Practical aspects of modeling of the oil and gas producing enterprise's electrotechnical complexes

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Abstract. When planning technological modes of the power supply systems of oil and gas production enterprises, modeling of their operating parameters is a very important task. The currently used models of interaction between hydromechanical and electrical systems, as a rule, are built using multi-circuit equivalent circuit. This leads to a significant expenditure of computational effort and is not always suitable for rapid assessment. The purpose of this paper is to develop the technique for modeling the operating parameters of the power supply system operation using single-circuit equivalent circuits, as well as taking into account the current technological parameters. In the proposed technique, the interaction between electrical and hydromechanical systems is shown. Use of this technique allows taking into account the influence of the magnetization current of power transformers without adding another branch into the equivalent circuit.

1. Introduction
The electrotechnical complex (ETC) of an oil and gas producing enterprise (OGPE) is part of the electrotechnological system and it is needed for the interaction of the electrical, mechanical and hydraulic subsystems. The normal operation mode parameters of the ETC depend on the current technological process parameters, mechanical and electrical equipment parameters [1]. The main electrical equipment of OGPE ETC is submersible induction motors (SIM), cable (CL) and overhead power lines (OL), power transformers (T) and static load (administrative complex, heating cables, etc.).

To calculate the normal mode of operation parameters of the power supply system of production wells, $L$- and $T$-shaped equivalent circuits of the power supply system elements are usually used [2-4]. Use of these equivalent circuits is not a problem when the object is not wider than a typical oil well, but it may require large computational effort, if we consider the power supply system of the field or group of fields, due to the presence of additional nodes and branches. When calculating these circuit parameters, specialists tend to use just the passport data of the electric equipment and do not take into account the current parameters of the technological process and equipment [5, 6]. This disadvantage reduces the visibility of the model of interaction between the electrical and hydromechanical subsystems of oil production, which may affect the energy efficiency of oil production when planning technological modes.

Thus, for express assessment of the parameters of the ETC and the technological modes, the task of building simplified equivalent circuits for the elements of the ETC OGPE and determining the parameters of these circuits based on the parameters of the technological process is important.
2. Structure of ETC OGPE

According to well-known approaches, the structure of OGPE ETC can be represented as a three-level system [6, 7] (Figure 1):

- Level of transformer substation (TS). The power source is an external power grid (PG). Usually, the power supply voltage at this level is 35-110 kV;
- Level of complete transformer substation (CTS). The power source is the TS, and the distribution of electricity through the package transformer substation occurs. Usually, the power supply voltage is 6-20 kV.
- Electric centrifugal pumps (ESP). The power source is the CTS, and the SIM ETC is directly supplied. Usually, the power supply voltage at this level is 0.4-1 kV.

![Figure 1](image)

**Figure 1.** ETC structure (PG – power grid; TS – transformer substation; PL – power line; CTS – complete transformer substation; T – power step-up transformer; CL – cable line, HP – hydroprotection, ESP – electric centrifugal pump; ESP CS – electric centrifugal pump control station).

Commonly, OGPE ETC is performed by the magistral circuit with concentrated loads [6].

3. Calculation of ETC operation parameters

To calculate branched electrical circuits, the nodal potentials method based on topological matrices is convenient. The advantage of the matrix-topological direction of the chains theory is a large degree of orderliness in the compilation of equations systems [8]. A detailed description of this method is presented in [2].

When applying this method, the system of nodal potentials equations is written as:

\[
[A] \cdot [G] \cdot [A]^{T} \cdot \varphi = -[A] \cdot [G] \cdot [E] + [A] \cdot [J]
\]

(1)

where \([A]\) is incidence matrix, \([G]\) is the branches conductance matrix, \([E]\) is the matrix-column of the electromotive force included in the branch, \([J]\) is the matrix-column of the current sources.

Usually, we are assuming that there are no current sources in the system, therefore \(-[J] = 0\).

Often, low-load transformers operate on the OGPE. In this case, the transformer magnetization current can be a significant part of the load current on the transformer high voltage side. These currents can be taken into account by representing the transformer as a \(L\)- or \(T\)-shaped equivalent circuit, which will lead to an increase in the incidence matrix and a significant increase in the number of mathematical operations with matrices.

One of the possible solutions to this problem without use of the above-mentioned equivalent circuits is the representation of the transformer magnetization current as a current source.

\[
\varphi = -([A] \cdot [G] \cdot [A]^{T})^{-1} \cdot ([A] \cdot [G] \cdot [E] - [A] \cdot [J])
\]

(2)
The current matrix formation feature is that the current in the branch corresponding to the \( i \)-th transformer must be calculated as the sum of the transformers magnetization currents which is located under considering transformer and the magnetization current of the \( i \)-th transformer.

Opposite to approaches to modelling ETC in \( a, b, c \) axes [9], it is proposed to make the calculations in the axes \( d, q \). Therefore, the parameters of the elements equivalent circuit will be given in these coordinate axes.

### 3.1. Equivalent circuit parameters calculation

The equivalent circuit of elements is proposed to be performed as a series connection of an active and reactive impedances [2, 3]. Using these parameters, the element conductivities matrix is formed:

\[
[G_i] = \begin{pmatrix} r_i & x_i \\ -x_i & r_i \end{pmatrix}
\]

where \( i \) is number of circuit’s element; \( r_i \) is active impedance of \( i \)-th element, Ohms; \( x_i \) is reactive impedance of \( i \)-th element, Ohms.

#### 3.1.1. SIM

Hydromechanical and electrical systems interact by an electrotechnological energy converter – a submersible induction motor. When calculating the parameters of the power supply system normal mode, it is proposed to present a model of interaction between the pump and the SIM by varying the parameters of the SIM equivalent circuit depending on the current technological parameters.

The pump power required to maintain the specified technological process parameters is calculated, kW [10]:

\[
N_{\text{pump}} = \frac{P_{\text{pump}} \cdot Q_{\text{pump}} \cdot 10^3}{\eta_{\text{pump}} \cdot \eta_{\text{hp}}},
\]

where \( P_{\text{pump}} \) is the required pressure of the pump, MPa; \( Q_{\text{pump}} \) is the specified flow rate of the pump, \( \text{m}^3/\text{s} \); \( \eta_{\text{pump}} \) is the efficiency of the pump at a given operating point, p.u.; \( \eta_{\text{hp}} \) is the efficiency taking into account losses in hydraulic protection, p.u.

To determine the pump efficiency at the operating point it is proposed to use the catalog pump characteristics. For calculation convenience, it is proposed to present the pump efficiency with a polynomial such as [10]:

\[
\eta_{\text{pump}}(Q_{\text{pump}}) = \sum_{i=0}^{n} k_i \cdot Q_{\text{pump}}^i,
\]

where \( k_i \) is the weighting factor; \( Q_{\text{pump}} \) is the current flow rate of the pump, \( \text{m}^3/\text{day} \); \( n \) is the polynomial degree.

Further calculation of the equivalent circuit parameters of the SIM is carried out according to the method described in [11], where:

\[
[G_i] = f(N_{\text{pump}}).
\]

The SIM mathematical model in the matrix form can be written as follows:

\[
\begin{pmatrix} I_d \\ I_q \end{pmatrix} = \begin{pmatrix} r_{\text{SIM}} & x_{\text{SIM}} \\ -x_{\text{SIM}} & r_{\text{SIM}} \end{pmatrix}^{-1} \begin{pmatrix} U_d \\ U_q \end{pmatrix}.
\]

The mathematical models of other ETC elements are shown in Table 1.
Table 1. Mathematical models of other ETC elements.

| Element          | Calculation of equivalent circuit parameters | Matrix representation |
|------------------|-----------------------------------------------|------------------------|
| Power line       | \( r_{PL} = r_0 \cdot l_{PL} \); \( x_{PL} = x_0 \cdot l_{PL} \) | \[
I_d = \begin{bmatrix} r_{PL} & x_{PL} \\ -x_{PL} & r_{PL} \end{bmatrix}^{-1} \begin{bmatrix} U_{d1} \\ U_{q1} \end{bmatrix} - \begin{bmatrix} U_{d2} \\ U_{q2} \end{bmatrix} \]
| Static load      | \( r_{SL} = \frac{U_r^2}{P} \); \( x_{SL} = \frac{Q}{Q} \) | \[
I_d = \begin{bmatrix} r_{SL} & x_{SL} \\ -x_{SL} & r_{SL} \end{bmatrix}^{-1} \begin{bmatrix} U_d \\ U_q \end{bmatrix} \]
| Transformer      | \( r_t = \frac{\Delta P_{SC}}{S_{TR}} \cdot U_{II}^2; \quad x_t = \left( \frac{u_{SC} U_{II}^2}{100 S_{TR}} \right)^2 - r_t^2 \) | \[
I_d = \begin{bmatrix} r_t & x_t \\ -x_t & r_t \end{bmatrix}^{-1} \begin{bmatrix} U_{d1} \\ U_{q1} \end{bmatrix} - \begin{bmatrix} U_{d2} \\ U_{q2} \end{bmatrix} + I_{d\mu} + I_{q\mu} \]

where \( r_0 \), \( x_0 \), are active and reactive impedances of power lines per unit length, Ohm/km; \( l_{PL} \) is length of power lines, km; \( U_r \) is the load rated voltage, V; \( P \) is load active power, W; \( Q \) is load reactive power, var; \( \Delta P_{SC} \) is the transformer short circuit losses, kW; \( U_{II} \) is the transformer high voltage, kV; \( S_{TR} \) is the transformer rated power, kVA; \( I_{d\mu} \) is the component of the transformer magnetization current along the axis \( d \), A; \( I_{q\mu} \) is the component of the transformer magnetization current along the axis \( q \), A.

4. Calculation method approbation

The ETC section of the oil field at the CTS-level is considered as a test. The scheme of this section is presented in Figure 2. The calculation was performed using the “classic” method according to [12] and the described matrix-topological method.

![Figure 2. Scheme of the oil field ETC section.](image-url)

To automate the calculations and the subsequent analysis of the obtained results, a user interface is being developed based on the equipment of National Instruments [13]. Before calculating, the user inputs the technological process parameters and selects the equipment (the user interface is shown in Figure 3). Converting into the equivalent circuit parameters occurs by an additional conversion unit.
After determining the equivalent circuit parameters, the calculation is performed. The calculation results are shown in Table 2.

![Figure 3. The user interface.](image)

### Table 2. Calculation results.

| Branch number | Without taking into account magnetization current, A | Taking into account magnetization current, A | Design values, A |
|---------------|-----------------------------------------------------|---------------------------------------------|-----------------|
|               | “Classic” method | Matrix-topological method | “Classic” method | Matrix-topological method |                  |
| 1              | 11,314               | 11,306                      | 12,539                   | 12,734                   | 12.3             |
| 2              | 178.2                | 181.212                     | 193.779                  | 195.998                  | 190.0            |
| 3              | 64.35                | 64.916                      | 68.047                   | 68.339                   | 68.8             |
| 4              | 23.4                 | 23.606                      | 23.4                     | 23.51                    | 23.2             |
| 5              | 23.4                 | 23.606                      | 23.4                     | 23.51                    | 23.2             |
| 6              | 113.85               | 116.313                     | 125.895                  | 127.809                  | 123.8            |
| 7              | 41.4                 | 42.296                      | 41.4                     | 42.095                   | 41.2             |
| 8              | 20.4                 | 20.858                      | 20.4                     | 20.759                   | 20.1             |
| 9              | 21                   | 21.471                      | 21                       | 21.569                   | 20.7             |

5. **Conclusions**

The calculation results show that the transformer magnetization currents can be a significant part of the load current. They make an especially great contribution when the transformer is operating with a low load. The relative calculation error was calculated as the ratio of the difference between the calculated and design values to the design value [14]. The relative error of calculations without taking into account the magnetization currents of transformers by the “classic” method in comparison with the design values is up to 8.01%. The relative calculation error taking into account the magnetization currents of transformers by the “classic” method in comparison with the design values is up to 1.98%. The relative error between the “classic” and matrix-topological method is not more than 1.73%. Thus, taking into account the transformer magnetization currents gives more accurate calculation results.

6. **Discussion**

This paper proposes a technique for modeling a power transformer as an element of an ETC, taking into account the magnetization current without adding an additional branch of magnetization in the transformer equivalent circuit. With regard to oil field power supply systems, this approach will significantly reduce the matrix of incidence and conductance, which ultimately will reduce the number of computational operations.

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