A SPREADSHEET APPLICATION IN DISTRIBUTION LOAD FLOW STUDIES USING SIMPLIFIED LOAD FLOW TECHNIQUES

by

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Abstract

In order to adopt effective designing strategies, the practical Distribution Engineer has to have a set of tools. These will have to be easy to understand, implement and develop. A modern spreadsheet which is well equipped with most of these requirements is used in this study for modelling electrical power distribution systems. The novelty of this method is the application of the spreadsheet for the solution of an engineering problem. This is rare, since spreadsheets were originally developed mainly for financial modelling.

Due to the nature of load flow studies, many calculations require to be repeatedly performed for each and every busbar in the system. Inversion of matrices in the calculations is also demanded, when certain algorithms are used. Both these facilities along with trigonometric and other functions are readily available with the modern spreadsheets, where these facilities are built in to the package itself, allowing easy computations.

The results from this technique were tested against the proven Newton-Raphson Load Flow Technique (NRLF) with very satisfactory agreement.

Although there are a limited number of recorded instances where spreadsheets have been used for engineering applications, exploitation of the spreadsheet to this depth, as done in this study is rare.

List of Principal Symbols

Pi - The active power injected at bus i

Qi - The reactive power injected at bus i

Ci - The capacitance of the voltage compensating capacitor banks at bus i

Bi - The shunt susceptance at bus i

Vi - The voltage magnitude at bus i

Ii - The nodal current magnitude at bus i

Qi - The voltage angle at bus i with respect to reference bus

Yik - The ikth element of Y matrix

Gik - The ikth element of G matrix

Bik - The ikth element of B matrix

k i - Implies that k is connected to i or coincident with i

1.0 Introduction

Distribution load flow studies have to be carried out constantly in order to design a good distribution system. This becomes highly necessary when the loading on existing networks grow due to rapid industrialisation and urbanisation. The following characteristics of general distribution networks are borne in mind when developing the proposed model.

1. The values of line resistances are comparable with corresponding line inductances.
2. The voltage angles at the bus bars are very small.
3. All the distribution transformers are off load tap changing type (OFTC) and could be on the nominal tap.
4. The effects of shunt admittance at distribution levels are extremely small.
5. Except for the bus 1, where power is injected, the loads at all other buses are known.

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Based on the above characteristics the following assumptions are made in the study.

i. All voltage angles are small. Hence the resulting second order terms could be neglected.

ii. All shunt elements except the capacitor banks have negligible effect on the system.

iii. Loads at all busbars other than at the slack bus are known.

Here the normal a.c. load flow equations to a power system is reduced to a simple set of non-linear equations using a technique similar to that used on the D.C. Network Analyser by Karunaratne(3) and the Modified D.C. Load Flow Technique by Lucas, Induruwa and Malembeka5. Then iterative techniques are used to arrive at the solution. Since the number of bus bars involved at distribution levels is far greater than that at higher transmission voltage levels, it would take a longer time to converge if the "Jacobian" matrix is to be inverted, or the bus admittance matrix, changed with each iteration. The set of equations developed under this study results in a constant "Jacobian" matrix of the same order as the Jacobian in the Newton-Raphson Load Flow (NRLF) technique. This allows greater flexibility to the user so that load flows could be carried out at different loading patterns using the same constant "Jacobian" inverted only once.

2.0 Load Flow Calculations

The modified Power Flow Equations represented in matrix form for a system with n busbars have been derived in Appendix I. (vide equation A1). Since the system of equations represented by equation A1 is singular, to make it non-singular, equation corresponding to bus 1 has been removed.

The resulting equation is as follows,

$$\underset{2(n-1)\times 1}{\begin{bmatrix} P^m \\ Q^m \end{bmatrix}} = \underset{2(n-1)\times 2(n-1)}{\begin{bmatrix} G^m & -B^m \\ B^m & G^m \end{bmatrix}} \underset{2(n-1)\times 1}{\begin{bmatrix} V \\ W \end{bmatrix}} \quad \ldots\ldots (1)$$

where the corresponding terms of the LHS vector for the ith busbar are given by

$$P_i^m = P_i + Q_i\theta_i/V_i + wC_iV_i\theta_i - G_{i1}V_i + B_{i1}W_i$$

$$Q_i^m = Q_i + P_i\theta_i/V_i - wC_iV_i - B_{i1}V_i - G_{i1}W_i$$

and the corresponding term of the vector W for the ith busbar is given by,

$$W_i = V_i\theta_i$$

Equation (1) can also be rewritten as follows.

$$\underset{2(n-1)\times 1}{\begin{bmatrix} P^m \\ Q^m \end{bmatrix}} = \underset{2(n-1)\times 2(n-1)}{\begin{bmatrix} M \end{bmatrix}} \underset{2(n-1)\times 1}{\begin{bmatrix} V \\ W \end{bmatrix}}$$

where $M = \begin{bmatrix} G^m & -B^m \\ B^m & G^m \end{bmatrix}$

Multiplying both sides by $[M]^{-1}$

$$\underset{2(n-1)\times 1}{\begin{bmatrix} V \\ W \end{bmatrix}} = \underset{2(n-1)\times 2(n-1)}{\begin{bmatrix} M \end{bmatrix}} \underset{2(n-1)\times 1}{\begin{bmatrix} P^m \\ Q^m \end{bmatrix}}$$

The above equation could be rewritten slightly differently as shown below,

$$\begin{bmatrix} V \\ W \end{bmatrix} = \begin{bmatrix} A \\ B \end{bmatrix} S \; ; \; S = \begin{bmatrix} P^m \\ Q^m \end{bmatrix} ; [M]^{-1} = \begin{bmatrix} A \\ B \end{bmatrix}$$

Separating the unknown vector in to two sub vectors, equations (2) and (3) are obtained

$$\underset{(n-1)\times 1}{[V]} = \underset{(n-1)\times 2(n-1)}{[A]} \underset{2(n-1)\times 1}{[S]} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

$$\underset{(n-1)\times 1}{[W]} = \underset{(n-1)\times 2(n-1)}{[B]} \underset{2(n-1)\times 1}{[S]} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

Using iterative techniques,

$$[V^P] = [A]\,[S^{P-1}]$$

$$[W^{P+1}] = [B]\,[S^P]$$

(The supercript denotes the iteration count)

3.0 Application of the Spreadsheet

Macro facilities offered by the LOTUS 123 Release 2.01 package was selected for this study and utilised in developing the final load flow program resulting in a set of sequential spreadsheet instructions. This could be depicted by the FLOW CHART in figure 1.

3.01 Reading bus and line data

As the first input, the number of busbars in the modelled power system is entered at a specified cell in the spreadsheet. Once this is complete, the voltage level of the power system has to be entered. Now the MACRO will create a table (fig. 2) and await input of all relevant bus data available for the modelled system. Here DATA FILL facility is utilised to create a specific row for each bus bar in the system.[G] and [B] submatrices of specific size are created at selected locations using the RANGE NAME CREATE facility along with the number of busbars obtained earlier from keyboard. By this method the ranges created, or the order of the matrices created will only conform to the order of the system of equations under consideration.

3.02 Forming submatrices [G] and [B] of Jacobian

After the ranges for the submatrices are formed, the GET VALUE feature of the package is used to obtain all line data from the keyboard. The ikth and kith elements for each line in the submatrices [G] and [B] are then calculated directly. These data are reserved at specified cells within those specified ranges created earlier, within the main spreadsheet for later use. The diagonal elements of these submatrices are calculated using the facility of addition of ranges and are stored at appropriate locations of the matrices formed earlier, using the PUT facility of the package.

3.03 Formation of the Jacobian [M] from submatrices [G] and [B] and its inversion

The Jacobian [M] is formed by using the copying facility of the spreadsheet to another specified range within the same spreadsheet, after excluding the bus bar 1 to make the matrix non-singular. This Jacobian along with the matrix inversion facilities of LOTUS are used to invert the Jacobian directly without application of other matrix inverting techniques.

3.04 Formation of vector [S] and Calculation of bus voltages and Angles

The bus data stored earlier in the table, are then copied to another location in the spreadsheet after introducing suitable initial guesses for the unknown data. The vector [S] is formed by calculating the corresponding first value of the vector [S] and copying this equation for the rest of the busbars. This vector along with the inverted Jacobian is used with the matrix multiplication facilities of the package, to calculate voltages at unknown busbars using equation (2). This process is continued after calculating the corresponding voltage angles using equation (3), with updated voltage values obtained from equation (2) until solution converges.

3.05 Calculation of Line Flows

Substituting the final solution for individual voltages and voltage angles in equations A4 and A5 directly (Appendix I), the active and reactive power flows are calculated for the line connecting bus 1 and bus 2. This is then copied for the rest of the system since the calculating process is the same for all the busbars.

4.0 Application of the Technique and Results

The technique was tested by applying it to the 10 bus system shown in figure 3. The NRLF technique was applied to the same system in order to check the accuracy of the technique developed. A comparison between the two techniques on the loadings are shown in Table I and the corresponding power flows are compared in Table II.

It is observed that the system of equations converge very fast requiring only one iteration for convergence.

5.0 Conclusion

The results obtained for the test network show that the results from the proposed technique are in good agreement with those from the NRLF technique, the reported deviation being extremely low (order of 0.0001 which is the set accuracy level for convergence).

Another key advantage offered by the proposed technique is its requirement to invert the Jacobian only once for a particular set of data. This is very useful when carrying out repeated load flow calculations at different loadings, applied to the same network. This is increasingly useful at distribution voltage levels where, the load curve tend to vary widely over time. Using this method only the loads need to be changed and no repeated matrix inversion is necessary.

Also in this method, memory utilisation is rational for the given number of busbars.

Since many of the packages available for distribution simulation studies are very expensive and require sophisticated computers to run, needing extensive training, this package could be used as a low cost, easy to understand, economical method of solving distribution load flow problems with very minimal familiarisation.

This is a novel application of the spreadsheet, and this shows that there is much more scope for the use of spreadsheet in solving engineering problems.

6.0 References

1. Bissel Chris and Chapman David "Modelling Applications of Spreadsheets" IEE Review July/August 1989 PP267-271
2. Elgerd Olle "Electric Energy Systems Theory - An Introduction", McGraw Hill 1983 PP 219-273
3. Karunaratne S. "Use of D.C. Network Analyser for A.C. Load Flow Studies" Trans IE (Cey) 1973
4. LOTUS 1-2-3 Release 2.01 Reference Manual
5. Lucas J.R. Induruwa A.S. and Malembeka A. "A Solution of the Power System Load Flow Problem on the Digital Computer Using Modified D.C. Load Flow techniques", Engineer, Vol. XVI, No. 3 - 1989
6. Selk Steve "Spreadsheet Software Solves Engineering Problems", Chemical Engineering June 1983 PP51-53

APPENDIX I

At distribution levels B_i is insignificant and therefore, can be ignored

At bus i, under balanced conditions.

$$P_i - jQ_i - jwC_i E_i = E_i^* I_i$$

$$P_i - jQ_i - jwC_i V_i^2 = V_i \angle{-\theta_i} \{\sum_{k \in i} Y_{ik} V_k \angle{\theta_k}\}$$

$$\frac{P_i - jQ_i}{V_i \angle{\theta_i}} - \frac{jwC_i V_i^2}{V_i \angle{\theta_i}} = \{\sum_{k \in i} Y_{ik} V_k \angle{\theta_k}\}$$

$$\frac{P_i - jQ_i}{V_i} (COS\theta_i + jSIN\theta_i) - jwC_i V_i (COS\theta_i + jSIN\theta_i)$$

$$= \{\sum_{k \in i} (G_{ik} + jB_{ik}) V_k (COS\theta_k + jSIN\theta_k)\}$$

$$\frac{P_i COS\theta_i + Q_i SIN\theta_i}{V_i} + wC_i V_i SIN\theta_i + j(\frac{P_i SIN\theta_i - Q_i COS\theta_i}{V_i} - wC_i V_i COS\theta_i)$$

$$= \{\sum_{k \in i} (G_{ik} V_k COS\theta_k - B_{ik} V_k SIN\theta_k) + j(B_{ik} COS\theta_k + G_{ik} V_k SIN\theta_i)\}$$

Assuming that all θ's are small so that second order terms can be neglected. $Cos\theta = 1$; $Sin\theta = \theta$ for all θ.

Now the equation becomes,

$$\frac{P_i+Q_i\theta_i}{V_i} + wC_iV_i\theta_i + j\left(\frac{P_i\theta_i-Q_i}{V_i} - wC_iV_i\right)$$
$$= \left(\sum_{k\epsilon i} (G_{ik}V_k - B_{ik}V_k\theta_k) + j(B_{ik}V_k + G_{ik}V_k\theta_k)\right)$$

Equating real parts,

$$\frac{P_i+Q_i\theta_i}{V_i} + wC_iV_i\theta_i = \sum_{k\epsilon i}(G_{ik}V_k - B_{ik}V_k\theta_k)$$

Equating imaginary parts,

$$\frac{P_i\theta_i-Q_i}{V_i} - wC_iV_i = \sum_{k\epsilon i}(B_{ik}V_k + G_{ik}V_k\theta_k)$$

Let $V_k\theta_k = V_k$ for all k

Representing the above equations in matrix form for a n bus system

$$\begin{bmatrix} \frac{P+Q\theta}{V} + wCV\theta \\ \hline \frac{P\theta-Q}{V} - wCV \end{bmatrix} = \begin{bmatrix} G & -B \\ \hline B & G \end{bmatrix} \begin{bmatrix} V \\ \hline V \end{bmatrix} \quad \text{-----(A1)}$$

2n x 1 2n x 2n 2n x 1

Since the system of equations represented by (A1) is singular, inorder to make it non singular, for purposes of inversion, factors pertaining to bus 1 (slack bus)are transferred to the left hand side.

Now the system becomes,

$$\begin{bmatrix} P^m \\ \hline Q^m \end{bmatrix} = \begin{bmatrix} G^m & -B^m \\ \hline B^m & G^m \end{bmatrix} \begin{bmatrix} V \\ \hline V \end{bmatrix}$$

2(n-1)x1 2(n-1)x2(n-1) 2(n-1)x1

where the corresponding terms of the LHS vector for the i^{th} busbar are given by,

$$P_i^m = P_i + Q_i\theta_i/V_i + wC_iV_i\theta_i - G_{ii}V_i + B_{ii}V_i$$
$$Q_i^m = Q_i + P_i\theta_i/V_i - wC_iV_i - B_{ii}V_i - G_{ii}V_i$$

and the corresponding term of the vector V for the i^{th} busbar is given by,

$$V_i = V_i\,\theta_i$$

Equation (1) can also be rewritten as follows

$$\begin{bmatrix} P^m \\ --- \\ Q^m \end{bmatrix} = \begin{bmatrix} & & \\ & M & \\ & & \end{bmatrix} \begin{bmatrix} V \\ --- \\ V \end{bmatrix}$$

2(n-1)x1 2(n-1)x2(n-1) 2(n-1)x1

$$\text{Where } M = \left[\begin{array}{cc} G^m & -B^m \\ \hline B^m & G^m \end{array}\right]$$

Multiplying both sides by $[\ M\ ]^{-1}$

$$\begin{bmatrix} V \\ --- \\ V \end{bmatrix} = \begin{bmatrix} & & \\ & M & \\ & & \end{bmatrix} \begin{bmatrix} P^m \\ --- \\ Q^m \end{bmatrix}$$

2(n-1)x1 2(n-1)x2(n-1) 2(n-1)x1

The above equation could be rewritten slightly differently as shown below,

$$\begin{bmatrix} V \\ \hline V \end{bmatrix} = \begin{bmatrix} A \\ \hline B \end{bmatrix} \begin{bmatrix} S \end{bmatrix} \; ; \; S = \begin{bmatrix} P^m \\ \hline Q^m \end{bmatrix} \qquad ; \; [\,M\,]^{-1} = \begin{bmatrix} A \\ \hline B \end{bmatrix}$$

Seperating the unknown vector in to two sub vectors equations (A2) and (A3) are obtained

$$\underset{(n-1)x1}{[\,V\,]} = \underset{(n-1)x2(n-1)}{[\,A\,]} \; \underset{2(n-1)x1}{[\,S\,]} \text{-----------(A2)}$$

$$\underset{(n-1)x1}{[\,V\,]} = \underset{(n-1)x2(n-1)}{[\,B\,]} \; \underset{2(n-1)x1}{[\,S\,]} \text{-----------(A3)}$$

Using itrative techniques,

$$[\,V^p\,] = [\,A\,]\,[\,S^{p-1}\,]$$

$$[\,V^{p+1}\,] = [\,B\,]\,[\,S^p\,]$$

(The superscript denotes the iteration count)

Respective line power flows in the system could be calculated from,

$$S_{ij} = E\,I^*$$

$$= E_i\,[E_i^* - E_j^*\,][Y_{ij}^*]$$

for all $i \neq j$

Separating this equation in to real and imaginary parts,

$$P_{ij} = G_{ij}V_i^2 - G_{ij}V_iV_jCOS(\theta_i-\theta_j) + B_{ij}V_iV_jSIN(\theta_i-\theta_j) \text{---(A4)}$$

$$Q_{ij} = B_{ij}V_i^2 - B_{ij}V_iV_jCOS(\theta_i-\theta_j) - G_{ij}V_iV_jSIN(\theta_i-\theta_j) \text{---(A5)}$$

Where , P_{ij} and Q_{ij} denote the corresponding active and reactive power flows between bus i and bus j for all busbars in the system except i=j

APPENDIX II

BUS	VOLTAGE NRLF	VOLTAGE MDCLF	ANGLE(DEG) NRLF	ANGLE(DEG) MDCLF
1	1	1	0	0
2	0.99883	0.998817	0.02931	0.029621
3	0.99769	0.997667	0.05841	0.059071
4	0.99703	0.997003	0.07582	0.076776
5	0.997	0.996975	0.07395	0.075
6	0.99683	0.996799	0.07792	0.07901
7	0.99479	0.994744	0.12919	0.13092
8	0.99396	0.993907	0.15003	0.152062
9	0.99362	0.993561	0.15859	0.160771
10	0.97611	0.975986	0.61422	0.618278

TABLE I

FROM	TO	ACTIVE POWER NRLF	ACTIVE POWER MDCLF	REACTIVE POWER NRLF	REACTIVE POWER MDCLF
1	2	0.48165	0.481732	0.46061	0.460633
1	5	0.63507	0.635316	0.60187	0.601937
1	10	1.03516	1.037766	0.99293	0.993529
2	1	-0.48085	-0.48092	-0.46031	-0.46033
2	3	0.38085	0.381017	0.37031	0.370371
3	2	-0.38023	-0.38038	-0.37009	-0.37014
3	4	0.24023	0.240391	0.24009	0.240142
4	3	-0.24	-0.24015	-0.24	-0.24005
5	1	-0.63239	-0.6326	-0.60088	-0.60094
5	6	0.05001	0.050042	0.045	0.045015
5	7	0.58238	0.582927	0.55587	0.556062
6	5	-0.05	-0.05003	-0.045	-0.04501
7	5	-0.58055	-0.58108	-0.5552	-0.55538
7	8	0.38055	0.381035	0.3652	0.365372
8	7	-0.3801	-0.38058	-0.36504	-0.3652
8	9	0.2101	0.210391	0.20004	0.20039
9	8	-0.21	-0.21028	-0.2	-0.2001
10	1	-0.99998	-1.00232	-0.97999	-0.98054

TABLE II

NRLF - RESULTS FROM NEWTON RAPHSON LOAD FLOW STUDIES

MDCLF - RESULTS FROM PROPOSED D.C. LOAD FLOW TECHNIQUE

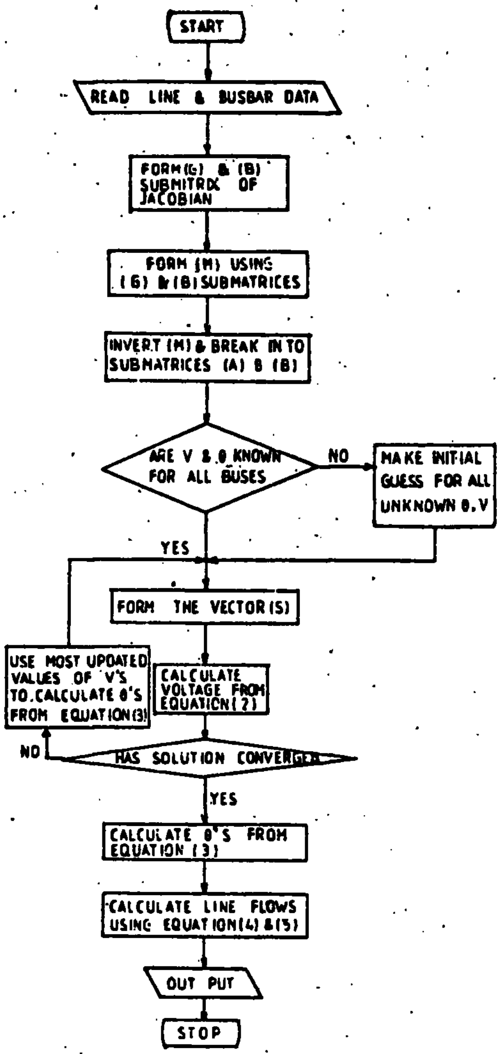

FIGURE - I

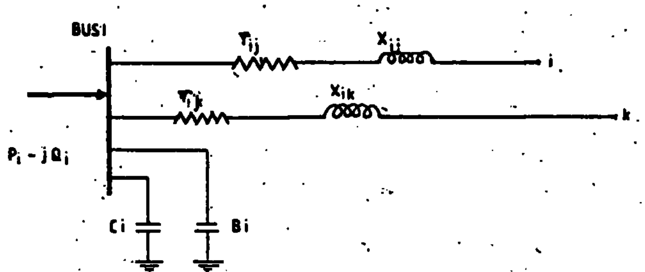

FIGURE - I - A

	A	B	C	D	E	F	G
1	NUMBER OF BUSBARS		10				
2	VOLTAGE LEVEL		33				
3							
4							
5		BUS	P	Q	VOLT	THETA	REMA
6							
7							
8		1			1	0	SL
9		2	- 0·1	- 0·09	0·998817	0·000517	LD
10		3	- 0·14	- 0·13	0·997667	0·001031	LD
11		4	- 0·24	- 0·24	0·997803	0·001340	LD
12		5	0	0	0·996975	0·001309	BR
13		6	- 0·05	- 0·045	0·996799	0·001379	LD
14		7	- 0·2	- 0·19	0·994744	0·002285	LD
15		8	- 0·17	- 0·165	0·993907	0·002654	LD
16		9	- 0·21	- 0·2	0·993561	0·002806	LD
17		10	- 1	- 0·98	0·975986	0·010791	LD
18							
19							
20							

FIGURE - 2

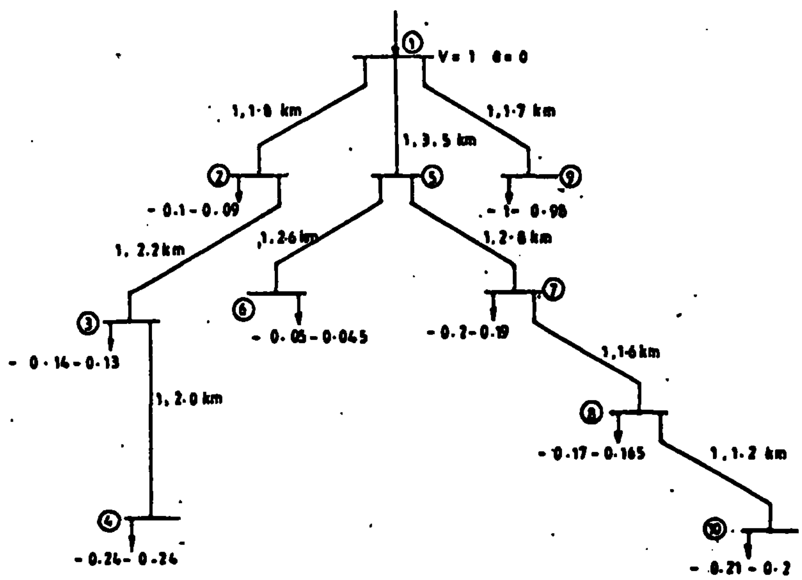

FIGURE - 3 .