

REAL-TIME UNBALANCED LOAD FLOW DEVELOPMENT USING DIRECT- Z_{BR} METHOD AND MODIFIED LAMBDA ITERATION FOR ON-LINE MONITORING AND CONTROL

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ABSTRACT

The interconnection of Distributed Generations (DG's) directly to the existing distribution systems has changed the characteristics of a distribution network from a passive network to an active one. This paper introduces a three phase load flow method that can handle both passive and active unbalanced radial distribution networks. The proposed method combines the direct- Z_{BR} method (Forward-Backward based method) and Modified Lambda iteration. The direct Z_{BR} load flow [1] is known as a fast and accurate method for solving passive radial three phase distribution systems. The Modified Lambda approach is chosen because of its simple algorithm that can be easily combined with direct Z_{BR} method in handling DG's which are operated as voltage controlled (PV) buses.

Keywords : Active Radial Distribution Networks, Unbalanced Load Flow, Direct Z_{BR} , Modified Lambda Iteration.

INTRODUCTION

Driven by the environmental concerns and fluctuations of electric energy cost, the interconnection of distributed generations (DG's) to existing distribution networks has gained its importance and emerged as complementary to the conventional centralized power plants. However, the proliferation of DG's has altered a distribution network from a passive system to an active one.

Distribution networks have characteristics such as unbalanced loads, un-transposed lines, radial topology, grounded or ungrounded systems, high resistance-to-reactance (R/X) ratios, and single- or two-phase lines. Therefore, traditional single-phase Newton Raphson or Fast-Decoupled load flow is not adequate for distribution load flow studies [2]. To analyze such distribution systems, a three-phase load flow software is exactly needed, and to improve a safe and reliable operating performance, on line monitoring and control is required as well.

For the past twenty years, there have been many load flow methods proposed for passive distribution systems. These methods can be broadly classified into four

categories, which are Bus Impedance methods [3], Newton-type methods [4-6], Forward-Backward (FB) and its variations [1, 7-8], and Sequential Power Flow (SPF) methods [9-12]. Among of those methods, SPF method can readily accommodate for PV buses as long as the DG models in the sequence-component frame can be formulated. However, SPF methods cannot handle the lateral network with single- or two-phase lines, and very high R/X ratios.

Due to the special characteristics of distribution systems, the FB based methods have been applied in most analysis of distribution systems; these methods do not require Jacobian matrices and can easily handle high R/X ratios. Among of the FB based methods, the direct Z_{BR} method is one of the best methods for solving radial distribution system problems, but these methods don't have rules for PV buses.

This paper introduces a three phase load flow method that can handle both passive and active unbalanced radial distribution networks. The proposed method combines the direct- Z_{BR} method and Modified lambda iteration. The direct Z_{BR} load flow [1] is known as a fast and accurate method for solving passive three phase radial distribution systems. The Modified Lambda approach is chosen because of its simple algorithm that can be easily combined with direct Z_{BR} method in handling DG's which are operated as voltage controlled (PV) buses.

METHODOLOGY

The proposed method consists of two stages. The first stage is building Three Phase Radial Distribution Load Flow using direct Z_{BR} method [1]. The second stage is combining the direct Z_{BR} load flow method with Modified Lambda iteration [13]. The following subsections describe the two stages.

A. Stage 1: Build Three Phase Radial Distribution Load Flow using direct Z_{BR} method

The direct Z_{BR} load flow [1] method has four steps. Fig. 1 describes the steps of building the direct Z_{BR} load flow.

Step 1: Data required and initialization

For ease of illustration, a five bus system (shown in Fig. 2) is used to describe the direct Z_{BR} load flow method. The reference bus is bus number 1 and the load (PQ) buses are bus number two until five. For the first iteration ($k=1$), loads, transformers, cogenerators, capacitors must be converted to their equivalent injected currents to the system. The direction of injected currents can be assumed flowing in to the bus or flowing out of the bus, the assumptions should be consistent for the whole system. For no load condition, all PQ bus voltages are set equal to the reference voltage, called V_{BUSnl} . These voltages, called V_{bus} , will be updated in each iteration.

Step 2: K- matrix construction.

The direct Z_{BR} method requires construction of K-matrix. The K matrix, derived from the graph theory [1, 13], is also called the branch-path incidence matrix. A row element of K-matrix is a branch of the network and a column element of K-matrix is a path of the network. Path is defined as the route oriented from a bus to the reference node. The value of element K-matrix is +1 if the i th branch is in the path from the j th bus to reference and is oriented in the same direction [13], and -1 otherwise.

For a three-phase power system with three phase lines "abc", the elements of K-matrix for each branch-path are expressed in 3x3 block elements, the values of diagonal elements of that block are 1, and the values of off-diagonal elements are 0. If the system has single- or two-phase lines, the elements of K-matrix are expressed appropriately to the number of lines of a branch-path. For example, if the branch-path consists of two-phase lines "ab0" the values of block elements (1,1) and (2,2) are 1, and, the value of block element (3,3) is 0. Similarly we can determine for "0bc", "a0c", "ab0", "a00", "0b0" and "00c" phase line(s). Following these rules, the K matrix of the network shown in Fig. 2 is given in (1).

Step 3: Z primitif construction.

Reference [7] is used to model the three-phase impedance of each branch of a three-phase power system as given in (3). For example, if the branch consists of two-phase lines (phase "a" and phase "b") the elements of matrix Z_{abc} related to phase "c" must be set to zero. Similarly, we can do it for any combination of branch phases.

For the network shown in Fig. 2, the primitif impedance matrix (Z_{prim}) is given in (2). The elements of matrix Z_{prim} are computed only once and therefore updating the matrix in each iteration is not required. In this paper Z_{BR} is set equal to Z_{prim} .

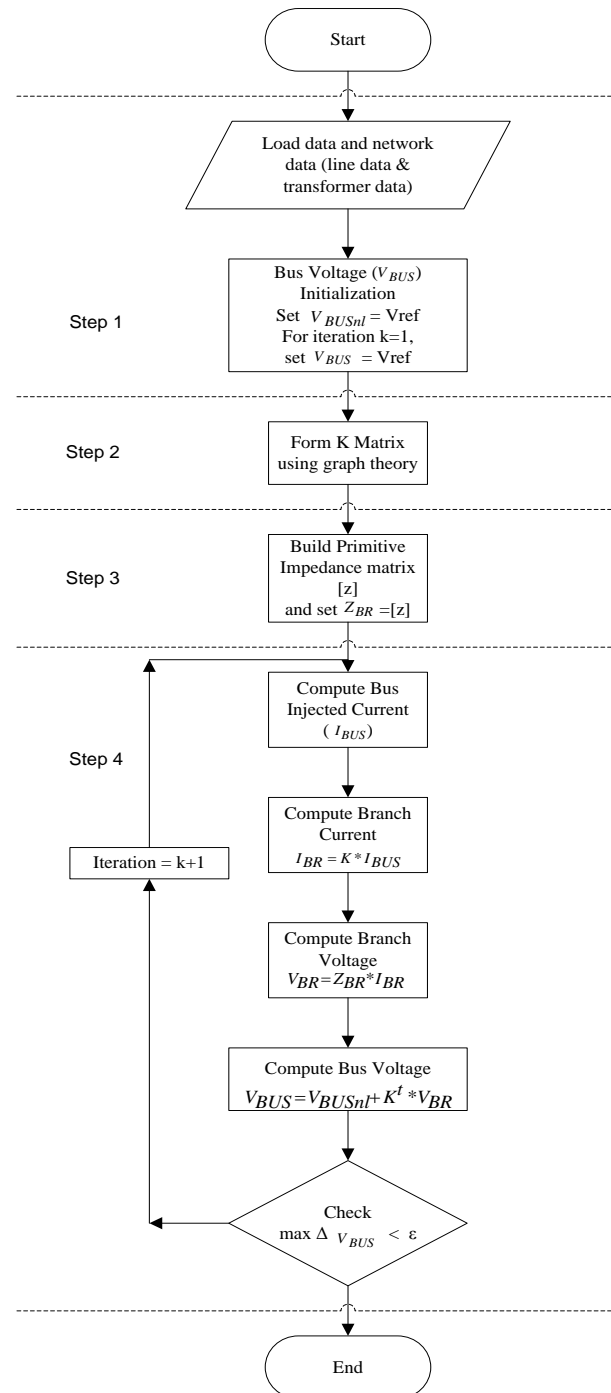


Figure 1. Flowchart of building direct Z_{BR} load flow

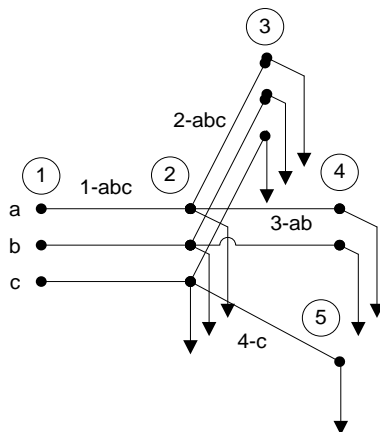


Figure2. Three-phase line, 5 bus radial distribution system.

$$\begin{matrix}
 \text{Bus} & \textcircled{2} & \textcircled{3} & \textcircled{4} & \textcircled{5} \\
 & a\ b\ c & a\ b\ c & a\ b\ 0 & 0\ 0\ c \\
 \text{Branch} & & & & \\
 \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} & \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} & \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} & \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} & \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
 \mathbf{K=} & & & &
 \end{matrix} \quad (1)$$

$$\begin{matrix}
 \text{Branch} & 1 & 2 & 3 & 4 \\
 \text{Branch} & a\ b\ c & a\ b\ c & a\ b\ 0 & 0\ 0\ c \\
 \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \end{matrix} & \begin{bmatrix} Z_{11} \\ abc \end{bmatrix} & \begin{bmatrix} Z_{22} \\ abc \end{bmatrix} & \begin{bmatrix} Z_{33} \\ ab\ 0 \end{bmatrix} & \begin{bmatrix} Z_{44} \\ 00\ c \end{bmatrix} \\
 \mathbf{ZBR=} & & & &
 \end{matrix} \quad (2)$$

$$\mathbf{Z}_{abc} = \begin{bmatrix} Z_{aa-n} & Z_{ab-n} & Z_{ac-n} \\ Z_{ba-n} & Z_{bb-n} & Z_{bc-n} \\ Z_{ca-n} & Z_{cb-n} & Z_{cc-n} \end{bmatrix} \quad (3)$$

Step 4: Iteration process

The objective of iteration process is to calculate the correct value of bus voltage (V_{bus}) at each bus except for the reference bus. For the first iteration ($k=1$), all the bus voltages are set equal to the reference bus. These voltages are used to calculate the injected current (I_{bus}) at each

bus except the reference bus. For bus i at iteration k , the I_{bus} can be expressed as:

$$I_{bus(i)}^{(k)} = \left(\frac{P_{(i)}^{spec} + jQ_{(i)}^{spec}}{V_{bus(i)}^{(k)}} \right)^* \quad (4)$$

Where $P_{(i)}^{spec}$ is the specified active power and $Q_{(i)}^{spec}$ is the specified reactive power at bus i .

Then the branch current (I_{BR}) is calculated using equation (5).

$$I_{BR}^{(k)} = K * I_{bus}^{(k)} \quad (5)$$

And the branch voltage (V_{BR}) is calculated using equation (6).

$$V_{BR}^{(k)} = Z_{BR} * I_{BR}^{(k)} \quad (6)$$

The new estimates of bus voltages at the $(k+1)^{th}$ iteration is calculated as,

$$V_{bus}^{(k+1)} = V_{bus_nl}^{(k)} + K^t * V_{BR}^{(k)} \quad (7)$$

The iteration process will stop until the differences between $V_{Bus}^{(k)}$ and $V_{Bus}^{(k+1)}$ at each bus are less than a preset tolerance value.

B. Stage 2: Combine Three Phase Radial Distribution Load Flow using direct ZBR method and Modified Lambda Iteration to account for PV buses

This paper introduces an application of three-phase load flow approach using the direct ZBR method which is combined with the Modified Lambda Iteration. In principal, 'Modified Lambda Iteration' is used to estimate the value of reactive power on the buses with specified injected active powers and constant voltage magnitudes (PV buses).

The lambda iteration concept is adopted from [14] with slightly modification as given in (8) and (9).

For a PV bus, if the difference of voltage in the iteration process (ΔV) is greater than the tolerance value, the reactive power Q is updated as,

$$Q^{(k+1)} = -(Q^{(k)} - \lambda * (Q^{(k)})) \quad (8)$$

If ΔV positive, reduce λ

$$\lambda^{(k+1)} = \lambda^{(k)} - \Delta\lambda^{(k)} \quad (9. a)$$

If ΔV negative, increase λ

$$\lambda^{(k+1)} = \lambda^{(k)} + \Delta\lambda^{(k)} \quad (9. b)$$

And the $\Delta\lambda^{(k)} = \Delta\lambda^{(k)}/2$ when the sign of $\Delta V^{(k)}$ changes in the iteration process.

Each value of Q estimated by Modified Lambda iteration is used by the direct Z_{BR} three phase load flow to

determine the voltage magnitude of all buses.

The procedure of the proposed method can be seen in Fig.3.

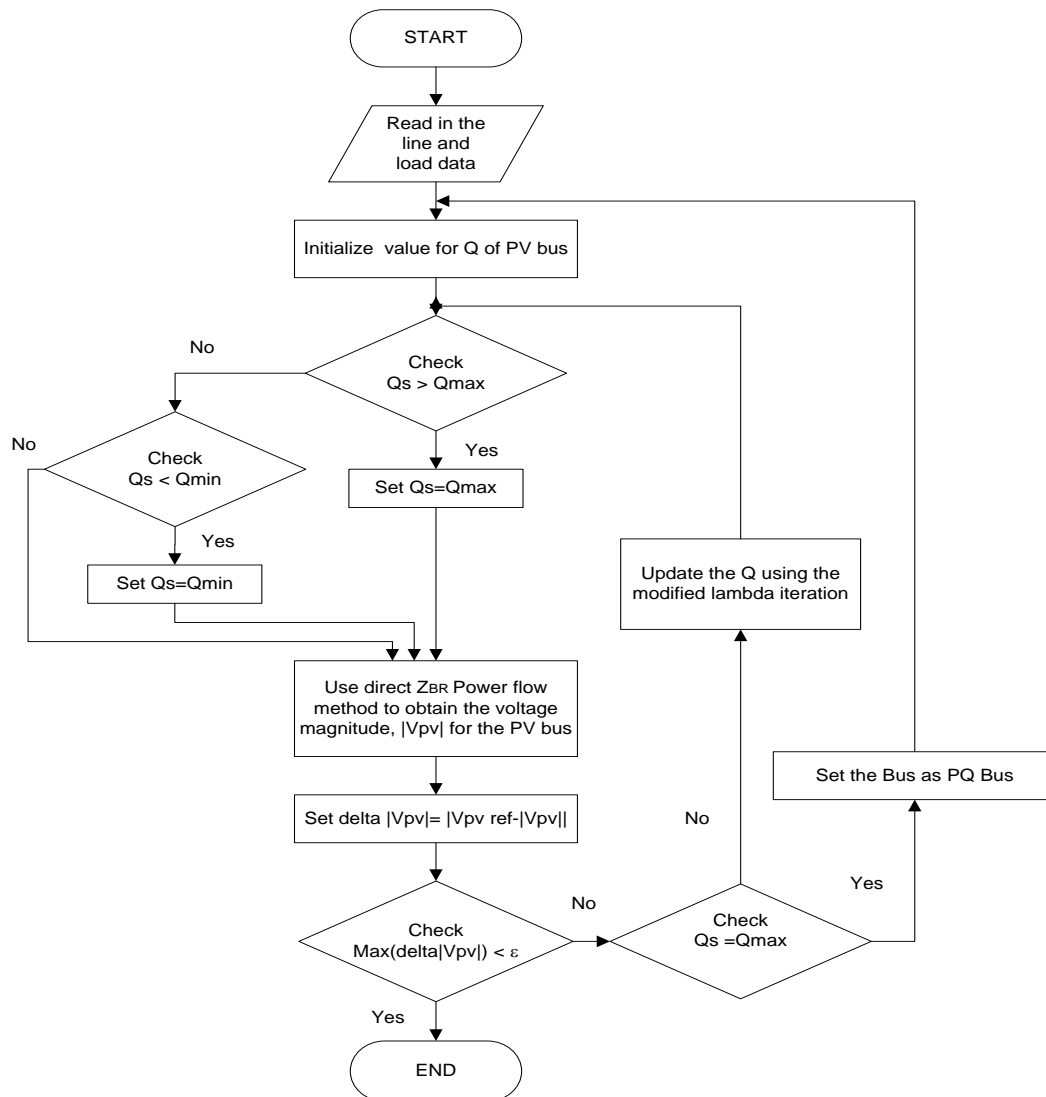


Figure 3. Flowchart of three phase active distribution load flow using direct Z_{BR} +modified Lambda iteration

DATA ANALYSIS

The test system used in this simulation are the system adapted from the benchmark system of the IEEE Standard 399-1997 (see fig.4) and Central-Java distribution power system (see fig. 6).

Test System 1 (IEEE Standard 399-1997)

The load data at node 10 is to 0.073MW + 0.063MVAR for phase “a”, 0.083MW + 0.073MVARfor phase “b”, and 0.093MW + 0.083MVARfor phase “c”. The load

data at node 15 is 0.033MW + 0.063MVAR for phase “a”, 0.043MW + 0.053MVAR for phase “b”, and 0.053MW + 0.043MVAR for phase “c”. Bus 1 is the slack bus,two simulation cases are studied for the first test system:

- Case 1: Buses 6 and 11 are PV buses, and the others are PQ buses with 1R/X ratio.
- Case 2: Buses 6 and11 are PV buses, and the others are PQ buses with high value of R/X ratio.

a. Case 1

In case 1, bus6 and 11 are PV buses and their voltage magnitudes are set to 1.00 per unit.To verify the proposed

method (direct $Z_{BR}+\text{Lambda}$ iteration), the results are compared with SPF method and a commercial ETAP software. The voltage magnitudes and phase angles of phase “a” for all buses are shown in Fig.5. The values are in very close agreement with those obtained by SPF method and ETAP software. Similar results are obtained for phases “b” and “c”, demonstrating that the proposed method can accurately solve for an active unbalanced distribution network. Table 1 shows the number of iteration and simulation time required by direct $Z_{BR}+\text{Lambda}$ and SPF methods. Although the iteration number and simulation time of direct $Z_{BR}+\text{Lambda}$ is higher than those of SPF, its superiority lies on its strong robustness for high R/X ratio.

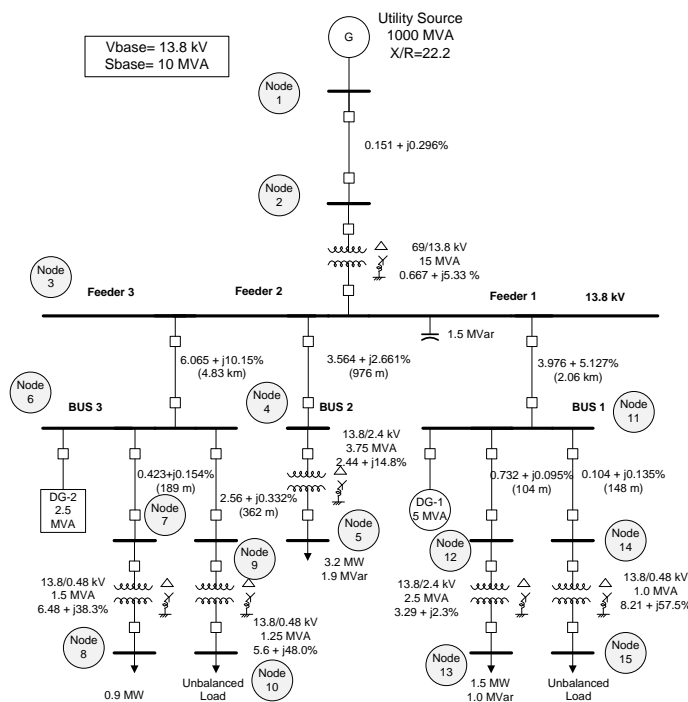


Figure 4. Test system 1(IEEE Standard 399-1997)

Table 1. Comparison of performance between $Z_{BR}+\text{Lambda}$ and SPF with 1R/X

	$Z_{BR}+\text{Lambda}$	SPF
Number of iterations (outer loop)	17	3
CPU time (sec)	0.153	0.028606

b. Case 2

The simulation for case 2 is aimed to show the impact of high values of R/X ratio. The network data are the same as those used in case 1 except that the values of R of the lines are multiplied by 5 and 6, respectively. When 5R/X is

used, both $Z_{BR}-\text{Lambda}$ and SPF methods converge. However, when 6R/X is used, the SPF method diverges but the proposed method (direct $Z_{BR}+\text{Lambda}$) still converges.

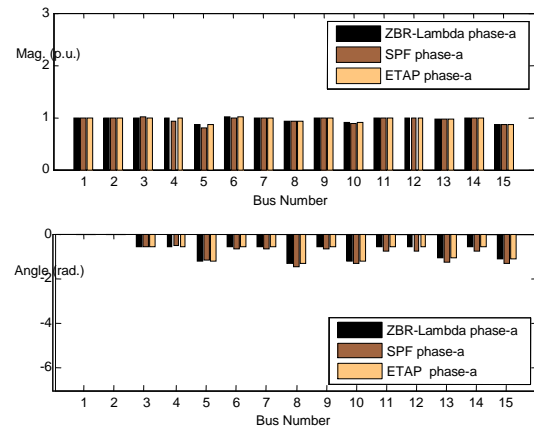


Figure 5. Magnitudes and phase angles of phase “a” for all buses in Test System 1 with 1R/X ratio.

Test System 2 (Center-Java Indonesia Distribution Power System)

The difference between test system 1 and 2 is that test system 1 doesn’t have lateral networks while test system 2 has lateral networks at bus 3 and 4 (phase “a”), at bus 8 (phase “b”), and at bus 10 (phase “c”). Therefore, the SPF method cannot be used for test system 2.

In case 2, the proposed method is compared with a commercial ETAP software. The comparison of voltage magnitudes and phase angles of phase “a”, “b” and “c” for each bus can be seen in Table 2. The results of the two methods are practically the same with negligible error.

CONCLUSION

The proposed method which combines the Direct Z_{BR} Three Phase load flow and Modified Lambda iteration is a new approach to solve for active unbalanced distribution networks accurately. The simulation results show that the proposed method can handle R/X ratio up to 6R/X with execution time less than 0.16 second.

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Table 2. Voltage Comparisons between the proposed method and ETAP software

Voltages Comparison												
No Bus	Proposed Method		ETAP		Proposed Method		ETAP		Proposed Method		ETAP	
	Mag "a"	Angle "a"	Mag "a"	Angle "a"	Mag "b"	Angle "b"	Mag "b"	Angle "b"	Mag "c"	Angle "c"	Mag "c"	Angle "c"
1	1	0	1	0.0001	1	-120	1	-120	1	120	1	120
2	0.9621	-0.0047	0.9622	-0.0047	0.9444	-120.561	0.9445	-120.561	0.9606	119.5509	0.9606	119.5509
3	0.9141	0.125	0.9141	0.125	0	0	0	0	0	0	0	0
4	0.861	0.934	0.862	0.935	0	0	0	0	0	0	0	0
5	0.9601	0.0332	0.9601	0.0332	0.9231	-120.686	0.9231	-120.686	0.9424	119.3851	0.9424	119.3852
6	0.9528	0.1749	0.9528	0.1749	0.8444	-121.201	0.8445	-121.202	0.8752	118.7125	0.8752	118.7126
7	0.9564	0.283	0.9565	0.284	0.8009	-121.436	0.8009	-121.436	0.8494	118.1925	0.8495	118.1925
8	0	0	0	0	0.7522	-121.141	0.7523	-121.141	0	0	0	0
9	0.98	0.4691	0.98	0.4691	0.7648	-121.626	0.7648	-121.626	0.8034	117.4495	0.8034	117.4495
10	0	0	0	0	0	0	0	0	0.7786	117.4527	0.7787	117.4527

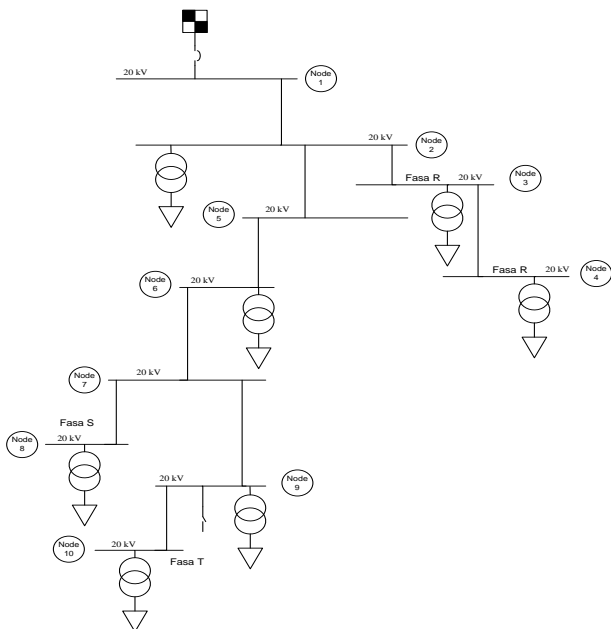


Figure 6. Test system 2 (Central-Java distribution power system)

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