WARDEQ - A FORTRAN IMPLEMENTATION OF THE WARD TYPE POWER EQUIVALENTS

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SOS-83-24-U

October 1983

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WARD TYPE POWER EQUIVALENTS

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Abstract

WARDEQ is a package of forty subroutines for determining the Ward-type external equivalents and for formulating the load flow problem for the reduced power systems. The external equivalent can be formed by subroutines of the package as: standard Ward equivalent, Ward equivalent with buffer zone, extended Ward equivalent and simplified extended Ward equivalent. The subroutine for contingency analysis of the reduced power system is also included. The TTM1 package is employed to solve the load flow equations. The package and documentation have been developed for the CDC 170/730 systems with the NOS 1.4 level 552 operating system and the Fortran Extended (FTN) version 4.8 compiler. Several numerical examples illustrate the use of WARDEQ in contingency analysis.

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

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I. INTRODUCTION

The computer program package called WARDEQ implements the practical WARD-type equivalent methods. The main purpose of the package is to determine for a power system with boundary buses its external equivalent or to formulate the load flow problem (i.e., the nodal admittance matrix, bus control variables and initial bus voltages) for the reduced power system.

The external equivalent can be formed by the subroutines of the package as

- standard Ward equivalent (the model with shunts in the external system) [1-4]
- standard Ward equivalent (the model without shunts in the external system) [1-4]
- Ward equivalent with buffer zone [5]
- extended Ward equivalent [1-4]
- simplified Ward equivalent [1,2,4].

The load flow problem for the reduced power system can be formulated with any of the external equivalents mentioned above.

In order to solve typical problems of on-line and off-line analysis of the power system, the user has to supply the main program where the subroutines of the WARDEQ package and his own subroutines are called.

Because typical problems in the simulation of power systems can be solved using the TTM1 computer package [6] the user can employ in the main program the subroutines from the TTM1 package in order to read the data files, to formulate the load flow problem for the unreduced (interconnected) power system, to determine the load flow solution of the reduced system and to calculate the sensitivity in the reduced power system.

The package has been investigated by solving the load-flow problem for changes of the operating conditions in the internal system of the reduced 26-bus system (Saskatchewan Power Corporation System) [7,8] and the IEEE 118-bus power system [9]. The whole package is written in Fortran IV for the CDC 170/730 system. At McMaster University it is available in the form of a library of binary relocatable subroutines which are linked with the user's program by the appropriate call to the main subroutine in the package. The name of the library is LIBWARD. The library is available as a group indirect file under the charge RJWBAND. The general sequence of NOS commands to use the package can be as follows:

/GET,LIBWARD/GR.- fetch the library,

/LIBRARY,LIBWARD.- indicate the library to the loader,

/FTN,...,GO.- compile, load and execute the program.

This document contains the user's manual of the package WARDEQ. A Fortran listing of the package is found in [10].

II. STRUCTURE OF THE PACKAGE

There are two different entries to the package and two corresponding main subroutines.

1. subroutine EQWARD - standard entry for determination of the external equivalent and to formulate the load flow problem for the reduced power system,
2. subroutine EQCONTI - entry for contingency analysis of the reduced power system.

The overall organization of the package is shown in Fig. 1. The subroutine EQWARD of the package checks the formal correctness of some parameters defined by the user, calls the subroutines EQDEIE, EQEXEQ, EQFORM and sets the return flag appropriately. The block diagram for this subroutine is shown in Fig. 2.

The subroutine EQDEIE is a higher level subroutine. It determines the buses of the interconnected power sytem belonging to the internal system, prepares the renumbering of the buses of the power system and renumbers the vectors describing the topology of the power system. This subroutine calls the following subroutines:

ORDEVE this subroutine forms the adjacency matrix of the graph of the interconnected power system,

INTERV this subroutine determines the buses belonging to the internal system,

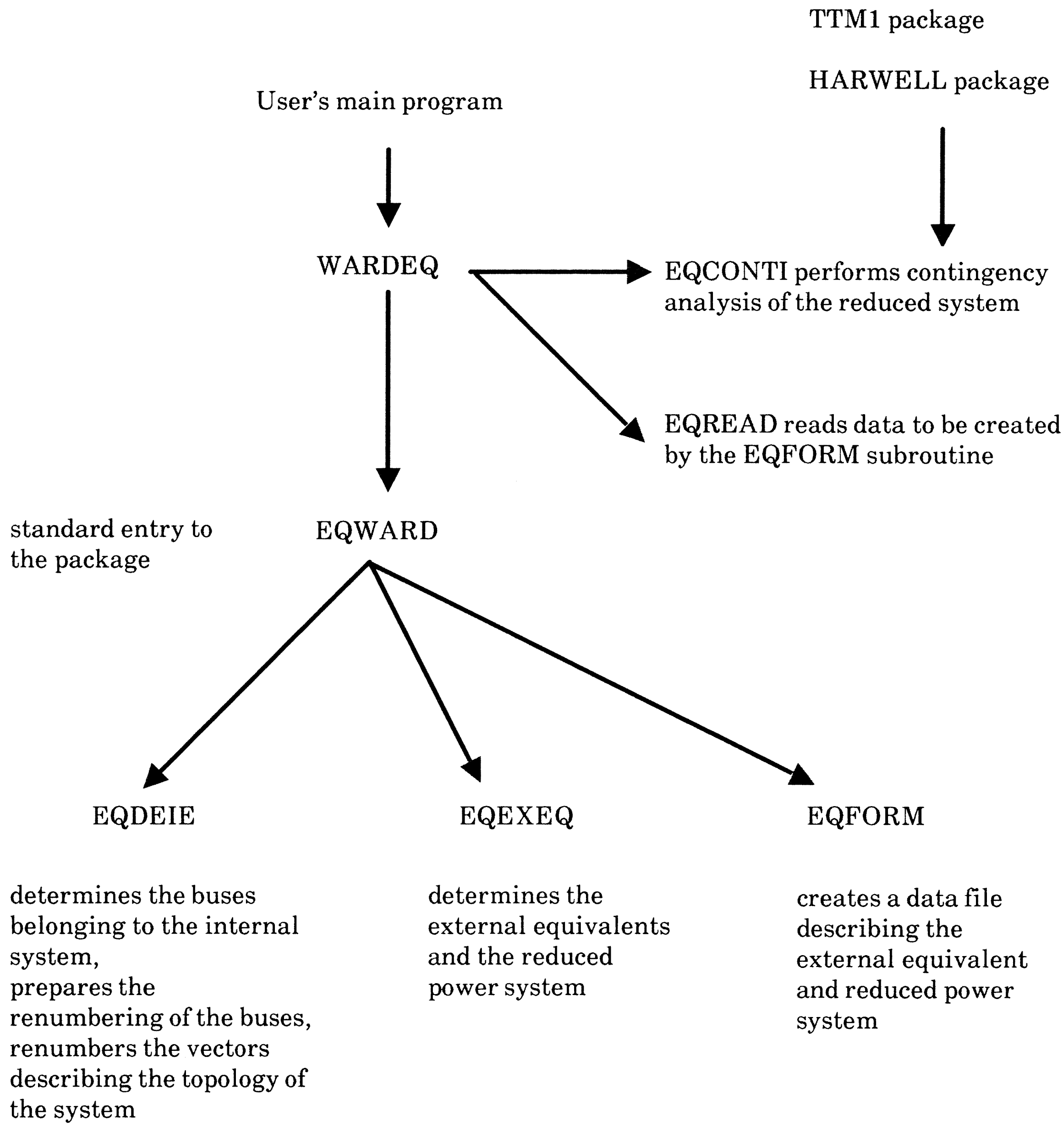

Fig. 1 Overall organization of the WARDEQ package.

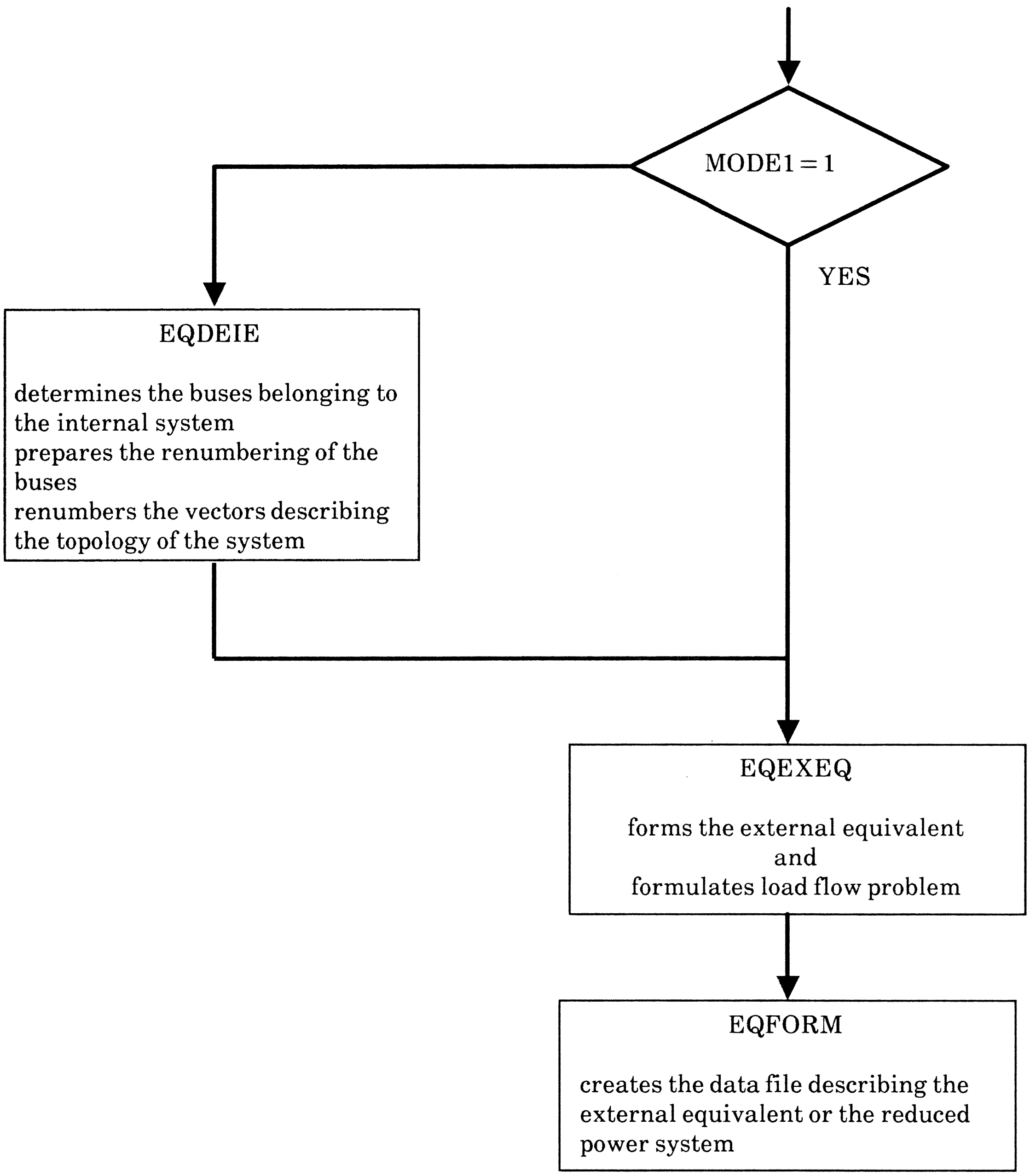

Fig. 2 Overall organization of the EQWARD subroutine.

CHNUMB this subroutine prepares the new indices of the buses of the interconnected power system,

CHANGI this subroutine renumbers the vectors describing the topology of the interconnected power system.

The structure of the subroutine EQDEIE is shown in Fig. 3.

The subroutine EQEXEQ is a higher level subroutine. It forms an external equivalent whose type is declared by the user or formulates the load flow problem of the reduced power system, i.e., the bus admittance matrix of the reduced power system, the bus control variables and the initial values of bus voltages. The subroutine EQEXEQ calls the following subroutines:

EQWAES this subroutine sets to zero the real part of the elements of the bus admittance matrix corresponding to the external system,

EQREMS this subroutine removes the shunt conductance and susceptance in the external system,

EQWEES this subroutine calculates the number and values of fictitious branches,

EQDRCI this subroutine divides the bus admittance matrix of the unreduced power system into the bus admittance matrix of the internal system and the bus admittance matrix of the external system,

GAUSEL this subroutine performs Gaussian elimination for a system of N equations,

EQINRC this subroutine attaches the external equivalent to the internal system and determines the admittance matrix of the reduced system,

EQINBR this subroutine attaches the fictitious branches to the relevant boundary buses,

EQBCV this subroutine determines the values of the bus control variables of the reduced power system.

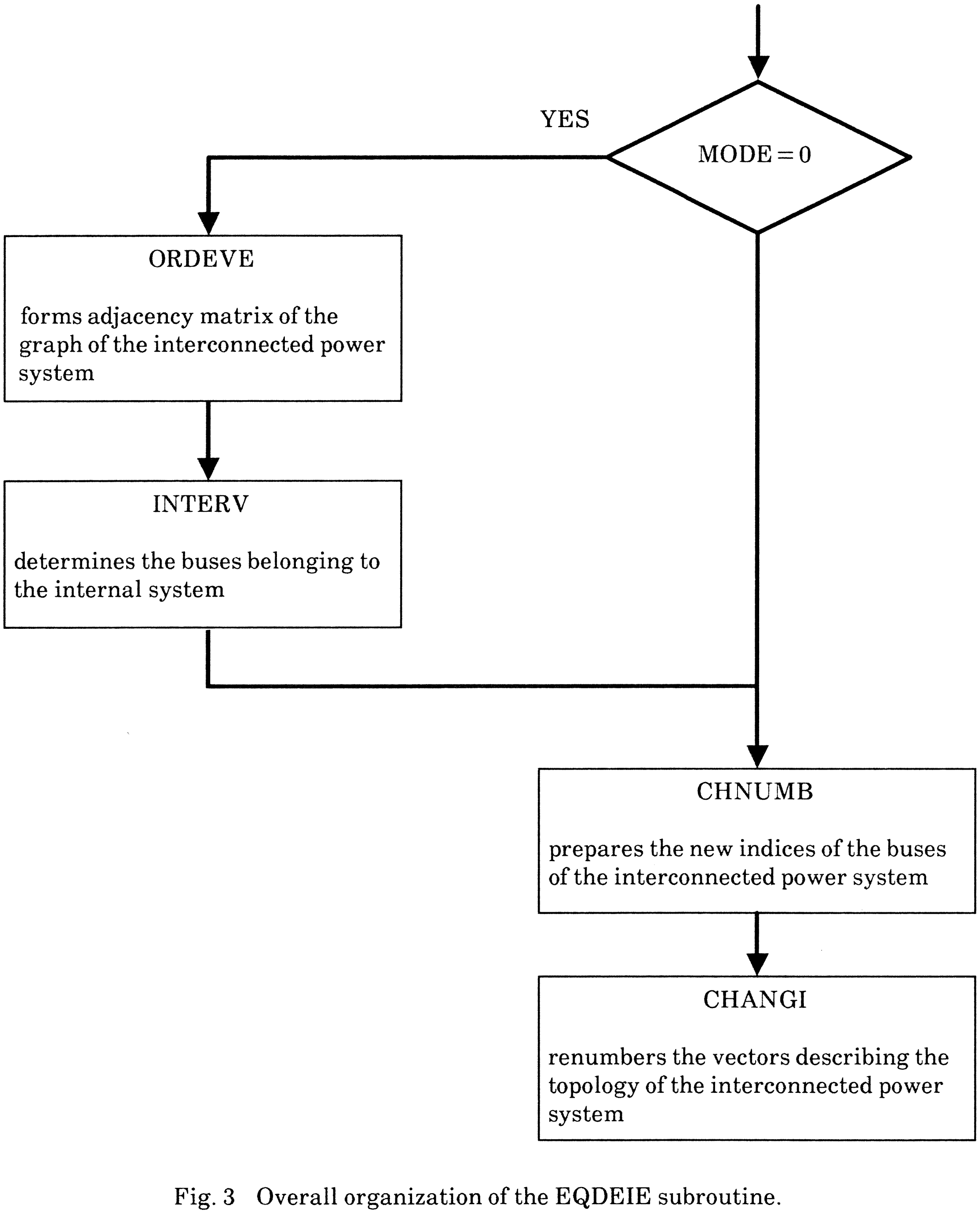

Fig. 3 Overall organization of the EQDEIE subroutine.

The EQEXEQ subroutine calls also subroutines CHNGJ, CHNGC, CHNGP, CHNGAD, and SPAMAT to perform renumbering and reordering of appropriate vectors. The overall organization of the EQEXEQ subroutine is shown in Fig. 4.

Two lower level subroutines of the package are dedicated for data manipulation, namely EQFORM and EQREAD. The subroutine EQFORM creates in a unified form the data file describing the external equivalents or the reduced power system and it is called by the subroutine EQWARD. The subroutine EQREAD reads data from the created data files.

To enable the user to perform a contingency analysis the highest level subroutine EQCONTI has been included in the package. This subroutine determines the load flow solution for a single line outage in the internal part of the reduced power system and compares the results of analysis for the unreduced and reduced power system. The subroutine EQCONTI calls the subroutine LFLFD1M from the TTM1 package [6] and subroutine MA28 from the Harwell Subroutine Library [11], therefore these libraries have to be available when EQCONTI is used.

In Table I, in alphabetical order, all subroutines of the WARDEQ package are listed. The description of the higher level subroutines EQDEIE, EQEXEQ and the subroutines EQFORM, EQREAD is given in Section VI.

III. LIST OF ARGUMENTS

Standard Entry

The subroutine call is

CALL EQWARD (NB, NLB, NTL, LBINP, LBOUT, YT, JRYT, ICYT, BTYP, V, BCV, NBOUND, JBOUND, NRET, JRET, NEWNUM, IOLDNU, IBINTE, NEXT, NFIC, WSP, LWSP, MODE1, MODE2, MODE3, OTPT, INPT, IFLAG, IWRITE)

The arguments are as follows.

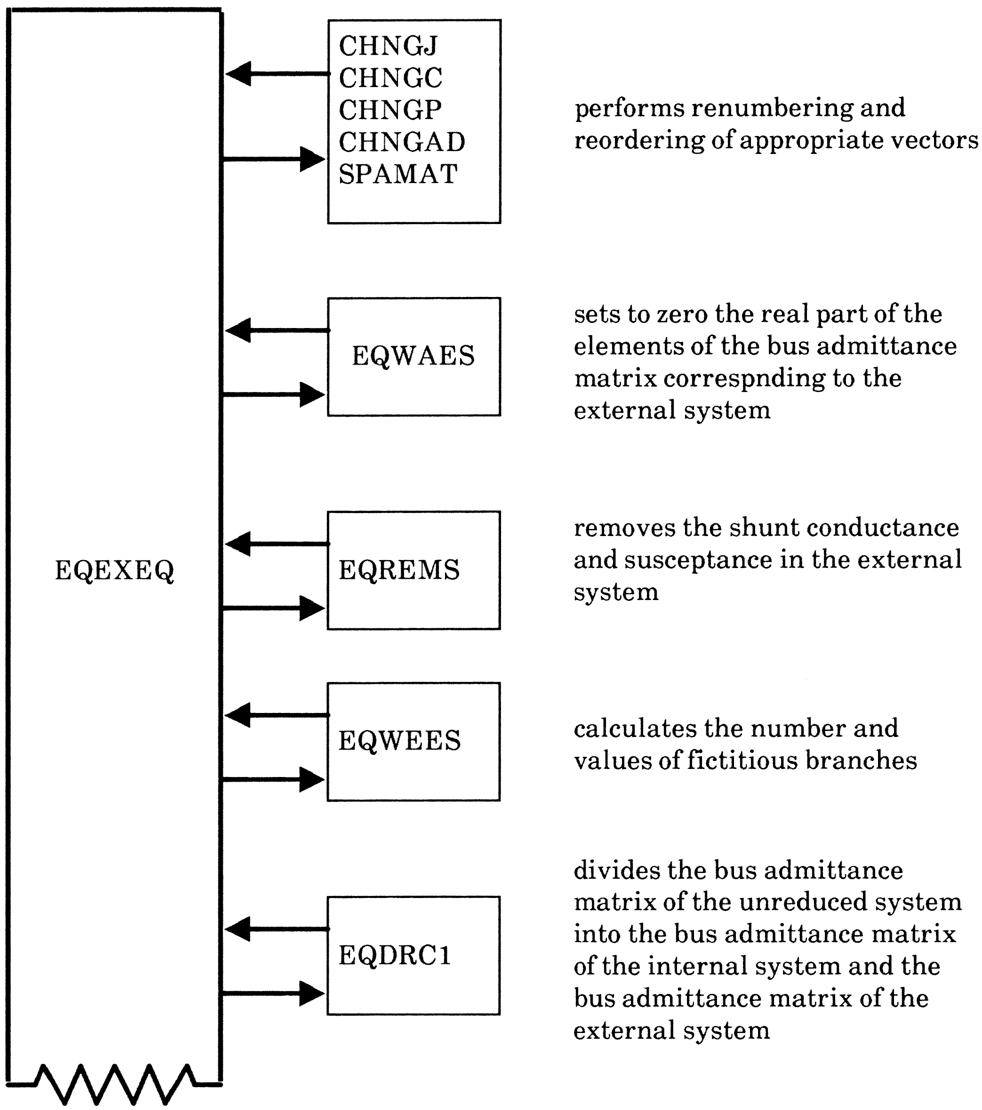

Fig. 4 Overall organization of the EQEXEQ subroutine.

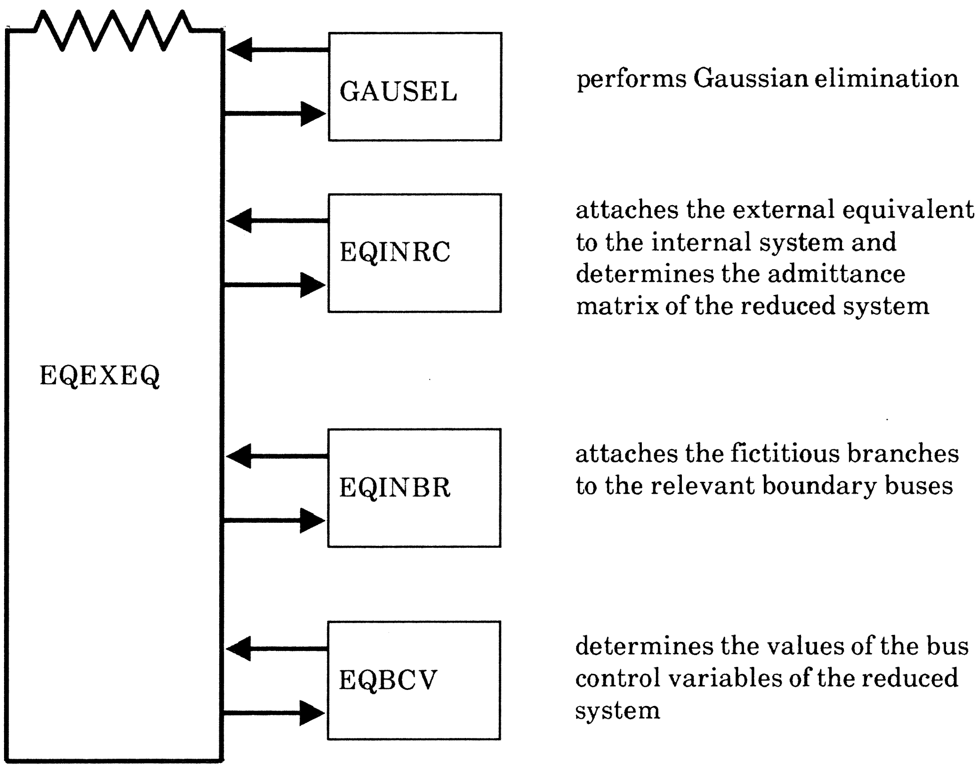

Fig. 4 Overall organization of the EQEXEQ subroutine. (Cont'd)

TABLE I

LIST OF SUBROUTINES OF THE WARDEQ PACKAGE

No.	Subroutine	Number of lines (source text)	Number of words (compiled code)	Description (page)	Listing (page of [10])
1	ASUB	132	364		5
2	BELONG	18	34		7
3	CHNGAD	31	47		7
4	CHNGC	22	31		7
5	CHNGI	14	14		8
6	CHNGJ	21	24		8
7	CHNGP	24	30		8
8	CHNUMB	66	104		9
9	EQBCV	171	445		10
10	EQCCC	61	240		12
11	EQCOMP	275	1412		13
12	EQCONTI	148	501	18	17
13	EQCURR	19	35		20
14	EQDDD	48	65		20
15	EQDEIE	107	355	44	22
16	EQDRCI	71	113		23
17	EQEXEQ	183	736		24
18	EQFORM	128	454	49	27
19	EQINBR	70	121		29
20	EQMOSO	41	47		31
21	EQINRC	43	111		30
22	EQREAD	154	774	52	31
23	EQREEY	21	31		35
24	EQREMS	30	31		35
25	EQWAES	48	53		35
26	EQWARD	146	531	8	36
27	EQWEES	164	433		38
28	GAUSEL	41	76		41
29	INTERV	53	61		41

TABLE I

LIST OF SUBROUTINES OF THE WARDEQ PACKAGE (cont'd)

No.	Subroutine	Number of lines (source text)	Number of words (compiled code)	Description (page)	Listing (page of [10])
30	MOVE	36	41		42
31	NOTE	14	25		43
32	ORDEVE	65	55		43
33	PRINAD	24	125		44
34	PRINTNC	43	236		44
35	RDATA	32	67	53	45
36	SETBIN	14	27		46
37	SETBIT	12	13		46
38	SETVEC	108	241		46
39	SPAMAT	72	117		48
40	ZERO	13	12		49

NB — is an INTEGER argument. On entry it must be set to the number of the buses of the unreduced system. On return from the subroutine NB is equal to the number of the buses of the reduced system.

NLB — is an INTEGER argument. On entry it must be set to the number of the load buses of the unreduced power system. On return from the subroutine NLB is equal to the number of the load buses of the reduced power system.

NTL — is an INTEGER argument. On entry it must be set to the number of the transmission lines of the unreduced power system. Not altered by the subroutine.

LBINP, LBOUT

are INTEGER vectors of dimension NTL. On entry LBINP(k), LBOUT(k) must be set to the indices of the buses incident with the kth line (k = 1,...,NTL). On return from the subroutine LBINP(k), LBOUT(k) equal the indices of buses incident with the kth line after renumbering.

YT — is a COMPLEX vector of dimension NB + 2*NTL. On entry it must contain all the nonzero elements of the bus admittance matrix of the unreduced power system. On return from the subroutine it stores all the nonzero elements of the admittance matrix of the reduced power system (for more details, see p. 16).

JRYT — is an INTEGER vector of dimension NB + 1. On entry it must contain the row indices of the sparse bus admittance matrix of the unreduced power system. On return from the subroutine it stores the row indices of the sparse bus admittance matrix of the reduced power system.

ICYT — is an INTEGER vector of dimension NB + 2*NTL. On entry it must contain the column indices of the sparse bus admittance matrix of the unreduced power system. On return from the subroutine it stores the column indices of the sparse admittance matrix of the reduced power system.

BTYP is an INTEGER vector of dimension NB. On entry it must contain bus types (0 for load, 1 for generator bus, 2 for slack bus) of the unreduced system. On return from the subroutine it stores bus types of the reduced power system.

V is a COMPLEX vector of dimension NB. On entry it must contain the initial values of the bus voltages (in rectangular form) of the unreduced power system. On return it stores the initial values of the bus voltages (in the same form) of the reduced power system (for more details, see p. 17).

BCV is an INTEGER vector of dimension 2*NB. On entry it must contain scheduled values of the bus control variables of the unreduced power system. On return from the subroutine it stores the bus control variables of the reduced power system (for more details see p. 17).

NBOUND is an INTEGER argument. On entry it must be set to the number of the boundary buses. Not altered by the subroutine.

JBOUND is an INTEGER vector of dimension NBOUND. On entry it must contain indices of the buses belonging to the boundary. Not altered by the subroutine.

NRET is an INTEGER argument. On entry it must be set to the number of retained buses. Not altered by the subroutine.

JRET is an INTEGER vector of dimension NRET. On entry it must contain the indices of the buses belonging to the buffer zone. Not altered by the subroutine.

NEWNUM is an INTEGER vector of dimension NB. On return from the subroutine NEWNUM(k) stores a new index of the kth bus (k = 1, ..., NB).

IOLDNU is an INTEGER vector of dimension NB. On return from the subroutine IOLDNU(k) stores the old index of the kth bus (k = 1, ..., NB).

IBINTE is an INTEGER vector of dimension NB. On return from the subroutine IBINTE(k) = 1 indicates that the kth bus belongs to the internal system, (k = 1,...,NB).

NEXT is an INTEGER argument. On return from the subroutine it is equal to the number of the buses belonging to the external system.

NFIC is an INTEGER argument. On return from the subroutine it stores the number of fictitious buses.

WSP is a REAL vector of dimension LWSP. WSP is used as workspace by a set of subroutines.

LWSP is the length of the workspace. It must be at least

LWSP=4*(NRET+NBOUND) + 11*NB+12*(JRYT(NB+1)−1).

MODE1 is an INTEGER argument. It must be set by the user to select the required mode of the work,

0 normal entry,

1 only subroutine EQEXEQ is called.

MODE2 is an INTEGER argument. It must be set by the user to select the required mode of the work,

0 the load flow problem is formulated for the reduced power system,

1 an external equivalent is determined.

MODE3 is an INTEGER argument. It must be set by the user to select the required type of the external equivalent,

1 - standard Ward equivalent without shunts in the external system,

2 - standard Ward equivalent with buffer zone,

3 - extended Ward equivalent,

4 - simplified Ward equivalent,

5 - standard Ward equivalent with the shunts in the external system.

OTPT index of the output unit, INTEGER parameter.

INPT index of the input unit, INTEGER parameter.

IFLAG return flag from the subroutine

0 normal return,

−1 the length of the workspace for Gaussian elimination is too small,

−2 the length of the workspace for the subroutine EQDEIE is too small,

−3 the length of the workspace for the subroutine EQEXEQ is too small,

−5 the parameter MODE1 is incorrect,

−6 the parameter MODE2 is incorrect,

−7 the parameter MODE3 is incorrect.

IWRITE parameter that controls output; for details see the description of the subroutines EQDEIE, EQEXEQ, and EQFORM, p. 44.

Remarks

1. The bus admittance matrix must be stored in a sparse form with the use of vectors YT, JRYT, ICYT. If the bus admittance matrix **Y** is

$$\mathbf{Y} = \begin{bmatrix} y_{11} & 0 & y_{13} & y_{14} \\ 0 & y_{22} & 0 & y_{24} \\ y_{13} & 0 & y_{33} & 0 \\ y_{14} & y_{24} & 0 & y_{44} \end{bmatrix} ,$$

then on entry to the EQWARD subroutine, vectors YT, JRYT and JCYT should be:

$$YT = [y_{11}, y_{13}, y_{14}, y_{22}, y_{24}, y_{33}, y_{13}, y_{44}, y_{14}, y_{24}] ,$$

$$JRYT = [1,4,6,8,11], \qquad JCYT = [1,3,4,2,4,3,1,4,1,2] .$$

The elements of the vector JRYT are computed according to formula

$$JRYT(I) = JRYT(I-1) + N_{I-1},$$

where N_{I-1} is equal to the number of the elements in the (I−1)th row, I=2, ..., NB+1, and JRYT(1) = 1.

2. The vector of bus control variables is defined as follows.

a) if the ith bus is a load bus

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

$$BCV(\ell) = -BLQ(i),$$

b) if the ith bus is a generator bus

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

$$BCV(\ell) = BVMOD(i),$$

c) if the ith bus is a slack bus

$$BCV(k) = BVMOD(i),$$

$$BCL(\ell) = BVARG(i),$$

where $k = 2^*i-1$, $\ell = 2^*i$, $i=1, ..., NB$, and

BGP(i) - is the value of the ith bus generated active power,

BLP(i) - is the value of the ith bus consumed active power,

BLQ(i) - is the value of the ith bus consumed reactive power,

BVMOD(i) - is the value of the modulus of the ith bus voltage,

BVARG(i) - is the value of the argument of the ith bus voltage.

3. If the external equivalent is determined the elements of the vector V can be set to zero with the exception of the elements corresponding to the boundary and retained buses. All elements of the vector BCV can also be set to zero.

4. If the load flow problem for the reduced system is formulated, the elements of the vectors V and BCV corresponding to the buses which belong to the external system can be set to zero.

5. If parameter MODE1 = 1, the vectors NEWNUM, IOLDNU, IBINTE should be initialized before entry to the EQWARD subroutine, the new indices of the buses have to be prepared as indicated by the vector IBINTE shown below.

1 ... NEXT	NRET	NBOUND	NB-bus
external buses	retained buses	boundary buses	internal buses

vector IBINTE

6. It is assumed that the buses are numbered consecutively from 1 to NB. The slack bus has the highest index and it has to belong to the internal system.

Entry for Contingency Analysis of the Reduced Power System

The subroutine call is

CALL EQCONTI (INB, NB, NLB, NEXT, NFIC, NBOUND, JBOUND, NRET, JRET, BTYP, BCV, V, NEWNUM, IOLDNU, IBINTE, YT, JRYT, ICYT, LBINP, LBOUT, NTL, MODE3, NEL, NLIN, LINPG, LINPB, LG, LB, LOUTG, LOUTB, LTAP, BV, ITEL, TOLV, T, WSP, LWSP, ICONT, IFLAG, INPT, OTPT, IFOREQ, IWRITE, IPRINT)

The arguments are as follows.

INB is an INTEGER argument. On entry it must be set to the number of the buses of the unreduced system. Not altered by the subroutine.

NB is an INTEGER argument. On entry it must be set to the number of buses of the reduced system. Not altered by the subroutine.

NLB is an INTEGER argument. On entry it must be set to the number of load buses of the reduced system. Not altered by the subroutine.

NEXT is an INTEGER argument. On entry it must be set to the number of buses belonging to the external system. Not altered by the subroutine.

NFIC is an INTEGER argument. On entry it must be set to the number of fictitious buses. Not altered by the subroutine.

NBOUND is an INTEGER argument. On entry it must be set to the number of boundary buses. Not altered by the subroutine.

JBOUND is an INTEGER vector of dimension NBOUND. On entry it must contain the indices of the buses belonging to the boundary. Not altered by the subroutine.

NRET is an INTEGER argument. On entry it must be set to the number of retained buses. Not altered by the subroutine.

JRET	is an INTEGER vector of dimension NRET. On entry it must contain the indices of the buses belonging to the buffer zone. Not altered by the subroutine.
BTYP	is an INTEGER vector of dimension NB. On entry it must contain bus types (0 for load, 1 for generator bus, 2 for slack bus) of the reduced system. Not altered by the subroutine.
BCV	is a REAL vector of dimension 2*NB. On entry it must contain values of the bus control variables of the reduced system. Not altered by the subroutine.
V	is a COMPLEX vector of dimension NB. On entry it must contain the initial values of the bus voltages (in rectangular form) of the reduced system. On return from the subroutine, the vector V stores the updated values of the bus voltages (load flow solution after removing the NLINth transmission line from the reduced power system).
NEWNUM	is an INTEGER vector of dimension NB. On entry NEWNUM(k) must contain a new index of the kth bus (k=1, ..., NB). Not altered by the subroutine.
IOLDNU	is an INTEGER vector of dimension NB. On entry IOLDNU(k) must contain the old index of the kth bus (k=1, ..., NB).
IBINTE	is an INTEGER vector of dimension NB. On entry IBINTE(k) must be set to one if the kth bus belongs to the internal system (k=1, ..., NB). Not altered by the subroutine.
YT	is a COMPLEX vector of dimension NEL. On entry it must contain all nonzero elements of the bus admittance matrix of the reduced power system. 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 of the reduced power system. Altered by the subroutine.

ICYT is an INTEGER vector of dimension NEL. On entry it must contain the column indices of the sparse bus admittance matrix of the reduced power system. Altered by the subroutine.

LBINP, LBOUT

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

NTL is an INTEGER argument. On entry it must be set to the number of the transmission lines of the unreduced system. Not altered by the subroutine.

MODE3 is an INTEGER argument. On entry it must be set to the number determining the type of the external equivalent (see description of the subroutine EQWARD). Not altered by the subroutine.

NEL is an INTEGER argument. It is equal to the number of nonzero elements of the bus admittance matrix of the reduced system.

NLIN is an INTEGER argument. On entry it must be set to the index of the transmission line to be removed. Not altered by the subroutine.

LINPG, LINPB

are REAL vectors of dimension NTL. On entry LINPG(k), LINPB(k) must be equal to the value of the input shunt conductance and susceptance of the kth transmission line (k = 1, ..., NTL) of the unreduced system. Not altered by the subroutine.

LG,LB are REAL vectors of dimension NTL. On entry LG(k), LB(k) must be equal to the value of the conductance and susceptance of the kth transmission line (k = 1, 2, ..., NTL) of the unreduced system. Not altered by the subroutine.

LOUTG, LOUTB

are REAL vectors of dimension NTL. On entry LOUTG(k), LOUTB(k) must be equal to the value of the output shunt conductance and susceptance of the kth transmission line (k = 1, 2, ..., NTL) of the unreduced system. Not altered by the subroutine.

LTAP is a REAL vector of dimension NTL. On entry LTAP(k) must be equal to the value of the kth line transformer ratio. Not altered by the subroutine.

BV is a COMPLEX vector of dimension NB. On entry it must contain the values of the bus voltages (in rectangular form) of the unreduced system. Not altered by the subroutine.

ITEL is an INTEGER variable. On entry ITEL is the upper bound of the number of iterations; if ITEL < 0 the number of iterations is unbounded. On return ITEL is equal to the number of iterations performed by subroutine LFLFD1M (for more details, see [6]).

TOLV is a REAL variable. On entry TOLV is the required accuracy of the solution. On return, TOLV holds the attained accuracy of the solution (for more details, see [6]).

T is a REAL variable. On entry to the subroutine T is upper bound on the total iteration time (in seconds); if T ≤ 0, the iteration time is unbounded. On return T is equal to the value of the total iteration time (for more details, see [6]).

WSP is a REAL vector of length LWSP. WSP is used as a workspace by the set of subroutines solving the load flow problem using the fast decoupled method.

LWSP is the length of the workspace WSP. It must be at least LWSP = max (10*NB + 5*NLB + 6*NEL – 5, 6*NB + 6*NEL + 16*NLB + 7*NZ2 – 5, 17*NB + 7*NEL – 6), where NZ2 is the integral part of (NEL*(NLB**2))/((NB – 1)**2)

ICONT is an INTEGER parameter. It must be set by the user to select the required mode of the work,

=0 only the load flow solution for the reduced power system is performed,

≠0 the power flow in the lines after outage for the reduced and unreduced system are computed and the load flow solutions for both systems are compared.

IFLAG is the return flag from the subroutine. Possible values of IFLAG are:

0 normal return,

−10 NLINth transmission line does not exist in the reduced power system,

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

−1 incorrect parameter (e.g., insufficient workspace),

1 limit of iterations reached,

2 limit of time reached.

INPT index of the input unit. If parameter ICONT ≠ 0 the data describing the unreduced power system is read from unit INPT.

OTPT is the index of the output unit. Integer parameter.

IFOREQ index of the input unit. Integer parameter. If IFOREQ > 0 the data describing the reduced power system is read from unit IFOREQ.

IWRITE is an INTEGER parameter that controls output (for more details see [6] pp. 130-133).

IPRINT — is an INTEGER parameter that controls output. If IPRINT is set to one and IFOREQ is greater than zero, the description of the reduced power system is printed out on unit OTPT.

IV. HOW TO USE THE PACKAGE

In order to use the WARDEQ package, the user has to prepare his own main program which declares all arguments appearing in the subroutine calls, assigns the necessary dimension of a storage and prepares the data in the form desired by subroutines EQWARD and EQCONTI.

Data for Standard Entry - the subroutine EQWARD

The necessary entry data for subroutine EQWARD may be prepared directly from the typical data describing the power system that is to be equivalenced. However, it is recommended to prepare data using the subroutine FORMPR from the TTM1 package [6]. The subroutine FORMPR reads the data describing the power system from formatted data group files (as discussed in [6]) and formulates the load flow problem. On return from this subroutine we obtain almost all necessary parameters for subroutine EQWARD, i.e., NB, NLB, NTL, LINPB, LINPG, YT, JRYT, ICYT, BCV, V. The user still has to provide the data describing the boundary buses and the buffer zone. It can be done using the auxiliary subroutine RDATA. The description of the subroutine RDATA is given in Section VI.

Data for Contingency Analysis - the subroutine EQCONTI

The necessary data for subroutine EQCONTI can be partitioned into five groups:

1) the data describing the reduced power system,
2) the line data of the unreduced power system,
3) the load flow solution for the unreduced power system - the operating point,

4) the auxiliary data, i.e., NLIN - the index of the line that will be removed, TOLV - the accuracy of the load flow solution, ITEL - the number of the iterations, T - CPU time, LWSP - the length of the workspace.

5) the load flow solution of the unreduced system after a line outage in the internal part of this system.

In order to determine the load flow solution after a line outage in the reduced system the user has to provide the data describing the reduced power system, the line data of the unreduced power system and the auxiliary data as in point 4.

The data describing the reduced power system can be obtained on return from the subroutine EQWARD and from the file created by this subroutine (the subroutine EQCONTI reads the data from such files).

The line data describing the unreduced power system, i.e., the vectors LINPG, LINPB, LG, LB, LOUTG, LOUTB, LTAP, may be prepared directly from the typical data describing the power system or using subroutine FORMPR from the TTM1 package [6]. The subroutine FORMPR reads the data describing the power system from the formatted data group files (as discussed in [6]) and on return from this subroutine we obtain the necessary vectors, i.e., LINPG, LINPB, LG, LB, LOUTG, LTAP and also the load flow solution for the unreduced system.

In order to compare the load flow solutions after a line outage in the internal part of the reduced and unreduced system, the user still has to provide the data describing the load flow solution after a line outage in the internal part of the unreduced power system. This data has to be arranged in free format and in the following sequence:

NLIN

1	X(1,1)	X(1,2)	X(1,3)	X(1,4)
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
K	X(K,1)	X(K,2)	X(K,3)	X(K,4)
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
NB	X(NB,1)	X(NB,2)	X(NB,3)	X(NB,4)

where

NLIN - the index of the line removed,

K - the index of the bus, K = 1, ..., NB,

X(K,1), X(K,2) - voltage of the kth bus, the real and imaginary part, respectively,

X(K,3), X(K,4) - voltage of the kth bus, the magnitude and angle, respectively.

The above data should be arranged on the input unit INPT.

<u>How to Determine an External Equivalent and the Reduced Power System</u>

To determine the external equivalent and to formulate the load flow problem for the reduced power system the user has to prepare a program where the subroutine EQWARD is called and has to provide the data as discussed earlier.

Below we discuss a simple example of such a program. The listing of the main program MAINEQ is shown on pages 27-28. In this program the data for subroutine EQWARD is prepared using the subroutines FORMPR from the TTM1 package [6] and the subroutine RDATA (see p. 53). The appropriate data for these subroutines should be available on the local file PSDATA and BUDATA, respectively.

Before calling the subroutines FORMPR and RDATA variables NB, NTL, LWSP, INPT, OTPT, IWRITE, IP are initiated. IP was set to 2 with the purpose of having the initial bus voltages vector V in rectangular coordinates as required by EQWARD. After calling the subroutines EQWARD and RDATA parameters LWSP, OTPT, IFOREQ and MODE1 are initiated. LWSP is the length of the workspace. OTPT and IFOREQ are the unit numbers of the output files. Because MODE1=0 the vectors NEWNUM, JOLDNU and JBINTE are computed by the subroutine EQWARD.

The user should still initialize variables MODE2, MODE3 and IWRITE. The following options can be chosen:

- an external equivalent is determined, MODE2 = 1,
- a reduced system is determined, MODE2 = 0,
- a type of the external equivalent, MODE3 = (1,2,3,4,5),
- print out level, IWRITE = (1,2,3,4).

Setting IWRITE to one, a data file describing either the external equivalent or the reduced system is created on local file IFOREQ.

Several examples of external equivalents computed with the aid of the program MAINEQ are presented in the report [1].

```
      PROGRAM MAINEQ(BUDATA,OUTTT,PSDATA,INPUT,RESUL,IFOREQ,OUTPUT,TAPE1
     1=BUDATA,TAPE2=OUTTT,TAPE3=PSDATA,TAPE4=INPUT,TAPE6=RESUL,TAPE7=IFO
     2REQ)
C
C        THIS IS THE MAIN PROGRAM FOR DETERMINING  EXTERNAL EQUIVALENTS
C        AND REDUCED POWER SYSTEMS
C
C        THE DATA DESCRIBING THE POWER SYSTEM IS READ FROM THE FILE
C        PSDATA
C        THE DATA DESCRIBING THE BOUNDARY AND BUFFER BUSES IS READ FROM
C        THE FILE BUDATA
C
C        THE RESULTS ARE PRINTED OUT ON FILES OUTTT, RESUL AND IFOREQ
C
      INTEGER BTYP(118),JRYT(119),ICYT(600),LBINP(179),LBOUT(179),OTPT,N
     1EWNUM(118),JOLDNU(118),JBINTE(118),JBOUND(30),JRET(30)
      REAL WSP(12000),BCV(236)
      COMPLEX YT(476),V(118)
C
      COMMON /MDFRMPR/ JINPG,JINPB,JLG,JLB,JOUTG,JOUTB,JTAP,JNR,JVM,JVA,
     1JGP,JLP,JLQ,JSTL,JMAX
C
      NB=118
      NTL=179
      LWSP=12000
      IWRITE=0
      INPT=3
      OTPT=6
      IP=2
C
C        SUBROUTINE FORMPR OF THE TTM1 LIBRARY FORMULATES THE LOAD FLOW
C        PROBLEM FOR THE UNREDUCED POWER SYSTEM
C
      CALL FORMPR (LBINP,LBOUT,BTYP,YT,JRYT,ICYT,BCV,V,WSP,LWSP,NB,NTL,N
     1LB,IP,INPT,OTPT,IFLAG,IWRITE)
C
      IF (IFLAG.GE.0) GO TO 10
      WRITE (OTPT,50) IFLAG
      STOP
   10 CONTINUE
C
      INPT=1
C
C        READ THE DATA DESCRIBING THE BOUNDARY BUSES AND THE BUFFER ZONE
C
      CALL RDATA (NBOUND,JBOUND,NRET,JRET,INPT)
C
      JSTR=JMAX+5
      LWSP=LWSP-JSTR
      MODE1=0
      OTPT=2
      IFOREQ=7
C
C        SET THE PARAMETER MODE2 TO 1 IF AN EXTERNAL EQUIVALENT IS
C        DETERMINED
C        SET THE PARAMETER MODE2 TO 0 IF A REDUCED SYSTEM IS DETERMINED
C        SET THE PARAMETER MODE3 ACCORDING TO THE TYPE OF THE EXTERNAL
C        EQUIVALENT
C        SET THE PARAMETER IWRITE (THE LEVEL OF PRINTING)
C
      PRINT 20
      READ (4,*) MODE2
      PRINT 30
      READ (4,*) MODE3
      PRINT 40
```

```
      READ (4,*) IWRITE
C
      CALL EQWARD (NB,NLB,NTL,LBINP,LBOUT,YT,JRYT,ICYT,BTYP,V,BCV,NBOUND
     1,JBOUND,NRET,JRET,NEWNUM,JOLDNU,JBINTE,NEXT,NFIC,WSP(JSTR),LWSP,MO
     2DE1,MODE2,MODE3,OTPT,IFOREQ,IFLAG,IWRITE)
C
      WRITE (OTPT,60) IFLAG
      STOP
   20 FORMAT (1X,"EXTERNAL EQUIVALENT: MODE=1"/1X,"REDUCED SYSTEM: MODE=
     10"/,1X,"MODE= ")
   30 FORMAT (1X,"STANDARD EQUIVALENT WITHOUT SHUNTS: MODE=1"/,1X,"EQUIV
     1ALENT WITH BUFFER ZONE: MODE=2"/,1X,"EXTENDED EQUIVALENT: MODE=3"/
     21X,"SIMPLIFIED EXTENDED EQUIVALENT: MODE=4"/,1X,"STANDARD EQUIVALE
     3NT WITH SHUNTS: MODE=5"/,1X,"MODE= ")
   40 FORMAT (1X,"THE LEVEL OF PRINT: IWRITE= 1, 2, 3, 4",/,1X"IWRITE=")
   50 FORMAT (2X,"IFLAG FROM FORMPR IFLAG= ",I3)
   60 FORMAT (2X,"IFLAG FROM EQWARD IFLAG= ",I3)
      END
```

V. CONTINGENCY SIMULATION

The most important aspect of any equivalencing method is the ability to accurately predict the affects of a contingency. To test the methods presented in [1] the 26-bus system [7,8] and the IEEE 118-bus system [9] were used. The listing of the user's program MAINCO for the contingency analysis of the reduced 26-bus and the IEEE 118-bus sytem is shown on pages 31-32.

Tests for the 26-Bus System

The single line diagram of the 26-bus system is shown in Fig. 6. This system has been divided into two subsystems as follows:

- buses in the external system 2,5,8,10,11,14,17,18,22,25,
- boundary buses 9,13,21,
- buses in the internal system 1,3,4,6,7,12,15,16,19,21,23,24,26.

With the aid of the program MAINEQ five reduced systems with different types of the external equivalents, i.e., the standard Ward equivalent with shunts, standard Ward equivalent without shunts, the Ward equivalent with buffer zone, extended Ward equivalent and simplified Ward equivalent were formed. For these systems, using the program MAINCO, single line outage cases involving lines 13-26 and 6-26 were studied.

The results for all the 26-bus studies are summarized in Tables II-IX. Tables II and V show the base case flow and the post contingency line flow in the reduced systems for the outage lines 13-26 and 6-26, respectively. The symbols used in the tables denote:

SW* - standard Ward equivalent with shunts,

SW - standard Ward equivalent without shunts,

WB - Ward equivalent with buffer zone,

EW - extended Ward equivalent,

SEW - simplified extended Ward equivalent,

P - the active power,

Q - the reactive power.

Tables VI and VII show the modulus of the bus voltage error for outage lines 13-26 and 6-26 respectively. The error ε_i for the ith bus is determined as follows:

$$\varepsilon_i = | V_i^u - V_i^r |,$$

where V_i^u is the complex voltage of the ith bus of the unreduced system and V_i^r is the complex voltage of the ith bus of the reduced system.

Tables VIII and IX show the angle errors as a percentage of the nominal for the outage lines 13-26 and 6-26, respectively.

Tests for the IEEE 118-Bus System

This system has been separated into two subsystems as follows:

- buses in the external system: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 38, 113, 114, 115, 117,
- boundary buses 24, 37, 43 and 65,
- buses in the internal system, namely all the buses not mentioned above.

Using the program MAINEQ two types of reduced systems were formed, i.e., the system with the standard Ward equivalent (model with shunts) and system with the extended Ward equivalent. For these systems, using the program MAINCO, a single line outage involving line (49-66) was studied. The results for all the 118-bus reduced system studies are summarized in Tables X and XI. Table X shows the base case flow and the post contingency line flow in selected lines of the reduced 118-bus system. Table XI shows the modulus of the bus voltage error and the angle error for the selected buses of this system.

```
      PROGRAM MAINCO(PSDATA,PSYSTE,INPUT,RESUL,IFOREQ,OUTPUT,TAPE3=PSDAT
     1A,TAPE4=PSYSTE,TAPE5=INPUT,TAPE6=RESUL,TAPE7=IFOREQ)
C
C        THIS IS THE MAIN PROGRAM FOR CONTINGENCY ANALYSIS OF THE REDUCED
C        POWER SYSTEM
C
C        THE DATA DESCRIBING THE UNREDUCED POWER SYSTEM IS READ FROM THE
C        FILE PSDATA
C        THE DATA DESCRIBING THE REDUCED POWER SYSTEM IS READ FROM THE
C        FILE IFOREQ
C
C        THE LOAD FLOW SOLUTION OF THE REDUCED POWER SYSTEM AFTER A LINE
C        OUTAGE IS PRINTED OUT ON THE FILE RESUL
C
C        THE LOAD FLOW SOLUTION OF THE UNREDUCED SYSTEM WITH A LINE
C        REMOVED IS READ FROM THE FILE PSYSTE
C
      REAL WSP(12000),BCV(236)
      INTEGER BTYP(118),JRYT(119),ICYT(700),LBINP(179),LBOUT(179),OTPT,J
     1OLDNU(118),JBOUND(30),JRET(30),JBINTE(118),NEWNUM(118),PSDATA,PSYS
     2TE,RESUL
      COMPLEX YT(476),V(118),BV(118)
C
      COMMON /MDFRMPR/ JINPG,JINPB,JLG,JLB,JOUTG,JOUTB,JTAP,JNR,JVM,JVA,
     1JGP,JLP,JLQ,JSTL,JMAX
C
      NB=118
      NTL=179
      LWSP=12000
      IWRITE=0
      INPT=3
      OTPT=6
      IP=2
C
C        SUBROUTINE FORMPR OF THE TTM1 LIBRARY FORMULATES THE LOAD FLOW
C        PROBLEM FOR THE UNREDUCED POWER SYSTEM
C
      CALL FORMPR (LBINP,LBOUT,BTYP,YT,JRYT,ICYT,BCV,V,WSP,LWSP,NB,NTL,N
     1LB,IP,INPT,OTPT,IFLAG,IWRITE)
C
      IF (IFLAG.GE.0) GO TO 10
      WRITE (OTPT,30) IFLAG
      STOP
   10 CONTINUE
C
      DO 20 I=1,NB
      BV(I)=V(I)
   20 CONTINUE
C
C
C        READ THE INDEX OF THE LINE TO BE REMOVED
C
      READ (5,*) NLIN
C
      INB=NB
      NEL=JRYT(NB+1)-1
      ITEL=20
      TOLV=1.0E-5
      T=3.0
      JSTAR=JMAX+1
      LWSP=LWSP-JSTAR
      ICONT=1
      INPT=4
      IFOREQ=7
      IWRITE=1
```

```
      IPRINT=2
C
C        CONTINGENCY ANALYSIS OF THE REDUCED POWER SYSTEM
C        SUBROUTINE EQCONTI IS FROM THE WARDEQ LIBRARY
C
      CALL EQCONTI (INB,NB,NLB,NEXT,NFIC,NBOUND,JBOUND,NRET,JRET,BTYP,BC
     1V,V,NEWNUM,JOLDNU,JBINTE,YT,JRYT,ICYT,LBINP,LBOUT,NTL,MODE3,NEL,NL
     2IN,WSP(JINPG),WSP(JINPB),WSP(JLG),WSP(JLB),WSP(JOUTG),WSP(JOUTB),W
     3SP(JTAP),BV,ITEL,TOLV,T,WSP(JSTAR),LWSP,ICONT,IFLAG,INPT,OTPT,IFOR
     4EQ,IWRITE,IPRINT)
C
      IF (IFLAG.LT.0) WRITE (OTPT,40) IFLAG
      STOP
   30 FORMAT (2X,"IFLAG FROM FORMPR IFLAG= ",I3)
   40 FORMAT (2X,"IFLAG FROM LFLFDM1 IFLAG= ",I3)
      END
```

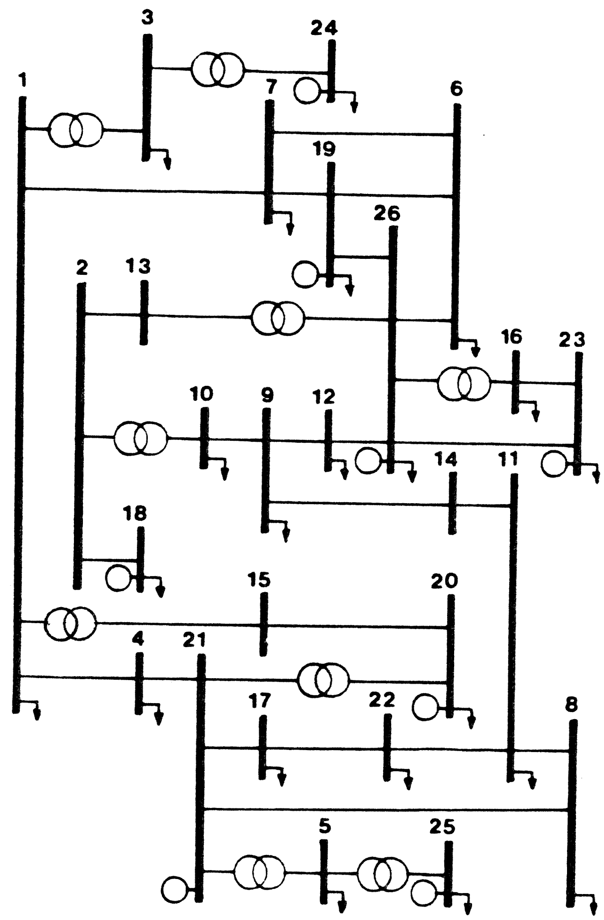

Fig. 6 The 26-bus power system.

TABLE II

CONTINGENCY ANALYSIS OF THE REDUCED 26-BUS SYSTEM . LINE (13,26) IS REMOVED

Line	Terminal	Base case flow		Post contingency flow							
				Exact		SW*		SW		WB	
No.	Buses	P	Q	P	Q	P	Q	P	Q	P	Q
1	13,26	1.777	0.472	–	–	–	–	–	–	–	–
2	26,16	1.265	0.451	1.265	0.451	1.265	0.451	1.265	0.451	1.265	0.451
3	16,23	-0.045	0.088	-0.045	0.088	-0.045	0.088	-0.045	0.088	-0.045	0.088
4	23,26	-0.085	-0.031	-0.085	-0.031	-0.085	-0.031	-0.085	-0.031	-0.085	-0.031
7	9,12	-0.195	0.057	0.462	-0.456	~	~	0.648	0.336	0.615	0.224
8	12,26	-0.628	-0.035	-0.002	-0.625	~	~	0.190	0.195	0.161	0.091
11	19,26	0.408	0.053	0.480	0.043	0.499	0.041	0.469	0.045	0.477	0.044
12	6,26	0.296	0.027	0.384	0.009	0.406	0.005	0.370	0.012	0.380	0.010
13	6,19	-0.810	-0.109	-0.816	-0.112	-0.819	-0.113	-0.815	-0.112	-0.816	-0.112
14	7,19	-0.220	-0.083	-0.143	-0.110	-0.125	-0.115	-0.156	-0.106	-0.146	-0.109
15	6,7	0.113	-0.019	0.032	0.003	0.012	0.009	0.045	-0.000	0.035	0.003
21	1,4	-0.050	0.174	-0.080	0.182	-0.084	0.184	-0.075	0.181	-0.079	0.182
22	4,21	-0.533	0.019	-0.563	0.026	-0.566	0.027	-0.558	0.025	-0.562	0.025
23	20,21	0.559	0.374	0.419	0.372	0.391	0.372	0.441	0.372	0.425	0.372
24	15,1	2.179	0.887	2.312	0.864	2.331	0.861	2.291	0.867	2.307	0.856
26	1,7	0.789	0.072	0.952	0.041	0.988	0.035	0.926	0.046	0.945	0.042
27	15,20	-2.179	-0.887	-2.312	-0.864	-2.331	-0.860	-2.291	-0.867	-2.307	-0.864
29	1,3	0.620	0.357	0.620	0.349	0.619	0.349	0.620	0.350	0.620	0.349
30	24,3	-0.050	-0.165	-0.050	-0.157	-0.050	-0.157	-0.050	-0.158	-0.050	-0.157

Retained bus for the WB method - 22.

TABLE III

CONTINGENCY ANALYSIS OF THE REDUCED 26-BUS SYSTEM . LINE (13,26) IS REMOVED

Line	Terminal	Base case flow		Post contingency flow					
				Exact		EW		SEW	
No.	Buses	P	Q	P	Q	P	Q	P	Q
1	13,26	1.777	0.472	–	–	–	–	–	–
2	26,16	1.265	0.451	1.265	0.451	1.265	0.451	1.265	0.451
3	16,23	-0.045	0.088	-0.045	0.088	-0.045	0.088	-0.045	0.088
4	23,26	-0.085	-0.031	-0.085	-0.031	-0.085	0.031	-0.085	0.031
7	9,12	-0.195	0.057	0.462	-0.456	0.508	-0.346	0.736	-0.382
8	12,26	-0.628	-0.035	-0.002	-0.625	0.050	-0.497	0.255	-0.580
11	19,26	0.408	0.053	0.480	0.043	0.489	0.060	0.510	0.040
12	6,26	0.296	0.027	0.384	0.009	0.395	0.007	0.420	0.001
13	6,19	-0.810	-0.109	-0.816	-0.112	-0.817	-0.113	-0.819	-0.115
14	7,19	-0.220	-0.083	-0.143	-0.110	-0.134	-0.113	-0.111	-0.121
15	6,7	0.113	-0.019	0.032	0.003	0.022	0.007	-0.002	0.014
21	1,4	-0.050	0.174	-0.080	0.182	-0.084	0.183	-0.092	0.186
22	4,21	-0.533	0.019	-0.563	0.026	-0.567	0.026	-0.576	0.028
23	20,21	0.559	0.374	0.419	0.372	0.401	0.372	0.360	0.371
24	15,1	2.179	0.887	2.312	0.864	2.329	0.861	2.368	0.856
26	1,7	0.789	0.072	0.952	0.041	0.973	0.038	1.020	0.030
27	15,20	-2.179	-0.887	-2.312	-0.864	-2.329	-0.861	-2.368	-0.854
29	1,3	0.620	0.357	0.620	0.349	0.620	0.347	.620	0.345
30	24,3	-0.050	-0.165	-0.050	-0.157	-0.050	-0.156	-.050	-0.153

TABLE IV

CONTINGENCY ANALYSIS OF THE REDUCED 26-BUS SYSTEM . LINE (6,26) IS REMOVED

Line	Terminal	Base case flow		Post contingency flow							
				Exact		SW*		SW		WB	
No.	Buses	P	Q	P	Q	P	Q	P	Q	P	Q
1	13,26	1.117	0.472	1.195	0.469	1.197	0.464	1.195	0.465	1.195	0.469
2	26,16	1.265	0.451	1.265	0.451	1.265	0.451	1.265	0.451	1.265	0.451
3	16,23	-0.045	0.088	-0.045	0.088	-0.045	0.088	-0.045	0.088	-0.045	0.088
4	23,26	-0.085	-0.031	0.085	-0.031	-0.085	-0.031	-0.085	0.031	-0.085	-0.031
7	9,12	-0.195	0.057	-0.169	0.049	-0.170	0.040	-0.170	0.040	-0.170	0.046
8	12,26	-0.628	-0.035	-0.601	-0.042	-0.602	-0.051	-0.603	-0.051	-0.602	-0.045
11	19,26	-0.408	0.053	0.662	0.024	0.660	0.024	0.661	0.024	0.662	0.024
12	6,26	0.296	0.027	–	–	–	–	–	–	–	–
13	6,19	-0.810	-0.109	-0.556	-0.083	-0.557	-0.082	-0.556	-0.083	-0.556	-0.083
14	7,19	-0.220	-0.083	-0.224	-0.078	-0.225	-0.078	-0.224	-0.078	-0.224	-0.078
15	6,7	0.113	-0.019	0.156	-0.017	0.157	-0.018	0.156	-0.017	0.156	-0.017
21	1,21	-0.050	0.174	-0.041	0.172	-0.041	0.172	-0.041	0.172	-0.041	0.172
22	4,21	-0.533	0.019	-0.524	0.018	-0.523	0.018	-0.524	0.018	-0.524	0.018
23	20,21	0.559	0.374	0.599	0.375	0.601	0.375	0.599	0.375	0.599	0.375
24	15,1	2.179	0.887	2.142	0.889	2.140	0.890	2.141	0.889	2.142	0.889
26	1,7	0.789	0.072	0.743	0.074	0.741	0.074	0.742	0.074	0.743	0.074
27	15,20	-2.179	-0.887	-2.142	-0.889	-2.140	-0.889	-2.141	-0.889	-2.142	-0.889
29	1,3	0.620	0.357	0.620	0.361	0.620	0.361	0.620	0.361	0.620	0.361
30	24,3	-0.050	-0.165	-0.050	-0.169	-0.050	-0.169	-0.050	-0.169	-0.050	-0.169

Retained bus for the WB method - 22.

TABLE V

CONTINGENCY ANALYSIS OF THE REDUCED 26-BUS SYSTEM . LINE (6,26) IS REMOVED

				Post contingency flow					
Line	Terminal	Base case flow		Exact		EW		SEW	
No.	Buses	P	Q	P	Q	P	Q	P	Q
1	13,26	1.117	0.472	1.195	0.469	1.195	0.466	1.196	0.474
2	26,16	1.265	0.451	1.265	0.451	1.265	0.451	1.265	0.451
3	16,23	-0.045	0.088	-0.045	0.088	-0.045	0.088	-0.045	0.088
4	23,26	-0.085	-0.031	-0.085	-0.031	-0.085	-0.031	-0.085	-0.031
7	9,12	-0.195	0.057	-0.169	0.049	-0.170	-0.41	-0.167	0.042
8	12,26	-0.628	-0.035	-0.601	-0.042	-0.602	-0.050	-0.599	-0.049
11	19,26	0.408	0.053	0.662	0.024	0.661	0.024	0.664	0.024
12	6,26	0.296	0.027	–	–	–	–	–	–
13	6,19	-0.810	-0.109	-0.556	-0.083	-0.556	-0.083	-0.553	-0.083
14	7,19	-0.220	-0.083	-0.224	-0.078	-0.224	-0.078	-0.225	-0.079
15	6,7	0.113	0.019	0.156	-0.017	0.156	-0.017	0.155	-0.017
21	1,4	-0.050	-0.174	-0.041	0.172	-0.041	0.172	-0.042	0.172
22	4,21	-0.533	0.019	-0.524	0.018	-0.524	0.018	-0.524	0.018
23	20,21	0.559	0.374	0.599	0.375	0.600	0.375	0.597	0.375
24	15,1	2.179	0.887	2.142	0.889	2.141	0.889	2.143	0.889
26	1,7	0.789	0.072	0.743	0.074	0.742	0.074	0.745	0.073
27	15,20	-2.179	-0.887	-2.142	-0.889	-2.141	-0.889	-2.143	-0.889
29	1,3	0.620	0.357	.620	0.361	0.620	0.361	.620	0.361
30	24,3	-0.050	-0.165	-0.050	-0.169	-0.050	-0.169	-.050	-0.169

TABLE VI

CONTINGENCY ANALYSIS OF THE REDUCED 26-BUS SYSTEM . LINE (13,26) IS REMOVED

Bus	Modulus of the bus voltage error				
No.	SE*	SE	WB	EW	SEW
1	0.0151	0.0097	0.0024	0.0080	0.0262
3	0.0153	0.0098	0.0024	0.0080	0.0264
4	0.0155	0.0105	0.0025	0.0086	0.0282
6	0.0047	0.0028	0.0007	0.0023	0.0076
7	0.0119	0.0075	0.0018	0.0061	0.0201
9	~	0.2580	0.2284	0.0462	0.0747
12	~	0.1168	0.1034	0.0211	0.0343
13	~	0.6803	0.6310	0.0472	0.2655
15	0.0138	0.0090	0.0022	0.0074	0.0243
16	0.0000	0.0000	0.0000	0.0000	0.0000
19	0.0049	0.0029	0.0007	0.0024	0.0078
20	0.0157	0.0112	0.0027	0.0092	0.0301
21	0.0168	0.0121	0.0029	0.0099	0.0325
23	0.0000	0.0000	0.0000	0.0000	0.0000
24	0.0147	0.0094	0.0023	0.0077	0.0253
22	–	–	0.0007	–	–

Retained bus for the WB method - 22

TABLE VII

CONTINGENCY ANALYSIS OF THE REDUCED 26-BUS SYSTEM . LINE (6,26) IS REMOVED

Bus	Modulus of the bus voltage error				
No.	SE*	SE	WB	EW	SEW
1	0.0011	0.0003	0.0	0.0003	0.0013
3	0.0011	0.0003	0.0	0.0003	0.0013
4	0.0011	0.0003	0.0	0.0003	0.0013
6	0.0006	0.0001	0.0	0.0002	0.0007
7	0.0009	0.0002	0.0	0.0003	0.0010
9	0.0027	0.0027	0.0008	0.0024	0.0020
12	0.0012	0.0012	0.0004	0.0011	0.0009
13	0.0001	0.0001	0.0	0.0	0.0001
15	0.0010	0.0003	0.0	0.0003	0.0012
16	0.0000	0.0000	0.0	0.0	0.0
19	0.0005	0.0001	0.0	0.0002	0.0006
20	0.0012	0.0003	0.0	0.0003	0.0014
21	0.0013	0.0003	0.0	0.0004	0.0015
23	0.0000	0.0000	0.0	0.0	0.0
24	0.0011	0.0003	0.0	0.0003	0.0012
22	–	–	0.0	–	–

Retained bus for the WB method - 22

TABLE VIII

CONTINGENCY ANALYSIS OF THE REDUCED 26-BUS SYSTEM . LINE (13,26) IS REMOVED

Bus	Angle error in percentage of the nominal				
No.	SE*	SE	WB	EW	SEW
1	-10.8	6.9	1.7	-5.7	-18.8
3	-13.0	8.3	2.0	-6.8	-22.4
4	-9.4	6.4	1.5	-5.2	-17.1
6	-6.3	3.9	.9	-3.1	-10.3
7	-18.1	11.4	2.7	-0.2	-30.5
9	11.2	52.5	48.1	6.6	-39.7
12	-2.5	67.7	61.6	3.7	-85.0
13	12.0	53.9	50.9	4.6	-29.0
15	9.0	5.8	1.5	-4.8	-15.7
16	-0.0	-0.0	0.0	-0.0	-0.0
19	-4.2	2.5	0.6	-2.0	-6.8
20	-5.0	3.6	0.8	-2.9	-9.5
21	-5.4	3.9	0.9	-3.2	-10.5
23	-0.0	-0.0	0.0	-0.0	-0.0
24	-13.9	8.9	2.15	-7.2	-23.9
22	–	–	-4.6	–	–

Retained bus for the WB method - 22

TABLE IX

CONTINGENCY ANALYSIS OF THE REDUCED 26-BUS SYSTEM . LINE (6,26) IS REMOVED

Bus	The Angle error in percentage of nominal				
No.	SE*	SE	WB	EW	SEW
1	0.8	0.2	0.0	0.2	0.9
3	0.9	0.2	0.0	0.3	-1.1
4	0.7	0.2	0.0	0.2	-0.8
6	0.4	0.1	0.0	0.1	-0.5
7	1.1	0.3	0.0	0.3	-1.3
9	0.6	0.5	0.1	0.4	1.2
12	0.4	0.3	0.0	0.3	0.7
13	-0.1	-0.0	0.0	0.0	-0.1
15	0.6	0.2	0.0	0.2	-0.8
16	-0.0	-0.0	-0.0	-0.0	-0.0
19	0.3	0.1	0.0	0.1	-0.4
20	0.4	0.1	0.0	0.1	-0.5
21	0.4	0.1	0.0	0.1	-0.5
23	-0.0	-0.0	-0.0	-0.0	-0.0
24	1.0	0.3	0.0	0.3	-1.2
22	–	–	-0.1	–	–

Retained bus for the WB method - 22.

TABLE X

CONTINGENCY ANALYSIS OF THE REDUCED 118-BUS SYSTEM . LINE (49,66) IS REMOVED

Line	Terminal	Base case flow		Post contingency flow					
				Exact		SW*		EW	
No.	Buses	P	Q	P	Q	P	Q	P	Q
52	37,39	0.434	-0.076	0.646	-0.125	0.649	-0.152	0.641	-0.126
53	37,40	0.325	-0.133	0.531	-0.193	0.532	-0.220	0.525	-0.194
55	39,40	0.158	-0.183	0.362	-0.259	0.363	-0.288	0.357	-0.259
59	43,44	-0.274	-0.035	-0.095	-0.096	-0.091	-0.109	-0.099	-0.101
61	44,45	-0.439	+0.012	-0.256	-0.031	-0.252	-0.045	-0.260	-0.036
62	45,46	-0.410	-0.077	-0.358	-0.066	-0.355	-0.074	-0.360	-0.070
74	53,54	-0.212	-0.028	-0.302	-0.001	-0.302	-0.001	-0.303	-0.001
98	49,66	-2.570	0.047	–	–	–	–	–	–
117	74,75	-0.591	-0.001	-0.595	0.002	-0.594	-.001	-0.597	0.003
149	82,96	-0.201	-0.002	-0.209	-0.000	-0.208	-.000	-0.209	0.000

TABLE XI

CONTINGENCY ANALYSIS OF THE REDUCED 118-BUS SYSTEM . LINE (49,66) IS REMOVED

Bus	Modulus of the bus voltage error		Angle error in % of nominal	
No.	SE*	EW	SE*	EW
24	0.0019	0.0023	1.1	-1.4
37	0.0059	0.0043	0.9	-1.2
39	0.0025	0.0038	0.4	-0.9
40	0.0009	0.0035	0.2	-0.7
43	0.0067	0.0037	1.0	-0.6
44	0.0030	0.0210	0.5	-0.4
45	0.0017	0.0015	0.4	-0.4
46	0.0008	0.0013	0.2	-0.4
49	0.0006	0.0012	0.2	-0.4
53	0.0004	0.0006	0.1	-0.2
54	0.0003	0.0005	0.1	-0.2
66	0.0001	0.0007	0.1	-0.6
74	0.0003	0.0004	0.2	-0.3
75	0.0002	0.0003	0.2	-0.3
82	0.0001	0.0001	-0.4	0.1
96	0.0001	0.0000	0.2	0.1

VI. DESCRIPTION OF THE HIGHER LEVEL SUBROUTINES

SUBROUTINE EQDEIE (NB, NTL, LBINP, LBOUT, NBOUND, JBOUND, NRET, JRET, NEWNUM, IOLDNU, IBINTE, NEXT, WSP, LWSP, MODE, OTPT, IFLAG, IWRITE)

Purpose

This subroutine distributes the workspace into a set of vectors used by the remaining subroutines, divides a set of power system buses into internal and external buses, determines new indices of the buses and partly performs renumbering.

List of Arguments

NB — is an INTEGER argument. On entry it must be set to the number of the buses of the unreduced power system. Not altered by the subroutine.

NTL — is an INTEGER argument. On entry it must be set to the number of the transmission lines of the unreduced power system. Not altered by the subroutine.

LBINP, LBOUT

are INTEGER vectors of dimensions NTL. On entry LBINP(k), LBOUT(k) must be set to the indices of buses incident with the kth line ($k = 1, ..., NTL$). On return from the subroutine LBINP(k), LBOUT(k) equal the indices of the buses incident with the kth line after renumbering.

NBOUND — is an INTEGER argument. On entry it must be set to the number of the boundary buses. Not altered by the subroutine.

JBOUND — is an INTEGER vector of dimension NBOUND. On entry it must contain the indices of the buses belonging to the boundary. Not altered by the subroutine.

NRET — is an INTEGER argument. On entry it must be set to the number of retained buses in the external system. Not altered by the subroutine.

JRET — is an INTEGER vector of dimension NRET. On entry it must contain the indices of the retained buses. Not altered by the subroutine.

NEWNUM — is an INTEGER vector of dimension NB. On return from the subroutine NEWNUM(k) stores a new index of the kth bus (k = 1,2,...,NB).

IOLDNU — is an INTEGER vector of dimension NB. On return from the subroutine IOLDNU(k) stores the old index of the kth bus (k = 1,...,NB).

IBINTE — is an INTEGER vector of dimension NB. On return from the subroutine IBINTE(k) is set to one when the kth bus belongs to the internal power system.

NEXT — is an INTEGER argument. On return from the subroutine it is equal to the number of the buses in the external system.

WSP — is a real vector of dimension LWSP. WSP is used as workspace by the set of subroutines.

LWSP — is the length of the workspace. It must be:

LWSP = 2*NB + 2*NTL + 2*((NB − 1)/50 + 1) + 4.

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

0 prepare renumbering for the reduced power system,

1 prepare renumbering of the buses of the external power system.

OTPT — is the index of the OUTPUT unit. INTEGER parameter.

IFLAG — is the return FLAG from the subroutine. INTEGER parameter.

IWRITE — is an INTEGER parameter that controls output.

<u>Input-Output</u>

Output data is controlled by parameter IWRITE. Possible values of IWRITE are as follows:

$\neq 4$ all prints are suppressed,

=4 vectors NEWNUM, IOLDNU are printed out.

Error Diagnostic

A successful return from EQDEIE is indicated by the value of IFLAG equal to zero. For IFLAG = −2 the length of the workspace is too small.

Related Software

This subroutine calls subroutines: ORDEVE, CHNUMB, INTERV, ZERO, CHNGI, SETBIN and is called by subroutine EQWARD.

SUBROUTINE EQEXEQ (NB, NLB, NFIC, JRYT, ICYT, YT, BTYP, V, BCV, NBOUND, NRET, NEXT, NEWNU, OLDNU, IBINTE, WSP, LWSP, MODE, OTPT, IFLAG, IWRITE)

Purpose

This subroutine distributes the workspace into a set of vectors used by the remaining subroutines and forms the bus admittance matrix of the reduced system. This system consists of the internal system and a fixed admittance equivalent network connected to the internal system at the boundary buses. The fixed admittance equivalent network can be determined as a standard Ward equivalent (with shunt or without in the external system), standard Ward equivalent with buffer zone, extended Ward equivalent and simplified extended Ward equivalent.

List of Arguments

NB — is an INTEGER argument. On entry it must be set to the number of the buses of a power system. On return from the subroutine NB is equal to the number of the buses of the reduced system.

NLB is an INTEGER argument. On entry it must be set to the number of the load buses in the power system. On return from the subroutine NLB is equal to the number of the load buses of the reduced system.

NFIC is an INTEGER argument. On entry it must be set to zero. On return from the subroutine NFIC is equal to the number of fictitious buses in the reduced system.

JRYT is an INTEGER vector of dimension NB+1. On entry it must contain the row indices of the sparse bus admittance matrix of the power system to be equivalized. On return from the subroutine it stores the row indices of the sparse bus admittance matrix of the reduced system.

ICYT is an INTEGER vector of dimension JRYT (NB+1) −1. On entry it must contain the column indices of the elements of the sparse bus admittance matrix of the power system to be equivalized. On return from the subroutine it stores the column indices of the sparse bus admittance matrix of the reduced system.

YT is a COMPLEX vector of dimension JRYT(NB+1)−1. On entry it must contain the nonzero elements of the bus admittance matrix of the power system. On return from the subroutine it stores the nonzero elements of the bus admittance matrix of the reduced system.

BTYP is an INTEGER vector of dimension NB. On entry it must contain the bus types (0 - for load, 1 - for generator bus, 2 - for slack bus) of the power system. On return from the subroutine it contains the bus types of the reduced system.

V is a COMPLEX vector of dimension NB. On entry it must be set to the initial values of bus voltages (in the rectangular form) of the power system. On return from the subroutine it stores the initial values of the bus voltages (in the same form) of the reduced power system.

BCV	is a REAL vector of dimension 2*NB. On entry it contains scheduled values of the bus control variables of the power system. On return from the subroutine it stores the values of the bus control variables of the reduced system.
NBOUND	is an INTEGER argument. On entry, it must be set to the number of the boundary buses. Not altered by the subroutine.
NRET	is an INTEGER argument. On entry it must be set to the number of the retained buses in the external system. Not altered by the subroutine.
NEXT	is an INTEGER argument. On entry it must be set to the number of the buses in the external system. Not altered by the subroutine.
NEWNU	is an INTEGER vector of dimension NB. On entry to the subroutine NEWNU(k) must contain new index of the kth bus (k=1,...,NB). Not altered by the subroutine.
OLDNU	is an INTEGER vector of dimension NB. On entry to the subroutine OLDNU(k) must contain the old index of the kth bus (k=1,...,NB) of the power system. Not altered by the subroutine.
IBINTE	is an INTEGER vector of dimension NB. On entry IBINTE(k) must be set to one if the kth bus belongs to the internal power system.
WSP	is a REAL vector of dimension LWSP. WSP is used as workspace by the set of subroutines.
LWSP	is the length of the workspace. It must be at least LWSP=4*(NRET+NBOUND) + 11*NB + 12*(JRYT (NB+1)−1).
MODE	is an INTEGER argument. It determines the type of the external equivalent.

MODE=1	standard Ward equivalent without shunts in the external system,
MODE=2	Ward equivalent with buffer zone,
MODE=3	extended Ward equivalent,
MODE=4	simplified Ward equivalent,

MODE = 5 standard Ward equivalent with shunts in the external system.

MODE is not altered by the subroutine.

OTPT is the index of the OUTPUT unit. INTEGER parameter.

IFLAG is the return flag from subroutine. INTEGER parameter.

IWRITE is an INTEGER parameter that controls output.

Input-Output

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

4 the coefficient matrix, before and after Gaussian elimination is printed out,

3 the admittance matrix of the reduced system is printed out,

2 the vector of bus control variables of the reduced system is printed out.

Errors Diagnostic

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

– 3 the length of the workspace is too small,

– 1 the length of the workspace for Gaussian elimination is too small.

Related Software

This subroutine calls subroutines: CHNGJ, CHNGP, CHNGC, CHNGAD, EQWAES, EQWEES, EQDRC1, EQINRC, EQINBR, SPAMAT, GAUSEL, PRINAD and is called by subroutine EQWARD.

SUBROUTINE EQFORM (NB, NBEQ, NLBE, NEXT, NFIC, NBOUND, JBOUND, NRET, JRET, BTYP, BCV, V, NEWNUM, OLDNUM, JBINTE, YT, JRYT, ICYT, LBINP, LBOUT, NTL, MODE, OTPT, IWRITE).

Purpose

This subroutine creates a data file describing the reduced power system, the data is printed out on unit OTPT.

List of Arguments

NB — is an INTEGER argument. On entry it must be set to the number of the buses of the unreduced power system. Not altered by the subroutine.

NBEQ — is an INTEGER argument. On entry, it must be set to the number of the buses of the reduced power system. Not altered by the subroutine.

NLBE — is an INTEGER argument. On entry it must be set to the number of the load buses in the reduced power system. Not altered by the subroutine.

NEXT — is an INTEGER argument. On entry it must be set to the number of the buses of the external system. Not altered by the subroutine.

NFIC — is an INTEGER argument. On entry it must be set to the number of the fictitious PV buses. Not altered by the subroutine.

NBOUND — is an INTEGER argument. On entry it must be set to the number of the boundary buses. Not altered by the subroutine.

JBOUND — is an INTEGER vector of dimension NBOUND. On entry it must contain the indices of the boundary buses. Not altered by the subroutine.

NRET — is an INTEGER argument. On entry it must be set to the number of the retained buses. Not altered by the subroutine.

JRET — is an INTEGER vector of dimension NRET. On entry it must contain the indices of retained buses. Not altered by the subroutine.

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

BCV is a REAL vector of dimension NBEQ. On entry it must contain the values of the bus control variables of the reduced power sytem. Not altered by the subroutine.

V is a COMPLEX vector of dimension NBEQ. On entry it must contain the initial bus voltages (in the rectangular form) of the reduced power system. Not altered by the subroutine.

OLDNUM is an INTEGER vector of dimension NB. On entry OLDNUM(k) must contain the old index of the kth bus. Not altered by the subroutine.

JBINTE is an INTEGER vector of dimenison NB. On entry JBINTE(k) must be set to 1 if the kth bus belongs to the internal system. Not altered by the subroutine.

YT is a COMPLEX vector of dimension JRYT(NBEQ + 1) − 1. On entry it must contain the nonzero elements of the bus admittance matrix of the reduced power system. Not altered by the subroutine.

JRYT is an INTEGER vector of dimension NBEQ + 1. On entry it must contain the row indices of the sparse bus admittance matrix of the reduced system. Not altered by the subroutine.

ICYT is an INTEGER vector of dimension JRYT(NBEQ + 1) − 1. On entry it must contain the column indices of the elements of the sparse bus admittance matrix of the reduced power system. Not altered by the subroutine.

LBINP, LBOUT

are INTEGER vectors of dimension NTL. On entry LBINP(k), LBOUT(k) must be set to the indices of buses incident with the kth line (k = 1,..,NTL) in the reduced power sytem. Not altered by the subroutine.

NTL is an INTEGER argument. On entry, it must be set to the number of the transmission lines of the unreduced system. Not altered by the subroutine.

MODE — is an INTEGER argument. On entry it must be set to the number denoting type of the external equivalent. Not altered by the subroutine (see, pp. 15, the parameter MODE3).

OTPT — is the index of the output unit. INTEGER parameter.

IWRITE — is an INTEGER parameter that controls output.

Input-Output

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

$\neq 1$ all printouts are suppressed,

$= 1$ all arguments of the subroutine are printed out on unit OTPT.

Related Software

This subroutine is called by subroutine EQWARD.

SUBROUTINE EQREAD (NB, NBEQ, NLBE, NEXT, NFIC, NBOUND, JBOUND, NRET, JRET, BTYP, BCV, V, NEWNUM, OLDNUM, JBINTE, YT, JRYT, ICYT, LBINP, LBOUT, NTL, MODE, INPT, OTPT, IWRITE)

Purpose

This subroutine reads input data describing the reduced power system from a file created by subroutine EQFORM. The meaning the arguments NB, NBEQ, NLBE, NEXT, NFIC, NBOUND, JBOUND, NRET, JRET, BTYP, BCV, V, NEWNUM, OLDNUM, JBINTE, YT, JRYT, ICYT, LBINP, LBOUT, NTL and MODE is the same as for the subroutine EQFORM.

The rest of the arguments are as follows:

INPT — is the index of the INPUT unit. INTEGER parameter.

OTPT is the index of the OUTPUT unit. INTEGER parameter.

IWRITE is an INTEGER parameter that controls output.

Input-Output

Output data is controlled by parameter IWRITE. Possible values IWRITE are:

$\neq 1$ all printouts are suppressed,

$= 1$ all arguments after calling the subroutine are printed out on unit OTPT.

The data is read from unit INPT.

SUBROUTINE RDATA (NBOUND, JBOUND, NRET, JRET, INPT).

Purpose

This subroutine reads from the file INPT data describing the boundary and retained buses.

List of Arguments

NBOUND is an INTEGER argument. On exit from the subroutine it stores the number of boundary buses.

JBOUND is an INTEGER vector of dimension no less than NBOUND. On exit from the subroutine it stores the indices of the boundary buses.

NRET is an INTEGER argument. On exit from the subroutine it stores the number of retained buses.

JRET is an INTEGER vector of dimension no less than NRET. On exit from the subroutine it stores the indices of the retained buses.

INPT is the index of the INPUT unit.

Remarks

The data must be available on the unit INPT arranged in a free format and in the following sequence:

NBOUND

JBOUND(1)

.
.
.
.

JBOUND (NBOUND)

NRET

JRET(1)

.
.
.
.

JRET (NRET)

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