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# LOAD FLOW ANALYSIS IN RADIAL DISTRIBUTION NETWORK USING BACKWARD/FORWARD SWEEP METHOD

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Abstract. *Load flow (LF) analysis is utilized to obtain the information of the power flow and voltage levels in an electric power system network in order to evaluate the performance of the power system. In this paper, the LF problem in a radial distribution network is solved by backward/forward sweep (BFS) optimization method. In this case, the BFS method improves the load flow path that makes the fast and converged computational process. The BFS method is tested on the 9-buses of radial distribution network in Makassar City and the results are compared with the Matlab/Simulink model for the same test-case scenarios. The comparison results which are indicated by absolute error deviation show that very small deviation with less than 3% for voltage magnitude and phase angle, while they have much smaller deviation by less than 0.2% for total active and reactive power losses. These results also indicate that the BFS method and Matlab/Simulink model yield very closed performance. It means that the BFS method can be considered as the alternative method for load flow study in distribution network.*

**Keywords:** Radial distribution network, Backward/Forward sweep, Matlab/Simulink model, Voltage parameters, Power losses

## 1. **Introduction.**

The radial distribution network is the most frequently implemented network in electricity distribution system due to the simplest configuration, and the installation investment is relatively inexpensive. The radial configuration means the distribution line is pulled in one direction from the main power source and then dispersed to the loads. The radial network can be overviewed like a branch of a tree with the main line that is connected to different capacity of electricity load circuits. Because there is only one source that supplies and branches to different loads, the current and power flowing towards the load along the distribution line is not the same. The power flow variation is depending on the physical impedance of the distribution line, the length of network and the variable power of customers connected to the branch of line. These characteristics put the distribution line as the non-linear and complex systems that needs the computational techniques to determine important network parameters, such as voltage magnitude, phase angle, active and reactive power flows including the network power losses.

Sort of mathematical approaches to determining these distribution line parameters has been proposed in scientific literature called power flow analysis method under steady state condition [1]. The set of mathematical equations represents the distribution line characteristics which are complex and non-linear; therefore, it is difficult to be solved by an

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analytical approach and other numerical assumptions. Due to the complex and non-linear nature of the power flow equation, the numerical solution can only be achieved by iteration process [2,3]. Methods of power flow analysis such as Gauss-Seidel, Newton-Raphson, and Fast-Decoupled utilize the iterative algorithms to solve the non-linear algebraic equations of power systems [4,5]. However, these methods might be failed to determine the accurate network parameters due to the high ratio R/X of distribution networks and these methods yield less convergence during the computational efforts. Therefore, it is important to have a computational technique for load flow analysis in distribution network. In this respect, the backward/forward sweep method is effectively and simply used to obtain the network parameters under steady state condition with fast and converged computational time.

Research related to the development of distribution system technology has greatly influenced the load flow analysis, by means of several simulation models that have contributed to solving the non-linear and complex problems. Various methods of load flow analysis of radial distribution network have been implemented based on the network topology [6,7]. However, these methods have deficiencies when the configuration of the distribution network using a mesh topology with problems the dispersed load points. A load flow solution technique for reducing the radial network to a single line equivalent model is presented with fast calculation [8,9]. However, these methods have disadvantage in the limited power that can be supplied to customers within complex and real-time utilizations. In this respect, the methods of load flow analysis of radial network which considers a numbering scheme for each bus, and network branch that exploits the features of existing network are highly important to be developed [10]. As a result, the algorithms of load flow analysis have been successfully applied to radial distribution networks which are more focused on the voltage levels and network power losses within the requirement of much faster and converged computational time [11,12].

This study aims to determine the operating characteristics of the power system under steady state conditions using the backward/forward sweep method. Especially the utilization of backward/forward sweep method in increasing the load flow path is considered a solution based on the quadratic equation used [13,14]. With this method, the power loss for each bus branch and the voltage for each bus can be determined. Similarly, to our approach, a backward/forward sweep-based method is used to solve radial distribution network problems and modify them as a solution in a simple distribution network [15,16]. In this method, the active and reactive power flow can be calculated easily in all branches including the voltage parameters. The backward/forward sweep method optimizes the load flow parameters of distribution network for each bus in real time through the increase in accuracy of equivalent current injection (ECI) through matrix calculations bus injection to branch current (BIBC) and between branch current to bus voltage (BCBV). The research and development of the backward/forward sweep model are notified able to yield the optimization results on load flow distribution network in real time much faster and more accurate than other load flow analysis methods [17,18].

The scientific contributions of our proposed method are listed as follows. Firstly, the load flow analysis model on radial network is presented and formulated using BFS optimization method by increasing the ECI accuracy for each bus. Secondly, the exact load flow solution method is introduced to show the approximated distribution network parameters with fast convergence levels by reduction of the line parameters in particular. Third, an extensive numerical result on distribution network parameters is obtained with the proposed BFS approximation method in comparison with simulation outcome from the Matlab/Simulink model. Finally, it is shown that the BFS method demonstrates a faster computation time and convergence computational process even though under low to medium load factors and high impedance network conditions.

The outline of the paper is organized as follows. Section 1 consists of introduction and research studies related to the radial distribution network, load flow analysis, and backward/forward sweep method. Next, Section 2 explains the configuration of radial distribution network with a single line diagram, injection flow in the radial distribution network, and backward/forward sweep method. After this section, Section 3 presents the simulation results and analysis including the comparison between Matlab/Simulink model and the proposed backward/forward sweep method. Finally, Section 4 concludes the results of this study and addresses our future studies.

2. **BFS Method for Radial Distribution Network.** Radial distribution network is the simple electricity network where the power flows in one direction from the power injection bus to the edge bus of network. In this respect, the radial distribution system is the most cost-effective to construct and is often employed in sparsely inhabited areas. A radial system uses a single power source to serve a group of customers. However, such radial system has weakness during the power outage, short-circuit, or downed power line, where it would disrupt electricity supply along the whole line and it would need to be repaired before power could be restored. In this study, the representation of radial network is focused on the normal and balanced supply load conditions.

Figure 1 shows a case study of 20 kV and 850 kVA with power factor of 0.95 lagging of distribution network in Makassar City. The available parameters from local electric utility are provided, such as voltage magnitude and phase angle, impedance between busses, active and reactive loads at each bus including the length of lines which are shown in Table 1. In addition, the bus no. 1 is considered as the slack bus, where the magnitude voltage of this bus is 4% slightly higher than other following buses to allow the power flow from bus no. 1 to bus no. 9 in one direction. Later on, these parameters will be the initial input data for Matlab/Simulink model.

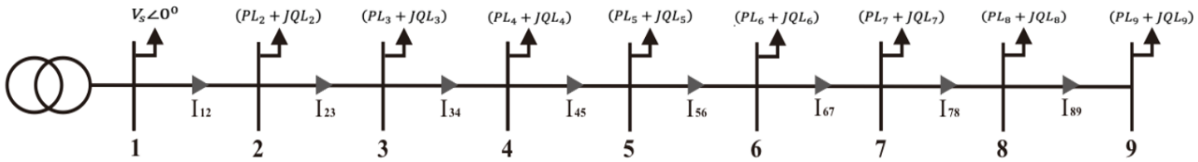

Figure 1. Radial distribution network with 9-buses

Table 1. Parameters of distribution networks

| Bus | Voltage | | Load power | |
|---|---|---|---|---|
| | Magnitude (kV) | Phase angle (degree) | P (kW) | Q (kVAr) |
| 1 | 20.819 | 0 | 83.600 | 24.59 |
| 2 | 20.752 | 0.0330 | 27.567 | 18.11 |
| 3 | 20.603 | −0.1490 | 117.533 | 34.57 |
| 4 | 20.523 | 0.0200 | 97.033 | 28.54 |
| 5 | 20.492 | 0.0690 | 55.233 | 16.24 |
| 6 | 20.319 | 0.0270 | 147.133 | 43.27 |
| 7 | 20.229 | 0.0100 | 67.300 | 19.79 |
| 8 | 20.134 | −0.1950 | 138.900 | 40.85 |
| 9 | 20.005 | 0.0127 | 68.000 | 54.8 |

| Initial bus | Final bus | Impedance | | Length (m) |
|---|---|---|---|---|
| | | R (ohms) | X (ohms) | |
| 1 | 2 | 0.669 | 0.0470 | 650 |
| 2 | 3 | 0.668 | 0.0470 | 645 |
| 3 | 4 | 0.680 | 0.0470 | 300 |
| 4 | 5 | 0.680 | 0.0470 | 424 |
| 5 | 6 | 0.681 | 0.0470 | 450 |
| 6 | 7 | 0.684 | 0.0470 | 436 |
| 7 | 8 | 0.684 | 0.0470 | 625 |
| 8 | 9 | 0.681 | 0.0470 | 642 |

2.1. **Backward/Forward sweep method.** The mathematical model of backward/forward sweep method applied to the 9-buses distribution network is presented as follows. To allow the power flow in one direction, a generator source is connected in the bus no. 1. Therefore, all buses can be denoted with voltage magnitude ($|V_i|$) and phase angle ($\theta_i{}^o$) as shown in (1):

$$V_i = |V_i| \angle \theta_i{}^o \tag{1}$$

where $V_i$ is the phasor form of voltage in kV, $i$ is the bus number from 1 to $N$ and $N$ is the total number of bus. In this case, the value of $N$ is 9. On the $i$ bus, the complex power of load is expressed as

$$S_i = P_i + jQ_i \tag{2}$$

where $S_i$ is complex power on the bus $i$, $P_i$ is the active power on bus $i$, and $Q_i$ is the reactive power on bus $i$. The equivalent injection current at the $k$th-iteration is as follows:

$$I_i^{(k)} = \left( \frac{P_i + Q_i}{V_i^{(k)}} \right)^* \tag{3}$$

where the value $I_i^{(k)}$ is the total current flow, and $k$ is the number of iterations.

In this study, the bus injection current to branch is determined in a radial distribution network as shown in Figure 1. Power injection at each bus can be converted to an equivalent current injection form as in (3) and the relationship between bus injection and branch currents can be obtained with the Kirchhoff's law for current (Kirchhoff Current Law) in the distribution network. Therefore, the branch currents can be formulated as a function of the equivalent current injection as $I_{12}$, $I_{23}$, $I_{34}$, $I_{45}$, $I_{56}$, $I_{67}$, $I_{78}$, and $I_{89}$ expressed as follows:

$$\begin{bmatrix} I_{12} \\ I_{23} \\ I_{34} \\ \vdots \\ I_{89} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ \vdots \\ I_9 \end{bmatrix} \tag{4}$$

Equation (4) is then simplified by the term of branch current matrix $[B]$ as the multiplication of bus injection to branch current $[BIBC]$ and node currents $[I_{node}]$ as shown in (5). In this case, the $BIBC$ matrix is the constant matrix which has elements containing only numbers 1 and 0. Then, branch current to bus voltage $[BCBV]$ is introduced in (6) as the matrix contains the impedance elements of distribution network.

$$[B] = [BIBC][I_{node}] \tag{5}$$

$$\begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} I_{12} \\ I_{23} \\ I_{34} \\ I_{45} \\ I_{36} \end{bmatrix} \tag{6}$$

The branch current to bus voltage $[BCBV]$ matrix in (6) is the matrix function of the backward/forward sweep algorithm based on the impedance of between buses. Therefore, the voltage deviation between two adjacent buses is simplified by (7) and (8) as follows:

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} I_{12} \\ I_{23} \\ I_{34} \\ I_{45} \\ I_{36} \end{bmatrix} \tag{7}$$

$$\begin{aligned} &[\Delta V] = [DLF][I_{node}] \\ &[DLF] = [BCBV][BIBC] \end{aligned} \tag{8}$$

where $[DLF]$ is introduced as the matrix of distribution load flow. To avoid instability during the numerical computational process, it is necessary to develop a matrix multiplication between $BIBC$ and $BCBV$ to produce matrix of voltage deviation $[\Delta V]$ as in

(9) and (10) as follows. In this case, the maximum value in the matrix multiplication of $[BCBV]$ and $[BIBC]$ can be achieved to produce the total $[DLF]$.

$$[\Delta V] = [BCBV][BIBC][I_{node}] \tag{9}$$

$$\begin{bmatrix} \Delta V_2^a \\ \Delta V_2^b \\ \Delta V_2^c \\ \vdots \\ \Delta V_j^a \\ \Delta V_j^b \\ \Delta V_j^c \\ \vdots \\ \Delta V_N^b \\ \Delta V_N^c \end{bmatrix} = \begin{bmatrix} \bar{V}_s^a - V_2^a \\ \bar{V}_s^b - V_2^b \\ \bar{V}_s^c - V_2^c \\ \vdots \\ \bar{V}_s^a - V_j^a \\ \bar{V}_s^b - V_j^b \\ \bar{V}_s^c - V_j^c \\ \vdots \\ \bar{V}_s^b - V_N^b \\ \bar{V}_s^c - V_N^c \end{bmatrix} = [BCBV][BIBC] \begin{bmatrix} I_2^a \\ I_2^b \\ I_2^c \\ \vdots \\ I_j^a \\ I_j^b \\ I_j^c \\ \vdots \\ I_N^b \\ I_N^b \end{bmatrix} = [DLF] \begin{bmatrix} I_2^a \\ I_2^b \\ I_2^c \\ \vdots \\ I_j^a \\ I_j^b \\ I_j^c \\ \vdots \\ I_N^b \\ I_N^b \end{bmatrix} \tag{10}$$

2.2. **Backward sweep.** The procedure for completing the power flow computation starts with the backward sweep. In this stage, the voltage at all buses is assumed to be equal to the voltage at the primary source. If there are multiple sources in the network, the injection current at those sources is zero and the voltage at each bus and the injection current are calculated in the previous iteration. When the bus voltage and the injection current are known, the load current can be determined in (11) as follows:

$$I_{pq}^1 = I_{89}^1 + I_8^1 + I_{78}^1 + I_7^1 + \cdots + I_{12}^1 + I_1^1 \tag{11}$$

Equation (11) indicates the current flows between bus $p$ and bus $q$ for the first iteration and the iteration will continue until the error tolerance limit is 0.0001.

2.3. **Forward sweep.** In the forward sweep, the parameters of bus voltage, impedance and branch current flows are initially known. After that, all bus voltages are updated and computed in (12) as follows:

$$V_i^1 = V_1^1 - Z_{12}I_2^1 - Z_{23}I_3^1 - \cdots - Z_{89}I_9^1 \tag{12}$$

Equation (12) shows the voltage at each bus in the first iteration. The iterations continue until it reaches an error tolerance limit value of 0.0001 as presented in (13) as follows:

$$\begin{aligned} e_i^k &= \left|V_i^k - V_i^{k-1}\right| \\ e_{\min}^k &= \min\left(e_2^k, e_3^k, \ldots, e_9^k\right) \\ e_{\min}^k &\leq \varepsilon = 0.0001 \end{aligned} \tag{13}$$

where $k$ is the number of iterations and $e$ is the error tolerance limit.

3. **Simulation Results and Analysis.** A load flow study is a numerical analysis and assessment of the power flow during normal operation and steady state conditions of electricity network. The objective is to determine the flow of power, current, voltage, real power, and reactive power when electricity power flows from the main source to dispersed loads. In this study, the power flow study report will provide the information of voltage in all busses and power losses along the feeders. The following Figure 2 shows a 9-buses radial distribution network simulated using Matlab/Simulink model using data in Table 1.

The simulation results of this model are shown in Table 2 by means of voltage magnitude and phase angle of each bus and active and reactive power losses. The average voltage magnitude and phase angle are 20.242 kV and 0.218522 degree, respectively, while the total active and reactive power losses are 0.0086 kW and 0.0035 kVAr, respectively. In

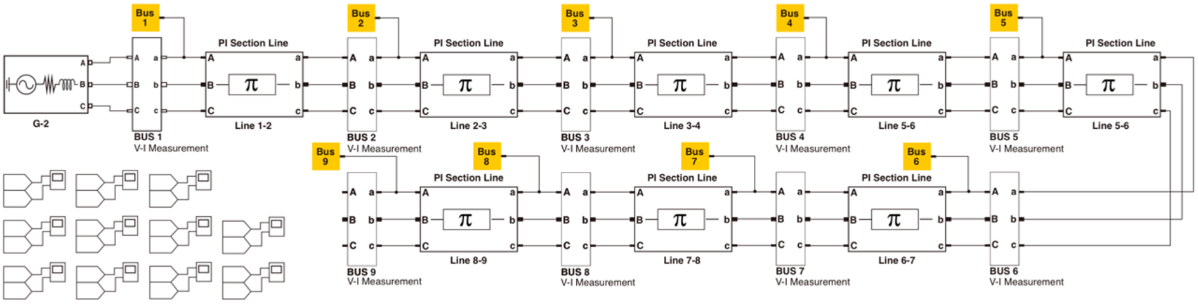

FIGURE 2. Matlab/simulink model of a 9-buses radial distribution network

TABLE 2. Simulation results of 9-buses distribution network with Matlab/Simulink model

| Bus | Voltage | |
|---|---|---|
| | Magnitude (kV) | Phase angle (degree) |
| 1 | 20.319 | 0 |
| 2 | 20.352 | 0.33 |
| 3 | 20.203 | 0.149 |
| 4 | 20.223 | 0.02 |
| 5 | 20.292 | 0.69 |
| 6 | 20.319 | 0.27 |
| 7 | 20.329 | 0.1 |
| 8 | 20.134 | 0.195 |
| 9 | 20.005 | 0.2127 |
| Average | 20.242 | 0.218522 |

| Initial bus | Final bus | Power losses | |
|---|---|---|---|
| | | P (kW) | Q (kVAr) |
| 1 | 2 | 0.0009 | 0.0004 |
| 2 | 3 | 0.0004 | 0.0003 |
| 3 | 4 | 0.0014 | 0.0004 |
| 4 | 5 | 0.0012 | 0.0004 |
| 5 | 6 | 0.0008 | 0.0005 |
| 6 | 7 | 0.0016 | 0.0006 |
| 7 | 8 | 0.0008 | 0.0004 |
| 8 | 9 | 0.0015 | 0.0005 |
| Total | | 0.0086 | 0.0035 |

addition, the computational time to run the Matlab/Simulink model is 0.07845 second. The overall data results from this Matlab/Simulink model will be used as the validated data for the output obtained using the BFS simulation model.

In comparison, the simulation results by using the backward/forward sweep model as explained in Section 2 is presented in Table 3. The magnitude of the voltage and the phase angle of each bus, and real and reactive power losses in between buses are shown. It is obtained that the minimum voltage magnitude is 20.007 kV at the bus no. 9 with the average voltage magnitude and phase angle as 20.242 kV and 0.00351 degree, respectively. Meanwhile, the total active and reactive power losses are 0.0075 kW and 0.0023 kVAr, respectively. In addition, the computational time required using the backward/forward sweep method is 0.06935 seconds.

Analysis of the simulation results using Matlab/Simulink model and backward/forward sweep model is shown in Table 4. The comparison performance between the BFS method and Matlab/Simulink model is measured by the absolute error deviation. It can be seen in Table 4 that absolute error deviation of all compared parameters is very small with less than 3% for voltage magnitude and phase angle, while they have much smaller deviation by less than 0.2% for total active and reactive power losses. These results indicate that the BFS method and Matlab/Simulink model are very close each other. It means that the BFS method can be considered as the alternative method for load flow study in distribution network where the conventional load flow study might be failed due to the high ratio of R/X. The success of the BFS method will be beneficial to be used for the investigation of loop model of distribution network with the higher number of buses and much more complex structure of network.

Table 3. Simulation results of 9-buses distribution network with backward/forward sweep model

| Bus | Voltage | |
|---|---|---|
| | Magnitude (kV) | Phase angle (degree) |
| 1 | 20.319 | 0 |
| 2 | 20.352 | 0.0262 |
| 3 | 20.203 | 0.0048 |
| 4 | 20.223 | 0.0823 |
| 5 | 20.292 | 0.1953 |
| 6 | 20.319 | 0.0254 |
| 7 | 20.329 | −0.1535 |
| 8 | 20.134 | −0.1593 |
| 9 | 20.007 | 0.0104 |
| Average | 20.242 | 0.00351 |

| Initial bus | Final bus | Power losses | |
|---|---|---|---|
| | | P (kW) | Q (kVAr) |
| 1 | 2 | 0.0008 | 0.0003 |
| 2 | 3 | 0.0003 | 0.0002 |
| 3 | 4 | 0.0012 | 0.0003 |
| 4 | 5 | 0.0010 | 0.0003 |
| 5 | 6 | 0.0006 | 0.0002 |
| 6 | 7 | 0.0015 | 0.0004 |
| 7 | 8 | 0.0007 | 0.0002 |
| 8 | 9 | 0.0014 | 0.0004 |
| Total | | 0.0075 | 0.0023 |

Table 4. Results of comparative data analysis without or with the use of backward/forward sweep

| Descriptions | | Matlab/Simulink | BFS method | Absolute error deviation |
|---|---|---|---|---|
| Average voltage | Magnitude (kV) | 20.242 | 20.242 | 0.000 |
| | Phase angle (degree) | 0.218522 | 0.00351 | 0.215 |
| Total losses | P (kW) | 0.0086 | 0.0075 | 0.0011 |
| | Q (kVAr) | 0.0035 | 0.0023 | 0.0012 |

4. **Conclusion.** The backward/forward sweep method has been used to solve the problems of load flow analysis in radial distribution network. In this study, the voltage magnitude and phase angle of each bus are determined, while the active and reactive power losses are simultaneously also obtained. The performance of the of BFS method is validated with the Matlab/Simulink model for the same test-case scenarios in 9-buses radial distribution network in Makassar City. With performance index of absolute error deviation of all compared parameters, it is obtained that voltage magnitude and phase angle have small deviation of less than 3%. Meanwhile, they have much smaller deviation by less than 0.2% for total active and reactive power losses. These results indicate that the performance of BFS method and Matlab/Simulink model are pretty similar for solving the load flow problems in distribution network. It means that the BFS method can be considered as an alternative method for load flow analysis in distribution network. In addition, the computational time with BFS method is slightly faster than running the Matlab/Simulink model. In the future of our study, the BFS method will be used to solve the load flow problems in loop distribution network.

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