

Analysis of the Effect of Increasing Load on Voltage Profile in Electric Power Distribution System

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Abstract

Power distribution systems are critical in delivering electricity reliably, but they are highly susceptible to voltage quality degradation due to uneven load growth. The research problem addressed in this study is how increasing loads affect the voltage profile and power losses in a distribution system, particularly in scenarios of rapid demand growth. The objective of this study is to analyze the impact of load increases on voltage levels and system efficiency in the IEEE 33-bus distribution network. The study employs a quantitative simulation method using the Newton-Raphson power flow technique in PSAT, integrated with MATLAB. Load scenarios were simulated at 25%, 50%, 75%, 100%, 125%, and 150% of the base load. Results indicate that as load increases, voltage levels at several buses, especially those farthest from the source, decrease significantly. The minimum system voltage drops from 11.55 kV under initial conditions to 9.39 kV at a 150% load increase, resulting in a voltage drop of up to 25.8%. Furthermore, both active and reactive power losses increase with higher load levels, indicating reduced system efficiency. The study implies that distribution networks like the IEEE 33-bus system require mitigation strategies, such as voltage regulation and loss reduction measures, to maintain voltage quality and energy efficiency under high load conditions.

INTRODUCITON

Modern electric power systems rely on transmission and distribution lines to transport energy from often remote generating plants to load centers (Lin, Zhou, & Wang, 2023). Although designed for optimal performance, the vast scale of the network presents various operational challenges, including voltage profile degradation, increased power losses, and the potential for reduced overall system stability (Ahmed, Khan, & Rahman, 2018).

As energy demand grows, the load on the distribution system also continues to increase significantly (Abebe, Kumar, & Tesfaye, 2025). This increased load puts pressure on crucial components such as transformers and conductors, ultimately resulting in voltage drops across the network (Dolatabadi, Ghorbanian, Siano, & Hatziargyriou, 2020). If this load growth is not matched by adequate capacity development, various serious problems can arise, ranging from voltage drops beyond tolerance limits, phase imbalances, and an increased risk of system disruptions (Chakraborty & Das, 2020).

Therefore, maintaining voltage stability is one of the most crucial aspects of distribution system operation (Eltamaly, El-Sayed, & Elghaffar, 2019). An ideal system should be able to maintain voltage levels within specified tolerance limits, despite load fluctuations (Moghavvemi & Faruque, 2020). Factors such as line impedance, imbalances, and uneven loading can cause voltage deviations, especially at buses located far from the source (Garcia, Martinez, & Santos, 2022). Therefore, analyzing the impact of increased load on the voltage profile is crucial to ensure power quality is maintained and the system operates reliably and efficiently (Abadia Gomez, 2019).

This research will analyze the impact of increased load on the voltage profile in a distribution system. The case study uses an IEEE 33 bus network, a common representation of a radial

distribution system. The analysis is conducted under various load scenarios, ranging from normal conditions to 150%. Power flow simulations are performed using the Newton-Raphson method through the Power System Analysis Toolbox (PSAT) integrated into Matrix Laboratory (MATLAB) software (Kumar, Singh, & Sharma, 2020).

Several previous studies have confirmed the negative impact of increasing loads on power system performance (Kumar, Mandal, & Chakraborty, 2025). A study by Mochamad Ifan Mashudi et al. (2023) explained a significant inverse relationship between nominal load and voltage profile, where load fluctuations also directly cause voltage fluctuations in the feeders. The study also identified that the highest probability of system disruption occurs during peak load conditions (Liu, Wang, & Zhang, 2024). Meanwhile, Humena et al. (2020), in their analysis of the 150 kV Gorontalo system, found that continued load growth can lead to increased power losses and even exceed the power supply capacity of the generator.

Unlike previous studies, this study will conduct a more structured and generalizable analysis. Unlike previous studies that used specific real-world systems, this study uses the IEEE 33 bus standard distribution system (Murthy, Raju, & Ravindra, 2023). The use of this standard system aims to provide a more general reference for the behavior of radial distribution networks. Furthermore, this study will analyze the impact of six different load increase scenarios (25% to 150%) incrementally, a stepwise approach not detailed in previous studies, to map the voltage profile in greater detail.

The objective of this study is to analyze the impact of increasing load on the voltage profile and system efficiency in an electrical distribution network, specifically using the IEEE 33-bus model as a representation of a radial distribution system. The benefits of this study is contribute to the literature on power distribution system analysis using IEEE 33-bus simulations, providing a general reference for other radial distribution networks.

METHOD

In general, electric power distribution networks are dominated by radial structures. This topology offers simplicity in analysis and lower construction costs compared to other configurations, especially for distribution distances that are not too long. In a radial system, power flows unidirectionally from a single main source bus to the load buses. This characteristic allows the representation of medium-voltage overhead lines (UMV) as a pure series impedance, ignoring the influence of the relatively short line capacitance. The following is an image of a radial distribution system.

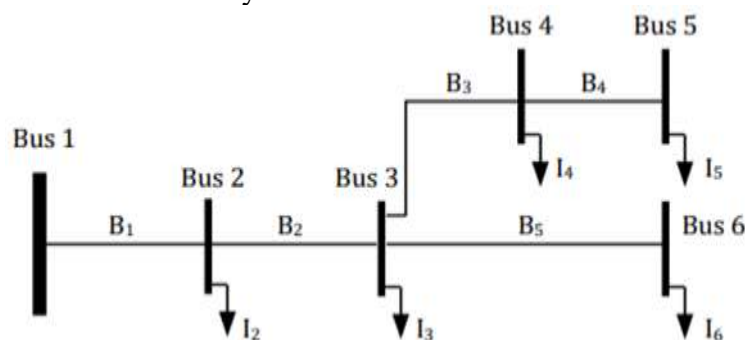


Figure 1. Simple Radial Distribution Network

Voltage Drop

Standard voltage, or nominal voltage, is a key reference value in electrical power systems used to design, operate, and protect equipment. To ensure global harmony and safety of electrical systems, these voltage values are regulated by international standards. One of the main standards used as a global reference is IEC 60038, published by the International Electrotechnical Commission (IEC), a global standardization body in the field of electricity and electronics. The division of standard voltage drops can be seen in the following table.:

Table 1. Voltage Setting and Voltage Drop

Highest Voltage for Equipment (kV)	Nominal System Voltage (kV)
3.6	3.3 / 3
7.2	6.6 / 6
12	11 / 10
24	22 / 20
36	33 / 30

Based on the table above, the voltage drop allowed by IEC for the IEEE 33 bus system is $\pm 10\%$. The calculation of the voltage drop that occurs can use the formula [3]:

$$\Delta V = V_s - V_r \tag{1}$$

$$V_{drop} = \frac{V_s - V_r}{V_s} \times 100\% \tag{2}$$

Where:

ΔV = Voltage drop (V)

V_s = Voltage on sending side (kV)

V_r = Voltage on receiving side (kV)

V_{drop} = Voltage drop regulation (%)

Power Flow Study

Power flow analysis plays an essential role in planning, designing extensions, and determining the most optimal operating conditions in an electric power system. The main objective of this study is to calculate two key parameters: first, the magnitude and phase angle of the voltage at each bus; second, the active and reactive power flows through each transmission line. Among the various methods available, the three most frequently applied approaches are the Gauss-Seidel, Newton-Raphson, and Fast-Decouple methods.

Bus Admittance Matrix

The bus admittance matrix (Y_{bus}) is a mathematical representation of all interconnected components in an electric power system. This matrix, which is always symmetrical, is created to simplify system analysis. The size of this matrix is determined by the number of buses in the system. With this matrix, the system voltage equation can be expressed in matrix form as follows:

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_i \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ Y_{ij} & Y_{ij} & \cdots & Y_{ii} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_i \end{bmatrix} \tag{3}$$

Where:

n = Total number of buses

Y_{ii} = All admittances connected on the i bus (p.u)

Y_{ij} = Admittance connected between bus i and bus j (p.u)
 V_i = Voltage on bus i (p.u)
 I_i = Current on bus i (p.u)

or

$$I_{bus} = Y_{bus}V_{bus} \quad (4)$$

Where:

I_{bus} = Bus current vector (p.u)
 Y_{bus} = Bus admittance matrix (\mathcal{U})
 V_{bus} = Bus voltage vector (p.u)

The diagonal element of each bus is the sum of the admittances connected to that bus. This is usually referred to as self-admittance, namely:

$$Y_{ii} = \sum_{j=0}^n y_{ij} \quad j \neq i \quad (5)$$

The off-diagonal element is the negative of the admittance between the two buses. It is usually referred to as mutual admittance, that is:

$$Y_{ij} = Y_{ji} = -y_{ij} \quad (6)$$

Newton Raphson Power Flow

The Newton-Raphson method has superior convergence characteristics compared to the Gauss-Seidel method, especially when applied to large-scale power systems. The equations for bus voltage and line admittance in polar form are as follows [8]:

$$Si^* = Pi - jQi = Vi^*Ii \quad (7)$$

And the current on bus i:

$$I_i = \frac{P_i - jQ_i}{V_i^*} \quad (8)$$

It is positive when the current flows into the bus and negative when the current flows out. If the shunt element is not included in the matrix, then the total current at bus p is:

$$I_i = \frac{P_i - jQ_i}{V_i^*} - Y_i V_i \quad (9)$$

Where:

Y_i = total shunt admittance at bus i
 $Y_i V_i$ = shunt current flowing from bus i to ground

The current flowing on bus i:

$$I_i = \sum_{j=1}^n V_j y_{ij} \quad (10)$$

In polar form:

$$I_i = \sum_{j=1}^n |Y_{ij}| |V_j| \angle \theta_{ij} + \delta_j \quad (11)$$

Complex power:

$$P_i - jQ_i = V_i^* I_i \quad (12)$$

Substitute equation (11) at bus I_i with equation (12):

$$P_i - jQ_i = |V_i| \angle -\delta_j \sum_{j=1}^n |Y_{ij}| |V_j| \angle \theta_{ij} + \delta_j \quad (13)$$

Then separate P_i and Q_i :

$$P_i = \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad (14)$$

$$Q_i = -\sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad (15)$$

In the equation above, the voltage is in p.u, and the voltage phase angle is in radians. Before explaining the Newton-Raphson method for nonlinear equations in the form of n variables, the nonlinear equation for a single variable is first described as follows:

$$\begin{bmatrix} \Delta P \\ \dots \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & \vdots & J_2 \\ \dots & \vdots & \dots \\ J_3 & \vdots & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \dots \\ \Delta |V| \end{bmatrix} \quad (16)$$

where the subvector of angle increments is located at the P-V and P-Q buses. The variables related to the change in voltage magnitude $\Delta|V|$ at the P-Q buses are divided by $|V|$. As can be seen, this will result in symmetric elements in the coefficient matrix. The submatrices J1, J2, J3, and J4 represent the negative partial derivatives of $[\Delta P]$ and their respective V values.

The new calculation for the phase angle and bus voltage is:

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \quad (17)$$

$$|V_i^{(k+1)}| = |V_i^{(k)}| + \Delta |V_i^{(k)}| \quad (18)$$

RESULTH AND DISCUSSION

System Analysis IEEE 33 Bus

The parameters of the standard IEEE 33-bus distribution system consist of 32 load buses and 1 source bus (generator) (Piyapong & Sirisamphan, 2025). This system operates at a nominal voltage of 12.66 kV, with a system frequency of 50 Hz, and a base power of 100 MVA. Based on the calculation results of the IEEE 33-bus system above, the voltage comparison of the IEEE 33-bus system for each load increase scenario is shown in Table 2.

Table 2. Bus Voltage Comparison IEEE 33 Bus System

Bus	Load Increase (%)	0	25	50	75	100	125	150
1	Voltage (kV)	12.66	12.66	12.66	12.66	12.66	12.66	12.66
2		12.62	12.61	12.60	12.59	12.58	12.57	12.55
3		12.44	12.38	12.32	12.26	12.19	12.12	12.04
4		12.35	12.26	12.17	12.08	11.98	11.87	11.75
5		12.25	12.14	12.03	11.90	11.77	11.63	11.47
6		12.02	11.84	11.66	11.46	11.25	11.02	10.77
7		11.98	11.79	11.59	11.37	11.15	10.90	10.63
8		11.80	11.56	11.31	11.04	10.76	10.44	10.10

Bus	Load Increase (%)	0	25	50	75	100	125	150
9		11.72	11.46	11.18	10.89	10.57	10.23	9.85
10		11.65	11.37	11.07	10.75	10.40	10.03	9.61
11		11.64	11.35	11.05	10.73	10.38	10.00	9.58
12		11.62	11.33	11.02	10.69	10.33	9.95	9.52
13		11.54	11.23	10.89	10.54	10.16	9.74	9.27
14		11.51	11.19	10.85	10.48	10.09	9.66	9.18
15		11.49	11.17	10.82	10.45	10.05	9.61	9.12
16		11.48	11.14	10.79	10.41	10.01	9.56	9.07
17		11.45	11.11	10.75	10.36	9.95	9.49	8.98
18		11.44	11.10	10.74	10.35	9.93	9.47	8.96
19		12.62	12.60	12.59	12.58	12.57	12.55	12.54
20		12.57	12.55	12.52	12.50	12.47	12.45	12.42
21		12.56	12.54	12.51	12.48	12.46	12.43	12.40
22		12.55	12.53	12.50	12.47	12.44	12.41	12.38
23		12.40	12.33	12.25	12.18	12.10	12.01	11.92
24		12.31	12.22	12.13	12.03	11.92	11.81	11.69
25		12.27	12.17	12.06	11.95	11.83	11.71	11.58
26		12.00	11.81	11.62	11.41	11.19	10.95	10.69
27		11.96	11.77	11.57	11.35	11.12	10.87	10.59
28		11.82	11.58	11.34	11.08	10.80	10.49	10.16
29		11.72	11.45	11.17	10.88	10.56	10.22	9.84
30		11.67	11.39	11.10	10.79	10.46	10.10	9.71
31		11.62	11.33	11.02	10.69	10.34	9.96	9.54
32		11.61	11.31	11.00	10.67	10.32	9.93	9.51
33		11.60	11.31	11.00	10.66	10.31	9.92	9.50

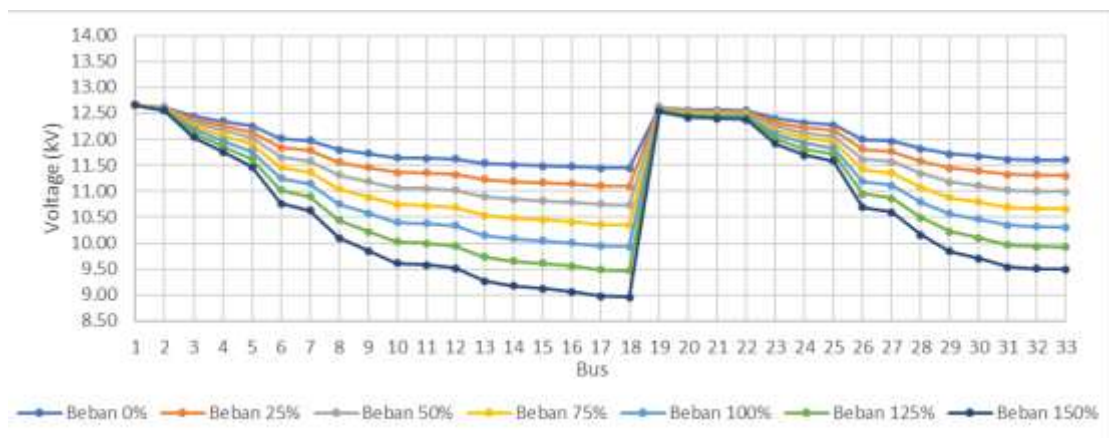


Figure 2. Bus Voltage Comparison Chart IEEE 33 Bus System

The minimum bus voltage under the initial condition is 11.44 kV with a voltage drop percentage of 9.62%, occurring at bus 18. At a 25% load increase, the minimum bus voltage is 11.10 kV with a voltage drop percentage of 12.32%, occurring at bus 18 (Pradhan & Mohanty, 2021). At a 50% load increase, the minimum bus voltage is 10.74 kV with a voltage drop percentage of 15.20%, occurring at bus 18. At a 75% load increase, the minimum bus voltage is 10.35 kV with a voltage drop percentage of 18.26%, occurring at bus 18. At a 100% load increase, the minimum bus voltage is 9.93 kV with a voltage drop percentage of 21.57%, occurring at bus 18 (Rahman, Ahmed, & Khan, 2023). At a 125% load increase, the minimum bus voltage is 9.47 kV with a voltage drop percentage of 25.20%, occurring at bus 18. At a 150% load increase, the minimum bus voltage is 8.96 kV with a voltage drop percentage of

29.24%, occurring at bus 18 (Singh, Kumar, & Sharma, 2021). The comparison of total power losses in the IEEE 33-bus system is shown in Table 3.

Table 3. Comparison of Total Power Losses IEEE 33 Bus System

Load Increase (%)	Total Power Losses (MW)	Total Power Losses (Mvar)
0	0.21099	0.14303
25	0.34436	0.23363
50	0.51982	0.35298
75	0.74515	0.50650
100	1.03090	0.70153
125	1.39239	0.94876
150	1.85337	1.26481

Based on Table 3, the total active power loss under the initial condition is 0.21099 MW, while the total reactive power loss is 0.14303 Mvar (Sharma, Ghosh, & Varma, 2018). At a 25% load increase, the total active power loss is 0.34436 MW, and the total reactive power loss is 0.23363 Mvar. At a 50% load increase, the total active power loss is 0.51982 MW, while the total reactive power loss is 0.35298 Mvar. At a 75% load increase, the total active power loss is 0.74515 MW, while the total reactive power loss is 0.50650 Mvar. At a 100% load increase, the total active power loss is 1.03090 MW, while the total reactive power loss is 0.70153 Mvar. At a 125% load increase, the total active power loss is 1.39239 MW, while the total reactive power loss is 0.94876 Mvar. At a 150% load increase, the total active power loss is 1.85337 MW, while the total reactive power loss is 1.26481 Mvar (Raju & Bijwe, 2014).

CONCLUSION

The analysis and simulation of the IEEE 33-bus system with load variations from 0% to 150% yield several critical conclusions. First, load increase directly causes degradation of the system's voltage profile, with the most significant voltage drops observed at buses located far from the source, particularly buses 18 and 33. This downward trend is predominantly found on the right-hand radial path of the system. Consequently, when the load reaches 150%, the system's minimum voltage drops to 8.96 kV (a 29.24% voltage drop), a value below the minimum tolerance limit specified by IEC 60038 standards. This indicates the system's inability to maintain voltage stability. Furthermore, load increase is directly proportional to the rise in both active and reactive power losses, which reduces operational efficiency. Therefore, technical interventions such as reactive power compensation or network reconfiguration are required to reduce losses and improve system performance under high-load conditions.

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