Research of frequency characteristics of hybrid inductive-capacitive converters

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Abstract. Current stabilization systems require stable operation when the magnitude and nature of the load resistance changes [1]. From this point of view, the most optimal solutions are circuit ones containing inductive-capacitive converters (ICC). The main disadvantages of ICC are large mass and dimensions. These disadvantages are eliminated by increasing the conversion frequency and hybrid execution of electromagnetic elements that perform the ICC function. An effective way to improve the mass-dimension parameters of ICC is the use of multifunctional integrated electromagnetic components (MIEC). In this article, the authors conducted the research of the frequency and energy characteristics of ICC based on a single-section MIEC. The parameters characterizing the ICC as a current stabilizer are estimated. The experimental confirmation of the adequacy of the developed mathematical models for calculating and constructing the MIEC frequency characteristics and estimating the ICC stabilization properties is carried out. The obtained results allow us to conclude that the use of the calculation method using the integrated parameters of MIEC is possible for the analysis of more complex MIEC schemes (two-section, three-section, three-electrodes) and electrotechnical devices based on them. The description of the electromagnetic processes by the system of differential equations leads to rather cumbersome mathematical derivations.

1. Introduction

Current stabilization systems require stable operation when the magnitude and nature of the load resistance changes [1]. From this point of view, the most optimal are circuit solutions containing inductive-capacitive converters (ICC). The main disadvantages of ICC are large mass and dimensions. These disadvantages are eliminated by increasing the conversion frequency and hybrid execution of electromagnetic elements that perform the ICC function [2]. An effective way to improve the mass-dimension parameters of ICC is the use of multifunctional integrated electromagnetic components (MIEC) [3].

When developing engineering calculation methods and design algorithms for the ICC, it is required to check the necessary condition for the operation of the ICC circuit in the short-circuit mode (decrease of the input and transfer resistances with increasing frequency). Also it is required to estimate the stabilization factor and the influence of the change in the load resistance on its value. Therefore, the actual task is to study the frequency characteristics of MIEC and to assess the stabilization properties of ICC based on them.
2. Formulation of the problem
The main tasks of the study are the construction and analysis of the frequency characteristics of the single-section structure of MIEC, the calculation of the stabilization ratio of current of the ICC on the basis of MIEC, the experimental confirmation of the adequacy of the developed mathematical models.

3. Theory
One-section MIEC combines the properties of an inductor and a capacitor, fulfills the role of an oscillating circuit, which makes it possible to create an ICC based on it, while reducing the consumption of electrically conductive, insulating and structural materials.

In articles [4, 5], the frequency and energy characteristics of a single-section MIEC were calculated by three methods of analyzing the operation of MIEC in the electrical circuits of the ICC. In this article, the calculation of electromagnetic processes is carried out using a system of linear equations, compiled on the basis of integral parameters.

The inductive-capacitive converter based on a single-section MIEC is considered as a quadripole. The main parameters of the ICC as a quadripole are input and transfer resistances, transfer conductivity [6]. For the correct operation of the ICC, it is important to reduce the input and transfer resistances and increase the transfer conductivity with rising frequency [7].

Indicators that are significant for ICC used in current stabilization systems (for example, capacitor storage systems) include the stabilization factor of the output load current, the deviation factor of the effective value of the load current, the range of variation in the effective value of the load current, the relative deviation of the output current [8].

4. Experimental results
The scheme of a single-section MIEC is shown in Figure 1.

The authors calculated the frequency characteristics of a single-section MIEC structure and made an experimental assessment of the adequacy of the developed mathematical models. The experimental layout is shown in Figure 2.

Electrical parameters of the prototype MIEC: capacitance - $C = 1.015 \ \mu F$; inductance of the electrodes - $L = 0.39 \ mH$; active resistance of the electrodes - $1 \ Ohm$. Geometric parameters of the prototype MIEC: length of the electrodes - $l = 20 \ m$; the number of turns - $w = 100$; width of copper tape - $b = 5 \ cm$, copper tape thickness - $\delta = 12 \ \mu m$.

The amplitude-frequency response is dependence of the electromagnetic element transmission coefficient on frequency—is constructed from the values measured with a generator and an electronic voltmeter or an oscilloscope.

The system of equations describing this scheme:

\[
\begin{align*}
\frac{U}{U_0} &= \frac{U}{U_0} + \frac{U}{U_0}, \\
U &= \left(\frac{U_0}{U_0} - I_L\right) \times (j\omega C)^{-1}, \\
U &= j\omega L \times \left(\frac{I_0 + I_L}{I_0 + I_L}\right), \\
U_L + U_0 &= U.
\end{align*}
\]
**Figure 2.** An experimental model of a single-section MIEC with connected devices:
1 – single-section MIEC; 2 – control system; 3 – load; 4 – oscillograph.

The results of calculations and experiments are presented in Figures 3 through 6.

![Voltage gain graph](image)

**Figure 3.** Dependence of the voltage gain on the relative frequency:
1 – calculated data; 2 – experimental data.

Figure 3 shows the dependence of the voltage gain on the relative frequency. The voltage transfer function (voltage gain) is the ratio of the voltages at the output and at the input of the circuit:

$$k_u = \frac{U_{\text{load}}}{U_{\text{input}}} \times (\frac{U_{\text{input}}}{U_{\text{load}}})^{-1},$$

(5)

where $U_{\text{load}}$, $U_{\text{input}}$ are complex voltages, respectively, at the input and output of the circuit.

In the MIEC resonance mode, the maximum voltage gain is achieved ($k_u = 9.1$). The permissible deviation of the voltage gain for MIECs operating in the ICC is 50% [9]. For the considered circuit of a device based on a single-section MIEC, this parameter is in the range from 4.55 to 9.1 in the frequency range from $0.85f_{\text{res.}}$ to $1.15f_{\text{res.}}$. Thus, in the frequency range from -15% to +15%, the voltage gain reduction does not exceed 50%. Comparison of the experimental results with the calculated data shows that the difference between the experimental data and the calculated data is no more than 9.6%.
Figure 4. Dependence of the current gain on the relative frequency:
1 – calculated data; 2 – experimental data.

Figure 4 shows the current gain as a function of the relative frequency. The current transfer function (current gain) is the ratio of the output $I_{\text{load}}$ and the input $I_{\text{input}}$ currents:

$$k_i = \frac{I_{\text{load}}}{I_{\text{input}}}.$$

In the MIEC resonance mode, the maximum amplitude load current is stabilized ($I_{\text{load,max}} = 0.145$). The allowable deviation of the ICC current gain is not more than 30 % [10]. For the considered circuit of a device based on a one-section MIEC, this parameter is in the range from 0.1 to 0.13 in the frequency range from $0.85 \cdot f_{\text{res}}$ to $1.15 \cdot f_{\text{res}}$. Thus, in the frequency range from -15 % to +15 %, the current gain reduction does not exceed 30 %. Comparison of the experimental results with the calculated data shows that the difference between them is no more than 8.8 %.

Figure 5. Dependence of the load current stabilization coefficient on the relative frequency:
1 – calculated data; 2 – experimental data.

Figure 5 shows the dependence of the current stabilization coefficient on the relative frequency. The criterion for the stabilization of the load current with changes in the load resistance from $Z_{\text{load}}$...
$= 0$ to $Z_{load max}$ (stabilization coefficient):

$$0 < \delta = I_{load}^2 \times Z_{load} \times (I_{input}^2 \times Z_{load max})^{-1} \leq 1.$$  \hspace{1cm} (7)

In the MIEC resonance mode, the load current stabilization coefficient is achieved ($\delta = 0.2$). The permissible deviation of the ICC current stabilization coefficient in the current stabilization system is not more than 15% [10]. For the considered scheme of ICC based on one-section MIEC, this parameter is in the range from 0.17 to 0.23 in the frequency range from $0.89 f_{res}$ to $1.05 f_{res}$. Comparison of the experimental results with the calculated data shows that the difference between them is no more than 6.3%.

![Figure 6](image)

**Figure 6.** Dependence of the input resistance on the relative frequency:
1 – calculated data; 2 – experimental data.

Figure 6 shows the dependence of the input resistance on the relative frequency. The input resistance is the ratio of the voltage at the input $U_{in}$ to the input current $I_{in}$:

$$Z_{in} = \frac{U_{in}}{I_{in}} (I_{in})^{-1}.$$  \hspace{1cm} (8)

The required condition for MIEC as an ICC is to decrease the input resistance of the ICC based on MIEC with an increase in the frequency (18.5 Ohm $> Z_{in}$ $> 4.3$ Ohm) will be performed in the frequency range from 0.5$f_{res}$ to 1.15$f_{res}$. In this comparison of the experimental results with the calculated data shows that the difference between them is no more than 4.5%.

5. **The discussion of the results**

The research results of the frequency characteristics of a one-section MIEC operating as an ICC, based on the MIEC mathematical model, show that the voltage gain reaches its maximum value in the MIEC resonant mode.

Based on the simulation results, it is established that in the MIEC resonance mode, the maximum voltage gain ($k_u = 9.1$) is reached and the load current of the maximum amplitude is stabilized ($I_{load max}$ $= 0.145$). For the circuit of the device based on a one-section MIEC, the deviation of these parameters is within the permissible limits in the frequency range from 0.85$f_{res}$ to 1.15$f_{res}$. Also, in the MIEC resonance mode, the stabilization coefficient of the load current $\delta$ is equal to 0.2. For the considered ICC scheme based on a one-section MIEC, the deviation of this parameter is within the permissible limits in the frequency range from $0.89 f_{res}$ to $1.05 f_{res}$.

As a result of the simulation, it was also found that the required condition for the operation of MIEC as an ICC is a reduction in the input and transfer resistances of the ICC with increasing frequency (18.5 Ohm $> Z_{in}$ $> 4.3$ Ohm and 55 Ohm $> Z_{transfer}$ $> 34$ Ohm) will be performed in the
frequency range from $0.5\cdot f_{res.}$ to $1.15\cdot f_{res.}$ and from $0.42\cdot f_{res.}$ to $1.4\cdot f_{res.}$, respectively.

The experimental confirmation of the adequacy of the developed models is carried out. The results of mathematical calculations are compared with the results of experiments. The discrepancy between the experimental results and the simulation does not exceed 15% for stabilizing the load current within ±15% of the frequency variation.

6. Conclusion
The following conclusions can be made based on the research results of the frequency characteristics of a one-section MIEC working as an ICC:
1. The authors performed a research and analyzed the ICC frequency characteristics based on a one-section MIEC using a mathematical model. The parameters characterizing the ICC as a current stabilizer are estimated.
2. Based on the simulation results, it is established that in the MIEC resonance mode, the maximum voltage gain is achieved and the load current of the maximum amplitude is stabilized. As a result of the simulation, it was also found that the required frequency dependence of the input and transmission resistances of the ICC is provided in the frequency range from $0.5\cdot f_{res.}$ to $1.15\cdot f_{res.}$ and from $0.42\cdot f_{res.}$ to $1.4\cdot f_{res.}$, respectively.
3. Experimental confirmation of the adequacy of the developed models is carried out. The results of mathematical calculations are compared with the results of experiments. The discrepancy between the experimental results and the simulation does not exceed 15% for stabilizing the load current within ±15% of the frequency variation.
4. The authors estimated and determined the most optimal method of calculation, using the MIEC integrated parameters. The obtained results allows one to conclude that the use of the calculation method using the integrated parameters of MIEC is possible for the analysis of more complex MIEC schemes (two-section, three-section, three-electrode) and electrotechnical devices based on them. The description of the electromagnetic processes by the system of differential equations leads to rather cumbersome mathematical derivations (differential equations of the 3rd, 4th order).

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