Optimizing the Power Supply System of the Gas Well Clusters by Choosing a Progressive Voltage Class Considering the Total Life Cycle of a Gas Field

I M Bogachkov¹, R N Khamitov²
¹OOO "Gazprom design" Tyumen Branch, Tyumen
²Professor of the Department of Electrical Engineering Omsk State Technical University, Omsk
Professor of the Department of "Power Engineering" Tyumen Industrial University, Tyumen

Abstract. The paper outlines the issue of correctly choosing the voltage class for power supply of the gas well clusters considering all periods of the life cycle of the Western Siberia gas fields. The voltage class incorrectly chosen at the design stage hinders the life cycle of a gas field. The paper considers the gas field process flow sheet for each period of its life cycle. Using the experimental design theory, mathematical models have been developed for calculating the optimal voltage class and discounted costs for the gas well cluster power supply system. An algorithm for choosing the optimal voltage has been developed, and an example of calculating the optimal voltage for the distribution networks of the Western Siberia gas fields is given. A progressive voltage class for the distribution networks has been proposed. Conclusions have been drawn.

1. Introduction
In the time of developing the design documents for operating Western Siberia gas fields (80th-90th), there was no experience in operating fields in the last period of their life cycle. Therefore, problems currently occur, associated with the need for a serious reconstruction of the power supply system to provide electricity to distributed gas compression consumers significantly affecting the gas production profitability.

Given this, when designing new gas fields, the experience of operating fields gained in the last period of their life cycle should be used.

2. Relevance
All gas fields pass four life cycle periods [1], [2]:
1. Increasing production—the pilot production (PP) period.
2. Stable production.
3. Declining production.
4. Liquidation of the field.

From the first to the third periods, the gas production volume, average formation pressure, and bottom hole pressure of wells decrease in time.

To maintain the gas production volume at the fields, booster compressor stations (BCS) are introduced in the second period and the BCS capacity increases in the third one, and modern
techniques are applied with installing mobile compressor units (MCU) at the wellheads of the gas well clusters [3].

During the entire gas field life cycle, its process flow sheet changes. In the first period, the formation energy is used for gas production; in subsequent ones, the formation energy decreases, which leads to the need to introduce the BCSs and MCUs in the second and third (the declining production period, when the equilibrium water content in the raw gas increases) periods, respectively.

Transforming the process flow sheet leads to a change in the gas field process equipment composition. Each period of the field life cycle is characterized by different power consumption.

The power supply section project documents are currently developed considering mainly the load of only the first period, and only sometimes the second one (depending on the designer qualification), and do not consider the load of the third period of the gas field life cycle. This situation subsequently leads to the need for a serious reconstruction of the power supply system and, as a result, high capital expenditures.

Currently, most of the large gas fields in Western Siberia are at the last stage of Cenomanian reservoir development—the third, declining production period of the life cycle [4], [5].

To extend the profitability period for the low-pressure Cenomanian gas production at the Western Siberia fields, the distributed gas compression is implemented using MCUs:
- the Vyngapurovsk gas field: 9 MKUs have been commissioned with a unit capacity of 0.45 and 1 MVA,
- the Yamburg oil and gas condensate field: 52 MCUs are being commissioned with a unit capacity of 1 MVA,
- the Yubileinoye gas field: 2 MCUs are being commissioned with a unit capacity of 1 MVA,
- the Zapadno-Tarkosalinsky gas field: 2 MCUs are being commissioned with a unit capacity of 1 MVA.

To implement the distributed gas compression using MCUs at the fields specified, the entire existing power supply system is currently being reconstructed.

Thus, one of the key problems of the gas industry electric power sector is creating an optimal power supply system at the design stage, considering the prospective growth of power loads.

If parameters such as the power source, the power supply circuit structure, the number and capacity of transformer substations, and the layout of substations on the gas field territory chosen at the design stage without considering the third period can be corrected (e.g., change the power of transformers or the number of transformer substations, etc.) during the field operation, then the voltage class, which is the main parameter of the power supply system, should be chosen initially considering all periods of the field's life cycle.

Very little attention is currently paid to optimizing the parameters of medium voltage distribution networks [6].

The initially correctly chosen voltage improves the power supply system reliability (by increasing the relay protection and automation (RPA) sensitivity), allows reducing discounted costs, the consumption of non-ferrous metals, and energy losses, and increasing the transmission distance at the same power and vice versa, which is very important for the gas industry.

Also, a rational choice of voltage class and improved energy efficiency allow minimizing the power supply costs, while retaining the amount of products [7], [8].

3. Research objective
The gas field power supply design experience has shown that some technical solutions can be taken separately, but most technical and economic problems are closely interrelated. E.g., to arrange transformer substations on the general gas field layout, the number and capacity of these substations, the power supply circuit, the voltage class, and the transmission wire cross-section should first be determined.
Therefore, the joint consideration of design problems such as the choice of the optimal power supply system voltage and the economically feasible layout of substations within the gas field power supply systems is quite logical and expedient.

The optimal voltage class for the gas field power supply system means the voltage class at which the system has the minimum discounted costs, considering the entire life cycle of the field.

The technique proposed is based on a rather general mathematical experimental design apparatus.

The main research objective is getting a mathematical model–response function (regression equation), i.e. the dependence between the output indicator of the Y object and the independent controlled input factors x1, x2, ..., x_n [9], [10], [11].

Thereat, a set of variable factors is found for which the chosen regression equation assumes an extreme value:

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

(1)

where \( b_0, b_i, b_{i,j} \) are the polynomial coefficients.

The idea of the proposed technique for determining the optimal voltage consists in planning a full factorial experiment (FFE) of the \( 2^k \) type, where \( k \) is the number of factors considered.

An experiment realizing all the possible factor level combinations is called a full factorial experiment [12].

It should be noted that the experimental design technique is an active experiment.

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

The mathematical experimental design theory allows finding the polynomial coefficients (1), evaluate their significance, and check the adequacy of the general sought-for function representation by the polynomial found in certainly designed experiments.

Thus, to find the optimal voltage, a technique is proposed based on the possibility of building an equation of the form \( R = f(U) \) using the results of determining the discounted costs at standard voltages, on the one hand, and mathematical interpolation theories, on the other hand.

Having found the first derivative of this equation and equating it to zero, we can determine the theoretical minimum of discounted costs and the corresponding optimal voltage, which will be defined using the Lagrange interpolation theory [13], [14].

The discounted costs determine the economic feasibility of the chosen technical solution.

4. Theoretical

External power supply of the gas well clusters is arranged according to the 3rd category of reliability [15]. The most common feed line circuit is ‘single-end feed single through trunk main’.

The power supply circuit for gas well clusters is shown in Fig. 1.

![Diagram](https://example.com/diagram)

**Figure 1.** ‘Single-End Feed Single Through Trunk Main’ Type Power Supply Circuit of Gas Well Clusters.
When building a mathematical model, the below design power of a single cluster has been adopted: in the first/second period of the life cycle–0.1 MW, and in the third one–1 MW.

The solution to the problem set is associated with the chosen list of factors affecting the choice of the voltage class in one degree or another.

In Table 1, for each affecting factor, the variation ranges are chosen, which allow covering a significant number of power supply circuits for gas well clusters.

### Table 1. Main Factor Variation Levels and Ranges.

| Factor | Factor Description                                      | Basic level, $x_{i0}$ | Variation Range, $A_x$ | Upper level, «+» | Lower level, «-» |
|--------|--------------------------------------------------------|------------------------|------------------------|------------------|------------------|
| Distribution network–single through trunk main | Number of gas well clusters N, pcs.                     | 6                      | 4                      | 10               | 2                |
|        | Distance from power supply to consumer L, km           | 10.25                  | 9.75                   | 20               | 0.5              |
|        | Electrical load growth factor during the period of declining production $k_{gr}$, p.u. | 5.5                    | 4.5                    | 10               | 1                |
|        | OHL power transfer distribution factor $k_{dist}$, p.u. | 0.7                    | 0.15                   | 0.85             | 0.55             |

Table 2 shows the change in the factors for the distribution network of the gas well cluster power supply system; the table contains sixteen combinations got in the FFE design of the $2^4$ type.

### Table 2. Changes in Factors in the FFE $2^4$.

| Experiment No. | Number of well clusters N, pcs. | Number of gas well clusters N, pcs. | Distance from power supply to consumer L, km | Electrical load growth factor during the period of declining production $k_{gr}$, p.u. | OHL transfer distribution factor $k_{dist}$, p.u. | Power transfer distribution factor $k_{dist}$, p.u. |
|----------------|---------------------------------|-------------------------------------|---------------------------------------------|----------------------------------------------------------------------------------|------------------------------------------------|------------------------------------------------|
| x1             | 10                              | 0.5                                 | 1                                           | 0.55                                                                            | 0.55                                              | 0.55                                              |
| x2             | 2                                | 20                                  | 1                                           | 0.55                                                                            | 0.55                                              | 0.55                                              |
| x3             | 2                                | 0.5                                 | 10                                          | 0.55                                                                            | 0.55                                              | 0.55                                              |
| x4             | 2                                | 0.5                                 | 1                                           | 1                                                                               | 1                                                 | 1                                                  |
| 5              | 2                                | 0.5                                 | 1                                           | 0.55                                                                            | 0.55                                              | 0.55                                              |
| 6              | 10                               | 20                                  | 10                                          | 1                                                                               | 1                                                 | 1                                                  |
| 7              | 10                               | 20                                  | 1                                           | 0.55                                                                            | 0.55                                              | 0.55                                              |
Table 3 shows the discounted cost calculation results for different voltage classes: 6, 10, 20, 35, and 110 kV.

To develop a mathematical model to calculate the optimal voltage using a software [16], 80 power supply circuits were built for the gas well clusters.

Discounted costs were calculated for each power supply circuit.

To calculate the discounted costs of power supply circuits for different voltage classes, the author has developed the PRADIZ software [17].

The software was developed in the Excel language according to [18], [19], and [20].

Table 3. Discounted Costs at Complex Change in Factors.

| Experiment No. | Discounted Costs, mln. RUB | Voltage Class |
|----------------|-----------------------------|---------------|
|                | *6 kV* | *10 kV* | *20 kV* | *35 kV* | *110 kV* |
| 1              | 47.60  | 46.60   | 47.60   | 128.90  | 313.20   |
| 2              | 233.80 | 233.00  | 232.60  | 315.40  | 524.60   |
| 3              | 24.70  | 20.60   | 43.20   | 71.50   | 236.00   |
| 4              | 18.40  | 18.30   | 18.50   | 37.60   | 88.90    |
| 5              | 18.30  | 18.20   | 18.50   | 37.60   | 88.90    |
| 6              | 3,281.10 | 2,795.90 | 826.40 | 746.80 | 1,502.40 |
| 7              | 293.30 | 271.80  | 263.20  | 407.40  | 749.00   |
| 8              | 115.80 | 84.80   | 182.60  | 302.00  | 1,048.70 |
| 9              | 48.90  | 47.00   | 47.20   | 128.90  | 313.20   |
| 10             | 553.40 | 308.10  | 255.10  | 330.40  | 631.10   |
When building the general model, the optimal voltage is chosen using the Lagrange technique by three points.

To do this, the discounted cost calculation results were analyzed for five voltage classes 6, 10, 20, 35, and 110 kV in each experiment (Table 3), which allowed choosing three discounted cost values: the lowest discounted costs \( R_2 \) and two closest upper and lower values \( R_1 \) and \( R_3 \), respectively.

The three discounted cost points chosen and the corresponding voltage class for each experiment are given in Table 4.

**Table 4. Discounted Costs and Corresponding Voltage Classes.**

| Experiment No. | Voltage Class, kV | Discounted Costs, mln. RUB |
|---------------|------------------|----------------------------|
|               | U1 | U2 | U3 | R1  | R2  | R3  |
| 1             | 6  | 10 | 20 | 47.60 | 46.60 | 47.60 |
| 2             | 10 | 20 | 35 | 233.00 | 232.60 | 315.40 |
| 3             | 6  | 10 | 20 | 24.70  | 20.60  | 43.20  |
| 4             | 6  | 10 | 20 | 18.40  | 18.30  | 18.50  |
| 5             | 6  | 10 | 20 | 18.30  | 18.20  | 18.50  |
| 6             | 20 | 35 | 110| 826.40 | 746.80 | 1,502.40 |
| 7             | 10 | 20 | 35 | 271.80 | 263.20 | 407.40 |
| 8             | 6  | 10 | 20 | 115.80 | 84.80  | 182.60 |
| 9             | 6  | 10 | 20 | 48.90  | 47.00  | 47.20  |
| 10            | 10 | 20 | 35 | 308.10 | 255.10 | 330.40 |
| 11            | 10 | 20 | 35 | 233.30 | 232.70 | 315.40 |
| 12            | 6  | 10 | 20 | 30.00  | 22.50  | 43.70  |
| 13            | 10 | 20 | 35 | 1,140.70 | 671.90 | 689.20 |
The optimal voltage is calculated by the analytical equation based on three points set by coordinates U1, R1; U2, R2; and U3, R3:

\[ F(U) = F_1(U)R1 + F_2(U)R2 + F_3(U)R3 \]  
(2)

Analytical expression (2) determines the dependence between the standard voltage and discounted costs.

The equation for determining the optimal voltage by three points is as follows:

\[ U_{opt} = \frac{R_1(U_2 + U_3) + R_2(U_1 + U_3) + R_3(U_1 + U_2)}{2(\frac{R_1}{A} + \frac{R_2}{B} + \frac{R_3}{C})}, \]  
(3)

where:

\[ A = (U_1 - U_3)(U_1 - U_2), \]  
(4)

\[ B = (U_2 - U_1)(U_2 - U_3), \]  
(5)

\[ C = (U_3 - U_1)(U_3 - U_2). \]  
(6)

As an example, let us give the optimal voltage calculation for the first experiment (Table 4). The lowest discounted costs for the experiment R2 = 46.6 mln. RUB at the voltage class U2 = 10 kV.

Let us choose the two discounted cost values closest to R2:
- upper R3 = 47.60 mln. RUB,
- lower R1 = 47.60 mln. RUB,
and the corresponding voltages:
- upper U3 = 20 kV,
- lower U1 = 6 kV.

The coefficients A, B, and C are written as follows:

\[ A = (10 - 20)(10 - 6) = 56, \]
\[ B = (10 - 6)(10 - 20) = -40, \]
\[ C = (20 - 6)(20 - 10) = 140. \]

Then, the optimal voltage for the first experiment is:

\[ U_{opt} = \frac{47.60}{56}(10+20) + \frac{46.60}{40}(6+20) + \frac{47.60}{140}(6+10) \approx 13.0 \text{ kV}. \]  
(7)

The off-standard optimal voltage values have been calculated for all experiments and are given in Table 5.

The initial data to build a mathematical model are the off-standard optimal voltage values calculated using the Lagrange technique.

The technique for optimizing the external power supply of gas fields using the experimental design theory comprises building the mathematical models that link the voltage class with the greatest impact factors.

Based on the results obtained, a mathematical model can be built that allows determining the optimal voltage.

The general view of this model is determined by the following equation:

\[ U_{opt} = b_0 + b_1*x_1 + b_2*x_2 + b_3*x_3 + b_4*x_4 + b_{12}*x_1*x_2 + b_{13}*x_1*x_3 + b_{23}*x_2*x_3 + b_{34}*x_3*x_4 + b_{123}*x_1*x_2*x_3 + b_{124}*x_1*x_2*x_4 + b_{134}*x_1*x_3*x_4 + b_{234}*x_2*x_3*x_4 + b_{1234}*x_1*x_2*x_3*x_4, \]  
(8)

Where b0, b1, b2, b3 are the polynomial coefficients; x1, x2, x3, x4 are factors.
The experiment for the distribution network of the gas well cluster power supply system comprises N = 24 = 16 calculations, for each of which a planned combination of factors x1, x2, x3, x4 is set and Uopt determined.

The calculation conditions are written in the form of an experimental design matrix (Table 5), where the columns x1...x1x2x3x4 correspond to the coded factor values.

The design matrix has the interaction effects of:
- the first order - x1x2, x1x3, x2x3, x1x4, and x2x4,
- the second order - x1x2x3, x1x2x4, x1x3x4, and x2x3x4,
- the third order - x1x2x3x4.

Table 5. The FFE Design Matrix $2^4$.

| Experiment No. | x0 | x1 | x2 | x3 | x4 | x1x2 | x1x3 | x2x3 | x1x4 | x2x4 | x3x4 |
|----------------|----|----|----|----|----|------|------|------|------|------|------|
| 1              | 1  | 1  | -1 | -1 | -1 | -1   | -1   | 1    | -1   | 1    | 1    |
| 2              | 1  | -1 | 1  | -1 | -1 | -1   | -1   | 1    | -1   | 1    | 1    |
| 3              | 1  | -1 | -1 | 1  | -1 | -1   | -1   | 1    | 1    | -1   | 1    |
| 4              | 1  | -1 | -1 | -1 | 1  | 1    | 1    | -1   | -1   | 1    | 1    |
| 5              | 1  | -1 | -1 | -1 | -1 | 1    | 1    | 1    | 1    | 1    | 1    |
| 6              | 1  | 1  | 1  | 1  | 1  | 1    | 1    | 1    | 1    | 1    | 1    |
| 7              | 1  | 1  | 1  | -1 | -1 | -1   | -1   | -1   | -1   | -1   | 1    |
| 8              | 1  | 1  | -1 | 1  | -1 | -1   | -1   | -1   | 1    | -1   | 1    |
| 9              | 1  | 1  | -1 | -1 | 1  | -1   | -1   | 1    | 1    | -1   | -1   |
| 10             | 1  | -1 | 1  | 1  | -1 | -1   | -1   | 1    | 1    | -1   | -1   |
| 11             | 1  | -1 | -1 | 1  | -1 | -1   | -1   | 1    | 1    | -1   | -1   |
| 12             | 1  | -1 | -1 | -1 | 1  | 1    | 1    | -1   | -1   | -1   | 1    |
| 13             | 1  | 1  | 1  | 1  | 1  | -1   | 1    | 1    | -1   | -1   | 1    |
| 14             | 1  | 1  | 1  | -1 | 1  | 1    | -1   | 1    | 1    | -1   | -1   |
| 15             | 1  | 1  | -1 | 1  | 1  | -1   | 1    | 1    | -1   | 1    | -1   |
| 16             | 1  | -1 | 1  | 1  | 1  | -1   | 1    | 1    | -1   | 1    | -1   |
| Ubi            | 17.35 | 2.08 | 5.46 | 2.89 | 1.70 | 1.33 | 0.94 | 3.70 | 0.90 | 1.18 | 1.06 |
| R20bi          | 506.4 | 274.7 | 449.9 | 333.9 | 116.9 | 241.0 | 228.5 | 310.6 | 92.81 | 112.0 | 92.66 |
| R35bi          | 398.5 | 201.5 | 352.6 | 251.8 | 133.0 | 175.6 | 180.5 | 238.5 | 81.06 | 129.7 | 128.7 |
| R110bi         | 226.3 | 86.05 | 151.8 | 85.60 | 12.00 | 42.54 | 70.89 | 44.06 | 9.06 | 10.49 | 11.74 |
| R220bi         | 296.4 | 102.6 | 151.5 | 74.03 | 11.16 | 12.30 | 56.70 | 12.34 | 6.06 | 1.23 | 11.05 |
| R330bi         | 661.4 | 278.6 | 202.0 | 242.5 | 25.71 | -18.35 | 166.4 | -15.86 | 13.03 | -12.01 | 25.69 |

8
| Item No. | Parameter | Formula |
|---------|-----------|---------|
|         | Distribution network–single through trunk main |

When calculating the optimal voltage using mathematical models, the voltage value, as a rule, turns out to be off standard.

Mathematical models of the optimal off-standard voltage and discounted costs for the external power supply of a gas field are given in Table 6.

Table 6. Mathematical Models of Optimal Off-Standard Voltage and Discounted Costs for the External Power Supply of a Gas Field.
Optimal off-standard voltage, kV

\[ U_{opt} = 17.4 + 2.1 \times x_1 + 5.5 \times x_2 + 2.9 \times x_3 + 1.7 \times x_4 + 1.33 \times x_1 \times x_2 + 0.94 \times x_1 \times x_3 + 3.69 \times x_2 \times x_3 + 0.9 \times x_1 \times x_4 + 1.79 \times x_2 \times x_4 + 1.06 \times x_3 \times x_4 + 1.35 \times x_1 \times x_2 \times x_3 \times x_4 + 0.45 \times x_1 \times x_3 \times x_4 + x_3 \times x_4 + x_2 \times x_3 \times x_4 + 1.14 + 0.63 \times x_1 \times x_2 \times x_3 \times x_4 \]

\[ R_{6 \text{ kV}} = 506.46 + 274 \times x_1 + 4503 \times x_2 + 334 \times x_3 + 117 \times x_4 + 241 \times x_1 \times x_2 + 229 \times x_1 \times x_3 \times x_2 + 311 \times x_2 \times x_3 + 93 \times x_3 \times x_4 + 112 \times x_1 \times x_2 \times x_3 + 93 \times x_3 \times x_4 + 89 \times x_1 \times x_2 \times x_4 + 49 \times x_2 \times x_3 \times x_4 + 49 \times x_1 \times x_3 \times x_4 + 49 \times x_1 \times x_2 \times x_3 \times x_4 \]

Discounted costs for 6 kV voltage, mln. RUB

\[ R_{10 \text{ kV}} = 400 + 202 \times x_1 + 353 \times x_2 + 252 \times x_3 \times x_4 \]

Discounted costs for 10 kV voltage, mln. RUB

\[ R_{20 \text{ kV}} = 226 + 86 \times x_1 + 151 \times x_2 + 85.6 \times x_3 \times x_4 \]

Discounted costs for 20 kV voltage, mln. RUB

\[ R_{35 \text{ kV}} = 296.5 + 102.6 \times x_1 + 151 \times x_2 + 74 \times x_3 \times x_4 \]

Discounted costs for 35 kV voltage, mln. RUB

\[ R_{110 \text{ kV}} = 661 + 202 \times x_1 + 202 \times x_2 + 242 \times x_3 + 25.7 \times x_4 + 18.35 \times x_1 \times x_2 + 166 \times x_1 \times x_3 + 13 \times x_1 \times x_2 \times x_3 \times x_4 + 13 \times x_1 \times x_2 \times x_3 \times x_4 + 13 \times x_1 \times x_2 \times x_3 \times x_4 + 12 \times x_2 \times x_3 \times x_4 + 24.7 \times x_1 \times x_2 \times x_3 \times x_4 \]

Discounted costs for 110 kV voltage, mln. RUB

For the standard voltage of a three-phase AC network—the voltage class adopted in the Russian Federation [21], [22], see Table 7.

**Table 7. The Standard Rated Voltage Scale.**

| Voltage Class, kV | 6  | 10 | 15 | 20 | 35 | - | - | 110 | 150 | 220 | 330 | 500 | 750 | 1150 |
|-------------------|----|----|----|----|----|---|---|-----|-----|-----|-----|-----|-----|-----|-----|
|                   |    |    |    |    |    |   |   |     |     |     |     |     |     |     |     |
The algorithm for calculating the optimal standard voltage is as follows:
1. Determine the source data (the number of the gas well clusters, the distance from the power source to the consumer, the electrical load growth factor, and the OHL power transfer distribution factor).
2. Calculate the optimal off-standard voltage using a mathematical model (according to Table 6).
3. Find the closest upper and the lower standard voltage values using the standard rated voltages scale (according to Table 7).
4. Calculate the discounted costs (according to Table 6) for both standard voltage values.
5. Compare the discounted costs and choose the voltage class with the lowest cost.

Based on the algorithm developed, the PRON software has been created in the C# programming language to choose the optimal voltage of the external power supply system.

5. Practical significance. An example of calculating the optimal voltage class for the gas well cluster power supply

5.1. The first operation
The below source data are determined based on the design specification:
- the field layout (Fig. 2),
- the number of the gas well clusters is 9,
- the distance from the power source to the consumer is 8.97 km,
- the type of external power supply circuit for the gas well clusters is single through trunk main,
- the electrical load growth factor during the periods of increasing and stable production is 1 p.u. (from Table 1),
- the electrical load growth factor during the period of declining production is 10 p.u. (from Table 1),
- the power transfer distribution factor is 0.55 p.u. (the load is evenly distributed along the line (from Table 1)).

Figure 2. The Gas Field Layout
1 - Power supply; 2 - Gas well clusters; 3 - Overhead line.
5.2. The second operation
The natural factor values (source data) are converted into the coded ones:

Factor x1—the gas well cluster number:

\[ x_1 = \frac{x_{1} - x_{1,\text{min}}}{\Delta x_1} = \frac{9 - 6}{4} = 0.75 \text{ p.u.} \quad (9) \]

Factor x2—the average length of the overhead line:

\[ x_2 = \frac{x_{2} - x_{2,\text{min}}}{\Delta x_2} = \frac{8.97 - 10.25}{9.75} = -0.131 \text{ p.u.} \quad (10) \]

Factor x3—the electrical load growth factor \( k_{gr} \):

In the first and second gas field development periods, the electrical load growth factor for the gas well clusters is \( k_{gr} = 1 \text{ p.u.} \),

\[ x_3 = \frac{x_{3} - x_{3,\text{min}}}{\Delta x_3} = \frac{1 - 5.5}{4.5} = -1 \text{ p.u.} \text{ (for the first and second periods)} \quad (11) \]

In the third gas field development period, the electrical load growth factor for the gas well clusters is \( k_{gr} = 10 \text{ p.u.} \),

\[ x_3 = \frac{x_{3} - x_{3,\text{min}}}{\Delta x_3} = \frac{10 - 5.5}{4.5} = 1 \text{ p.u.} \text{ (for the third period)} \quad (12) \]

Factor x4—the OHL power transfer distribution factor \( k_{dist} \):

Fig. 2 shows that the load is evenly distributed along the overhead line, therefore, \( k_{dist} = 0.55 \text{ p.u.} \) is adopted.

\[ x_4 = \frac{x_{4} - x_{4,\text{min}}}{\Delta x_4} = \frac{0.55 - 0.7}{1.5} = -1 \text{ p.u.} \quad (13) \]

5.3. The third operation
The optimal voltage of the gas well cluster external power supply for the first and second periods of the gas field life cycle is found.

When calculating the optimal voltage using mathematical models, the voltage value, as a rule, turns out to be off standard.

Mathematical models of the optimal non-standard voltage and discounted costs for the external power supply of the gas field are given in Table 6.

When substituting the found factor values into the equation (Table 6), the off-standard optimal voltage value is got:

\[
U_{\text{opt}} = 17.4 + 2.1 * 0.75 + 5.5 * (-0.131) + 2.9 * (-1) + 1.7 * (-1) + 1.33 * 0.75 *
(-0.131) + 0.94 * 0.75 * (-1) + 3.69 * (-0.131) * (-1) + 0.9 * 0.75 * (-0.131) + 1.79 *
(-0.131) * (-1) + 1.06 * (-1) * (-1) + 1.35 * 0.75 * (-0.131) * (-1) + 0.85 * 0.75 *
(-0.131) * (-1) + 0.45 * 0.75 * (-1) * (-1) + 1.14 * (-0.131) * (-1) * (-1) + 0.63 * 0.75 *
(-0.131) * (-1) * (-1) = 14.85 \text{ kV}. \quad (14)
\]

The closest upper (Usu) and lower (Usl) standard voltage values are found by Table 7.

\[
\text{Usl} = 10 \text{ kV} < 14.85 \text{ kV} < \text{Usu} = 20 \text{ kV} \quad (15)
\]

5.4. The fourth operation
To determine the standard optimal voltage using the equations in Table 6, the discounted costs are calculated for the closest upper and lower standard voltage values:

\[
R_{10 \text{ kV}} = 400 + 202 * 0.75 + 353 * (-0.131) + 252 * (-1) + 133 * (-1) + 176 * 0.75 *
(-0.131) + 180 * 0.75 * (-1) + 239 * (-0.131) * (-1) + 81 * 0.75 * (-1) + 130 * (-0.131) *
(-1) + 129 * (-1) + 169 * 0.75 * (-0.131) * (-1) + 78.3 * 0.75 * (-0.131) * (-1) +
76.9 * 0.75 * (-1) * (-1) + 125.6 * (-0.131) * (-1) * (-1) + 74.2 * 0.75 * (-0.131) * (-1) *
(-1) = \text{RUB 142.78 min.} \quad (16)
\]

\[
R_{20 \text{ kV}} = 226 + 86 * 0.75 + 151 * (-0.131) + 85.6 * (-1) + 12 * (-1) + 45.3 * 0.75 *
(-0.131) + 71 * 0.75 * (-1) + 44.1 * (-0.131) * (-1) + 9.06 * 0.75 * (-1) + 10.48 *
(-0.131) * (-1) + 11.73 * (-1) * (-1) + 41.8 * 0.75 * (-0.131) * (-1) + 7.7 * 0.75 *
(-0.131) * (-1) + 8.83 * 0.75 * (-1) * (-1) + 10.13 * (-0.131) * (-1) * (-1) + 7.33 * 0.75 *
\]
$$(-0.131) \times (-1) \times (-1) = \text{RUB} \ 136.94 \text{ mln.}$$  

(17)

$$R_{10} = \text{RUB} \ 142.78 \text{ mln.}$$  

(18)

$$R_{20} = \text{RUB} \ 136.94 \text{ mln.}$$  

(19)

5.5. **The fifth operation**

A standard voltage with a lowest discounted cost is chosen.

For the given power supply circuit, the optimal voltage is 20 kV.

The discounted costs are $R_{20} = \text{RUB} \ 450.94 \text{ mln.}$

For the first and second periods of the life cycle, the optimal voltage of the external power supply is 20 kV.

5.6. **The sixth operation**

The optimal voltage of the gas well cluster external power supply for the **third life cycle period** of the gas fields is determined.

$$U_{\text{opt}} = 17.4 + 2.1 \times 0.75 + 5.5 \times (-0.131) + 2.9 \times 1 + 1.7 \times (-1) + 1.33 \times 0.75 \times (-0.131) + 0.94 \times 0.75 \times 1 + 3.69 \times (-0.131) \times 1 + 0.9 \times 0.75 \times (-0.131) + 1.79 \times (-0.131) \times (-1) + 1.06 \times 1 \times (-1) + 1.35 \times 0.75 \times (-0.131) \times 1 + 0.85 \times 0.75 \times (-0.131) \times (-1) + 0.45 \times 0.75 \times 1 \times (-1) + 1.14 \times (-0.131) \times 1 \times (-1) + 0.63 \times 0.75 \times (-0.131) \times 1 \times (-1) \times (-1) = 18.45 \text{ kV}$$  

(20)

5.7. **The seventh operation**

To determine the standard optimal voltage using the equations in Table 6, the discounted costs are calculated for the closest upper and lower standard voltage values:

$$R_{10 \text{ kV}} = 400 + 202 \times 0.75 + 353 \times (-0.131) + 252 \times 1 + 133 \times (-1) + 176 \times 0.75 \times (-0.131) + 180 \times 0.75 \times 1 + 239 \times (-0.131) \times 1 + 81 \times 0.75 \times (-1) + 130 \times (-0.131) \times (-1) + 129 \times (-1) \times (-1) + 169 \times 0.75 \times (-0.131) \times (-1) + 78.3 \times 0.75 \times (-0.131) \times (-1) + 76.9 \times 0.75 \times (-1) \times (-1) + 125.6 \times (-0.131) \times (-1) \times (-1) + 74.2 \times 0.75 \times (-0.131) \times (-1) \times (-1) = 495.09 \text{ mln. RUB}$$  

(21)

$$R_{20 \text{ kV}} = 226 + 86 \times 0.75 + 151 \times (-0.131) + 85.6 \times 1 + 12 \times (-1) + 45.3 \times 0.75 \times (-0.131) + 71 \times 0.75 \times 1 + 44.1 \times (-0.131) \times 1 + 9.06 \times 0.75 \times (-1) + 10.48 \times (-0.131) \times (-1) + 11.73 \times 1 \times (-1) + 41.8 \times 0.75 \times (-0.131) \times 1 + 7.7 \times 0.75 \times (-0.131) \times (-1) + 8.83 \times 0.75 \times 1 \times (-1) + 10.13 \times (-0.131) \times 1 \times (-1) + 7.33 \times 0.75 \times (-0.131) \times 1 \times (-1) \times (-1) = \text{RUB} \ 362.26 \text{ mln.}$$  

(22)

$$R_{10} = \text{RUB} \ 495.09 \text{ mln.}$$  

(23)

$$R_{20} = \text{RUB} \ 362.26 \text{ mln.}$$  

(24)

5.8. **The eighth operation**

A standard voltage with a lowest discounted cost is chosen.

**In the third period** of the field’s life cycle, for this power supply circuit, the optimal voltage of the gas well cluster external power supply is 20 kV.

The minimum discounted costs are $R_{20} = \text{RUB} \ 362.26 \text{ mln.}$

For the gas field external power supply, for the entire life cycle of the field, we accept the voltage class of **20 kV**.

Fig. 3. shows a surface plot of the target functions for an example of the optimal distribution network voltage calculation.
Figure 3. Target Function of the Distribution Network for an Example of Choosing the Optimal Voltage Class from Appendix A.

1–the target function surface for \( k_{gr} = 1 \) p.u. and \( L = 8.75 \) km,

2–the target function surface for \( k_{gr} = 10 \) p.u. and \( L = 8.75 \) km.

Fig. 3 shows that the optimal standard voltage class is 20 kV.

6. Experimental research results
In the PRON software, the power supply system of the distribution network of some operating Western Siberia gas fields has been studied for the optimal voltage class. The research results are given in Figs. 4 & 5.
Figure 4. The Dependence between the Voltage Class and the Discounted Costs of the OHL Distribution Network. The Yubileynoe Gas Field.
Figure 5. The Dependence between the Voltage Class and the Discounted Costs of the CGTP 22 OHL Distribution Network. The Second Section of the Achimov Deposits. The Urengoy Gas Field.

When analyzing the plots of the dependence between the voltage class and the discounted costs of the distribution network, it can be concluded that the voltage class of 20 kV is optimal for the distribution network of the gas well cluster external power supply. With an increase in electrical load, the difference between the discounted costs is minimal.

7. Conclusion
1. The study has shown that when building mathematical models for choosing the optimal voltage class of the distribution network of the gas well cluster power supply, all the affecting factors should be considered and significant factors chosen as variables such as the gas well cluster number, the distance from the power source to the consumer, the electrical load growth factor, and the OHL power transfer distribution factor.
2. The off-standard values of the optimal voltage have been calculated using the Lagrange interpolation technique for all combinations of changes in the affecting factors. A single mathematical model with linear polynomials for choosing the optimal voltage has been developed.

3. An algorithm has been developed for choosing the standard optimal voltage class for the gas well cluster power supply, considering all periods of the gas field life cycle with a complex change in the affecting factors.

4. The external power supply of some operating Western Siberia gas fields has been studied for the optimal voltage class. It has been found that the optimal voltage class for the distribution network is **20 kV**.

8. References

[1] Beznosikov A F 2016 Development And Operation Of Gas And Gas Condensate Fields: Study Guide (Tyumen: TIU) 80 P

[2] Khachaturov V R 2016 Mathematical Modeling Of Liquidation Of Gas Fields Exposition Oil Gas 6(52) pp 34 - 36

[3] Vorontsov M A 2014 Prospects For The Application Of Straightened Compression In Field Gas Production Systems Vestsi Gazovoy Nauki: Nauch. Those. Sb. 4(20) pp 164-173

[4] Sarancha A V 2014 Low-Pressure Gas Of Cenomanian Deposits Of Yamalo-Nenets Autonomous Okrug Academic Journal Of Western Siberia T 10 3(52) pp 146-147

[5] Minlikaev V Z 2015 Application Of Mobile Compressor Units At The Final Stage Of Development Of Gas Deposits Gas Industry 1(717) pp 15-17

[6] Murthy G V K 2012 Reliability Improvement Of Radial Distribution System With Distributed Generation International Journal Of Engineering Science And Technology (IJEST) Vol 4 9

[7] Prof. Dr.-Ing. Franz Wosnitza, FH Aachen, Fachbereich Elektrotechnik Und Informationstechnik. Energieeffizienz Und Energiemanagement [Electron. Resource] Https://Www.Springer.Com/De/Book/9783834819413 (Date Of Treatment 02/14/2020)

[8] IT-Gestütztes Ressourcen Und Energiemanagement [Electron. Resource] Https://Www.Springer.Com/De/Book/97836423 50290 (Date Of Treatment 02/14/2020)

[9] Ivobozhenko B A 1975 Planning An Experiment In Electromechanics (M: Energiya)

[10] Fedorov A A 1980 On the Issue Of Optimizing The Construction Of An Industrial Power Supply Network Tr. Mosk. Energ. In-T Issue 446 pp 10-14

[11] 1966 Methods Of Mathematical Modeling In Power Engineering Ed. Melentieva L A (SR AN SSSR)

[12] Venikov V A 1971 Modeling Of Energy Systems Electricity I

[13] Venikov V A 1978 Theory Of Similarity And Modeling (Moscow: Higher School) 470 P

[14] Kireeva E A 1971 Research, Selection And Optimization Of The Main Parameters Of The Power Supply System Of Industrial Enterprises.: Dis. ... Cand. Those. Sciences (M)

[15] STO Gazprom 2-6.2-1028-2015 Category Of Electrical Receivers Of Industrial Facilities Of PJSC Gazprom (M)

[16] Bogachkov I M Evidence 2018615185 Russian Federation Certificate Of Official Registration Of The Computer Program Program For Calculating The Voltage Loss In The Network 6-35 Kv Applicant And Copyright Holder OOO Gazprom Proetirovaniie (RU) No. 2018612204 Declared 03/12/2018 Publ. 04/27/2018 Register Of Computer Programs 1 P

[17] Bogachkov I M Evidence 2020619917 Russian Federation Certificate Of Official Registration Of The Computer Program Program For Calculating The Discounted Costs Of The External Power Supply System Of Industrial Enterprises (PRADIZ) Applicant And Copyright Holder Bogachkov AND M (RU) No 2020617970 Declared 07/29/2020 Publ. 08/26/2020 Register Of Computer Programs 1 P

[18] Walkenbach D 2011 Excel 2010: Professional Programming In VBA - Excel 2010 Power Programming With VBA (M.: "Dialectics") 944 p ISBN 978-5-8459-1721-8
[19] 2009 Methodology For Assessing The Economic Efficiency Of Investment Projects In The Form Of Capital Investments, JSC "Gazprom" (Moscow)

[20] № VK 477 Dated 06.21.1999 Methodological Recommendations For Evaluating The Effectiveness Of Investment Projects (Second Edition) Approved By The Ministry Of Economy Of The Russian Federation, The Ministry Of Finance Of The Russian Federation The State Committee Of The Russian Federation For Construction, Architectural And Housing Policy (M: Economics)

[21] Shabad M A 2010 Calculations Of Relay Protection And Automation Of Distribution Networks 4th Ed., Isp. And Add. PEIPK (St. Petersburg)

[22] GOST 721-77 Power Supply Systems, Networks, Sources, Converters And Receivers Of Electrical Energy Rated Voltages Over 1000 V