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MINIMIZING POWER LOSSES IN DISTRIBUTION NETWORKS THROUGH VOLTAGE UPGRADING: A CASE STUDY APPROACH

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Abstract

Various mechanisms can be implemented to address the rapid growth in electricity consumption and ensure the sustainability of the power supply. One of the key strategies adopted by the Ministry of Electricity in the Kurdistan Region to mitigate these challenges is the transition from 11 kV feeders and 11/0.416 kV transformers to a more robust system using 33 kV feeders and 33/0.416 kV transformers. This conversion is expected to enhance the overall performance of the distribution network by reducing voltage drop, minimizing feeder loading, and lowering power losses. To assess the impact of this voltage upgrade, a detailed network analysis is conducted, focusing on key performance indicators such as voltage stability, feeder utilization, and power efficiency. The study presents a comparative evaluation of voltage drop and power losses before and after the implementation of the 33 kV system. Load flow analysis is performed using the Electrical Transient Analyzer Program (ETAP) software, which allows for accurate modelling and simulation of the distribution network's behaviour under different operating conditions. The findings of this research provide valuable insights into the benefits of upgrading the distribution network voltage and serve as a reference for future network expansion plans in rapidly growing urban areas. By implementing higher voltage levels, the distribution system can better accommodate increasing demand while improving overall efficiency and reducing technical losses. With a voltage upgrade, the rate of power losses is reduced by 65%.

Keywords: 33 kV system, Loss minimisation, Power losses, Voltage drop, Voltage upgrade.

1. Introduction

The rapid increase in electricity demand poses significant challenges to distribution networks, particularly in densely populated urban centres where the number of high-rise buildings is continually increasing. As cities expand vertically, the strain on existing distribution infrastructure grows, necessitating innovative approaches to maintain efficiency, reliability, and stability in power delivery. During the last decades, there has been a huge expansion in the distribution networks of Duhok city, Iraq, due to a change in construction styles and standards. Previously, all the residential buildings were horizontal, and using vertical buildings for residency was unusual. Currently, several modern cities with vertical buildings have been constructed, and many are under construction or are in the master plan of the city to be constructed soon. Accordingly, there is a rapid growing in the demand load. Therefore, the traditional solutions such as reconfiguration, load balancing, and capacitor placement are unable to meet this rapid growth [1]. Other conventional methods include adding several 11 kV feeders and also constructing a new 132/33/0.416 substation, which is very costly compared to the proposed 33 kV system [2]. Moreover, the availability of land for the new substations and the path for the new feeders is another challenge to meet the fast increase in the load demand. Several studies have confirmed the effectiveness of this kind of conversion [3].

A study confirmed that the voltage upgrade technique has a direct and great impact on voltage improvement and loss reduction of the distribution system [4]. With the voltage upgrading, the voltage level of the existing system is increased to a higher level, such as changing an 11 kV system to a 33 kV system, and so on. The higher voltage system requires less current for the same amount of the load, and hence the power losses are lower since the losses are directly proportional to the square of the current [5]. Therefore, this method has a significant positive influence on power loss minimisation and voltage profile improvement [6, 7]. Another study states that moving from 11 kV to 33 kV allows for approximately nine times the power density over the same conductor size if thermal limits permit [8, 9].

Moreover, it has been shown by a study conducted in Basra, Iraq, that by replacing 11 kV lines and 33/11/0.416 kV transformers with 33 kV lines and 33/0.416 transformers, the total power losses of a defined part of the distribution network are reduced from 7.33% to 2.82% of the total supplied real power. In addition, voltage upgrading increases the handling capability of the distribution network [1]. The study has demonstrated that if 10% of the system voltage is increased, the power losses of the network would be decreased by 17.3%. On the other hand, a study conducted in Ireland about changing the voltage level from 10 kV to 20 kV showed an improvement in the voltage profile was 50%, increased the thermal capacity of the conductors, and reduced the power losses by 75% [10, 11].

The voltage upgrade technique has emerged as a high-impact strategy for improving voltage profiles and reducing technical losses in distribution systems [12]. By increasing the operating voltage from 11 kV to 33 kV, the system requires less current to deliver the same amount of power. Since power losses are proportional to the square of the current, this transition significantly minimises energy dissipation as $P_{loss} = I^2 * R$, where P_{loss} is the power losses, I is the current, and R is the conductor resistance.

Regarding the technical simulations, recent studies on metropolis networks show that upgrading 11 kV feeders can result in a 49% reduction in technical losses and improve average bus voltages to 0.99% [13]. On the other hand, a study in Ireland documented a 50% improvement in voltage profiles and a 75% reduction in power losses when upgrading from 10 kV to 20 kV [14].

In addition to loss reduction, voltage upgrading increases the handling capability and thermal capacity of existing conductors, making it a vital tool for the sustainability and resilience of modern vertical cities [15, 16]. Beyond efficiency, the upgrade provides a critical improvement to the voltage profile, which directly enhances power quality for end-users. In a standard radial distribution network, voltage drop occurs as current travels through the impedance of the line. By shifting to 20 kV, the voltage drop is effectively reduced by 50%, ensuring that customers at the end of long rural feeders receive a stable voltage within statutory limits [17]. This stability is increasingly important as the grid integrates distributed generation, such as residential solar PV, which can otherwise cause local voltage fluctuations. As of late 2024, ESB Networks reported the successful conversion of over 378 kilometres of the medium-voltage network in a single year, underscoring the ongoing scale of this national infrastructure project [17].

Recent studies utilising IEEE 33-bus simulations in 2025 have highlighted that, as load demand increases, particularly with the rapid growth of electric vehicle charging and heat pump integration, traditional 10 kV systems are prone to voltage sags reaching up to 25.8% at the end of long feeders [18]. The researchers concluded that power lines at 20 kV are significantly more efficient. Specifically, doubling the voltage from 10 kV to 20 kV reduces line current by half, which results in an approximate 75% reduction in active power losses. The study finds that a 20 kV network can deliver up to four times more power than a 10 kV network over the same distance, effectively doubling the service radius of substations. Higher voltage systems reduce the need for extensive new infrastructure. Because 20 kV lines have a smaller "protected zone" compared to 35 kV lines, they require less land clearing and have a lower environmental footprint [19].

During the last decades, there has been a huge expansion in the distribution networks of Duhok city, Iraq, due to a fundamental change in construction standards. Historically, residential buildings in Duhok were horizontal; however, several modern high-rise complexes are currently under construction or integrated into the city's future master plan. In 2021, the average demand in Duhok reached 1500 MW during peak winter months, while the supplied electricity averaged only 637.44 MW, highlighting a critical shortage [20].

This study aims to simulate, analyse, and compare the voltage drop and power losses in the distribution system of a residential development known as AVRO City Complex, located in Duhok City, Iraq. The complex is supplied by two 33 kV feeders, with Feeder 1 (F1) having an installed capacity of 13.2 MVA and situated approximately 1.6 km from the Tanahee 132/33 kV substation. For this study, the actual operational load is assumed to be 20% of the installed capacity, based on historical data and insights provided by the Duhok Electricity Directorate.

In addition to the case study, this research examines the broader benefits of upgrading medium-voltage distribution networks from 11 kV to 33 kV. The conventional 11 kV system, composed of 11 kV lines and 11/0.416 kV transformers, is compared with an upgraded 33 kV system using 33/0.416 kV transformers. The upgrade is driven by increasing electricity demand, especially in urban areas experiencing vertical expansion and a growing number of residential, commercial, and industrial consumers. As urban density increases, the existing 11 kV infrastructure may no longer ensure reliable and efficient power delivery, thereby justifying the need for transitioning to a more robust 33 kV distribution network.

2. Methodology

The methodology for upgrading the voltage of the electrical network includes several strategies, as illustrated below:

2.1. Existing system background

The main distribution system of the Duhok governorate is its 11 kV distribution network. It extends to all geographic areas of the Governorate and provides a primary connection to all consumers of the system. Hence 11 kV distribution network is considered as the 'core network' for carrying out analysis of the distribution system. MV/LV Distribution Transformers are also considered as a part of the 11 kV primary distribution system when carrying out analysis [21]. Table 1 illustrates the data of the existing 11kV system of Duhok city.

Table 1. Existing 11 kV system of Duhok City [21].

Parameter	Value
Feeders	
No of feeders	389
Total feeder length	5,304 km
Total no of connected consumers	302,181
Distribution transformers	
Total no of connected transformers	10,384
Installed capacity	2,594 MVA
By ownership	
General (Distribution-ministry of electricity)	5,575
Bulk (Private)	3,388
Indicator	
Average length/feeder	13.6 km
Average no of transformers/feeder	23
Average 11 kV length /transformer	512 m
Average consumers /transformer (dist.)	52

AVRO city complex is a residential complex in Duhok city, which was constructed in 2013 using a 33 kV system. This complex has been a part of this study. The project is in Duhok City, Iraq. The feeding of the complex is through two feeders of 33 kV. The installed capacity of the feeder number 1 (F1) is 13.2 MVA, and it is located around 1.6 km from the Tanahee 132/33 kV substation. The 33 kV system is used to feed this project with the power supply. For the study, the project's actual load is about 20% of the installed capacity. This is a percentage proposal based on previous experience and data received from Duhok Electricity Directorate.

2.2. Modelling and simulation

The Electrical Transient Analyser Program (ETAP) was utilised as the primary simulation tool to evaluate the performance improvements associated with upgrading the medium-voltage distribution system from 11 kV to 33 kV. The existing 11 kV network, including overhead lines and 11/0.416 kV distribution transformers, was modelled in ETAP based on actual feeder data, load profiles, and transformer specifications. A parallel model representing the upgraded 33 kV configuration was then developed by adjusting the voltage levels, replacing transformers with 33/0.416 kV units, and modifying conductor parameters accordingly. Both models were simulated under identical load conditions to ensure accurate comparison. The simulation focused on key parameters such as voltage drop, line losses, and loading levels. The results clearly demonstrated that the 33 kV system offers enhanced voltage regulation and significantly reduced power losses, confirming the technical advantages of voltage upgrading for meeting increased demand and improving distribution network performance.

Many consumers in the AVRO complex, located in Duhok City, Iraq, are residential users, along with some additional types of loads. This case study is viewed as a representative example of a typical distribution network. The network has recently been developed, and its voltage level has been upgraded. Figure 1 shows the load flow analysis of feeder no.1 of the AVRO city complex. It shows the voltage of buses, active and reactive power of branches, as well as illustrating the apparent power consumed by the connected loads.

The upper and lower voltage limits for buses and loads are shown in Table 2. It indicates that critical overvoltage and undervoltage occur at 110% and 90% of the nominal voltage, respectively, while marginal overvoltage and undervoltage are defined at 105% and 95%.

Table 2. The upper and lower limits of bus voltages.

Function	Critical	Marginal
Overvoltage	110%	105%
Undervoltage	90%	95%

2.3. Theoretical prediction

There are several factors influencing the voltage drop improvement. The main factors that affect the voltage drop in an AC distribution system are the resistance of the conductor, the length and size of the conductor, the voltage of the system, and the amount of the load.

Eq. (1) demonstrates that the power, P, is directly proportional to the square of the voltage and inversely proportional to the resistance of the conductors.

$$P = \frac{V^2}{R_c} \tag{1}$$

where V is the voltage of the system, and R_c is the resistance of the conductor.

Eq. (2) shows the relations between the factors contributing to the voltage drop.

$$Voltage\ drop = \frac{R*L*I}{A} \tag{2}$$

where R, L, I, and A are the resistance, length, current, and size of the conductor, respectively.

It is obvious from equation 2 that the voltage drop is directly proportional to the resistance, length, and the load of the conductor, and inversely proportional to the size of the conductor.

Improving the voltage drop using the above factors is not applicable, as they can only improve the voltage drop to certain limits. In addition, the capacity of power transmission and distribution systems is not upgraded as required. Therefore, the optimal way to reduce the current and hence improve the voltage is to increase the voltage level.

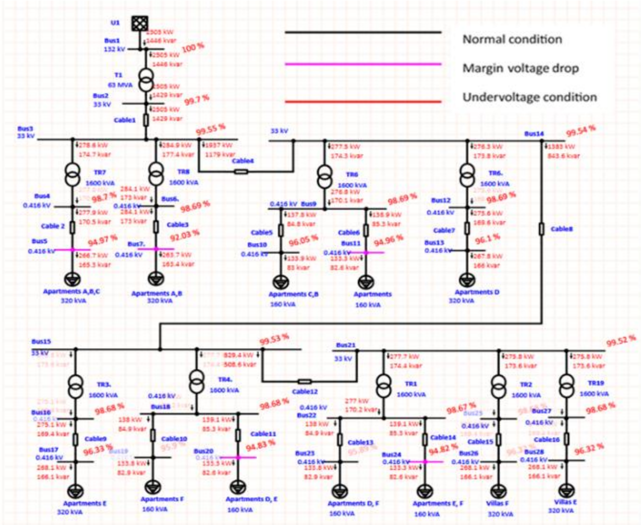

Fig. 1. Load flow of feeder 1-33 kV system.

3. Results and Discussion

This study has been conducted on a small part of the Duhok distribution network. The targeted part of the network is called AVRO city. This city is one of the first residential complexes where the 33 kV system is adopted. In addition to the advantage of voltage profile improvement and power loss reduction, the upgrading of the system voltage increases the system handling capacity and decreases the cost of construction, as the handling capacity of 33 kV lines is three times higher than the handling capacity of 11 kV lines.

3.1. Power losses analysis

Tables 3, 4, and 5 are extracted from the simulation report of ETAP. Table 3 illustrates the information on buses, including the voltage drop and real power loading. It includes data of 132 kV, 33 kV, and 0.416 kV buses. There is no voltage drop in 132 kV and 33 kV buses, while there is a marginal voltage drop in four buses of 0.416 kV. It is clear from Fig. 1 that there are only five buses subjected to a voltage drop of less than 5%, which is called the margin voltage drop.

Table 3. The voltage and loading of buses.

Bus ID	Nominal kV	Voltage	MW Loading
Bus1	132	100	2.505
Bus2	33	99.7	2.505
Bus3	33	99.55	2.501
Bus4	0.416	98.7	0.278
Bus5	0.416	94.97	0.267
Bus6	0.416	98.69	0.284

Bus7	0.416	92.03	0.264
Bus9	0.416	98.69	0.277
Bus10	0.416	96.05	0.134
Bus11	0.416	94.96	0.133
Bus12	0.416	98.69	0.276
Bus13	0.416	96.1	0.268
Bus14	33	99.54	1.937
Bus15	33	99.53	1.383
Bus16	0.416	98.68	0.275
Bus17	0.416	96.33	0.268
Bus18	0.416	98.68	0.277
Bus19	0.416	95.9	0.134
Bus20	0.416	94.83	0.133
Bus21	33	99.52	0.829
Bus22	0.416	98.67	0.277
Bus23	0.416	95.89	0.134
Bus24	0.416	94.82	0.133
Bus25	0.416	98.68	0.275
Bus26	0.416	96.32	0.268
Bus27	0.416	98.68	0.275
Bus28	0.416	96.32	0.268

The loading of cables and transformers is shown in Table 4, which has been extracted from the load flow report.

Table 4. Cable loading.

ID	Type	kW Flow	kVar Flow	Amp Flow	% Loading
Cable1	**Cable**	2500.6	1530.9	51.53	25.7
Cable 2	**Cable**	277.9	170.5	458.5	44.2
Cable3	**Cable**	284.1	173	467.8	45.1
Cable4	**Cable**	1936.8	1191.6	39.97	19.9
Cable5	**Cable**	137.8	84.83	227.6	22
Cable6	**Cable**	138.9	85.26	229.2	22.1
Cable7	**Cable**	275.6	169.6	455.1	43.9
Cable8	**Cable**	1382.9	856.5	28.59	14.2
Cable9	**Cable**	275.1	169.4	454.4	32.9
Cable10	**Cable**	138	84.88	227.8	16.5
Cable11	**Cable**	139.1	85.3	229.4	16.6
Cable12	**Cable**	829.3	521.5	17.22	8.6
Cable13	**Cable**	138	84.88	227.8	16.5
Cable14	**Cable**	139.1	85.3	229.5	16.6
Cable15	**Cable**	275.1	169.4	454.4	32.9
Cable16	**Cable**	275.1	169.4	454.4	32.9
T1	**Transf. 2W**	2505	1445.6	12.65	4.6
TR1	**Transf. 2W**	277.7	174.4	5.765	20.5
TR2	**Transf. 2W**	275.8	173.6	5.728	20.4
TR3	**Transf. 2W**	275.8	173.6	5.728	20.4
TR4	**Transf. 2W**	277.7	174.4	5.764	20.5
TR6	**Transf. 2W**	277.5	174.3	5.759	20.5
TR6	**Transf. 2W**	276.3	173.8	5.736	20.4
TR7	**Transf. 2W**	278.6	174.7	5.779	20.6
TR8	**Transf. 2W**	284.9	177.4	5.897	21
TR21	**Transf. 2W**	275.8	173.6	5.728	20.4

The summarised information for the system is given in Table 5, showing total losses of 101 kW (active) and 44.1 kVar (reactive). The negative sign of the reactive power reflects the presence of capacitive reactive power, which is typical in networks using underground cables. The table also presents the generated power and the total power consumed by the load.

Table 5. Data of the system.

Study ID	Category	Study ID	Category
Study Case ID	LF	**Load-MW**	2.404
Data Revision	Base	**Load-Mvar**	1.49
Configuration	Normal	**Generation-MW**	2.505
Loading Cat	Design	**Generation-Mvar**	1.446
Generation Cat	Design	**Loss-MW**	0.101
Diversity Factor	Normal Loading	**Loss-Mvar**	-0.0441

The percentage of the losses is calculated using Eq. (3).

$$Power\ losses\ (\%) = \frac{\text{Generated power} - \text{Consummed power}}{\text{Generated power}} \quad (3)$$

$$Power\ losses\ (\%) = \frac{2505+j1446-2404-j1490}{2505+j1446} * 100\% = 3.8\% \quad (4)$$

3.2. Simulation results of the 11 kV system

The load flow analysis by ETAP is conducted assuming the utilisation of 11 kV instead of 33 kV, and the voltage profile as well as the power losses are evaluated. Referring to Fig. 2, the number of buses suffering from margin voltage drop has increased to 12 buses.

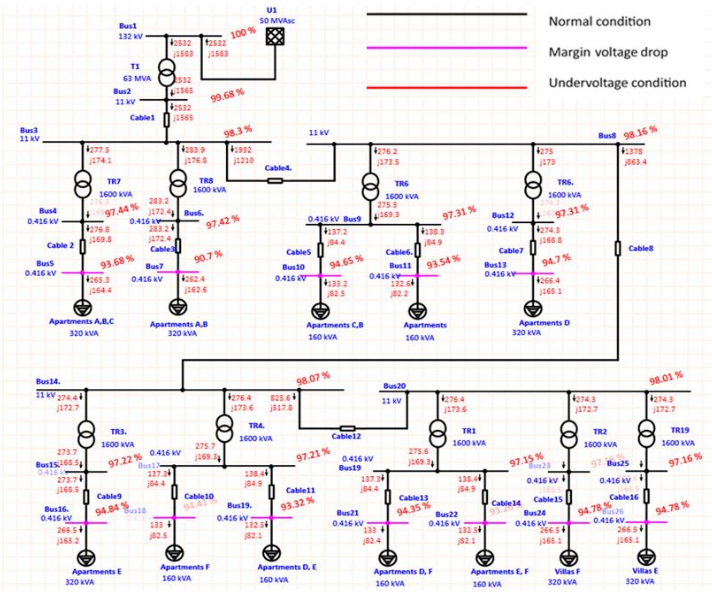

Fig. 2. Load flow analysis of feeder 1-11 kV.

Table 6 shows a summary of extracted data from the load flow of the proposed 11 kV system.

Table 6. Data of the 11 kV system.

Study ID	Category
Study Case ID	LF
Data Revision	Base
Configuration	Normal
Loading Category	Design
Generation Category	Design
Diversity Factor	Normal Loading
Buses	27
Branches	26
Power Grids	1
Loads	12
Load-MW	2.39

Study ID	Category
Load-Mvar	1.481
Generation-MW	2.532
Generation-Mvar	1.583
Loss-MW	0.142
Loss-Mvar	0.101
Branches	26
Power Grids	1
Loads	12
Load-MW	2.39
Load-Mvar	1.481

Based on equation 3 and the data of Table 6, the power losses of the 11 kV system are 5.83%. A significant improvement is clearly observed when comparing the power losses and voltage drop between the 11 kV and 33 kV systems. The number of buses suffering from the drop in voltage is reduced, as well as decreasing the power losses. The study has some limitations that could have influenced the results.

- All loads are assumed to be similar and to consume around 20% of the installed capacity.
- The power factor of all loads is considered 85%.
- The system components, such as transformers, busbars, and cables, are assumed to be according to relevant standards.

4. Conclusion

The study illustrates the influence of changing the system voltage level from 11 kV to 33 kV on both the voltage drop and the rate of the power losses. The possibility of mitigating the voltage drop and reducing power loss in the power system is demonstrated by using the 33 kV system. With an 11 kV system, the number of buses suffering from voltage drop is 12, while this rate decreases to only five buses by utilising the 33 kV system. In addition, the percentage of power losses, which was 5.83% with an 11 kV system, is reduced to 3.80% with the voltage level of a 33 kV system. This shows a reduction in power losses in the distribution system by 65%.

Abbreviations

kV	Kilo Volt
ETAP	Electrical Transient Analyzer Program
MV	Medium Voltage
LV	Low Voltage
km	Kilo Metre
MoE	Ministry of Electricity
KRG	Kurdistan Regional Government
kW	Kilo Watt
kVar	Kilo- volt – ampere- reactive

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