Selecting the Voltage Class for a System of External Power Supply System for the Entire Life Cycle of a Gas Field

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Abstract. This article deals with the problem of voltage class selection taking into consideration all of the life-cycle periods of a gas field based on the data from the existing gas fields in Western Siberia. The incorrect voltage class may hinder the operation of the gas field at the final relief stage. The work aims to develop criteria and algorithms for the selection of the best voltage class for the external power supply system at gas fields taking into consideration their entire life cycle. To achieve the goal set, we dealt with the following objectives: analyzing literature on gas field development technology, analyzing the actual rated electrical load in every life cycle period of the gas fields in Western Siberia; analyzing literature on the methods of determining the voltage class for industrial facilities; analyzing the existing criteria and developing new criteria for the selection of the best voltage class taking into consideration the entire life cycle of the gas fields in Western Siberia; developing a formula for the objective function to calculate the voltage class; developing selection guidelines for the best voltage class of the power supply system of gas fields that would take a number of shifting parameters throughout their life cycles; developing a generic programmatic selection algorithm for the best voltage class, and studying the power mains of the external power supply system at the existing gas fields in Western Siberia. Our research relied on the following methods: experiment planning (complete factorial experiment) and computer programming methods.

1. Introduction
O. E. Aksyutin formulated the goal of the energy-saving policy of Gazprom PJSC until 2020. It promotes the efficient use of energy resources to ensure the sustainable growth of the company, as well as energy efficiency and competitive ability improvements [1].

The correct voltage class selected taking into consideration the entire life cycle of a gas field is one of the objectives that can facilitate the achievement of the goal set by Gazprom PJSC.

All of the gas fields feature four periods in their life cycles [2], [3]: increasing output; stable output; decreasing output; and field decommissioning.

During periods 1-3, the gas production output, average formation pressure, and bottom hole pressures decrease over time.

To maintain the gas outputs, gas compressors are installed at the gas field in the second period, and during the third period, the compressors are used more intensively, and brand-new mobile compressor units (MCU) are installed at the head of the gas well clusters [4], [5].

Currently, the majority of large gas fields in Western Siberia are at the final development stage of the Cenomanian deposit, i.e. the third life cycle period or the ‘decreasing output’ period [6],
To implement distributed gas compressing at the Yamburgskoye OGCF [7], [8], [9], 52 1-MVA MCUs were put into operation. This requires a complete overhaul of the power supply system at the Yamburgskoye OGCF, including the following:

- The construction of a 410 km 10 kV power line;
- The construction of a 124-169.2 km 35 kV power line;
- The construction of two 10/35 kV substations (SS);
- The construction of 4-5 35/10 kV SS;
- The reconstruction of the existing 110 kV SS for the complex gas treatment facility No. 2 (CGTU2), CGTU4, and CGTU6 — the construction of a 35 kV indoor switchgear (ISG).

Thus, one of the key objectives in the gas industry power supply is the creation of a suitable power supply system at the design stage that would consider the potential increase of electrical loads.

2. Statement of problem

The voltage class is the key power supply system parameter, and it must be selected taking into account all the gas field life cycle periods.

The correct voltage class that takes into consideration the entire gas field life cycles will help install MCU in time to preserve the gas well stock, prevent their waterflooding, and reduce the costs of renovating the entire power supply system.

*The goal of this work* is to develop criteria and algorithms for the selection of the best voltage class for the external power supply system at gas fields taking into consideration their entire life cycle.

Gas fields, unlike factories, have long power lines with small electrical loads (low density) that increase over the life cycle of the field.

Depending on their power consumption, gas fields can be classified as small (one CGTU up to 7 MW), medium (up to 10 CGTU with the aggregate power consumption between 8 and 75 MW), and large (over 10 CGTU with the aggregate power over 75 MW) [10], [11].

We analyzed the existing gas fields in Western Siberia to analyze the electrical load dynamics throughout their life cycle.

The analysis showed that over the gas field life cycle the well yield and average formation pressure decrease and the rated yearly average electrical load increases.

We determined the growth factors for the rated yearly average electrical consumption for the power mains: in the second period, it is between 1.37 and 2.63 p.u. (due to the commissioning of the gas booster stations), and in the third period, it is between 3.03 and 3.74 p.u. (due to the commissioning of GBS and MCU). We determined the growth factor for the yearly average electrical consumption for the power mains of the gas well clusters in the third period as 3.98-8.03 p.u. (due to the commissioning of MCU).

The analysis of the existing voltage class selection methods shows that the previously developed objective functions (mathematical models) of the external power supply voltage class identification system do not account for such important factors as the distribution of the load over the power line, the increase of the electrical loads, and the minimum discounted costs.

3. Theory

Finding the best voltage class for a gas field power supply system means finding the class that will facilitate the minimum discounted costs throughout the life cycle of the field.

Generally, selecting the best voltage class requires preliminary identification of non-standard voltage with minimum discounted costs.

The suggested new method is based on relatively generic mathematical tools for experiment planning.

The concept behind the suggested method of selecting the best voltage is the complete factorial experiment (CFE) planning of the $2^k$ type where $k$ is the number of the factors covered.

The experiment implementing all of the possible factor level combinations is called the complete factorial experiment [12].
The research performed shows that all of the impact factors must be accounted for when developing mathematical models for the selection of the best voltage class for the external power supply systems of gas fields. Significant factors like CGTU performance, the number of CGTUs, the distance between the power source and the consumer, the electrical load growth factor, and the load distribution factor for the power line, shall be used as the varying factors. Factor levels and variation ranges are presented in Table 1.

Table 1. Basic factor levels and variation ranges.

| Factor | Factor name | Primal level, \( x_{i0} \) | Variation range, \( \Delta x \) | Top-level, + | Bottom level, – |
|--------|-------------|-----------------------------|--------------------------------|-------------|-----------------|
| x1     | Number of CGTUs, pcs | 10.5 | 4.5 | 15 | 6 |
| x2     | The distance \( L \) between the power source and the consumer, km | 105 | 45 | 150 | 60 |
| x3     | Electrical load growth factor \( k_{gr} \), p. u. | 3 | 2 | 5 | 1 |
| x4     | Load distribution factor for the power line \( k_{dist} \), p. u. | 0.775 | 0.225 | 1 | 0.55 |

A gas field with medium power consumption (7-75 MW)

| x1     | Number of CGTUs, pcs | 3.5 | 1.5 | 5 | 2 |
| x2     | The distance \( L \) between the power source and the consumer, km | 45 | 30 | 75 | 15 |
| x3     | Electrical load growth factor \( k_{gr} \), p. u. | 3 | 2 | 5 | 1 |
| x4     | Load distribution factor for the power line \( k_{dist} \), p. u. | 0.775 | 0.225 | 1 | 0.55 |

A gas field with small power consumption (7 MW)

| x1     | CGTU performance, MW. | 4.5 | 2.5 | 7 | 2 |
| x2     | The distance \( L \) between the power source and the consumer, km | 11.5 | 8.5 | 20 | 3 |
| x3     | Electrical load growth factor \( k_{gr} \), p. u. | 2.5 | 1.5 | 5 | 1 |

4. Analysis results

The following voltage classes were used when developing the mathematical models for the external power supply systems of gas fields: 6, 10, 20, 35, and 110 kV for fields with small power consumption, 20, 35, 110, 220, and 330 kV for fields with medium and large power consumption.

A total of 229 power supply diagrams were prepared to facilitate the mathematical models. For each of the diagrams, we calculated the discounted costs in the PRADIZ signature software [15].
We prepared independent mathematical models for the following power supply diagrams:
- the double through-mains scheme with a transformer at the end of the line for a small power consumption gas field (one CGTU up to 7 MW);
- the double through-mains scheme with transformers distributed along the power line for a medium power consumption gas field (up to ten CGTUs with an aggregate power between 7 and 75 MW);
- the double through-mains scheme with transformers distributed along the power line for a large power consumption gas field (over ten CGTU with an aggregate power above 75 MW);

The obtained mathematical models used to calculate the optimum off-standard voltage and discounted costs for the external power supply systems of gas fields are presented in Table 2.

Table 2. The mathematical models used to calculate the optimum off-standard voltage and discounted costs for the external power supply systems of gas fields.

| No. | Parameter                                           | Formula                                                                 |
|-----|-----------------------------------------------------|-------------------------------------------------------------------------|
| 1   | A gas field with large power consumption (over 75 MW) | $U_{\text{opt}} = 133 + 15.4 \cdot x_1 + 32.2 \cdot x_2 + 27.3 \cdot x_3 + 12.5 \cdot x_4 + 0.0047 \cdot x_1 \cdot x_2 + 5.67 \cdot x_1 \cdot x_3 - 1.2 \cdot x_2 \cdot x_3 - 7.7 \cdot x_1 \cdot x_4 - 2.4 \cdot x_2 \cdot x_4 + 5.16 \cdot x_3 \cdot x_4 - 4.35 \cdot x_1 \cdot x_2 \cdot x_3 + 1.23 \cdot x_1 \cdot x_2 \cdot x_4 - 7 \cdot x_1 \cdot x_3 \cdot x_4 - 4.6 \cdot x_2 \cdot x_3 \cdot x_4 + 3.52 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4$ |
| 2   | Discounted costs for 20 kV, million rubles           | $R_{20 \, \text{kB}} = 145476 + 78584 \cdot x_1 + 101482 \cdot x_2 + 92009 \cdot x_3 + 39534 \cdot x_4 + 52731 \cdot x_1 \cdot x_2 + 5070 \cdot x_1 \cdot x_3 + 65763 \cdot x_2 \cdot x_3 + 11500 \cdot x_1 \cdot x_4 + 26410 \cdot x_2 \cdot x_4 + 25979 \cdot x_3 \cdot x_4 + 33928 \cdot x_1 \cdot x_2 \cdot x_3 + 7321 \cdot x_1 \cdot x_2 \cdot x_4 + 4363 \cdot x_1 \cdot x_3 \cdot x_4 + 16264 \cdot x_2 \cdot x_3 \cdot x_4 + 922 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4$ |
| 3   | Discounted costs for 35 kV, million rubles           | $R_{35 \, \text{kB}} = 63930 + 33936 \cdot x_1 + 43442 \cdot x_2 + 39754 \cdot x_3 + 16055 \cdot x_4 + 22780 \cdot x_1 \cdot x_2 + 21213 \cdot x_1 \cdot x_3 + 27672 \cdot x_2 \cdot x_3 + 5793 \cdot x_1 \cdot x_4 + 11270 \cdot x_2 \cdot x_4 + 10983 \cdot x_3 \cdot x_4 + 14450 \cdot x_1 \cdot x_2 \cdot x_3 + 4312 \cdot x_1 \cdot x_2 \cdot x_4 + 3350 \cdot x_1 \cdot x_3 \cdot x_4 + 7544 \cdot x_2 \cdot x_3 \cdot x_4 + 2352 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4$ |
| 4   | Discounted costs for 110 kV, million rubles          | $R_{110 \, \text{kB}} = 21253 + 8960 \cdot x_1 + 7114 \cdot x_2 + 8587 \cdot x_3 + 2290 \cdot x_4 + 4272 \cdot x_1 \cdot x_2 + 4525 \cdot x_1 \cdot x_3 + 4103 \cdot x_2 \cdot x_3 + 1673 \cdot x_1 \cdot x_4 + 2823 \cdot x_2 \cdot x_4 + 1396 \cdot x_3 \cdot x_4 + 3358 \cdot x_1 \cdot x_2 \cdot x_3 + 201 \cdot x_1 \cdot x_2 \cdot x_4 + 803 \cdot x_1 \cdot x_3 \cdot x_4 + 1996 \cdot x_2 \cdot x_3 \cdot x_4 - 616 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4$ |
| 5   | Discounted costs for 220 kV, million rubles          | $R_{220 \, \text{kB}} = 23255 + 7905 \cdot x_1 + 4820 \cdot x_2 + 3241 \cdot x_3 + 1261 \cdot x_4 + 661 \cdot x_1 \cdot x_2 + 2063 \cdot x_1 \cdot x_3 + 1445 \cdot x_2 \cdot x_3 + 1234 \cdot x_1 \cdot x_4 + 378 \cdot x_2 \cdot x_4 + 564 \cdot x_3 \cdot x_4 + 1295 \cdot x_1 \cdot x_2 \cdot x_3 + 394 \cdot x_1 \cdot x_2 \cdot x_4 + 543 \cdot x_1 \cdot x_3 \cdot x_4 + 1034 \cdot x_2 \cdot x_3 \cdot x_4 + 1052 \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4$ |
| 6   | Discounted costs for 330 kV, million rubles          | $R_{330 \, \text{kB}} = 38508 + 12300 \cdot x_1 + 8052 \cdot x_2 + 4392 \cdot x_3 + 2098 \cdot x_4 + 1025 \cdot x_1 \cdot x_2 + 2727 \cdot x_1 \cdot x_3 + 2232 \cdot x_2 \cdot x_3 + 2138 \cdot x_1 \cdot x_4 + 889 \cdot x_2 \cdot x_4 + 982 \cdot x_3 \cdot x_4 + 2114 \cdot x_1 \cdot x_2 \cdot x_3 + 948 \cdot x_1 \cdot x_2 \cdot x_4 + 1024 \cdot x_1 \cdot x_3 \cdot x_4$ |
A gas field with medium power consumption (7-75 MW)

\[ x_4 + 1987 \times x_2 \times x_3 \times x_4 + 2047 \times x_1 \times x_2 \times x_3 \times x_4 \]

Optimum off-standard voltage, kV, million rubles
\[ U_{\text{opt}} = 76 + 18 \times x_1 + 16.9 \times x_2 + 16.7 \times x_3 + 2.19 \times x_4 + 3.9 \times x_1 \times x_2 + 9.3 \times x_1 \times x_3 + 2.2 \times x_2 \times x_3 + 12 \times x_1 \times x_2 \times x_3 \times x_4 - 11 \times x_2 \times x_4 - 3.5 \times x_3 \times x_4 + 5.4 \times x_1 \times x_2 \times x_3 \times x_4 + 4.5 \times x_1 \times x_2 + 7.37 \times x_1 \times x_3 \times x_4 - 11 \times x_2 \times x_3 \times x_4 + 3.8 \times x_1 \times x_2 \times x_3 \times x_4 \]
\[ R_{20 \text{ kV}} = 13852 + 5697 \times x_1 + 11015 \times x_2 + 8216 \times x_3 + 2590 \times x_4 + 4390 \times x_1 \times x_2 + 3111 \times x_1 \times x_3 + 7614 \times x_2 \times x_3 \times x_4 \]
\[ x_3 + 1851 \times x_1 \times x_4 + 1880 \times x_2 \times x_4 + 1478 \times x_3 \times x_4 + 3377 \times x_1 \times x_2 \times x_3 + 1343 \times x_1 \times x_2 \times x_4 + 762 \times x_1 \times x_3 \times x_4 + 1700 \times x_2 \times x_3 \times x_4 + 1169 \times x_1 \times x_2 \times x_3 \times x_4 \]
\[ R_{35 \text{ kV}} = 6558 + 2699 \times x_1 + 4537 \times x_2 + 3389 \times x_3 + 1115 \times x_4 + 1784 \times x_1 \times x_2 + 1263 \times x_1 \times x_3 + 3077 \times x_2 \times x_3 + 708 \times x_1 \times x_4 + 665 \times x_2 \times x_4 + 536 \times x_3 \times x_4 + 1237 \times x_1 \times x_2 \times x_3 + 329 \times x_1 \times x_2 \times x_4 + 144 \times x_1 \times x_3 \times x_4 + 672 \times x_2 \times x_3 \times x_4 + 347 \times x_1 \times x_2 \times x_3 \times x_4 \]
\[ R_{110 \text{ kV}} = 5296 + 1284 \times x_1 + 1287 \times x_2 + 720 \times x_3 \]

Discounted costs for
20 kV, million rubles
\[ x_3 + 313 \times x_1 \times x_4 + 118 \times x_2 \times x_4 - 190 \times x_3 \times x_4 + 375.2 \times x_1 \times x_2 \times x_3 - 225 \times x_1 \times x_2 \times x_4 + 116 \times x_1 \times x_3 \times x_4 + 307 \times x_2 \times x_3 \times x_4 - 35 \times x_1 \times x_2 \times x_3 \times x_4 \]
\[ R_{220 \text{ kV}} = 8534 + 1691 \times x_1 + 2339 \times x_2 + 802 \times x_3 - 101 \times x_4 + 168 \times x_1 \times x_2 - 43 \times x_1 \times x_3 - 97 \times x_2 \times x_3 \]

Discounted costs for
35 kV, million rubles
\[ x_3 \times x_4 - 129 \times x_1 \times x_2 \times x_3 \times x_4 \]

Power mains - Double through-mains scheme

A gas field with small power consumption (7 MW)

\[ U_{\text{opt}} = 33.8 + 4.87 \times x_1 + 15.6 \times x_2 + 14.8 \times x_3 + 2.22 \times x_1 \times x_2 + 2.35 \times x_1 \times x_3 + 11.07 \times x_2 \times x_3 + 9.4 \times x_1 \times x_2 \times x_3 \]
\[ R_{6 \text{ kV}} = 5700 + 1864 \times x_1 + 4960 \times x_2 + 3671 \times x_3 + 1654 \times x_1 \times x_2 + 1260 \times x_1 \times x_3 + 3310 \times x_2 \times x_3 + 1103 \times x_1 \times x_2 \times x_3 \]
\[ R_{10 \text{ kV}} = 2337 + 720 \times x_1 + 1784 \times x_2 + 1374 \times x_3 + 547 \times x_1 \times x_2 + 455 \times x_1 \times x_3 + 1106 \times x_2 \times x_3 + 338 \times x_1 \times x_2 \times x_3 \]
\[ R_{20 \text{ kV}} = 1184 + 331 \times x_1 + 700 \times x_2 + 572 \times x_3 + 201 \times x_1 \times x_2 + 309 \times x_1 \times x_3 + 400 \times x_2 \times x_3 + 184 \times x_1 \times x_2 \times x_3 \]
\[ R_{35 \text{ kV}} = 954 + 209 \times x_1 + 378 \times x_2 + 267 \times x_3 + 89 \times x_1 \times x_2 + 192.5 \times x_1 \times x_3 + 123 \times x_2 \times x_3 + 84.4 \times x_1 \times x_2 \times x_3 \]
\[ R_{110 \text{ kV}} = 1417 + 107.75 \times x_1 + 401 \times x_2 + 191.6 \times x_3 + 6.45 \times x_1 \times x_2 + 67.45 \times x_1 \times x_3 + 9.93 \times x_2 \times x_3 + 5.95 \times x_1 \times x_2 \times x_3 \]
The voltage value obtained through the calculation of the optimum voltage using mathematical models is usually off-standard.

The standard voltage of three-phase alternating current mains corresponds with the voltage class established in the Russian Federation [13], [14], see Table 3.

Table 3. The scale of normal voltage ratings.

| Voltage class, kV |
|------------------|
| 6   | 10  | 15  | 20  | 35  | -   | -   | 11  | 150 | 220 | 330 | 500 | 750 | 1150 |

We used the mathematical models to develop a selection algorithm for the optimum voltage class of the external power supply system of a gas field.

The optimum standard voltage class selection algorithm comprises the following steps:
1. Selecting the power supply scheme (see Table 2);
2. Calculating the optimum off-standard voltage using mathematical models (see Table 2);
3. Using the scale of normal voltage ratings (Table 3) to determine the nearest higher and lower standard voltage values;
4. Calculate the discounted costs (Table 2) for both of the standard voltages;
5. Compare the discounted costs and select the voltage class associated with smaller costs.

5. Discussion of results
Based on the developed C# algorithm, we created PRON, a program that facilitates the selection of the optimum voltage for the systems of external power supply.

We used the PRON software to study the existing external power supply systems of the gas fields in Western Siberia to determine their optimum voltage classes. The results of the research are shown in Figures 1-11.

Figure 1. The voltage class-discounted costs diagram for the SS6/35 kV-SS35/6kV CGTU 51 power supply line. Section 5 of Achimov deposits.
Figure 2. The voltage class-discounted costs diagram for the SS6/35 kV-SS35/6kV CGTU 41 power supply line. Section 4 of Achimov deposits.

Figure 3. The voltage class-discounted costs diagram for the SS6/10 kV-ISG 10 kV CGTU 21 power supply line. Section 2 of Achimov deposits.
Figure 4. The voltage class-discounted costs diagram for the SS 110/6 kV - ISG 6 kV CGTU 31 power supply line. Section 1 of Achimov deposits.

Figure 5. The voltage class-discounted costs diagram for the GTU-3 SS6/10 kV-ISG 10 kV CGTU 22 power supply line. Section 2 of Achimov deposits.
Figure 6. The voltage class-discounted costs diagram for the Byngapur-Peschanaya power supply line. Vyngapur gas field.

Figure 7. The voltage class-discounted costs diagram for the Kirpichnaya-Talanga power supply line. Western Tarkosale oil field.
Figure 8. The voltage class-discounted costs diagram for the Tarkosale CGTU power supply line. Komsomolskoye gas field.

Figure 9. The voltage class-discounted costs diagram for the Bazovaya PGP-9 power supply line. Medvezhye gas field.
Figure 10. The voltage class-discounted costs diagram for the Yamburg power supply line. Yamburg gas field.

Figure 11. The voltage class-discounted costs diagram for the Urengoy power supply line. Urengoy gas field.
Thus, the voltage class-discounted costs charts for the power mains (Figures 2-12) show that the higher the voltage class, the smaller the difference in discounted costs. The charts show that the cost values for the 6 kV mains vary greatly, while for 110 kV grids, the discounted cost values merge.

Therefore, the higher the voltage class, the better the external power supply mains can adapt to the increasing electrical loads, i.e. to the development (life cycle prolongation) of a gas field.

6. Conclusions
1. We developed three mathematical models featuring linear polynomials to facilitate the selection of optimum voltage.
2. We developed a selection algorithm for the optimum voltage class of an external power supply system taking into account all of the gas field life cycle periods and the complex dynamics of impact factors.
3. We studied the existing external power supply systems of the gas fields in Western Siberia to determine their optimum voltage classes. We established that the best voltage class for large and medium gas fields is 110 kV, while the small fields do better with 35 kV or 110 kV power mains.
4. The 6 kV power mains are neither good nor promising for the power supply of new gas fields as they hinder their development.
5. When designing the external power supply systems for new gas fields, we recommend using 110 kV power mains. This voltage class provides sufficient power reserves for the entire life cycle of a gas field along with the smallest discounted costs.

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