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POWER FLOW ANALYSIS OF UNBALANCED DISTRIBUTION SYSTEMS

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Abstract:

Power-flow or load-flow analyses play a crucial role in assessing the overall functionality of the current system and in planning future expansions within the limitations imposed by steady-state conditions. They are also important in ensuring the power transfer from generators to consumers by considering reliable and economic aspects. The study of the active and reactive power flow from the source to the consumers under steady state conditions with certain equality and inequality constraints is known as load flow or power flow. The constraints are in the form of minimum and maximum values of voltages and reactive powers to be maintained at the buses. The unbalanced radial distribution system has got primary concern for dispatching load without any technical problems. For this, the conventional methodologies of compensation face difficulties in improving system security by minimizing severity. The technological advancements in compensating system parameters can enhance the system performance. The complete analysis is presented for unbalanced radial distribution systems (URDS)-13 node system with supporting graphical and numerical results.

Key words: Unbalanced Distribution System, Load flow Solution, Optimization, Power flow, Base load.

1. Introduction

The distribution system is a critical component of the electrical infrastructure, responsible for efficiently delivering electrical energy from the transmission system to individual consumers. This process involves distribution substations that connect to the transmission system and use transformers to lower voltage levels. Primary distribution lines then carry this power to distribution transformers near customer premises, which further adjust the voltage for lighting, industrial equipment, and household appliances. The secondary distribution system operates on a 400/230 V, 3-phase, 4-wire system, providing electricity at either 50 or 60 Hz, depending on the region [1]. Ground connections are established to ensure safety in case of conductor falls or distribution transformer failures. Overall, the distribution system plays a crucial role in meeting customer energy demands by effectively managing the flow of electrical energy within specified voltage parameters [2].

The analytical study of three-phase distribution systems is crucial for ensuring the efficient and reliable delivery of electrical power to end-users. Several key aspects have been explored in the literature to address the complexities associated with these systems. Load Flow Analysis: In understanding the steady-state behavior of three-phase distribution networks, load flow analysis emerges as a fundamental aspect. Classic methods such as Gauss-Seidel and Newton-Raphson have been widely employed to determine the flow of active and reactive power, ensuring system stability and preventing issues like overloading [3].

Short Circuit Analysis: Investigating the impact of short circuits is imperative for designing protective devices. The symmetrical components analysis method has been instrumental in assessing the system's response to various short-circuit scenarios, aiding in the proper sizing of protective equipment [4]. Voltage Regulation: Maintaining stable voltage levels within permissible limits is crucial for the reliable operation of customer equipment. Modern methods involving voltage regulators and tap-changing transformers have been explored to enhance voltage regulation under varying load conditions [5, 6].

Harmonic Analysis: The proliferation of non-linear loads necessitates a thorough examination of harmonics in distribution systems. Fourier analysis and advanced simulation tools are employed to identify and mitigate harmonic distortions, ensuring compatibility with sensitive electronic equipment [7]. Optimal Capacitor Placement: The optimization of capacitor placement for power factor correction and loss reduction is a significant analytical aspect. Algorithms based on load profiles and system topology have been developed to determine the optimal locations for capacitor installations [8,9].

Reliability Analysis: Evaluating the reliability and availability of three-phase distribution systems is vital for delivering uninterrupted power to end-users. Reliability indices such as SAIDI and SAIFI have been utilized to assess system performance and guide improvements [10, 11]. Distribution Automation: Advanced control and monitoring systems, such as SCADA, play a pivotal role in the automation of distribution systems. These technologies enhance the system's responsiveness to faults and disturbances in real-time, improving overall reliability [12]. Feeder Reconfiguration: Optimizing the configuration of feeders is essential for load balancing and loss reduction. Automated feeder reconfiguration algorithms have been developed based on load patterns to enhance system efficiency and reliability [13, 14].

The paper aims to achieve the following objectives like introduce and demonstrate the backward/forward sweep methodology as a solution to the load flow problem in unbalanced radial distribution systems. Address the need to improve the performance of distribution systems in order to provide efficient, reliable, and uninterrupted electric power supply to consumers. This involves compensating parameters through strategies such as network reconfiguration and the integration of distributed generations. Calculation of the total losses, voltages and power flows in URDS-13 network is carried out in this work.

2. Unbalanced Distribution Load Flow Formulation

The passage underscores the significance of load flow studies in electrical power systems for understanding steady-state solutions. It outlines the basic requirements for load flow calculations, emphasizing convergence properties, computing efficiency, and implementation flexibility.

Additionally, the passage enumerates the necessity for power flow studies, covering aspects such as line flows, bus voltages, system voltage profiles, and the effects of system changes. It highlights the importance of load flow analysis in economic system operation, loss minimization, transformer tap setting, and system improvements.

While acknowledging load flow analysis as a crucial tool in power system engineering, the passage recognizes challenges in applying traditional methods to distribution systems. It points out the distinctive characteristics of distribution networks and the need for more efficient techniques tailored to these features.

2.1. Mathematical Modelling

2.1.1. Unbalanced Radial Distribution System Line Model

In contrast to transmission lines, distribution lines lack transposition and consistent equality among their line currents. This disparity arises from the prevalence of single-phase and two-phase loads in distribution systems. The accurate calculation of distribution line impedance becomes essential, particularly considering the dynamic nature of their configurations and the absence of transposition.

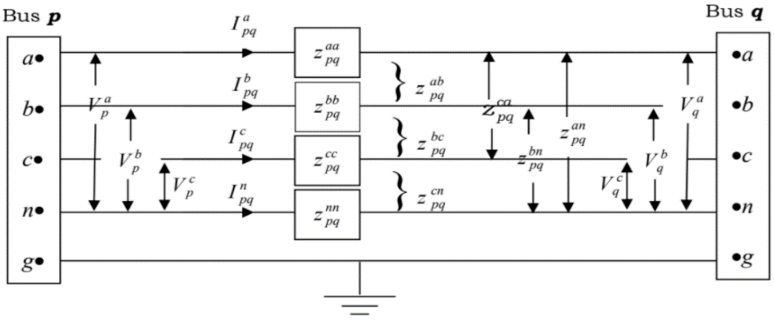

Fig 1: Unbalanced Distribution System Line Model

Utilizing Carson expressions, the Untransposed Radial Distribution System (URDS) with N conductors is represented by an N×N primitive impedance matrix. As an illustration, considering the 4-wire URDS line depicted in Figure 1, the corresponding 4×4 impedance matrix is derived through the Kron reduction method, employing Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL).

$$\begin{bmatrix} V_p^a \\ V_p^b \\ V_p^c \\ V_p^n \end{bmatrix} = \begin{bmatrix} V_q^a \\ V_q^b \\ V_q^c \\ V_q^n \end{bmatrix} + \begin{bmatrix} z_{pq}^{aa} & z_{pq}^{ab} & z_{pq}^{ac} & z_{pq}^{an} \\ z_{pq}^{ba} & z_{pq}^{bb} & z_{pq}^{bc} & z_{pq}^{bn} \\ z_{pq}^{ca} & z_{pq}^{cb} & z_{pq}^{cc} & z_{pq}^{cn} \\ z_{pq}^{na} & z_{pq}^{nb} & z_{pq}^{nc} & z_{pq}^{nn} \end{bmatrix} \begin{bmatrix} I_{pq}^a \\ I_{pq}^b \\ I_{pq}^c \\ I_{pq}^n \end{bmatrix} \qquad (1)$$

The same equation can be expressed as:

$$\begin{bmatrix} V_p^{abc} \\ V_p^n \end{bmatrix} = \begin{bmatrix} V_q^{abc} \\ V_q^n \end{bmatrix} + \begin{bmatrix} Z_{pq}^{abc} & z_{pq}^n \\ z_{pq}^{n^T} & z_{pq}^{nn} \end{bmatrix} \begin{bmatrix} I_{pq}^{abc} \\ I_{pq}^n \end{bmatrix} \qquad (2)$$

In the scenario of a grounded neutral, where the voltages V_p^n ,V_q^n are identical, the expression from equation (2), specifically the first row, leads to the derivation of equation (3):

$$I_{pq}^n = -z_{pq}^{nn^{-1}} z_{pq}^{n^T} I_{pq}^{abc} \qquad (3)$$

Substituting eqn. (3) into eqn. (2), the final expression is:

$$V_p^{abc} = V_q^{abc} + Ze_{pq}^{abc} I_{pq}^{abc} \qquad (4)$$

Where,

$$Ze_{pq}^{abc} = Re_{pq}^{abc} + jXe_{pq}^{abc} \qquad (5)$$

I_{pq}^{abc} is the current vector through the conductor connecting buses p and q is equivalent to the summation of load currents from all buses beyond the line between p and q. This summation also includes the charging currents from all buses beyond the conductor in buses p and q for each phase. Consequently, the voltage at bus q can be mathematically computed when the voltage at bus p is known. This is expressed by the reformulation of equation (4) as:

$$\begin{bmatrix} V_q^a \\ V_q^b \\ V_q^c \end{bmatrix} = \begin{bmatrix} V_p^a \\ V_p^b \\ V_p^c \end{bmatrix} - \begin{bmatrix} z_{e_{pq}}^{aa} & z_{e_{pq}}^{ab} & z_{e_{pq}}^{ac} \\ z_{e_{pq}}^{ba} & z_{e_{pq}}^{bb} & z_{e_{pq}}^{bc} \\ z_{e_{pq}}^{ca} & z_{e_{pq}}^{cb} & z_{e_{pq}}^{cc} \end{bmatrix} \begin{bmatrix} I_{pq}^a \\ I_{pq}^b \\ I_{pq}^c \end{bmatrix} \qquad (6)$$

2.1.2. Load Flow Analysis

Load flow studies are crucial for ensuring the stability, reliability, and economic efficiency of electrical power transfer in power systems. They play a vital role in the planning of new networks or expansions to existing ones, aiding decisions related to generator sites, increased load demands, and transmission site locations.

Power flow analysis provides essential information about nodal voltages, phase angles, power injections, and interconnecting power flows. This data is instrumental in determining optimal locations and capacities for generating stations, substations, and new lines, while also regulating voltage levels within prescribed tolerances.

The classification of buses, such as load buses (PQ), generator buses (PV), and slack buses (reference), is based on specified and obtained quantities. The forward-backward sweep load flow method is a widely used algorithm in distribution systems, offering efficiency in solving radial distribution systems.

In distribution networks, the equivalent current injection-based model is practical. Complex loads, expressed as Si=Pi+jQi, and equivalent current injections are used in iterative processes for voltage and current estimations at each bus. This method efficiently models the distribution network's radial structure, making it a valuable tool in load flow analysis.

2.2. Backward and Forward Sweep Flow Chart

The following flow chart is used for solving distribution load flow using backward and forward sweep load flow algorithm. From this, the node voltages are obtained, using the total power losses are calculated from fundamentals.

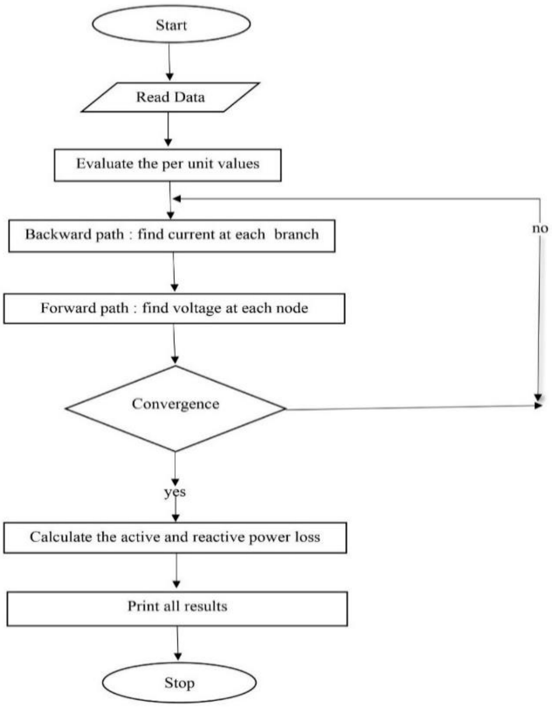

Fig 2: Flow Chart of Backward Forward Sweep Method

3. Results and Analysis

3.1. Test System

The entire analysis was performed for the following cases.

- Case-1: To perform load variations on the 13-node system from base values.
- Case-2: To Compare base load with Light load.

Case-1:

In case-1, to find out the Voltage magnitudes and other system parameters of Base Load. By using the Backward-Forward Sweep load flow method the load variation and other system parameters performance are tested on URDS-13 node system.

- From results it is observed that the voltage magnitude for end nodes has decreased.
- The minimum voltage is obtained at node-13 in R-Phase and B-Phase this is due to line losses.
- The voltage magnitude at node-13 in Phase-R is 0.971839 p.u.

The voltage magnitude results are shown in the Table 1: and its graphical representation is shown in Fig 3.

Table 1: Voltage magnitude for URDS-13 under Base Load

Node No	**Voltage magnitude, p.u.**		
	R-Phase	**Y-Phase**	**B-Phase**
1	1	1	1
2	1.020737	1.041848	1.017071
3	1.018277	1.040253	1.014919
4	1.018272	1.04025	1.014915
5	-	1.031475	1.015181
6	-	1.028436	1.013328
7	0.987623	1.036842	0.973828
8	0.987623	1.036842	0.973828
9	0.984941	-	0.97345
10	-	-	0.972387
11	0.980049	-	-
12	0.987612	1.036845	0.973828
13	0.971839	1.040706	0.968062

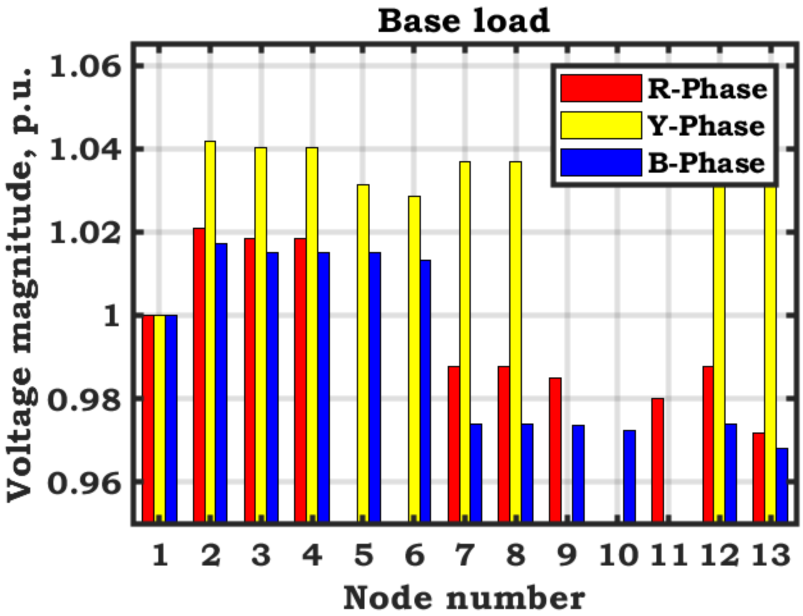

Fig 3: Graphical Representation for Voltage Magnitude

Similarly, the apparent power flow results are tabulated in the Table 2 and the entire results are shown in the Fig 4.

Table 2: Apparent Power Flow,KVA

Line No	Sending node	Receiving node	Power flow, kVA		
			R-Phase	Y-Phase	B-Phase
1	2	5	0	833.1581	454.2414
2	2	3	337.1175	260.2069	260.3597
3	3	4	336.3049	259.8084	259.8087
4	5	6	0	460.6744	453.3969
5	1	2	2518.749	2398.901	2205.078
6	9	11	268.428	0	100
7	2	7	2156.865	1335	1562.295
8	7	9	269.159	0	238.8915
9	7	8	0	0	0
10	7	12	1123.812	151.4317	452.3554
11	9	10	0	0	325.7784
12	12	13	863.6988	151.4321	532.5433

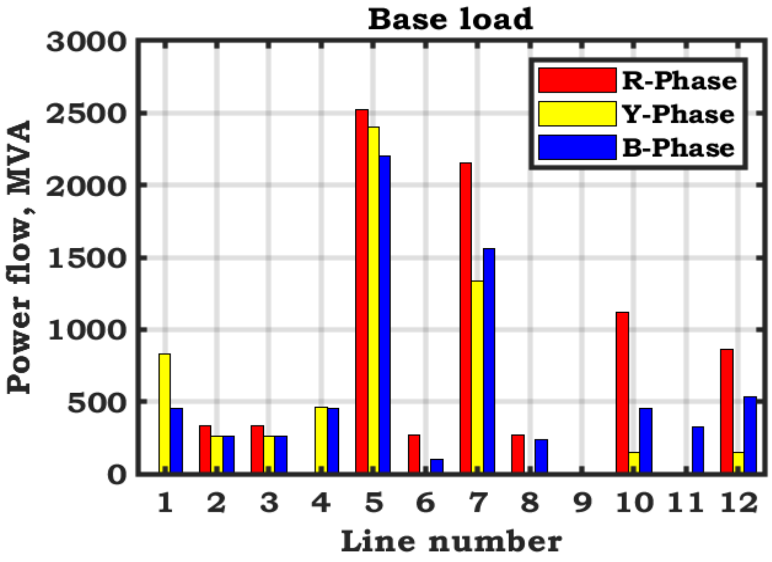

Fig 4: Graphical Representation for Apparent Power

The Table.3 illustrates the Power losses of the system Active Power losses, reactive power losses and other parameters such as Minimum node voltage and No .of. Iterations.

From the table.4.3. Total power losses are determined, Total active power losses are 111.3776 kW. Minimum Voltage is occurred at node-13.

Table 3.Total Power Losses, kW

Parameters	R-Phase	Y-Phase	B-Phase
Total active power losses, kW	41.72271	7.614791	62.04006
	111.3776		
Total reactive power losses, kVAr	155.19	34.82725	80.94109
	270.9583		
Minimum voltage node	13	1	13
Minimum voltage, p.u.	0.971839	1	0.968062
Number of iterations	6		

Case-2:

In case-2, the voltage magnitude and other system parameters of the base load are compared with voltage magnitude and other system parameters of Light load.

- From results it is observed that voltage magnitude in light load case is decreased compared to the base load.
- Minimum voltage is obtained at the node-13.
- The voltage magnitudes in all phases are decreased under Light load condition.

The voltage magnitude results are shown in the Table 4 and its graphical representation is shown in Fig 5.

Table 4: Voltage magnitude for Light load compared with Base load

Node No	Voltage magnitude, p.u.					
	Base load			Light load		
	R-Phase	Y-Phase	B-Phase	R-Phase	Y-Phase	B-Phase
1	1	1	1	1	1	1
2	1.020737	1.041848	1.017071	1.018976	1.040708	1.018295
3	1.018277	1.040253	1.014919	1.016392	1.038864	1.016104
4	1.018272	1.04025	1.014915	1.016387	1.03886	1.0161
5	0	1.031475	1.015181	0	1.029517	1.016335
6	0	1.028436	1.013328	0	1.026256	1.014392
7	0.987623	1.036842	0.973828	0.978926	1.033398	0.980286
8	0.987623	1.036842	0.973828	0.978926	1.033398	0.980286
9	0.984941	0	0.97345	0.975938	0	0.981892
10	0	0	0.972387	0	0	0.982831
11	0.980049	0	0	0.971225	0	0
12	0.987612	1.036845	0.973828	0.978912	1.033401	0.980283
13	0.971839	1.040706	0.968062	0.964352	1.036673	0.975165

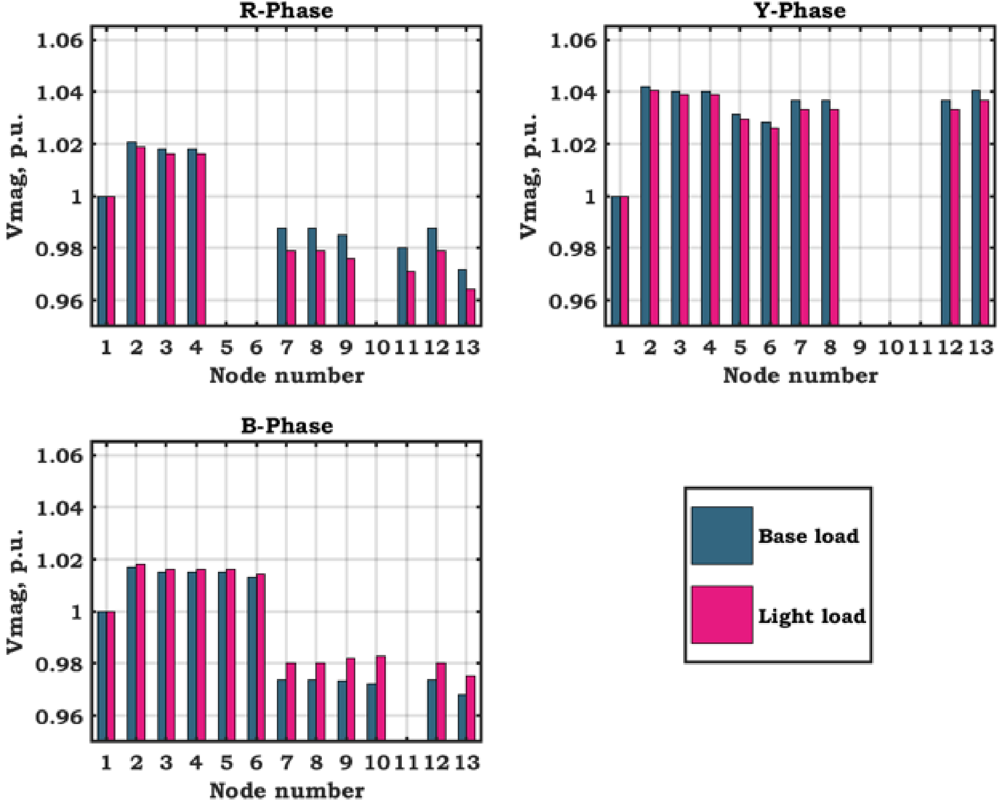

Fig 5: Graphical Representation for Voltage magnitudes of light load

Similarly, the apparent power flow results for light load compared with Base load are tabulated in the Table 5. and the entire results are shown in the Fig 6.

From the table it is observed that apparent flow increased in all phases in light load case.

Table 5: Apparent Power Flow, KVA

Line No	Sending node	Receiving node	Power flow, kVA					
			Base load			Light load		
			R-Phase	Y-Phase	B-Phase	R-Phase	Y-Phase	B-Phase
1	2	5	0	833.1581	454.2414	0	895.1173	486.9224
2	2	3	337.1175	260.2069	260.3597	352.3968	287.1677	270.1255
3	3	4	336.3049	259.8084	259.8087	351.5033	286.6589	269.5443
4	5	6	0	460.6744	453.3969	0	492.2885	485.9853
5	1	2	2518.749	2398.901	2205.078	2699.78	2579.622	2195.963
6	9	11	268.428	0	100	255.621	0	100
7	2	7	2156.865	1335	1562.295	2315.549	1417.108	1537.286
8	7	9	269.159	0	238.8915	256.4037	0	277.0552
9	7	8	0	0	0	0	0	0
10	7	12	1123.812	151.4317	452.3554	1175.261	151.3996	697.6917
11	9	10	0	0	325.7784	0	0	305.0783
12	12	13	863.6988	151.4321	532.5433	810.1858	151.4	490.104

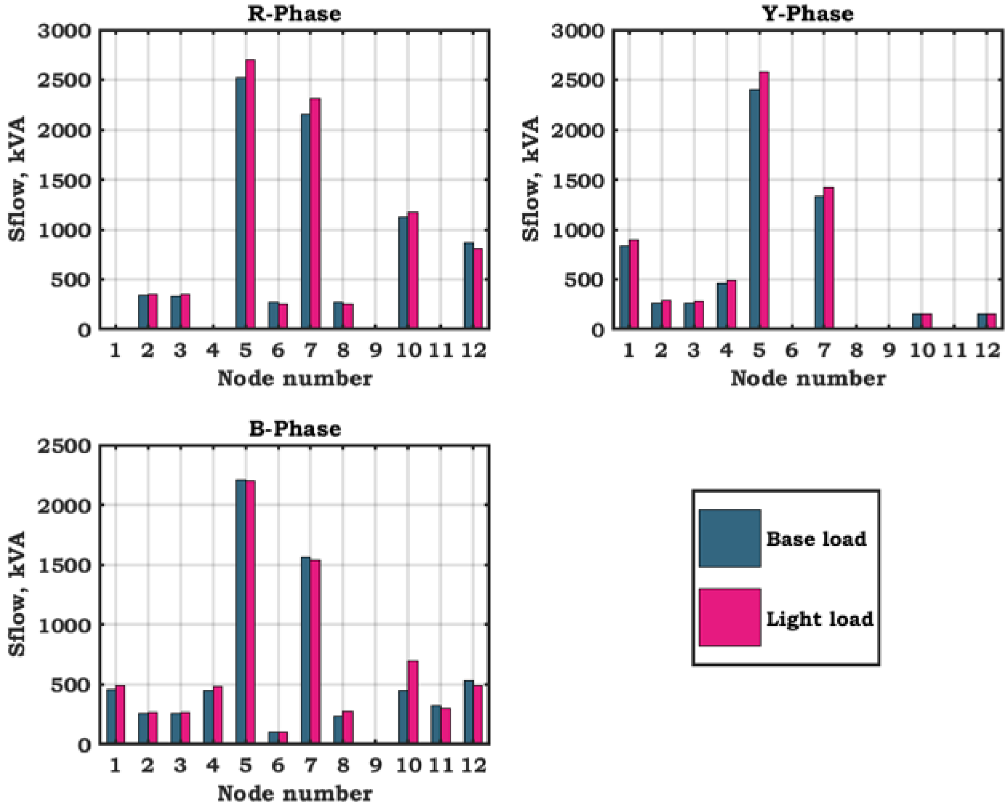

Fig 6: Graphical Representation of Apparent flow

Table 6 show the total power losses of light load compared with Base load. From the table total active power losses are 116.1809 kW. It is observed that Active power losses are increased for light load case. We can say that minimum voltage can cause more power losses in the system.

Table 6: Total Power losses, kW

Parameters	**Base load**			**Light load**		
	R-Phase	**Y-Phase**	**B-Phase**	**R-Phase**	**Y-Phase**	**B-Phase**
Total active power losses, kW	41.72271	7.614791	62.04006	54.90254	4.629178	56.64914
	111.3776			116.1809		
Total reactive power losses, kVAr	155.19	34.82725	80.94109	168.8408	49.01955	70.49895
	270.9583			288.3593		
Minimum voltage node	13	1	13	13	1	13
Minimum voltage, p.u.	0.971839	1	0.968062	0.964352	1	0.975165
Number of iterations	6			6		

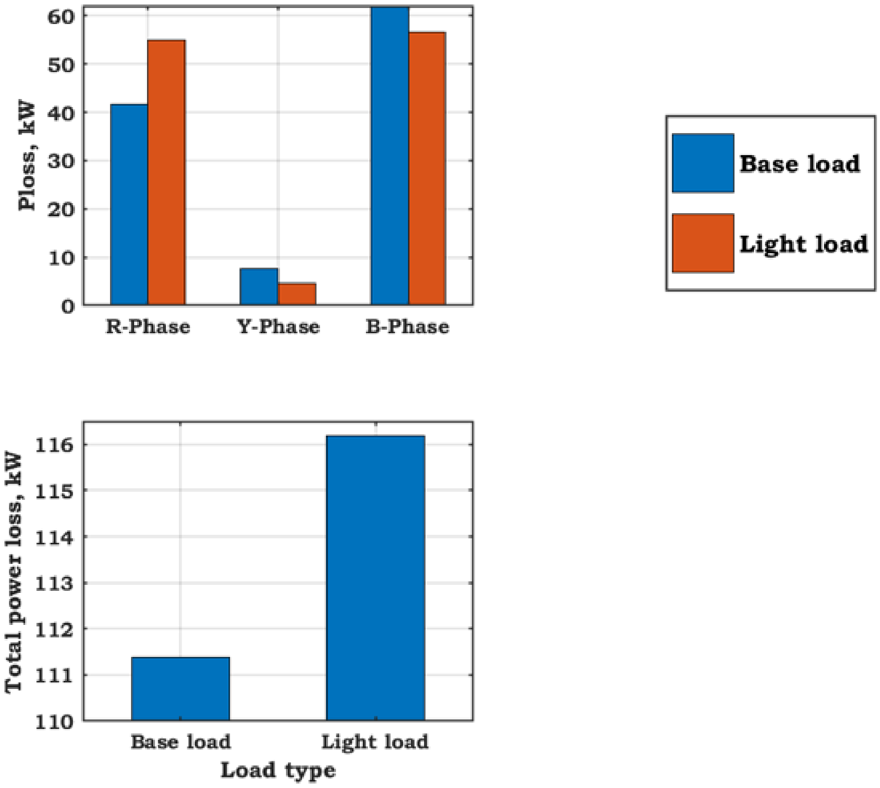

Fig 7: Graphical Representation

From Table 6. it is observed that Total Power losses are increased in Light Load case.

5. Conclusion and Future Scope

In this paper the analysis of the 13-node Un-balanced Radial Distribution System is done and detailed representation is presented in graphical form. The analysis presents the power and voltage magnitudes for the complete distribution system. And the load flow analysis of the system is based on the backward forward sweep method. Starting with calculating the load currents and line currents and next to that voltage drops and power loss will be calculated. After the complete calculations are done these are analyzed with light load also. During this process the voltage magnitude changes at any node . To compensate that change or to improve the voltage magnitude the compensation methods are recommended in the future work. .

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