

Power flow calculation of power system based on the MATLAB

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ABSTRACT

With the rapid development of computer in the world, power flow calculation of power system has entered a new stage under the trend of the times. As we all know, power flow calculation of power system is an important analysis and calculation for studying steady-state operation. In the study of power system planning and design and existing power system operation mode, it is necessary to use power flow calculation to quantitatively analyze and compare the rationality, reliability and economy of power supply scheme or operation mode.

Firstly, this study illustrates the basic knowledge of power flow calculation, the basic principle of Newton-Raphson method and the modified equation. Then, based on the flow chart of Newton-Raphson method, MATLAB is programmed and debugged. Finally, based on an example of a power system, the results of the program written in this study are compared with those of the program Matpower in MATLAB. Similarly, the results of the program written in this study are compared with those of the manual calculation to verify the correctness of the method and program used in this study.

Keywords: Electric Power System, Power Flow Calculation, Newton-Raphson Method, MATLAB, Matpower

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1. Introduction

Power flow calculation of power system is a basic electrical calculation to study the steady-state operation of power system[1,2]. Its task is to determine the operation state of the whole system according to given operation conditions and network structure, such as voltage amplitude and phase angle on buses, power distribution and power loss in the network. It is used to check whether the components of the system are overloaded, whether the voltage at each point meets the requirements, whether the distribution and distribution of power are reasonable, and the power loss[3,4]. The operation and expansion of existing power systems, the planning and design of new power systems and the static and transient stability analysis of power systems are all based on power flow calculation. The results of power flow calculation can be used for power system steady-state research, security estimation or optimal power flow, etc[5]. The results of power flow calculation play an important role in studying the operation mode of the system and determining the power supply scheme in the stage of power grid planning[6].

Early power flow calculation of power system was mainly carried out by manual calculation or by using the method of AC calculator simulation. With the development of computer technology, Gauss iteration method based on node impedance matrix emerges as the times require[7,8]. The convergence of Gauss iteration method is good, but with the

continuous expansion of the system scale, the problem solving scale is limited because of its large memory occupation. Newton's method is a typical mathematical method for solving non-linear equations. It solves the power flow calculation problem of power system based on admittance matrix. The core of Newton's method is to form and solve the revised equation repeatedly. As long as the sparsity of the coefficient matrix of the equation is kept as far as possible in the iteration process, the calculation efficiency of Newton power flow program can be greatly improved, and its convergence is also very good. Newton-Raphson method is mainly used in power flow technology of practical power system[9,10].

In recent years, the research on power flow algorithms is still how to improve traditional power flow algorithms, such as Gauss-Seidel method, Newton method and fast decoupling method[11]. In order to further improve the convergence and calculation speed of the algorithm, the higher order or non-linear terms of Taylor series are taken into account and a second-order power flow algorithm is generated because Newton's method adopts the method of successive linearization in solving the non-linear power flow equation. Newton's method has good convergence and few iterations. It has been widely used in power flow calculation. So far, there is no better method to replace Newton's method. It is a typical method for solving nonlinear equations in mathematics. Newton power flow algorithm has the outstanding advantage of fast convergence. If a better initial value is chosen, the algorithm will have convergence characteristics. Generally, it can converge to a very accurate solution by 4 to 5 iterations. Moreover, the number of iterations is almost independent of the size of the network. Newton method also has good convergence reliability.

For the system based on nodal admittance matrix, Newton method can also converge reliably. The amount of memory needed by Newton's method and the time needed for each iteration are higher than that of Spark's method[12,13].

2. Power Flow Calculation Based on Newton Method

2.1 Nodal Voltage Equation

Node voltage equation of power network:

$$I_B = Y_B U_B \quad (1)$$

I_B is the node injected current column vector.

The injected current may be positive or negative, and the injected network is positive and the outflow network is negative. U_B is the node voltage column vector. Since the node voltage is relative to the reference node, a reference node should be selected first. In the power system, the earth is often used as a reference node. If there is no grounding branch in the whole network, a node should be selected as a reference. Assuming that the number of nodes in the network is n (excluding the reference nodes), then I_B and U_B are $n \times n$ column vectors. Y_B is the $n \times n$ order node admittance matrix whose order is equal to the number of nodes in the network except the reference nodes. The diagonal element $Y_{ii} (i = 1, 2, \dots, n)$ of the node admittance matrix becomes a self-admittance. The self-admittance is numerically equivalent to the current applied to node i when a voltage is applied to node i and the remaining nodes are grounded. Therefore, it can be defined as:

$$Y_{ii} = I_i / U_i (U_j = 0, j \neq i) \quad (2)$$

The off-diagonal element Y_{ji} of the nodal admittance matrix is called mutual admittance. The value of mutual admittance is equal to the current injected into the network through node j when

voltage is applied to node i and other nodes are grounded. Therefore, it can be defined as:

$$Y_{ji} = -Y_{ij} / U_i (U_j = 0, j \neq i) \quad (3)$$

The mutual admittance between nodes j and i is equal to the negative value from branch to admittance of connecting nodes j and i . Obviously, constant Y_{ij} equals Y_{ji} . These properties of mutual admittance determine that the nodal admittance matrix is a symmetric sparse matrix. Moreover, as the number of branches connected by each node always has a limit, with the increase of the number of nodes in the network, the number of non-zero elements is relatively less and less, and the sparsity of node admittance matrix. That is, the ratio of the number of zero elements to the total elements is getting higher and higher[14,15].

2.2 Node Classification of Power Flow Calculation

The purpose of solving network equations with general circuit theory is to give a voltage source (or current source) to study the current (or voltage) distribution in the network, which is generally expressed by linear algebraic equations. However, in the power system, it is very rare to give the voltage or current on the generator or load connected bus. Generally, the amplitude of the active power and bus voltage of the generator on the generator bus, as well as the active power and reactive power consumed by the load on the bus are given. Therefore, according to the different nature of the nodes in the power system, the nodes can be divided into three types[16].

The parameters given by the PQ node are the active power P and reactive power Q of the node, and the unknown is the voltage vector of the node. Usually the substation bus is PQ node. When the output power P and Q of some generators are given, they can also be used as PQ nodes. In power

flow calculation, most of the nodes belong to PQ nodes.

The parameters given by the PU node are the active power P and the voltage amplitude U of the node. The phase angle between the reactive power Q and the voltage vector θ of the node is required. Such nodes often have adjustable reactive power in operation to maintain a given voltage value. A generator bus with certain reactive power reserves is usually chosen as the PQ node.

The last one is the balanced node. In power flow calculation, such nodes usually have only one node. The balance node is also called $U\theta$ node because the given operation parameters are U and θ . The P and Q of the balance node are to be measured. The power balance of the whole system is assumed by the balance node[17].

2.3 Constraint Conditions of Power Flow Calculation

Power system operation must meet certain technical and economic requirements. These requirements are sufficient constraints for some variables in power flow problems. The commonly used constraints are as follows:

Node voltage should satisfy:

$$U_{i \min} \leq U_i \leq U_{i \max} \quad (i = 1, 2, \dots, n) \quad (4)$$

According to the requirement of ensuring power quality and power supply safety, all electrical equipment in power system must operate near rated voltage. The voltage amplitude of PU node must be given according to the above conditions. Therefore, this constraint is for PQ nodes.

The active and reactive power of the node should satisfy:

$$\begin{aligned} P_{Gi \min} &\leq P_{Gi} \leq P_{Gi \max} \quad (i = 1, 2, \dots, n) \\ Q_{Gi \min} &\leq Q_{Gi} \leq Q_{Gi \max} \quad (i = 1, 2, \dots, n) \end{aligned} \quad (5)$$

The active and reactive power of PQ node and the active power of PU node must satisfy the above conditions when given. Therefore, the P and Q of balanced node and Q of PU node should be checked according to the above conditions.

The phase difference of voltage between nodes should satisfy:

$$|\theta_{ij}| = |\theta_i - \theta_j| < |\theta_i - \theta_j|_{\max} \quad (6)$$

In order to ensure the stability of the system, it is required that the voltage phases at both ends of some transmission lines do not exceed a certain value. The main significance of this constraint lies in this. Therefore, power flow calculation can be reduced to solving a set of nonlinear equations and satisfying certain constraints. The commonly used methods are iterative method and Newton method. In the process of calculation, or after the results are obtained, the constraints are used to check. If it fails to meet the requirements, it is necessary to modify the given values of some variables, or even to modify the operation mode of the system and recalculate it.

2.4 Equivalent Circuit of Non-standard Variable Ratio Transformer

Transformer equivalent circuit is more convenient for repeated calculation by computer and more suitable for power flow calculation of complex network. The schematic diagram of double winding transformer is shown in figure 1. It can be represented by a circuit connected in series with an ideal transformer by impedance. The ratio of ideal transformer is $K = U_1/U_2 \cdot U_1$ and U_2 are the actual voltages of transformers with high and low windings respectively. Now the transformer impedance is converted to the low-voltage side according to the actual ratio as an example, and the transformer equivalent circuit is deduced, as shown in figure 2[18,19].

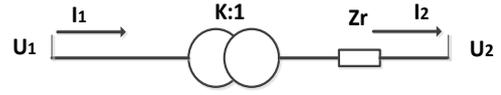


Figure 1: Principle diagram of double winding transformer



Figure2: Transformer impedance is reduced to the low-voltage side equivalent model

$$U_1 \dot{I}_1 = U_1 \dot{I}_2 / K \quad (7)$$

$$\dot{I}_1 = \dot{I}_2 / K \quad (8)$$

$$\dot{I}_2 = \frac{U_1}{KZ_T} - \frac{U_2}{Z_T} = \frac{Y_T U_1}{K} - Y_T U_2 \quad (9)$$

$$\dot{I}_1 = \frac{U_1}{K^2 Z_T} - \frac{U_2}{KZ_T} = \frac{Y_T U_1}{K^2} - \frac{Y_T U_2}{K} \quad (10)$$

In equation (10), $Y_T = 1/Z_T$, according to the nodal current equation, it can be obtained that:

$$\dot{I}_1 = Y_{11} U_1 + Y_{12} U_2 \quad (11)$$

$$-\dot{I}_2 = Y_{12} U_1 + Y_{22} U_2 \quad (12)$$

Through comparison, it can be concluded that:

$$\begin{aligned} Y_{11} &= Y_T / K^2 \\ Y_{12} &= -Y_T / K \\ Y_{21} &= -Y_T / K \\ Y_{22} &= Y_T \end{aligned} \quad (13)$$

Therefore, the admittance of each branch can be obtained as follows:

$$\begin{aligned} Y_{12} &= -Y_{21} = Y_T / K \\ Y_{21} &= -Y_{12} = Y_T / K \\ Y_{10} &= Y_{11} - Y_{12} = \frac{K-1}{K^2} Y_T \\ Y_{20} &= Y_{22} - Y_{21} = \frac{K-1}{K} Y_T \end{aligned} \quad (14)$$

Thus, the transformer equivalent circuit expressed by admittance can be obtained, as shown in figure 3.

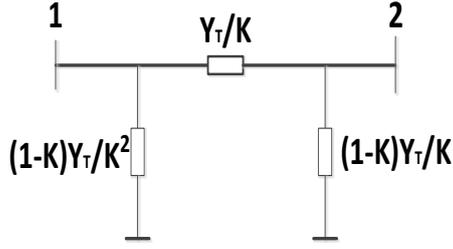


Figure3: Transformer equivalent circuit

2.5 The Basic Principles of Newton Raphson's Law

Newton-Raphson method is an effective method for solving nonlinear equations. Newton-Raphson method is the most widely used and effective power flow calculation method at present. This process transforms the solution of non-linear equations into the repeated solution of corresponding linear equations, i.e. the successive linearization process, which is the core of Newton's method. Taking the solving process of the non-linear equation as an example, this study illustrates that:

$$f(x) = 0 \quad (15)$$

Let $x^{(0)}$ be the initial value of the equation. And the real solution x is near it:

$$x = x^{(0)} - \Delta x^{(0)} \quad (16)$$

Where $\Delta x^{(0)}$ is the correction of the initial value $x^{(0)}$. If $\Delta x^{(0)}$ is obtained, then the real solution x can be obtained by formula (16).

$$f(x^{(0)} - \Delta x^{(0)}) = 0 \quad (17)$$

Expand the above formula according to Taylor series:

$$\begin{aligned} & f(x^{(0)} - \Delta x^{(0)}) \\ &= f(x^{(0)}) - f'(x^{(0)})\Delta x^{(0)} + f'(x^{(0)})\frac{(\Delta x^{(0)})^2}{2!} - \Lambda \\ &+ (-1)^n f^n(x^{(0)})\frac{(\Delta x^{(0)})^n}{n!} = 0 \end{aligned} \quad (18)$$

When we choose a better initial value, that is, $\Delta x^{(0)}$ is very small, the $(\Delta x^{(0)})^2$ and higher order

terms contained in equation (18) can be omitted. Therefore, formula (18) can be simplified as follows:

$$f(x^{(0)}) - f'(x^{(0)})\Delta x^{(0)} = 0 \quad (19)$$

This is a formal equation for the variable $\Delta x^{(0)}$, which can be used to find the modified $\Delta x^{(0)}$.

Since equation (19) is a simplified result of equation (18), the true solution of equation (15) can not be obtained after equation (19) has solved $\Delta x^{(0)}$. In fact, the correction of $\Delta x^{(0)}$ with $x^{(0)}$ gives the following results:

$$x^{(1)} = x^{(0)} - \Delta x^{(0)} \quad (20)$$

Now if we take $x^{(1)}$ as the initial value, formula (20) can get a more approaching true solution of $x^{(2)}$:

$$x^{(2)} = x^{(1)} - \Delta x^{(1)} \quad (21)$$

This repeated process constitutes a successive linearization process for solving non-linear equations. The parametric equation for the t th iteration is:

$$f(x^{(t)}) - f'(x^{(t)})\Delta x^{(t)} = 0 \quad (22)$$

$$f(x^{(t)}) - f'(x^{(t)})\Delta x^{(t)} = 0 \quad (23)$$

The left end of the upper formula can be regarded as the error caused by the approximate solution $x^{(t)}$. When $f(x^{(t)}) \rightarrow 0$ is used, the original equation (15) is satisfied, so $x^{(t)}$ becomes the solution of the equation[20].

2.6 Modified equation

When the active and reactive power is separated in polar coordinates, the nodal power equation is:

$$P_i = U_i \sum_{j=1}^n U_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \quad (24)$$

$$Q_i = U_i \sum_{j=1}^n U_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij})$$

In the above formula, $\delta_{ij} = \delta_i - \delta_j$ is the phase angle difference between i and j node voltage.

From the power equation, it can be seen that the injection power of node I is a function of the voltage amplitude and phase angle of each node. Substitution formula (23) can calculate the active power and reactive power of node I. The difference between them and the injection power of a given PQ node satisfies the following equation:

$$\begin{aligned}\Delta P_i &= P_i - U_i \sum_{j=1}^n U_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) = 0 \\ \Delta Q_i &= Q_i - U_i \sum_{j=1}^n U_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) = 0\end{aligned}\quad (25)$$

In a system with n nodes, the 1 ~ m node is assumed to be PQ node, the m+1 ~ n-1 node is PV node, and the n node is balanced node. V_n and δ_n are given, and the voltage amplitude $V_{m+1} \sim V_{n-1}$ of the PV node is also given. Therefore, only the voltage phase angle $\delta_1, \delta_2, \dots, \delta_{n-1}$ of n-1 node and the voltage amplitude V_1, V_2, \dots, V_m of m nodes are unknown. It is known that a total of $n-1+m$ equations are included, which is exactly the same as the number of unknown quantities, while the equation in rectangular coordinate form is less than $n-1-m$.

The modified equation can be written from equation (25):

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \pm \begin{bmatrix} H & N \\ K & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ V_{D_2}^{-1} \Delta V \end{bmatrix} \quad (26)$$

Among them:

$$\left\{ \begin{array}{l} \Delta P = \begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \vdots \\ \Delta P_m \end{bmatrix}; \Delta Q = \begin{bmatrix} \Delta Q_1 \\ \Delta Q_2 \\ \vdots \\ \Delta Q_m \end{bmatrix}; \Delta \delta = \begin{bmatrix} \Delta \delta_1 \\ \Delta \delta_2 \\ \vdots \\ \Delta \delta_{n-1} \end{bmatrix} \\ \Delta V = \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_m \end{bmatrix}; V_{D_2} = \begin{bmatrix} V_1 & & & \\ & V_2 & & \\ & & \ddots & \\ & & & M \\ & & & & V_m \end{bmatrix} \end{array} \right. \quad (27)$$

Among them: H is $(n-1) \times (n-1)$ order square matrix, its element is $H_{ij} = \frac{\partial \Delta P_i}{\partial \delta_j}$; N is

$(n-1) \times m$ order matrix, its element is $N_{ij} = V_j \frac{\partial \Delta P_i}{\partial V_j}$; K is $m \times (n-1)$ order matrix, its

element is $K_{ij} = \frac{\partial \Delta Q_i}{\partial \delta_j}$; L is $m \times m$ order matrix, its

element is $L_{ij} = V_j \frac{\partial \Delta Q_i}{\partial V_j}$.

The expression of Jacobian matrix elements can be obtained by calculating partial derivative of formula (27).

The expressions for calculating non-diagonal elements are as follows:

$$\begin{aligned}H_{ij} &= -V_i V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \\ N_{ij} &= -V_i V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \\ K_{ij} &= V_i V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \\ L_{ij} &= -V_i V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij})\end{aligned}\quad (28)$$

The expressions for calculating the diagonal elements are as follows:

$$\begin{aligned}H_{ii} &= V_i^2 B_{ii} + Q_i \\ N_{ii} &= -V_i^2 G_{ii} - P_i \\ K_{ii} &= V_i^2 G_{ii} - P_i \\ L_{ii} &= V_i^2 B_{ii} - Q_i\end{aligned}\quad (29)$$

3. Power Flow Computing Program Based on MATLAB

3.1 Introduction of MATLAB

MATLAB is an interactive and object-oriented programming language, which is widely used in industry and academia. It is mainly used for matrix operation. At the same time, it also has powerful functions in numerical analysis, automatic control simulation, digital signal processing, dynamic analysis, drawing and so on[21].

The structure of MATLAB programming language is complete, and it has excellent portability. Its basic data elements are arrays that do not need to be defined. It can efficiently solve industrial computing problems, especially the calculation of matrices and vectors. Compared with C language and FORTRAN language, MATLAB is easier to master. Through M language, the algorithm can be written in a way similar to mathematical formula, which greatly

reduces the difficulty of the program and saves time, so that the main energy can be focused on the idea of the algorithm rather than programming[22].

3.2 Flow Chart of Power Flow Calculation Based on MATLAB

The programming of power flow calculation program is based on Newton Raphson method. The flow chart of the program is as follows:

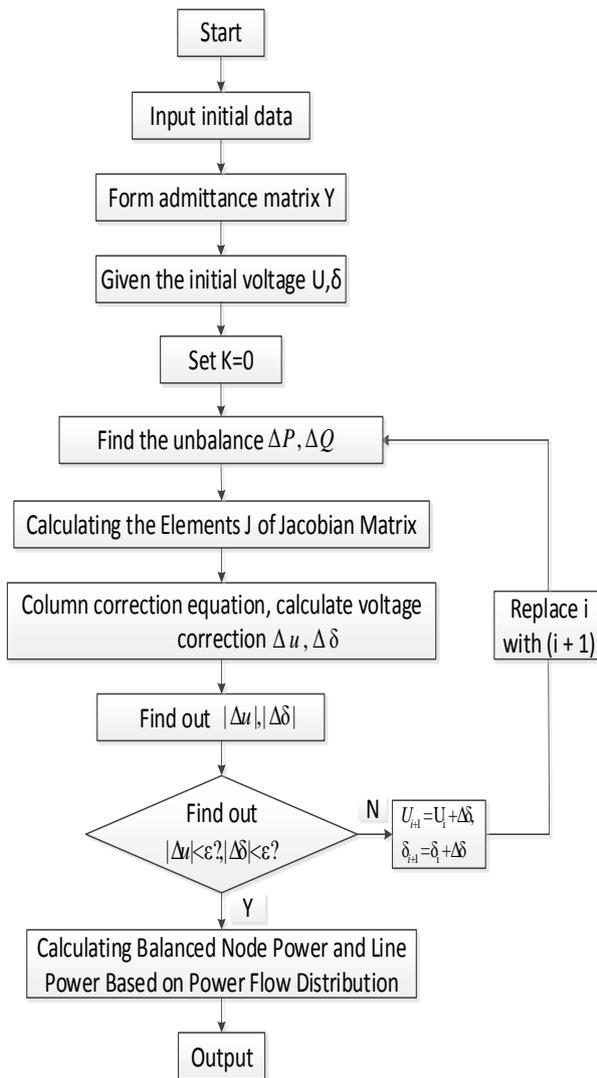


Figure 4: Flow chart of power flow calculation

Based on the flow chart, the principle of power flow calculation can be clearly understood and understood. In combination with MATLAB, the power flow calculation can be programmed.

(1)The program first inputs the original data, which is the known quantity of the power system, that is, the node information includes the node number, node type, voltage, phase angle, generator active, generator reactive, load active, load reactive, reactive power compensation. And the information of the branch includes the first node, the last node, the branch resistance, the branch reactance, the branch susceptance, the transformer ratio and other information.

(2)Define the function calculation node admittance matrix Y.

(3)Calculating the node offset is also the amount of imbalance.

(4) Set the accuracy, then make a convergence judgment, and if it converges, directly output the result.

(5) If it does not converge, calculate the Jacobian matrix.

(6) Solve the equation and get the node voltage correction.

(7) Correct the node voltage and get a new approximate solution.

(8) After several iterations, the appropriate results can be achieved, and the voltage, active loss and reactive power loss of each node are output.

4. Verification of Power Flow Computing Program Based on MATLAB

4.1 Verification of program results based on Matpower

The schematic diagram of the system structure of three generators with nine nodes is shown in figure 5 below. Among them, P_{Li} represents load, B_i represents bus, G_i represents generator, T_i represents transformer.

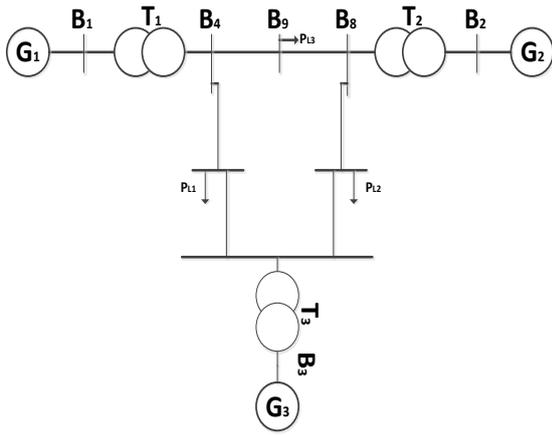


Figure 5: The schematic diagram of the system structure of the 9-node system of three generators

In table 1 below, the bus data of 3 generators and 9-bus system are given, in which the unitary values of each parameter in the table are calculated with 100MVA as the reference power.

Table 1 Generator data of the system.

Generator	No.1	No.2	No.3
Bus number	B ₁	B ₂	B ₃
Type	Slack	PV	PV
Busbar voltage	1.04	1.025	1.025
Active power	-	1.63	0.85

The transmission line and transformer data of 3 generators 9-bus system are given in table 2 below. The unitary values of the parameters in the table are calculated using 100MVA as the reference power.

Table 2 Transmission line and transformer data of the system.

Bus number	Type	R	X	B/2
B ₁ -B ₄	Transformer	0	0.0567	0
B ₂ -B ₈	Transformer	0	0.0625	0
B ₃ -B ₆	Transformer	0	0.0586	0
B ₄ -B ₉	Transmission line	0.01	0.085	0.088
B ₄ -B ₅	Transmission line	0.017	0.092	0.0079
B ₈ -B ₉	Transmission line	0.032	0.161	0.153
B ₆ -B ₅	Transmission line	0.039	0.17	0.179
B ₇ -B ₈	Transmission line	0.0085	0.072	0.0745
B ₆ -B ₇	Transmission line	0.0119	0.1008	0.1045

Table 3 Load parameters of the system.

Load Number	Bus Number	Active power	Reactive power
P _{L1}	B ₁	0.9	0.3
P _{L2}	B ₇	1	0.35
P _{L3}	B ₉	1.25	0.5

Among them, the reference power is 100 MVA and the reference voltage is 230 kV.

The results of bus running according to the program written in MATLAB are shown in table 4.

Node I	Node J	I->J active power	I->J reactive power	J->I active power	J->I reactive power	active power loss	reactive power loss
1	4	71.95	54.68	71.94	-50.33	0	4.34
2	8	163	30.40	-163	-14.04	0	16.35
3	6	85	14.24	-85	-10.10	0	4.14
4	5	30.84	14.22	-30.62	-20.96	0.21	9.05
5	9	41.18	36.11	-40.78	-41.98	0.32	11.43
6	6	-59.37	-9.03	60.77	-2.86	1.40	24.15
7	7	24.33	12.96	-24.11	-22.67	0.106	11.51
8	8	-75.88	-12.32	76.38	9.03	0.49	11.73
9	9	86.61	5.01	-84.21	-8.01	2.39	27.13

Table 4 Operating results of the program bus.

The calculated injection power of the balanced node is 71.95+j54.68. According to the results of running the branch of the program written in MATLAB, as shown in table 5.

Table 5 The running result of the program running branch.

Node number	Voltage amplitude	Phase angle	Active power of generator	Reactive power of generator	Active load	Load reactive power
1	1.04	0	0.719	0.549	0	0
2	1.025	9.487	1.630	0.304	0	0
3	1.025	4.774	0.850	0.142	0	0
4	1.011	-2.260	0	0	0	0
5	0.989	-3.709	0	0	0.90	0.3
6	1.018	2.038	0	0	0	0
7	0.997	0.783	0	0	1	0.35
8	1.012	3.847	0	0	0	0
9	0.973	-4.060	0	0	1.25	0.5

Figure 6 is the result of the operation of matpower, a self-contained program of MATLAB.

Bus Data									
Bus #	Voltage		Generation		Load				
	Mag (pu)	Ang (deg)	P (MW)	Q (MVar)	P (MW)	Q (MVar)	P (MW)	Q (MVar)	
1	1.040	0.000	71.64	27.05	-	-	-	-	
2	1.025	9.280	163.00	6.65	-	-	-	-	
3	1.025	4.665	85.00	-10.86	-	-	-	-	
4	1.026	-2.217	-	-	-	-	-	-	
5	1.013	-3.687	-	-	90.00	30.00	-	-	
6	1.032	1.967	-	-	-	-	-	-	
7	1.016	0.728	-	-	100.00	35.00	-	-	
8	1.026	3.720	-	-	-	-	-	-	
9	0.996	-3.989	-	-	125.00	50.00	-	-	
Total:			319.64	22.84	315.00	115.00			

Branch Data									
Brnch #	From Bus	To Bus	From Bus Injection		To Bus Injection		Loss (I ² * Z)		
			P (MW)	Q (MVar)	P (MW)	Q (MVar)	P (MW)	Q (MVar)	
1	1	4	71.64	27.05	-71.64	-23.92	0.000	3.12	
2	4	5	30.70	1.03	-30.54	-16.54	0.166	0.90	
3	5	6	-59.46	-13.46	60.82	-18.07	1.354	5.90	
4	3	6	85.00	-10.86	-85.00	14.96	0.000	4.10	
5	6	7	24.18	3.12	-24.10	-24.30	0.088	0.75	
6	7	8	-75.90	-10.70	76.38	-0.80	0.475	4.03	
7	8	2	-163.00	9.18	163.00	6.65	0.000	15.83	
8	8	9	86.62	-8.38	-84.32	-11.31	2.300	11.57	
9	9	4	-40.68	-38.69	40.94	22.89	0.258	2.19	
Total:							4.641	48.38	

Figure 6: The running result of Matpower in MATLAB

Comparing the program written by this method with the result of Matpower, it can be concluded that under the permissible range, the difference between the calculation results is not very large, so the program is correct.

5. Calibration of program results based on manual calculation

The equivalent circuit diagram of the system is shown in figure 7.

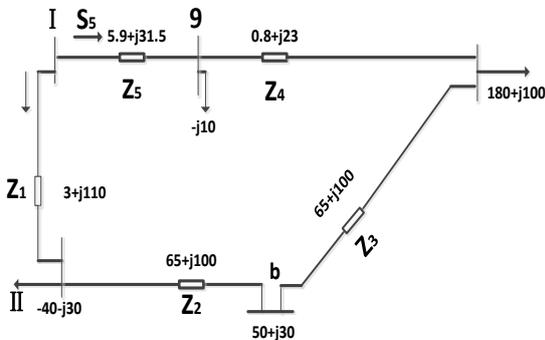


Figure 7: Equivalent circuit diagram of the system

(1) Preliminary power distribution is calculated.

Assuming that the voltage of the whole network is rated, the power distribution is calculated by the calculation method of the power supply network with equal voltage at both ends.

$$S_I = \frac{\sum S_m Z_m^*}{Z_\Sigma^*} = \frac{(S_g Z_5^* + S_x (Z_5^* + Z_4^*) + S_b (Z_5^* + Z_3^*) + S_{II} (Z_5^* + Z_4^* + Z_3^* + Z_2^*))}{Z_5^* + Z_4^* + Z_3^* + Z_2^* + Z_1^*} \quad (30)$$

$$= 22.13 - j4.48(\text{MVA})$$

$$S_5 = \frac{\sum S_m Z_m^*}{Z_\Sigma^*} = \frac{S_{II} Z_1^* + S_b (Z_1^* + Z_2^*) + S_x (Z_5^* + Z_4^* + Z_3^*) + S_g (Z_1^* + Z_4^* + Z_3^* + Z_2^*)}{Z_5^* + Z_4^* + Z_3^* + Z_2^* + Z_1^*} \quad (31)$$

$$= 167.87 - j94.48(\text{MVA})$$

Check:

$$S_1 + S_5 = 190 + j90 (\text{MVA}) \quad (32)$$

$$S_{II} + S_b + S_x + S_g + S_I = 190 - j90 (\text{MVA}) \quad (32)$$

This shows that there are no errors in the calculation.

Assuming that the capacity of the connection transformer connecting bus I and II is 60MVA, $R_T = 3\Omega$, $X_T = 11\Omega$, the ratio is 231/110kV; the total capacity of the line terminal step-down transformer is 240MVA, $R_T = 0.8\Omega$, $X_T = 23\Omega$, the ratio is 231/121kV; and the voltage on line I is 242kV.

(2) Calculating cycle power.

If the loop network is disconnected at the high voltage side of the tie transformer, the voltage above the opening is 242kV, and the voltage below the opening is 266.2kV. It can be seen that the flow direction of cyclic power is clockwise, and its numerical value is:

$$S_C = \frac{U_N dU^*}{Z_\Sigma^*} = 4.88 + j12.74(\text{MVA}) \quad (34)$$

The power distribution is shown in figure 8.

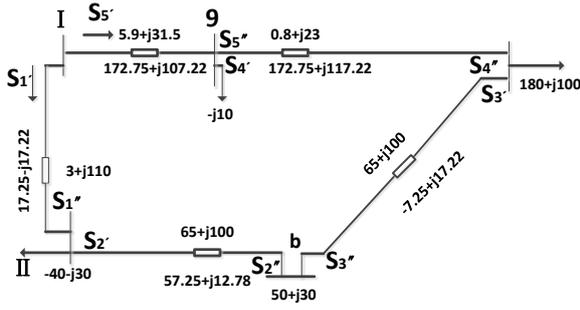


Figure 8: Power distribution diagram

(3) Calculate the power loss of each line segment.

The power loss is calculated according to the rated network voltage of 220kV.

$$S_2'' = 57.25 + j12.78 (\text{MVA}) \quad (35)$$

$$\Delta S_2 = \Delta P_2 + j\Delta Q_2 = 4.62 + j7.11 (\text{MVA}) \quad (36)$$

$$S_2' = S_2'' + \Delta S_2 = 61.78 + j19.89 (\text{MVA}) \quad (37)$$

Similarly, it can be calculated that:

$$S_3' = S_3'' + \Delta S_3 = \pm 6.78 + j17.94 (\text{MVA}) \quad (38)$$

$$S_4' = S_4'' + \Delta S_4 = 173.95 + j138.81 (\text{MVA}) \quad (39)$$

$$S_5' = S_5'' + \Delta S_5 = 179.66 + j159.30 (\text{MVA}) \quad (40)$$

$$S_1' = S_1'' + \Delta S_1 = 21.91 - j8.79 (\text{MVA}) \quad (41)$$

$$S_1' = S_5' + \Delta S_1' = 201.57 + j150.51 (\text{MVA}) \quad (42)$$

(4) Calculate the voltage drop of each line segment.

According to U_5 and S_5' , U_g is calculated.

$$\Delta U_5 = 25.12 (\text{kV}); \sigma U_5 = 19.50 (\text{kV}) \quad (43)$$

$$U_g = \sqrt{(242 - \Delta U_5)^2 + \sigma U_5^2} = 217.75 (\text{kV}) \quad (44)$$

Similarly, according to U_g and S_4' , U_x is calculated.

$$U_x = \sqrt{(217.75 - \Delta U_4)^2 + \sigma U_4^2} = 203.24 (\text{kV}) \quad (45)$$

According to U_x and S_3' , U_b is calculated.

$$U_b = \sqrt{(203.24 - \Delta U_3)^2 + \sigma U_3^2} = 196.79 (\text{kV}) \quad (46)$$

According to U_b and S_2' , U_π is calculated.

$$U_\pi = \sqrt{(196.79 - \Delta U_2)^2 + \sigma U_2^2} = 223.58 (\text{kV}) \quad (47)$$

According to U_π and S_2' , U_1 is calculated.

$$U_1 = \sqrt{(223.58 - \Delta U_1)^2 + \sigma U_1^2} = 219.17 (\text{kV}) \quad (48)$$

The $U_1 = 219.7 \text{kV}$ obtained in clockwise order is quite different from the initial $U_1 = 242 \text{kV}$. This difference is due to the mismatch of transformer ratio. If the voltage at each point is converted to the actual voltage according to the given transformer ratio, then:

$$U_1 = 242 (\text{kV})$$

$$U_g = 219.17 (\text{kV})$$

$$U_x' = 106.46 (\text{kV}) \quad (49)$$

$$U_b' = 103.08 (\text{kV})$$

$$U_\pi' = 117.11 (\text{kV})$$

$$U_1' = 241.09 (\text{kV})$$

The results obtained by computer programming are shown in table 6.

Table 6 The results obtained by computer programming.

Node number	I	g	x	b	II
Voltage amplitude	1.1	0.9896	0.9733	0.9468	-2.4079
Phase angle	0	-5.2055	-9.8227	-7.8396	-2.4079
Node head power	1.8159 +j1.594 9	-1.7493 -j1.159 7	-0.0507 +j0.159 7	-0.5546 -j0.146 4	-0.2038 +j0.077 6
Branch end power	-1.7570 -j1.280 6	1.7570 +j1.380 6	0.0546 -j0.153 6	0.6038 +j0.222 4	0.2041 -j0.068 0
Power loss	0.0589 +j0.314 3	0.0077 +j0.220 9	0.004 +j0.006 1	0.0492 +j0.076 0	0.0003 +j0.009 6

When calculating with computer programming, we use the standard unit value. Compared with the result calculated by hand after converting the reference value into a nominal value, the results of the two methods are basically the same. So after checking, the method adopted in this study is accurate and reliable.

6. Conclusion

This study illustrates the purpose, task, function and various methods of power flow calculation, explains the advantages of Newton-Raphson method in power flow calculation, elaborates the principle and steps of Newton-Raphson method in detail, and uses the MATLAB software to program a specific system for power flow calculation. The idea and overall structure of power flow calculation design are as follows: according to the principle block diagram of Newton-Raphson method, programming with MATLAB language, power loss and voltage results of power flow calculation can be obtained by inputting bus data and branch data into the software. The main characteristics of the method used in this study are stable operation and accurate calculation.

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