**Methods for Determining and Applying Indicators of Deep Penetration Networks to Increase the Reliability of Urban Power Supply Systems**

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**Abstract:** This article examines methods for assessing the performance of deep penetration networks and their application in enhancing the reliability and efficiency of urban electricity supply systems. The performance of deep penetration networks is considered as a strategy for the development of existing urban networks. A key aspect of the modern and forward-looking development of urban electricity supply is the reduction of energy losses, material consumption, and the number of intermediate network connections, as well as the optimization of the operating modes of electrical loads through the implementation of high-voltage networks.

**INTRODUCTION**

More than 40% of the electricity generated in the country is delivered through urban power supply networks (ETT). These networks have developed into an independent sector of the electric power industry, and ensuring their effective functioning is considered a matter of national significance. Cities serve as the main consumers of electricity, as not only the majority of the population resides there, but many industrial and manufacturing enterprises are also concentrated in urban areas. In connection with this, large cities and major towns have formed various public utility facilities that provide electricity to urban loads and meet the energy needs of major industrial enterprises. Such facilities include large shopping centers, recreational complexes, office buildings, business centers, banks, major sports arenas, advanced medical centers, urban electric transport, water supply and sewage systems, and other infrastructure units. The expansion of cities and the growth of urban populations are accompanied by rapid electrification of municipal services, industry, and manufacturing sectors. As a result, electricity consumption in cities and their surrounding territories increases significantly. Global statistical data on electric energy development indicate that in developed countries, electricity consumption typically doubles every ten years. The substantial growth in electricity usage in the municipal sector is partly due to the increase in the number of high-rise buildings, which reflects more efficient use of developed land areas. Another factor is the growing presence of traditional household electrical appliances, as well as the emergence of new, more energy-intensive electrical devices in daily life [1,2]. When analyzing the rising demand for electricity and the trends in consumption, it becomes clear that a defining feature of modern societal development is the rapid increase in the number of consumers and the urban population. Based on this, it is considered appropriate to use deep penetration (ChK) in energy supply systems implemented in countries with developed energy systems.

**METHODS**

Deep penetration networks. Depending on the ability of deep penetration networks to pass through urban areas, they can be implemented in the form of cable and overhead The placement of deep penetration network substations is determined by the load distribution of existing or planned networks. In single-transformer substations, centralized transformer backup is typically provided, often in the form of one or more transformers serving all substations in the city. In the design of new residential areas, deep penetration networks are usually implemented using configurations with two redundant transformers and dual-transformer schemes. [3].



**FIGURE 1**. Deep access network diagram for urban and industrial enterprises.

In this context, overhead networks with voltages of 35–220 kV are typically configured as two-circuit systems, which are more efficient in urban environments than single-circuit alternatives. Currently, with improvements in technical standards, it is recommended that new urban networks be designed for 10 kV, which may create challenges when integrating new 10 kV networks with existing 6 kV systems. Therefore, the use of deep penetration networks with three-phase transformers rated at 35–110/10/6 kV is advised. However, mass production of such transformers has not yet been established, highlighting the need to develop designs for these configurations. One of the key objectives of modern and forward-looking urban power supply development is to reduce energy losses and material consumption, minimize the number of intermediate network connections, and optimize the operating modes of the power supply system.

Deep introduction is a power supply system in which consumer loads of 35 kV and above are connected with a minimal number of intermediate transformation stages. High-voltage deep integration can be achieved by directly splitting the DC from the main power source into both the DC network and the ring network. [3]. Deep penetration networks in power systems serve several important purposes. Their implementation is linked to the extension of high-voltage transmission lines. Although increasing the length of high-voltage networks raises their construction cost, it significantly lowers the overall cost of medium-voltage networks by reducing their required length. Additionally, this approach makes it possible to complete the the construction of distribution substations and the deployment of 6–10 kV supply networks [3,4].



**FIGURE 2**. Radial schemes of deep access networks used in the city's energy supply system.

City networks should be supplied from the 10 kV city substation bus (1) via a single L-1 line. When the load increases, which can lead to contact corrosion, it becomes necessary to increase the nominal cross-section of the supply networks or their number (up to 10 kV). When using a 35–220 kV deep penetration line, a 35–220/10 kV transformer of the L-2 design with voltage regulation is installed near the contact to mitigate corrosion effects. Under normal operation, the circuit is energized through L-2, while L-1 remains in reserve. The development of this network configuration allows for reductions in both capital and operational costs, as well as decreased consumption of non-ferrous metals and lower energy losses.

The power supply of deep-entry substations can be organized using several types of high-voltage network configurations, including radial systems, trunk networks with one-sided or two-sided power feed, and ring circuits with dual-sided supply. For consumer-type high-voltage networks, substations, and deep-entry networks—such as radial and trunk configurations—the main structural layouts of deep-entry systems commonly used in urban power supply networks are described in the literature [2,3].



**FIGURE 3**. The main types of deep access substation schemes.

a) Radial diagram of a two-transformer deep-entry substation.

b) Trunk diagram of a two-transformer deep-entry substation.

c) Pasta diagram of a two-transformer deep-entry substation.

d) Two-stage ring diagram of a two-transformer deep-entry substation.

e) Single-circuit radial scheme of a single-transformer deep-entry substation.

Practical experience in designing urban power networks indicates that the radial deep penetration scheme (Fig. 6a) is the simplest, easiest to implement, and most widely used option. Constructing deep-entry networks according to the radial-tight principle ensures the required level of reliability. The main deep-entry configuration (Fig. 6b) is generally employed as an extension of radial deep-entry systems in areas with a load density of at least 30 MW/km, a city radius exceeding 15 km, and operating voltages of 220 kV or higher. The other schemes (Fig. 6c, d, and e) are primarily applied in countries with very large power systems.

These configurations are designed to enhance the reliability and energy efficiency of urban electricity supply systems, based on the experience of developed countries, it can be implemented on the basis of a deeply integrated grid (ChKT). In this method, it is carried out by directing the 35 kV voltage from the substations directly to the transformers through overhead and cable networks. Based on this, there is no need to use 6-10 kV overhead and cable networks. As a result, the reliability of the power supply system, the increase of energy efficiency, the reduction of energy waste and the saving of spent funds are achieved. To use this deep penetration network (DPN), it is necessary to create a topological model of the urban power supply system [3.4].

Urban expansion is typically accompanied by the development of new residential buildings, industrial zones, and other infrastructure, which leads to a considerable increase in the physical size of cities. Consequently, this growth necessitates a continuous increase in the capacities of individual generators and the overall output of power plants, as well as higher nominal voltages and greater capacities of power transmission networks. It also requires modernization of electrical equipment and improvements in its operating performance.

The rise in electrical loads and energy consumption within cities demands in-depth analysis and the formulation of appropriate strategies for the development of urban power supply systems (UPS). An urban power supply system refers to the network of electrical lines and transformer substations located within a city’s limits, designed to provide electricity to all consumers. A city's electrical grid encompasses all power facilities located within its territory—from main substations and power plant busbars to the service entrances of individual consumers—designed to ensure reliable electricity supply throughout the city. The configuration of an urban power supply system is influenced by both the scale of the city and the size of its population.

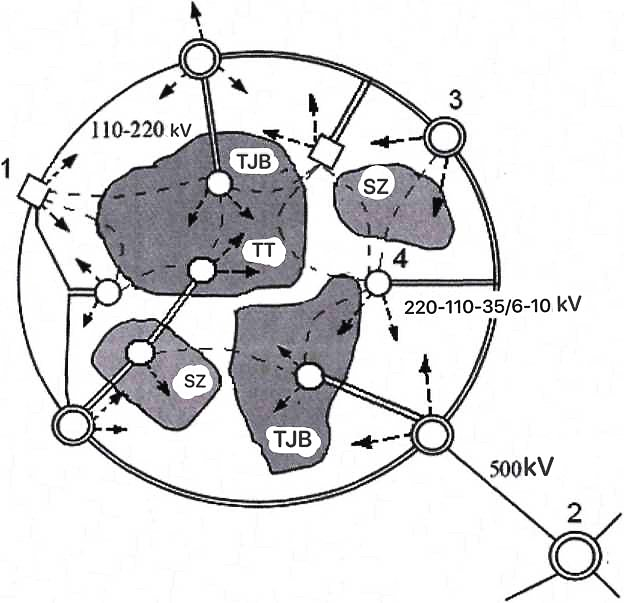
In large cities with high load density, power supply systems typically include five key components in their structural layout:

* the external power supply system of the city;
* high-voltage (220–110–35 kV) deep-entry networks (ChKT), including deep-entry substations (ChKP);
* medium-voltage (6–10 kV) distribution networks with distribution nodes;
* medium-voltage transformers in the distribution infrastructure, including 6–10/0.4 kV transformer substations;
* low-voltage distribution networks (up to 1000 V).

The external power supply system is characterized by the establishment of a ring-shaped power network surrounding the city, which can be considered its supporting base network. This ring is typically formed from high-capacity step-down substations of the main power system operating at primary transmission voltages or inter-system communication lines, from which the deep-entry (CT) networks are supplied. As urban electrical loads grow, the demand on this support ring correspondingly increases [3,4].

Constructing power plants within the urban area becomes necessary when the external power supply faces disruption. Therefore, it is advisable to develop at least several internal generation sources within the city, each possessing sufficient capacity to ensure reliability. When choosing energy sources for individual neighborhoods of large cities and new areas of housing complexes, the specifics of pollutants, compactness of installation, and cost-effectiveness are of decisive importance.

According to modern urban planning standards and sanitary–hygienic requirements, large power plants should not be constructed within the boundaries of major cities. For this reason, significant amounts of electrical energy for large urban areas must be supplied from remote generation sources located outside the city.



*1-thermal power plants (IES); 2-base substation of the electric power system system; 3-base substation of the external power supply system; 4- deep access substation; TT - distribution networks SZ - industrial zones;*

*TJB - residential buildings.*

**FIGURE 4**. Scheme of a large city power supply system.

It is not It is not feasible to create an economically efficient urban power grid using only 6–10 kV for electricity transmission and distribution, since doing so would necessitate installing hundreds of kilometers of 6–10 kV lines from remote generation sources to consumers.Such networks are not possible in a limited area of ​​the city.

In addition, a large amount of non-ferrous metal is consumed in high-power transmission. We will consider this in the following example. Let's calculate how many cables are needed to supply 1 km2 of electricity in an urban area with a surface load density of 30 MVA / km2. The load of this area = 30 MVA. The current flow in a 10 kV transmission line

( 1 )

The power capacity of a cable network is determined by the thermal regime of the insulation. Long-term permissible heating current for 10 kV cables with woven polyethylene insulation and aluminum conductors with a cross section of 240 mm2.

The necessary number of 10 kV cables that ensure the transmission of electricity of the required power in normal and post-fault modes, taking into account the laying conditions, the temperature of the ground, the number of cables laid in one trench, the permissible load of the cables;

=10

The same power can be transmitted at 110 kV with much lower aluminum consumption. Load current in 110 kV power transmission.

(2)

Long-term permissible heating current for 110 kV cables with aluminum conductors and woven polyethylene insulation of cross section 185 mm2

The required number of 110 kV cables that provide the necessary power transmission in normal and post-fault modes;

When using a voltage of 110 kV compared to 10 kV, saving of non-ferrous metal is determined [3].

The advantages of transmission and distribution of high-voltage electrical energy derive from the basic laws of electrical engineering and help to reduce energy losses in electrical networks and structures, increase the conductivity of equipment, and reduce the consumption of electrical energy. Modern world trends in the development of electrical networks indicate the desire of many developed countries to introduce higher voltage classes. Therefore, one of the primary and defining characteristics of modern and future urban electricity supply development is to enhance the role of high-voltage deep access networks and substations in cities.

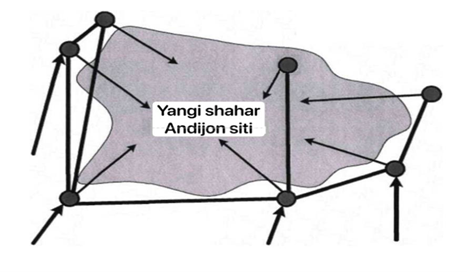
Deep entry substations (DEPs) are located directly at the main consumer distribution centers, meaning that the required power is transmitted directly to the center of high-voltage electrical loads.

Deep penetration (DP) is seen as one solution to the following problem. A large city can be imagined as a large energy circle, with electricity flowing from everywhere. The problem is that not all parts of the city have a strong enough system to provide the city with the electricity it needs.

A strong power system allows for the construction of multiple transmission lines to deliver large amounts of electricity to a city. However, a weak grid connected to a large city is not able to handle the load. Instead, the weak system is powered by the city grid instead of supplying it [3.4].

Based on the given data, this problem can be solved by building deep penetration networks (DCPs) from the strong system to the adjacent areas of the weak system. Considering that the reconstruction of the existing power supply system in large cities takes a lot of time and requires a lot of money, it would be more appropriate to implement it in the power supply systems of newly built cities.

As an example, we can take the newly built city of Andijan.



Andijan city

**FIGURE 5**. Location of deep penetration networks (DPNs) to ensure uniformity

of energy flows to a large city.

Urban power grids should be implemented in a complex, in an interconnected manner, considering all consumers within the city and surrounding areas, using power supply networks of 35 kV and above along with 6–10 kV distribution networks. In general, solar power plants (SPPs) in urban areas should be planned and implemented according to a schedule aligned with the city’s long-term development plan (typically 20–30 years), taking into account the evolving dynamics of key urban data [3,4,5]. Electrical networks should be designed to optimize efficiency, ensure the required reliability of power supply, and comply with established power quality standards.

**RESULTS**

Deep penetration refers to a power supply system that delivers electricity to consumers from the highest voltage class within the electrical network, characterized by a minimal number of transformation stages. It includes supply networks and step-down substations, enabling the transmission of large amounts of power over extensive areas. Deep penetration networks are widely used in external and internal power supply schemes for industrial enterprises and are considered the most progressive power supply schemes.

Using them allows you to:

- placement of deep access substations in large electricity consumption units (electrolysis plants, rolling mills, nitrogen-oxygen stations, etc.);

- with the exception of intermediate distribution devices, since their functions are performed by secondary voltage conductors of deep-entry substations;

- Use of simplified primary switching schemes for ChKP;

- to drastically reduce the length of 6/10 kV power lines, thereby reducing power, energy, and voltage losses, as well as decreasing the length of cable routes and the number of switching and protective devices required;

-reduction of capacitive currents in 6/10 kV networks, which in most cases allows these currents to be carried without compensating devices;

-supplying electricity to specific groups of consumers.

with non-linear, highly variable, and shock loads directly from deep-entry substations through dedicated networks, significantly reducing the impact of these loads on the power supply system and improving the quality of electricity;

- increase the efficiency of the power supply and reduce the capital and operating costs of the system.

The implementation of deep penetration networks is linked to an extension of the high-voltage network. Although this increases the cost of the high-voltage system, it significantly reduces the expenses associated with medium-voltage networks by shortening their required length. Consequently, there is no need to construct additional distribution substations or 6–10 kV supply networks. Deep access refers to an urban power supply system in which the high-voltage supply network is located close to consumer equipment, thereby reducing the number of stages in the conversion of electricity from the source to the load. Deep introduction is a power supply system in which consumer loads with voltages of 35 kV and above are connected with a minimal number of intermediate transformation stages. High-voltage deep introduction (DI) can be implemented by directly connecting the network to the power source. source (PS) and dividing it into a ring network [3.4.5].

Deep-entry substations can vary in purpose, as they are utilized not only to supply electricity to urban areas but also within the power systems of large industrial enterprises and other city consumers. Deep entry points—a shortened form of deep-entry substations—are substations with voltages ranging from 35 to 220 kV, typically implemented using simplified switching circuits on the primary voltage side and receiving power directly from the main power system or electrical grid.

What are the objectives of deep networks in power systems? The implementation of deep networks is linked to an extension of high-voltage transmission lines. network. The implementation of deep penetration networks involves extending the high-voltage network. Although this increases the cost of the high-voltage system, it substantially reduces the expenses associated with medium-voltage networks by shortening their required length. Consequently, the construction of distribution substations and the installation of 6–10 kV supply networks are largely considered complete. At the same time, there will be no need to build distribution points and 6-10 kV supply networks[3.4.6].

The supply of electricity to industrial consumers can be carried out from the power system networks and their generating sources. Own Power plants (primarily thermal power plants) may be utilized in the following situations:

-at enterprises with high heat demand;

-when the consumer is located far from the main energy system grid;

-in areas experiencing an energy shortage where the industrial facility is situated.

- when special requirements are imposed on the reliability of electricity supply, when an own power source is needed as a reserve;

- when the production facility has production waste (wood, agricultural, etc.) that can be economically used as fuel for power plants;

- when it is appropriate to use unconventional energy sources.

The connections must be equipped with isolating protection designed to isolate the enterprise's power plant from the power supply organization's networks in the event of an emergency in the power system that leads to a shortage of electricity, a decrease in frequency to unacceptable limits, or a disruption in stability.

**DISCUSSION**

Deep networks offer the following technical advantages:

* voltage monitoring devices are positioned closer to the load center due to the absence of parallel networks;
* relay protection can be implemented more simply;
* additional reserves are created in low-voltage networks with the possibility of automation;
* short-circuit currents in low-power transformers are reduced because urban networks are connected through high-resistance transformers rather than directly to parallel 6–10 kV networks.

Currently, in the electrical supply system, the short-circuit power limits for urban networks are as follows:

* 6 kV – 200 MVA;
* 10 kV – 350 MVA (depending on the calculation of these capacities);
* 35 kV – 60 MVA for electrical equipment.

The maximum transformer power corresponding to short-circuit capacities does not exceed the values specified for secondary voltage deep-entry networks:

* 6 kV network – 16 MVA;
* 10 kV network – 32 MVA.

It is necessary to install high-power transformers in the power supply system. In this case, measures are taken to limit short-circuit currents, such as using reactor circuits.

Before using deep networks, it was required to analyze the implementation of deep penetration substations (DPP) [5.6].

Accordingly, a deep-entry substation is defined as a substation of 35 kV or higher, constructed directly near a major load center. The focus of this study is on the specific features of substation construction. In this context, three main categories should be analyzed:

* initial design conditions;
* potential challenges during the construction process;
* performance characteristics of deep-entry substations;
* criteria for assessing the effectiveness of their construction.

The first category presents the greatest challenges, as it is at this stage that the feasibility of constructing a deep-entry substation is determined. When evaluating the initial design conditions, several factors are considered, the most important of which include:

* requirements for the quality of supplied electricity and the reliability of power delivery to consumers;
* territorial characteristics of the area, including any limitations and specific requirements for network construction;
* the structure of the existing electrical network in the area and the potential for modifications.

In summary, deep-entry substations are typically built near major industrial centers that demand improved quality and reliability of power supply, especially in regions served by a 110 kV regional power grid. Naturally, such projects are typically feasible under conditions of economic prosperity, as constructing a deep-entry substation can be an order of magnitude more expensive than building conventional power networks [6,7].

**CONCLUSION**

Deep penetration networks are considered the most advanced power supply schemes, as their use allows them to be conveniently located near large consumers, eliminate distribution points (DPs), reduce the length of power networks, increase system reliability, and reduce capital costs for equipment.

Deep access is a power supply system for industrial enterprises in which the high-voltage network is situated close to consumer equipment, thereby reducing the number of stages in the transmission of electricity from the source to the load. Power supply networks of 35 kV and above, along with 6–10 kV distribution networks, should be interconnected to serve all consumers within the city and in adjacent areas.

In general, solar power plants (SPPs) in urban areas should be planned and implemented according to a schedule aligned with the city’s long-term development plan (typically 15–25 years), taking into account the evolving dynamics of key urban data. Electrical networks should be designed to optimize efficiency, ensure the required reliability of power supply, and comply with established power quality standards. In newly built cities, 35 kV voltage will be transmitted directly to transformers through overhead and cable networks. Accordingly, there will be no need to use 6-10 kV overhead and cable networks. As a result, the reliability of the power supply system is enhanced, energy efficiency is increased, energy losses are reduced, and financial resources are saved. Based on a deep-rooted network, if the reliability of power supply, energy efficiency, and measures to prevent energy losses are properly managed, an uninterrupted power supply can be achieved in the system. If a deep-rooted energy supply system is implemented in newly constructed facilities, institutions, and residential areas, and if devices and networks are selected correctly, it can become the basis for increasing energy efficiency.

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