The efficiency of electric power supply with the transmission of peak loads to distributed generation

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Abstract. A model of a radial power supply system in MatLAB was compiled to perform the research. The transformer substation is represented by a step-down transformer, the load of the substations in the form of a resistance. Electricity is transmitted to the substations along three power transmission lines. The power center is represented by an ideal source. A reserve source of limited power is connected to the remote substation. We made calculations of the voltage drop in the lines, voltage at the inputs of substations and electricity losses for transit. The study of the radial power supply system was performed in the daytime maximum mode; the minimum load mode was performed at night and in the peak load mode. As a result of modeling the operating modes, the indicators of the classical radial power supply scheme were compared with the indicators of the system when the local generation facilities were switched on during the working shift or during peak hours. Connection of reserve sources allows reducing voltage fluctuations along the line and reducing power losses for transit.

1. Introduction
We often use a radial connection scheme for consumers when we design district distribution electric networks. Power lines (PL) are connected to the power center in the form of diverging beams. Each consumer is connected to the existing power transmission line by a branch or by a separate line [1]. The advantages of the scheme are the minimum length of the transmission line and the capital costs of construction. Each power line is connected to a feeder cell with an automatic switch, which ensures metering of electricity consumption, selectivity of protection operation, the possibility of putting it into scheduled repair, high reliability of the power supply system.

Other load connection schemes with double-sided power supply and ring work as radial in case of failure of any section of the power transmission line [2].

The radial circuit has a significant drawback. It is the inability to maintain the same voltage for all consumers. In a radial power supply system, the effective voltage drops due to distancing from the power center (PC).

For all consumers it is very difficult to meet the requirements of GOST in terms of power quality - relative voltage deviation in the transfer points. At the beginning of the line, the voltage is always high or elevated. The receivers connected in the middle of the line have a voltage close to nominal. The receivers at the end of the line are usually powered by low or reduced voltage. The voltage drop on the power line depends on the design and power consumption; with increasing loads the voltage decreases...
at the transmission points along the entire line and the losses increase in the power line. It is required to use transformers with automatic voltage regulation at the output to compensate the voltage drop [5].

2. Materials and methods
A mathematical model of the power supply system was developed to study the influence of the operating modes of the distribution network on the amount of electrical energy losses and voltage deviation along the radial line [5]. The research was carried out using the software complex «Simulink» on the «MatLab» platform.

Figure 1 shows a radial power supply scheme, which consists of three electrical transformer substations (TS): TS1-TS3, connected by overhead power lines (OPL): OPL1, OPL2, OPL3 with the power center (PC). The loads of substations are presented in the form of complex resistances $Z_n$ connected to the buses of transformer substations.

Figure 1. Radial diagram of the power supply system

The power supply system of the district includes two radial lines. The first is selected for calculations. It is the most loaded. The 110/10 kV transformer substation is the power supply center. The district is powered by six transformer substations 10 / 0.4 kV with an installed capacity of 12,000 kVA. The total design power of the receivers of the first radial line is 5 MW in summer and 6 MW – in winter.

The reliability category of consumers who receive power from substations determines the method of their connection [5]. Consumers of 1 and 2 categories of reliability are connected to TS-1. The first line is double-circuit and is made of the AC-95 wire. The second and third lines are single-circuit. They are made of AC-50 and AC-35 wires. The length of the lines from the power center to the TS-3 varied from 5 to 10 km.

Two transformers with a capacity of 2,000 kVA are installed at TS-1 and one transformer with a capacity of 2,000 kVA is installed at substations 2 and 3. A diesel generator with a capacity of 1000 kVA is connected to the TS-3 buses through the sectional switch Sp. The reserve source is switched on during the working shift from 8-00 to 17-00. It is possible to turn on only during peak load hours from 8-00 to 10-00. During the rest of the working shift the connection is performed automatically when the voltage on the TS-3 buses drops below the threshold value.

3. Results and Discussion
The losses of electricity for transit and the voltage at the input of consumers' transformer substations in peak mode with switched on and off local generation are presented in Tables 1 and 2. The first row of tables 1 and 2 presents the results of calculations in normal mode, both circuits of power transmission line-1 are working. The second line shows the results of calculations in emergency mode, when the power transmission line-12 is out of order, the transit of electricity goes only through the power transmission line-11.
In normal operation the voltage at the output of the power center is 10.5 kV. In accordance with the requirements of GOST, the voltage at the input of consumers' transformer substations differs from the nominal by ± 10% and cannot be lower than 9.5 kV. Analysis of the data in Table 1 shows that the voltage at the input of TS-3 in the peak power mode is 9.63 kV when connected to the power center 1, at a distance of 3 km. The requirements of GOST are met.

Table 1. Voltage on power transmission lines

| Mode of operation | Without generation | With generation |
|-------------------|--------------------|-----------------|
|                   | l Zl | P f | I | U 1 | U h | P f | I | U 1 | U h |
| PLC-1             | 3    | 0.75 | 6000 | 346.8 | 260.1 | 10.24 | 5000 | 289.0 | 216.8 | 10.28 |
| PLC -11           | 3    | 1.5  | 6000 | 346.8 | 520.2 | 9.98  | 5000 | 289.0 | 433.5 | 10.07 |
| PLC -2            | 1.2  | 0.42 | 4000 | 231.2 | 97.1  | 10.14 | 3000 | 173.4 | 72.8  | 10.21 |
| PLC -3            | 1.6  | 1.37 | 2000 | 115.6 | 159.1 | 9.63  | 1000 | 57.8  | 79.5  | 9.84  |
| PLC -1            | 6    | 1.5  | 6000 | 346.8 | 520.2 | 9.98  | 5000 | 289.0 | 433.5 | 10.07 |
| PLC -11           | 6    | 3    | 6000 | 346.8 | 1040.5| 9.46  | 5000 | 289.0 | 867.1 | 9.63  |
| PLC -2            | 1.2  | 0.42 | 4000 | 231.2 | 97.1  | 9.38  | 3000 | 173.4 | 72.8  | 9.56  |
| PLC -3            | 1.6  | 1.37 | 2000 | 115.6 | 159.1 | 9.11  | 1000 | 57.8  | 79.5  | 9.48  |

The voltage at the input of the most distant TS-3 decreases to 9.73 kV when connected to power center 2 at a distance of 6 km, but it does not exceed the permissible limit. In case of planned or emergency shutdown of the power transmission line-12 in the maximum power mode the voltage at the input of TS-1 is 9.46 kV, at the input of TS-2 is 9.38 kV and TS-3 is 9.11 kV. Operation of the network in this mode is impossible; the input voltage is below the minimum allowable level.

Table 2. Electricity losses for transit in power lines

| Mode of operation | Without generation | With generation |
|-------------------|--------------------|-----------------|
|                   | l Zl | P f | I | P el | Δ P el | l Zl | P f | I | P el | Δ P el |
| PLC -1            | 3    | 0.75 | 6000 | 346.8 | 162.38 | 2.71 | 5000 | 289.0 | 112.77 | 2.26 |
| PLC -11           | 3    | 1.5  | 6000 | 346.8 | 324.77 | 5.41 | 5000 | 289.0 | 225.53 | 4.51 |
| PLC -2            | 1.2  | 0.42 | 4000 | 231.2 | 57.74  | 1.44 | 3000 | 173.4 | 32.48  | 1.08 |
| PLC -3            | 1.6  | 1.37 | 2000 | 115.6 | 50.04  | 2.50 | 1000 | 57.8  | 12.51  | 1.25 |
| Total emergency   | 6000 | 346.8 | 490.28 | 8.17 | 5000 | 289.0 | 303.00 | 6.06 |
| Total normal      | 6000 | 346.8 | 270.16 | 4.50 | 5000 | 289.0 | 157.75 | 3.16 |
| PLC -1            | 6    | 1.5  | 6000 | 346.8 | 324.77 | 5.41 | 5000 | 289.0 | 225.53 | 4.51 |
| PLC -11           | 6    | 3    | 6000 | 346.8 | 649.54 | 10.83 | 5000 | 289.0 | 451.07 | 9.02 |
| PLC -2            | 1.2  | 0.42 | 4000 | 231.2 | 57.74  | 1.44 | 3000 | 173.4 | 32.48  | 1.08 |
| PLC -3            | 1.6  | 1.37 | 2000 | 115.6 | 50.04  | 2.50 | 1000 | 57.8  | 12.51  | 1.25 |
| Total emergency   | 6000 | 346.8 | 815.05 | 13.58 | 5000 | 289.0 | 528.53 | 10.57 |
| Total normal      | 6000 | 346.8 | 432.54 | 7.21 | 5000 | 289.0 | 270.52 | 5.41 |
Connecting local generation facilities with a capacity of 1000 kVA to 10 kV buses of TP-3 allows reducing the transit power, the current in the transmission line and the voltage drop on the complex resistance of the lines. As a result, the voltage at the inputs TS-1 and TS-2 does not exceed the permissible limit. At the input of TS-3 the voltage is 9.48 kV, which corresponds to the error of the automatic operation and allows the operation of the substation. During the rest of the working shift the currents in the power transmission line are less and the voltage at the inputs of the transformer substation corresponds to GOST. To analyze the components of losses, calculations of electricity losses for transit were performed for all transmission lines. Table 2 shows the calculation results for the peak load mode. For the power supply circuit from PC-1 the power loss is 270 kW in normal mode and 490 kW – in emergency mode. The relative losses are 4.5% and 8%. The power losses were 432 kW and 815 kW, or 7% and 14% when powered from the CP-2 at a distance of 6 km. The amount of losses is too large, the requirements for energy efficiency of the network economy are violated; the operation of the network is economically unprofitable.

The connection of local generation allows unloading all the lines, reducing the currents and powering for heating the wires. As a result, the currents in power transmission line-1 fell by 16%, the power losses in the first case decreased 1.5 times and amounted to 3% and 6%. In the second case, the power loss in the normal mode was 270 kW and in the emergency mode was 528 kW. The relative losses for transit were 5.5% and 10.5%. The connection of local generation will allow operating long-distance power lines or increasing the power of consumers without reconstruction of transmission lines.

In real operation, the power consumption varies greatly during the day. Figure 2 shows the daily load schedule of the considered power system. The vertical line shows the total power of consumers in kVA connected to TS-1, TP-2 and TS-3. The magnitude of the peak loads is 6000 kVA, the time does not exceed two hours [4]. During working hours the transit power is 5000 kVA, at night the power is significantly less. When local generation is switched on, the transit power during working hours drops to 4000 kVA.

![Figure 2. Daily load schedule in winter](image)

The results of modeling the radial power supply system are presented in Tables 3-4. The maximum transit power will be through the wires of power transmission line-1, heat losses are proportional to the square of the current. Power transmission line-1 is the longest and has the maximum resistance. Consequently, the losses in the power transmission line-1 account the majority of all losses of the radial system.

When operating in peak mode, the current is maximum and the voltage drop is the largest. This is the most difficult mode for the power system. At the input of TS-1 in the peak mode the voltage drops to 9.98 kV, at the other TS it will be even lower [5]. It is necessary to calculate the power transmission
line according to the peak load in order to ensure the fulfillment of the requirements of GOST in terms of voltage retention at the input to the transformer substation. The duration of peak loads does not exceed 1-2 hours per day (Figure 2). The size of the peak does not exceed 20% of the power of the daily maximum. At other time the power of the loads is low, the current in the line is less and the financial costs for an increased cross-section of the power line wires are used irrationally.

| Table 3. Voltage drop in power transmission line-1 and on the buses of TS-1 |
|-------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
|                   | hour | kW   | A  | kV  | kW  | A  | kV  | kW  | A  | kV  | kW  | A  | kV  | kW  | A  | kV  |
|                   | 4    | 1000 | 58 | 0.09 | 10.41 | 1000 | 58 | 0.09 | 10.41 | 1000 | 58 | 0.09 | 10.41 |
|                   | 6    | 4000 | 231 | 0.35 | 10.15 | 3000 | 173 | 0.26 | 10.24 | 3000 | 173 | 0.26 | 10.24 |
|                   | 8    | 6000 | 347 | 0.52 | 9.98  | 5000 | 231 | 0.35 | 10.15 | 5000 | 231 | 0.35 | 10.15 |
|                   | 10   | 5000 | 289 | 0.43 | 10.07 | 4000 | 231 | 0.35 | 10.15 | 4000 | 231 | 0.35 | 10.15 |
|                   | 16   | 5000 | 289 | 0.43 | 10.07 | 4000 | 231 | 0.35 | 10.15 | 4000 | 231 | 0.35 | 10.15 |
|                   | 18   | 4000 | 231 | 0.35 | 10.15 | 3000 | 173 | 0.26 | 10.24 | 3000 | 173 | 0.26 | 10.24 |
|                   | 20   | 4000 | 231 | 0.35 | 10.15 | 3000 | 173 | 0.26 | 10.24 | 3000 | 173 | 0.26 | 10.24 |
|                   | 22   | 1000 | 58  | 0.09 | 10.41 | 1000 | 58 | 0.09 | 10.41 | 1000 | 58 | 0.09 | 10.41 |
|                   | 24   | 1000 | 58  | 0.09 | 10.41 | 1000 | 58 | 0.09 | 10.41 | 1000 | 58 | 0.09 | 10.41 |

It is proposed to calculate the power transmission line not by the peak power, but by the value of the daily maximum to increase the energy efficiency of the system and reduce the losses of electricity transit. As a rule, this period takes 10-14 hours of time and most of the time of the day the power transmission line will operate in a mode close to the calculated [5]. At the same time, the cross-section of wires will decrease; capital investments for the construction of overhead and cable lines will decrease.

| Table 4. Losses of electricity for transit in transmission lines-1 |
|-------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
|                   | hour | kW   | A  | kW  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh | kW  | A  | kWh |
|                   | 4    | 1000 | 58  | 3.01 | 12.03 | 0   | 1000 | 58 | 3.01 | 12.03 | 0   | 1000 | 58 | 3.01 | 12.03 | 0   | 1000 | 58 | 3.01 | 12.03 | 0   | 1000 | 58 | 3.01 | 12.03 | 0   | 1000 | 58 | 3.01 | 12.03 | 150.3 | 288. | 66.16 | 150.3 | 288. | 66.16 |
|                   | 6    | 4000 | 231 | 48.11 | 96.23 | 1000 | 3000 | 173 | 27.06 | 54.13 | 42.10 |
|                   | 8    | 6000 | 347 | 75.18 | 150.3 | 1000 | 5000 | 289 | 75.18 | 66.16 | 54.13 | 42.10 |
|                   | 10   | 5000 | 289 | 75.18 | 150.3 | 1000 | 4000 | 231 | 48.11 | 96.23 | 42.10 |
|                   | 16   | 5000 | 289 | 451.0 | 96.23 | 1000 | 4000 | 231 | 48.11 | 96.23 | 42.10 |
|                   | 18   | 4000 | 231 | 48.11 | 96.23 | 1000 | 3000 | 173 | 27.06 | 54.13 | 42.10 |
|                   | 20   | 4000 | 231 | 48.11 | 96.23 | 1000 | 3000 | 173 | 27.06 | 54.13 | 42.10 |
|                   | 22   | 1000 | 58  | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  |
|                   | 24   | 1000 | 58  | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  | 0   | 1000 | 58 | 3.01 | 6.01  |
|                   | Total| 1130 | 721 | 409  | 150.3 | 288. | 66.16 | 150.3 | 288. | 66.16 |

The total losses for transit per day were 1130 kWh and after connecting the generation during the working shift the value of the loss was 721 kWh. Losses decreased by 409 kWh, almost 1.6 times. Transit losses during the peak were 216 kWh, and after connecting a reserve source - 150 kWh.
The reduction of losses during the peak was 66 kWh. The decrease of losses will be 9% with a daily loss of 721 kWh.

The problem of peak load can be solved by using reserve or emergency power, located at the consumer or in the collective use. Now these generating capacities are idle, their operating time does not exceed several tens of hours per year. The equipment is aging morally and physically, but it does not produce its own resource. Using it as peak generating capacity will increase resource production and systematically upgrade equipment.

Switching on of reserve sources is possible according to the schedule, for example, at the beginning of a work shift. It is possible to turn on local generation when the voltage on the buses of consumers drops to a minimum level [4]. The additional power of the reserve source will allow you to unload the power transmission line, the transit current decreases and the voltage drop on the line decreases.

On a large territory of our country, power equipment is operated in extremely harsh conditions – at ambient temperatures up to minus 50 degrees with precipitation and the risk of ice. It is necessary to provide comfortable environmental conditions for power equipment and automation cabinets to increase the reliability of power supply. Reserve sources will operate in intermittent mode. Their working time, depending on the load schedule, can vary from several hours to half an hour. There will be long downtime between the cycles of the diesel generator. The control systems provide for a procedure for cold starting the engine and preparing the generator for connection to the network and placing it under load in the winter period.

The procedure for cold starting of reserve source includes power supply to the control panel, checking the temperature regime, heating the automation cabinets, the engine and sectional switches [5]. The heating of the automation cabinets will be executed by a temperature stabilization system based on a self-heating cable. The engine is warmed up by a tubular electric heater by heating the coolant. The sectional switch is heated by a stream of hot air from a heat gun.

Now the current legislation allows the sale of electricity on the wholesale market to small producers. As a rule, the cost of electricity at reserve sources is much higher than that at thermal power plants or hydroelectric power plants. But during the day the price on the balancing market changes very much [6]. The most expensive electricity is just during peak hours. The supply of electricity at a high price from reserve sources during peak hours will be economically profitable.

4. Conclusion
The model takes into account the daily voltage fluctuations in the network, which occur continuously. The current in the lines and the voltage drop on the line resistance increase with increasing loads. The voltage at the consumer transformer substation decreases. The voltage increases under low load. We identified the influence of the brand of the wire and the length of the line.

The inclusion of local generation at TS-3 reduces the losses on the transit of electricity almost 1.5 times. Reducing the transit power allows you to reduce the currents in the lines and reduce the voltage drop at the full resistance of the power line.

For the example under consideration the daily transit is 840,000 kWh and the losses in the transmission line are 1,130 kWh. In our case, the duration of peak loads does not exceed 2 hours per day. The relative loss reduction of 43 % will be 409 kWh per day.

The peak power exceeds the daily maximum by an average of 20%, but lasts no more than 2 hours. Losses of electricity for transit during the peak time amount to 16% of daily losses in summer and 20% in winter. Switching on only during peak hours gives a loss reduction of 9%.

Connecting reserve generators in the middle or at the end of the line will reduce the power of transmission lines and increase the voltage at the points of transmission of electricity for the most distant receivers. This approach makes a possibility to extend the life of existing transmission lines with a systematic increase in consumer loads.
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