Identification of parameters of power circuits pulse energy conversion systems of electromechanical equipment

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Abstract. This article considers the problem of identifying the parameters of pulsed energy conversion systems in order to determine the stability boundary of the operational process. The peculiarity of this identification is due to the analysis of experimentally obtained synchronized time series.

1. Introduction

Nowadays, pulsed systems of energy and electromechanical equipment conversion (PSE) are widely used in industrial installations and consumer devices. Their advantages include high efficiency, low cost, small weight and size parameters. But at the same time, there is probability of nonlinear effects leading to emergences, and it significantly limits the range of their application [1]. The PSE operation is carried out in a wide range of external and internal parameters (for example, changes in temperature and humidity, instability of input voltage and load, aging of elements, etc.), which significantly complicates this problem solution both from the point of modeling and system design [2].

Solution to the problem is to identify the parameters of the PSE power circuit in order to determine the maintenance stability threshold and to improve sufficiency degree of PSE mathematical model.

2. PSE mathematical problem

A mathematical model of a down-type voltage converter in the form of a dynamic system is a system of differential equations with a discontinuous right-hand side, whose solution in sections of the structure constant is carried out similarly to solving a system of ordinary differential equations [3, 4, 5].

Formation of a system of differential equations is determined in accordance with the value of the pulse function $K_F$. To form a system of differential equations, closed contours I, II and node 1 are used (Fig. 1). According to the second and first laws of Kirchhoff there is:

$$E \cdot K_F(\xi) = R_L \cdot i_L + L \frac{di_L}{dt} + u_C + C \frac{du_C}{dt} \cdot R_C$$

$$C \frac{du_C}{dt} \cdot R_C + u_C = i_u \cdot R_u$$

$$i_L = C \frac{du_C}{dt} + i_L$$

Equations (1-3) are transformed into a system of differential equations; as a result, the following system of differential equations is obtained:
where $K_F$ is pulse function reflecting the key element state ($K_F = 0$ the key is in non-conducting state, $K_F = 1$ key is in conducting state).

\begin{align}
\frac{di}{dt} &= -\frac{1}{L} \left[ \left( RL + \frac{RCR}{RC+R_H} \right) i_L + \frac{1}{L} \left( \frac{RC}{RC+R_H} - 1 \right) u_C + \frac{E}{L} \cdot K_F(t) \right] \\
\frac{du}{dt} &= \frac{R_H}{C(R_C+R_H)} u_C - \frac{1}{C(R_C+R_H)} \frac{1}{1}
\end{align}

3. Criteria of authenticity

To verify the validity of the PSE parameters identification, it is necessary to formulate a criterion for each of them. Comparison of the obtained value with the resistance value measured by the RLC-meter is a criterion of validity of determination of resistance load and capacitance parameters. For inductance there will be comparison of the resultant values with the defined ones in [6] under the same initial conditions. It is also planned to use a complex criterion, which consists in comparing the bifurcation boundaries defined in a numerical experiment with already known parameters with an experimentally obtained diagram.

To verify identification of inductance according the second criterion it is necessary to perform a sequence of steps:

- To record the values $E$, $C$, $RL$, $RC$, $Rn$, $Uref$;
- To determine the inductance $L_{exp}$;
- To determine the bifurcation boundary experimentally;
- To conduct mathematical simulation with the identified $L_{exp}$ to determine the theoretical bifurcation boundary;
- To compare the results.

4. Identification of the PSE parameters

The main parameters of pulse converter elements are the parameters of inductance $L$ (resistance and inductance), the capacitor (equivalent series resistance, capacitance) and the value of load resistance.

The parameters that can be determined are: voltage $E$, direct current resistance $i_L$, current through load $i_L$, timing pulse $C_F$, moment to switching function change $K_F$, output voltage $U_n$.

Parameter determination is subject to the following assumptions:

- Resistance of the keys is the same;
- The load resistance has no response to the inertial component;
• The load resistance does not depend on the current flowing;
• Throttle resistance is constant;
• All calculations are valid only for stationary modes;
• There may be noise in the signal conversion circuits;
• Width of timing pulse is relatively small if compared to PWM period;
• During the time t₀, the current changes insignificantly;
• The PWM period is constant.

In accordance with the elements parameters, voltage $E$ and switching function $K_F$ in the converter circuits there are set certain values of the currents and output voltage. Solving the inverse problem, it is possible to identify the parameters of the PSE elements.

The input data for the calculations are the input voltage $E$, output voltage $U_n$, direct current resistance $i_L$ and current in load circuit.

**Determination of load resistance**

To determine the load resistance, it is necessary to know only two parameters $U_n$ and $i_n$. The calculation is completed in accordance with Ohm’s law:

$$R_n = \frac{U_n}{i_n} \quad (5).$$

**Determination of inductance parameters**

Based on [6, 7] it is to conclude that the change of load and input voltage leads to a change in inductance and does not change its resistance.

The inductance value depends on many factors: the amplitude of magnetic induction (current variable component) total signal intensity (according to DC), rpm, temperature, and magnetic core aging [8, 9, and 10]. These dependences are given in [2]. When the level of the constant and variable components increases its influence can be partially compensated. Every set of parameters and mode of PSE operation will correspond certain inductance value. Other methods [11, 12, 13, and 14] are not suitable for solving the problem, because the equivalent circuit of the identification object is different.

Other widely used methods, voltmeter-ammeter, bridge and resonant, etc. are unsuitable for the problem: measurements are carried out at currents of small magnitude, at one frequency of sinusoidal current. The real circuit works at high currents. Waveform is rectangular, so, frequency has a very wide range. Conducting identification of $RL$-chain by supplying to the input of the unit steps are also not suitable, because the initial conditions are zero, and the amplitude of the magnetic induction does not correspond to the actual working value.

To determine inductance, $L$ is determined from (1 and 2):

$$L = \frac{dt}{di_L} \left( EK_F(\xi) - i_L R_L - U_n \right) \quad (6)$$

$$L = \frac{dt}{di_L} \left( EK_F(\xi) - i_L R_C R_L \right) \quad (7)$$

When using formula (6), the inductance value can be obtained on the basis of only the parameters taken directly. In other cases, when using formula (7), the output voltage is determined through total capacitance parameters ($R_C, C, U_C$). The second option of the calculation can be applied only when the parameters of capacitance are known and can serve as to verify the identified values of the capacitance and inductance.

To determine inductance and capacitance, it is necessary to determine $di/dt$, $du/dt$. These values can be determined based on the geometric meaning of the derivative. A differentiation step $\Delta t$ is selected on the constancy area of the structure ($K_F=const$) and the increment of current $\Delta i$ and voltage $\Delta u$ is determined. Then their ratio $\Delta i/\Delta t$, $\Delta u/\Delta t$ is determined.

To determine the optimal differentiation step $\Delta t$, to calculate $\Delta i / \Delta t$ a set of experiments was conducted and the results of the study proved that the highest accuracy and repeatability of the experiment results is attained in determining current increment $\Delta i$ along the boundaries of steady areas structure. Since the result of the numerical determination of the derivative is very sensitive to noise,
the switching time is excluded. In this case, an additional condition is required: the supply voltage \( E \) does not change significantly during the public key time \( K_F \). Otherwise, the increment \( \Delta t \) is necessary to be decreased.

Figure 2. Determining of the current derivative on time.

Determining of capacitance can be carried out by analogy with inductance by formula (8) obtained from (2 and 3).

\[
C = \left( \frac{i_L \cdot R_n - u_C}{R_n + R_C} \right) \cdot \frac{dt}{du_C}
\]

The problem with this approach is that the resistance value \( R_2 \) has a dynamic nature and varies with time on various factors [15]. Thus, one equation and two unknown variables are obtained. A solution to this problem is possible if the value of inductance (6) is predetermined, and then (7) is used as the second equation.

Another option to determine the value of the capacitor capacitance is performed using formula (9):

\[
C = \frac{1}{2\pi f Z_C}
\]

where \( f \) is the PWM frequency, \( Z_C \) is the capacitor impedance. To determine the value \( Z_C \) the following method is offered.

The time series of currents on the inductor \( (i_L) \) and on the load \( (i_n) \) are written down from the current transducers on the inductor CT1 and on the load CT2 (Fig. 7). Also, a time series of voltage values on the load \( U_n \) is written down from the voltage sensor VS. Time series are written down using the data acquisition L-card E20-D with a sampling frequency for each 3.3 (3) MHz range.

The values of the time series for the current of the capacitor are calculated, in accordance with the first Kirchhoff rule, according to formula (10):

\[
i_c = i_L - i_n
\]

As a result, there are two time series \( i_c \) and \( U_n \), which are periodic signals (Fig. 3 and Fig. 4). A fast Fourier transform of 2048 points is performed with these rows (Fig. 5 and Fig. 6).
As a result of the Fourier transform, two spectra are obtained in which the highest values of harmonic amplitudes are on the frequency of the PWM operation ($f_{PWM}$) and on frequencies that are multiples of it: $2f_{PWM}$, $3f_{PWM}$, $4f_{PWM}$ etc.

Knowing the harmonic amplitude values for $i_C$ and $U_n$ series, it is possible to calculate the phase value for each harmonic using formulas (1) and (2):

$$\varphi_U = \arctan \frac{\text{Im} U'}{\text{Re} U'}$$  \hspace{1cm} (11)

and

$$\varphi_I = \arctan \frac{\text{Im} I'}{\text{Re} I'}$$  \hspace{1cm} (12)

where $I'$, $U'$ are the amplitudes of the current harmonic and the voltage harmonic amplitude respectively; $\varphi_I$, $\varphi_U$ are the values of the current phase and voltage phase, respectively.

The phase difference ($\Delta \varphi$) is calculated by formula (13):

$$\Delta \varphi = \varphi_U - \varphi_I$$  \hspace{1cm} (13)

Now the impedance of the capacitor can be calculated using the formula (14):

$$Z_C = \frac{U'}{I'} e^{i\Delta \varphi}$$  \hspace{1cm} (14)

Sequential equivalent resistance $R_C$ of the capacitor is calculated by formula (15):

$$R_C = \left| Z_C \cos \Delta \varphi \right|$$  \hspace{1cm} (15)

Values $C$, $Z_C$, $R_C$ are calculated for the first five largest amplitudes of harmonics from the Fourier spectrum. The total value of the capacitor capacitance is calculated by the formula:
The final value of the series equivalent resistance of the capacitor is calculated by the same formula:

\[ R_{C_{res}} = \sum_{k=1}^{5} \frac{R_{Ck}}{U_{k}} \]  \hspace{1cm} (17)

5. Results of the experiment

Experimental studies were carried out on the installation "Pulse voltage converter" (24V-60W) [16]. In determining the inductance data were recorded on three channels \((K_F, U_n, i_L)\) by means of an oscillographs Tektronix TPS2014. The input voltage \(E\) was formed by the power supply Aktakom ATN-4235, with its own digital voltmeter, that monitors \(E\). A set of load resistance values was measured in advance using the RLC MNPI E7-20 meter. Synchronized time series were maintained through the data acquisition L-CARD E20-10, and then processed on a computer by means of the Python interpreter using the NumPy library. The bifurcation diagrams were constructed by solving equations (5), (6), and (7).

The results of the experimental determination are given in Tables 1 and 2, in which it is clearly shown that the deviation from the reference values is no more than 14%, which is a good result. The PSE nominal frequency \((f_{PWM})\) is 14 kHz.

### Table 1. Comparison of experimental results by the first criteria

| \(R_{NN}, \text{Ohm}\) | 5     | 10    | 20    |
|------------------------|-------|-------|-------|
| \(L, \text{uH}\)       | 0.62  | 0.788 | 0.88  |
| \(L_{exp}, \text{uH}\) | 0.644 | 0.908 | 1.023 |
| Discrepancy            | 3.7%  | 13.2% | 14.0% |

### Table 2. Comparison of experimental results by the second criteria

| \(R_{NN}, \text{Ohm}\) | 5     | 10    | 20    |
|------------------------|-------|-------|-------|
| Bif.boundary theor.    | 31    | 42    | 50    |
| Bif.boundary exp.      | 32.5  | 48    | 54    |
| Discrepancy            | 4.6%  | 12.5% | 7.4%  |
6. Conclusion

The obtained results make an assumption about the possibility of identifying the PSE parameters in order to determine the limits of the stability of the operational process and to develop corrective actions in real time.

The limitation of the presented approach is the impossibility of its use during the transition process. Each parameter combination corresponds to its own combination of PSE parameters, which requires a stability check after each control system correction upon completion of the transition process.

7. References

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