The algorithm for selecting the optimal voltage class of the gas field power supply system, taking into account the entire life cycle

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Abstract. The paper proposes an algorithm for choosing the optimal voltage class of a power supply distribution grid of gas well clusters, in which there is a multiple electrical load increase during field's life cycle. Building a mathematical model with considering factors allows to design both a trunk line and a single radial grid and evaluate the magnitude and direction of the influence of individual factors, i.e. to conduct a quantitative analysis of the gas field power supply diagram. An extreme experiment is used to construct mathematical models. The optimization parameter is accepted as economic - the minimum of discounted costs. The paper presents six response functions - regression equations. The distribution grids of a number of operating gas fields in Western Siberia have been investigated taking into account the entire life cycle of the field at "PRON" computer program. The proposed algorithm can be used in the design of the power supply system for new gas fields, which allows to select the optimal voltage class for the power supply system of gas clusters, considering the entire life of the gas field, taking into account the minimum discounted costs. It can improve the efficiency of decisions, reduce funds and design time.

1. Introduction

According to the Federal Customs Service, natural gas takes the second place in the ranking of Russia's main export goods. Most of the gas fields in Western Siberia are in the stage of falling production.

In order to extend the profitability of gas production at the fields, a modern technology of distributed gas compression is being introduced with the installation of mobile electric compressor units (MCUs) at the clusters of gas wells [1 - 4]. As a result, there is a significant increase in the electrical load. This, in turn, leads to a serious reconstruction of the electric grid facilities of the gas fields. As a result of theoretical studies of existing gas fields in Western Siberia of the Yamalo-Nenets Autonomous District, the following pattern has been revealed: with a decrease in the flow rate of wells and the average reservoir pressure in the course of the life cycle, the calculated average annual electrical load increases.

At the moment, at the end of the life cycle of gas fields in Western Siberia in the Yamal-Nenets Autonomous District, practically all electrical facilities are not adapted to the growth of electrical load. Thus, the wrong choice of the main parameters of the power supply system at the design stage reduces the profitable period of gas production.
2. Problem statement
All known methods for choosing the optimal voltage \([6-9]\) are classified into three main categories - empirical formulas, methods using the combination of mathematical theory and analytical methods.

Analysis of the existing methods for calculating the voltage class has established that they take into account only two factors: load power and the length of the transmission line and do not take into account the industry specificity of gas fields.

To achieve this goal, it was decided to use the combined mathematical theory.

Nowadays, the issue of choosing the optimal voltage class for the power supply system of gas fields, taking into account the entire life cycle, has been poorly developed by scientists.

The existing methods are not applicable to the power supply system of gas fields for the following reasons:

1. Gas fields differ from industrial enterprises by long power lines with low electrical loads, which multiply at the end of the field's life cycle.
2. In a market economy, to perform technical and economic calculations, discounted costs are currently used, which allow taking into account capital investments (CAPEX) and operating costs (OPEX), adjusted for inflation.

One of the most common scientific and technical problems is the search for optimal functions. Search for optimal conditions at the moment when the possibility of occurrence of optimal conditions for implementation is established.

The design of power supply systems is associated with the application 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, etc.

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

Experiment planning is used to solve the following problems [9]:
1. search for optimal conditions;
2. construction of interpolation formulas;
3. study of composition-properties diagrams.

In general, to select the optimal voltage class, firstly the non-standard voltage at the lowest discounted cost should be determined.

The developed method for determining the optimal voltage class for power supply systems of gas fields using the theory of experimental planning [9] consists in obtaining regression models connecting the value of the voltage class with factors that have the greatest influence on the voltage.

The idea of the proposed method for making a decision on determining the optimal voltage consists in planning a full factorial experiment (FFE) of type \(2^k\), where \(k\) is the number of factors under consideration.

An experiment in which all possible combinations of factor levels are realized is called a full factorial experiment.

For each planned experiment, the optimal values of the desired function corresponding to the minimum of the selected optimality criterion are determined.

Thus, to find the optimal voltage, a method is proposed which based on the fact that, using the results of determining the discounted costs at standard voltages, on the one hand, and the mathematical interpolation theories of Lagrange, on the other, an equation of the form \(R = f(U)\) can be drawn up.

Having found the first derivative of this equation and equating it to zero, it is possible to determine the theoretical minimum of discounted costs and the corresponding optimal voltage, which will be determined by Lagrange interpolation theory.

Discounted costs determine the economic feasibility of the selected technical solution.

3. Theory
The algorithm of the methodology is based on the developed six regression models, which are obtained using the theory of experiment planning.

The regression model for determining the optimal voltage of the distribution grid is:
\[ U_{opt} = 18.04 \cdot 3.48 \cdot x_1 + 6.62 \cdot x_2 + 6 \cdot x_3 + 2.41 \cdot x_4 + 2.54 \cdot x_1 \cdot x_2 + x_1 \cdot x_3 + +6.22 \cdot x_2 \cdot x_3 + 1.12 \cdot x_1 \cdot x_4 + 2.05 \cdot x_2 \cdot x_4 + 0.72 \cdot x_3 \cdot x_4 + 4.56 \cdot x_1 \cdot x_2 \cdot x_3 + +0.99 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4 - 0.59 \cdot x_1 \cdot x_3 \cdot x_4 + 0.62 \cdot x_2 \cdot x_3 \cdot x_4 - 0.49 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4 \] \text{kV, (1)}

where \( x_1 \) is the factor "Number of gas clusters" N, PCs; \( x_2 \) is the factor "Distance from power source to consumer" L, km; \( x_3 \) is the factor "Coefficient of growth of electrical load" \( k_{incr} \), p.u.; \( x_4 \) is the factor "Load distribution factor along overhead lines" \( k_{distr} \), p.u.

The regression model of discounted costs for voltage 6 kV is:
\[ R_{6kV} = 506 + 275 \cdot x_1 + 450 \cdot x_2 + 334 \cdot x_3 + 117 \cdot x_4 + 241 \cdot x_1 \cdot x_2 + 229 \cdot x_1 \cdot x_3 + +311 \cdot x_2 \cdot x_3 + 93 \cdot x_1 \cdot x_4 + 112 \cdot x_2 \cdot x_4 + 93 \cdot x_3 \cdot x_4 + 210 \cdot x_1 \cdot x_2 \cdot x_3 + +89 \cdot x_1 \cdot x_2 \cdot x_4 + 67 \cdot x_1 \cdot x_3 \cdot x_4 + 88 \cdot x_2 \cdot x_3 \cdot x_4 + 66 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4 \text{ million rubles (2)} \]

The regression model of discounted costs for voltage 10 kV is:
\[ R_{10kV} = 399 + 202 \cdot x_1 + 353 \cdot x_2 + 252 \cdot x_3 + 133 \cdot x_4 + 176 \cdot x_1 \cdot x_2 + 181 \cdot x_1 \cdot x_3 + +239 \cdot x_2 \cdot x_3 + 81 \cdot x_1 \cdot x_4 + 130 \cdot x_2 \cdot x_4 + 129 \cdot x_3 \cdot x_4 + 169 \cdot x_1 \cdot x_2 \cdot x_3 + +78 \cdot x_1 \cdot x_2 \cdot x_4 + 77 \cdot x_1 \cdot x_3 \cdot x_4 + 126 \cdot x_2 \cdot x_3 \cdot x_4 + 74 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4 \text{ million rubles (3)} \]

The regression model of discounted costs for voltage 20 kV is:
\[ R_{20kV} = 226 + 86 \cdot x_1 + 152 \cdot x_2 + 86 \cdot x_3 + 12 \cdot x_4 + 43 \cdot x_1 \cdot x_2 + 71 \cdot x_1 \cdot x_3 + +44 \cdot x_2 \cdot x_3 + 9 \cdot x_1 \cdot x_4 + 10 \cdot x_2 \cdot x_4 + 11 \cdot x_3 \cdot x_4 + 41 \cdot x_1 \cdot x_2 \cdot x_3 + +7 \cdot 68 \cdot x_1 \cdot x_2 \cdot x_4 + 8 \cdot 83 \cdot x_1 \cdot x_3 \cdot x_4 + 10 \cdot 1 \cdot x_2 \cdot x_3 \cdot x_4 + 7 \cdot 34 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4 \text{ million rubles (4)} \]

The regression model of discounted costs for voltage 35 kV is:
\[ R_{35kV} = 296 + 103 \cdot x_1 + 152 \cdot x_2 + 74 \cdot x_3 + 11 \cdot x_4 + 12 \cdot 3 \cdot x_1 \cdot x_2 + 56 \cdot 7 \cdot x_1 \cdot x_3 + +12 \cdot 3 \cdot x_2 \cdot x_3 + 6 \cdot 06 \cdot x_1 \cdot x_4 + 1 \cdot 23 \cdot x_2 \cdot x_4 + 1 \cdot 10 \cdot 5 \cdot x_3 \cdot x_4 + 12 \cdot x_1 \cdot x_2 \cdot x_3 + -4 \cdot x_1 \cdot x_2 \cdot x_4 + 5 \cdot 95 \cdot x_1 \cdot x_3 \cdot x_4 + 1 \cdot 11 \cdot x_2 \cdot x_3 \cdot x_4 + 3 \cdot 94 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4 \text{ million rubles (5)} \]

The regression model of discounted costs of 110 kV grid is:
\[ R_{110kV} = 661 + 279 \cdot x_1 + 202 \cdot x_2 + 242 \cdot x_3 + 25 \cdot x_4 + 18 \cdot x_1 \cdot x_2 + 166 \cdot x_1 \cdot x_3 + -16 \cdot 10 \cdot x_2 \cdot x_3 + 13 \cdot x_1 \cdot x_4 + 26 \cdot x_3 \cdot x_4 + 18 \cdot x_1 \cdot x_2 \cdot x_3 + -25 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4 + 12 \cdot x_2 \cdot x_3 \cdot x_4 + 25 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4 \text{ million rubles (6)} \]

The main levels and intervals of variation of factors used in regression models are presented in Table 1.

| Factor | Factor name | Basic zero level, \( x_{i0} \) | Variation interval, \( \Delta x \) | Upper level, \( +\) | Lower level, \( -\) |
|--------|-------------|-----------------|-----------------|----------------|----------------|
| \( x_1 \) | Number of gas clusters N, PCs | 9 | 7 | 16 | 2 |
| \( x_2 \) | Distance from power source to consumer L, km | 10.25 | 9.75 | 20 | 0.5 |
| \( x_3 \) | The coefficient of increase in electrical load during the period of falling production \( k_{incr} \), p.u. | 5.5 | 4.5 | 10 | 1 |
| \( x_4 \) | Load distribution coefficient on OHL \( k_{distr} \), p.u. | 0.7 | 0.15 | 0.85 | 0.55 |

The range of the number of clusters of gas wells N is 2 ... 16 PCs connected to the power line is typical for the gas fields of Western Siberia in the Yamalo-Nenets Autonomous District.

The distance from the power source to consumers at gas fields is much higher than at medium-sized industrial enterprises, the range of the length of power lines L from power sources to the designed facility is 0.5 ... 20 km.
During the period of declining production, the electrical load on the clusters of gas wells increases 4 ... 10 times. To take into account the growth of the electrical load, the growth rate is introduced (during the period of declining production of the gas field, the appearance of the MCU), it is adopted at intervals of 1 ... 10 times.

The natural values of the factors (initial data) are converted into coded ones by the formula (7) and the data in Table 1.

\[ x_j = \frac{x_j - x_{j0}}{\Delta x_j} \]  

(7)

where \( x_j \) is the coded value of the factor; \( x \) is natural value of factors; \( x_{j0} \) is the natural value of the main level; \( \Delta x_j \) is variation interval; \( j \) is factor number.

Since the power supply diagram for gas clusters is of the single radial type, and depending on the geography of the gas well clusters, the distribution of the cluster pads may not be equal, for this, the load distribution coefficient along the power transmission line is introduced, which is taken at intervals of 0.55 ... p.u.

The algorithm for choosing the optimal voltage is as follows:
1. To determine the number of gas well clusters, the distance from the power source to the load (cluster), the load distribution coefficient on the power transmission lines;
2. To calculate the optimal non-standard voltage in the first period of the field life cycle according to the regression model (1) - \( U_{opt1.l.c.p} \);
3. To find on the scale of standard rated voltages (according to Table 2) the nearest higher (\( U_{n.h.1.l.c.p} \)) and the nearest lower (\( U_{n.l.1.l.c.p} \)) standard voltage in the first period of the life cycle;
4. To calculate the discounted costs using regression models (1) ... (5) for the nearest standard voltages (\( R_{n.h.1.l.c.p} \), \( R_{n.l.1.l.c.p} \)) in the first period of the life cycle;
5. To determine the optimal standard voltage at the minimum discounted costs for the first period of the life cycle from item 4 - \( U_{opt.s.1.l.c.p} \);
6. To calculate the optimal non-standard voltage in the third period of the life cycle according to the regression model (1) - \( U_{opt3.l.c.p} \);
7. To find on the scale of standard rated voltages (according to Table 2) the nearest higher (\( U_{n.h.3.l.c.p} \)) and the nearest lower standard voltage (\( U_{n.l.3.l.c.p} \)), in the third period of the life cycle;
8. To calculate the discounted costs using regression models (1) ... (5) for the nearest standard voltage (\( R_{n.h.3.l.c.p} \), \( R_{n.l.3.l.c.p} \));
9. To determine the optimal standard voltage at the minimum discounted costs from item 8 for the third period of the life cycle - \( U_{opt.s.3.l.c.p} \);
10. To compare the optimal standard voltage of the first (\( U_{opt.s.1.l.c.p} \)) and the third (\( U_{opt.s.3.l.c.p} \)) life periods:
   11.1 If \( U_{opt.s.1.l.c.p} = U_{opt.s.3.l.c.p} \), then the optimal voltage, taking into account the entire life cycle of the deposit (\( U_{opt.s.} \)), is determined as, \( U_{opt.s.} = U_{opt.s.1.l.c.p} = U_{opt.s.3.l.c.p} \) (Figure 1).
   11.2 If \( U_{opt.s.1.l.c.p} < U_{opt.s.3.l.c.p} \), then \( U_{opt.s.} \) should be selected as follows (Figure 2):
      - to determine the discounted costs for \( U_{opt.s.1.l.c.p} \) in the first (\( R_{u1.l.c.p.1} \)) and in the third (\( R_{u1.l.c.p.3} \)) period of the life cycle;
      - to determine the difference in discounted costs (\( \Delta R_{u1.l.c.p.} \)) for the optimal standard voltage class of the first period of the life cycle (\( U_{opt.s.1.l.c.p} \)):
        \[ \Delta R_{u1.c.p.} = R_{u1.c.p.3} - R_{u1.c.p.1} \]  
        (8)
      - to determine the discounted costs for \( U_{opt.s.3.l.c.p} \) in the first (\( R_{u3.l.c.p.1} \)) and in the third (\( R_{u3.l.c.p.3} \)) period of the life cycle
      - to determine the difference in discounted costs (\( \Delta R_{u3.l.c.p.} \)) for the optimal standard voltage class of the third period of the life cycle (\( U_{opt.s.3.l.c.p} \)):
        \[ \Delta R_{u3.c.p.} = R_{u3.c.p.3} - R_{u3.c.p.1} \]  
        (9)
– to compare $\Delta Ru_{1\text{l.c.p.}}$ and $\Delta Ru_{3\text{l.c.p.}}$ and choose the optimal voltage class ($U_{\text{opt.s.}}$) with a minimum difference in discounted costs.

11.3 If $U_{\text{opt.s.1l.c.p.}} > U_{\text{opt.s.3l.c.p.}}$, then $U_{\text{opt.s}}$ choose as follows:
– to determine the discounted costs for $U_{\text{opt.s.1l.c.p.}}$ in the first ($Ru_{1\text{l.c.p.1}}$) and in the third ($Ru_{1\text{l.c.p.3}}$) period of the life cycle;
– to determine the difference in discounted costs ($\Delta Ru_{1\text{l.c.p.}}$) for the optimal standard voltage class of the first period of the life cycle ($U_{\text{opt.s.1l.c.p.}}$):

$$\Delta R_{\text{u1c.p.}} = R_{\text{u1c.p.3}} - R_{\text{u1c.p.1}}; \quad (10)$$

– to determine the discounted costs for $U_{\text{opt.s.3l.c.p.}}$ in the first ($Ru_{3\text{l.c.p.1}}$) and in the third ($Ru_{3\text{l.c.p.3}}$) period of the life cycle;
– to determine the difference in discounted costs ($\Delta Ru_{3\text{l.c.p.}}$) for the optimal standard voltage class of the third period of the life cycle ($U_{\text{opt.s.3l.c.p.}}$):

$$\Delta R_{\text{u3c.p.}} = R_{\text{u3c.p.3}} - R_{\text{u3c.p.1}} \quad (11)$$

– to compare $\Delta Ru_{1\text{l.c.p.}}$ and $\Delta Ru_{3\text{l.c.p.}}$ and choose the optimal voltage class ($U_{\text{opt.s.}}$) with a minimum difference in discounted costs.

The standard voltage of the three-phase alternating current grid is the voltage class used in the territory of the Russian Federation (Table 2).

Table 2. Scale of rated voltage of a three-phase alternating current grid, kV

| Voltage class, kV |
|-------------------|
| 6  | 10  | 15 | 20  | 35 | -   | -   | -   | 110 | -   | 220 | 330 | 500 | 750 | 1150 |

On the basis of the obtained regression models, a program for choosing the optimal voltage of the power supply system - "PRON" has been created [10]. The program is developed in C#.
2 – the dependence of discounted costs on the voltage class of the distribution grid in the third stage of the life cycle of the field R2 (U);
3 – optimal non-standard voltage of the distribution grid in the first and second stages of the field life cycle $U_{opt1l.c.p.}$;
4 – the nearest lower standard voltage in the first and second stages of the life cycle of the $U_{n.l.1l.c.p.}$ field;
5 – the nearest lower standard voltage in the third stage of the field life cycle $U_{n.l.3l.c.p.}$;
6 – optimal non-standard voltage of the distribution grid in the third stage of the field life cycle $U_{opt3l.c.p.}$;
7 – the nearest higher standard voltage in the first and second stages of the field life cycle $U_{n.h.1l.c.p.}$;
8 – the nearest higher standard voltage in the third stage of the field life cycle $U_{n.h.3l.c.p.}$;
9 – optimal standard voltage during the first and second stages of the field life cycle $U_{opt.s.1l.c.p.}$;
10 – optimal standard voltage in the third stage of the field life cycle $U_{opt.s.3l.c.p.}$;
11 – optimal standard voltage taking into account the life cycle of the field $U_{opt.s.}$;
12 – discounted costs of the nearest lower standard voltage in the third stage of the field life cycle $R_{n.l.3l.c.p.}$;
13 – discounted costs of the nearest higher standard voltage in the third stage of the field life cycle $R_{n.h.3l.c.p.}$;
14 – discounted costs of the nearest lower standard voltage in the first stage of the field life cycle $R_{n.l.1l.c.p.}$;
15 – discounted costs of the nearest higher standard voltage in the first stage of the field life cycle $R_{n.h.1l.c.p.}$.

**Figure 1.** Selection of the optimal voltage taking into account the entire life cycle of the $U_{opt.s.}$ subject to $U_{opt.s.1l.c.p.} = U_{opt.s.3l.c.p.}$.
2 – the dependence of discounted costs on the voltage class of the distribution grid in the third stage of the life cycle of the field R2 (U);
3 – optimal non-standard voltage of the distribution network in the first and second stages of the field life cycle $U_{\text{o}}$;
4 – the nearest lower standard voltage in the first and second stages of the life cycle of the field $U_{\text{n}}$;
5 – the nearest lower standard voltage in the third stage of the field life cycle $U_{\text{n},3}$;
6 – optimal non-standard voltage of the distribution network in the third stage of the field life cycle $U_{\text{o}}$;
7 – the nearest higher standard voltage in the first and second stages of the field life cycle $U_{\text{n},3}$;
8 – the nearest higher standard voltage in the third stage of the field life cycle $U_{\text{n},3}$;
9 – optimal standard voltage during the first and second stages of the field life cycle $U_{\text{o},3}$;
10 – optimal standard voltage in the third stage of the field life cycle $U_{\text{o}}$;
11 – optimal standard voltage taking into account the life cycle of the field $U_{\text{o}}$;
12 – discounted costs of the nearest lower standard voltage in the third stage of the field life cycle $R_{\text{n}}$;
13 – discounted costs of the nearest higher standard voltage in the third stage of the field life cycle $R_{\text{n}}$;
14 – discounted costs of the nearest lower standard voltage in the first stage of the field life cycle $R_{\text{n}}$;
15 – discounted costs of the nearest higher standard voltage in the first stage of the field life cycle $R_{\text{n}}$;
16 – discounted costs $U_{\text{o}}$ in the third period of the life cycle $R_{\text{n}}$;
17 – discounted costs $U_{\text{o}}$ in the first period of the life cycle $R_{\text{n}}$;
18 – the difference between the discounted costs of the third to the first period of the life cycle of the optimal standard voltage class of the third period of the life cycle $R_{\text{n}}$;
19 – discounted costs $U_{\text{o}}$ in the third period of the life cycle $R_{\text{n}}$;
20 – discounted costs $U_{\text{o}}$ in the first period of the life cycle $R_{\text{n}}$;
21 – the difference in the discounted costs of the third to the first period of the life cycle of the optimal standard voltage class of the first period of the life cycle $R_{\text{n}}$.

Figure 2. Choosing the optimal voltage taking into account the entire life cycle of the gas field $U_{\text{o}}$ subject to $U_{\text{o}} < U_{\text{o}}$.

4. Results of the experiments
The analysis of the existing distribution grids of the Second section of the Achimov deposits has been carried out according to the criterion of the optimal voltage class, taking into account the developed factor "load growth factor" at different stages of the field life cycle, considering the industry specifics in the "PRON" computer program. The calculation results are presented in Table 3.

Table 3. Technical characteristics of the existing distribution grids for the gas well pads of the Second section of the Achimov deposits at the Urengoy oil and gas condensate field

| No | line | $N_{\text{cluster}}$, PCs | $l$, km | $U$, kV | Calculated optimal class voltage, kV |
|----|------|-----------------|-------|------|----------------------------------|
|    |      |                 |       |      | Life cycle period |
|    |      |                 |       |      | I $K_{incr}=1$ | II $K_{incr}=1$ | III $K_{incr}=10$
|----|------|-----------------|-------|------|-------------------|-----------------|------------------|
|  1 | OHL Cluster K2A06 | 8 | 13.1 | 10 | 10 | 10 | 20
|  2 | OHL Cluster K2A32 | 12 | 12.1 | 10 | 10 | 10 | 20

The Second section of the Achimov deposits, CGPP 22
5. Discussion
When designing a power supply system for new gas fields for a distribution grid should be 20 kV. This voltage class has a sufficient power reserve for the transmission of electricity, taking into account the entire life cycle of the field at the lowest discounted costs.

6. Conclusions
An algorithm for solving the problem of choosing a standard optimal voltage class for a power supply system has been developed, taking into account the specifics and life cycle of a gas field with a complex change in influencing factors.

7. References

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