NUMERICAL TECHNIQUES FOR LOAD FLOW STUDIES

BY

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Abstract

The paper presents a comprehensive study for the different digital load flow techniques. Through numerical application on 16-bus power system, a comparison between the different methods regarding the computer time taken to obtain the problem final solution, the number of iterations, the core requirement, and the time per iteration.

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List of Symbols :

A. Complex quantities at bus P

$E_p = E_p \underline{\theta_p} = e_p + J f_p$	Nodal voltage.
I_p	Nodal injected current.
$S_p = P_p + J Q_p$	Net nodal injected power.
$S_p = p_p + J Q_p$	Power mismatch .
I_p	Current mismatch .
$E_p = E_p \underline{\theta_P}$	Correction to nodal voltage.

B. Matrices :

$Y = G + J B$	Nodal admittance matrix .
Z	Nodal impedance matrix .
J	Jacobian matrix .

C. General :

n	Number of buses in system .
x_{pq}	Reactance of branch between buses p & q .
s	Slack bus index .

Introduction :

Load flow (or power flow) is the solution for the static operating condition of an electric-power transmission system, and is the most frequently performed of roution digital-computer power network calculations.

Over the last 26 years an enormous amount of effort has been expended in research and development on the numerical calculation process. The aim is to present the underlying principles and techniques of the popularly accepted approaches, those more recent methods that seem to offer particular promise, and a selection of other methods that contain ideas of practical or theoretical interest 1 .

Adopted Methods for Load-Flow Studies :

1. Gauss-Seidel Method Using Y_{BUS} 4 , 8 :

The Y - matrix iterative methods of load-flow calculation are based on the iterative solution of the linear equation (1) :

$$I_{Bus} = Y_{Bus} \quad E_{Bus} \tag{1}$$

Assuming values for the voltages at different buses except the slack bus, then, currents are calculated from the bus loading equation as :

$$I_p = \frac{P_p - J\, Q_p}{E_p^{*}} \qquad p = 1, 2, \ldots, n \quad p \neq s \tag{2}$$

Selecting the ground as the reference bus, a set of n-1 simultaneous equations can be written in the form

$$E_p = \frac{1}{Y_{pp}} \left(I_p - \sum_{\substack{q=1 \\ q \neq p}}^{n} Y_{pq} E_q \right) \qquad p = 1, 2, \ldots, n \quad p \neq s \tag{3}$$

From (1),(3):

$$E_p = \frac{1}{Y_{pp}} \left(\frac{P_p - J\, Q_p}{E_p^{*}} - \sum_{\substack{q=1 \\ p \neq q}}^{n} Y_{pq} E_q \right) \tag{4}$$

$$p = 1, 2, \ldots, n \quad p \neq s$$

It is noted that, the admittance matrix iterative methods converge slowly, because of the loose mathematical coupling between the buses at each iteration cycle.

Acceleration techniques are invariably used in practice to speed up the convergence. A fixed empirically determined acceleration factor α ($1 < \alpha < 2$) is applied to each voltage change reevaluation thus :

$$E_p = \alpha\, S_p^{*} / E_p^{*}\, Y_{pp} \tag{5}$$

2. Gauss-Seidel Method Using Z_{Bus} [1, 2, 4] :

The major difference in principle between the Y-matrix iterative methods and the Z-matrix methods is that in the latter, the linear equation(1) is solved directly for E_{Bus} in terms of I_{Bus} using the inverse of Y_{Bus} as :

$$\begin{aligned} E_{Bus} &= Y_{Bus}^{-1}\, I_{Bus} \\ &= Z_{Bus}\, I_{Bus} \end{aligned} \tag{6}$$

The bus current I_p ($p \neq s$) is evaluated from

$$I_p = (P_p^{sp} - J\, Q_p) / E_p^{*} \tag{7}$$

where :

Q_p = calculated values of reactive power for a PV-node (equivalent to setting $\Delta Q_p = 0$)

The bus voltages are reevaluated by the iterative application of :

$$E_p^{k+1} = E_s + \sum_{\substack{q=1 \\ q\neq s}}^{p-1} Z_{pq}\, I_q^{k+1} + \sum_{q\neq p}^{n} Z_{pq}\, I_q^{k} \qquad q=1,2,\ldots, n$$

where :

$$I_q^{k+1} = \frac{P_q - J\, Q_q}{(E_q^{k+1})^*}$$

3. Newton-Raphson Method Using Y_{Bus} in Rectangular Coordinates [4]

The load flow problem can be solved by the Newton-Raphson method using a set of nonlinear equations to express the specified real and reactive powers in terms of bus voltages .
Substituting from the network performance equation (1) for I_p in (2) :

$$P_p - J\, Q_p = E_p^* \sum_{q=1}^{n} Y_{pq}\, E_q \qquad (8)$$

since

$$E_p = e_p + J\, f_p$$

and

$$Y_{pq} = G_{pq} - J\, B_{pq}$$

equation (8) becomes :

$$P_p - J\, Q_p = (e_p - J\, f_p) \sum_{q=1}^{n} (G_{pq} - J\, B_{pq})(e_q + J\, f_q)$$

Separating the real and imaginary parts :

$$P_p = \sum_{q=1}^{n} e_p(e_q\, G_{pq} + f_q\, B_{pq}) + f_p\,(f_q\, G_{pq} - e_q\, B_{pq})$$

$$Q_p = \sum_{q=1}^{n} f_p(e_q\, G_{pq} + f_q\, B_{pq}) - e_p(f_q\, G_{pq} - e_q\, B_{pq})$$

Newton-Raphson method requires that a set of linear equations be formed expressing the relationship between the changes in real and reactive powers and the components of bus voltages as follows :

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \cdot \begin{bmatrix} \Delta e \\ \Delta f \end{bmatrix} \qquad (9)$$

Equation (9) can be solved for Δe_p and Δf_p

To reduce the computation time and to increase the rate of the convergence, a multiplication factor λ for the J-matrix can be introduced ($\lambda \ll 1$).
So

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \lambda \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \cdot \begin{bmatrix} \Delta e \\ \Delta f \end{bmatrix}$$

4. Newton-Raphson Method Using Y_{Bus} in Polar Coordinates [2,5]

The power flow of the general n-node power system can also be described by a set of n-simultaneous complex equation(8).
If the voltage vector E_p at node p be expressed in polar form as:

$$E_p = |E_p| \; e^{-J\theta_p}$$

Then equation (8) is reduced to a set of 2n real simultaneous equations :

$$P_p = |E_p| \sum_{q=1}^{n} |E_q| \left(G_{pq} \cos(\theta_p-\theta_q) + B_{pq} \sin(\theta_p-\theta_q)\right) \quad (11)$$

$$Q_p = |E_p| \sum_{q=1}^{n} |E_q| \left(G_{pq} \sin(\theta_p-\theta_q) - B_{pq} \cos(\theta_p-\theta_q)\right) \quad (12)$$

The elements of the Jacobian are calculated from equations(11&12).
The equations relating changes in power to changes in voltage magnitudes and phase angles for the N-R method is :

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta |E| \end{bmatrix} \quad (13)$$

Equation (13) can be solved for $\Delta\theta_p$ and $|E|$

In general, for a small change in the magnitude of bus voltage the real power at the bus does not changes appreciably. Likewise, for a small change in the phase angle of the bus voltage the reactive power does not change appreciably.
Therefore, using polar coordinates, a solution for the load flow problem can be obtain assuming the elements of the submatrices J_2 and J_3 to be zero.

So, the simplified matrix equation is [4] :

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & 0 \\ 0 & J_4 \end{bmatrix} \cdot \begin{bmatrix} \Delta \theta \\ \Delta |E| \end{bmatrix} \qquad (14)$$

5- Decoupled Methods [8] :

An inherent characteristic of any practical electric-power transmission system operating in the steady state is the strong interdependance between active powers and voltage magnitudes. Correspondingly, the coupling between "P-θ" and "Q- |E| " components of the problem is relatively weak. In the load-flow problem, recent tends towards this objective by decoupling (solving separated) the P-θ and Q- |E| problems are :

5.1: The Fast Decoupled Load-Flow Method Using Y_{Bus} in Polar Coordinates [7,8]

The first step in applying the P-θ & Q- |E| decoupling principle is to negect the coupling submatrices J_2 and J_3, giving two separated equations

$$[\Delta P/V] = [B'] [\Delta \theta] \qquad (16)$$

$$[\Delta Q/V] = [B''] [\Delta V] \qquad (17)$$

where:

$$B'_{pq} = -1/x_{pq} \qquad (p \neq q)$$

$$B'_{pp} = \sum_{p \neq q} 1/x_{pq} \quad \text{and} \quad B''_{pq} = -B'_{pq}$$

5-2 A New Decoupled Load Flow (Voltage Vectors) Method [6]

The two separated equations are :

$$\Delta P^k = T^k \quad \Delta \theta^{k+1} \qquad (18)$$

$$\Delta Q^k/V = U \quad \Delta V^{k+1} \qquad (19)$$

where :

$$T_{pq} = -\frac{V_p V_q}{Z^2_{pq} / x_{pq}} , \quad T_{pp} = -\sum_{q=0}^{n} T_{pq} \qquad p \neq q$$

$$U_{pq} = -\frac{1}{Z^2_{pq}/x_{pq}} , \quad U_{pp} = -\sum_{q=0}^{n} U_{pq} \qquad p \neq q$$

The relations (18 & 19) represent the new decoupled load-flow method for solving the load-flow problem.

6. Fast Load-Flow Method Retaining Nonlinearity [10]

The Taylor series expansion of quadratic equations corresponding to the load flow equations is given by :

$$\left[Y_s\right] = \left[Y(x_e)\right] + \left[J\right]\left[\Delta x\right] + \tfrac{1}{2}\left[H\right]\begin{bmatrix}\Delta x_1 & \Delta x_1 \\ \Delta x_1 & \Delta x_2 \\ \Delta x_n & \Delta x_n\end{bmatrix} \qquad (20)$$

where :

$$J \equiv \begin{bmatrix}\frac{\partial Y_1}{\partial x_1} & \cdots & \frac{\partial Y_1}{\partial x_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial Y_n}{\partial x_1} & \cdots & \frac{\partial Y_n}{\partial x_n}\end{bmatrix}_{x=x_e}, \quad H \equiv \begin{bmatrix}\frac{\partial^2 Y_1}{\partial x_1 \partial x_2} & \cdots & \frac{\partial^2 Y_1}{\partial x_n\, \partial x_n} \\ \cdots & \cdots & \cdots \\ \frac{\partial^2 Y_n}{\partial x_1\, \partial x_1} & \cdots & \frac{\partial Y_n}{\partial x_n\, \partial x_n}\end{bmatrix}$$

The most important fact is that no terms above third, or the second derivative, exist because the original equation is quadratic. It is seen that the third term which is complicated and of high dimensionality can be expressed as a vector as :

$$\left[Y_s\right] = \left[Y(x_e)\right] + \left[J\right]\left[\Delta x\right] + \left[Y(\Delta x)\right] \qquad (21)$$

Rewriting (21), we have :

$$J \;\; \Delta x^{(k+1)} = Y_s - Y(x_e) - Y\,(\Delta x^k)$$

and defining ΔY^k as below :

$$\Delta Y^k = Y_s - Y(x_e) - Y(\Delta x^k)$$

the final numerical expression can be written as :

$$J \;\; \Delta x^{(k+1)} = \Delta Y^k$$

In order to solve the equation for Δx, the matrix J is triangular factorized to produce the triangulated matrix J' and new vector $\Delta Y'^k$ (the sign ' denotes triangular-factorized matrix).

$$\left[\; J' \;\right] \left[\; \Delta x^{(k+1)} \;\right] = \left[\; \Delta Y'^k \;\right]$$

and Δx is obtained by the back substitution.

Numerical Application :

The different mentioned techniques are applied to have the load flow solution for the power system shown in Fig. 1 which is the 220 KV part of Egyptian unified electric power system and with system data as mentioned in tables 1 & 2 .

Results :

The problem solution using the fast load-flow method retaining nonlinearity[10] is given in tables 3-1 & 3-2. Table 4 illustrates a comparison between the different techniques for having the problem solution. The results obtained are from computer programes on ICL computer [12].

Comments :

Gauss-Seidel method using Y_{Bus} is an efficient and simple method. It requies smaller computer storage (6.72 K) and small time to obtain the final solution (18 Sec), although it uses the largest number of iterations (13), so that the convergence is low but the time per iteration is very small (1.4 Sec).

Gauss-Seidel method using Z_{Bus} uses small space in the computer (11.712 K), small number of iterations(3) and small time to obtain the final solution (20 Sec). The time per iteration is large (6.6 Sec) comparing with the last method, but the convergence is high.

N-R method using Y_{Bus} in rectangular coordinates is a complex method and uses large space in the memory of the computer (24.576 K), the overall time which is used to obtain the final solution is large (27 Sec) but the number of iterations is small (3), the time per iteration is large (9 Sec) comparing with other methods.

N-R method using Y_{Bus} in polar corrdinates is nearly similar to last method (in rectangular coordinates) but the main difference is that, the voltage magnitude for polar coordinates (1.07 P.U) is higher than that for rectangular coordinates (1.04 P.U) for the second iteration in each bus [12] . Although the convergence region obtained with polar coordinates may be wider than one obtained with rectangular coordinates and the convergence with polar coordinates is less stable than that with rectangular coordinates.

The relations (18 & 19) represent the new decoupled load-flow method for solving the load-flow problem.

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The Taylor series expansion of quadratic equations corresponding to the load flow equations is given by :

$$\left[Y_s \right] = \left[Y(x_e) \right] + \left[J \right]\left[\triangle x \right] + \tfrac{1}{2} \left[H \right] \begin{bmatrix} \triangle x_1 & \triangle x_1 \\ \triangle x_1 & \triangle x_2 \\ \triangle x_n & \triangle x_n \end{bmatrix} \qquad (20)$$

where :

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and defining $\triangle Y^k$ as below :

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the final numerical expression can be written as :

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The approximation method of N-R in polar coordinates, uses large number of iterations (7) , large overall time to obtain the final solution (49 Sec), and the convergence is low but the storage required is small (18.304 K).

The modification of N-R method by the use of factor λ ($\lambda \leqslant 1$), reduces the total time to obtain the final solution (17 Sec). The time per iteration (4.25 Sec) and the time per bus (1.13 Sec) is also reduced , but the storage required is similar to the normal N-R method (24.448 K).

The fast decoupled method using Y_{Bus} in polar coordinates uses a large number of iterations (6), small time per iteration (3.3 Sec) and the storage required is small (17.472 K) compared with the normal N-R method [9] .

The new decoupled (voltage vectors) method using Y_{Bus} in polar coordinates is similar to the fast decoupled method.

The fast load-flow method retaining nonlinearity with triangular technique is similar to the normal N-R method but the only difference is that the storage required is high (34.368 K) and the total time required to obtain the final solution is small (21 Sec). If the elements of the J-matrix are stored using the sparsity techniques, it will save the space taken in the memory of the computer.
The algorithm used for this method is the exact expression, which takes into account all the terms of the Taylor series expansion and retains the nonlinearity of the original equation.

The modification of the fast load-flow method retaining nonlinearity without using triangular technique, it is similar to the last method (with triangular technique) but the only difference is that the storage requirement is small (25.024 K) comparing to the last method, and the total time taken to obtain final solution is small (18. Sec), therefore, the time per iteration is also small (4.5 Sec).

Conclusions :

From the above analysis and the results obtained by applying the different techniques on the actual power system shown in Fig.1 , it could be concluded that :

1- Gauss-Seidel method using Y_{Bus} is preferred when the network is small compared with other methods, added to this Gauss-Seidel method using Z_{Bus} is preferred when it is wanted to make highconvergence, small computation time, and small computer storage.

2- N-R method in rectangular coordinates is preferred when the network is large but the space required in the computer and the time per iteration are large.

3- N-R method in polar coordinates is preferred for the same reasons mentioned before but the problem of stability will appear.

4- The approximation method can be considered as a modification of N-R method. It may be used when it is wanted to decrease the computation time and space in the computer.

5- The multiplication of J-matrix by factor λ (in N-R method) is preferred when it is wanted to decrease the computation time and the time per iteration .

6- The fast and new decoupled methods are preferred when it is wanted to decrease the computation time, the time per iteration and the storage in the computer .

7- The fast load-flow method with triangular technique is used to decrease the computation time and the time per iteration, but the storage required is large.

8- The fast load flow method without using triangular technique is preferred when it is wanted to decrease the computation time, the time per iteration and computer storage compared with last method.

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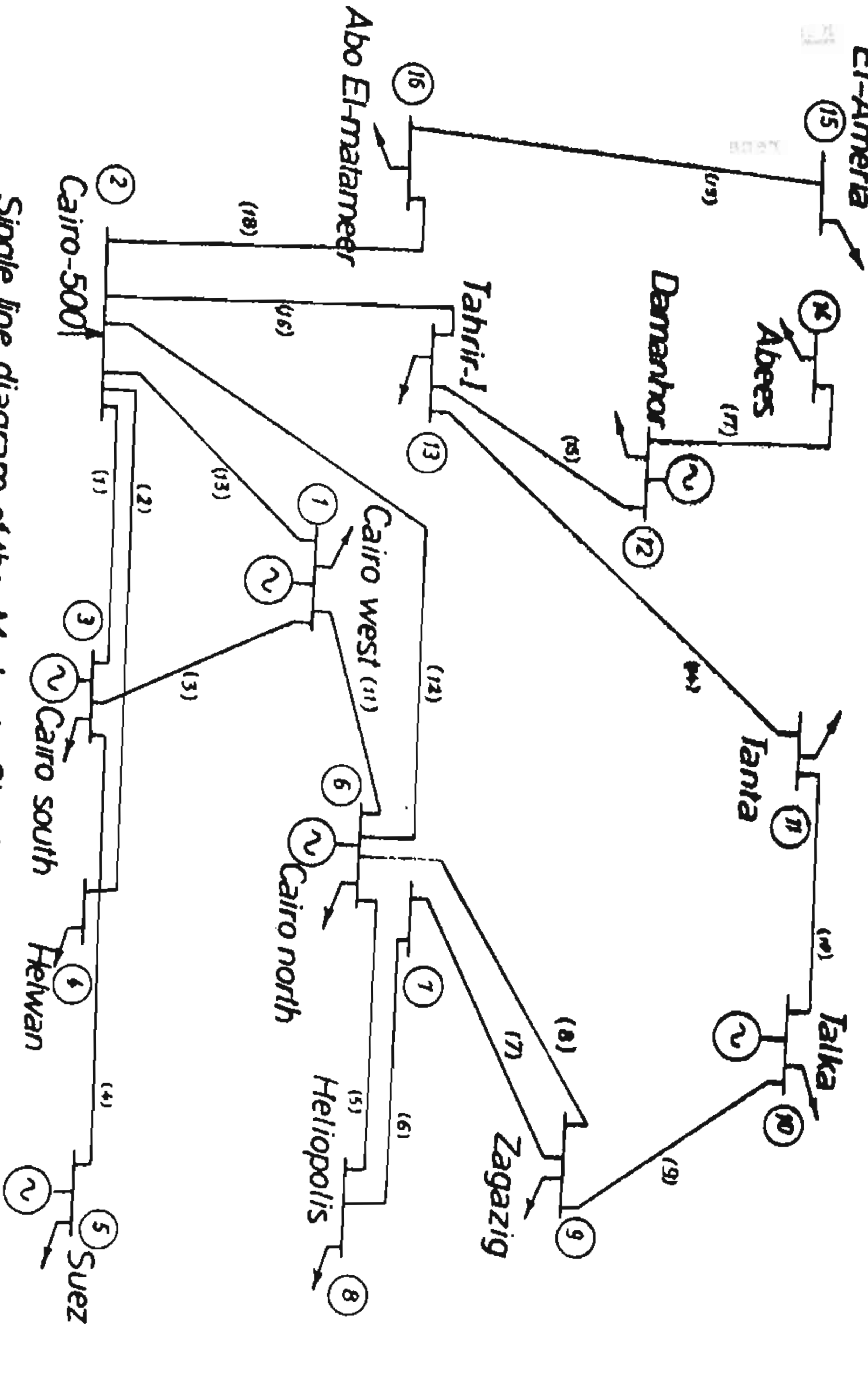

Single line diagram of the Moderate Size Real Electric Network.
(220 K.V Network)

Table 1 Data for branches of the moderate size real electric network.

Branch number	From node	to node	Cross-section mm^2/cond	length km.	Resistance Ω/ph.	Inductive reactance Ω/ph.	Permissible Continious current Load Amp.
1	2	3	400	37.29	2.9459	14.6672	865
2	2	4	240	2.94	0.3822	1.2111	600
3*	3	1	400	46.6	1.864	9.2582	1700
4*	3	5	240	135	8.775	27.805	1200
5	6	8	240	19.24	2.5012	7.9254	600
6	7	8	240	19.24	2.5012	7.9254	600
7	7	9	400	60	4.8	23.8409	850
8	6	9	400	60	4.8	23.8409	850
9	10	9	400	60	4.8	23.8409	850
10	10	11	400	50	4.0	19.8674	850
11*	1	6	400	16.4	0.656	3.2583	1700
12*	2	6	400	24	0.96	4.7682	1700
13*	2	1	400	11	0.44	2.1854	1700
14	13	11	400	43	3.44	17.086	850
15*	13	12	400	63	2.52	12.5165	1700
16*	2	13	400	69	2.79	13.7085	1700
17*	12	14	400	47	1.88	9.3377	1700
18*	2	16	400	130.5	5.22	25.927	1700
19*	16	15	240	35	2.275	7.2087	1700

* These branches are double circuit , the others are single circuit.

Table 2. Node data for the moderate network

Node No.	Name of country	Permissible generation		local consumption	
		MW	MVAR	MW	MVAR
1	Cairo West	175	....	65	47
2	Cairo - 500	1250	....	—	—
3	Cairo south	120	....	60	45
4	Helwan	—	—	300	225
5	El-Suez	75	....	96	72
6	Cairo North	60	....	65	37
7	Cairo North (II)	—	—	0.0	0.0
8	Heliopolis	—	—	220	118
9	Zagazig	—	—	100	66
10	Talka	66	....	35	19
11	Tanta	—	—	210	136
12	Damanhor	160	....	100	66
13	Tahrir I	—	—	68	42
14	Abees	—	—	120	90
15	El-Ameria	—	—	200	150
16	Abo-El-Matameer	—	—	200	150

Table 3-1

VA		VM	DELT'
1.060000	0.000000	1.060000	0.000000
1.043465	0.003915	1.043473	0.003752
1.053539	0.007926	1.053568	0.007523
1.035998	-0.001396	1.035999	-0.001347
1.032202	0.008021	1.032233	0.007771
1.047407	-0.004718	1.047417	-0.004505
1.018962	-0.036563	1.019617	-0.035867
1.032536	-0.056080	1.034058	-0.054259
1.072286	-0.086441	1.075765	-0.080440
1.005878	-0.085054	1.009468	-0.084356
1.013297	-0.037635	1.013995	-0.037124
1.020904	-0.031600	1.021393	-0.030943
1.001455	-0.046374	1.002528	-0.046274
0.874968	-0.095519	0.880167	-0.108737
0.897654	-0.085100	0.901679	-0.094520

Table 3-2

CIBR		SBR	
0.015315	-0.023516	0.015948	-0.024896
0.222819	-0.168087	0.231846	-0.176265
-0.053225	-0.064751	-0.056418	-0.068636
0.016810	-0.054114	0.017281	-0.057145
0.181358	-0.081726	0.190341	-0.084744
-0.018983	-0.020911	-0.018428	-0.022655
0.084843	-0.007065	0.088898	-0.006999
-0.034895	-0.071588	-0.031229	-0.079779
0.022443	-0.124906	0.034862	-0.131995
0.165710	-0.265674	0.175653	-0.281614
-0.122307	-0.088603	-0.127687	-0.093381
-0.019504	-0.590281	-0.020674	-0.625698
0.122999	-0.009298	0.125864	-0.005606
0.044978	-0.037979	0.047118	-0.037351
0.217595	-0.083085	0.226727	-0.087549
0.088651	-0.080326	0.092853	-0.076058
0.339779	-0.367115	0.353110	-0.384402
0.171732	-0.189437	0.170277	-0.155434

```
10.52.33 FREE *CRO ,34 TRANSFERS

10.52.33 FREE *LPO ,41 TRANSFERS
0.47 :DELETED : 00
10.52.34 0.47 DELETED,CLOCKED 0.18
END OF MACRO
PARAMETER NUMBER 4 UNACCESSED
END OF MACRO
MAXIMUM ONLINE BS USED 295 KWORDS
10.52.35 0.47 FINISHED : 1 LISTFILES
BUDGET        USED      LEFT
TIME(G)        48      998890
MONEY         133      992919
```