Load distribution factor along the power transmission lines as a factor in choosing a voltage class

I M Bogachkov¹, R N Khamitov²
¹Tyumen branch of LLC "Gazprom engineering", Tyumen, 625000, Russia
²Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia

Abstract. Gas fields differ from industrial enterprises by long power transmission lines with low electrical loads (low density), which grow many times during the life cycle. Power supply to gas well clusters is carried out according to the scheme - "main circuit with one through line with transformer substations distributed along the line". The distribution of transformer substations along the transmission line affects the voltage loss, and, consequently, the choice of voltage class. The purpose of the research is to quantify the distribution of transformer substations along the power line to develop a mathematical model for calculating the optimal voltage class. To achieve this goal, the following tasks are solved: five power supply schemes are built for gas well clusters; electric moments are calculated for each scheme; the load distribution coefficient is determined. The problems were solved using an experimental-theoretical method (analysis and synthesis) and a software product – Mathcad. As a result, the coefficient is calculated in the work - for even load distribution, when placing the entire load at the end of the line and when placing the load at the beginning of the line.

1. Introduction
Finding the optimal conditions is one of the most common scientific and technical tasks. The search for optimal conditions occurs when the possibility of carrying out the process is established and there is a need to find the best conditions for its implementation.

The design of power supply systems is associated with the use of the best solutions, which are determined by the optimization criterion. To do this, it is necessary to perform a large number of calculations, taking into account a number of restrictions and etc.

The application of a unified mathematical theory, including, for example, similarity theory, modeling theory, and experimental theory [1], opens up prospects for solving the problems of optimization of complex power supply systems.

Any mathematical model is associated with the formalization of the object under study and, to a greater or lesser extent, it is an object’s idealization.

1.1 The selection of the voltage class, which is the main parameter for optimizing the power supply system.

Nowadays there are the methods for selecting the voltage for industrial enterprises using mathematical models that are obtained using the theory of experimental planning. For example, in the research [2] the question of choosing a voltage class in systems of in-plant power supply, the rational construction of which lays the foundation for the normal functioning of the enterprise, is considered.

However, gas fields differ from industrial enterprises by long power transmission lines with low electrical loads (low density), which grow many times during the life cycle of a field.

Thus, the urgent task is the optimization of the power supply system by selecting a rational voltage class, taking into account the prospective growth of electrical loads during the life cycle of a gas field.

Another feature of the gas field power supply system is that the choice of the voltage class is closely related to the distribution of transformer substations along the transmission line, which must be quantified.
2. The problem statement

Power supply of gas well clusters is performed according to the third reliability category [3]. The most common power supply scheme is "a main circuit with a single through line with transformer substations distributed along the line for gas well clusters with one-way power supply".

The actual number of hours of gas fields operation is constant and it is 7650 hours for gas industry facilities.

The method for determining of the optimal voltage class for gas field power supply systems using the experimental planning theory consists in obtaining mathematical models that relate the value of the voltage class to the factors which have the greatest influence on the voltage.

Using the experiment planning method makes it easier to find the best solution.

Figure 1 shows the object of research, it is affected by "n" variable controlled factors, which are represented by the letter "x", the result of the impact is the optimization parameter, which is denoted by "y".

![Figure 1. Scheme of the research object](image)

where 1 is the research object; 2 is changeable and controlled factors; 3 is optimization parameters.

The optimization parameter "y" for the mathematical model is assumed to be the voltage class. It is important for the formation of a mathematical model to make a reasonable choice of factors that determine the success of the problem solution as well as the optimization parameter.

The analytical method was used to select the factors that affect the response function of the optimal voltage class of the distribution grid of the gas well cluster power supply system:

- the number of gas well clusters;
- distance from a power source to an electricity consumer;
- coefficient of increase of electric load;
- load distribution coefficient for overhead lines (OHL).

A mathematical model is an equation that relates an optimization parameter to the variable factors being studied[4, 5, 6]:

\[
y = f(x_1, x_2, x_3, x_4) = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i,j}^{n} b_{ij} x_i x_j + \ldots + \ldots,
\]

where \( x_1 \) is the factor "number of gas well clusters"; \( x_2 \) is the factor "distance from a power source to an electricity consumer"; \( x_3 \) is the factor "electric load growth coefficient"; \( x_4 \) is the factor "load distribution coefficient for overhead lines"; \( b_0, b_i, b_{ij} \) are the coefficients of the polynomial.

As it is known [7], the distribution of the electric load along the transmission line affects the value of the active and reactive load moment, and, consequently, the voltage loss.

The selected factors for constructing a mathematical model for calculating the optimal voltage class allow:

1. To build mathematical models of the distribution grid with the connection of transformer substations throughout the lines.
2. To conduct a dynamic experiment over time, taking into account the prospects for increasing electrical loads in the subsequent periods of the gas field's life.
3. To take into account the impact on the voltage class of transformer substations distribution along the power line (an uniform line or at the end of a line).

One of the main requirements for a factor is that it must be a variable quantity which can be calculated.

Table 1 shows the selected levels and intervals of variation for all factors except x4.

**Table 1.** Main levels and intervals of factor variation

| Factor     | Name of the factor                        | Main zero level, xi0 | The range of variation, Δx | Top level, «+» | Bottom level, «-» |
|------------|------------------------------------------|----------------------|-----------------------------|----------------|-------------------|
| Distribution grid – "Trunk scheme with one through trunk" |                           |                      |                             |                |                   |
| x1         | Number of gas clusters N, PCs            | 6                    | 4                           | 10             | 2                 |
| x2         | Distance from a power source to consumer L, km | 10,25                | 9,75                        | 20             | 0,5               |
| x3         | Coefficient of increase in electric load during the period of falling production kpr, a.u. | 5,5                  | 4,5                         | 10             | 1                 |
| x4         | Load distribution coefficient for OHL kdist, a.u. | –                    | –                           | –              | –                 |

The purpose of this research is to quantify the factor x4 - "load distribution coefficient for overhead lines" to develop a mathematical model for calculating the optimal voltage class.

To achieve this goal, the following tasks are solved:

1. Five power supply diagrams are built;
2. The time for active and reactive load is calculated;
3. The coefficient of load distribution is defined.

3. **Theory**

To assess the influence of the distribution of transformer substations on the choice of the optimal voltage class, five distribution grid schemes are constructed for gas well clusters, which are shown in Fig. 2.

The estimated electrical load of one gas wells cluster for the existing gas fields in Western Siberia is assumed to be 0.1 MW.
Figure 2. Distribution grid – "Main circuit with one through-line"

a) the gas well clusters are concentrated in the beginning of OHL; b) gas well clusters are spread evenly; c) gas well clusters are uniformly distributed in OHL; d) gas well clusters are distributed in the middle and at the end of OHL; e) all the gas well clusters are connected at the end of OHL.

The length of overhead power lines for all schemes is assumed to be 10 km, and ten gas well clusters with a total electrical load of 1 MW are connected to the OHL.

Power supply schemes differ in different distribution of transformer substations of gas well clusters along the power line. For example, in Fig. 2B shows ten clusters of gas wells with a uniform connection of clusters to the overhead line after 1 km.

For each circuit, the active load moment is calculated using the formula:

$$Ma(n) = \sum_{i=0}^{n} L_i \cdot \sum_{j=1}^{n} P_j, \text{ kW·km}$$ (2)

where $L_i$ is the length of the section from the previous to the next desoldering, km; $P_j$ is the electric active load, kW.

And the moment of reactive load:

$$Mp(n) = \sum_{i=0}^{n} L_i \cdot \sum_{j=1}^{n} Q_j, \text{ kvar·km}$$ (3)
where \( L_i \) is the length of the section from the previous to the next desoldering, km, \( Q_j \) is the electric reactive load, kW.

The voltage loss at the end of the overhead line is determined by the expression:

\[
\Delta U = a_2(R_0 M_a + X_o M_P), \% 
\]

where \( a_2 = \frac{1}{10 \cdot U_a^2} \), \( R_0 \) – specific resistance (active), Ohms / km, \( X_o \) – specific resistance (reactive), Ohms / km, \( U_N \) – UN-rated voltage class, kV, \( M_a \) – active load moment, kW·km, \( M_P \) – reactive load moment, kV·km.

The load distribution coefficient for each circuit is determined by the ratio of the active load moment of each circuit to the active load moment of the load distribution circuit at the end of the line.

\[
k_{\text{avg}} = \frac{M_a}{M_{a1}}, \text{ a.u.} \]  

The voltage loss was calculated using a computer program [8].

4. The results of research

Table 2 shows the calculated values of power supply schemes according to Fig. 2.

**Table 2.** Calculated values of power supply schemes

| No | Parameter                              | Value          |
|----|----------------------------------------|----------------|
| 1  | The time of the active load kW×km      | 1900 3500 5500 8000 10000 |
| 2  | Voltage loss at the end of the line, \( \Delta U \) % | 1,48 2,73 4,3 6,26 7,28 |
| 3  | Power supply scheme                    | Fig. 2a Fig. 2b Fig. 2c Fig. 2d Fig. 2e |
| 4  | Load distribution coefficient for OHL, a.u. | 0,19 0,35 0,55 0,8 1 |

4. Discussion of results

When studying the load distribution on the overhead line, it should be noted that with the same load of 1 MW, but with different distribution of transformer substations on the overhead line, the electric moment and voltage loss change.

In Table 3, the main levels and intervals of variation of factor \( x_4 \) – "load distribution coefficient for OHL"are selected. The lower level is made uniform distributions of the load on the transmission line is 0,55 a.u., for top level of accepted load distribution at the end of the line – 1 a. u.

**Table 3.** Main levels and intervals of variation of the \( x_4 \) factor

| Factor | Name of the factor | The basic level zero, \( x_{i0} \) | The range of variation in, \( \Delta x \) | Top level, \( +\) | Bottom level, \( -\) |
|--------|-------------------|-------------------------------|---------------------|----------------|-----------------|
| Distribution grid – " Trunk scheme with one through trunk" | The distribution ratio of the load on OHL \( k_{distr} \), a.u. | 0,7 0,15 0,85 0,55 |
Load distribution at the beginning of the line is not included in the range of variation, since according to the analysis of existing distribution grids of the power supply system for gas fields in Western Siberia, gas well clusters are connected evenly or at the end of the line.

5. Conclusions

The following tasks have been solved:

1. Five schemes of power supply have been built - the gas well clusters are concentrated in the beginning of OHL, and the gas well clusters are distributed relatively evenly; the gas well clusters are evenly distributed over OHL, and the gas well clusters are distributed in the middle and at the end of OHL, and all the gas well clusters are connected at the end of OHL.

2. The active load moment (10 km long line, the number of transformer substations 10 with a capacity of 100 kW) has been calculated for load distribution at the beginning of the line - 1900 kWh km; for load distribution relatively evenly along the line - 3500 kWh km; for load distribution evenly along the line - 5500 kWh km; for load distribution in the middle and at the end of the line - 8000; for load distribution at the end of the line - 10000 kWh km.

3. The load distribution ratio has been defined, it is amounted to:
   – when the load is evenly distributed, $kdistr = 0.55$ a.u.;
   – when the entire load is placed at the end of the line, $kdistr = 1$ a.u.;
   – when the load is placed at the beginning of the line, $kdistr = 0.19$ a.u.

Thus, the study allows us to quantify the factor "load distribution coefficient for overhead lines" and use it in the formation of a mathematical model for choosing the optimal voltage class.

Reference

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