SIMULATION OPTIMIZATION SYSTEMS
Research Laboratory

XLF3 - A FORTRAN IMPLEMENTATION OF THE COMPLEX LAGRANGIAN METHOD TO POWER SYSTEM ANALYSIS AND DESIGN

J.W. Bandler, M.A. El-Kady, H.K. Grewal
and J. Wojciechowski

SOS-83-18-U

October 1983

McMASTER UNIVERSITY
Hamilton, Canada L8S 4L7
Department of Electrical and Computer Engineering

XLF3 - A FORTRAN IMPLEMENTATION OF THE COMPLEX LAGRANGIAN METHOD TO POWER SYSTEM ANALYSIS AND DESIGN

J.W. Bandler, M.A. El-Kady, H.K. Grewal
and J. Wojciechowski

SOS-83-18-U

October 1983

XLF3 - A FORTRAN IMPLEMENTATION OF THE COMPLEX LAGRANGIAN METHOD TO POWER SYSTEM ANALYSIS AND DESIGN

J.W. Bandler, M.A. El-Kady, H.K. Grewal and J. Wojciechowski

Abstract

XLF3 is a package of twelve Fortran subroutines which have been designed to solve steady-state power flow problems in compact complex mode. The power systems incorporating phase shifting transformers and tap-changing-under-load transformers have been considered. The load flow solution has been obtained by complex Newton method and the Harwell package ME28 has been employed to represent and solve appropriate sets of sparse linear equations. The complex Lagrangian method, exploiting the Jacobian at the load flow solution has been used to evaluate sensitivities of real network functions. The package and user-oriented documentation have been developed for the CDC 170/815 system with the NOS 2.1 - 580/577 operating system and the Fortran Extended (FTN) version 4.8 compiler. Some numerical examples on a 6-bus, 23-bus, 26-bus and the IEEE 118-bus systems have been presented in order to illustrate the use of XLF3 package.

This work was supported by the Natural Sciences and Engineering Research Council of Canada under Grants A7239, A1708 and G0647.

The authors are with the Simulation Optimization Systems Research Laboratory and the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada L8S 4L7.

M.A. El-Kady is also with Ontario Hydro, Toronto, Canada.

J. Wojciechowski is on leave from the Institute of Electronics Fundamentals, Technical University of Warsaw, Warsaw, Poland.

I. INTRODUCTION

This report elaborates a user-oriented description of the package XLF3 comprising Fortran subroutines to solve the steady-state power flow problems. The package implements Newton's algorithm in complex mode [1] in a manner similar to previous packages [2,3]. The complex Lagrangian method [3,4] is used to evaluate sensitivities of a real function with respect to network control variables including the adjustable parameters of phase-shifting and tap-changing-under-load transformers [5,6].

The package has been modularized into 12 subroutines which may be called from the user's main program in an appropriate sequence depending upon the nature of the problem. The data files for some of the power systems [7] available in a formatted style are read and preprocessed by the data handling subroutines. The nodal admittance matrix is formulated using the transmission network data and is stored in a sparse form [8]. The bus data is treated by using recently developed compact complex notation [9] and the perturbed load flow equations are developed which are solved by Newton's iterative method, using the Harwell package ME28 [10]. The load flow solution is obtained in rectangular and/or polar mode and can be stored in a special format, which can be readily used for further analysis. In order to evaluate sensitivities of a function, the user has to supply the derivatives of the function of interest with respect to complex bus voltages and complex conjugate of bus voltages. These derivatives form the right-hand-side vector of an adjoint system, whose matrix of coefficients is the transpose of the Jacobian available at the load flow solution. The adjoint system is solved by the package ME28 and the solution is directly used in sensitivity calculations. The sensitivity expressions for various control variables [11] have been implemented in the package and some numerical results have been displayed for a 6-bus, 23-bus, 26-bus and the IEEE 118-bus systems.

The XLF3 package and its documentation have been prepared for the CDC 170/815 system with the NOS 2.1 580/577 operating system and the Fortran Extended (FTN) version 4.8 compiler. At McMaster University, the package is available as a permanent indirect group file LIBXLF3 under the charge RJWBAND and exists as a library of binary relocatable subroutines. The user must access the Harwell package ME28 available under the same charge as a permanent group file LIBCHSM. The general sequence of NOS commands to use the XLF3 package are as follows:

```
/GET, LIBXLF3, LIBCHSM/GR.

/LIBRARY, LIBXLF3, LIBCHSM.
```

II. GENERAL DESCRIPTION AND INFORMATION

The mathematical formulation of the load flow problem results in a system of nonlinear algebraic equations, called the power flow equations [12], which can be established in a bus or loop frame of reference. The bus frame of reference employs the nodal admittance matrix [5,13] and requires minimal computer storage. This approach also motivates the exploitation of network sparsity by ordered elimination and skillful programming [8,14].

The power flow equations are basically expressed in the complex form and the variables in these equations are generally functions of the network states and control parameters of the power system under consideration. These equations are usually separated into real and imaginary parts [12], but the compact complex notation developed by Bandler and El-Kady facilitates the formulation in complex mode, and the conjugate notation exploited by them directly handles the complex functions and constraints. These concepts are briefly described in this section and the theoretical results have been implemented in the package XLF3.

The power flow equations are written in the admittance form [15] as

$$\underset{\sim}{Y}_T \underset{\sim}{V}_M = \underset{\sim}{I}_M \quad , \tag{1}$$

where $\underset{\sim}{Y}_T$ is the nodal admittance matrix, $\underset{\sim}{V}_M$ and $\underset{\sim}{I}_M$ are column vectors of the bus voltages and bus currents, respectively.

The bus loading equations are also written in the matrix form

$$\underset{\sim}{E}_M^* \underset{\sim}{I}_M = \underset{\sim}{S}_M^* \quad , \tag{2}$$

where $\underset{\sim}{E}_M$ is a diagonal matrix of components of $\underset{\sim}{V}_M$ in corresponding order, and $\underset{\sim}{S}_M$ is a vector of the bus powers given by

$$\underset{\sim}{S}_M \triangleq \underset{\sim}{P}_M + j\underset{\sim}{Q}_M \quad . \tag{3}$$

Substituting (1) into (2), we get

$$\underset{\sim}{E}_M^* \underset{\sim}{Y}_T \underset{\sim}{V}_M = \underset{\sim}{S}_M^* \quad , \tag{4}$$

that is a system of nonlinear equations representing the typical load flow problem.

We write (4) in the perturbed form

$$\underset{\sim}{K}^S \delta\underset{\sim}{V}_M + \underset{\sim}{\bar{K}}^S \delta\underset{\sim}{V}_M^* = \delta\underset{\sim}{S}_M^* - \underset{\sim}{E}_M^* \delta\underset{\sim}{Y}_T \underset{\sim}{V}_M \quad , \tag{5}$$

where $\delta\underset{\sim}{V}_M$, $\delta\underset{\sim}{V}_M^*$, $\delta\underset{\sim}{S}_M^*$, and $\delta\underset{\sim}{Y}_T$ represent first-order changes of $\underset{\sim}{V}_M$, $\underset{\sim}{V}_M^*$, $\underset{\sim}{S}_M^*$ and $\underset{\sim}{Y}_T$, respectively,

$$\underset{\sim}{K}^S \triangleq \underset{\sim}{E}_M^* \underset{\sim}{Y}_T,$$

and $\underset{\sim}{\bar{K}}^S$ is a diagonal matrix of components of $\underset{\sim}{I}_M$. For a load flow problem, the nodal admittance matrix is kept constant, and (5) is expressed in the form

$$\underset{\sim}{K}^S \delta\underset{\sim}{V}_M + \underset{\sim}{\bar{K}}^S \delta\underset{\sim}{V}_M^* = \delta\underset{\sim}{S}_M^* \quad , \tag{6}$$

representing a set of linear equations, which can be solved by the Newton-Raphson iterative method. We use the complex conjugate notation and write (6) in the consistent form

$$\begin{bmatrix} \underset{\sim}{K}^S & \underset{\sim}{\bar{K}}^S \\ \underset{\sim}{\bar{K}}^{S*} & \underset{\sim}{K}^{S*} \end{bmatrix} \begin{bmatrix} \delta\underset{\sim}{V}_M \\ \delta\underset{\sim}{V}_M^* \end{bmatrix} = \begin{bmatrix} \delta\underset{\sim}{S}_M^* \\ \delta\underset{\sim}{S}_M \end{bmatrix} \quad . \tag{7}$$

The system of complex equations (7) is equivalent to the more compact system of complex equations

$$\tilde{\underset{\sim}{K}}^{S}\ \delta \underset{\sim M}{V} = \tilde{\underset{\sim}{d}}^{S} \quad , \tag{8}$$

where $\tilde{\underset{\sim}{K}}^{S}$ and $\tilde{\underset{\sim}{d}}^{S}$ are, respectively, given by

$$\tilde{\underset{\sim}{K}}^{S} = \bar{\underset{\sim}{K}}^{S*} - \underset{\sim}{K}^{S*}\ (\bar{\underset{\sim}{K}}^{S})^{-1}\ \underset{\sim}{K}^{S} \tag{9}$$

and

$$\tilde{\underset{\sim}{d}}^{S} = \delta \underset{\sim M}{S} - \underset{\sim}{K}^{S*}\ (\bar{\underset{\sim}{K}}^{S})^{-1}\ \delta \underset{\sim M}{S}^{*} \quad . \tag{10}$$

In the jth iteration of the Newton-Raphson method in the complex mode, the system of equations (8) are solved with

$$\delta \underset{\sim M}{V} = \underset{\sim M}{V}^{j+1} - \underset{\sim M}{V}^{j} \quad , \tag{11}$$

$$\delta \underset{\sim M}{S}^{*} = \underset{\sim M}{S}^{*}\ (\text{scheduled})\ - \underset{\sim}{K}^{S}\ \underset{\sim M}{V}^{j} \tag{12}$$

and the matrices $\underset{\sim}{K}^{S}$ and $\bar{\underset{\sim}{K}}^{S}$ are calculated at $\underset{\sim M}{V}^{j}$. The iterations are carried on until the required accuracy is obtained.

Apart from solving the load flow problem, the package is capable of providing the sensitivities of a general function f with respect to power network controls. The two types of network control variables, namely, bus-type control varibles and transmission-element control variables, are presented in Table II. The generalized, complex Lagrangian method [4], which exploits the Jacobian matrix of the load flow solution, is employed to derive the first-order changes and gradients of functions of interest. These generalized sensitivity expressions are displayed in Table III and have been implemented in this package to obtain the exact sensitivities. The user may refer [11] for explanation and derivation of the theoretical results.

The package XLF3 can be used in conjunction with gradient-type optimization packages [16]. In order to make XLF3 more general, few other subroutines have been included, for example, subroutines to read and preprocess the data describing a power system. The package uses a sparse representation of the bus admittance matrix, the matrix of perturbed load flow equations and the matrix of coefficients of the adjoint system. The subroutines of the Harwell package ME28 are called in appropriate manner to solve sets of linear equations in complex mode.

III. STRUCTURE OF THE PACKAGE

The package has been modularized into 12 Fortran subroutines. The overall structure of the package is shown in Fig. 1. The Harwell package ME28 [10] is called by XLF3 package in order to solve a set of linear equations in complex mode.

There is no one general entry to the package XLF3. The user may orient his program to call any of the package subroutines, after making the package accessible for his program. The sequence of call statements in the main program should be appropriate to the user's problem and to obtain various network sensitivities, it is user's responsibility to provide the derivatives of the function of interest with respect to complex bus voltages and their complex conjugates. For a real function f, the user can use

$$\frac{\partial f}{\partial \underset{\sim}{V}_M^*} = \left(\frac{\partial f}{\partial \underset{\sim}{V}_M}\right)^* \quad . \tag{13}$$

The subroutines of the package can be divided into four categories:

- subroutines for data handling
- subroutines for formulating load flow problem
- subroutines for solving load flow problem
- subroutines for sensitivity calculations.

These groups of subroutines are shown in Fig. 2.

The data file describing the power system under investigation, is assumed to be a formatted one, with the standard structure acceptable by the recent package [17]. Subroutine RDATAX reads the data from such a file and is capable of reading the complex turns ratio of the phase-shifting transformers. Subroutine FORMDTX creates a standard data file

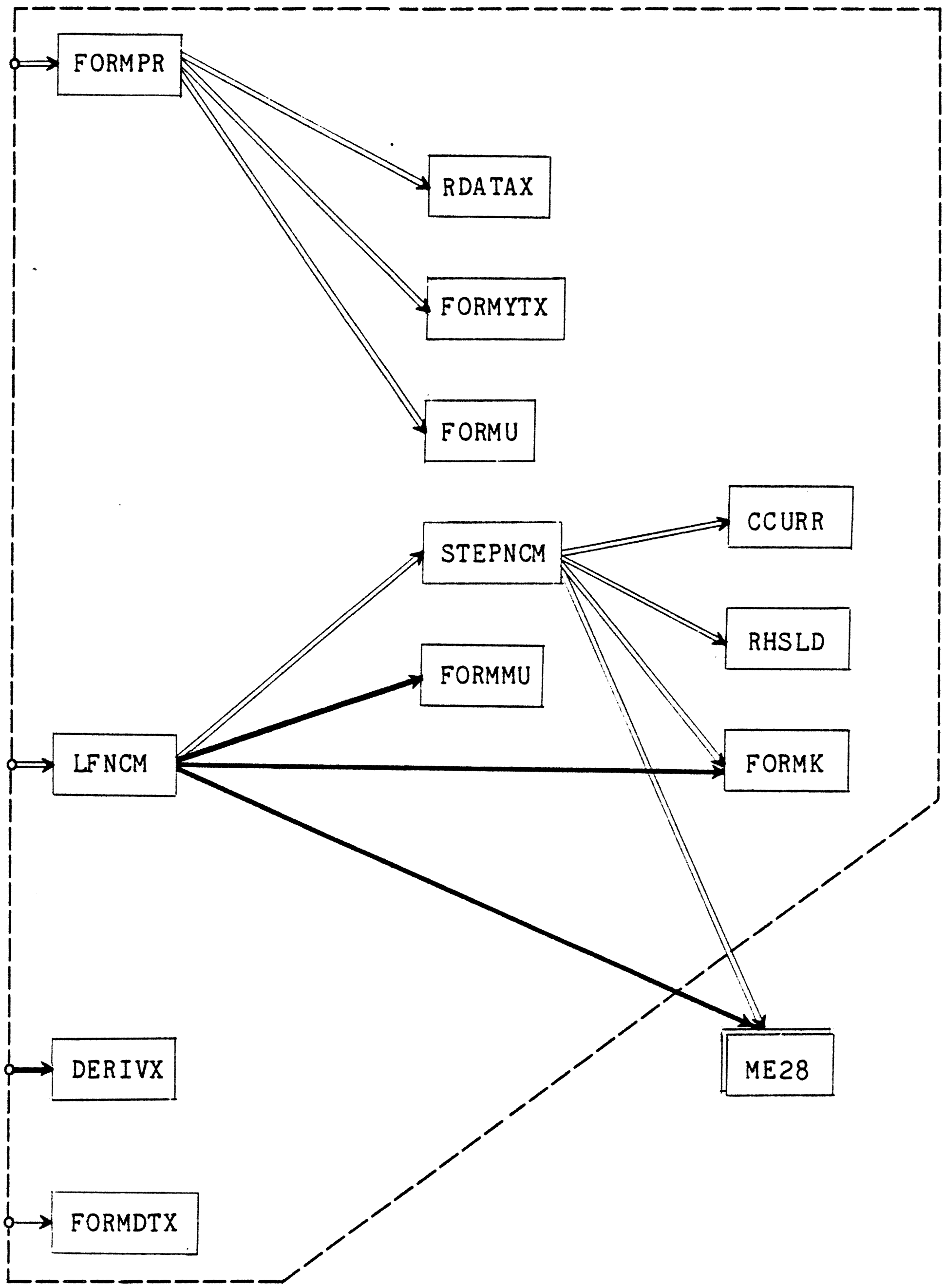
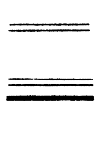


Fig. 1 Structure of the XLF3 package.



load flow solution

load flow solution and sensitivity evaluation

for creating a formatted data file

from the load flow solution.

The nodal admittance matrix of the power system is formulated by subroutine FORMYTX in a sparse form, and proper care is taken to establish the entries corresponding to installation of phase-shifting transformers. Example 1 illustrates a sample power system, where a large (impractical) value of phase angle ϕ has been used. Subroutine FORMU forms the vector of bus control variables, i.e., the right-hand-side of the power flow equations. A higher level subroutine FORMPR is also provided which calls the three subroutines and formulates the load flow problem as shown in Fig. 2b. Example 2 illustrates the use of subroutine FORMPR.

The next group of subroutines shown in Fig. 2c, solves the load flow problem using complex Newton's method, described in Section II. Subroutine RHSLD calculates the right-hand-side vector of (8), and subroutine CCURR evaluates the current injected into a bus. Subroutine FORMK formulates the matrix of perturbed load flow equations (7) and stores this matrix of coefficients in a sparse form. The higher level subroutine STEPNCM performs one Newton iteration using the Harwell package ME28 and terminates the process whenever any of the following limit is reached:

VEPS - required accuracy of the solution

ITEL - limit of Newton iterations

TIMEL - limit of iteration time

and the cause of termination is indicated by IFLAG on exit from the highest level subroutine LFNCM. Example 3 describes the functioning of subroutines FORMPR and LFNCM, and displays a summary of every Newton iteration.

FORMDTX RDATAX

Fig. 2a Data handling subroutines

FORMPR FORMU FORMYTX

Fig. 2b Load flow problem formulating subroutines

CCURR FORMK LFNCM

RHSLD STEPNCM

Fig. 2c Load flow solving subroutines

DERIVX FORMMU

Fig. 2d Subroutines for sensitivity calculations

Fig. 2 Functional groups of the XLF3 package
(alphabetically arranged)

In order to use the package for sensitivity evaluation, the user has to provide subroutine FORMMU in his main program. This subroutine is used to supply the right-hand-side vector of the adjoint system, and the transpose of the Jacobian at the load flow is used as the matrix of coefficients for the system. Subroutine DERIVX is called in the main program by the user, indicating the control variable description and the required sensitivity is determined for the function under consideration. Table II summarizes the various control variables and their respective codes with which the package is familiar. Examples 3, 4 and 5 illustrate the use of this subroutine in a straightforward manner. This group of subroutines is shown in Fig. 2d.

The package has some additional powerful features which are explained in the next section, and the subroutines are listed in alphabetical order in Table I.

TABLE I

LIST OF SUBROUTINES OF THE XLF3 PACKAGE

	Subroutine	Number of lines (source text)	Description (page)	Listing (page of [18])
1	CCURR	20	13	17
2	DERIVX	80	15	18
3	FORMDTX	39	20	6
4	FORMK	99	23	15
5	FORMMU	18	26	20
6	FORMPR	55	29	4
7	FORMU	45	33	5
8	FORMYTX	61	36	7
9	LFNCM	167	40	10
10	RDATAX	85	45	8
11	RHSLD	38	49	14
12	STEPNCM	47	51	13

IV. DESCRIPTION OF SUBROUTINES

The formal description of the subroutines of the package XLF3 is given in this section.

COMPLEX FUNCTION CCURR (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 FORMYTX). 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 RDATAX and FORMYTX). 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 FORMYTX). 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 subroutine RHSLD.

Method

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

$$I_i = \sum_{j=1}^{m} Y_{ij} V_j , \qquad (14)$$

where

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

V_j is the jth bus voltage,

m is total number of buses of the power system.

References

See also [5,13].

SUBROUTINE DERIVX(LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,L1,L2,DSX,NTL,ICODE, DF1,DF2)

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

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

LTAP is a COMPLEX vector of dimension NTL. On entry to the subroutine, LTAP(k) must contain the complex turns ratio of the kth transmission element (k=1,2,...,NTL). The vector is not altered by the subroutine.

BTYP is an INTEGER vector of dimension NB of bus types (0 for load bus, 1 for generator bus and 2 for slack bus). It is not altered by the subroutine.

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

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.

L1,L2 are INTEGER variables. On entry they must indicate the indices of the buses between which the transmission element is inserted (for ICODE > 2) and for bus-type control variable only L1, the bus index need to be specified.

DSX is a COMPLEX vector of dimension NB. On entry it must furnish the bus voltages of the adjoint system in rectangular coordinates (for details refer subroutine LFNCM). DSX is not altered by the subroutine.

NTL is an INTEGER parameter. On entry it must indicate the number of transmission elements. It is not altered by the subroutine.

ICODE is an INTEGER variable. On entry, it must indicate the code number of the control variable of the power system (for details refer Table I). ICODE is not altered by the subroutine.

DF1 is a REAL variable. On exit, it contains sensitivity of the function with respect to A-type of control variables (see Table II).

DF2 is a REAL variable. On exit, it contains sensitivity of the function with respect to B-type of control variables (see Table II).

Related Software

This subroutine is called by the user in his main program.

TABLE II

CODE NUMBER OF CONTROL VARIABLES

Description	A-type variable	B-type variable	Code number
Load bus	P_l	Q_l	1
Generator bus	P_g	$\|V_g\|$	1
Slack bus	V_n	-	1
Shunt admittance at a bus	G_{i0}	B_{i0}	2
Line admittance of a transmission line	G_{ij}	B_{ij}	3
Phase-shifting transformer turns ratio			
1. Rectangular coordinates	a_1	a_2	4
2. Polar coordinates	$\|a\|$	ϕ	5
TCUL* transformer turns ratio	a	-	6
Transformer internal impedance	R_t	X_t	7

*TCUL stands for tap-changing-under-load.

TABLE III

FORMULAS FOR SENSITIVITY CALCULATIONS

Variable code number	Bus index/indices	Sensitivity formula for DF1 and DF2
1	i	$\hat{V}_i^{*}$
2	i	† $-\hat{V}_i^R V_i^* V_i$
3	i, j	† $(V_i - V_j)(V_j^* \hat{V}_j^R - V_i^* \hat{V}_i^R)$
4	i, j	† $\frac{V_i}{a^2}\left[\frac{2V_i^* \operatorname{Re}\{\frac{\hat{V}_i^R}{Z_t}\}}{a^*} - V_j^* \left(\frac{\hat{V}_i^{*R}}{Z_t^*} + \frac{\hat{V}_j^R}{Z_t}\right)\right]$
5		$\frac{a_1 \frac{df}{da_1} + a_2 \frac{df}{da_2}}{\lvert a \rvert}, \quad - a_2 \frac{df}{da_1} + a_1 \frac{df}{da_2}$
6		$\frac{df}{da_1}$
7		† $\frac{1}{Z_t^2}\left(\frac{V_i}{a} - V_j\right)\left(\frac{\hat{V}_i^R V_i^*}{a^*} - \hat{V}_j^R V_j^*\right)$

$$† \quad \underset{\sim}{\hat{V}}^R = \begin{bmatrix} \underset{\sim}{\hat{V}}_L \\ \underset{\sim}{\hat{V}}_{G1} \\ 0 \end{bmatrix}$$

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 the complex Lagrangian method.

Subroutine DERIVX calculates sensitivities by using the formulas for sensitivity calculation shown in Table III. The code numbers for various variables are given in Table II.

References

See also [3,4,9,11].

SUBROUTINE FORMDTX (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 XLF3.

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 element (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 element (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 element (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 element (k=1,2,...,NTL). Neither vectors are altered by the subroutine.

LTAP is a COMPLEX vector of dimension NTL. On entry to the subroutine, it must retain the complex turns ratios of transmission elements. 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 elements 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 FORMDTX transfers data describing the power system into the file assigned to the unit OTPT in the PROGRAM statement.

References

See also [17].

SUBROUTINE FORMK (YT,JRTY,ICYT,BTYP,V,AI,AK,IRK,ICK,N,NK,OTPT,IWRITE)

Purpose

This subroutine formulates a matrix of perturbed load flow equations 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 elements of the power system). On entry, it stores the nonzero elements of the bus admittance matrix (for details, see the description of subroutine FORMTYX). 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 surbroutines RDATAX and FORMYTX). JRTY 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 FORMYTX). 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). 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.

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

AK — is a COMPLEX vector. The dimension of this vector should be declared NB. On return AK stores all nonzero elements of the matrix of coefficients of pertrubed load flow equations.

IRK — is an INTEGER vector of length same as vector AK. On return IRK contains the row indices of the nonzero elements stored in AK.

ICK — is an INTEGER vector of length same as vector AK. On return ICK contains the column indices of the nonzero elements stored in AK.

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

NK — is an INTEGER variable. On return, NK 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 controled by the parameter IWRITE. Possible values of IWRITE are

< 3 all printouts are suppressed,

≥ 3 sparse adjoint matrix is printed out, i.e., vectors IRK, ICK and AK.

Related Software

This subroutine is called by subroutines LFNCM and STEPNCM.

Method

This subroutine uses the method described in [9] to formulate the matrix of perturbed load flow equations 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 matrix of coefficients is stored in a sparse form by vectors AK, IRK and ICK.

References

For details of the method, see also [4,9].

SUBROUTINE FORMMU (V,AI,NB,DS,DSN,IDER,YT,JRYT,ICYT,BTYP,NYT,OTPT)

Purpose

This subroutine forms right-hand-side vector of the adjoint equations and is used to calculate sensitivities of a real power network function with respect to specified control variables.

List of Arguments

V is a COMPLEX vector of dimension N. On entry it must store values of bus voltage (except the slack bus) in rectangular coordinates.

AI is a COMPLEX vector of dimension NB-1. On entry, it must store the injected currents (in rectangular coordinates). Not altered by the subroutine.

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

DS is a COMPLEX vector of dimension 2*N and is calculated in this subroutine. It is user's responsibility to supply the derivatives of function of interest w.r.t. $\underset{\sim}{V}$ and $\underset{\sim}{V}^*$.

DSN is a real quantity, indicating the partial derivative of function considered w.r.t. slack bus voltage.

IDER is an integer equal to zero if sensitivities are not to be calculated and equals M if sensitivities are required for the Mth function.

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 FORMYTX). 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 RDATAX and FORMYTX). 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 FORMYTX). Not altered by the subroutine.

BTYP is an INTEGER vector of dimension NB. On entry, it must contain bus types and is not altered by this subroutine.

NYT is an INTEGER equal to non-zero elements in YT. Not altered by the subroutine.

OTPT is an INTEGER parameter equal to the number of the output unit.

Error Diagnostics

An unsuccessful return from FORMMU is indicated by the value of IAMUF equal to -1, indicating that the subroutine is missing in user's program.

Common Blocks

COMMON/AMUF/IAMUF

Related Software

This subroutine is called in subroutine LFNCM.

Examples

The use of the subroutine is shown in Examples 3, 4 and 5.

Method

This subroutine forms the right-hand-side vector of adjoint equations in order to calculate sensitivities of a real network function with respect to specified control variables.

References

For details of the method, see [3,4,9].

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 element (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 FORMYTX).

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 RDATAX and FORMYTX).

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 FORMYTX).

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 elements. On return, NTL is equal to the number of transmission elements.

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

$\neq 1$ 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 RDATAX).

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 RDATAX. For details, see the description of subroutine RDATAX.

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

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 RDATAX, FORMYTX, and FORMU, respectively. For more details see the description of subroutines RDATAX, FORMPR and FORMU.

Vector V is the vector of initial bus voltages defined as

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

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

Examples

The use of subroutine FORMPR is shown in Examples 2,3 and 4.

References

For details of the method, see also [7,9,11].

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 Examples 2-5.

References

See also [7,9,11] and the description of subroutine RDATAX.

SUBROUTINE FORMYTX (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 element (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 element (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 element (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 element (k = 1, 2, ..., NTL). Neither vector is altered by the subroutine.

LTAP is a COMPLEX vector of dimension NTL. On entry to the subroutine, it must contain the transformation ratios of the transmission elements. 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 elements. 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 incorporating phase-shifting transformers having complex turns ratio [5]. 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

$$
\begin{array}{c|ccccc|}
 & 1 & 2 & 3 & 4 & 5 \\
1 & Y_{11} & 0 & 0 & Y_{14} & 0 \\
2 & 0 & Y_{22} & Y_{23} & 0 & 0 \\
3 & 0 & Y_{32} & Y_{33} & Y_{34} & 0 \\
4 & Y_{41} & 0 & Y_{43} & Y_{44} & Y_{45} \\
5 & 0 & 0 & 0 & Y_{54} & Y_{55}
\end{array},
$$

then

YT = [Y_{11}, Y_{14}, Y_{22}, Y_{23}, Y_{33}, Y_{32}, Y_{34}, Y_{44}, Y_{41}, Y_{43}, Y_{45}, Y_{55}, Y_{54}],

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 1.

References

For more details see also [5,6,8,13].

SUBROUTINE LFNCM (NB,NLB,NYT,JRYT,ICYT,BTYP,YT,V,BCV,W,LW,DSX,DSN,IFLAG, OTPT,IWRITE)

Purpose

This subroutine is the highest level subroutine for solving the load flow problem using the complex Newton 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.

NLB is an INTEGER variable. On entry, it indicates the number of load buses, and is not altered by the subroutine.

NYT is an INTEGER variable. On entry it indicates the number of nonzero elements in the bus admittance matrix. 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 RDATAX and FORMYTX). 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 FORMYTX). 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 FORMYTX). 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.

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 LFNCM.

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

DSX is a COMPLEX vector of dimension 2x(NB-1). On exit, it contains solution vector of the adjoint system, when IDER ≠ 0.

DSN is a real quantity, indicating adjoint voltage associated with the slack bus.

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 LFNCM is indicated by the value of IFLAG equal to zero. Possible nonzero values of IFLAG are

-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 STEPNCM.

Common Blocks

COMMON/MDLFNCM/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 STEPNCM).

JMAX is the length of workspace used by the subroutine.

COMMON/XLF3ID/ITEL,TIMEL,VEPS,IDER,IADJ,MODE

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. (Default value = 10)

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. (Default value = 2)

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. (Default value = 10^{-6})

IDER is an INTEGER variable. It is zero when sensitivities are not required and equals M if sensitivities of Mth function are to be calculated. (Default value = 0)

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.

Related Software

This subroutine calls subroutines FORMMU,FORMK,STEPNCM of the package XLF3. Subsequently, subroutines RHSLD,CCURR and FORMK are called as well as subroutines ME28A, ME28B and ME28C of ME28.

Method

See references [1,2,3,9].

Examples

The use of the subroutine is illustrated in Examples (2-5).

SUBROUTINE RDATAX (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 FORMDTX 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 element (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 element (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 element (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 element (k=1,2,...,NTL).

LTAP is a COMPLEX vector of dimension NTL to store complex turns ratio of the transmission elements.

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(ℓ)=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(ℓ+1)=JRYT(ℓ)+d_ℓ, 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 elements 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 elements of the power system are printed out,

≥ 2 the same as above, and additionally, data describing buses and transmission elements 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 XLF3.

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.

Examples

The use of subroutine RDATAX is illustrated in Example 1.

SUBROUTINE RHSLD (JRYT,ICYT,BTYP,YT,V,BCV,DS,AI,N,OTPT,IWRITE)

Purpose

This subroutine calculates the right-hand-side vector of perturbed load flow equations and the bus injected currents.

List of Arguments

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 RDATAX and FORMYTX). 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 FORMYTX). 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 FORMYTX.) 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.

DS is a COMPLEX vector of length 2*N. This vector contains the correction in the complex powers.

AI a COMPLEX vector the length of N. It must store the injected currents.

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 DS of mismatches of bus complex control variables is printed out.

Related Software

This subroutine is called by subroutine STEPNCM.

Method

See references [1,4 and 9].

SUBROUTINE STEPNCM (YT,JRYT,ICYT,V,AI,BTYP,BCV,AK,IRK,ICK,ICN,DS,IKEEP, IW,WR,NB,IH,EPS,OTPT,IWRITE)

Purpose

This subroutine performs one iteration of the solution of the load flow problem using the complex Newton's method.

List of Arguments

YT is a COMPLEX vector of dimension NYT=NB+2xNTL, where NTL is the number of transmission elements. On entry, it stores nonzero elements of the bus admittance matrix (for details, see the description of subroutine FORMYTX). 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 RDATAX and FORMYTX). 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 FORMYTX). 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 the rectangular coordinates). On return, V stores the updated values of bus voltages in rectangular coordinates.

AI is a COMPLEX vector of dimension NB-1. On return, it stores the injected currents.

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.

AK is a COMPLEX vector of dimension LICK. LICK should be at least 3 times as large as the number of nonzero elements of the matrix of perturbed load flow equations in complex mode. If parameter MODE was set up to 1 or 2, then on return, AK stores nonzero elements of factors of the matrix. If parameter MODE is set by the user to 3, then on entry, AK must remain unchanged since the previous call to one of the subroutines STEPNCM or LFNCM and is not altered by STEPNCM [7].

IRK is an INTEGER vector of length LIRK to store the row indices of nonzero elements of the adjoint matrix. LIRK should be at least as large as the number of nonzero elements of the adjoint matrix, plus the number of adjoint equations. IRK is used as a workspace and need not be preserved for any subsequent calls to the subroutine.

ICK is an INTEGER vector of dimension NZ to store the column indices of nonzero elements of the adjoint matrix. NZ is the number of nonzeros. ICK 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 STEPNCM or LFNCM and is not altered by STEPNCM.

DS is a COMPLEX 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 perturbed load flow 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 ME28A, ME28B and ME28C of the package ME28. 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.

IH is an INTEGER variable. It must be set by the user. If MODE=3, then it is assumed that the matrix of perturbed load flow equations is not structurally and numerically changed since the previous call to subroutine LFNCM or STEPNCM. Vectors AK, ICN must be preserved since the last call to one of these subroutines. If MODE=2, then it is assumed that the perturbed equations are not going to be changed structurally since the previous call to subroutine LFNCM or STEPNCM. Vector ICN must be preserved since the last call to one of these subroutines. In other cases, the matrix of interest is formulated in subroutine STEPNCM from the beginning.

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

≤ 1 all printouts are suppressed,

= 2 results of iteration are printed out, i.e., parameters MODE, and vector V of bus voltages.

≥ 3 more printouts may appear due to calls to other subroutines.

Related Software

This subroutine calls subroutines RHSLD, FORMK, and subroutines ME28A, ME28B and ME28C of the package ME28. Subroutine STEPNCM is called by subroutine LFNCM.

Common Blocks

COMMON/LAK/NZ,LICK,LIRK

where

NZ = the number of nonzero elements of the matrix of coefficients.

LICK = 3xNT is the assumed minimal length of vectors AK, ICN.

LIRK = NT+NR is the assumed minimal length of vector IRK (NR - number of adjoint equations).

Method

Subroutine STEPNCM implements the Newton method in complex mode to perform one iteration of the solution of the power flow equations [1,2,3]. Mismatches of control variables and the matrix of perturbed load flow equations are calculated in order to determine the bus voltage corrections.

The complex state variables are taken as the complex power at buses and special notation is used to incorporate the corresponding generator bus variables [4,9]. A sparse matrix technique is used [8,10] to solve the system of load flow equations.

References

For details of the method, see also [1,9].

VI. EXAMPLES

Example 1

A 6-bus sample power system, shown in Fig. 3 (page 57) is considered in this example. The system comprises 3 load buses, 2 generator buses and one slack bus. There are 7 transmission lines and one phase shifting transformer in the power network. The phase-shifting transformer is inserted between buses 1 and 4, and has turns ratio $a = 0.8 + j0.6$ or $1\angle 36.8^{\circ}$, however, the practical value of ϕ is within $\pm 10^{\circ}$.

In this example, the data for the system is read by subroutine RDATAX and the nodal admittance matrix is formulated by subroutine FORMYTX. The computer program and results are given on pages 58-60. Note that the nodal admittance matrix is unsymmetrical (i.e., $Y_{14} \neq Y_{41}$ due to the presence of the phase-shifting transformer, having $\phi \neq 0$).

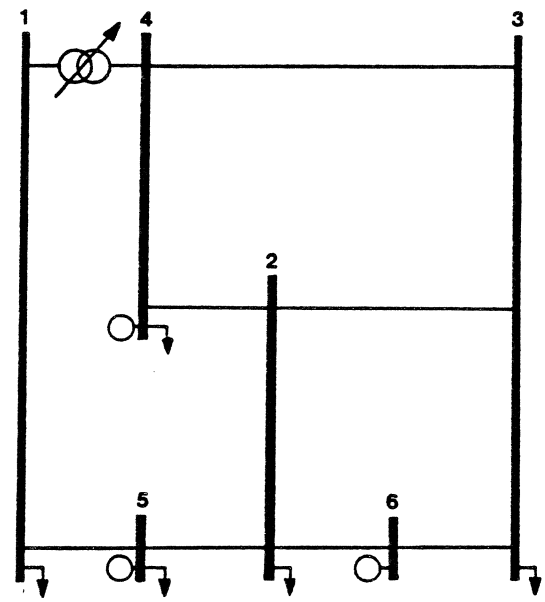


Fig. 3 6-bus sample power system

```
      PROGRAM EXMPL1(DATA6,OUTPUT,TAPE4=DATA6,TAPE6=OUTPUT)
C
C     THIS IS THE MAIN PROGRAM FOR FORMULATING AND STORING THE
C     BUS ADMITTANCE MATRIX OF 6-BUS SAMPLE SYSTEM USING
C     THE XLF3 PACKAGE
C
      INTEGER BTYP(10),JRYT(10),ICYT(50),LBINP(8),LBOUT(8),BNR(6),OTPT
      REAL LINPG(8),LINPB(8),LG(8),LB(8),BLQ(6),BSTL(6),LOUTG(8),LOUTB(8
     1),BVMOD(6),BVARG(6),BGP(6),BLP(6),LR(8),LX(8)
      COMPLEX YT(40),Z,LTAP(8)
      INPT=4
      OTPT=6
      NB=6
      NTL=8
      IWRITE=0
C
      CALL RDATAX (LBINP,LBOUT,LINPG,LINPB,LG,LB,LOUTG,LOUTB,LTAP,BNR,BT
     1YP,BVMOD,BVARG,BGP,BLP,BLQ,BSTL,JRYT,NB,NTL,NLB,INPT,OTPT,IWRITE)
C
C     WRITING THE TRANSMISSION DATA OF THE SYSTEM
C
      WRITE (OTPT,40) NB
      DO 10 I=1,NTL
      Z=1/CMPLX(LG(I),LB(I))
      LR(I)=REAL(Z)
      LX(I)=AIMAG(Z)
      WRITE (OTPT,50) LBINP(I),LBOUT(I),LR(I),LX(I),LTAP(I)
   10 CONTINUE
      WRITE (OTPT,60)
C
C     FORMULATING AND WRITING THE BUS ADMITTANCE MATRIX
C
      IWRITE=3
      CALL FORMYTX (LBINP,LBOUT,LINPG,LINPB,LG,LB,LOUTG,LOUTB,LTAP,BSTL,
     1JRYT,ICYT,YT,NB,NTL,NYT,OTPT,IWRITE)
      WRITE (OTPT,60)
C
C     WRITING THE STORAGE SCHEME OF THE BUS ADMITTANCE MATRIX
C
      WRITE (OTPT,70)
      N1=NB+1
      DO 30 I=1,NYT
      IF (I.GT.N1) GO TO 20
      WRITE (OTPT,80) I,JRYT(I),ICYT(I),YT(I)
      GO TO 30
   20 WRITE (OTPT,90) I,ICYT(I),YT(I)
   30 CONTINUE
      WRITE (OTPT,60)
      STOP
   40 FORMAT (///,6X,"TRANSMISSION NETWORK DATA OF",I3,"-BUS SAMPLE",1X,
     1"SYSTEM",//,1X,66("-"),//,4X,"ELEMENT",8X,"RESISTANCE",8X,"REACTAN
     2CE",7X,"TURNS RATIO",//,4X,7("-"),8X,10("-"),8X,9("-"),7X,11("-"),
     3/)
   50 FORMAT (4X,I3,",",I1,5X,2(F13.6,5X),3X,2(F5.2,1X))
   60 FORMAT (/,1X,66("-"),//)
   70 FORMAT (//,9X,"STORAGE SCHEME OF THE BUS ADMITTANCE MATRIX",//,1X,
     166("-"),//,5X,"INDEX",4X,"JRYT",4X,"ICYT",10X,"REAL(YT)",8X,"IMAG
     2INARY(YT)",//,5X,5("-"),2(4X,4("-")),10X,8("-"),8X,13("-"),/)
   80 FORMAT (5X,I3,6X,I3,5X,I3,5X,2(1X,F13.6,5X))
   90 FORMAT (5X,I3,14X,I3,5X,2(1X,F13.6,5X))
      END
```

TRANSMISSION NETWORK DATA OF 6-BUS SAMPLE SYSTEM

ELEMENT	RESISTANCE	REACTANCE	TURNS RATIO	
1,4	.050000	.200000	.80	.60
1,5	.025000	.100000	1.00	0.00
2,3	.100000	.400000	1.00	0.00
2,4	.100000	.400000	1.00	0.00
2,5	.050000	.200000	1.00	0.00
2,6	.018750	.075000	1.00	0.00
3,4	.150000	.600000	1.00	0.00
3,6	.037500	.150000	1.00	0.00

BUS ADMITTANCE MATRIX YT

THE SEQUENCE IN EACH ROW IS: COLUMN INDEX, REAL(YT), IMAG(YT)

BUS NO. 1						
	1:	3.529412	-14.117647	4:	-3.764706	3.058824
	5:	-2.352941	9.411765			
BUS NO. 2						
	2:	5.490196	-21.960784	3:	-.588235	2.352941
	4:	-.588235	2.352941	5:	-1.176471	4.705882
	6:	-3.137255	12.549020			
BUS NO. 3						
	3:	2.549020	-10.196078	2:	-.588235	2.352941
	4:	-.392157	1.568627	6:	-1.568627	6.274510
BUS NO. 4						
	4:	2.156863	-8.627451	1:	1.882353	4.470588
	2:	-.588235	2.352941	3:	-.392157	1.568627
BUS NO. 5						
	5:	3.529412	-14.117647	1:	-2.352941	9.411765
	2:	-1.176471	4.705882			
BUS NO. 6						
	6:	4.705882	-18.823529	2:	-3.137255	12.549020
	3:	-1.568627	6.274510			

STORAGE SCHEME OF THE BUS ADMITTANCE MATRIX

INDEX	JRYT	ICYT	REAL(YT)	IMAGINARY(YT)
1	1	1	3.529412	-14.117647
2	4	4	-3.764706	3.058824
3	9	5	-2.352941	9.411765
4	13	2	5.490196	-21.960784
5	17	3	-.588235	2.352941
6	20	4	-.588235	2.352941
7	23	5	-1.176471	4.705882
8		6	-3.137255	12.549020
9		3	2.549020	-10.196078
10		2	-.588235	2.352941
11		4	-.392157	1.568627
12		6	-1.568627	6.274510
13		4	2.156863	-8.627451
14		1	1.882353	4.470588
15		2	-.588235	2.352941
16		3	-.392157	1.568627
17		5	3.529412	-14.117647
18		1	-2.352941	9.411765
19		2	-1.176471	4.705882
20		6	4.705882	-18.823529
21		2	-3.137255	12.549020
22		3	-1.568627	6.274510

Example 2

The load flow problem of a 6-bus power system, shown in Fig. 4 (page 62) is formulated by subroutine FORMPR. The flat-voltage profile is supplied by a formatted group file BØØ6FVA. The problem is solved by subroutine LFNCM in complex mode. The mode of operation is selected (MODE=1) in which the matrix of perturbed load flow equations is formulated and factorized in the first iteration, and is updated and factorized in the subsequent iterations using the pivotal strategy determined earlier. The computer program and results for the example are given on pages 63-64.

The problem is repeated with another value of MODE (MODE=3), which holds the matrix of perturbed load flow equations constant after the first iteration. The computer program and results are given on pages 65-67. It can be observed that the total analysis time in the second case has been reduced considerably.

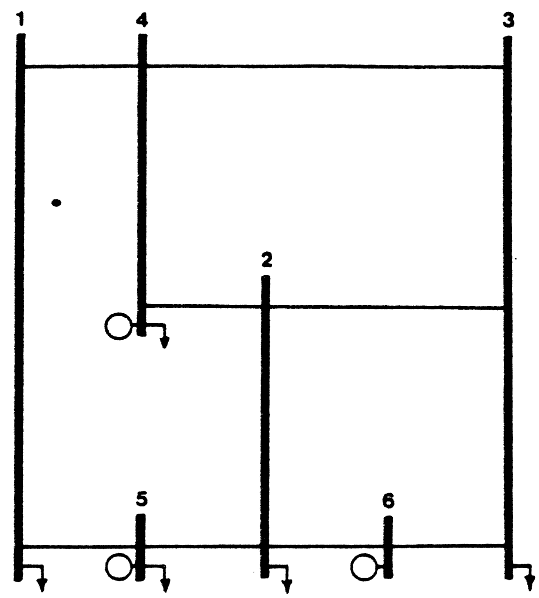


Fig. 4 6-bus power system

```
      PROGRAM EXMPL2(B006F,OUTPUT,TAPE4=B006F,TAPE6=OUTPUT)
C
C     THIS IS THE MAIN PROGRAM FOR FORMULATING AND SOLVING
C     THE LOAD FLOW PROBLEM OF 6-BUS SYSTEM USING THE XLF3
C     PACKAGE
C
      INTEGER BTYP(10),JRYT(10),ICYT(50),LBINP(8),LBOUT(8),OTPT
      REAL BCV(12),WS(3000)
      COMPLEX YT(40),V(6),DSX(6)
      INPT=4
      OTPT=6
      LWS=3000
      IP=0
      NB=6
      NTL=8
      NYT=NB+2*NTL
      IFLAG=0
      IWRITE=1
C
C     SUBROUTINE FORMPR FORMULATES THE LOAD FLOW PROBLEM
C
      CALL FORMPR (LBINP,LBOUT,BTYP,YT,JRYT,ICYT,BCV,V,WS,LWS,NB,NTL,NLB
     1,IP,INPT,OTPT,IFLAG,IWRITE)
      WRITE (OTPT,30) IFLAG
      IF (IFLAG.LT.0) GO TO 10
C
      MODE=1
C
C     SUBROUTINE LFNCM SOLVES THE LOAD FLOW EQUATIONS USING
C     THE COMPLEX NEWTON METHOD
C
      CALL LFNCM (NB,NLB,NYT,JRYT,ICYT,BTYP,YT,V,BCV,WS,LWS,DSX,MODE,IFL
     1AG,OTPT,IWRITE)
      WRITE (OTPT,20) IFLAG
10    STOP
20    FORMAT (///10X,"RETURN FLAG FROM LFNCM:",I3)
30    FORMAT (///10X,"RETURN FLAG FROM FORMPR:",I3)
      END
```

B006FVA

NB = 006,   NTL = 008

RETURN FLAG FROM FORMPR: 0

LOAD FLOW SOLUTION OF 6-BUS SYSTEM USING THE COMPLEX NEWTON METHOD

IT = 1	EPS = .584072E+00	ITERATION TIME .040	TOTAL TIME .040
IT = 2	EPS = .197986E+00	ITERATION TIME .024	TOTAL TIME .064
IT = 3	EPS = .225269E-01	ITERATION TIME .025	TOTAL TIME .089
IT = 4	EPS = .444466E-03	ITERATION TIME .025	TOTAL TIME .114
IT = 5	EPS = .227614E-06	ITERATION TIME .025	TOTAL TIME .139

RESULTS OF ANALYSIS
NUMBER OF ITERATIONS: 5
RETURN FLAG: 0
ACCURACY OBTAINED: .227614E-06
ANALYSIS TIME: .139SECONDS

VECTOR OF BUS VOLTAGES

BUS	RECTANGULAR CORDINATES		POLAR COORDINATES	
1	.773014	-.600187	.978659	-.660199
2	.920852	-.282640	.963252	-.297806
3	.861895	-.269978	.903189	-.303557
4	.866050	-.538849	1.020000	-.556577
5	.925317	-.474752	1.040000	-.474048
6	1.040000	0.000000	1.040000	0.000000

RETURN FLAG FROM LFNCM: 0

```
      PROGRAM EXMPL2(B006F,OUTPUT,TAPE4=B006F,TAPE6=OUTPUT)
C
C     THIS IS THE MAIN PROGRAM FOR FORMULATING AND SOLVING
C     THE LOAD FLOW PROBLEM OF 6-BUS SYSTEM USING THE XLF3
C     PACKAGE
C
      INTEGER BTYP(10),JRYT(10),ICYT(50),LBINP(8),LBOUT(8),OTPT
      REAL BCV(12),WS(3000)
      COMPLEX YT(40),V(6),DSX(6)
      COMMON /XLF3ID/ ITEL,TIMEL,VEPS,IDER,ILOAD,IADJ
      INPT=4
      OTPT=6
      LWS=3000
      IP=0
      NB=6
      NTL=8
      NYT=NB+2*NTL
      IFLAG=0
      IWRITE=1
C
C     SUBROUTINE FORMPR FORMULATES THE LOAD FLOW PROBLEM
C
      CALL FORMPR (LBINP,LBOUT,BTYP,YT,JRYT,ICYT,BCV,V,WS,LWS,NB,NTL,NLB
     1,IP,INPT,OTPT,IFLAG,IWRITE)
      WRITE (OTPT,30) IFLAG
      IF (IFLAG.LT.0) GO TO 10
C
      MODE=1
      VEPS=1.0E-01
C
C     SUBROUTINE LFNCM SOLVES THE LOAD FLOW EQUATIONS USING
C     THE COMPLEX NEWTON METHOD
C
      CALL LFNCM (NB,NLB,NYT,JRYT,ICYT,BTYP,YT,V,BCV,WS,LWS,DSX,MODE,IFL
     1AG,OTPT,IWRITE)
      WRITE (OTPT,20) IFLAG
C
      MODE=3
      VEPS=1.0E-06
C
      CALL LFNCM (NB,NLB,NYT,JRYT,ICYT,BTYP,YT,V,BCV,WS,LWS,DSX,MODE,IFL
     1AG,OTPT,IWRITE)
   10 STOP
   20 FORMAT (///10X,"RETURN FLAG FROM LFNCM:",I3)
   30 FORMAT (///10X,"RETURN FLAG FROM FORMPR:",I3)
      END
```

```
B006FVA

NB = 006,    NTL = 008

          RETURN FLAG FROM FORMPR:  0

                 ************
                 *          *
                 *  MODE= 1 *
                 *          *
                 ************

LOAD FLOW SOLUTION OF   6-BUS SYSTEM USING THE COMPLEX NEWTON METHOD
--------------------------------------------------------------------


IT =  1    EPS = .584072E+00    ITERATION TIME  .039    TOTAL TIME   .039


IT =  2    EPS = .197986E+00    ITERATION TIME  .024    TOTAL TIME   .063


IT =  3    EPS = .225269E-01    ITERATION TIME  .024    TOTAL TIME   .087


RESULTS OF ANALYSIS
NUMBER OF ITERATIONS:          3
RETURN FLAG:                   0
ACCURACY OBTAINED:  .225269E-01
ANALYSIS TIME:              .087SECONDS

VECTOR OF BUS VOLTAGES

   BUS          RECTANGULAR CORDINATES            POLAR COORDINATES
   ---          ----------------------         ---------------------

    1           .773449      -.600275          .979058      -.659998
    2           .920995      -.282553          .963362      -.297676
    3           .862041      -.269940          .903317      -.303468
    4           .866357      -.538568         1.020113      -.556184
    5           .925603      -.474431         1.040108      -.473648
    6          1.040000      0.000000         1.040000      0.000000


          RETURN FLAG FROM LFNCM:  0
```

```
************
*          *
*  MODE=3  *
*          *
************
```

LOAD FLOW SOLUTION OF 6-BUS SYSTEM USING THE COMPLEX NEWTON METHOD

IT = 1 EPS = .428145E-03 ITERATION TIME .005 TOTAL TIME .005

IT = 2 EPS = .173828E-04 ITERATION TIME .008 TOTAL TIME .013

IT = 3 EPS = .655533E-06 ITERATION TIME .007 TOTAL TIME .020

RESULTS OF ANALYSIS
NUMBER OF ITERATIONS: 3
RETURN FLAG: 0
ACCURACY OBTAINED: .655533E-06
ANALYSIS TIME: .020SECONDS

VECTOR OF BUS VOLTAGES

BUS	RECTANGULAR CORDINATES		POLAR COORDINATES	
1	.773014	-.600187	.978659	-.660199
2	.920852	-.282640	.963252	-.297806
3	.861895	-.269978	.903189	-.303557
4	.866050	-.538849	1.020000	-.556577
5	.925317	-.474752	1.040000	-.474048
6	1.040000	0.000000	1.040000	0.000000

Example 3

In this example, we investigate a 23-bus power system shown in Fig. 5 (page 69). The flat voltage profile is taken as a starting point. The load flow problem is formulated and solved in five iterations using Mode 1. The Jacobian available at the solution is transposed and used as a matrix of coefficients for an adjoint system, whose right-hand-side vector is supplied by subroutine FORMMU. The reactive power at bus 20 (a generator bus) is taken as a function of interest. The derivatives of this function w.r.t. bus voltages are deduced in the following manner:

$$f = Q_{20} = \mathrm{Im}\{S_{20}\} = \frac{S_{20} - S_{20}^{*}}{2j}$$

$$= \frac{[\sum_{i=1}^{23} (Y_{20,i}^{*} V_i^{*} V^{20})] - [\sum_{i=1}^{23} (Y_{20,i} V_i V_{20}^{*})]}{2j}$$

$$\frac{df}{dV_i} = 0.5j\, Y_{20,i} V_{20}^{*}$$

$$\frac{df}{dV_{20}} = 0.5j[Y_{20,20} V_{20}^{*} - \sum_{i=1}^{23} Y_{20,i}^{*} V_i^{*}] .$$

We use (13) to supply the derivatives of Q_{20} w.r.t. complex conjugate of bus voltages. The sensitivities with respect to bus-type control variables and phase shifting transformer control variables are determined by specifying their code numbers in subroutine DERIVX. The computer program and results are shown on pages 70-76.

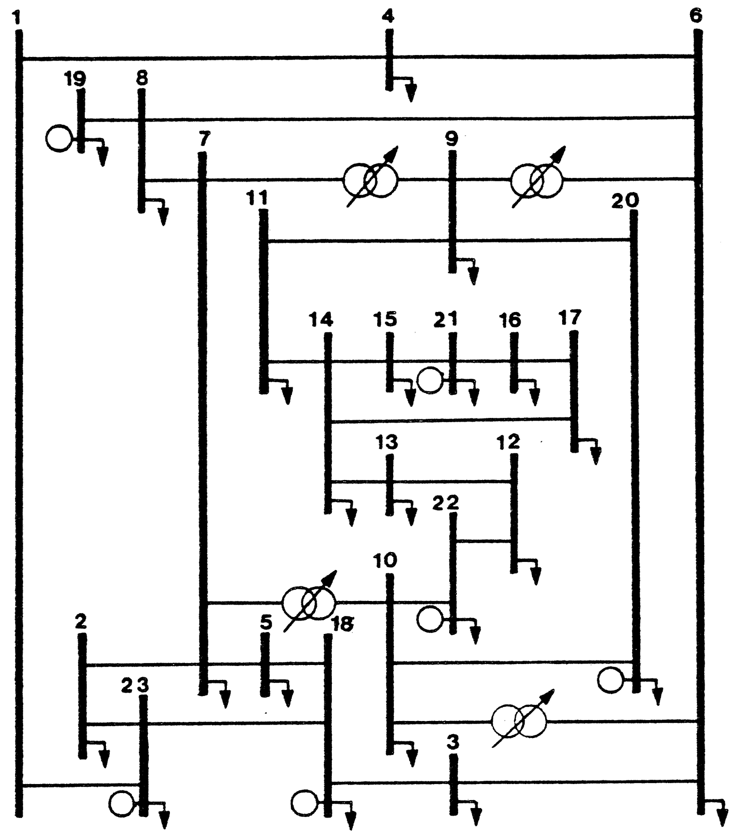


Fig. 5 23-bus power system

```
      PROGRAM EXMPL3(B023F,OUTPUT,TAPE4=B023F,TAPE6=OUTPUT)
C
C     THIS IS THE MAIN PROGRAM FOR LOAD FLOW SOLUTION AND
C     SENSITIVITY EVALUATION OF Q20 OF 23-BUS SYSTEM USING
C     THE XLF3 PACKAGE
C
      INTEGER BTYP(30),JRYT(30),ICYT(200),LBINP(30),LBOUT(30),BNR(23),OT
     1PT
      REAL BCV(46),LINPG(30),LINPB(30),LG(30),LB(30),LOUTG(30),LOUTB(30)
     1,BVMOD(23),BVARG(23),BGP(23),BLP(23),WS(10000),BLQ(23),BSTL(23),DR
     21(22),DR2(22),DS1(22),DS2(22)
      COMPLEX YT(150),V(23),LTAP(30),DSX(46),DLX(22)
      COMMON /XLF3ID/ ITEL,TIMEL,VEPS,IDER,ILOAD,IADJ
      INPT=4
      OTPT=6
      LWS=10000
      IP=0
      NB=23
      NTL=30
      NYT=NB+2*NTL
      IFLAG=0
      IWRITE=1
      IDER=1
C
C     SUBROUTINE RDATAX READS THE DATA FILE AND PREPROCESSES IT
C
      CALL RDATAX (LBINP,LBOUT,LINPG,LINPB,LG,LB,LOUTG,LOUTB,LTAP,BNR,BT
     1YP,BVMOD,BVARG,BGP,BLP,BLQ,BSTL,JRYT,NB,NTL,NLB,INPT,OTPT,IWRITE)
C
C     SUBROUTINE FORMYTX FORMULATES THE NODAL ADMITTANCE MATRIX
C     OF THE SYSTEM AND STORES IT IN A SPARSE FORM
C
      CALL FORMYTX (LBINP,LBOUT,LINPG,LINPB,LG,LB,LOUTG,LOUTB,LTAP,BSTL,
     1JRYT,ICYT,YT,NB,NTL,NYT,OTPT,IWRITE)
C
C     SUBROUTINE FORMU CONSTRUCTS THE VECTOR OF BUS CONTROL VARIABLES
C     OF THE SYSTEM UNDER INVESTIGATION
C
      CALL FORMU (BTYP,BVMOD,BVARG,BGP,BLP,BLQ,BCV,NB,OTPT,IWRITE)
C
      DO 10 I=1,NB
      R1=BVMOD(I)
      R2=BVARG(I)
      V(I)=CMPLX(R1*COS(R2),R1*SIN(R2))
10    CONTINUE
      MODE=1
C
C     SUBROUTINE LFNCM SOLVES THE LOAD FLOW EQUATIONS USING
C     THE COMPLEX NEWTON METHOD
C
      CALL LFNCM (NB,NLB,NYT,JRYT,ICYT,BTYP,YT,V,BCV,WS,LWS,DSX,MODE,IFL
     1AG,OTPT,IWRITE)
      WRITE (OTPT,130) IFLAG
      IF (IFLAG.LT.0) GO TO 120
      N=NB-1
      WRITE (OTPT,140) NB
      DO 20 I=1,N
      J=2*I-1
      DLX(I)=DSX(J)
20    CONTINUE
C
      DO 30 I=1,N
      DR1(I)=0.0
      DR2(I)=0.0
      DS1(I)=0.0
```

```
      DS2(I)=0.0
30    CONTINUE
C
C     SENSITIVITIES OF Q20 W.R.T. BUS-TYPE CONTROL VARIABLES
C
      ICODE=1
      DO 40 I=1,N
      CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,I,L2,DLX,NTL,ICODE,D
     1F1,DF2)
      DR1(I)=DF1
      DR2(I)=DF2
40    CONTINUE
C
      ICODE=2
      DO 50 I=1,N
      CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,I,L2,DLX,NTL,ICODE,D
     1F1,DF2)
      DS1(I)=DF1
      DS2(I)=DF2
50    CONTINUE
C
      WRITE (OTPT,150)
      WRITE (OTPT,160)
      DO 60 I=1,N
      IF (BTYP(I).NE.0) GO TO 60
      WRITE (OTPT,170) I,DR1(I),DR2(I),DS1(I),DS2(I)
60    CONTINUE
      WRITE (OTPT,180)
      WRITE (OTPT,190)
      DO 70 I=1,N
      IF (BTYP(I).NE.1) GO TO 70
      WRITE (OTPT,170) I,DR1(I),DR2(I),DS1(I),DS2(I)
70    CONTINUE
C
C     SENSITIVITIES OF Q20 W.R.T. LINE CONTROL VARIABLES
C
      WRITE (OTPT,180)
      WRITE (OTPT,200)
      ICODE=3
      DO 80 I=1,NTL
      TAP1=REAL(LTAP(I))
      IF (TAP1.NE.1) GO TO 80
      L1=LBINP(I)
      L2=LBOUT(I)
      CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,L1,L2,DLX,NTL,ICODE,
     1DF1,DF2)
      WRITE (OTPT,210) I,LBINP(I),LBOUT(I),DF1,DF2
80    CONTINUE
C
C     SENSITIVITIES OF Q20 W.R.T. PHASE-SHIFTER CONTROL VARIABLES
C
      WRITE (OTPT,150)
      WRITE (OTPT,220)
      DO 110 I=1,NTL
      TAP1=REAL(LTAP(I))
      IF (TAP1.EQ.1) GO TO 110
      ITN=0
      ICODE=5
      L1=LBINP(I)
      L2=LBOUT(I)
90    CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,L1,L2,DLX,NTL,ICODE,
     1DF1,DF2)
      IF (ITN.EQ.1) GO TO 100
      DM=DF1
      DA=DF2
```

```
      ICODE=7
      ITN=ITN+1
      GO TO 90
100   DR=DF1
      DX=DF2
      WRITE (OTPT,230) LBINP(I),LBOUT(I),DM,DA,DR,DX
110   CONTINUE
      WRITE (OTPT,150)
C
120   STOP
130   FORMAT (///,30X,"RETURN FLAG FROM LFNCM: ",I3)
140   FORMAT ("1",16X,I3,"-BUS SYSTEM: SENSITIVITIES OF Q 20")
150   FORMAT (/,1X,68("-"),/)
160   FORMAT (1X,"LOAD BUS QUANTITIES - TOTAL DERIVATIVES",//,5X,64("-")
     1,//,5X,"BUS",7X,"REAL",9X,"REACTIVE",9X,"SHUNT",10X,"SHUNT",/,15X,
     2"POWER",9X,"POWER",8X,"CONDUCTANCE",4X,"SUSCEPTANCE",//,5X,64("-")
     3,/,1X)
170   FORMAT (5X,I3,F13.6,3F15.6)
180   FORMAT (/,5X,64("-"),/)
190   FORMAT (1X,"GENERATOR BUS QUANTITIES - TOTAL DERIVATIVES",//5X,64(
     1"-"),//,5X,"BUS",7X,"REAL",10X,"VOLTAGE",9X,"SHUNT",10X,"SHUNT",/,
     215X,"POWER",8X,"MAGNITUDE",5X,"CONDUCTANCE",4X,"SUSCEPTANCE",//,5X
     3,64("-"),/,1X)
200   FORMAT (1X,"LINE QUANTITIES - TOTAL DERIVATIVES",//,5X,64("-"),//,
     15X,"LINE",5X,"ELEMENT",8X,"LINE",9X,"LINE",/,5X,"INDEX",15X,"CONDU
     2CTANCE",3X,"SUSCEPTANCE",//,5X,64("-"),/,1X)
210   FORMAT (5X,I3,6X,I3,",",I2,4X,F10.6,4X,F10.6)
220   FORMAT (1X,"PHASE SHIFTER QUANTITIES - TOTAL DERIVATIVES",//,5X,64
     1("-"),//,5X,"ELEMENT",3X,"TURNS RATIO",3X,"TURNS RATIO",5X"INTERNA
     2L",6X,"INTERNAL",/,16X,"MAGNITUDE",4X,"PHASE ANGLE",4X,"RESISTANCE
     3",4X,"REACTANCE",//,5X,64("-"),/,1X)
230   FORMAT (5X,I3,",",I2,4(F13.6,1X))
      END
```

```
C
C
      SUBROUTINE FORMMU (V,AI,NB,DS,DSL,IDER,YT,JRYT,ICYT,BTYP,NYT,OTPT)
C
C     SUBROUTINE FORMMU FORMULATES THE RHS VECTOR OF
C     ADJOINT EQUATIONS FOR REACTIVE POWER INJECTED
C     AT BUS 20, I.E. THE VECTOR CONSTITUTING PARTIAL
C     DERIVATIVES OF Q20 W.R.T. COMPLEX BUS VOLTAGES
C     AND THEIR COMPLEX CONJUGATES
C
      COMPLEX V(1),AI(1),DS(1),DF(23),YT(1),DSL,AV1,AV2
      INTEGER JRYT(1),ICYT(1),BTYP(1),IDER,OTPT
      N=NB-1
      DO 10 I=1,N
      DS(I)=(0.,0.)
      DF(I)=(0.,0.)
      DS(N+I)=(0.,0.)
10    CONTINUE
      DF(NB)=(0.,0.)
      DO 30 I=1,NB
      IF (I.NE.20) GO TO 30
      KK=JRYT(I+1)-JRYT(I)
      DO 20 J=1,KK
      KJ=JRYT(I)+J-1
      KA=ICYT(KJ)
      AV1=YT(KJ)*CONJG(V(I))
      DF(KA)=DF(KA)+0.5*CMPLX(-AIMAG(AV1),REAL(AV1))
      AV2=CONJG(YT(KJ)*V(KA))
      DF(I)=DF(I)+0.5*CMPLX(AIMAG(AV2),-REAL(AV2))
20    CONTINUE
30    CONTINUE
      DSL=DF(NB)
      DO 40 I=1,N
      J=2*I-1
      DS(J)=DF(I)
      DS(J+1)=CONJG(DF(I))
40    CONTINUE
      RETURN
      END
```

B023FVA

NB = 023, NTL = 030

LOAD FLOW SOLUTION OF 23-BUS SYSTEM USING THE COMPLEX NEWTON METHOD

IT = 1	EPS = .584070E+00	ITERATION TIME .190	TOTAL TIME .190
IT = 2	EPS = .152699E+00	ITERATION TIME .104	TOTAL TIME .294
IT = 3	EPS = .786330E-02	ITERATION TIME .101	TOTAL TIME .395
IT = 4	EPS = .652878E-04	ITERATION TIME .099	TOTAL TIME .494
IT = 5	EPS = .271433E-08	ITERATION TIME .103	TOTAL TIME .597

RESULTS OF ANALYSIS
NUMBER OF ITERATIONS: 5
RETURN FLAG: 0
ACCURACY OBTAINED: .271433E-08
ANALYSIS TIME: .597SECONDS

VECTOR OF BUS VOLTAGES

BUS	RECTANGULAR CORDINATES		POLAR COORDINATES	
1	1.031418	.017945	1.031574	.017396
2	1.005891	.026282	1.006234	.026122
3	1.003961	.086396	1.007671	.085844
4	1.001518	.067001	1.003757	.066800
5	.997403	.054635	.998898	.054722
6	1.006146	.140558	1.015916	.138801
7	.989754	.080713	.993039	.081369
8	.993140	.041381	.994001	.041643
9	1.011231	.213710	1.033567	.208271
10	1.012282	.247284	1.042049	.239591
11	.980648	.248576	1.011663	.248253
12	.943054	.387331	1.019498	.389713
13	.946466	.352799	1.010081	.356800
14	.952933	.339457	1.011589	.342209
15	.947715	.341780	1.007461	.346118
16	.940763	.412506	1.027228	.413233
17	.945536	.400687	1.026932	.400825
18	1.028160	.061542	1.030000	.059785
19	1.047517	.072160	1.050000	.068778
20	1.023344	.235091	1.050000	.225811
21	.930060	.487328	1.050000	.482643
22	.933993	.479747	1.050000	.474509
23	1.040000	0.000000	1.040000	0.000000

RETURN FLAG FROM LFNCM: 0

23-BUS SYSTEM: SENSITIVITIES OF Q 20

LOAD BUS QUANTITIES - TOTAL DERIVATIVES

BUS	REAL POWER	REACTIVE POWER	SHUNT CONDUCTANCE	SHUNT SUSCEPTANCE
1	-.027283	-.064159	.029033	-.068274
2	-.074231	-.161124	.075159	-.163139
3	-.056177	-.210826	.057042	-.214073
4	-.081538	-.255446	.082152	-.257369
5	-.091249	-.248788	.091048	-.248240
6	-.085686	-.380627	.088435	-.392840
7	-.115786	-.333055	.114180	-.328434
8	-.050300	-.156842	.049698	-.154966
9	-.013171	-.604234	.014070	-.645479
10	.014266	-.584846	-.015491	-.635063
11	.066100	-.375822	-.067650	-.384640
12	.178112	-.054704	-.185125	-.056858
13	.168556	-.081238	-.171972	-.082884
14	.152606	-.134387	-.156164	-.137519
15	.157880	-.101017	-.160245	-.102530
16	.174080	-.045264	-.183689	-.047762
17	.169298	-.078138	-.178539	-.082403

GENERATOR BUS QUANTITIES - TOTAL DERIVATIVES

BUS	REAL POWER	VOLTAGE MAGNITUDE	SHUNT CONDUCTANCE	SHUNT SUSCEPTANCE
18	.017130	-3.875226	-.018173	0.000000
19	.025362	-3.088068	-.027962	0.000000
20	-.045990	24.835083	.050705	0.000000
21	.179395	-5.952396	-.197783	0.000000
22	.191903	-12.288996	-.211573	0.000000

LINE QUANTITIES - TOTAL DERIVATIVES

LINE INDEX	ELEMENT	LINE CONDUCTANCE	LINE SUSCEPTANCE
1	23, 1	-.001430	.000038
2	23, 2	-.006900	.003388
3	18, 3	-.007346	.002687
4	6, 3	-.008747	-.003884
5	18, 5	-.002087	.008291
6	1, 4	-.011138	.002113
7	2, 7	-.009728	-.000822
8	7, 5	-.002294	-.000372
9	6, 4	-.008678	-.003569
10	19, 8	.000160	.010813
11	6, 8	-.020462	-.011084
12	7, 8	-.006841	-.002781
13	10,20	-.008313	.005694
14	20, 9	.012080	.009537
15	11, 9	.011265	-.002857
16	14,11	.022200	.005985
17	22,10	.141267	.032510
18	12,13	.000599	.000496
19	13,14	.000781	.000133
20	15,14	.000150	-.000122
21	21,15	.009977	.006432
22	17,14	.002550	.001491
23	21,16	.002251	.001339
24	16,17	.000401	.000063
25	22,12	.002929	.002741
30	23,18	.000144	.001096

PHASE SHIFTER QUANTITIES - TOTAL DERIVATIVES

ELEMENT	TURNS RATIO MAGNITUDE	TURNS RATIO PHASE ANGLE	INTERNAL RESISTANCE	INTERNAL REACTANCE
9, 6	-2.222672	.119084	-1.897789	1.157490
10, 6	-2.268930	.093914	-2.832088	1.031926
9, 7	-1.812562	-.098801	-1.858320	.505437
10, 7	-2.483371	-.114197	-5.044258	1.875749

Example 4

A 26-bus power system, shown in Fig. 6 (page 78) is considered. The load flow solution is obtained from a flat voltage profile and the voltage angle at bus 20 (a generator bus) is analysed. The function and its derivatives w.r.t. bus voltages are given by

$$f = \tan^{-1} \left[\frac{j(V_{20}^{*} - V_{20})}{V_{20} + V_{20}^{*}}\right] ,$$

$$\frac{df}{dV_{20}} = - j \frac{0.5}{V_{20}} ,$$

$$\frac{df}{dV_i} = 0 \qquad \text{for all other values of } i.$$

Using (13), the right-hand-side vector of the adjoint system is provided in subroutine FORMMU, and the sensitivities w.r.t. various network control variables are obtained by indicating appropriate code numbers in subroutine DERIVX. The results of this example are given on pages 79-85.

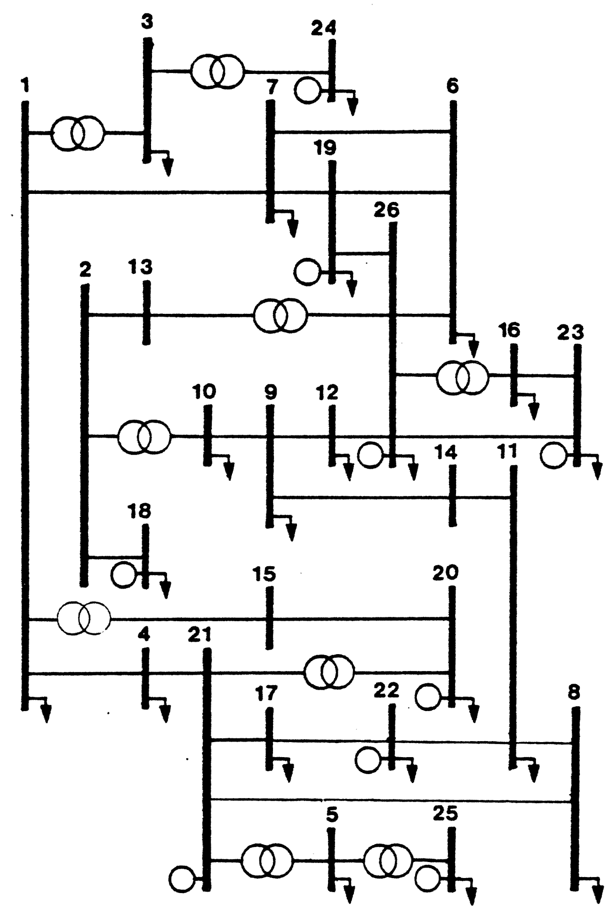


Fig. 6 26-bus power system

```
      PROGRAM EXMPL4(B026F,OUTPUT,TAPE4=B026F,TAPE6=OUTPUT)
C
C     THIS IS THE MAIN PROGRAM FOR SENSITIVITY EVALUATION OF
C     DELTA 20 OF 26-BUS SYSTEM USING THE XLF3 PACKAGE
C
      INTEGER BTYP(32),JRYT(32),ICYT(200),LBINP(32),LBOUT(32),BNR(26),OT
     1PT
      REAL BCV(52),LINPG(32),LINPB(32),LG(32),LB(32),LOUTG(32),LOUTB(32)
     1,BVMOD(26),BVARG(26),BGP(26),BLP(26),WS(10000),BLQ(26),BSTL(26),DR
     21(25),DR2(25),DS1(25),DS2(25)
      COMPLEX YT(150),V(26),LTAP(32),DSX(52),DLX(25)
      COMMON /XLF3ID/ ITEL,TIMEL,VEPS,IDER,ILOAD,IADJ
      INPT=4
      OTPT=6
      LWS=10000
      IP=0
      NB=26
      NTL=32
      NYT=NB+2*NTL
      IFLAG=0
      IWRITE=1
      IDER=1
C
C     SUBROUTINE RDATAX READS THE INPUT FILE AND PREPROCESSES IT
C
      CALL RDATAX (LBINP,LBOUT,LINPG,LINPB,LG,LB,LOUTG,LOUTB,LTAP,BNR,BT
     1YP,BVMOD,BVARG,BGP,BLP,BLQ,BSTL,JRYT,NB,NTL,NLB,INPT,OTPT,IWRITE)
C
C     SUBROUTINE FORMYTX FORMULATES THE NODAL ADMITTANCE MATRIX
C     OF THE SYSTEM AND STORES IT IN A SPARSE FORM
C
      CALL FORMYTX (LBINP,LBOUT,LINPG,LINPB,LG,LB,LOUTG,LOUTB,LTAP,BSTL,
     1JRYT,ICYT,YT,NB,NTL,NYT,OTPT,IWRITE)
C
C     SUBROUTINE FORMU CONSTRUCTS THE VECTOR OF BUS CONTROL
C     VARIABLES OF THE SYSTEM UNDER CONSIDERATION
C
      CALL FORMU (BTYP,BVMOD,BVARG,BGP,BLP,BLQ,BCV,NB,OTPT,IWRITE)
C
      DO 10 I=1,NB
      R1=BVMOD(I)
      R2=BVARG(I)
      V(I)=CMPLX(R1*COS(R2),R1*SIN(R2))
   10 CONTINUE
      MODE=1
C
C     SUBROUTINE LFNCM SOLVES THE LOAD FLOW EQUATIONS USING
C     THE COMPLEX NEWTON METHOD
C
      CALL LFNCM (NB,NLB,NYT,JRYT,ICYT,BTYP,YT,V,BCV,WS,LWS,DSX,MODE,IFL
     1AG,OTPT,IWRITE)
      WRITE (OTPT,130) IFLAG
      IF (IFLAG.LT.0) GO TO 120
      N=NB-1
      WRITE (OTPT,140) NB
      DO 20 I=1,N
      J=2*I-1
      DLX(I)=DSX(J)
   20 CONTINUE
C
      DO 30 I=1,N
      DR1(I)=0.0
      DR2(I)=0.0
      DS1(I)=0.0
      DS2(I)=0.0
```

```
   30 CONTINUE
C
C     SENSITIVITIES OF DELTA 20 W.R.T. BUS-TYPE CONTROL VARIABLES
C
      ICODE=1
      DO 40 I=1,N
      CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,I,L2,DLX,NTL,ICODE,D
     1F1,DF2)
      DR1(I)=DF1
      DR2(I)=DF2
   40 CONTINUE
C
      ICODE=2
      DO 50 I=1,N
      CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,I,L2,DLX,NTL,ICODE,D
     1F1,DF2)
      DS1(I)=DF1
      DS2(I)=DF2
   50 CONTINUE
      WRITE (OTPT,150)
      WRITE (OTPT,160)
      DO 60 I=1,N
      IF (BTYP(I).NE.0) GO TO 60
      WRITE (OTPT,170) I,DR1(I),DR2(I),DS1(I),DS2(I)
   60 CONTINUE
      WRITE (OTPT,180)
      WRITE (OTPT,190)
      DO 70 I=1,N
      IF (BTYP(I).NE.1) GO TO 70
      WRITE (OTPT,170) I,DR1(I),DR2(I),DS1(I),DS2(I)
   70 CONTINUE
C
C     SENSITIVITIES OF DELTA 20 W.R.T. LINE CONTROL VARIABLES
C
      WRITE (OTPT,180)
      WRITE (OTPT,200)
      ICODE=3
      DO 80 I=1,NTL
      TAP1=REAL(LTAP(I))
      IF (TAP1.NE.1) GO TO 80
      L1=LBINP(I)
      L2=LBOUT(I)
      CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,L1,L2,DLX,NTL,ICODE,
     1DF1,DF2)
      WRITE (OTPT,210) I,LBINP(I),LBOUT(I),DF1,DF2
   80 CONTINUE
C
C     SENSITIVITIES OF DELTA 20 W.R.T. TAP-CHANGING-UNDER-LOAD
C     TRANSFORMER CONTROL VARIABLES
C
      WRITE (OTPT,180)
      WRITE (OTPT,220)
      DO 110 I=1,NTL
      TAP1=REAL(LTAP(I))
      IF (TAP1.EQ.1) GO TO 110
      ITN=0
      ICODE=6
      L1=LBINP(I)
      L2=LBOUT(I)
   90 CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,L1,L2,DLX,NTL,ICODE,
     1DF1,DF2)
      IF (ITN.EQ.1) GO TO 100
      DA=DF1
      ICODE=7
      ITN=ITN+1
```

```
      GO TO 90
  100 DR=DF1
      DX=DF2
C
      WRITE (OTPT,230) LBINP(I),LBOUT(I),DA,DR,DX
  110 CONTINUE
      WRITE (OTPT,150)
C
  120 STOP
  130 FORMAT (///30X,"RETURN FLAG FROM LFNCM: ",I3)
  140 FORMAT ("1",16X,I3,"-BUS SYSTEM: SENSITIVITIES OF DELTA 20")
  150 FORMAT (/,1X,68("-"),/)
  160 FORMAT (1X,"LOAD BUS QUANTITIES - TOTAL DERIVATIVES",//,5X,64("-")
     1,//,5X,"BUS",7X,"REAL",9X,"REACTIVE",9X,"SHUNT",10X,"SHUNT",/,15X,
     2"POWER",9X,"POWER",8X,"CONDUCTANCE",4X,"SUSCEPTANCE",//,5X,64("-")
     3,/,1X)
  170 FORMAT (5X,I3,F13.6,3F15.6)
  180 FORMAT (/,5X,64("-"),/)
  190 FORMAT (1X,"GENERATOR BUS QUANTITIES - TOTAL DERIVATIVES",//5X,64(
     1"-"),//,5X,"BUS",7X,"REAL",10X,"VOLTAGE",9X,"SHUNT",10X,"SHUNT",/,
     215X,"POWER",8X,"MAGNITUDE",5X,"CONDUCTANCE",4X,"SUSCEPTANCE",//,5X
     3,64("-"),/,1X)
  200 FORMAT (1X,"LINE QUANTITIES - TOTAL DERIVATIVES",//,5X,64("-"),//,
     15X,"LINE",5X,"ELEMENT",8X,"LINE",9X,"LINE",/,5X,"INDEX",15X,"CONDU
     2CTANCE",3X,"SUSCEPTANCE",//,5X,64("-"),/,1X)
  210 FORMAT (5X,I3,6X,I3,",",I2,4X,F10.6,4X,F10.6)
  220 FORMAT (1X,"TCUL TRANSFORMER QUANTITIES - TOTAL DERIVATIVES",//,5X
     1,64("-"),//,5X,"ELEMENT",5X,"TURNS RATIO",9X,"INTERNAL",11X,"INTER
     2NAL",/,36X,"RESISTANCE",9X,"REACTANCE",//,5X,64("-"),/,1X)
  230 FORMAT (5X,I3,",",I2,3(F15.6,3X))
      END
```

```
C
      SUBROUTINE FORMMU (V,AI,NB,DS,DSL,IDER,YT,JRYT,ICYT,BTYP,NYT,OTPT)
C
C     SUBROUTINE FORMMU FORMULATES THE RHS VECTOR OF ADJOINT
C     EQUATIONS FOR THE PHASE ANGLE OF VOLTAGE AT BUS 20,
C     I.E. VECTOR CONSTITUTING THE PARTIAL DERIVATIVES OF
C     DELTA 20 W.R.T. COMPLEX BUS VOLTAGES AND THEIR
C     COMPLEX CONJUGATES
C
      COMPLEX V(1),AI(1),DS(1),YT(1),DSL,AV1
      INTEGER JRYT(1),ICYT(1),BTYP(1),IDER,OTPT
      N=NB-1
      DO 10 I=1,N
      DS(I)=(0.,0.)
      DS(N+I)=(0.,0.)
   10 CONTINUE
      AV1=-0.5/V(20)
      A1=REAL(AV1)
      A2=AIMAG(AV1)
      DS(39)=CMPLX(-A2,A1)
      DS(40)=CONJG(DS(39))
      DSL=(0.0,0.0)
      RETURN
      END
```

B026FVA

NB = 026, NTL = 032

LOAD FLOW SOLUTION OF 26-BUS SYSTEM USING THE COMPLEX NEWTON METHOD

IT = 1	EPS = .402187E+00	ITERATION TIME .175	TOTAL TIME .175
IT = 2	EPS = .808703E-01	ITERATION TIME .096	TOTAL TIME .271
IT = 3	EPS = .409234E-02	ITERATION TIME .094	TOTAL TIME .365
IT = 4	EPS = .140210E-04	ITERATION TIME .092	TOTAL TIME .457
IT = 5	EPS = .220316E-09	ITERATION TIME .094	TOTAL TIME .551

RESULTS OF ANALYSIS
NUMBER OF ITERATIONS: 5
RETURN FLAG: 0
ACCURACY OBTAINED: .220316E-09
ANALYSIS TIME: .551SECONDS

VECTOR OF BUS VOLTAGES

BUS	RECTANGULAR CORDINATES		POLAR COORDINATES	
1	1.032758	.077289	1.035646	.074698
2	1.064366	.094339	1.068539	.088403
3	1.042361	.054945	1.043809	.052664
4	.985904	.097867	.990750	.098942
5	.974084	.259812	1.008138	.260657
6	1.032445	.055418	1.033931	.053625
7	1.013184	.018057	1.013345	.017820
8	.944119	.040265	.944977	.042622
9	.961374	-.108770	.967507	-.112661
10	1.036971	.069245	1.039280	.066677
11	.898219	-.099219	.903683	-.110016
12	.967044	-.074065	.969876	-.076440
13	1.046329	.015720	1.046447	.015023
14	.938820	-.107130	.944912	-.113620
15	.927337	.097007	.932397	.104229
16	1.035263	-.047118	1.036334	-.045482
17	.931762	.027804	.932176	.029832
18	1.039703	.252818	1.070000	.238534
19	1.045549	.096578	1.050000	.092110
20	.970579	.240784	1.000000	.243174
21	.993843	.229511	1.020000	.226954
22	.885590	-.088488	.890000	-.099589
23	.999647	-.026551	1.000000	-.026554
24	.998949	.045841	1.000000	.045857
25	.935917	.352222	1.000000	.359944
26	1.010000	0.000000	1.010000	0.000000

RETURN FLAG FROM LFNCM: 0

26-BUS SYSTEM: SENSITIVITIES OF DELTA 20

LOAD BUS QUANTITIES - TOTAL DERIVATIVES

BUS	REAL POWER	REACTIVE POWER	SHUNT CONDUCTANCE	SHUNT SUSCEPTANCE
1	.267581	-.007722	-.286998	-.008283
2	.008245	.001363	-.009414	.001557
3	.267275	-.006188	-.291205	-.006742
4	.290383	-.002045	-.285035	-.002007
5	.296479	.000000	-.301324	.000000
6	.080168	-.000773	-.085701	-.000826
7	.216789	-.004509	-.222613	-.004630
8	.269938	-.009039	-.241050	-.008071
9	.056949	-.002912	-.053309	-.002726
10	.009824	.002211	-.010611	.002388
11	.222100	-.005921	-.181376	-.004835
12	.025652	.000475	-.024130	.000447
13	.001374	.000267	-.001504	.000292
14	.133023	-.004979	-.118771	-.004446
15	.276482	-.005600	-.240364	-.004868
16	0.000000	0.000000	0.000000	0.000000
17	.272539	-.003772	-.236823	-.003278

GENERATOR BUS QUANTITIES - TOTAL DERIVATIVES

BUS	REAL POWER	VOLTAGE MAGNITUDE	SHUNT CONDUCTANCE	SHUNT SUSCEPTANCE
18	.007581	.025614	-.008680	0.000000
19	.080415	-.039806	-.088657	0.000000
20	.307280	-.354038	-.307280	0.000000
21	.296479	-.219182	-.308457	0.000000
22	.255422	-.053318	-.202320	0.000000
23	0.000000	0.000000	0.000000	0.000000
24	.267232	-.045456	-.267232	0.000000
25	.296479	-.000000	-.296479	0.000000

LINE QUANTITIES - TOTAL DERIVATIVES

LINE INDEX	ELEMENT	LINE CONDUCTANCE	LINE SUSCEPTANCE
3	16,23	0.000000	0.000000
4	23,26	0.000000	0.000000
6	9,10	.003064	-.008097
7	9,12	.000136	-.001057
8	12,26	.000889	-.001936
9	9,14	.001597	-.000024
10	11,14	.003088	.000301
11	19,26	-.003739	.007844
12	6,26	-.002147	.004467
13	6,19	-.000122	.000023
14	7,19	.004441	-.010615
15	6, 7	.002757	-.005050
16	11,22	.000393	.000206
17	8,11	-.007535	.005931
18	17,22	-.005194	.001658
19	8,21	-.011203	.005182
20	17,21	-.014022	.004697
21	1, 4	.000448	.000296
22	4,21	-.005019	.000829
25	2,13	-.000102	.000594
26	1, 7	-.002295	.002933
27	15,20	-.007868	.004280
28	2,18	-.000436	-.000098

TCUL TRANSFORMER QUANTITIES - TOTAL DERIVATIVES

ELEMENT	TURNS RATIO	INTERNAL RESISTANCE	INTERNAL REACTANCE
13,26	.022095	-.025511	.133014
26,16	0.000000	0.000000	0.000000
2,10	-.061836	-.122407	-.153065
20,21	.006226	-.258633	.198019
15, 1	.186552	-1.571927	1.408706
1, 3	-.049465	-.149478	-.011940
24, 3	.046384	-.009770	-.007182
5,21	.000000	-.011448	.000000
5,25	.000000	-.126153	-.000000

Example 5

The IEEE 118-bus system [16,19] shown in Fig. 7 (page 87) is considered in this example. The data file B118SVB available under charge RJWBAND is used which carries an optimal solution of an economic dispatch problem in a formatted style. The matrix of perturbed load flow equations is evaluated at this solution and its tranpose is used as matrix of coefficients of an adjoint system. The real power at bus 118, the slack bus, is considered and its derivatives w.r.t. bus voltages are obtained in the following manner:

$$f = P_n = \frac{S_n + S_n^*}{2} \quad ,$$

where S_n is the complex power injected at the slack bus given by

$$S_n = V_n \sum_{k=1}^{n} (Y_{nk}^* \; V_k^*) \quad ,$$

the nonzero elements of vector $\frac{df}{d\underline{V}_M}$ are

$$\frac{df}{dV_k} = 0.5[Y_{nk} \; V_n^* + \delta_{kn} \sum_{k=1}^{n} Y_{nk}^* \; V_k^*] \quad ,$$

$$\text{where } \delta_{kn} = \begin{cases} 0 & \text{for } k \neq n \\ 1 & \text{for } k = n \end{cases} \quad .$$

The nodal admittance matrix stored in a sparse form has been used to supply these derivatives in subroutine FORMMU and the sensitivities w.r.t. controllable parameters of tap-changing-under-load and phase shifting transformers have been obtained by specifying appropriate codes. The computer program and results of this example are shown on pages 88-98.

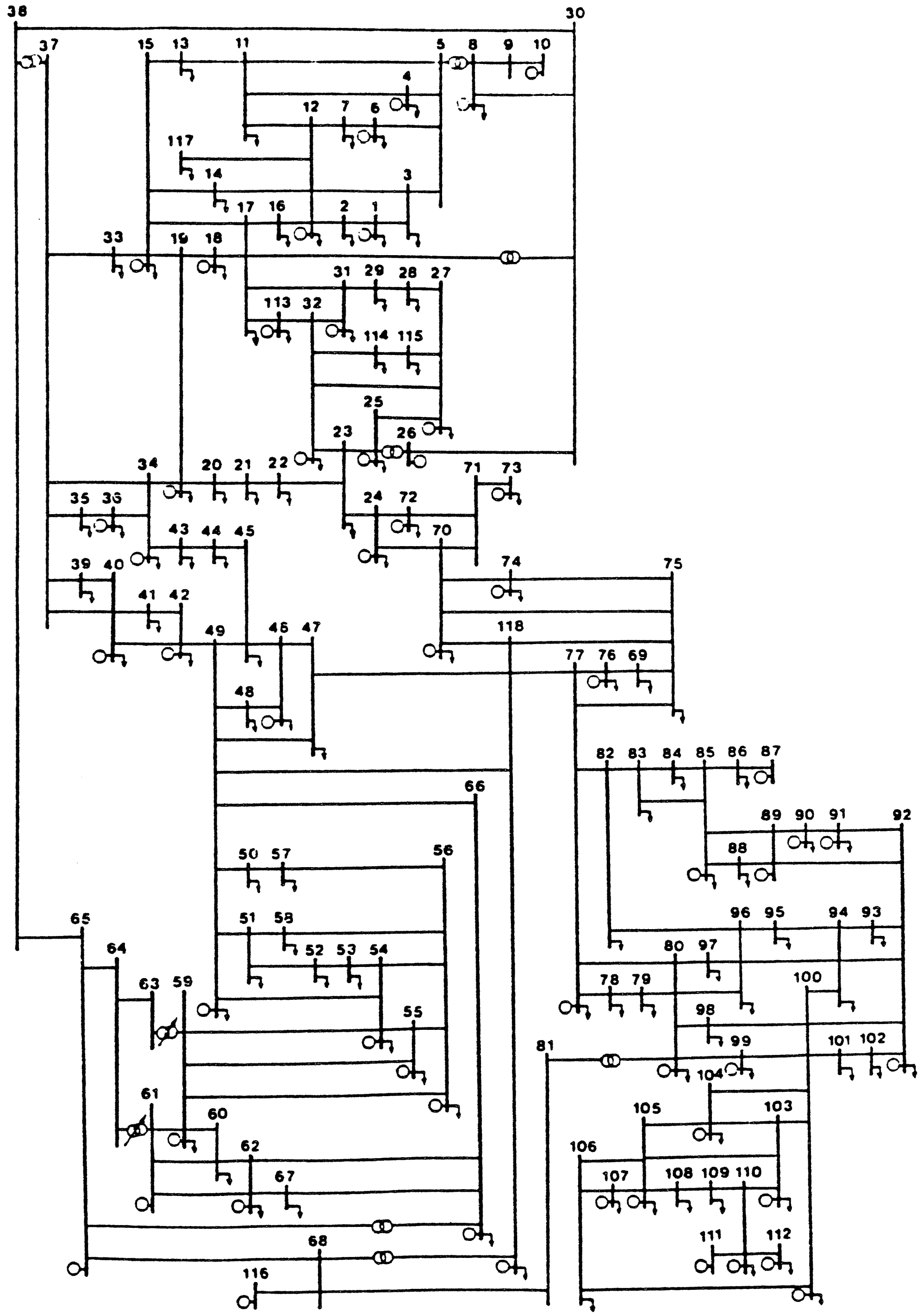


Fig. 7 The IEEE 118-bus system

```
      PROGRAM EXMPL5(B118F,OUTPUT,TAPE4=B118F,TAPE6=OUTPUT)
C
C     THIS IS THE MAIN PROGRAM FOR SENSITIVITY EVALUATION OF REAL
C     POWER AT SLACK BUS OF THE IEEE 118-BUS SYSTEM USING THE
C     XLF3 PACKAGE
C
      INTEGER BTYP(179),JRYT(179),ICYT(1200),LBINP(179),LBOUT(179),BNR(1
     118),OTPT
      REAL BCV(236),LINPG(179),LINPB(179),LG(179),LB(179),LOUTG(179),LOU
     1TB(179),BVMOD(118),BVARG(118),BGP(118),BLP(118),WS(30000),BLQ(118)
     2,BSTL(118),DR1(117),DR2(117),DS1(117),DS2(117)
      COMPLEX YT(1200),V(118),LTAP(179),DSX(236),DLX(117)
      COMMON /XLF3ID/ ITEL,TIMEL,VEPS,IDER,ILOAD,IADJ
      INPT=4
      OTPT=6
      LWS=30000
      IP=0
      NB=118
      NTL=179
      NYT=NB+2*NTL
      IFLAG=0
      IWRITE=0
      IDER=1
C
C     SUBROUTINE RDATAX READS THE INPUT FILE AND PREPROCESSES IT
C
      CALL RDATAX (LBINP,LBOUT,LINPG,LINPB,LG,LB,LOUTG,LOUTB,LTAP,BNR,BT
     1YP,BVMOD,BVARG,BGP,BLP,BLQ,BSTL,JRYT,NB,NTL,NLB,INPT,OTPT,IWRITE)
C
C     SUBROUTINE FORMYTX FORMULATES THE NODAL ADMITTANCE
C     MATRIX OF THE SYSTEM AND STORES IT IN A SPARSE FORM
C
      CALL FORMYTX (LBINP,LBOUT,LINPG,LINPB,LG,LB,LOUTG,LOUTB,LTAP,BSTL,
     1JRYT,ICYT,YT,NB,NTL,NYT,OTPT,IWRITE)
C
C     SUBROUTINE FORMU CONSTRUCTS THE VECTOR OF BUS CONTROL
C     VARIABLES OF THE SYSTEM UNDER CONSIDERATION
C
      CALL FORMU (BTYP,BVMOD,BVARG,BGP,BLP,BLQ,BCV,NB,OTPT,IWRITE)
C
      DO 10 I=1,NB
      R1=BVMOD(I)
      R2=BVARG(I)
      V(I)=CMPLX(R1*COS(R2),R1*SIN(R2))
10    CONTINUE
      MODE=1
C
C     SUBROUTINE LFNCM SOLVES THE LOAD FLOW EQUATIONS USING
C     THE COMPLEX NEWTON METHOD
C
      CALL LFNCM (NB,NLB,NYT,JRYT,ICYT,BTYP,YT,V,BCV,WS,LWS,DSX,MODE,IFL
     1AG,OTPT,IWRITE)
      WRITE (OTPT,170) IFLAG
      IF (IFLAG.LT.0) GO TO 160
      N=NB-1
      WRITE (OTPT,180) NB
      DO 20 I=1,N
      J=2*I-1
      DLX(I)=DSX(J)
20    CONTINUE
C
      DO 30 I=1,N
      DR1(I)=0.0
      DR2(I)=0.0
      DS1(I)=0.0
```

```
      DS2(I)=0.0
30    CONTINUE
C
C     SENSITIVITIES OF P(SLACK) W.R.T. BUS-TYPE CONTROL VARIABLES
C
      ICODE=1
      DO 40 I=1,N
      CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,I,L2,DLX,NTL,ICODE,D
     1F1,DF2)
      DR1(I)=DF1
      DR2(I)=DF2
40    CONTINUE
C
      ICODE=2
      DO 50 I=1,N
      CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,I,L2,DLX,NTL,ICODE,D
     1F1,DF2)
      DS1(I)=DF1
      DS2(I)=DF2
50    CONTINUE
      WRITE (OTPT,190)
      WRITE (OTPT,200)
      DO 60 I=1,N
      IF (BTYP(I).NE.0) GO TO 60
      WRITE (OTPT,210) I,DR1(I),DR2(I),DS1(I),DS2(I)
60    CONTINUE
      WRITE (OTPT,220)
      WRITE (OTPT,230)
      DO 70 I=1,N
      IF (BTYP(I).NE.1) GO TO 70
      WRITE (OTPT,210) I,DR1(I),DR2(I),DS1(I),DS2(I)
70    CONTINUE
C
C     SENSITIVITIES OF P(SLACK) W.R.T. LINE CONTROL VARIABLES
C
      WRITE (OTPT,220)
      WRITE (OTPT,240)
      ICODE=3
      DO 80 I=1,NTL
      TAP1=REAL(LTAP(I))
      IF (TAP1.NE.1) GO TO 80
      L1=LBINP(I)
      L2=LBOUT(I)
      CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,L1,L2,DLX,NTL,ICODE,
     1DF1,DF2)
      WRITE (OTPT,250) I,LBINP(I),LBOUT(I),DF1,DF2
80    CONTINUE
C
C     SENSITIVITIES OF P(SLACK) W.R.T. TAP-CHANGING-UNDER-LOAD
C     TRANSFORMER CONTROL VARIABLES
C
      WRITE (OTPT,220)
      WRITE (OTPT,260)
      DO 110 I=1,NTL
      TAP1=REAL(LTAP(I))
      IF (TAP1.EQ.1) GO TO 110
      IF (I.EQ.93) GO TO 110
      IF (I.EQ.95) GO TO 110
      L1=LBINP(I)
      L2=LBOUT(I)
      ITN=0
      ICODE=6
90    CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,L1,L2,DLX,NTL,ICODE,
     1DF1,DF2)
      IF (ITN.EQ.1) GO TO 100
```

```
      DA=DF1
      ICODE=7
      ITN=ITN+1
      GO TO 90
100   DR=DF1
      DX=DF2
      WRITE (OTPT,270) LBINP(I),LBOUT(I),DA,DR,DX
110   CONTINUE
C
C     SENSITIVITIES OF P(SLACK) W.R.T. PHASE SHIFTING TRANSFORMER
C     CONTROL VARIABLES
C
      WRITE (OTPT,220)
      WRITE (OTPT,280)
      I=93
120   ITN=0
      ICODE=5
      L1=LBINP(I)
      L2=LBOUT(I)
130   CALL DERIVX (LBINP,LBOUT,LG,LB,LTAP,BTYP,V,NB,L1,L2,DLX,NTL,ICODE,
     1DF1,DF2)
      IF (ITN.EQ.1) GO TO 140
      DM=DF1
      DA=DF2
      ICODE=7
      ITN=ITN+1
      GO TO 130
140   DR=DF1
      DX=DF2
      WRITE (OTPT,290) LBINP(I),LBOUT(I),DM,DA,DR,DX
      IF (I.EQ.95) GO TO 150
      I=95
      GO TO 120
150   WRITE (OTPT,190)
C
160   STOP
170   FORMAT (///30X,"RETURN FLAG FROM LFNCM:",I3)
180   FORMAT ("1",16X,I3,"-BUS SYSTEM: SENSITIVITIES OF P(SLACK)")
190   FORMAT (/,1X,68("-"),/)
200   FORMAT (1X,"LOAD BUS QUANTITIES - TOTAL DERIVATIVES",//,5X,64("-")
     1,//,5X,"BUS",7X,"REAL",9X,"REACTIVE",9X,"SHUNT",10X,"SHUNT",/,15X,
     2"POWER",9X,"POWER",8X,"CONDUCTANCE",4X,"SUSCEPTANCE",//,5X,64("-")
     3,/,1X)
210   FORMAT (5X,I3,F13.6,3F15.6)
220   FORMAT (/,5X,64("-"),/)
230   FORMAT (1X,"GENERATOR BUS QUANTITIES - TOTAL DERIVATIVES",//5X,64(
     1"-"),//,5X,"BUS",7X,"REAL",10X,"VOLTAGE",9X,"SHUNT",10X,"SHUNT",/,
     215X,"POWER",8X,"MAGNITUDE",5X,"CONDUCTANCE",4X,"SUSCEPTANCE",//,5X
     3,64("-"),/,1X)
240   FORMAT (1X,"LINE QUANTITIES - TOTAL DERIVATIVES",//,5X,64("-"),//,
     15X,"LINE",5X,"ELEMENT",8X,"LINE",9X,"LINE",/,5X,"INDEX",15X,"CONDU
     2CTANCE",3X,"SUSCEPTANCE",//,5X,64("-"),/,1X)
250   FORMAT (5X,I3,6X,I3,",",I3,3X,F10.6,4X,F10.6)
260   FORMAT (1X,"TCUL TRANSFORMER QUANTITIES - TOTAL DERIVATIVES",//,5X
     1,64("-"),//,5X,"ELEMENT",5X,"TURNS RATIO",9X,"INTERNAL",11X,"INTER
     2NAL",/,36X,"RESISTANCE",9X,"REACTANCE",//,5X,64("-"),/,1X)
270   FORMAT (5X,I3,",",I3,F14.6,3X,2(F15.6,3X))
280   FORMAT (1X,"PHASE SHIFTER QUANTITIES - TOTAL DERIVATIVES",//,5X,64
     1("-"),//,5X,"ELEMENT",3X,"TURNS RATIO",3X,"TURNS RATIO",5X"INTERNA
     2L",6X,"INTERNAL",/,16X,"MAGNITUDE",4X,"PHASE ANGLE",4X,"RESISTANCE
     3",4X,"REACTANCE",//,5X,64("-"),/,1X)
290   FORMAT (5X,I3,",",I3,F12.6,2F14.6,1X,F14.6)
      END
```

```
C
      SUBROUTINE FORMMU (V,AI,NB,DS,DSL,IDER,YT,JRYT,ICYT,BTYP,NYT,OTPT)
C
C     SUBROUTINE FORMMU EVALUATES THE PARTIAL DERIVATIVES OF REAL
C     SLACK POWER W.R.T. COMPLEX BUS VOLTAGES AND THEIR CONJUGATES
C
      COMPLEX V(1),AI(1),DS(1),DF(118),YT(1),DSL,AV1,AV2
      INTEGER JRYT(1),ICYT(1),BTYP(1),IDER,OTPT
      N=NB-1
      DO 10 I=1,N
      DS(I)=(0.,0.)
      DF(I)=(0.,0.)
      DS(N+I)=(0.,0.)
10    CONTINUE
      DF(NB)=(0.,0.)
C
      DO 30 I=1,NB
      IF (I.NE.NB) GO TO 30
      KK=JRYT(I+1)-JRYT(I)
      DO 20 J=1,KK
      KJ=JRYT(I)+J-1
      KA=ICYT(KJ)
      AV1=YT(KJ)*CONJG(V(I))
      DF(KA)=DF(KA)+0.5*AV1
      AV2=CONJG(YT(KJ)*V(ICYT(KJ)))
      DF(I)=DF(I)+0.5*AV2
20    CONTINUE
30    CONTINUE
      DSL=DF(NB)
      DO 40 I=1,N
      J=2*I-1
      K=J+1
      DS(J)=DF(I)
      DS(K)=CONJG(DF(I))
40    CONTINUE
      RETURN
      END
```

118-BUS SYSTEM: SENSITIVITIES OF P(SLACK)

LOAD BUS QUANTITIES - TOTAL DERIVATIVES

BUS	REAL POWER	REACTIVE POWER	SHUNT CONDUCTANCE	SHUNT SUSCEPTANCE
2	-1.039480	-.001776	1.222015	-.002087
3	-1.036504	-.005536	1.284263	-.006860
5	-.995079	-.007493	1.152184	-.008676
7	-1.018347	-.000194	1.124920	-.000214
9	-.977067	.000778	1.172358	.000933
11	-1.027684	-.003698	1.141535	-.004108
13	-1.039668	-.007191	1.086555	-.007516
14	-1.030295	.000799	1.090055	.000845
16	-1.026259	-.007931	1.096103	-.008471
17	-1.005144	.002108	.968617	.002032
20	-1.033789	-.004819	.903283	-.004211
21	-1.028398	-.008006	.872155	-.006790
22	-1.014626	-.007771	.850805	-.006516
23	-.983963	-.001731	.832173	-.001464
28	-1.039391	-.148142	.446264	-.063605
29	-1.038307	-.072010	.528257	-.036636
30	-.998461	-.000823	1.097824	-.000904
33	-1.031377	-.005461	.952281	-.005042
35	-1.029373	-.001356	.953935	-.001257
37	-1.012143	-.005472	.951330	-.005143
38	-1.004240	-.002092	1.088326	-.002267
39	-1.061038	-.005893	.981905	-.005454
41	-1.090438	-.001984	1.084327	-.001973
43	-1.053792	-.002668	.966027	-.002446
44	-1.058629	-.003158	1.002369	-.002990
45	-1.052171	-.005841	1.006600	-.005588
47	-1.010749	.000872	1.038441	.000896
48	-1.005823	.001667	1.037093	.001719
50	-1.008318	-.001080	1.002412	-.001074
51	-1.025980	-.006817	.953519	-.006336
52	-1.031752	-.008662	.939432	-.007887
53	-1.025027	-.007288	.909682	-.006468
57	-1.020321	-.000690	.954047	-.000645
58	-1.027549	-.004319	.938594	-.003945
60	-.987745	.000007	.969808	.000007
63	-.978277	.001177	1.018111	.001225
64	-.969480	.000824	1.001903	.000852
67	-.970500	-.001316	1.012369	-.001372
68	-.996487	.011340	1.037755	.011810
69	-1.045342	.007383	.944950	.006674
71	-1.027714	.000585	.996009	.000567
75	-1.037294	.001418	.974123	.001331
78	-.982543	-.007871	.982164	-.007868
79	-.975549	-.007183	.987800	-.007273
81	-.952472	.001083	.960059	.001091
82	-.947823	-.005311	.928035	-.005200
83	-.927885	-.004839	.900134	-.004694
84	-.885244	-.005147	.854794	-.004970
86	-.863121	-.001071	.844713	-.001048
88	-.844329	-.002407	.821415	-.002341

93	-.895657	-.007314	.870630	-.007110
94	-.921829	-.008117	.903981	-.007960
95	-.937759	-.012071	.901174	-.011600
96	-.943976	-.006223	.928789	-.006123
97	-.947014	-.004244	.968086	-.004339
98	-.944671	-.001492	.991460	-.001566
101	-.901381	-.005396	.889725	-.005326
102	-.874498	-.002702	.858778	-.002654
106	-.977820	-.003407	.904207	-.003150
108	-.982431	-.000472	.917336	-.000441
109	-.985982	-.000648	.922193	-.000606
114	-1.026927	-.003365	.752992	-.002468
115	-1.027243	.002406	.712915	.001669
117	-1.037589	-.003583	1.116755	-.003856

GENERATOR BUS QUANTITIES - TOTAL DERIVATIVES

BUS	REAL POWER	VOLTAGE MAGNITUDE	SHUNT CONDUCTANCE	SHUNT SUSCEPTANCE
1	-1.050857	.882783	1.389758	0.000000
4	-1.032740	.726316	1.249615	0.000000
6	-1.013095	-.311308	1.121196	0.000000
8	-.994774	-.167660	1.181891	0.000000
10	-.957590	-.165486	1.106614	0.000000
12	-1.024958	-.571404	1.132170	0.000000
15	-1.029115	-.164177	.968294	0.000000
18	-1.024733	.081266	.964171	0.000000
19	-1.030086	-.162855	.949328	0.000000
24	-.995664	-.377848	.824509	0.000000
25	-.940147	.297842	.884584	0.000000
26	-.947080	-.220668	.966117	0.000000
27	-1.016621	-1.020986	.688587	0.000000
31	-1.024528	-1.433695	.628127	0.000000
32	-1.023842	.515771	.778513	0.000000
34	-1.033093	-.198182	.950116	0.000000
36	-1.031219	-.001704	.956321	0.000000
40	-1.077351	-.769418	1.013680	0.000000
42	-1.092801	1.205544	1.322289	0.000000
46	-1.026242	-.034182	1.026242	0.000000
49	-.992892	-.107537	1.033005	0.000000
54	-1.006052	-.459040	.907961	0.000000
55	-1.018023	-.034121	.918766	0.000000
56	-1.020272	-.256278	.920796	0.000000
59	-.987729	.229232	.968073	0.000000
61	-.965655	-.071162	.965655	0.000000
62	-.976510	-.071795	.976510	0.000000
65	-.959474	-.587420	.959474	0.000000
66	-.954143	.177197	1.053948	0.000000
70	-1.026790	-.014542	.986129	0.000000
72	-1.023735	.184778	.983195	0.000000
73	-1.029367	.064730	1.008883	0.000000
74	-1.046155	-.091067	.964137	0.000000
76	-1.018810	-.456361	.909822	0.000000
77	-.975753	-.110255	.995366	0.000000
80	-.945021	.463286	1.022135	0.000000
85	-.858860	-.313478	.841768	0.000000

87	-.856185	.013011	.873394	0.000000
89	-.822792	-.390672	.822792	0.000000
90	-.870385	.138436	.853065	0.000000
91	-.867543	-.096896	.833189	0.000000
92	-.860097	-.422372	.846391	0.000000
99	-.935353	-.084126	.954153	0.000000
100	-.919584	.230646	.956735	0.000000
103	-.945492	.251899	.964496	0.000000
104	-.962487	-.167148	.905604	0.000000
105	-.972445	-.234093	.905565	0.000000
107	-1.003723	-.021297	.905860	0.000000
110	-.990648	-.291774	.937876	0.000000
111	-.974205	-.011202	.935626	0.000000
112	-1.034338	.282971	.993378	0.000000
113	-1.012186	.595070	.992044	0.000000
116	-.989912	-.101326	.989912	0.000000

LINE QUANTITIES - TOTAL DERIVATIVES

LINE INDEX	ELEMENT	LINE CONDUCTANCE	LINE SUSCEPTANCE
1	1, 2	.005907	.000431
2	1, 3	.002608	.000663
3	4, 5	.005167	.002790
4	3, 5	.010658	.003982
5	5, 6	.001480	.000585
6	6, 7	.000100	.000056
7	8, 9	.015260	.002412
9	9, 10	.018509	.002885
10	4, 11	.002433	.000186
11	5, 11	.003263	.002010
12	11, 12	.000015	-.000013
13	2, 12	.002397	.000337
14	3, 12	.005473	-.000089
15	7, 12	.000109	.000073
16	11, 13	.001053	.000335
17	12, 14	.000470	.000032
18	13, 15	.003579	-.000271
19	14, 15	.003609	.000051
20	12, 16	.000277	.000140
21	15, 17	.001565	.000958
22	16, 17	.005243	.000160
23	17, 18	.001191	.000684
24	18, 19	.000103	.000037
25	19, 20	.000589	.000089
26	15, 19	.000097	.000002
27	20, 21	.000684	.000145
28	21, 22	.001604	.000472
29	22, 23	.006653	.002225
30	23, 24	.000221	.000157
31	23, 25	.018081	.005633
33	25, 27	.051632	.013823
34	27, 28	.025240	.016133
35	28, 29	.002822	.002589
37	8, 30	.001919	.000110
38	26, 30	.045091	.010806

39	17, 31	.036663	.000447
40	29, 31	.003828	.003464
41	23, 32	.009073	.003225
42	31, 32	.008225	.000007
43	27, 32	.002992	.000094
44	15, 33	.000184	.000066
45	19, 34	.000166	.000037
46	35, 36	.000003	.000004
47	35, 37	.000578	.000422
48	33, 37	.000392	.000398
49	34, 36	.000012	-.000003
50	34, 37	.000541	.000503
52	37, 39	.004096	.003041
53	37, 40	.007490	.005482
54	30, 38	.000993	.000194
55	39, 40	.000580	.000388
56	40, 41	.001487	.000161
57	40, 42	.020740	.000275
58	41, 42	.011793	.000203
59	43, 44	.001486	-.000167
60	34, 43	.000052	.000155
61	44, 45	.000756	.000160
62	45, 46	.001969	.001185
63	46, 47	.000703	.000422
64	46, 48	.001111	.000713
65	47, 49	.000638	.000487
66	42, 49	.075668	.025329
67	76, 69	.000428	.000527
68	45, 49	.009025	.005811
69	48, 49	.000328	.000256
70	49, 50	.000756	.000393
71	49, 51	.004163	.001993
72	51, 52	.000151	.000068
73	52, 53	.000237	-.000004
74	53, 54	.000960	.000568
75	49, 54	.004715	.000349
76	75, 69	.000222	-.000046
77	54, 55	.000458	.000242
78	54, 56	.000398	.000268
79	55, 56	.000002	-.000003
80	56, 57	.000304	-.000011
81	50, 57	.000996	.000233
82	56, 58	.000136	.000018
83	51, 58	.000066	-.000014
84	54, 59	.001548	.000459
85	56, 59	.002473	.001453
86	12, 117	.000760	.000382
87	55, 59	.002695	.001396
88	59, 60	.001379	-.000001
89	59, 61	.005479	.001662
90	60, 61	.001308	.000841
91	60, 62	.000359	.000220
92	61, 62	.000338	.000203
94	63, 64	.000695	.000235
96	38, 65	.028028	.007030
97	64, 65	.002111	.000440
98	49, 66	.013829	.004827
99	68, 116	.000603	.000337
100	62, 66	.004960	.001403
101	62, 67	.000635	.000086
103	66, 67	.002143	.000759
104	65, 68	.004657	.002720
105	47, 118	-.016239	.035168

106	49,118	-.010104	.006947
108	118, 70	-.049288	.046071
109	24, 70	.008643	.001179
110	70, 71	.000036	.000006
111	24, 72	.008723	.001155
112	71, 72	.000038	.000003
113	71, 73	.000059	.000003
114	70, 74	.000506	.000399
115	70, 75	.000036	.000042
116	118, 75	-.060013	.051863
117	74, 75	.000282	.000146
118	76, 77	.010451	.003985
119	118, 77	-.017906	-.060490
120	75, 77	.010911	.006554
121	77, 78	.000153	.000133
122	78, 79	.000137	.000085
123	77, 80	.003669	.001967
124	114,115	.000542	-.000113
125	79, 80	.003740	.002054
126	68, 81	.004339	.003053
128	77, 82	.003336	.001562
129	82, 83	.001239	.000670
130	83, 84	.003983	.002730
131	83, 85	.009680	.007021
132	84, 85	.001259	.001004
133	85, 86	.000061	.000034
134	86, 87	.000969	.000221
135	85, 88	.002767	.000834
136	85, 89	.014305	.004715
137	88, 89	.004538	.001596
138	89, 90	.010502	.005362
139	27,115	.000601	.000205
140	90, 91	.000120	.000007
141	89, 92	.008457	.003773
142	32,114	.000240	.000056
143	91, 92	.000113	.000069
144	92, 93	.004145	.002355
145	92, 94	.012792	.007037
146	93, 94	.002389	.001255
147	94, 95	.000667	.000439
148	80, 96	.002224	.000300
149	82, 96	.000109	.000041
150	94, 96	.001520	.000888
151	80, 97	.000775	.000134
152	80, 98	.000280	.000021
153	80, 99	.001361	.000151
154	92,100	.015461	.007244
155	94,100	.000729	.000231
156	95, 96	.000315	.000153
157	96, 97	.000443	.000059
158	98,100	.002316	.001211
159	99,100	.000562	.000417
160	100,101	.002110	.000798
161	92,102	.000839	.000428
162	101,102	.002839	.001430
163	100,103	.002176	.001319
164	100,104	.007399	.003724
165	103,104	.002233	.000640
166	103,105	.003745	.001488
167	100,106	.012454	.006701
168	104,105	.000277	.000170
169	105,106	.000086	.000053
170	105,107	.002495	.001571

171	105,108	.000303	.000163
172	106,107	.001643	.001054
173	108,109	.000044	.000021
174	103,110	.007701	.004073
175	109,110	.000170	.000053
176	110,111	.000708	.000450
177	110,112	.003358	.002325
178	17,113	.000170	.000021
179	32,113	.013191	-.000185

TCUL TRANSFORMER QUANTITIES - TOTAL DERIVATIVES

ELEMENT	TURNS RATIO	INTERNAL RESISTANCE	INTERNAL REACTANCE
8, 5	.316354	11.930163	-.084332
26, 25	-.004820	.529850	-.131223
30, 17	-.058476	5.266261	.337658
38, 37	.094365	5.157105	.443463
66, 65	-.000316	9.261379	-.008021
118, 68	-1.670888	-13.543352	-36.080895
81, 80	.037468	.371101	.078608

PHASE SHIFTER QUANTITIES - TOTAL DERIVATIVES

ELEMENT	TURNS RATIO MAGNITUDE	TURNS RATIO PHASE ANGLE	INTERNAL RESISTANCE	INTERNAL REACTANCE
63, 59	.039796	.239011	1.860750	.312149
64, 61	.029692	-.142203	.000229	-.009722

VII. REFERENCES

[1] J.W. Bandler and M.A. El-Kady, "Newton's load flow in complex mode", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-80-2-R, 1980.

[2] J.W. Bandler, M.A. El-Kady and H. Gupta, "XLF1 - A program for complex load flow analysis by conjugate elimination", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-81-15, 1981.

[3] J.W. Bandler, M.A. El-Kady, H.K. Grewal and H. Gupta, "XLF2 - A program for analysis and sensitivity evaluation of complex load flows by the complex Lagrangian method", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-82-7, 1982.

[4] J.W. Bandler and M.A. El-Kady, "A generalized, complex adjoint approach to power network sensitivities", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-80-17-R, 1980.

[5] G.W. Stagg and A.H. El-Abiad, Computer Methods in Power System Analysis. New York: McGraw-Hill, 1968.

[6] Z.X. Han, "Phase shifter and power flow control", IEEE Trans. Power Apparatus and Systems, vol. 101, 1982, pp. 3790-3795.

[7] J.W. Bandler, M.A. El-Kady and J. Wojciechowski, "Formatted data files for test power systems", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-83-9D, 1983.

[8] I.S. Duff, "A survey of sparse matrix research", Proc. IEEE, vol. 65, 1977, pp. 500-535.

[9] M.A. El-Kady, "A unified approach to generalized network sensitivities with applications to power system analysis and planning", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-80-10-T, 1980.

[10] "Document SOC-D2: ME28, sparse matrix techniques", Origin of the package: Harwell Subroutines Library, AERE, Harwell, Oxfordshire, England.

[11] J.W. Bandler, M.A. El-Kady and H.K. Grewal, "Application of the complex Lagrangian approach to non-reciprocal power networks", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-83-22-R, 1983.

[12] B. Stott, "Review of load-flow calculation methods", Proc. IEEE, vol. 62, 1974, pp. 916-926.

[13] C.A. Gross, Power System Analysis. New York: Wiley, 1979.

[14] W.F. Tinney and J.W. Walker, "Direct solutions of sparse network equations by optimally ordered triangular factorization", Proc. IEEE, vol. 55, 1967, pp. 1801-1809.

[15] J.E. Van Ness and J.H. Griffin, "Elimination methods for load flow studies", AIEE Trans. Power Apparatus and Systems, vol. 80, 1961, pp. 299-302.

[16] J.W. Bandler, M.A. El-Kady and H.K. Grewal, "Sensitivity evaluation and optimization of the IEEE 118-bus power system", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-83-19-R, 1983.

[17] J.W. Bandler, M.A. El-Kady and J. Wojciechowski, "TTM1 - A Fortran implementation of the Tellegen theorem method to power system simulation and design", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-82-12-U2, 1983.

[18] J.W. Bandler, M.A. El-Kady, H.K. Grewal and J. Wojciechowski, "XLF3 - A Fortran implementation of the complex Lagrangian method to power system analysis and design", Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, Report SOS-83-18-L, 1983.

[19] "American Electric Power 118 Bus Test System", American Electric Power Service Corporation, New York, NY, December 1962.