Identification of mathematical models parameters of electromechanical consumers of regionally isolated electrotechnical complexes

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Abstract. This article considers and develops a method for identifying the parameters of mathematical models of electromechanical consumers of regionally isolated electrotechnical complexes. The validity of the proposed method application to identify parameters to determine influence of consumer characteristics on the quality of electrical energy at the point of common coupling is shown. The description of the mathematical model of the electrical energy distribution point consisting of several consumes is shown. The mathematical model is developed in the Cauchy normal form. A modification of the Marquardt method is proposed as an identification tool.

1. Introduction

Regionally isolated electrotechnical complexes (RIEC) [1] are characterized by a number of features. Firstly they are: comparable power consumers, sources of generation of electrical energy (EE) and energy storages. All of these power components are in dynamic interaction [2,3]. The next RIEC characteristic feature directly related to the issues of the electric energy quality [4] are random and intermittent components in the generated electricity [5]. This circumstance causes difficulties in fulfilling the requirements to supply electrical energy of the required quality to the consumer. Diesel power plants used in RIEC as the main source of EE generate a chain of negative impacts on the ecology in the region of operation. At the same time, a whole range of economic and social problems arises depending on the quality requirements of the supplied EE [6].

Solving problems of electric energy quality assessment and EE quality management in regionally isolated electrotechnical complexes requires a number of activities leading to the improvement of the quality of electric energy in RIEC. As a rule, the mechanism of forecasting the quantity and quality of power consumption [7] is activated, based on mathematical modeling of control processes [8] of the most energy-consuming elements of RIEC. It is necessary to consider mutual conversion of energies of different physical natures and impact of this effect on the quality of the electrical energy consumed by RIEC is required [9,10]. It is necessary to note that recently there is an increase of application of EE electromechanical consumers in RIEC greatly affecting quality parameters of electrical energy [11]. For example, automated electric drive systems based on alternating current machines controlled by frequency converters [12] can be considered as characteristic representatives of such EE consumers. This trend causes an increase in the problems of maintaining the EE quality indicators at the common coupling point (CCP) of the RIEC at the required level. At the same time, there are also problems in determining the share contribution to the decline in the EE quality indicators in the CCP, each non-linear EE consumer.

This article formulates the solution of the problem to determine the equity contribution to the decline in the EE quality indicators in the CCP from each EE consumer connected to the CCP, is formulated as the task to identify the parameters of mathematical models of electromechanical EE consumers [13]. The principles of developing an information system for monitoring the parameters of mathematical models of electromechanical consumers of regionally isolated electrotechnical complexes are being developed [14].
Figure 1. RIEC typical common coupling point: a) single-line diagram; b) equivalent circuit

The typical equivalent circuit is considered (Fig. 1.b) of regionally isolated electrotechnical complex [1]. A system of differential equations to determine the nature and current changes of each consumer of electrical energy (EE) connected to the common coupling point (CCP) in normal Cauchy form is written:

\[
\begin{align*}
\frac{d i_1(t)}{dt} &= \frac{1}{L_1}(u_{ab}(t) - R_1 \cdot i_L(t)) \\
\frac{d i_2(t)}{dt} &= \frac{1}{L_2}(u_{ab}(t) - R_2 \cdot i_L(t)) \\
\vdots \\
\frac{d i_n(t)}{dt} &= \frac{1}{L_n}(u_{ab}(t) - R_n \cdot i_L(t)) \\
u_{ab}(t) &= e(t) - \left( L \frac{dt(t)}{dt} + R \cdot i(t) \right) \\
i(t) &= i_1(t) + i_2(t) + \ldots + i_n(t)
\end{align*}
\]  

(1)

Simultaneous equations (1) are:

- \( u_{ab}(t) \) is voltage in CCP;
- \( R_k, L_k, k=1..n \) are the resistance and inductance of the \( k-th \) EE supplier connected to the CCP, \( k=1..n \).
- \( e(t), L, R \) are electromotive force, inductance and resistance of an equivalent source,
- \( n \) is the number of EE consumers connected to the CCP.

Simultaneous equations (1) can be solved with respect to currents by one of the well-known numerical methods. From the form of the equations of (1) that the current of each electric power consumer is formed depending on the nature of voltage changes in the CCP. At the same time, the dynamics of the voltage change in the CCP is influenced by the current behavior of each consumer of electrical energy in the CCP under consideration. According to the schedule of voltage changes in the
CAP, the quality of electrical energy in the CAP is determined according to the requirements [4]. Thus, in order to assess the share contribution of each specific EE consumer connected to the CAP, it is necessary to know not only the nature of the current change of the given consumer, but also the mutual influence of all consumers.

3. Theory

According to simultaneous equations (1) the characteristic currents changes of each EE consumer connected to the CCP are largely affected with parameters of EE consumers who generally can be regarded as a function of time. Thus, the task of monitoring the equity contribution of each EE consumer connected to the CCP can be formulated as the task of monitoring the parameters of mathematical models of EE consumers connected to the CCP. The parameters of mathematical models of individual consumers must be identified in real time. Analysis of existing approaches [13,14] shows that it is advantageous to develop techniques of parameter identification of mathematical models of EE consumers as an optimization task, or search for an extremum (minimum in this case) of some objective function \( Z \). This function depends on the desired parameters of mathematical models of EE consumers. According to studies, more than 50% of the produced electric energy is converted into mechanical work engines; therefore, a significant proportion of EE consumers can be regarded as the active inductive load, while they will have two main parameters – inductance \( L \) and active resistance \( R \). Thus, according to objectives to determine the minimum of the objective function \( Z(R,L) \), a mathematical model of each of the consumers (Fig. 1) has:

\[
\begin{align*}
\frac{\partial R_k}{\partial \tau} &= -\frac{\partial Z(R_k,L_k)}{\partial R_k} \\
\frac{\partial L_k}{\partial \tau} &= -\frac{\partial Z(R_k,L_k)}{\partial L_k}
\end{align*}
\]

(2)

Simultaneous equations (2) \([R_{k_{\text{min}}},R_{k_{\text{max}}}], [L_{k_{\text{min}}},L_{k_{\text{max}}}]\) have the range of allowable values of active resistance \( R \) and inductance \( L \) of the \( k \)-th EE supplier connected to CCP, \( k=1,..n \).

Simultaneous equations (2) describe the process of identifying the parameters of EE consumers as some transition process occurring in the fictitious time \( \tau \). To solve simultaneous equations (2) it is proposed to use the modified Marquardt method [15], its formula will look like:

\[
\begin{bmatrix}
R^{j+1} \\
L^{j+1}
\end{bmatrix} = \begin{bmatrix}
R^j \\
L^j
\end{bmatrix} + \begin{bmatrix}
h^j & 0 \\
0 & h^j
\end{bmatrix} \begin{bmatrix}
I & 0 \\
0 & I
\end{bmatrix}^{-1} - \begin{bmatrix}
h^j & 0 \\
0 & h^j
\end{bmatrix} A_f - \begin{bmatrix}
h^j & 0 \\
0 & h^j
\end{bmatrix} A_f^{-1} \begin{bmatrix}
h^j & 0 \\
0 & h^j
\end{bmatrix} \begin{bmatrix}
I & 0 \\
0 & I
\end{bmatrix}^{-1}
\]

(3)

where:

- \( j \) is number of the current iteration;
- \( \begin{bmatrix}
R^j \\
L^j
\end{bmatrix} \) is the values of the desired parameters of the mathematical model of the EE consumer at the \( j \)-th iteration step;
- \( h^j \) is an integration step at the \( j \)-th iteration;
- \( a \) is a Marquardt method parameter equal to one;
- \( A_f \) is Jacobi matrix corresponding to the Hesse matrix in the Marquardt method:
\[
A_f = \begin{bmatrix}
\frac{\partial^2 Z(R, L)}{\partial R^2} & \frac{\partial Z(R, L)}{\partial R \partial L} \\
\frac{\partial Z(R, L)}{\partial L \partial R} & \frac{\partial^2 Z(R, L)}{\partial L^2}
\end{bmatrix}.
\]  

(4)

In general, the strategy of the modified Marquardt method requires the construction of a sequence of vectors \( x^j = [R \quad L]^T \), where \( j = 0, 1, 2, 3, \ldots \), and:

\[
Z(x^{j+1}) < Z(x^j).
\]  

(5)

Where:

\( x^j \) is the previous set of the required EE consumer parameters. The set of parameters of the EE consumer, corresponding to the beginning of the calculation \( x^{(0)} \) is set on empirical considerations;

\( x^{j+1} \) is the subsequent set of the required parameters of the EE consumer, calculated according to rule (3).

The process of identifying the EE consumer parameters is completed if one of the two conditions is met:

1) \( j \geq L \), where \( L \) is the maximum number of iterations;

2) \( \| \nabla Z(x^j) \| < \varepsilon \), where:

\( \varepsilon \) is a small positive number; \( \nabla Z(x^{(k)}) \) is the vector of the gradient of the objective function, defined as follows:

\[
\nabla Z(R^{(j)}, L^{(j)}) = \begin{bmatrix}
\frac{\partial Z(R, L)}{\partial R} & \frac{\partial Z(R, L)}{\partial L}
\end{bmatrix}^T.
\]  

(6)

The objective function \( Z(R, L) \) used in the process of identifying the parameters of mathematical models of EE consumers does not explicitly depend on the required parameters of consumers and is defined as:

\[
Z(R^{(j)}, L^{(j)}) = \alpha \sum_{k=0}^{N} (i_{\chi, k} - i_{P, k})^\beta.
\]  

(7)

Where:

\( \alpha \) is some parameter of the objective function;

\( \beta \) is an exponent;

\( i_{\chi, k} \) is the current value obtained from the measurement experiment;

\( i_{P, k} \) is the value of the current obtained by calculation;

\( N \) is the number of points in the measurement interval.

It is assumed that in order to obtain the target function (6) it is necessary to make a series of measurements of the voltage applied to the EE consumer in the CCP and the current consumed by the considered EE consumer. A series consisting of \( N \) current and voltage measurements should be performed at a set sufficiently short time interval of less than 0.0001 sec. The values of the current obtained by calculation \( i_{P, k} \), \( k = 0, \ldots, N \) can be performed using the mathematical model (1) with the current values \( R \) and \( L \) at each \( j \)-th step of parameter identification, carried out using equation (3). When calculating the value of \( i_{P, k} \), \( k = 0, \ldots, N \) using simultaneous equations (1) time values \( t_k \) and \( u_{ab, k} \), \( k = 0, \ldots, N \) must correspond to the same values determined from the measurement experiment.

4. The experiment results
Based on the parameter identification method (3), implemented in the Object Pascal language in the Delphi 7 development environment, a series of computational experiments were conducted to identify the parameters of mathematical models of EE consumers connected to the CCP. The object of the study was considered the electrotechnical complex (Fig. 1 a) consisting of two EE consumers. It was assumed that the operation of the semiconductor valve of consumer 1 will result that it will have non-linear active resistance. Consumer 2 valve during the experiment remained always open, therefore, consumer 2 was considered as linear. In the course of computational experiments, the nonlinearity degree of characteristics of consumer 1 was changed by changing the firing angle of the VS 1 semiconductor gate in the range from 0º up to 90º, as well as by changing the resistance value $R_{V1}$ in the range from 10% up to 80% from the resistance value $R_1$ (Fig. 1 b). Availability of nonlinearity of consumer 1 settings reflected on the change of consumer 1 current form which, in turn, provided influence on the voltage curve in the CCP. Due to this effect there occurred distortion in the CCP voltage curve that caused changes in EE quality indices in the CCP, among which there is non-sinusoidal voltage coefficient $K_c$.

Figure 2. Changing of the parameters R2 and L2 in the process of identification: 1- changing of R2; 2- changing of L2; 3 - changing of the objective function $Z(R2, L2)$.

Table 1. The results of parameters identification of a mathematical model of EE consumers connected to the CCP (thyristor unlocking angle is $VS1 – 90^\circ$).

| № | 1   | 2      | 3     | 4    | 5     | 6    | 7     | 8     | 9    | 10   |
|---|-----|--------|-------|------|-------|------|-------|-------|------|------|
| $R_{V1}$ kg | 0  | 0.1*R1 | 0.25*R1 | 0.3*R1 | 0.35*R1 | 0.4*R1 | 0.5*R1 | 0.7*R1 | 0.8*R1 | 0.9*R1 |
|  | 0   | 0.757 | 2.145 | 2.272 | 2.616 | 3.188 | 3.584 | 4.931 | 5.424 | 5.882 |
The development of EE consumers is shown identifying the parameters of EE consumers in parameters based on the model (1) and consumers connected to the identification estimation.

5. The results discussion

When conducting numerical experiments (their results are in Table1) nonsinusoidal voltage value of the coefficient $K_v$ in the CCP varied both as within the values satisfying the requirements [4] (experiments from 1 to 8), as out the requirements (experiments from 9 to 10). As follows from the results of computational experiments shown in Table 1, regardless of the values of non-sinusoidal voltage factor $K_v$ to the CCP parameter estimation of customer 2, which is regarded as linear, they have a smaller range of values than the evaluation parameters of customer 1. The error in estimation of active resistance of consumer 2 is +1%, -0.5%; the error in estimating the inductance of consumer 2 is +4.25%, -3.5%. Thus, the estimation of the parameters of the mathematical model of consumer 1, performed using the method of identifying the parameters of mathematical models proposed in the article, can be considered as useful. The error in estimating the parameters of consumer 1 are as follows: resistance is determined with an error of +42%, inductance is determined with an error of +101%, -2.75%. Therefore, the estimation of the parameters of the mathematical model of nonlinear consumer 1 cannot be satisfactorily recognized, and to estimate the parameters of the mathematical model of consumer 1, it is necessary to develop a highly specialized method for identifying the parameters of mathematical models. In further publications it will be shown that this is possible on the basis of the energy approach to the RIEC simulation [42].

Based on the results of computational experiments, given in Table 1, it can be concluded that consumer 2, its integral parameter estimate using the identification method proposed in the article, does not exceed ±5%, can be considered as linear and, therefore, has no significant effect on the decrease in the quality indicators of the voltage in CCP, which characterize its shape.

6. Conclusion

In the course of computational experiments to estimate the parameters of the proposed mathematical model of EE consumers (1) connected to the CCP, it was determined: the parameters estimation of the mathematical models of “linear” EE consumers (1) using the proposed parameter identification method (6) for EE consumers may be considered satisfactory; for “nonlinear” EE consumers connected to the CCP and influencing EE quality parameters in the CCP due to their nonlinear characteristics, the parameters of their mathematical models may be estimated using specialized mathematical model based on the model (1) and special identification method of parameters based on method (6) with its narrow specialization.

In general, the following conclusions can be made based on the results of this research:
- the application validity of mathematical model (1) and method (6) for solving problems of identifying the parameters of EE consumers in CCP under the condition of the linear nature of the load of EE consumers is shown;
- with a significant non-linearity of the nature of the load (in the test example for customer 1), the development of a specialized method for identifying parameters is required.

| R1*, Ohm | 0.404 | 0.427 | 0.452 | 0.469 | 0.479 | 0.481 | 0.507 | 0.535 | 0.552 | 0.568 |
| L1, mH  | 0.989 | 1.002 | 1.074 | 1.057 | 1.075 | 1.130 | 1.139 | 1.281 | 1.341 | 1.405 |
| R2*, Ohm| 0.404 | 0.405 | 0.398 | 0.405 | 0.405 | 0.398 | 0.405 | 0.398 | 0.398 | 0.398 |
| L2, mH  | 0.989 | 0.987 | 1.016 | 0.987 | 0.986 | 1.017 | 0.987 | 1.017 | 1.017 | 1.017 |

%
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