

Evaluation of Power Loss Based on Backward Forward Sweep Algorithm: A Case Study of Igosun Feeder Offa, Nigeria

Ayodele Isqeel Abdullateef ^{a*}, Abimbola Joan Gbenle ^b, Rasaq Atanda Alao ^c and Bello Sunday Raji ^d

^{a,b,c,d}Department of Electrical and Electronics Engineering, University of Ilorin, Ilorin, Kwara State

Abstract

Electrical energy is usually generated long distances from the load centres; therefore, it needs an extensive network of conductors to bring it to the consumers. Due to the long distance covered by these conductors, power losses occur in the distribution system. Power losses affect the system's efficiency, reducing grid reliability, voltage instability, needless switchgear tripping, and blackouts. Power losses could be technical and non-technical. Technical losses are inherent due to the component on the distribution network; thus, it is unavoidable and can only be reduced, not eliminated. This paper evaluates the power loss on the 11 kV Igosun distribution feeder, Offa, Kwara State using the backward forward sweep algorithm implemented in MATLAB platform. The data, extracted from the feeder's topology, were used to calculate the corresponding real and reactive power load at the respective buses. The results show a total real power loss of 873.5688 kW and a total reactive power loss of 504.3703 kVAR on the feeder. The knowledge of the feeder's power losses will benefit electric power utilities to improve the quality of the power supply and revenue generation.

Keywords-Distribution system, Feeder, Power losses, Backward forward sweep, Technical losses,

1. Introduction

Electrical energy is fundamental to the economic growth of a nation [1, 2]. Its availability increases industrial development; agricultural productivity and improves people's living standards. Traditionally, the three principal parts of the power system are generation, transmission and distribution. The distribution system links the transmission system and the consumers; thus, the activities on this network are vital to the consumers' sustainability of adequate power supply. However, the distribution system does not account completely for the power delivered to it due to the power losses associated with the system. Power loss is part of electricity supplied to the transmission and distribution systems that are not paid for by consumers and are categorised as technical losses (TL) and non-technical losses (NTL). TL are losses that are associated with the infrastructure/components of the power system, such as distribution lines, switchgear and transformers. It is about 23% of the total losses and directly depends on the network characteristics and operation [3]. Regardless of the design and construction of the power system, TL is unavoidable because they occur naturally; however, it can be reduced to the barest minimum. In contrast, non-technical losses result from energy theft, metering problems, administrative practices, terrorist activities and billing of unmetered supply of energy, among others [4].

Distribution network losses are the difference between the electrical energy going into and exiting the network and properly

accounted for [5]. Losses on this network have been estimated at 13% of the total power generated in the system [6], which results in the distribution network's inefficiency leading to grid reliability reduction. Problems such as voltage instability, needless switchgear tripping, and blackouts might occur due to power system losses. Factors such as the length and quality of the conductors, the type of electrical loads on the network and unbalanced phase loading mainly contribute to the power losses on the distribution network [7]. These affect the utilities that incur a significant loss of revenue due to operating costs and the consumers who have to pay more for the cost of electricity due to the cost incurred by the utilities.

Furthermore, the expansion of electricity to rural and urban areas due to an increase in population growth over the years implies an increase in the route length of the feeders, which results in more power loss. Although the percentages of losses in both transmission and distribution networks are relative to countries; however, their effect on the utilities and well-being of the system is the same. For instance, Iran's transmission and distribution power loss is reported as 9.2% of the total losses [8]. While 5% of electricity transmitted and distributed has been estimated as losses in the USA [9]. Losses in transmission and distribution lines in Nigeria were reported as 16% as of 2014 [10]. The economic consequences of losses on transmission and distribution in Nigeria have been estimated at fifty billion Naira as of 2020 [11].

The quantity of power losses in the distribution systems is one of the criteria to measure its performance; therefore, necessary actions toward the evaluation and reduction of the losses are always a priority for the utilities and researchers. Adegboyega

*Corresponding author. Tel.: +2348086215103

E-mail: abd_lateef.aii@unilorin.edu.ng

and Onime [12] determined losses on the different feeders based on the monthly maximum loading on the feeders, resistance, size of each feeder conductor, route length and maximum current drawn from each feeder conductor. The losses were computed using the data obtained from the Power Holding Company of Nigeria for five years. Results reveal that losses occurring on each feeder increase yearly and are attributed to illegal connections and route length of feeders, among others. The loss factor approach has been proposed to evaluate power losses on distribution feeders [13, 14]. Monthly loading, feeder route length, and cross-sectional area data of four 11kV feeders were used for the computation. The results show grid inefficiencies, and power imbalance increased slightly yearly. In addition, Uchechukwu and Ephraim [15] has proposed a statistical analysis method for evaluating losses on power distribution networks. It was carried out to estimate the revenue cost and how to reduce the losses. A year data, including the transformer and length of the conductor, were taken from six 11kV distribution networks of Akani injection substation of the Port Harcourt Electricity Distribution Company and used to evaluate the supplied energy, billed energy and energy loss.

Furthermore, a modified DistFlow method has been proposed to analyse a distribution feeder's power flow [16]. The proposed method is non-iterative and linear and depends on a differentiated manipulation of power losses on the feeder. It improves the calculation accuracy in node voltages, losses, and overall active and reactive power flows. The author in [17] proposed the evaluation of technical power losses on the distribution network using the load loss factor. Relevant documented data of 33kV/11kV Port Harcourt Electricity Distribution Company of injection substations were collected and collated for evaluation. The data include monthly maximum loading, feeder route length, cross-sectional area, conductor size, and transformer rating. The data were used to compute the monthly power losses, energy losses and loss in revenue. The evaluation of TL on 33kV/11kV distribution networks has been proposed [18]. The field data was extracted from Enugu Electricity Distribution Company and simulated using Electrical Transient and Analysis Program software. The result shows a significant loss in the distribution network. Other studies have proposed a similar approach for calculating the distribution feeder's power loss [19, 20].

Furthermore, the losses in the power system networks can be estimated by carrying out the load flow analysis using Newton-Raphson and Gauss-Seidel methods and their modifications. However, these methods are ineffective for a radial distribution network because it has a high resistance-to-reactance ratio, a wide range of resistance and reactance values, and unbalanced load distribution, among others [21]. Moreover, the convergence of the classical Newton-Raphson technique in the radial distribution analysis may not be easily attained [22]. The backwardforward sweep (BFS) method based on Kirchhoff's laws is another technique used for load flow analysis. This technique works well with the radial structure of distribution systems to achieve high speed and good convergence with low memory requirements [23]. In addition, it is suitable for weakly meshed networks with a compensation-based power flow approach. Three variants of BFS methods exist, the current, the power and the admittance summation methods [24]. These methods differ based on the electrical quantity being calculated during the iterations. The advantages of BFS include high computation efficiency, less memory size, and no requirement for a Jacobian matrix, and it is suitable for online and offline problems. Thus, this study adopts the BFS technique to evaluate the real and reactive power loss in Igosun primary distribution feeder.

2. METHODOLOGY

2.1 Description of the study area

Offa is located in Kwara state, Nigeria, with a population of about 120,100. It is situated within geographical coordinates 8°9'N 4°43'E. The town has two electric power distribution substations. One of the substations is the Idi-Ogun substation, fed through the 33 kV transmission station along Ojoku road. The substation comprises four feeders: Erin-Ile feeder, Igosun feeder, Industrial feeder and Offa feeder. The Igosun feeder of Idi-Ogun substation in Offa, Kwara State, was used as a case study.

Primary distribution system losses exist on the distribution lines and in transformers; however, this paper is limited to distribution lines. Therefore, the system total power loss refers to the total real power loss on the distribution lines. The single-line diagram representation of the system is illustrated in Figure 1.

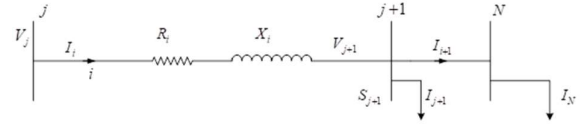


Fig. 1: single-line diagram of a distribution feeder

The source bus is denoted as j . The voltage at bus j is V_j , the bus next to the source bus is the first load bus and denoted as $j+1$ with apparent power S_{j+1} .

The impedance Z of the line, is represented as

$$Z = R_i + jX_i \quad (1)$$

where

R_i is the resistance of branch i , j signifies the imaginary part and X_i is the reactance of branch i . The distribution system is assumed balanced; therefore, single phase representation is used.

The total real power loss on the distribution system can be expressed as

$$P_{LOSS} = \sum_{i=1}^{N-1} I_i^2 R_i \quad (2)$$

where,

N is the total number of buses, $N-1$ is the total number of branches, I_i and R_i are the currents in and resistance of branch i , respectively.

2.2 Backward Forward Sweep (BFS) Load Flow Analysis

The BFS algorithm is an iterative process that uses algebraic equations to determine the outgoing power and voltage values at different nodes. This makes the BFS algorithm very robust and numerically efficient for convergence over the wide variations in the voltages of a radial distribution system. In the BFS technique, the load flow process goes from one branch to another in sequential order until all the buses in the feeder have been traced or covered. The bus voltages are initially assumed to be 1 p.u. Based on these voltages and the determined real and reactive power, the branch currents proceeding from the end bus to the source are evaluated one after the other; hence, the name

backward sweep. It is used to determine the branches' real and reactive power loss. The respective sum of these gives the total power loss on the system. Figure 2 shows the Backward Forward Sweep algorithm as applied in this study

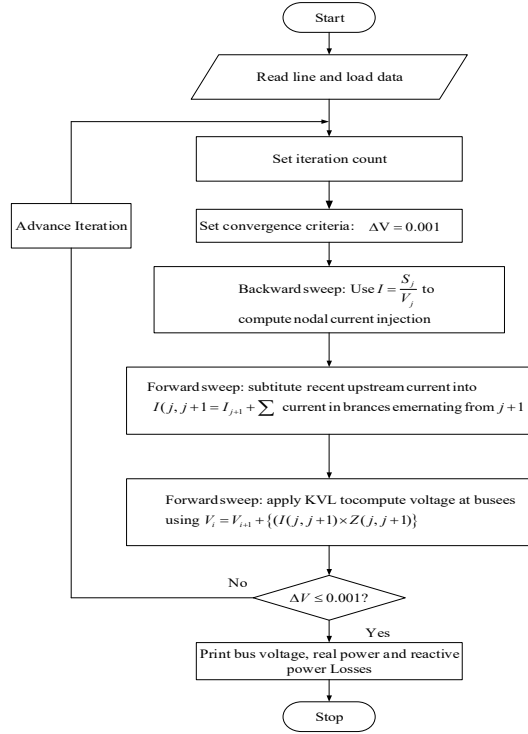


Fig. 2. Flow chat of backward forward sweep algorithm

The current at the respective node from the first load bus is determined as

$$I_j^k = \frac{S_j}{V_j^k} \quad (3)$$

S_j is the apparent power at bus j .

The backward sweep current I_i traced from the end node to the source node in each iteration is expressed as

$$I_i^k = I_{j+1}^k + \sum \text{(Current in branches emanating from bus } j+1) \quad (4)$$

The voltage drop along branch i at k th iteration is

$$V_{Drop(i)}^k = V_j^k - V_{j+1}^k = I_i^k z_i \quad (5)$$

The new line voltage at each bus after iteration is expressed as

$$V_j^{k+1} = V_j^k - I_i^k z_i \quad (6)$$

where

V_j and V_{j+1} are voltages at bus j and the bus next to j respectively. The real and reactive power losses on branch i at k th iteration are respectively given as 7 and 8.

$$P_{LOSS,i}^k = (I_i^k)^2 R_i \quad (7)$$

$$Q_{LOSS,i}^k = (I_i^k)^2 X_i \quad (8)$$

where:

I_i^k is the current in branch i at k th iteration

The single-line diagram of Igosun feeder topology is illustrated in Figure 3.

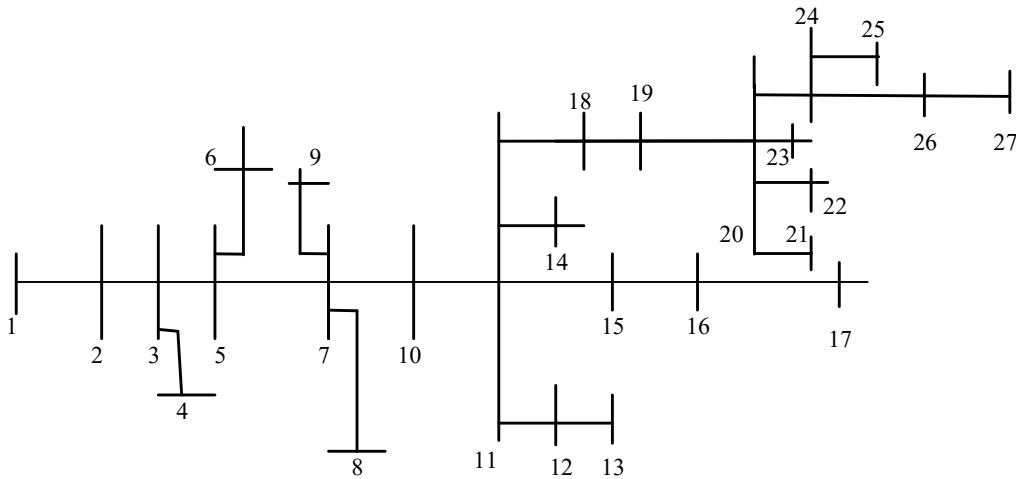


Fig. 3: single-line diagram of Igosun feeder topology

The load and line data shown in Table 1 and Table 2 were extracted from the feeder's topology and used to calculate the corresponding real and reactive power load at the respective buses. The topology comprises 27 buses, of which the first bus is the source bus while the other 26 buses are load buses. It is assumed that all buses lie directly on the main feeder.

Table 1: Load Data from the System Topology

Bus/Node j	Transformer rating / apparent power S (MVA)
2	0.5
3	0.5
4	0.5
5	0.1
6	0.5
7	0.2
8	0.3
9	0.5
10	0.5
11	0.5
12	0.1
13	0.5
14	0.5
15	0.5
16	0.3
17	0.3
18	0.2
19	0.2
20	0.3
21	0.5
22	0.3
23	0.3
24	0.05
25	0.3
26	0.3
27	0.3
TOTAL	9.05

Table.2: Line Data from the System Topology

Sending bus	Receiving bus	Branch number i	Branch distance l (km)
1	2	1	0.1
2	3	2	0.6
3	4	3	0.4
3	5	4	0.8
5	6	5	0.15
5	7	6	0.05
7	8	7	1
7	9	8	0.4
7	10	9	0.4
10	11	10	0.25
11	12	11	0.3
12	13	12	0.5
11	14	13	0.8
11	15	14	0.5

15	16	15	0.3
16	17	16	0.4
11	18	17	1.1
18	19	18	0.3
19	20	19	0.1
20	21	20	0.35
20	22	21	0.85
20	23	22	1.95
20	24	23	3.25
24	25	24	0.4
24	26	25	1.2
26	27	26	0.4
TOTAL			16.85

The real and reactive loads at different buses, resistance, reactance and the overall impedance of the lines were evaluated based on equations 9 and 10

$$P_j = S_j \cos \theta \quad (9)$$

$$Q_j = S_j \sin \theta \quad (10)$$

The line parameters, comprising the resistance R , reactance X and impedance Z , were determined using equations 11, 12 and 13 respectively.

$$R_i = \frac{\rho l_i}{A} \quad (11)$$

$$X_i = Z_i \sin \theta \quad (12)$$

$$Z_i = \frac{R_i}{\cos \theta} \quad (13)$$

ρ is the resistivity of the conductor, l is the length of the conductor, and A is the cross-sectional area of the conductor.

All Aluminum conductors (AAC) of size 100 mm² with resistivity of $2.82 \times 10^{-8} \Omega m$ was used to determine the value of the resistance. The resistances of the branches i were determined based on the topology's distances of separation between the buses.

3. Results and Discussion

The load data required for the load flow analysis of the system were evaluated using equations 9 and 10; the results are presented in Table 3. At the same time, the line data was calculated based on equations 11, 12 and 13 and presented in Table 4. These values were used for the load flow analysis of the system.

Table 3: Values of the Real and Reactive Power (Load Data)

Bus j	Apparent Power S_j kVA	Real Power P_j kW	Reactive Power Q_j kVAr
2	500	433.0	250
3	500	433.0	250
4	500	433.0	250
5	100	86.6	50
6	500	433.0	250

7	200	173.2	100
8	300	259.8	150
9	500	433.0	250
10	500	433.0	250
11	500	433.0	250
12	100	86.6	50
13	500	433.0	250
14	500	433.0	250
15	500	433.0	250
16	300	259.8	150
17	300	259.8	150
18	200	173.2	100
19	200	173.2	100
20	300	259.8	150
21	500	433.0	250
22	300	259.8	150
23	300	259.8	150
24	50	43.30	25
25	300	259.8	150
26	300	259.8	150
27	300	259.8	150
TOTAL	9050	7837.3	4525

Table 4: Values of Resistance, Reactance and Impedance (Line Data)

Sen d. bus	Receiv ing bus	Leng th (m)	Resista nce R(Ω)	Reacta nce X(Ω)	Impeda nce Z(Ω)
0	1	100	0.0282	0.01628	0.03256
1	2	600	0.1692	0.09769	0.19538
2	3	400	0.1128	0.06512	0.13025
2	4	800	0.2256	0.13025	0.26050
4	5	150	0.0423	0.02442	0.04884
4	6	50	0.0141	0.00814	0.01628
6	7	1000	0.282	0.16281	0.32563
6	8	400	0.1128	0.06512	0.13025
6	9	400	0.1128	0.06512	0.13025
9	10	250	0.0705	0.04070	0.0814
10	11	300	0.0846	0.04884	0.09769
11	12	500	0.141	0.08140	0.16281
10	13	800	0.2256	0.13025	0.26050
10	14	500	0.141	0.08140	0.16281
14	15	300	0.0846	0.04884	0.09769
15	16	400	0.1128	0.06512	0.13025
10	17	1100	0.3102	0.17909	0.35819
17	18	300	0.0846	0.04884	0.09769
18	19	100	0.0282	0.01628	0.03256
19	20	350	0.0987	0.05698	0.11397
19	21	850	0.2397	0.13839	0.27679
19	22	1950	0.5499	0.31749	0.63498
19	23	3250	0.9165	0.52915	1.058314
23	24	400	0.1128	0.06512	0.13025
23	25	1200	0.3384	0.19538	0.39076
25	26	400	0.1128	0.06512	0.13025

The results of the load flow analysis with BFS algorithm, implemented in MATLAB environment, are presented in Tables 5 and 6 respectively. Table 5 shows the BFS load flow results of the currents and voltages at different buses at the first iteration, 1st, $k = 1$, using equations 3 to 6, while the last, 11th, iteration is in Table 6. The value of the current at the last bus is the same as the current in the last branch, $I_j = I_i$. The backward sweep current I_i increases progressively from the last branch to the first branch. The value of the voltage drop doesn't have any definite pattern, as it varies directly with the line current and the impedance of the line. Although the current increases linearly, the line impedance value depends on the distances between buses, which varies and determines the voltage drop. The values of the voltages at different buses were determined with the forward sweep. The voltages at the buses decrease from the first bus to the last due to the voltage drops along the lines.

Table 5: Backward Forward Sweep Load Flow at 1st Iteration

Bus j	I_j (A)	I_i (A)	V_{DROP} (V)	V_{new} (V)
2	45.45455	822.7273	26.79089	10973.21
3	45.45455	777.2727	151.8644	10821.34
4	45.45455	731.8182	95.32228	10726.02
5	9.090909	686.3636	178.8033	10547.22
6	45.45455	677.2727	33.08157	10514.14
7	18.18182	631.8182	10.28711	10503.85
8	27.27273	613.6364	199.8215	10304.03
9	45.45455	586.3636	76.37623	10227.65
10	45.45455	540.9091	70.4556	10157.2
11	45.45455	495.4545	40.33435	10116.86
12	9.090909	450	43.96074	10072.9
13	45.45455	440.9091	71.78774	10001.11
14	45.45455	395.4545	103.0191	9898.095
15	45.45455	350	56.98614	9841.109
16	27.27273	304.5455	29.75121	9811.358
17	27.27273	277.2727	36.11589	9775.242
18	18.18182	250	89.54965	9685.692
19	18.18182	231.8182	22.64644	9663.046
20	27.27273	213.6364	6.95675	9656.089
21	45.45455	186.3636	21.24029	9634.849
22	27.27273	140.9091	39.0022	9595.847
23	27.27273	113.6364	72.15778	9523.689
24	4.545455	86.36364	91.39985	9432.289
25	27.27273	81.81818	10.65715	9421.632
26	27.27273	54.54545	21.3143	9400.318
27	27.27273	27.27273	3.552383	9396.765

Table 6 shows the BFS load flow results of the currents and voltages at different buses at the final (i.e. 11th) iteration where the desired convergence was attained with all parameters as determined in Table 3. The values in Table 7 are those obtained after the convergence, meeting the set convergence criterion of

10-5 as the difference between the final iteration and the immediately preceding iteration

Table 6: Backward Forward Sweep Load Flow at final (11th) Iteration

J	I_j (A)	I_i (A)	V_{DROP} (V)	V_{new} (V)	V_{new} p.u
2	45.5779	914.430	29.777	10970.22	0.997293
3	46.2943	868.853	169.7574	10800.47	0.98186
4	46.75815	822.5587	107.1416	10693.32	0.972120
5	9.531778	775.8005	202.1023	10491.22	0.953747
6	47.82953	766.2688	37.4286	10453.79	0.950344
7	19.15324	718.4392	11.69745	10442.1	0.949281
8	29.37035	699.286	227.7121	10214.38	0.928580
9	49.37236	669.9156	87.25922	10127.12	0.920647
10	49.76959	620.5433	80.82827	10046.3	0.913299
11	50.00085	570.7737	46.46599	9999.83	0.909075
12	10.05131	520.7728	50.87458	9948.955	0.904450
13	50.68012	510.7215	83.15443	9865.801	0.896891
14	51.30333	460.0414	119.8445	9745.956	0.885996
15	51.65606	408.7381	66.54973	9679.407	0.879946
16	31.10574	357.082	34.88353	9644.523	0.876774
17	31.24328	325.9763	42.45973	9602.064	0.872914
18	21.06041	294.733	105.573	9496.491	0.863317
19	21.11987	273.6726	26.73522	9469.755	0.860886
20	31.70734	252.5527	8.224003	9461.531	0.860139
21	52.98653	220.8454	25.17025	9436.361	0.857851
22	31.94922	167.8589	46.46163	9389.899	0.853627
23	32.24559	135.9096	86.30105	9303.598	0.845781
24	5.438395	103.664	109.7091	9193.889	0.835808
25	32.67584	98.22565	12.79429	9181.095	0.834645
26	32.76726	65.54981	25.61438	9155.481	0.832316
27	32.78255	32.78255	4.270059	9151.211	0.831928

Table 7 presents the BFS load flow results of the real and reactive power losses on the lines at the last iteration based on equations 7 and 8. The real power loss varies directly as the product of the square of the current on the line and the resistance of the line. At the same time, the reactive power loss varies directly as the product of the square of the current on the line and the reactance of the line. Therefore, no fixed pattern is observed in the power loss as the current, resistances, and reactances vary, respectively.

Table 7: Base Case Real and Reactive Power Losses on the Lines

Sendin g Bus j	Rece iving Bus j	V DROP (V)	V_{new} P.U	P_{Loss} (W)	Q_{Loss} (VAR)
1	2	29.77708	0.997293	23580.39	13614.54
2	3	169.7574	0.9818605	127730	73747.12
3	4	107.1416	0.9721204	76320.79	44065.12
3	5	202.1023	0.9537474	135781.1	78395.54

5	6	37.4286	0.9503448	24837.2	14340.18
5	7	11.69745	0.9492814	7277.784	4201.954
7	8	227.7121	0.9285803	137898.2	79617.93
7	9	87.25922	0.9206477	50623.17	29228.16
7	10	80.82827	0.9132996	43436.34	25078.72
10	11	46.46599	0.9090755	22967.67	13260.78
11	12	50.87458	0.9044505	22943.89	13247.05
12	13	83.15443	0.896891	36777.94	21234.38
11	14	119.8445	0.885996	47745.56	27566.72
11	15	66.54973	0.8799461	23556.42	13600.71
15	16	34.88353	0.8767748	10787.14	6228.141
16	17	42.45973	0.8729149	11986.19	6920.432
11	18	105.573	0.8633173	26946.31	15557.92
18	19	26.73522	0.8608868	6336.26	3658.349
19	20	8.224003	0.8601392	1798.677	1038.497
20	21	25.17025	0.857851	4813.864	2779.367
20	22	46.46163	0.8536272	6753.93	3899.498
20	23	86.30105	0.8457817	10157.44	5864.572
20	24	109.7091	0.8358081	9848.923	5686.445
24	25	12.79429	0.834645	1088.326	628.3636
24	26	25.61438	0.8323164	1454.029	839.5089
26	27	4.270059	0.8319282	121.2256	69.99171

4. Conclusion

Evaluation of power losses on Igosun 11kV distribution feeder, Offa has been carried out in this study. This was achieved using backward forward sweep algorithm effective for the radial distribution network. The load flow analysis was implemented in MATLAB 2015 environment. The base case shows that there are real and reactive power losses along the distribution lines, which vary directly as the product of the voltage drop on the line and the branch current. The sum of real power loss on all the branches is 873,568.8 W, while the sum of the reactive power loss on all the branches is 504,370.3 VAR.

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