CL,NL
      EXTERNAL FDF
C
      NCOUNT=1
      NV=5
      M=35
      L=10
      LEQ=0
C
C     INTIALIZATION OF CONTROL VARIABLES FOR OPTIMIZATION
C
      X(1)=1.02
      X(2)=1.04
      X(3)=1.04
      X(4)=-0.3
      X(5)=1.25
C
C     DEFINING CONTROL VARIABLES FOR OPTIMIZATION
C
      CCV(1)=9
      ICV(1)=4
      CCV(2)=9
      ICV(2)=5
      CCV(3)=9
      ICV(3)=6
      CCV(4)=7
      ICV(4)=4
      CCV(5)=7
      ICV(5)=5
C
C     DEFINING THE SET OF TRANSMISSION LINES WHICH ARE TO BE REMOVED
C
      NL=5
      LREM(1)=1
      LREM(2)=3
      LREM(3)=4
      LREM(4)=5
      LREM(5)=7
C
C     DEFINING TRANSMISSION LINE CAPACITIES
C
      NTL=8
      CL(1)=1.
      CL(2)=2.5
      CL(3)=1.
      CL(4)=1.
      CL(5)=1.5
      CL(6)=3.5
      CL(7)=1.
      CL(8)=2.
C
C     DEFINING VECTOR C OF CONSTANT TERMS IN THE CONSTRAINTS
C
      C(1)=1.1
```

```
      C(2)=1.1
      C(3)=1.1
      C(4)=4.0
      C(5)=4.0
      C(6)=-0.9
      C(7)=-0.9
      C(8)=-0.9
      C(9)=0.3
      C(10)=0.3
C
C     DEFINING MATRIX DC OF COEFFICIENTS IN THE CONSTRAINTS
C
      DO 10 I=1,L
      DO 10 J=1,NV
   10 DC(I,J)=0.
      DO 20 I=1,NV
      DC(I,I)=-1.0
      DC(I+NV,I)=1.0
   20 CONTINUE
      EPS=1.0E-4
      DX=0.1
      MAXF=50
      KEQS=3
      IWW=1500
      WRITE (6,30)
      CALL SECOND (TM1)
      CALL MMLA1Q (FDF,NV,M,L,LEQ,C,DC,L,X,DX,EPS,MAXF,KEQS,WW,IWW,IFLAG
     1)
      CALL SECOND (TM2)
      CPU=TM2-TM1
      WRITE (6,60) IFLAG,EPS,CPU,MAXF
      WRITE (6,40)
      WRITE (6,50) (I,WW(I),I=1,M)
      STOP
C
   30 FORMAT (///" OPTIMIZATION OF LINE OVERLOADING OF 6-BUS POWER SYSTE
     1M")
   40 FORMAT (//" FUNCTION VALUES"/)
   50 FORMAT (5(3X,I4,":",F10.6))
   60 FORMAT (//" IFLAG:",12X,I2/" ACCURACY:",E11.5/" CPU TIME:",5X,F6.3
     1," SECONDS"/" F. EVAL:",9X,I3)
      END
```

```
C
C
C
C
      SUBROUTINE RHSL2 (LBINP,LBOUT,BTYP,VR,Y,RHS,CURR,NB,LN,IWRITE)
C
C     SUBROUTINE RHSL2 FORMULATES RHS VECTOR OF ADJOINT EQUATIONS
C     WHEN THE FUNCTION  IS MODULUS  OF THE CURRENT OF LN-TH LINE
C     (SEE SOC-258, EQ.25)
C
      INTEGER LBINP(1),LBOUT(1),BTYP(1)
      REAL RHS(1)
      COMPLEX VR(1),CURR,Y,YY
      NR=NB+NB
      DO 10 L=1,NR
      RHS(L)=0.
   10 CONTINUE
      J1=LBINP(LN)
      J2=LBOUT(LN)
      CURR=(VR(J1)-VR(J2))*Y
      YY=CONJG(CURR)*Y/CABS(CURR)
      I=0
      K=J1
   20 IF (BTYP(K).EQ.2) GO TO 40
      K2=K+K
      IF (BTYP(K).EQ.1) GO TO 30
      RHS(K2-1)=REAL(YY)
      RHS(K2)=AIMAG(YY)
      GO TO 40
   30 RHS(K2-1)=AIMAG(VR(K)*YY)
   40 I=I+1
      IF (I.EQ.2) GO TO 50
      K=J2
      YY=-YY
      GO TO 20
   50 IF (IWRITE.LT.4) GO TO 60
      WRITE (6,70)
      WRITE (6,80) (I,RHS(I),I=1,NR)
   60 RETURN
   70 FORMAT (//" RHS VECTOR OF ADJOINT EQUATIONS"/)
   80 FORMAT (5(2X,I4,":",E13.7))
      END
```

```
C
C
C
      SUBROUTINE FDF (NV,M,X,DF,F)
C
C     THIS SUBROUTINE EVALUATES THE ERROR FUNCTIONS AND
C     THEIR DERIVATIVES W.R.T. V4, V5, V6, P4 AND P5
C
      INTEGER LBINP(8),LBOUT(8),BTYP(8),JRYT(7),ICYT(30),ICV(5),CCV(5),L
     1REM(5),OTPT
      REAL BCV(12),W(850),X(5),DF(35,5),F(35),CL(8)
      COMPLEX BCS(6),YT(22),V(6),VR(6),YL(8),VI(6,6),CC,CURR
      COMMON /MNFDF/ NCOUNT,CCV,ICV,LREM,CL,NL/MDLFTTM/JT,JICN,JICT,JIRT
     1,JIKEEP,JIW,JCS,JVD,JRHS,JSENS,JDEL,JICV,JCCV,JMAX
C
C     INITIALIZATION OF SOME VARIABLES AND FORMULATION OF THE LOAD
C     FLOW EQUATIONS
C
      IF (NCOUNT.NE.1) GO TO 40
      INPT=4
      OTPT=6
      NB=6
      NTL=8
      LITER=7
      BTIME=2.
      LW=850
      TOLV=1.E-4
      IVT=1
      IP=1
      IWRITE=1
      CALL FORMPR (LBINP,LBOUT,BTYP,YT,JRYT,ICYT,BCV,V,W,LW,NB,NTL,NLB,I
     1P,INPT,OTPT,IFLAG,IWRITE)
      IF (IFLAG.GE.0) GO TO 10
      WRITE (6,280) IFLAG
      STOP
   10 IWRITE=0
      J1=NTL+NTL
      J2=J1+NTL
      DO 20 I=1,NTL
      YL(I)=CMPLX(W(J1+I),W(J2+I))
   20 CONTINUE
C
C     EACH COLUMN OF MATRIX VI STORES THE INITIAL BUS VOLTAGES FOR
C     DIFFERENT CONTINGENCIES
C
      DO 30 JC=1,5
      DO 30 JR=1,NB
   30 VI(JR,JC)=V(JR)
      NR=NB+NB
      WRITE (6,250)
      WRITE (6,260) (LBINP(I),LBOUT(I),CL(I),I=1,NTL)
      WRITE (6,270)
   40 WRITE (6,220) NCOUNT,(X(I),I=1,NV)
C
C     CONTROL VARIABLES UPDATING
C
      R=X(1)
      BCV(8)=R
      DO 50 JC=1,5
      VI(4,JC)=CMPLX(R,AIMAG(VI(4,JC)))
   50 CONTINUE
      R=X(2)
      BCV(10)=R
      DO 60 JC=1,5
      VI(5,JC)=CMPLX(R,AIMAG(VI(5,JC)))
```

```
   60 CONTINUE
      R=X(3)
      BCV(11)=R
      DO 70 JC=1,5
      VI(6,JC)=CMPLX(R,AIMAG(VI(6,JC)))
   70 CONTINUE
      BCV(7)=X(4)
      BCV(9)=X(5)
C
C     CALCULATION OF VALUES OF THE FUNCTIONS REPRESENTING LINE
C     OVERLOADING AND THEIR DERIVATIVES
C
      NF=0
      DO 200 I=1,NL
C
C     NODAL ADMITTANCE MATRIX UPDATING AFTER THE LINE REMOVAL
C
      IB1=LBINP(LREM(I))
      IB2=LBOUT(LREM(I))
      K1=JRYT(IB1)+1
      K2=JRYT(IB2)+1
      K3=JRYT(IB1+1)-1
      K4=JRYT(IB2+1)-1
      DO 80 J=K1,K3
      IF (ICYT(J).EQ.IB2) GO TO 90
   80 CONTINUE
   90 IC1=J
      DO 100 J=K2,K4
      IF (ICYT(J).EQ.IB1) GO TO 110
  100 CONTINUE
  110 IC2=J
      CC=YT(J)
      K5=K1-1
      K6=K2-1
      YT(K5)=YT(K5)+CC
      YT(K6)=YT(K6)+CC
      YT(IC1)=(0.,0.)
      YT(IC2)=(0.,0.)
C
C     LOAD FLOW ANALYSIS WHILE THE LINE INDEXED BY LREM(I) IS OUT
C
      MODE=1
      VEPS=TOLV
      ITEL=LITER
      TIMEL=BTIME
      DO 120 JR=1,NB
      V(JR)=VI(JR,I)
  120 CONTINUE
      CALL LFTTM (NB,NTL,JRYT,ICYT,BTYP,YT,V,BCV,W,LW,IVT,IP,ITEL,VEPS,T
     1IMEL,MODE,IFLAG,OTPT,IWRITE)
      IF (IFLAG.LT.0) GO TO 210
      DO 130 JR=1,NB
      CURR=V(JR)
      VI(JR,I)=CURR
      ABSV=REAL(CURR)
      ARGV=AIMAG(CURR)
      VR(JR)=CMPLX(ABSV*COS(ARGV),ABSV*SIN(ARGV))
  130 CONTINUE
C
C     CALCULATION OF VALUES OF FUNCTIONS REPRESENTINGS LINE OVERLOADING
C     AND ITS DERIVATIVES W.R.T.  V4,V5,V6,P4,P5 WHILE THE LINE INDEXED
C     BY LREM(I) IS OUT
C
      DO 190 J=1,NTL
C
```

```
C     CALCULATION OF THE VALUE OF A SINGLE FUNCTION AND ITS SENSITIVITY
C
      IF (J.EQ.LREM(I)) GO TO 190
      CALL RHSL2 (LBINP,LBOUT,BTYP,VR,YL(J),W(JRHS),CURR,NB,J,IWRITE)
      CALL SENSIT (LBINP,LBOUT,YT,JRYT,ICYT,VR,BTYP,W(JCS),W(JRHS),CCV,I
     1CV,W(JVD),W(JSENS),W(JT),W(JIRT),W(JICT),W(JICN),W(JIKEEP),W(JIW),
     2NB,NV,IVT,MODE,IFLAG,OTPT,IWRITE)
      IF (IFLAG.GE.0) GO TO 140
      WRITE (6,290) IFLAG
      STOP
  140 MODE=3
      NF=NF+1
      F(NF)=(CABS(CURR)-CL(J))/CL(J)
C
C     DERIVATIVE CALCULATIONS
C
      J1=JSENS-1
      L1=LBINP(J)
      L2=LBOUT(J)
      DO 170 LV=1,3
      LL=ICV(LV)
      IF (L1.NE.LL.AND.L2.NE.LL) GO TO 170
      R1=CABS(YL(J)/(VR(L1)-VR(L2)))
      R2=COS(AIMAG(V(L1)-V(L2)))
      IF (L1.EQ.LL) GO TO 150
      R3=REAL(V(L2))
      R4=REAL(V(L1))
      GO TO 160
  150 R3=REAL(V(L1))
      R4=REAL(V(L2))
  160 W(J1+LV)=W(J1+LV)+R1*(R3-R4*R2)
  170 CONTINUE
      DO 180 L=1,NV
      DF(NF,L)=W(J1+L)/CL(J)
  180 CONTINUE
  190 CONTINUE
      YT(K5)=YT(K5)-CC
      YT(K6)=YT(K6)-CC
      YT(IC1)=CC
      YT(IC2)=CC
  200 CONTINUE
      NCOUNT=NCOUNT+1
      IF (IWRITE.LT.1) RETURN
      WRITE (6,230)
      WRITE (6,240) (I,F(I),I=1,M)
      RETURN
  210 WRITE (6,300) IFLAG
      STOP
  220 FORMAT (/" ITERATION",I3,":",3(F13.8,1X),1X,2(1X,F13.8))
  230 FORMAT (/" FUNCTION VALUES"/)
  240 FORMAT (5(3X,I4,": ",F10.6))
  250 FORMAT (//" LINE CAPACITIES")
  260 FORMAT (/(4(" (",I1,",",I1,"):",F5.2,3X)))
  270 FORMAT (//21X,"V4",12X,"V5",12X,"V6",14X,"P4",12X,"P5"/)
  280 FORMAT (//" RETURN FLAG FROM FORMPR :",I3)
  290 FORMAT (//" RETURN FLAG FROM SENSIT :",I3)
  300 FORMAT (//" RETURN FLAG FROM LFLFD1M :",I3)
      END
```

OPTIMIZATION OF LINE OVERLOADING OF 6-BUS POWER SYSTEM

B006SVA

NB = 006, NTL = 008

LINE CAPACITIES

(1,4): 1.00	(1,5): 2.50	(2,3): 1.00	(2,4): 1.00
(2,5): 1.50	(2,6): 3.50	(3,4): 1.00	(3,6): 2.00

	V4	V5	V6	P4	P5
ITERATION 1:	1.02000000	1.04000000	1.04000000	-.30000000	1.25000000
ITERATION 2:	1.07669488	1.05206068	1.09218795	-.28382807	1.31045756
ITERATION 3:	1.09784548	1.10000000	1.10000000	-.14815942	1.44752494
ITERATION 4:	1.10000000	1.10000000	1.10000000	-.03942507	1.59497226
ITERATION 5:	1.10000000	1.10000000	1.10000000	-.03762881	1.59759524
ITERATION 6:	1.10000000	1.10000000	1.10000000	-.03762832	1.59759596

IFLAG: 2
ACCURACY: .86720E-06
CPU TIME: 6.761 SECONDS
F. EVAL: 6

FUNCTION VALUES

1:	-.054368	2:	-.882641	3:	-.849612	4:	-.303375	5:	-.054368
6:	-.821899	7:	-.182979	8:	-.499439	9:	-.280611	10:	-.563431
11:	-.684930	12:	-.121332	13:	-.697396	14:	-.082483	15:	-.666896
16:	-.192708	17:	-.833053	18:	-.508585	19:	-.124850	20:	-.561966
21:	-.066905	22:	-.185213	23:	-.412615	24:	-.855526	25:	-.310060
26:	-.115490	27:	-.581922	28:	-.071329	29:	-.559823	30:	-.251904
31:	-.836495	32:	-.458874	33:	-.610442	34:	-.062621	35:	-.172464

6 DESCRIPTION OF SUBROUTINES

The formal description of all alphabetically ordered subroutines of the package TTM1 is given in this chapter.

COMPLEX FUNCTION CURR (X,YT,JRYT,ICYT,MB)

Purpose

This function subprogram calculates the value of current injected into the MBth bus.

List of Arguments

X is the COMPLEX vector of length NB (number of buses of the power system). On entry, it must store values of bus voltages (rectangular coordinates). Not altered by the subroutine.

YT is a COMPLEX vector of dimension NYT. On entry, it contains nonzero elements of the bus admittance matrix (for details, see the description of subroutine FORMYT). Not altered by the subroutine.

JRYT is an INTEGER vector of dimension (NB+1). On entry, it must contain the row indices of the sparse bus admittance matrix (for details, see the description of subroutines RDAT and FORMYT). JRYT is not altered by the subroutine.

ICYT is an INTEGER vector of dimension NYT. On entry, it must contain the column indices of elements of the sparse bus admittance matrix (for details, see the description of subroutine FORMYT). ICYT is not altered by the subroutine.

MB is an INTEGER argument. The current at the MBth bus is calculated by the subroutine. Not altered by the subprogram.

Related Software

This subprogram is called by subroutines DERIV, LFLDBM, LFLFDCM.

Method

The current I_i injected into the ith bus is calculated using the formula

$$I_i = \sum_{j=1}^{m} y_{ij} V_j , \tag{6.1}$$

where

y_{ij} is an element of the nodal admittance matrix,

V_i is the ith bus voltage,

m is the number of buses of the power system.

References

See also [23].

SUBROUTINE DCVARF (CCVF,ICVF,BTYP,N)

Purpose

This subroutine declares the power system control variables for the load flow problem.

List of Arguments

CCVF is an INTEGER vector of dimension 2xN. On exit, CCVF(j) contains the code number of the jth control variable of the load flow problem (j=1,2,..., 2xN).

ICVF is an INTEGER vector of dimension 2xN. On exit, ICVF(j) contains the index of a bus associated with the jth control variable (j=1,2,...,2xN).

BTYP is an INTEGER vector of dimension N of bus types (0 signifies a load bus, 1 signifies a generator bus). BTYP is not altered by the subroutine.

N is an INTEGER argument. It must be set up by the user to the number of buses excluding the slack bus. Not altered by the subroutine.

Related Software

This subroutine is called by subroutine LFTTM.

Method

Bus active and reactive powers are used as control variables associated with a load bus and bus active power and bus voltage modulus are used as control variables associated with a generator bus in the load flow problem. The code number of the bus active power is 7, of the bus reactive power is 8, and of the bus voltage modulus is 9 (for details, see the description of subroutine DERIV).

Vectors CCVF and ICVF are defined as follows:

a) If the ith bus is a load bus

CCVF(k)=7,

ICVF(k)=i,

CCVF(ℓ)=8,

ICVF(ℓ)=i,

b) If the ith bus is a generator bus

CCVF(k)=7,

ICVF(k)=i,

CCVF(ℓ)=9,

ICVF(ℓ)=i,

where k=2xi-1, ℓ=2xi and i=1,2,...,N.

References

See also [1,23].

SUBROUTINE DERIV (LBINP,LBOUT,YT,JRYT,ICYT,V,VT,CCV,ICV,PDR,SENS, NCV,IWRITE)

Purpose

This subroutine calculates sensitivities of a real function of the power system state and control variables with respect to specified control variables when the solution of the adjoint system is given.

List of Arguments

LBINP, LBOUT

are INTEGER vectors of dimension NTL (number of transmission lines). On entry to the subroutine, LBINP(k) and LBOUT(k) must contain the indices of buses incident with the kth transmission line (k=1,2,...,NTL). These vectors are not altered by the subroutine.

YT is a COMPLEX vector of dimension NYT=NB+2xNTL, where NB is the number of buses. On entry to the subroutine, it contains all nonzero elements of the nodal admittance matrix (for details, see the description of subroutine FORMYT). Not altered by the subroutine.

JRYT is an INTEGER vector of dimension (NB+1). On entry, it must contain the row indices of the sparse bus admittance matrix (for details, see the description of subroutines RDAT and FORMYT). Not altered by the subroutine.

ICYT is an INTEGER vector of length NYT. On entry, it must contain the column indices of elements of the sparse bus admittance matrix (for details, see the description of subroutine FORMYT).

Not altered by the subroutine.

V is a COMPLEX vector of dimension NB. On entry, it must contain bus voltages in rectangular coordinates. Not altered by the subroutine.

VT is a COMPLEX vector of dimension NB. On entry, it must contain bus voltages of the adjoint system in rectangular coordinates. VT is not altered by the subroutine.

CCV is an INTEGER vector of dimension NCV. On entry, CCV(j) must contain the code number of the jth control variable (j=1,2...,NCV). Not altered by the subroutine.

ICV is an INTEGER vector of dimension NCV. On entry, ICV(j) must contain the index of a bus or of a transmission line associated with the jth control variable (j=1,2,...NCV). Not altered by the subroutine.

PDR is a COMPLEX vector of length NCT, where NCT is the number of line-type control variables, i.e., variables with code 1, 2, 3, 4, 5, 6 or 11. On entry, PDR(i) should be equal to twice the value of the formal partial derivative of the function with respect to current of the element associated with the ith line type variable appearing in CCV (i=1,2,...,NCT). PDR is not altered by the subroutine.

SENS is a REAL vector of length NCV. On exit, it contains sensitivities of the function with respect to control variables defined by vectors CCV and ICV.

NCV is an INTEGER variable. On entry, it must be set to the number of control variables. Not altered by the subroutine.

IWRITE is an INTEGER parameter that controls outputs.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 2 all prints are suppressed,

≥ 3 vector SENS of sensitivities is printed out.

Related Software

This subroutine calls function subroutine CURR and is called by subroutines SENSIT and STEP.

Method

The total derivative of a real function $f(\underset{\sim}{x},\underset{\sim}{u})$ of the power system state and control variables with respect to a control variable u can be obtained using (2.3).

Subroutine DERIV calculates sensitivities $\hat{\eta}_u$ appearing in this formula. Power system control variables with respect to which sensitivities are to be calculated, are defined by vectors CCV and ICV. The possible code numbers are given in Table 6.1.

The formulas for sensitivity calculation implemented in the subroutine are shown in Table 6.2. An explanation of currents and voltages appearing in these formulas is given in Fig. 6.1 (see also the description of subroutine READDT and [3]).

Let us assume that

CCV = [7, 8, 11, 1, 3]

In this case, the user must initialize vector PDR as:

$$PDR(1) = 2\frac{\partial f}{\partial I_{sl}} = \frac{\partial f}{\partial I_{sl1}} - j\frac{\partial f}{\partial I_{sl2}} \quad ,$$

$$PDR(2) = 2\frac{\partial f}{\partial I_{si}} = \frac{\partial f}{\partial I_{si1}} - j\frac{\partial f}{\partial I_{si2}} \quad ,$$

$$PDR(3) = 2\frac{\partial f}{\partial I_{t}} = \frac{\partial f}{\partial I_{t1}} - j\frac{\partial f}{\partial I_{t2}} \quad ,$$

where $I=I_1+jI_2$.

References

For details of the method, see also [3].

TABLE 6.1

CODE NUMBERS OF CONTROL VARIABLES

Type of variable	Code number
Input shunt conductance of a line (G_{si})	1
Input shunt susceptance of a line (B_{si})	2
Line conductance (G_t)	3
Line susceptance (B_t)	4
Output shunt conductance of a line (G_{so})	5
Output shunt susceptance of a line (B_{so})	6
Bus active power (P)	7
Bus reactive power (Q)	8
Modulus of bus voltage ($\|V_i\|$)	9
Argument of bus voltage (δ_i)	10
Bus static load ($B_{s\ell}$)	11

TABLE 6.2

FORMULAS FOR SENSITIVITY CALCULATION

Formula for $\hat{\eta}_u$	Control variable	Indices
$-\mathrm{Re}\left(V_p(\hat{V}_p + 2\frac{\partial f}{\partial I_r})\right)$	G_{si} G_t G_{so}	$p = i,\ r = si$ $p = t,\ r = t$ $p = o,\ r = so$
$\mathrm{Im}\left(V_p(\hat{V}_p + 2\frac{\partial f}{\partial I_r})\right)$	B_{si} B_t B_{so} $B_{s\ell}$	$p = i,\ r = si$ $p = t,\ r = t$ $p = o,\ r = so$ $p = i,\ r = s\ell$
$\mathrm{Re}(\hat{V}_i/V_i^*)$	P	—
$\mathrm{Im}(\hat{V}_i/V_i^*)$	Q	—
$-\mathrm{Re}(V_i\hat{I}_i + I_i\hat{V}_i)/\lvert V_i\rvert$	$\lvert V_i\rvert$	—
$\mathrm{Im}(V_i\hat{I}_i - I_i\hat{V}_i)$	δ_i	—

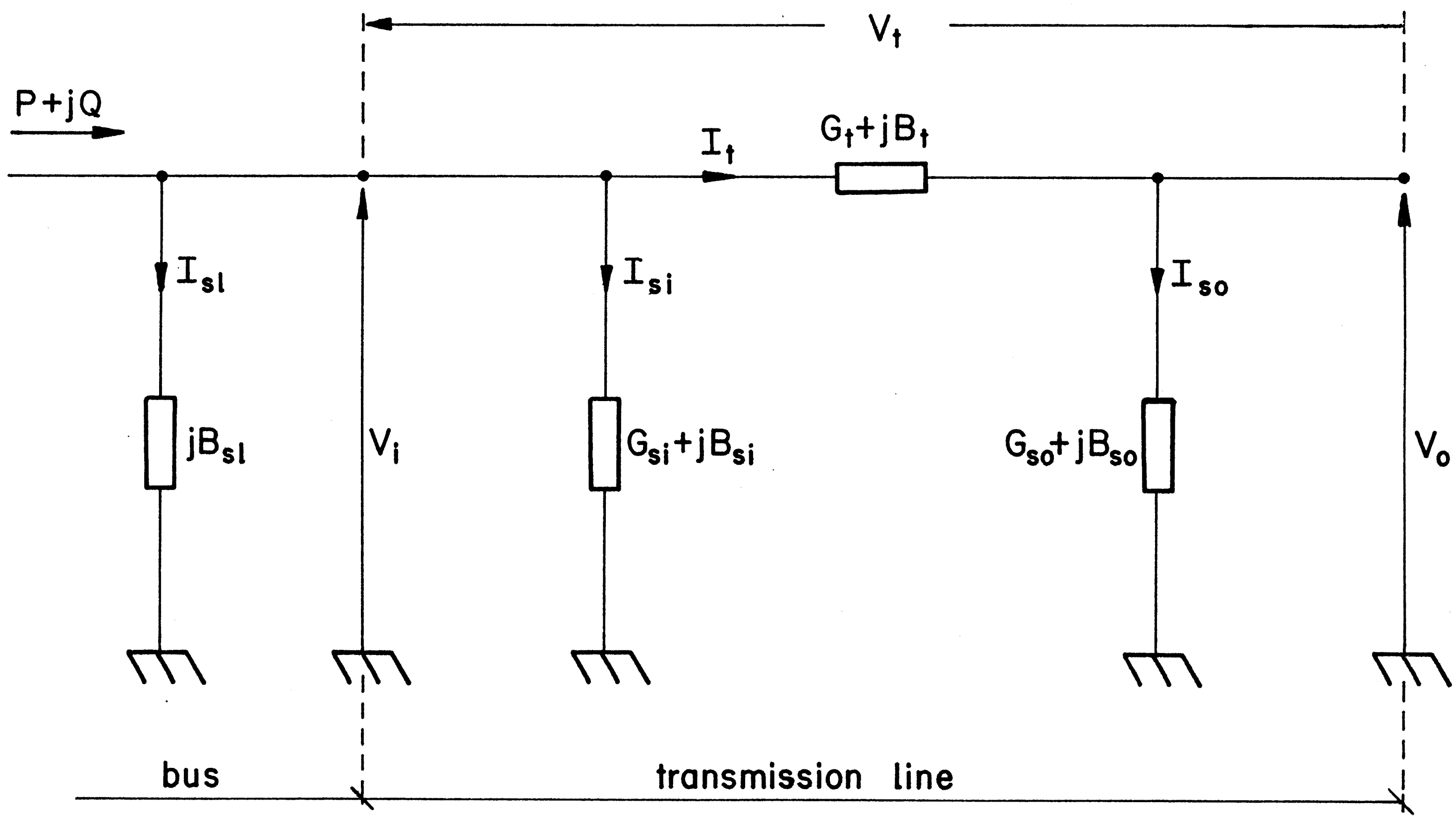

Fig. 6.2 Model of a bus and of a transmission line for sensitivity calculation.

SUBROUTINE EXCT (V,ITYP,I,RHST,NR,IP,IWRITE)

Purpose

This subroutine forms the right-hand side vector of the adjoint equations for the ith state variable of the load flow problem given in a rectangular or polar formulation.

List of Arguments

V — is a COMPLEX vector of dimension NB-1 (NB is the number of bases of the power system). On entry to the procedure, it must contain values of voltages of all buses except the slack bus (in rectangular coordinates). Not altered by the subroutine.

ITYP — is an INTEGER variable. On entry, it stores type of a bus described by the ith state variable (0 for load bus, 1 for generator bus). Not altered by the subroutine.

I — is an INTEGER argument. On entry, it contains an index of the current state variable. Not altered by the subroutine.

RHST — is a REAL vector of length NR. On exit, RHST stores the right-hand side vector of the adjoint equations.

NR — is an INTEGER argument. It must be set be the user to 2x(NB-1). NR is not altered by the subroutine.

IP — is an INTEGER variable, which must be set by the user
= 1 polar version of the load flow equations is used,
≠ 1 rectangular version is used.

IWRITE — is an INTEGER variable that controls outputs.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 3 all printouts are suppressed,

≥ 4 index of the bus, state variable identifier, the value of IP and the right-hand side vector RHST are printed. The state variable identifier is equal to 1 when the state variable is V_{m1} or $|V_m|$, depending on the value of IP, or is equal to 0 when the state variable is V_{m2} or δ_m.

Related Software

This subroutine is called by subroutine STEP.

Method

This subroutine forms the right-hand side vector of the adjoint system for the ith state variable of the load flow problem [1]. It is assumed that state variables associated with the mth bus are indexed by (2xm-1) and (2xm). If the value of ℓ=MOD(i,2) is equal to 1, then the state variable is either V_{m1} or $|V_m|$ depending on IP. If ℓ=0, then the state variable is V_{m2} or δ_m. Index of a bus associated with the ith state variable is equal to the integral part of $(i+\ell)/2$. In the implementation under consideration, the (2xk-1)th and (2xk)th elements of the right-hand side vector are associated with the kth adjoint bus (k=1,2,...,NB-1).

References

For details of the method, see also [1,2].

SUBROUTINE FORMDTF (LBINP,LBOUT,LINPG,LINPB,LR,LX,LOUTG,LOUTB,LTAP,BNR, BTYP,BVMOD,BVARG,BGP,BLP,BLQ,BSTL,HDLN,NB,NTL,OTPT)

Purpose

This subroutine creates a formatted standard data file describing the power system with the structure acceptable by the package TTM1.

List of Arguments

LBINP, LBOUT

are INTEGER vectors of dimension NTL. On entry LBINP(k), LBOUT(k) must contain the indices of buses incident with the kth transmission line (k=1,2,...,NTL). These vectors are not altered by the subroutine.

LINPG, LINPB

are REAL vectors of dimension NTL. On entry, LINPG(k) and LINPB(k) must contain the input shunt conductance and susceptance of the kth transmission line (k=1,2,...,NTL). These vectors are not altered by the subroutine.

LR, LX are REAL vectors of dimension NTL. On entry, LR(k) and LX(k) must contain the resistance and reactance of the kth transmission line (k=1,2,...,NTL). These vectors are not altered by the subroutine.

LOUTG, LOUTB

are REAL vectors of dimension NTL. On entry, LOUTG(k) and LOUTB(k) must store the output shunt conductance and susceptance of the kth transmission line (k=1,2,...,NTL). Neither vectors are altered by the subroutine.

LTAP is a REAL vector of dimension NTL. On entry to the subroutine, it must retain the line transformer ratios. LTAP is not altered by the subroutine.

BNR is an INTEGER vector of dimension NB. On entry, BNR(i) must contain the original index of the ith bus.

BTYP is an INTEGER vector of dimension NB. On entry, it must contain bus types (0 for load bus, 1 for generator bus, 2 for slack bus). Not altered by the subroutine.

BVMOD is a REAL vector of dimension NB. On entry to the subroutine, it contains the values of the moduli of bus voltages. Not altered by the subroutine.

BVARG is a REAL vector of dimension NB. On entry to the subroutine, it must contain the values of the arguments of bus voltages (in radians). Not altered by the subroutine.

BGP is a REAL vector of dimension NB. On entry, it must contain the values of bus generated active powers. Not altered by the subroutine.

BLP is a REAL vector of dimension NB. On entry, it must contain the values of bus consumed active powers. Not altered by the subroutine.

BLQ is a REAL vector of dimension NB. On entry, it must store the values of bus consumed reactive powers. Not altered by the subroutine.

BSTL is a REAL vector of dimension NB. On entry, it must contain bus static loads. Not altered by the subroutine.

HDLN is a REAL matrix with 8 elements. On entry, it should contain an identifier of the created file. The file identifier will be

"BNNN" followed by the contents of matrix HDLN, where NNN is the number of buses of the system under consideration. The file identifier appears as the first non-empty record.

NB is an INTEGER parameter. On entry, NB must be equal to the total number of buses and is not altered by the subroutine.

NTL is an INTEGER parameter. On entry, NTL must be equal to the number of transmission lines and is not altered by the subroutine.

OTPT is an INTEGER parameter. It must be set by the user to the number of the output unit.

Method

Subroutine FORMDTF transfers data describing the power system into the file assigned to the unit OTPT in the PROGRAM statement.

Examples

The use of subroutine FORMDTF is shown in Examples 5.2 and 5.4.

References

See also [24].

SUBROUTINE FORMPR (LBINP,LBOUT,BTYP,YT,JRYT,ICYT,BCV,V,WS,LWS,NB,NTL, NLB,IP,INPT,OTPT,IFLAG,IWRITE)

Purpose

The aim of this subroutine is to read input data describing the power system and to formulate the load flow problem, i.e., the nodal admittance matrix (in a sparse form), the right-hand side vector of the power flow equations, and the vector of initial bus voltages.

List of Arguments

LBINP, LBOUT

are INTEGER vectors of dimension NTL. On return from the subroutine, elements LBINP(k) and LBOUT(k) contain the indices of buses incident with the kth transmission line (k=1,2,...,NTL).

BTYP is an INTEGER vector of length NB. On return from the subroutine, it contains bus types (0 for load bus, 1 for generator bus, 2 for slack bus).

YT is a COMPLEX vector of dimension NYT=NB+2xNTL. On return from the subroutine, it stores all nonzero elements of the nodal admittance matrix (for details, see the description of subroutine FORMYT).

JRYT is an INTEGER vector of dimension NB+1. On return from the subroutine, it contains the row indices of the sparse bus admittance matrix (for details, see the description of subroutines RDAT and FORMYT).

ICYT is an INTEGER vector of length 2x(NB+NTL). On return from the subroutine, the first NB+2xNTL elements of ICYT contain the column indices of the sparse bus admittance matrix. The last NB entries of ICYT are used by the subroutine as a workspace (for more details, see the description of subroutine FORMYT).

BCV is a REAL vector of length 2xNB. On exit from the subroutine, it stores the values of bus control variables (for details, see the description of subroutine FORMU).

V is a COMPLEX vector of dimension NB. On return, it stores the initial values of bus voltages in polar coordinates if parameter IP is set by the user to 1, or in rectangular coordinates if IP≠1.

WS is a REAL vector of length LWS used as a workspace by the subroutine.

LWS is the length of the workspace vector WS. It must be declared at least as LWS=7x(NB+NTL).

NB is an INTEGER variable. On entry, NB must be at least as large as the number of buses. On return, NB is equal to the number of buses.

NTL is an INTEGER variable. On entry, NTL must be at least as large as the number of transmission lines. On return, NTL is equal to the number of transmission lines.

NLB is an INTEGER parameter. On return, NLB is equal to the number of load buses.

IP is an INTEGER argument which must be set by the user

= 1 then on return vector V of bus voltages is in polar coordinates,

≠ 1 then on return vector V is in rectangular coordinates.

INPT is an INTEGER parameter. It must be set by the user to the number of the input unit associated with the file containing input data (for details, see the description of subroutine RDAT).

OTPT is an INTEGER parameter. It must be set by the user to the number of the output unit.

IFLAG is the return flag from the subroutine. INTEGER parameter.

IWRITE is an INTEGER parameter that controls outputs.

Error Diagnostics

A successful return from FORMPR is indicated by the value of IFLAG equal to zero. If the length LWS of the workspace vector WS has been declared too small, then on return from the subroutine IFLAG=-1.

Input-Output

Input data is read in subroutine FORMPR with the aid of subroutine RDAT. For details, see the description of subroutine RDAT.

Output data is controlled by the parameter IWRITE. Output prints may appear only due to call to subroutines RDAT, FORMYT and FORMU. For details, see the description of subroutines RDAT, FORMYT and FORMU.

Common Blocks

COMMON/MDFRMPR/JINPG, JINPB, JLG, JLB, JOUTG, JOUTB, JTAP, JNR, JVM, JVA, JGP, JLP, JLQ, JSTL, JMX

where

JINPG, JINPB, JLG, JLB, JOUTG, JOUTB, JTAP, JNR, JVM, JVA, JGP,

JLP, JLQ, JSTL

indicate locations in the workspace vector WS of the first element of vectors LINPG, LINPB, LG, LB, LOUTG, LOUTB, LTAP, BNR, BVMOD, BVARG, BGP, BLP, BLQ, BSTL, respectively.

JMX is the length of the workspace used by the subroutine.

Related Software

This subroutine calls subroutines FORMU, FORMYT and RDAT.

Method

This subroutine reads input data describing the power system, formulates the sparse bus admittance matrix (vectors YT, JRYT, ICYT) and the right-hand side vector BCV of the power flow equations using subroutines RDAT, FORMYT, and FORMU, respectively. For more details see the description of subroutines RDAT, FORMPR and FORMU.

Vector V is the vector of initial bus voltages defined as

$$V(i) = \begin{cases} \text{CMPLX(BVMOD(i), BVARG(i))} & \text{if IP=1,} \\ \text{BVMOD(i)*CMPLX(COS(BVARG(i)), SIN(BVARG(i)))} & \text{if IP}\neq\text{1,} \end{cases}$$

$$i=1,2,\ldots, NB.$$

Examples

The use of subroutine FORMPR is shown in Examples 5.3, 5.4, 5.5, 5.7 and 5.8.

References

For details of the method, see also [1,4,23].

SUBROUTINE FORMTA(YT,JRYT,ICYT,BTYP,T,IRT,ICT,N,NT,OTPT,IWRITE)

Purpose

This subroutine forms a real, approximate adjoint matrix of the power system and stores it in a sparse form.

List of Arguments

YT is a COMPLEX vector of dimension NYT=NB+2xNTL (NB is the number of buses and NTL the number of transmission lines of the power system). On entry, it contains nonzero elements of the bus admittance matrix (for details, see the description of subroutine FORMYT). Not altered by the subroutine.

JRYT is an INTEGER vector of dimension NB+1. On entry, it must contain the row indices of the sparse bus admittance matrix (for details, see the description of subroutines RDAT and FORMYT). JRYT is not altered by the subroutine.

ICYT is an INTEGER vector of dimension NYT. On entry, it must contain the column indices of the sparse bus admittance matrix (for details, see the description of subroutine FORMYT). ICYT is not altered by the subroutine.

BTYP is an INTEGER vector of length N of bus types (0 for load bus, 1 for generator bus). BTYP is not altered by the subroutine.

T is a REAL vector. The dimension of this vector should be declared slightly less than 4x(N+2xNTL). On return T stores all nonzero elements of the adjoint matrix.

IRT is an INTEGER vector of length the same as vector T. On return, IRT contains the row indices of the nonzero elements stored in T.

ICT is an INTEGER vector of length the same as vector T. On return, ICT contains the column indices of the nonzero elements stored in T.

N is an INTEGER argument. It must be set by the user to NB-1. Not altered by the subroutine.

NT is an INTEGER variable. On return, NT is equal to the number of nonzero elements of the adjoint matrix.

OTPT is the number of the output unit. INTEGER parameter.

IWRITE is an INTEGER parameter that controls outputs.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 3 all printouts are suppressed,

≥ 4 sparse adjoint matrix is printed out, i.e., vectors IRT, ICT and T.

Related Software

This subroutine calls subroutine PTELT and is called by subroutines SENSIT and STEP.

Method

Subroutine FORMTA uses the method described in [2] to form a real, approximate adjoint matrix of the power system. In this implementation, the (2xi-1)th and (2xi)th rows of the adjoint matrix are associated with the ith bus of the power system (i=1,2,..., N). On return from the subroutine, the adjoint matrix is stored in a sparse form by vectors T, IRT and ICT.

References

For details of the method, see also [3,4].

SUBROUTINE FORMTAD (YT,JRYT,ICYT,BTYP,T,IRT,ICT,N,NT,OTPT,IWRITE)

Purpose

This subroutine forms a real, approximate, decoupled adjoint matrix of the power system and stores it in a sparse form.

List of Arguments

All arguments have the same names and meaning as in subroutine FORMTA.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 3 all printouts are suppressed,

≥ 4 sparse adjoint matrix is printed out, i.e., vectors IRT, ICT and T.

Related Software

This subroutine calls subroutine PTELT, and is called by subroutines SENSIT and STEP.

Method

Subroutine FORMTAD uses the method described in [2] to form a real, approximate, decoupled adjoint matrix of the power system. In this implementation, the (2xi-1)th and (2xi)th rows of the adjoint matrix are associated with the ith bus of the power system (i=1,2,...,N). On return from the subroutine, the adjoint matrix is stored in a sparse form by vectors T, IRT and ICT.

Examples

The use of subroutine FORMTAD is illustrated in Example 5.6.

References

For details of the method, see also [3,4].

SUBROUTINE FORMTD (YT,JRYT,ICYT,BCS,V,BTYP,T,IRT,ICT,N,NT,OTPT,IWRITE)

Purpose

This subroutine forms a real, decoupled adjoint matrix of the power system and stores it in a sparse form.

List of Arguments

All arguments have the same names and meaning as in subroutine FORMTE, except for the dimension of vectors T, IRT and ICT, which should be declared slightly less than 2x(N+2xNTL).

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 3 all printouts are suppressed,

≥ 4 sparse adjoint matrix is printed out, i.e., vectors IRT, ICT and T.

Related Software

This subroutine calls subroutine PTELT, and is called by subroutines SENSIT and STEP.

Method

Subroutine FORMTD uses the method described in [2] to form a real, decoupled adjoint matrix of the power system. In this implementation, the (2xi-1)th and (2xi)th rows of the adjoint matrix are associated with the ith bus of the power system (i=1,2,...N). On return from the subroutine, the adjoint matrix is stored in a sparse form by vectors T, IRT and ICT.

References

For details of the method, see also [3,4].

SUBROUTINE FORMTE (YT,JRYT,ICYT,BCS,V,BTYP,T,IRT,ICT,N,NT,OTPT,IWRITE)

Purpose

This subroutine forms a real, exact adjoint matrix of the power system and stores it in a sparse form.

List of Arguments

YT is a COMPLEX vector of dimension NYT=NB+2xNTL (NB is the number of buses and NTL the number of transmission lines of the power system). On entry, it stores the nonzero elements of the bus admittance matrix (for details, see the description of subroutine FORMYT). Not altered by the subroutine.

JRYT is an INTEGER vector of dimension NB+1. On entry, it must contain the row indices of nonzero elements of the bus admittance matrix (for details, see the description of subroutines RDAT and FORMYT). JRYT is not altered by the subroutine.

ICYT is an INTEGER vector of dimension NYT. On entry, it must contain the column indices of elements of the sparse bus admittance matrix (for details, see the description of subroutine FORMYT). ICYT is not altered by the subroutine.

BCS is a COMPLEX vector of dimension N. On entry, it must contain the values of complex powers injected into buses (excluding the slack bus). Not altered by the subroutine.

V is a COMPLEX vector of dimension N. On entry to the procedure, it must store the values of bus voltages (excluding the slack bus) in rectangular coordinates.

BTYP is an INTEGER vector of length N of bus types (0 for load bus, 1 for generator bus). BTYP is not altered by the subroutine.

T is a REAL vector. The dimension of this vector should be declared slightly less than 4x(N+2xNTL). On return, T stores all nonzero elements of the adjoint matrix.

IRT is an INTEGER vector of length the same as vector T. On return, IRT contains the row indices of the nonzero elements stored in T.

ICT is an INTEGER vector of length the same as vector T. On return, ICT contains the column indices of the nonzero elements stored in T.

N is an INTEGER argument. It must be set by the user to NB-1. Not altered by the subroutine.

NT is an INTEGER variable. On return, NT is equal to the number of nonzero elements of the adjoint matrix.

OTPT is the number of the output unit. INTEGER parameter.

IWRITE is an INTEGER parameter that controls outputs.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 3 all printouts are suppressed,

≥ 4 sparse adjoint matrix is printed out, i.e., vectors IRT, ICT and T.

Related Software

This subroutine calls subroutine PTELT, and is called by subroutines SENSIT and STEP.

Method

This subroutine uses the method described in [2] to form a real, adjoint matrix of the power system. In this implementation, the (2xi-1)th and (2xi)th rows of the adjoint matrix are associated with the ith bus of the power system (i=1,2,...N). On return from the subroutine, the adjoint matrix is stored in a sparse form by vectors T, IRT and ICT.

Examples

The use of subroutine FORMTE is illustrated in Examples 5.4, 5.6, 5.7 and 5.8.

References

For details of the method, see also [3,4].

SUBROUTINE FORMTM (YT,JRYT,ICYT,BCS,V,BTYP,T,IRT,ICT,N,NT,OTPT,IWRITE)

Purpose

Subroutine FORMTM forms a real, mixed adjoint matrix of the power system and stores it in a sparse form.

List of Arguments

All arguments have the same names and meaning as in subroutine FORMTE, except for the dimension of vectors T, IRT and ICT, which should be declared equal to or slightly greater than 4x(N+NTL).

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

$\leq$ 3 all printouts are suppressed,

$\geq$ 4 sparse adjoint matrix is printed out, i.e., vectors T, IRT and ICT.

Related Software

This subroutine calls subroutine PTELT, and is called by subroutines SENSIT and STEP.

Method

The system of adjoint equations of the power system has the following form [2]

$$\begin{bmatrix} \underset{\sim}{G}_{LL} + \underset{\sim}{\psi}_{L1} & \underset{\sim}{G}_{LG} & -\underset{\sim}{B}_{LL} + \underset{\sim}{\psi}_{L2} & -\underset{\sim}{B}_{LG} \\ \bar{\underset{\sim}{B}}_{GL} & \bar{\underset{\sim}{B}}_{GG} - \underset{\sim}{\psi}_{G2} & \bar{\underset{\sim}{G}}_{GL} & \bar{\underset{\sim}{G}}_{GG} + \underset{\sim}{\psi}_{G1} \\ \underset{\sim}{B}_{LL} + \underset{\sim}{\psi}_{L2} & \underset{\sim}{B}_{LG} & \underset{\sim}{G}_{LL} - \underset{\sim}{\psi}_{L1} & \underset{\sim}{G}_{LG} \\ \underset{\sim}{0} & \mathrm{diag}\{V_{g2}\} & \underset{\sim}{0} & \mathrm{diag}\{V_{g1}\} \end{bmatrix} \begin{bmatrix} \hat{\underset{\sim}{V}}_{L1} \\ \hat{\underset{\sim}{V}}_{G1} \\ \hat{\underset{\sim}{V}}_{L2} \\ \hat{\underset{\sim}{V}}_{G2} \end{bmatrix} = \begin{bmatrix} \hat{\underset{\sim}{J}}_{L1} \\ \hat{\underset{\sim}{J}}_{G1} \\ \hat{\underset{\sim}{J}}_{L2} \\ \hat{\underset{\sim}{J}}_{G2} \end{bmatrix}. \tag{6.2}$$

Under the assumption of flat voltage profile $(\mathrm{diag}\{V_{g2}\}=\underset{\sim}{0})$, we may write the matrix $\hat{\underset{\sim}{T}}$ of system (6.2) as

$$\hat{\underset{\sim}{T}} = \begin{bmatrix} \underset{\sim}{G}_{LL} + \underset{\sim}{\psi}_{L1} & \underset{\sim}{G}_{LG} & -\underset{\sim}{B}_{LL} + \underset{\sim}{\psi}_{L2} & -\underset{\sim}{B}_{LG} \\ \bar{\underset{\sim}{B}}_{GL} & \bar{\underset{\sim}{B}}_{GG} - \underset{\sim}{\psi}_{G2} & \bar{\underset{\sim}{G}}_{GL} & \bar{\underset{\sim}{G}}_{GG} + \underset{\sim}{\psi}_{G1} \\ \underset{\sim}{B}_{LL} + \underset{\sim}{\psi}_{L2} & \underset{\sim}{B}_{LG} & \underset{\sim}{G}_{LL} - \underset{\sim}{\psi}_{L1} & \underset{\sim}{G}_{LG} \\ \underset{\sim}{0} & \underset{\sim}{0} & \underset{\sim}{0} & \mathrm{diag}\{V_{g1}\} \end{bmatrix}. \tag{6.3}$$

For several applications, e.g., the load flow problem, we have $\hat{\underset{\sim}{J}}_{G2}=\underset{\sim}{0}$. This and (6.3) imply that the system of adjoint equations may be written in the form

$$\begin{bmatrix} \underset{\sim}{G}_{LL} + \underset{\sim}{\psi}_{L1} & \underset{\sim}{G}_{LG} & -\underset{\sim}{B}_{LL} + \underset{\sim}{\psi}_{L2} & \underset{\sim}{0} \\ \bar{\underset{\sim}{B}}_{GL} & \bar{\underset{\sim}{B}}_{GG} - \underset{\sim}{\psi}_{G2} & \bar{\underset{\sim}{G}}_{GL} & \underset{\sim}{0} \\ \underset{\sim}{B}_{LL} + \underset{\sim}{\psi}_{L2} & \underset{\sim}{B}_{LG} & \underset{\sim}{G}_{LL} - \underset{\sim}{\psi}_{L1} & \underset{\sim}{0} \\ \underset{\sim}{0} & \underset{\sim}{0} & \underset{\sim}{0} & \mathrm{diag}\{V_{g1}\} \end{bmatrix} \begin{bmatrix} \hat{\underset{\sim}{V}}_{L1} \\ \hat{\underset{\sim}{V}}_{G1} \\ \hat{\underset{\sim}{V}}_{L2} \\ \hat{\underset{\sim}{V}}_{G2} \end{bmatrix} = \begin{bmatrix} \hat{\underset{\sim}{J}}_{L1} \\ \hat{\underset{\sim}{J}}_{G1} \\ \hat{\underset{\sim}{J}}_{L2} \\ \hat{\underset{\sim}{J}}_{G2} \end{bmatrix}. \tag{6.4}$$

In the implementation discussed, the (2xi-1)th and (2xi)th rows of the matrix of (6.4) are associated with the ith bus of the power system (i=1,2,...,N). On return from the subroutine, the adjoint marix is stored in a sparse form by vectors T, IRT and ICT.

Examples

The use of subroutine FORMTM is illustrated in Examples 5.6 and 5.7.

References

See also [2-4].

SUBROUTINE FORMU (BTYP,BVMOD,BVARG,BGP,BLP,BLQ,BCV,NB,OTPT,IWRITE)

Purpose

This subroutine forms the vector of bus control variables of the power system.

List of Arguments

BTYP is an INTEGER vector of dimension NB. On entry, it must store bus types (0 for load bus, 1 for generator bus, 2 for slack bus). Not altered by the subroutine.

BVMOD is a REAL vector of dimension NB. On entry to the subroutine, it contains the values of the moduli of bus voltages. Not altered by the subroutine.

BVARG is a REAL vector of dimension NB. On entry to the subroutine, it must store the values of the arguments of bus voltages (in radians). Not altered by the subroutine.

BGP is a REAL vector of dimension NB. On entry, it must store the values of bus generated active powers. Not altered by the subroutine.

BLP is a REAL vector of dimension NB. On entry, it contains the values of bus consumed active powers. Not altered by the subroutine.

BLQ is a REAL vector of dimension NB. On entry, it contains the values of bus consumed reactive powers. Not altered by the subroutine.

BCV is a REAL vector of dimension 2xNB. On return, it stores the values of bus control variables.

NB is an INTEGER parameter. On entry, NB must be equal to the number of buses of the power system and is not altered by the subroutine.

OTPT is the number of the output unit. INTEGER parameter.

IWRITE is an INTEGER parameter that controls outputs.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 2 all printouts are suppressed,

≥ 3 vector BCV of bus control variables is printed.

Related Software

This subroutine is called by subroutine FORMPR.

Method

The vector of bus control variables is defined as follows:

a) If the ith bus is a load bus

BCV(k)=BGP(i)-BLP(i),

BCV(ℓ)=-BLQ(i),

b) If the ith bus is a generator bus

BCV(k)=BGP(i)-BLP(i),

BCV(ℓ)=BVMOD(i),

c) If the ith bus is the slack bus

BCV(k)=BVMOD(i),

BCV(ℓ)=BVARG(i),

where k=2xi-1, ℓ=2xi and i=1,2,...NB.

Examples

The use of subroutine FORMU is illustrated in Example 5.6.

References

See also [1,23] and the description of subroutine RDAT.

SUBROUTINE FORMYT (LBINP, LBOUT, LINPG, LINPB, LG, LB, LOUTG, LOUTB, LTAP, BSTL, JRYT, ICYT, YT, NB, NTL, NYT, OTPT, IWRITE)

Purpose

This subroutine forms the nodal admittance matrix of a power system and stores it in a sparse form.

List of Arguments

LBINP, LBOUT

are INTEGER vectors of dimension NTL. On entry to the procedure, LBINP(k) and LBOUT(k) must store the indices of the buses incident with the kth transmission line (k = 1, 2, ..., NTL).

LINPG, LINPB

are REAL vectors of dimension NTL. On entry, LINPG(k) and LINPB(k) must store the input shunt conductance and susceptance of the kth transmission line (k = 1, 2, ..., NTL). These vectors are not altered by the subroutine.

LG, LB are REAL vectors of dimension NTL. On entry, LG(k) and LB(k) must store the conductance and susceptance of the kth transmission line (k = 1, 2, ..., NTL). These vectors are not altered by the subroutine.

LOUTG, LOUTB

are REAL vectors of dimension NTL. On entry, LOUTG(k) and LOUTB(k) must contain the output shunt conductance and susceptance of the kth transmission line (k = 1, 2, ..., NTL). Neither vector is altered by the subroutine.

LTAP is a REAL vector of dimension NTL. On entry to the subroutine, it must contain the line transformer ratios. LTAP is not altered by the subroutine.

BSTL is a REAL vector of dimension NB. On entry it must contain bus static loads. Not altered by the subroutine.

JRYT is an INTEGER vector of dimension (NB+1). On entry JRYT(i) stores the index of the first element of the ith row of the bus admittance matrix stored by vector YT (i = 1, 2, ..., NB). JRYT (NB+1) indicates the first vacant position in vector YT and is equal to (NYT+1). JRYT is not altered by the subroutine.

ICYT is an INTEGER vector of length 2x(NB+NTL). On return from the subroutine, the first NYT elements of ICYT contain the column indices of elements of the sparse bus admittance matrix (see the description of the method). The last NB entries of ICYT are used by the subroutine as a workspace.

YT is a COMPLEX vector of dimension NYT. On return, it contains the nonzero elements of the bus admittance matrix (see the description of the method).

NB is an INTEGER parameter, which must be set by the user to the number of buses. Not altered by the subroutine.

NTL is an INTEGER parameter, which must be set by the user to the number of transmission lines. Not altered by the subroutine.

NYT is an INTEGER parameter. On return, NYT is the number of nonzero elements of the nodal admittance matrix of power system.

OTPT is the number of the output unit. INTEGER parameter.

IWRITE is an INTEGER parameter that controls outputs.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 2 all prints are suppressed,

≥ 3 sparse bus admittance matrix is printed, i.e., vectors JRYT, ICYT, YT.

Related Software

This subroutine is called by subroutine FORMPR.

Method

This subroutine forms the nodal admittance matrix of a power system [23]. The model of a transmission line is as shown in Fig. 6.2 (see the description of subroutine READDT). Because it is assumed that transformer ratios are real numbers only then the nodal admittance matrix is symmetrical. Vectors JRYT, ICYT and YT store the nodal admittance matrix in a sparse form. Vector YT stores row by row all nonzeros of the nodal admittance matrix. The diagonal element is kept as the first element of each row. Element JRYT(k) indicates the position in vector YT of the diagonal element of the kth row of the nodal admittance matrix (k = 1, 2, ..., NB). JRYT(NB+1) indicates the first vacant position in the vector YT and is equal to NYT+1. Element ICYT(j) contains the column index of the element YT(j) (j = 1, 2, ..., NYT).

If, for example, the nodal admittance matrix is

$$
\begin{array}{c c}
 & \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\
\begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} &
\begin{bmatrix}
y_{11} & 0 & 0 & y_{14} & 0 \\
0 & y_{22} & y_{23} & 0 & 0 \\
0 & y_{23} & y_{33} & y_{34} & 0 \\
y_{14} & 0 & y_{34} & y_{44} & y_{45} \\
0 & 0 & 0 & y_{45} & y_{55}
\end{bmatrix}
\end{array} ,
$$

then

YT $= [y_{11}, y_{14}, y_{22}, y_{23}, y_{33}, y_{23}, y_{34}, y_{44}, y_{14}, y_{34}, y_{45}, y_{55}, y_{45}]$,

JRYT = [1, 3, 5, 8, 12, 14],

ICYT = [1, 4, 2, 3, 3, 2, 4, 4, 1, 3, 5, 5, 4].

Examples

The use of this subroutine is illustrated in Example 5.6.

References

For more details see also [4, 23].

SUBROUTINE LFLFD1M (NB, NLB, NYT, JRYT, ICYT, BTYP, YT, V, BCV, W, LW, ITEL, VEPS, TIMEL, MODE, IFLAG, OTPT, IWRITE)

Purpose

This subroutine is the highest level subroutine of the family of subroutines implementing the fast decoupled method for the power system load flow problem. This subroutine distributes the workspace provided by the user into a set of vectors used by the remaining subroutines. It also checks correctness of some parameters defined by the user and initiates the solution of the load flow problem.

List of Arguments

NB is an INTEGER variable which must be set by the user to the number of buses, and is not altered by the subroutine.

NLB is an INTEGER variable which must be set by the user to the number of loads, and is not altered by the subroutine.

NYT is an INTEGER variable which must be set by the user to the number of nonzero elements of the bus admittance matrix. NYT is not altered by the subroutine.

JRYT is an INTEGER vector of length NB+1. On entry, it must contain the row indices of the sparse bus admittance matrix (for details see the description of subroutines RDAT and FORMYT). JRYT is not altered by the subroutine.

ICYT is an INTEGER vector of length NYT. On entry, it must contain the column indices of elements of the sparse bus admittance matrix (for details see the description of subroutine FORMYT). ICYT is not altered by the subroutine.

BTYP is an INTEGER vector of length NB-1 of bus types (0 for load bus, 1 for generator bus). BTYP is not altered by the subroutine.

YT is a COMPLEX vector of dimension NYT. On entry, it contains nonzero elements of the bus admittance matrix of the power system. (For details, see the description of subroutine FORMYT.) Not altered by the subroutine.

V is a COMPLEX vector of dimension NB. On entry to the procedure, it must store the initial values of bus voltages (in rectangular coordinates). On return, V stores the updated values of bus voltages.

BCV is a REAL vector of dimension 2x(NB-1). On entry, it stores the scheduled values of bus control variables for the load flow problem (for details see the description of subroutine FORMU). BCV is not altered by the subroutine.

W is a REAL vector of length LW. W is used as a workspace by the set of subroutines for solving the load flow problem with the use of fast decoupled method.

LW is the length of the workspace W. It must be at least LW = max (10xNB+5xNLB+6xNYT+6xNZ2-4,6xNB+16xNLB+6xNYT+7xNZ2-4, 17xNB+7xNYT-15), where NZ2 is the integral part of (NYTx(NLB**2))/((NB-1)**2)

ITEL is an INTEGER variable. On entry, ITEL is the upper bound on the number of iterations; if ITEL<0 the number of iterations is unbounded. On return ITEL is equal to the number of iterations performed by the subroutine.

VEPS is a REAL variable. On entry, VEPS is the required accuracy of the solution. The iterative procedure terminates when the maximal value of the modulus of corrections of bus voltages is not greater than VEPS. On return, VEPS holds the attained accuracy of the solution.

TIMEL is a REAL variable. On entry to the subroutine, TIMEL is the upper bound on total iteration time (in seconds); if TIMEL$\leq$0, the iteration time is unbounded. On return, TIMEL is equal to the value of the total iteration time.

MODE is an INTEGER parameter. It must be set by the user to select the required mode of the iterative procedure

0 form and factorize approximate Jacobian matrices, and perform P-δ and Q-$|V|$ iterations,

1 perform P-δ iteration (for factorized matrix),

2 perform Q-$|V|$ iteration (for factorized matrix),

3 perform P-δ and Q-$|V|$ iteration (for factorized matrices).

IFLAG is the return flag from the subroutine. INTEGER parameter.

OTPT is the number of the output unit. INTEGER parameter.

IWRITE is an INTEGER parameter that controls outputs.

Error Diagnostics

A successful return from LFLFD1M is indicated by the value of IFLAG equal to zero. Possible nonzero values of IFLAG are

-2 incorrect usage (e.g., singular P-δ or Q-$|V|$ matrix),

-1 incorrect parameters (e.g., insufficient workspace or incorrect value of MODE),

1 limit of iterations reached,

2 limit of time reached.

Input-Output

Output data, controlled by the parameter IWRITE, may appear due to a call to subroutine LFLFDAM. For details see the description of subroutine LFLFDAM.

Common Blocks

COMMON/MDLFLF/JA1,JICN1,JIKP1,JA2,JICN2,JIKP2,JVM,JVA,NZ,NZR

where

JA1,JICN1,JIKP1,JA2,JICN2,JIKP2,JVM,JVA

indicate the locations in the workspace vector W of the first element of vectors A1,ICN1,IKP1,A2,ICN2,IKP2,VM,VA, respectively, (see the description of subroutines LFLFDAM, LFLDFBM, LFLDFDCM).

NZ is the number of nonzero elements of matrix A1.

NZR is the number of nonzero elements of matrix A2.

Related Software

This subroutine calls subroutine LFLFDAM. Subsequently, subroutines LFLFDBM, LFLFDCM and CURR are called as well as subroutines MA28A and MA28C of the package MA28.

Method

See references [4, 6, 25].

Examples

The use of the subroutine is illustrated in Examples 5.5 and 5.7.

SUBROUTINE LFLFDAM(NB,NLB,NZ,NZR,JRYT,ICYT,BTYP,YT,V,BCV,LICN1,LIRN1,
LICN2,LIRN2,A1,ICN1,IKEEP1,A2,ICN2,IKEEP2,RHS,W,VM,VA,NRB,IRN1,IW1,W1,
IRN2,IW2,W2,MODE,ITE,VEPS,TIMEX,IERR,OTPT,IWRITE)

Purpose

This subroutine implements the fast decoupled iterative method for the power system load flow problem [6] using a sparse representation of the power system bus admittance matrix and approximate Jacobian matrix, as required by the method.

List of Arguments

NB is an INTEGER variable which must be set by the user to the number of buses and is not altered by the subroutine.

NLB is an INTEGER variable which must be set by the user to the number of loads and is not altered by the subroutine.

NZ is an INTEGER parameter. On return, it is equal to the number of nonzero elements of the matrix of $P-\delta$ equations.

NZR is an INTEGER parameter. On return, it is equal to the number of nonzero elements of the matrix of $Q-|V|$ equations.

JRYT is an INTEGER vector of length NB+1. On entry, it must contain the row indices of the sparse bus admittance matrix (for details, see the description of subroutines RDAT and FORMYT). Not altered by the subroutine.

ICYT is an INTEGER vector of length NYT (see the description of LFLFD1M). On entry, it must contain the column indices of elements of the sparse bus admittance matrix (for details, see the description of subroutine FORMYT). Not altered by the subroutine.

BTYP is an INTEGER vector of dimension NB-1. On entry, it contains bus types (0 for load bus, 1 for generator bus). Not altered by the subroutine.

YT is a COMPLEX vector of dimension NYT (see the description of LFLFD1M). On entry, it stores nonzero elements of the bus admittance matrix of the power system (for details see the description of subroutine FORMYT). Not altered by the subroutine.

V is a COMPLEX vector of length NB. On entry, it must be set to the initial values of bus voltages (rectangular coordinates). On return, V holds the updated values of bus voltages.

BCV is a REAL vector of dimension 2x(NB-1). On entry, it stores the scheduled values of bus control variables for the load flow problem (for details see the description of subroutine FORMU). BCV is not altered by the subroutine.

LICN1 is an INTEGER variable which must be set by the user to the length of vectors A1 and ICN1. Should be 2 to 4 times as large as NZ. This parameter appears in the call statement to subroutine MA28A of the package MA28 [4].

LIRN1 is an INTEGER variable which must be set by the user to the length of vector IRN1. Should be equal to NZ+2x(NB-1). This parameter appears in the call statement to subroutine MA28A of the package MA28 [4].

LICN2 is an INTEGER variable which must be set by the user to the length of vector ICN2. Should be 2 to 4 times as large as NZR. This parameter appears in the call statement to subroutine MA28A of the package MA28 [4].

LIRN2 is an INTEGER variable which must be set by the user to the length of vector IRN2. Should be equal to NZR+2xNLB. This parameter appears in the call statement to subroutine ME28A of the package MA28 [4].

A1 is a REAL vector of length LICN1. If MODE=0, then on entry A1(k) (k=1,...,NZ) must store the nonzero elements of the matrix of P-δ equations. If MODE = 1 or 3 is used then A1 must be preserved from the previous call to this subroutine [4].

ICN1 is an INTEGER vector of length LICN1. If MODE=0, then on entry, ICN1(k) must hold the column index of the nonzero element stored in A1(k) (k=1,2,...,NZ). If MODE = 1 or 3 is used, then ICN1 must be preserved from the previous call to this subroutine [4].

IKEEP1 is an INTEGER vector of length 5x(NB-1). It need never be referenced by the user and should be preserved between subsequent calls to this subroutine [4].

A2 is a REAL vector of length LICN2. If MODE=0, then on entry A2(k) (k=1,2,...,NZR) must store the nonzero elements of the matrix of Q-$|V|$ equations. If MODE=1 or 2 is used, then A2 must be preserved from the previous call to this subroutine [4].

ICN2 is an INTEGER vector of length LICN2. If MODE=0 then on entry, ICN2(k) must contain the column index of the nonzero element stored in A2(k) (k=1,2,...,NZR). If MODE=1 or 2 is used, then ICN2 must be preserved from the previous call to this subroutine [4].

IKEEP2 is an INTEGER vector of length 5 x NLB. It need never be referenced by the user and should be preserved between subsequent calls to this subroutine [4].

RHS is a REAL vector of length NB-1. It is used as a workspace to store a right-hand side of the P-δ or Q-$|V|$ equations.

W is a REAL vector of length (NB-1). W is used as a workspace by subroutines LFLFDBM and LFLFDCM called by subroutine LFLFD1M.

VM is a REAL vector of length NB. On return, it contains the current values of the moduli of bus voltages.

VA is a REAL vector of length NB. On return, it contains the current values of the arguments of bus voltages.

NRB is an INTEGER vector of length NB-1 and is used as a workspace by the subroutine.

IRN1 is an INTEGER vector of length LIRN1 to store the row indices of nonzero elements of the matrix of P-δ equations. IRN1 is used as a workspace and need not be preserved for any subsequent calls to the subroutine.

IW1 is an INTEGER vector of length 8x(NB-1) used as a workspace by the called subroutine MA28A of the package MA28 [4].

W1 is a REAL vector of length NB-1. W1 is used as a workspace by the subroutine MA28A of the package MA28 [4].

IRN2 is an INTEGER vector of length LIRN2 to store the row indices of nonzero elements of the matrix of Q-$|V|$ equations. IRN2 is used as a workspace and need not to be preserved to any subsequent calls to the subroutine.

IW2 is an INTEGER vector of length 8 x NLB. IW2 is used as a workspace by the called subroutine MA28A of the package MA28 [4].

W2 is a REAL vector of length NLB. W2 is used as a workspace by the called subroutine MA28A from the package MA28 [4].

MODE is an INTEGER parameter. It must be set by the user to select the required mode of the iterative procedure

0 to form and factorize approximate Jacobian matrices, and perform the P-δ and Q-|V| iterations,

1 perform the P-δ iteration for the factorized matrix,

2 perform the Q-|V| iteration for the factorized matrix,

3 perform the P-δ and Q-|V| iterations for the factorized matrices.

ITE is an INTEGER variable. On entry, ITE is the upper bound on the number of iterations; if ITE < 0 the number of iterations is unbounded. On return, ITE is equal to the number of iterations performed by the subroutine.

VEPS is a REAL variable. On entry, VEPS is the required accuracy of the solution. The iterative procedure terminates when the maximal value of the modulus of corrections of bus voltages is not greater than VEPS. On return, VEPS is the value of the achieved accuracy.

TIMEX is a REAL variable. On entry, TIMEX is the upper bound of the total iteration time (in seconds); if TIMEX < 0, the iteration time is unbounded. On return, TIMEX is equal to the value of the total iteration time.

IERR is the return flag from the subroutine. INTEGER parameter.

OTPT is the number of the output unit. INTEGER parameter.

IWRITE is an INTEGER parameter that controls outputs.

Error Diagnostics

A successful return from LFLFDAM is indicated by the value of IERR equal to zero. Possible nonzero values of IERR are

-2 return from the subroutine MA28A unsuccessful, i.e., IFLAG < 0 (for more details see [4]),

1 limit of iterations reached,

2 limit of time reached.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 0 all printouts are suppressed,

= 1 total number of iterations ITE, return flag IERR, attained accuracy VEPS and execution time TIMEX are printed out,

= 2 the same as above, and additionally

- vector V of the solution obtained in rectangular and polar coordinates,
- iteration number, type of iteration (i.e., $P-\delta$ or $Q-|V|$), the obtained accuracy and iteration time for each iteration are printed out,

= 3 the same as above and additionally

- vector V of bus voltages for each iteration is printed out in rectangular coordinates,

≥ 4 the same as above and additionally

- vectors A1,IRN1,ICN1 and A2,IRN2,ICN2 are printed.

Related Software

This subroutine calls subroutines LFLFDBM and LFLFDCM of the package TTM1 and subroutine MA28A of MA28. This subroutine is called by subroutine LFLFD1M.

Method

Subroutine LFLFD1M applies the fast decoupled method to the solution of the power flow problem given by Stott and Alsac [6]. In this method, the exact Newton-Raphson formula is replaced by the set of two separate systems of equations

$$\Delta \underset{\sim}{P} = \underset{\sim}{A} \; \Delta \underset{\sim}{\delta} \; , \tag{6.5}$$

$$\Delta \underset{\sim}{Q} = \underset{\sim}{B} \; \Delta |\underset{\sim}{V}| \, . \tag{6.6}$$

Equation (6.5) enables us to calculate the vector $\Delta \underset{\sim}{\delta}$ of the argument corrections of bus voltages, while from equation (6.6) we obtain the vector of modulus corrections $\Delta|\underset{\sim}{V}|$ of load bus voltages. Let ε_δ be the accuracy of the last P-δ iteration (6.5) performed by the subroutine and ε_v be the accuracy of the last Q-$|V|$ iteration (6.6). The basic scheme is that one solution of the system (6.5) is followed by the solution of the system (6.6) and so on. However, if after kth iteration

$$\varepsilon_\delta \geq 2 \, \varepsilon_v \; , \tag{6.7}$$

then the (k+1)th iteration is the P-δ one. If

$$\varepsilon_v \geq 2 \, \varepsilon_\delta \tag{6.8}$$

the (k+1)th iteration is the Q-$|V|$ one.

References

A more detailed description of the method is given in [6,25]. See also [4].

SUBROUTINE LFLFDBM (N,YT,V,VM,VA,BCV,JRYT,ICYT,A1,LICN1,ICN1,IKEEP1, RHS,W,CORRA)

Purpose

This subroutine determines the right-hand side vector of the P-δ equations of the fast decoupled load flow, calculates argument corrections and updates bus voltages.

List of Arguments

N is an INTEGER variable which must be set by the user to the number of buses (excluding the slack bus) and is not altered by the subroutine.

YT is a COMPLEX vector of dimension NYT (see subroutine LFLFD1M). On entry, it must store nonzero elements of the bus admittance matrix (for more details see the description of subroutine FORMYT).

V is a COMPLEX vector of dimension N. On entry, it must be set to the initial values of bus voltages (in rectangular coordinates). On return, V stores the updated values of bus voltages.

VM is a REAL vector of dimension N. On entry, it must contain current values of bus voltage moduli. VM is not altered by the subroutine.

VA is a REAL vector of dimension N. On entry, it must contain arguments of the initial values of bus voltages. On return, VA stores updated arguments of bus voltages.

BCV is a REAL vector of dimension 2xN. On entry, it contains the scheduled values of bus control variables for the load flow problem (for more details, see the description of subroutine FORMU). BCV is not altered by the subroutine.

JRYT is an INTEGER vector of length N+2. On entry, it must contain the row indices of the sparse bus admittance matrix (for details see the description of subroutines RDAT and FORMYT). Not altered by the subroutine.

ICYT is an INTEGER vector of length NYT (see the description of LFLFD1M). On entry, it must contain the column indices of elements of the sparse bus admittance matrix (for details see the description of subroutine FORMYT). Not altered by the subroutine.

A1 is a REAL vector of length LICN1. On entry, it must store the nonzero elements in the factors of the matrix of P-δ equations (e.g., due to a previous call to LFLFDAM with MODE=0). Not altered by the subroutine [4].

LICN1 is an INTEGER variable equal to the length of vectors A1 and ICN1. It is not altered by the subroutine [4].

ICN1 is an INTEGER vector of length LICN1. On entry, it must contain the column indices of elements stored in A1 (e.g., due to a previous call to LFLFDAM with MODE=0). Not altered by the subroutine [4].

IKEEP1 is an INTEGER vector of length 5xN. It must be unchanged since the last call to LFLFDAM with MODE=0 and is not altered by the subroutine [4].

RHS is a REAL vector of length N. On return, it stores the right hand side of P-δ equations.

W is a REAL vector of length N used as a workspace.

CORRA is a REAL variable. On return, CORRA is equal to the maximal value of the modulus of the corrections of bus voltages.

Related Software

This subroutine calls function subprogram CURR of the TTM1 package, subroutine MA28C of MA28, and is called by subroutine LFLFD1M.

Method

Subroutine LFLFDBM performs one P-δ iteration of the fast decoupled method. For details see [6,25] and [4].

SUBROUTINE LFLFDCM (N,NLB,YT,V,VM,VA,BCV,JRYT,ICYT,BTYP,NRB,A2,LICN2,
ICN2,IKEEP2,RHS,W,CORRM)

Purpose

This subroutine determines the right-hand side vector of the Q-|V| equations of the fast decoupled load flow, calculates modulus corrections and updates bus voltages.

List of Arguments

N is an INTEGER variable which must be set by the user to the number of buses (excluding the slack bus) and is not altered by the subroutine.

NLB is an INTEGER variable which must be set by the user to the number of load buses and is not altered by the subroutine.

YT is a COMPLEX vector of dimension NYT (see subroutine LFLFD1M). On entry, it must contain nonzero elements of the bus admittance matrix (for more details see the description of subroutine FORMYT).

V is a COMPLEX vector of dimension N. On entry, it must be set to the initial values of bus voltages (in rectangular coordinates). On return, V stores the updated values of bus voltages.

VM is a REAL vector of dimension N. On entry, it must contain moduli of the initial values of bus voltages. On return, VM stores updated moduli of bus voltages.

VA is a REAL vector of dimension N. On entry, it must contain current values of bus voltage arguments and is not altered by the subroutine.

BCV is a REAL vector of dimension 2xN. On entry, it contains the scheduled values of bus control variables for the load flow problem (for more details see the description of subroutine FORMU). BCV is not altered by the subroutine.

JRYT is an INTEGER vector of length NB+1. On entry, it must contain the row indices of the sparse bus admittance matrix (for more details see the description of subroutines RDAT and FORMYT). Not altered by the subroutine.

ICYT is an INTEGER vector of length NYT (see the description of LFLFD1M). On entry, it must contain the column indices of elements of the sparse bus admittance matrix (for details see the description of subroutine FORMYT). Not altered by the subroutine.

BTYP is an INTEGER vector of length N of bus types (0 for load bus, 1 for generator bus). BTYP is not altered by the subroutine.

NRB is an INTEGER vector of length N. On entry, it must contain bus indices ordered in the following way: load buses, generator buses.

A2 is a REAL vector of length LICN2. On entry, it must store the nonzero elements in the factors of matrix of Q-|V| equations (e.g., due to a previous call to LFLFDAM with MODE=0). Not altered by the subroutine [4].

LICN2 is an INTEGER variable equal to the length of vectors A2 and ICN2. It is not altered by the subroutine [4].

ICN2 is an INTEGER vector of length LICN2. On entry, it must contain the column indices of elements stored in A2 (e.g., due to a previous call to LFLFDAM with MODE=0). Not altered by the subroutine [4].

IKEEP2 is an INTEGER vector of length 5xNLB. It must be unchanged since the last call to LFLFDAM with MODE=0 and is not altered by the subroutine [4].

RHS is a REAL vector of length N. On return, it stores the right hand side of the Q-|V| equations.

W is a REAL vector of length NLB used as a workspace.

CORRM is a REAL variable. On return, CORRM is equal to the maximal value of the modulus of the corrections of bus voltages.

Related Software

This subroutine calls function subprogram CURR of the TTM1 package, subroutine MA28C of MA28, and is called by subroutine LFLFD1M.

Method

Subroutine LFLFDCM performs one Q-|V| iteration of the fast decoupled method. For details see [6,25] and [4].

SUBROUTINE LFTTM (NB,NTL,JRYT,ICYT,BTYP,YT,V,BCV,W,LW,IVT,IP,ITEL,VEPS, TIMEL,MODE,IFLAG,OTPT,IWRITE)

Purpose

This subroutine is the highest level subroutine for solving the load flow problem using the Tellegen theorem method. It distributes the workspace provided by the user into a set of vectors used by the remaining subroutines, checks the correctness of some parameters defined by the user, and initiates the solution of the load flow problem.

List of Arguments

NB is an INTEGER variable which must be set by the user to the number of buses, and is not altered by the subroutine.

NTL is an INTEGER variable which must be set by the user to the number of transmission lines. Not altered by the subroutine.

JRYT is an INTEGER vector of length NB+1. On entry, it must contain the row indices of the sparse bus admittance matrix (for more details see the description of subroutines RDAT and FORMYT). JRYT is not altered by the subroutine.

ICYT is an INTEGER vector of length NB+2xNTL. On entry, it must contain the column indices of elements of the sparse bus admittance matrix (for details see the description of subroutine FORMYT). ICYT is not altered by the subroutine.

BTYP is an INTEGER vector of length NB-1 of bus types (0 for load bus, 1 for generator bus). BTYP is not altered by the subroutine.

YT is a COMPLEX vector of dimension NYT = NB+2xNTL. On entry, it contains nonzero elements of the bus admittance matrix of the power system (for details see the description of subroutine FORMYT). Not altered by the subroutine.

V is a COMPLEX vector of dimension NB. On entry to the procedure, it must contain the initial values of bus voltages in rectangular (if IP≠1) or polar (if IP=1) coordinates. If subroutine LFTTM was called with the parameter IP=1, then on return V holds the updated bus voltages in polar coordinates. The real and imaginary parts of bus voltages are available in the workspace vector W starting from the element W(JCS) and W(JSENS), respectively. If the subroutine was called with IP≠1 then on return vector V stores the updated bus voltages in rectangular coordinates. Moduli and arguments of bus voltages are available in the workspace vector W starting from the elements W(JCS) and W(JSENS), respectively.

BCV is a REAL vector of dimension 2x(NB-1). On entry, it contains the scheduled values of bus control variables for the load flow problem (for details see the description of subroutine FORMU). BCV is not altered by the subroutine.

W is a REAL vector of length LW. W is used as a workspace by the set of subroutines called by LFTTM.

LW is the length of the workspace W. It should be declared at least as LW = 70xNB+56xNTL-35.

IVT is an INTEGER variable. This parameter is to select the proper version of adjoint matrix, namely

1 exact (subroutine FORMTE is called),

2 decoupled (subroutine FORMTD is called),

3 approximate (subroutine FORMTA is called),

4 approximate decoupled (subroutine FORMTAD is called),

5 mixed (subroutine FORMTM is called).

IP is an INTEGER variable which must be set by the user

= 1 polar version of the power flow equations is used,

≠ 1 rectangular version is used.

ITEL is an INTEGER variable. On entry, ITEL is the upper bound on the number of iterations. On return, ITEL is equal to the number of iterations performed by the subroutine.

VEPS is a REAL variable. On entry to the subroutine, VEPS is the required accuracy of the solution. The iterative procedure terminates when the maximal value of the modulus of the corrections of bus voltages is not greater than VEPS. On return, VEPS is the attained accuracy of the solution.

TIMEL is a REAL variable. On entry to the subroutine, TIMEL is the upper bound on total iteration time (in seconds). On return, TIMEL is the value of the total iteration time.

MODE is an INTEGER parameter. It must be set by the user to select the required mode of the iterative procedure.

1 form and factorize into LU factors the adjoint matrix and perform ITEL iterations setting MODE=2 after completing the first iteration,

2 update and factorize the adjoint matrix using the pivotal strategy determined in the last call to the subroutine with MODE=1 and perform ITEL iterations,

3 perform ITEL iterations using the adjoint matrix factorized

in the last call to the subroutine.

IFLAG is the return flag from the subroutine. INTEGER parameter.

OTPT is the number of the output unit. INTEGER parameter.

IWRITE is an INTEGER parameter that controls outputs.

Error Diagnostics

A successful return from LFTTM is indicated by the value of IFLAG equal to zero. Possible nonzero values of IFLAG are

-3 incorrect parameter IVT,

-2 incorrect parameter MODE,

-1 insufficient workspace,

1 limit of iterations reached,

2 limit of time reached.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 0 all printouts are suppressed,

$= 1$ total number of iterations ITEL, return flag IFLAG, attained accuracy VEPS, execution time TIMEL and the vector of bus voltages at the solution in rectangular and polar coordinates are printed out,

≥ 2 more printouts may appear due to the call to subroutine STEP.

Common Blocks

COMMON/MDLFTTM/JT,JICN,JICT,JIRT,JIKEEP,JIW,JCS,JVD,JRHS,JSENS,
JDEL,JICV,JCCV,JMAX

where

JT,JICN,JICT,JIRT,JIKEEP,JIW,JCS,JVD,JRHS,JSENS,JDEL,JICV,JCCV

indicate locations in the workspace vector W of the first element of vectors T,ICN,ICT,IRT,IKEEP,IW,BCS,VD,RHS,SENS,UDEL,ICV,CCV, respectively (see also the description of subroutine STEP).

JMAX is the length of workspace used by the subroutine.

Related Software

This subroutine calls subroutines DCVARF and STEP of the package TTM1. Subsequently,subroutines DERIV,EXCT,FORMTA,FORMTAD,FORMTD,FORMTE, FORMTM,MISM and PQ are called as well as subroutines MA28A, MA28B and MA28C of MA28.

Method

See references [1-4].

Examples

The use of the subroutine is illustrated in Examples 5.4, 5.6 and 5.8.

SUBROUTINE MISM (BCV,BCS,V,BTYP,UDEL,N,IWRITE)

Purpose

This subroutine calculates the mismatches of the bus control variables.

List of Arguments

BCV is a REAL vector of dimension 2xN. On entry, it must contain the values of the bus control variables (for details, see the description of subroutine FORMU). Not altered by the subroutine.

BCS is a COMPLEX vector of dimension N. On entry, it must contain the values of the complex powers injected into the buses (for details, see the description of subroutine PQ). Not altered by the subroutine.

V is a COMPLEX vector of dimension N. On entry, it must store the values of bus voltages in rectangular coordinates. V is not altered by the subroutine.

BTYP is an INTEGER vector of dimension N. On entry, it contains bus types (0 for load bus, 1 for generator bus and 2 for slack bus). Not altered by the subroutine.

UDEL is a REAL vector of dimension 2xN. On return, it stores the mismatches of the bus control variables.

N is an INTEGER parameter. The mismatches of the control variables of the first N buses only are calculated by the subroutine. Usually, for load flow purposes, N=NB-1 (i.e., the slack bus is omitted). This parameter is not altered by the subroutine.

IWRITE is an INTEGER parameter that controls outputs.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 3 all printouts are suppressed,

≥ 4 vector UDEL of mismatches of bus control variables is printed out.

Related Software

This subroutine is called by subroutine STEP.

Method

Vector of mismatches is defined as a vector of differences of the scheduled and the current values of the bus control variables, i.e.,

a) If the jth bus is a load bus

UDEL(k)=BCV(k)-REAL(BCS(j)),

UDEL(ℓ)=BCV(ℓ)-AIMAG(BCS(j)),

b) If the jth bus is a generator bus

UDEL(k)=BCV(k)-REAL(BCS(j)),

UDEL(ℓ)=BCV(ℓ)-CABS(V(j)),

c) If the jth bus is the slack bus

UDEL(k)=BCV(k)-CABS(V(j)),

UDEL(ℓ)=BCV(ℓ)-ARG(V(j)),

where k=2xj-1, ℓ=2xj and j=1,2,..., NB.

SUBROUTINE PQ (V,YT,JRYT,ICYT,BCS,N,IWRITE)

Purpose

This subroutine calculates the values of the complex powers injected into the buses for the given vector of bus voltages.

List of Arguments

V is a COMPLEX vector of dimension NB (number of buses of the power system). On entry to the procedure, it must store the values of bus voltages in rectangular coordinates. Not altered by the subroutine.

YT is a COMPLEX vector. On entry, it contains nonzero elements of the bus admittance matrix (for details, see the description of subroutine FORMYT). Not altered by the subroutine.

JRYT is an INTEGER vector of dimension NB+1. On entry, it must contain the row indices of the sparse bus admittance matrix (for details, see the description of subroutines RDAT and FORMYT). JRYT is not altered by the subroutine.

ICYT is an INTEGER vector. On entry, it must contain the column indices of elements of the sparse bus admittance matrix (for details, see the description of subroutine FORMYT). ICYT is not altered by the subroutine.

BCS is a COMPLEX vector of dimension N. On return, it stores the complex powers injected into the buses.

N is an INTEGER parameter. The complex powers of the first N buses only are calculated by the subroutine. Usually, for load flow purposes, N=NB-1 (i.e., the slack bus is omitted), or N=NB.

This parameter is not altered by the subroutine.

IWRITE is a INTEGER parameter that controls outputs.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 2 all printouts are suppressed,

≥ 3 bus complex powers are printed out.

Related Software

This subroutine is called by subroutines STEP and SENSIT.

Method

A complex power S_i injected into the ith bus is calculated using the formula

$$S_i = V_i\left(\sum_{j=1}^{m} Y_{ij} V_j\right)^* , \quad i=1,2,\ldots,N, \qquad (6.9)$$

where

Y_{ij} is an element of the nodal admittance matrix,

V_i is the ith bus voltage,

m is the number of buses of the power system,

* denotes the complex conjugate.

References

See also [4,23].

SUBROUTINE PTELT (T,NT,R,IRT,ICT,IR,IC)

Purpose

The aim of this subroutine is to place a nonzero element of the adjoint matrix into the vector T and to store its row and column indices in vectors IRT and ICT.

List of Arguments

T — is a REAL vector used as a stack of nonzero elements of the adjoint matrix. Updated by the subroutine.

NT — is an INTEGER parameter used as a pointer of vector T. On entry, NT must be equal to the current last entry to vector T. On return, NT is increased by 1.

R — is a REAL argument. On entry, it stores the value of a current nonzero element of the adjoint matrix. Not altered by the subroutine.

IRT — is an INTEGER vector to store the row indices of nonzero elements of the adjoint matrix. Updated by the subroutine.

ICT — is an INTEGER vector to store the column indices of nonzero elements of the adjoint matrix. Updated by the subroutine.

IR — is an INTEGER argument. On entry, it must store the row index of the current nonzero element. Not altered by the subroutine.

IC — is an INTEGER argument. On entry, it must store the column index of the current nonzero element. Not altered by the subroutine.

Related Software

This subroutine is called by subroutines FORMTA, FORMTAD, FORMTD, FORMTE and FORMTM.

Method

A nonzero element of the adjoint matrix with the value R, and the row and the column indices IR and IC, is added to the stack T of nonzeros of the adjoint matrix. Stack pointer NT is increased by 1. The original row and column indices are stored in vectors IRT and ICT, i.e., on return from the subroutine elements T(NT), IRT(NT) and ICT(NT), store the value, the row index, and the column index of the element considered.

SUBROUTINE RDAT (LBINP,LBOUT,LINPG,LINPB,LG,LB,LOUTG,LOUTB,LTAP,BNR,
BTYP,BVMOD,BVARG,BGP,BLP,BLQ,BSTL,JRYT,NB,NTL,NLB,INPT,IWRITE)

Purpose

This subroutine reads input data describing the power system from a file created by subroutine FORMTDF and preprocesses this data.

List of Arguments

LBINP, LBOUT

are INTEGER vectors of dimension NTL. On return, LBINP(k) and LBOUT(k) store the indices of buses incident with the kth transmission line (k=1,2,...,NTL).

LINPG, LINPB

are REAL vectors of dimension NTL. On return, LINPG(k) and LINPB(k) store the input shunt conductance and susceptance of the kth transmission line (k=1,2,...,NTL).

LG, LB are REAL vectors of dimension NTL. On return, LG(k) and LB(k) store the conductance and susceptance of the kth transmission line (k=1,2,...,NTL).

LOUTG, LOUTB

are REAL vectors of dimension NTL. On return, LOUTG(k) and LOUTB(k) store the output shunt conductance and susceptance of the kth transmission line (k=1,2,...,NTL).

LTAP is a REAL vector of dimension NTL to store the line transformer ratios.

BNR is an INTEGER vector of dimension NB. If the original index of the ith bus appearing on the input is ℓ, then on return from the subroutine, $BNR(\ell)=i$ (i=1,2,...,NB).

BTYP is an INTEGER vector of dimension NB of bus types (0 for load bus, 1 for generator bus and 2 for slack bus).

BVMOD is a REAL vector of dimension NB. On return, it stores the scheduled values of the moduli of bus voltages.

BVARG is a REAL vector of dimension NB. On return, it stores the values of the arguments of bus voltages.

BGP is a REAL vector of dimension NB. On return, it contains the values of bus generated active powers.

BLP is a REAL vector of dimension NB. On return, it contains the values of bus consumed active powers.

BLQ is a REAL vector of dimension NB. On return, it contains the values of bus consumed reactive powers.

BSTL is a REAL vector of dimension NB. On return, it stores the values of bus static loads.

JRYT is an INTEGER vector of dimension NB+1, defined in the following way: JRYT(1)=1, $JYRT(\ell+1)=JRYT(\ell)+d_\ell$, where d_ℓ is the number of buses connected with the ℓth bus, including the bus itself (ℓ=1,2,..., NB).

NB is an INTEGER parameter. On return, NB is equal to the total number of buses of the power system.

NTL is an INTEGER parameter. On return, NTL is equal to the number of transmission lines of the power system.

NLB is an INTEGER parameter. On return, NLB is equal to the number of load buses of the power system.

INPT is an INTEGER parameter. It must be set by the user to the number of the input unit associated with the file containing the input data.

IWRITE is an INTEGER parameter that controls outputs.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

- ≤ 0 all printouts are suppressed,
- $= 1$ data identifier, the number of buses and the number of transmission lines of the power system are printed out,
- ≥ 2 the same as above, and additionally, data describing buses and transmission lines is printed out.

Related Software

This subroutine is called by subroutine FORMPR.

Method

This subroutine reads data describing the power system from a file assigned to the INPUT unit in the PROGRAM statement. The data file must have a structure acceptable to TTM1.

Data describing the power system is partially reordered by the subroutine. On input, the ordering of line data and bus data is arbitrary.

On return from the subroutine, all vectors containing bus data (i.e., BNR, BTYP, BVMOD, BVARG, BGP, BLP, BLQ, BSTL) are ordered according to the original bus indices.

It is assumed that a transmission line has the representation as in Fig. 6.2 (see the description of subroutine READDT), and that the slack bus has the highest index.

Examples

The use of subroutine RDAT is illustrated in Example 5.6.

SUBROUTINE READDT (LBINP,LBOUT,LINPG,LINPB,LR,LX,LOUTG,LOUTB,LTAP,BNR,
BTYP,BVMOD,BVARG,BGP,BLP,BLQ,BSTL,NB,NTL,INPT)

Purpose

This subroutine reads input data describing the power system from an unformatted file using package PWRDD [8].

List of Arguments

LBINP, LBOUT

are INTEGER vectors of dimension NTL. On return, LBINP(k) and LBOUT(k) are the indices of buses incident with the kth tranmission line (k=1,2,...,NTL).

LINPG, LINPB

are REAL vectors of dimension NTL. On return, LINPG(k) and LINPB(k) contain the input shunt conductance and susceptance of the kth transmission line (k=1,2,...,NTL).

LR, LX are REAL vectors of dimension NTL. On return, LR(k) and LX(k) store the resistance and the reactance of the kth transmission line (k=1,2,...,NTL).

LOUTG, LOUTB

are REAL vectors of dimension NTL. On return, LOUTG(k) and LOUTB(k) store the output shunt conductance and susceptance of the kth transmission line (k=1,2,...,NTL).

LTAP is a REAL vector of dimension NTL to store the line transformer ratios.

BNR is an INTEGER vector of dimension NB. On return, BNR(i) is the original index of the ith bus appearing on the input.

BTYP is an INTEGER vector of dimension NB of bus types (0 for load bus, 1 for generator bus and 2 for slack bus).

BVMOD is a REAL vector of dimension NB. On return, it stores the values of the moduli of bus voltages.

BVARG is a REAL vector of dimension NB. On return, it contains the values of the arguments of bus voltages (in radians).

BGP is a REAL vector of dimension NB. On return, it contains the values of bus generated active powers.

BLP is a REAL vector of dimension NB. On return, it contains the values of bus consumed active powers.

BLQ is a REAL vector of dimension NB. On return, it contains the values of bus consumed reactive powers.

BSTL is a REAL vector of dimension NB. On return, it contains the values of bus static loads.

NB is an INTEGER parameter. On return, NB is equal to the total number of buses of the power system.

NTL is an INTEGER parameter. On return, NTL is equal to the number of transmission lines of the power system.

INPT is an INTEGER parameter. It must be set by the user to the number of the input unit.

Error Diagnostics

Input data is retrieved by READDT by means of calls to appropriate subroutines of the package PWRDD. If input data is incorrect, then the program terminates and the following message is printed out:

INCORRECT INPUT DATA. STOP "N1". IFLAG="N2"

Possible values of N1 are the following:

1 unsuccessful return from subroutine DD00DF of PWRDD (data file inaccessible),

2 unsuccessful return from subroutine DD00DN of PWRDD (structure of input data file incorrect),

3 unsuccessful return from subroutine DD11DR of PWRDD (structure of the logical record containing the transmission-line data incorrect),

4 unsuccessful return from subroutine DD11DR of PWRDD (structure of logical record containing the bus data incorrect).

N2 is the value of the return flag from the previously called subroutine before the program terminated [8].

Related Software

This subroutine calls subroutines DD00DF, DD00DN, DD11DR, DD11GS, DD11IN and DD11RN of the package PWRDD [8].

Method

This subroutine reads the data describing the power system from a file assigned to the INPUT unit in the program statement. Data is read using the package PWRDD and then stored. Only the data needed by the package TTM1 is retrieved.

It is assumed that the model of a transmission line is as in Fig. 6.2. It is also assumed that the buses in the data file are numbered consecutively from 1 to NB and that the slack bus has the highest index. The bus ordering is arbitrary. Vectors BNR, BTYP, BVMOD, BVARG, BGP, BLP, BLQ and BSTL preserves the bus ordering of the input file. The value of BNR(i) is equal to the original index of the ith bus.

Examples

The use of subroutine READDT is illustrated in Example 5.5.

References

For more details of the method, see also [7-9].

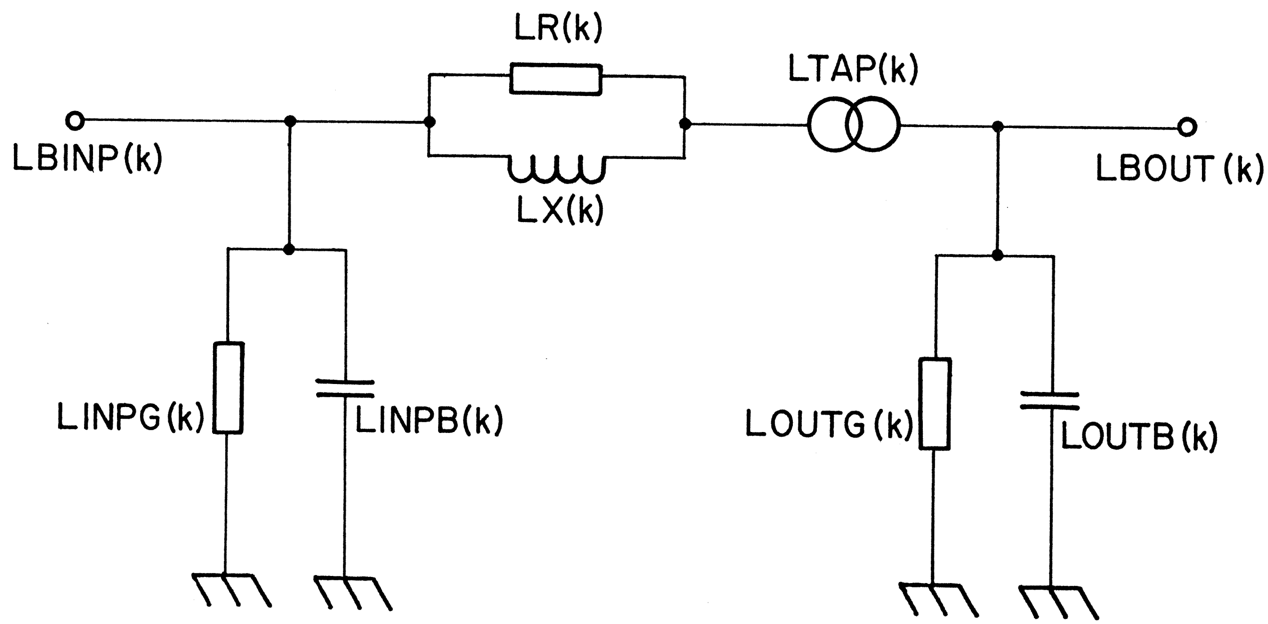

Fig. 6.2 Transmission line model used in subroutine READDT.

SUBROUTINE SENSIT (LBINP,LBOUT,YT,JRYT,ICYT,V,BTYP,BCS,RHST,CCV,ICV,PDR, SENS,T,IRT,ICT,ICN,IKEEP,IW,NB,NCV,IVT,MODE,IFLAG,OTPT,IWRITE)

Purpose

This subroutine forms the adjoint equations and calculates sensitivities of a real function of the power system state and control variables with respect to specified control variables.

List of Arguments

LBINP, LBOUT

are INTEGER vectors of dimension NTL (number of transmission lines). One entry to the subroutine, LBINP(k) and LBOUT(k) must store the indices of buses incident with the kth transmission line (k=1,2,...,NTL). These vectors are not altered by the subroutine.

YT is a COMPLEX vector of dimension NB+2xNTL. On entry to the subroutine, it stores all nonzero elements of the nodal admittance matrix (for details, see the description of subroutine FORMYT). Not altered by the subroutine.

JRYT is an INTEGER vector of dimension NB+1. On entry, it must contain the row indices of the sparse bus admittance matrix (for details, see the description of subroutines RDAT and FORMYT). Not altered by the subroutine.

ICYT is an INTEGER vector of dimension NB+2xNTL. On entry, it must contain the column indices of elements of the sparse bus admittance matrix (for details, see the description of subroutine FORMYT). Not altered by the subroutine.

V is a COMPLEX vector of length NB. On entry, it must contain bus voltages in rectangular coordinates. Not altered by the subroutine.

BTYP is an INTEGER vector of dimension NB-1 of bus types (0 for load bus and 1 for generator bus). BTYP is not altered by the subroutine.

BCS is a COMPLEX vector of dimension NB-1. It is used as a workspace by the subroutine.

RHST is a REAL vector of dimension 2xNB. On entry, elements RHST(1), RHST(2), ..., RHST(2xNB-2) must store the right-hand side vector of the adjoint equations. On exit, these elements store the solution of the adjoint equations. Elements RHST(2xNB-1) and RHST(2xNB) should be set to the real and imaginary parts of the adjoint voltage of the slack bus.

CCV is an INTEGER vector of dimension NCV. On entry, CCV(j) (j=1,2,...,NCV) must store the code number of the jth control variable of the power system (for details, see the description of subroutine DERIV). Not altered by the subroutine.

ICV is an INTEGER vector of dimension NCV. On entry, ICV(j) (j=1,2,...,NCV) must contain the index of the bus or of the transmission line associated with the jth control variable (for details, see the description of subroutine DERIV). ICV is not altered by the subroutine.

PDR is a COMPLEX vector of length NCT, where NCT is the number of line-type control variables, i.e., variables with code 1, 2, 3, 4, 5, 6 or 11. On entry, PDR(i), (i=1,2,...,NCT) should be equal to twice the value of the formal partial derivative of a function with respect to current of the element associated with the ith line-type variable appearing in CCV (for details, see the description of subroutine DERIV).

SENS is a REAL vector of dimension NCV. On exit, it stores sensitivities of a function with respect to the control variables defined by vectors CCV and ICV.

T is a REAL vector of dimension LICN. LICN should be at least 3 times as large as the number of nonzero elements of the adjoint matrix. If parameter MODE was set to 1 or 2, then on return, T stores nonzero elements of the factors of the adjoint matrix. If parameter MODE is set by the user to 3, then on entry, T must remain unchanged since the last call to one of the subroutines SENSIT, STEP or LFTTM and is not altered by SENSIT[4].

IRT is an INTEGER vector of dimension NT to store the column indices of nonzero elements of the adjoint matrix. NT is the number of nonzeros. IRT is used as a workspace and need not be preserved for any subsequent calls to the subroutine.

ICT is an INTEGER vector of dimension NT to store the column indices of nonzero elements of the adjoint matrix. NT is the number of nonzeros. ICT is used as a workspace and need not be preserved for any subsequent calls to the subroutine.

ICN is an INTEGER vector of dimension LICN. If parameter MODE was set up to 1, then on return ICN stores the column indices of the factors of the adjoint matrix. If parameter MODE is set up by the user to 2 or 3, then on entry, ICN must remain unchanged since the last call to one of the subroutines SENSIT, STEP or

LFTTM and is not altered by SENSIT [4].

IKEEP is an INTEGER vector of length 10x(NB-1). It need never be referenced by the user, and should be preserved between subsequent calls to the subroutine [4].

IW is an INTEGER vector of length 16x(NB-1). IW is used as a workspace by the called subroutines MA28A, MA28B and MA28C of the package MA28 [4]. It need not be preserved for any subsequent calls to the subroutine.

NB is an INTEGER variable, which must be set by the user to the number of buses. Not altered by the subroutine.

NCV is an INTEGER variable, which must be set by the user to the number of control variables. Not altered by the subroutine.

IVT is an INTEGER variable. This parameter is to select one of the following versions of the adjoint matrix

1 exact (subroutine FORMTE is called),

2 decoupled (subroutine FORMTD is called),

3 approximate (subroutine FORMTA is called),

4 approximate decoupled (subroutine FORMTAD is called),

5 mixed (subroutine FORMTM is called).

MODE is an INTEGER variable. It must be set up by the user. If MODE=3, it is assumed that the adjoint matrix is not changed structurally and numerically since the last call to subroutine LFTTM, SENSIT or STEP. Vectors T and ICN must be preserved by the user since the previous call to one of these subroutines. If MODE=2, then it is assumed that the adjoint equations are not going to be changed structurally since the last call to LFTTM, SENSIT or STEP. Vector ICN must be preserved since the previous call to one of these subroutines. In the other cases, the adjoint matrix is formulated in subroutine SENSIT from the beginning.

IFLAG is the return flag from the subroutine. INTEGER parameter.

OTPT is an INTEGER parameter equal to the number of the output unit.

IWRITE is an INTEGER parameter that controls outputs.

Error Diagnostics

A successful return from SENSIT is indicated by the value of IFLAG equal to zero. Possible nonzero values of IFLAG are

- 3 incorrect parameter IVT,

- 2 incorrect parameter MODE.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

≤ 2 all printouts are suppressed,

= 3 parameters MODE, IVT and the vector SENS of sensitivities are printed out,

≥ 4 more printouts appear due to a call to subroutines FORMTA, FORMTAD, FORMTD, FORMTE, FORMTM and PQ.

Common Blocks

COMMON/TOO/NT,LICN,LIRN

where

NT is the number of nonzero elements of the adjoint matrix.

LICN = 3xNT is the assumed minimal length of vectors T and ICN.

LIRN = NT+NR is the assumed minimal length of vector IRT (NR - number of adjoint equations).

Related Software

This subroutine calls subroutines DERIV, FORMTA, FORMTAD, FORMTD, FORMTM, FORMTM and PQ.

Examples

The use of the subroutine is shown in Examples 5.7 and 5.8.

Method

This subroutine forms the set of adjoint equations, solves them using a sparse matrix technique and calculates sensitivities of a real function of the power system state and control variables with respect to the control variables.

References

For details of the method, see [3,4].

SUBROUTINE STEP (YT,JRYT,ICYT,V,VD,BTYP,BCV,BCS,UDEL,T,IRT,ICT,ICN,RHST, IKEEP,IW,CCVF,ICVF,SENS,NB,IVT,MODE,IP,EPS,OTPT,IWRITE)

Purpose

This subroutine performs one iteration of the solution of the load flow problem using the adjoint network concept to calculate all needed gradients.

List of Arguments

YT is a COMPLEX vector of dimension NYT=NB+2xNTL, where NTL is the number of transmission lines. On entry, it stores nonzero elements of the bus admittance matrix (for details, see the description of subroutine FORMYT). Not altered by the subroutine.

JRYT is an INTEGER vector of length NB+1. On entry, it must contain the row indices of the sparse bus admittance matrix (for details, see the description of subroutines RDAT and FORMYT). JRYT is not altered by the subroutine.

ICYT is an INTEGER vector of length NYT. On entry, it must contain the column indices of elements of the sparse bus admittance matrix (for details, see the description of subroutine FORMYT). ICYT is not altered by the subroutine.

V is a COMPLEX vector of dimension NB. On entry to the procedure, it must contain the initial values of bus voltages (in polar coordinates if parameter IP is set by the user to 1, or in the rectangular if IP≠1). On return, V stores the updated values of bus voltages (polar coordinates for IP=1, rectangular coordinates for IP$\neq$1.)

VD is a COMPLEX vector of dimension NB-1. On return, it stores the corrections of bus voltages.

BTYP is an INTEGER vector of length NB-1 of bus types (0 for load bus and 1 for generator bus). BTYP is not altered by the subroutine.

BCV is a REAL vector of dimension 2x(NB-1). On entry, it contains the values of bus control variables for the load flow problem (for details, see the description of subroutine FORMU). BCV is not altered by the subroutine.

BCS is a COMPLEX vector of dimension NB-1. On return, it stores the bus complex powers, calculated for the initial bus voltages.

UDEL is a REAL vector of dimension 2x(NB-1). On return, it stores mismatches of the bus control variables (for details, see the description of subroutine MISM).

T is a REAL vector of dimension LICN. LICN should be at least 3 times as large as the number of nonzero elements of the adjoint matrix. If parameter MODE was set up to 1 or 2, then on return, T stores nonzero elements of factors of the adjoint matrix. If parameter MODE is set by the user to 3, then on entry, T must remain unchanged since the previous call to one of the subroutines SENSIT, STEP or LFTTM and is not altered by STEP [4].

IRT is an INTEGER vector of length LIRN to store the row indices of nonzero elements of the adjoint matrix. LIRN should be at least as large as the number of nonzero elements of the adjoint matrix, plus the number of adjoint equations. IRT is used as a workspace and need not be preserved for any subsequent calls to the subroutine [4].

ICT is an INTEGER vector of dimension NT to store the column indices of nonzero elements of the adjoint matrix. NT is the number of nonzeros. ICT is used as a workspace and need not be preserved for any subsequent calls to the subroutine.

ICN is an INTEGER vector of dimension LICN. If parameter MODE is set to 1, then on return, ICN stores the column indices of the factors of the adjoint matrix. If parameter MODE is set by the user to 2 or 3, then on entry, ICN must remain unchanged since the previous call to one of the subroutines SENSIT, STEP or LFTTM and is not altered by STEP [4].

RHST is a REAL vector of dimension 2xNB. It is used by the subroutine as a workspace to store the right-hand side and the solution vectors of the adjoint equations.

IKEEP is an INTEGER vector of length 10x(NB-1). It need never be referenced by the user, and should be preserved between subsequent calls to this subroutine [4].

IW is an INTEGER vector of length 16x(NB-1). IW is used as a workspace by called subroutines MA28A, MA28B and MA28C of the package MA28 [4]. It need not be preserved for any subsequent calls to the subroutine.

CCVF is an INTEGER vector of length 2x(NB-1). On entry, it must contain the codes of the control variables for the load flow problem (for more details, see the description of subroutine DCVARF). CCFV is not altered by the subroutine.

ICVF is an INTEGER of length 2x(NB-1). On entry, ICVF(k) must store the index of a bus associated with the kth control variable (for more details, see the description of subroutine DCVARF). ICVF is not altered by the subroutine.

SENS is a REAL vector of dimension 2x(NB-1). It is used by the subroutine as a workspace vector to store the sensitivity of a state variable with respect to the control variables.

NB is an INTEGER variable, which must be set by the user to the number of buses. Not altered by the subroutine.

IVT is an INTEGER variable. This parameter is to select the version of adjoint matrix

1 exact (subroutine FORMTE is called),

2 decoupled (subroutine FORMTD is called),

3 approximate (subroutine FORMTA is called),

4 approximate decoupled (subroutine FORMTAD is called),

5 mixed (subroutine FORMTM is called).

MODE is an INTEGER variable. It must be set by the user. If MODE=3, then it is assumed that the adjoint matrix is not structurally and numerically changed since the previous call to subroutine LFTTM, STEP or SENSIT. Vectors T, ICN must be preserved since the last call to one of these subroutines. If MODE=2, then it is assumed that the adjoint equations are not going to be changed structurally since the previous call to subroutine LFTTM, STEP or SENSIT. Vector ICN must be preserved since the last call to one of these subroutines. In other cases, the adjoint matrix is formulated in subroutine STEP from the beginning [4].

IP is an INTEGER variable which must be set by the user

= 1 polar version of the load flow equations is used,

≠ 1 rectangular version is used.

EPS is a REAL variable. On return, EPS holds the achieved accuracy of the iteration, i.e., the maximum value of the modulus of the corrections of the bus voltages.

OTPT is an INTEGER parameter equal to the number of the output unit.

IWRITE is an INTEGER parameter that controls outputs.

Input-Output

Output data is controlled by the parameter IWRITE. Possible values of IWRITE are

$\leq$ 1 all printouts are suppressed,

= 2 results of iteration are printed out, i.e., parameters MODE, IVT, IP and vector V of bus voltages. If IP=1, then V is in polar coordinates. If IP≠1, then V is in rectangular coordiantes.

$\geq$ 3 more printouts may appear due to calls to other subroutines.

Related Software

This subroutine calls subroutines DERIV, EXCT, FORMTA, FORMTAD, FORMTD, FORMTE, FORMTM, MISM, PQ and subroutines MA28A, MA28B and MA28C of the package MA28. Subroutine STEP is called by subroutine LFTTM.

Common Blocks

COMMON/TOO/NT,LICN,LIRN

where

NT is the number of nonzero elements of the adjoint matrix.

LICN = 3xNT is the assumed minimal length of vectors T, ICN.

LIRN = NT+NR is the assumed minimal length of vector IRT (NR - number of adjoint equations).

Method

Subroutine STEP implements the Tellegen theorem method to perform one iteration of the solution of the power flow equations [1,2,3]. Mismatches of control variables and sensitivities of state variables w.r.t. control variables are calculated in order to determine the bus voltage corrections.

As state variables are taken bus voltages in polar or rectangular coordinates, depending on the version of power flow equations (polar or rectangular). As control variables are taken load bus active and reactive powers, active powers and moduli of voltages of generators.

The number of needed voltage corrections is equal to $2xn_L+n_G$ when the polar formulation of load flow equations is used, or to $2xn_L+2xn_G$ when the rectangular formulation is used (n_L - number of load buses, n_G - number of generator buses). This implies that the iteration time is smaller when the polar formulation is applied. A sparse matrix technique is used [4] to solve the system of adjoint equations.

References

For details of the method, see also [1-4].

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