Inductive-Capacitive Converters for High-Voltage Secondary Power Supplies

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Abstract—Ensuring high energy efficiency of the consumer power supply process is important for high-voltage secondary power supplies used in current stabilization systems. More effective are push-pull converters with inductive-capacitive converters (ICC). The ICC technical flaws are the huge mass and big sizes of its constituent electromagnetic elements. These technical flaws are eliminated by rising frequency and using hybrid electromagnetic components that operating as ICC. In this article, the two-section multifunctional integrated electromagnetic components (MIEC) frequency characteristics and energy parameters are analyzed. The research on the mathematical model showed the following. It is possible to regulate the level of the stabilized load current when feeding the MIEC from the inverter by changing the amplitude of the supply voltage of the MIEC. It is shown that the investigated structure of MIEC has high voltage gain and is recommended for use in high voltage sources of secondary power supply with the function of current stabilization. The evaluation of the ICC stabilization properties was made. The authors have developed the mathematical model that allows the construction of MIEC frequency characteristics. The developed mathematical model is adequate, which is confirmed experimentally.

Keywords—high-voltage secondary power source; inductive-capacitive converter; multifunctional integrated electromagnetic component; hybrid performance; frequency characteristics.

I. INTRODUCTION

It is important to ensure high energy efficiency of the power supply process of the consumer for high-voltage secondary power supplies used in current stabilization systems [1, 2, 3]. This is achieved by using inductive-capacitive converters (ICC), which can provide a high voltage gain and the required value of the load current stabilization factor when the resistance value and the load pattern change in a wide range of frequency variation [4, 5, 6]. The ICC technical flaws are the huge mass and big sizes of its constituent electromagnetic elements (EME). The effective technical means of reducing the weight and dimensions of electrical devices are an increase in the frequency of conversion and the functional integration of EME [7, 8, 9]. Hybrid EMEs include such as the indicon, decon, okon, a helical stripline, a multifunctional integrated electromagnetic component (MIEC), which are integral LC-circuits. In this article, it is proposed to use MIEC, operating in resonance mode, as a parametric current stabilizer and voltage amplifier [10, 11].

For charge systems of capacitive storage, which include parametric current stabilizers, an important parameter characterizing the efficiency of operation is the voltage gain of the ICC [12 – 15]. In addition, when developing methods and algorithms for calculating high-voltage secondary power sources based on ICC, it is required to check the performance of the ICC circuit [16, 17, 18]. Consequently, the actual scientific and technical challenge is to build the MIEC frequency characteristics and to calculate the ICC stabilization parameters [19, 20, 21]. In this case, the ICC stabilization properties investigated when the frequency deviates from the resonance frequency [22, 23, 24].

II. FORMULATION OF THE PROBLEM

The objectives of the research are to estimate the voltage gain, to analyze the ICC stabilization properties, to build the frequency characteristics of the two-section MIEC structure, operating as an ICC, as part of a high-voltage secondary power source, to experimentally confirm the adequacy of the developed mathematical models.

III. THEORY

In the article [25, 26], a circuit-based solution of a two-section MIEC with high voltage gain is most effective for use in secondary power supplies for high-voltage consumers. Fig. 1 shows the investigated scheme of a two-section MIEC.

![Fig. 1. Scheme of a two-section MIEC with integral parameters.](image-url)
The developed mathematical model of ICC, represented in Fig. 1, is a system of linear algebraic equations that use the MIEC integrated parameters for describing the electromagnetic processes taking place in MIEC, including total capacitance, inductance of the electrodes, input and output currents:

\[ U_{in} = U_{in} + U_1, \]  
\[ U_1 = (U_2 - L_1) / (j \omega C_{11}), \]  
\[ U_2 = (U_6 - L_2) / (2j \omega C_{22}), \]  
\[ U_{in} = (R_1 + j \omega (L_1 + M_{12})) / (U_{in} + L_2), \]  
\[ U_{in} = (R_2 + j \omega (L_2 + M_{21})) / (U_{in} + L_2), \]  
\[ i_2 = i_2 + i_3, \]  
\[ i_3 = i_2, \]  
\[ i_2 = i_2 / 2, \]  
\[ i_2 = \omega C_{22} U_{in} / (2j), \]  
where \( M_{12} \) and \( M_{21} \) are mutual inductance between the inductive elements of each section MIEC; \( R_1 \) and \( R_2 \), \( L_1 \) and \( L_2 \) are active resistances and inductances of the first and second conductive electrodes of MIEC, respectively; \( C_{11} \) and \( C_{22} \) are capacitances between the conductive electrodes of the first and second sections, respectively.

With the help of this mathematical model, the voltage gain and load current stabilization, the input and transmission resistances, and the conductivity of the MIEC are calculated. The obtained data allow to calculate the permissible frequency range variation depending on the specified accuracy of stabilizing the load current.

IV. EXPERIMENTAL RESULTS

The authors have developed the mathematical model that allows the construction of MIEC frequency characteristics. This mathematical model is developed to determine the range of variation in load resistance and frequency at which the load current is stabilized with a specified accuracy. The developed mathematical model is adequate, which is confirmed experimentally. The scheme of the experiment with a two-section MIEC is shown in Fig. 2.

![Scheme of the experiment with a two-section MIEC](image)

The electrical parameters and geometric dimensions of the MIEC laboratory sample, which was used for the experiments, are given in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>inductance, mH</td>
<td>0.029</td>
</tr>
<tr>
<td>active resistance of the electrodes, mOhm</td>
<td>183</td>
</tr>
<tr>
<td>capacity, mF</td>
<td>0.289</td>
</tr>
<tr>
<td>number of turns</td>
<td>34</td>
</tr>
</tbody>
</table>

The results of comparing the calculations made with the help of the mathematical model and the experiments are presented in Fig. 3 through 7.

Fig. 3 shows the voltage gain versus relative frequency obtained using the mathematical model of ICC.

![Graph of voltage gain versus relative frequency](image)

The mathematical model shows that this ICC scheme allows to obtain a large value of the voltage gain, the value of which depends on the quality factor of the resonant LC-circuit. The quality of the circuit is also determined by the active load resistance. An analytical dependence is obtained from the mathematical model:

\[ k_{el}(\alpha) := \frac{4 \cdot 2.845 \cdot \alpha \cdot Z_4 \cdot \frac{C_{22}}{L_4} \cdot \left[ 4 + (2.845 \cdot \alpha)^2 \right]}{\sqrt{\left[ 8 - (2.845 \cdot \alpha)^2 \right]^2 \cdot 4 \cdot (2.845 \cdot \alpha)^2 \cdot Z_4^2 \cdot \frac{C_{22}}{L_4} + 24 \cdot (2.845 \cdot \alpha)^4}} \]

The greater the load resistance, the greater the voltage gain of the ICC.

The developed mathematical model is adequate, which is confirmed experimentally. Experimental research have fixed the result, the difference between which and the calculated data does not exceed 11%. Consequently, the developed mathematical model can be used to select MIEC parameters to ensure an efficient operating mode of ICC for high-voltage secondary power supplies.

Fig. 4 through 7 demonstrated the results of comparing of theoretical and experimental research made with the help of the mathematical model and MIEC laboratory sample.

The graphical dependences of the parameters under study on the frequency will be given as a function of the relative frequency, under which the ratio of the operating conversion frequency to the frequency at which resonance occurs in the circuit takes. We introduce the designation of the relative frequency: \( \alpha \).
The voltage gain depending on the relative frequency will vary according to the graph in Fig.4. When \( f = f_{\text{res}} \), the gain will take the maximum value equal to \( k_u = 10 \).

The voltage gain varies from 5 to 10 when the frequency is adjusted from \( 0.85f_{\text{res}} \) up to \( 1.15f_{\text{res}} \). The permissible deflection of the voltage gain for ICC is not more than 50% [27, 28, 29].

![Graph of voltage gain versus relative frequency](image)

Fig. 4. Graph of voltage gain versus relative frequency.

The criterion for stabilizing the load current when the load resistance varies from zero to maximum value (stabilization factor):

\[
0 < \delta = \frac{(I_n)^2 \cdot Z_l}{(I_n)^2 \cdot Z_{l_{\text{max}}}} \leq 1
\]

where \( \delta \) is load current stabilization factor [30].

The stabilization factor depending on the relative frequency will vary according to the graph is shown in Fig. 5.

![Graph of stabilization factor versus relative frequency](image)

Fig. 5. Graph of stabilization factor versus relative frequency.

The maximum value of stabilization factor of the load current is observed in the resonant mode. Stabilization factor varies from 0.55 to 0.75 when the frequency changes from \( 0.7f_{\text{res}} \) up to \( 1.5f_{\text{res}} \). Experimental research have fixed the result, the difference between which and the calculated data does not exceed 15%.

The input resistance depending on the relative frequency will vary according to the graph in Fig. 6.

![Graph of transfer resistance versus relative frequency](image)

Fig. 6. Graph of stabi input resistance versus relative frequency.

The transfer resistance depending on the relative frequency will vary according to the graph is shown in Fig. 7.

![Graph of transfer resistance versus relative frequency](image)

Fig. 7. Graph of transfer resistance versus relative frequency.

The performance of MIEC as an ICC increases with decreasing ICC input resistance as the frequency increases (10 Ohm > \( Z_{\text{in}} \geq 1.5 \) Ohm). In the frequency range from \( 0.7f_{\text{res}} \) to \( 1.5f_{\text{res}} \) this is exactly what happens, this condition is satisfied. Experimental research have fixed the result, the difference between which and the calculated data does not exceed 13%.

The transfer conductivity depending on the relative frequency will vary according to the graph is shown in Fig. 8.

![Graph of transfer conductivity versus relative frequency](image)

Fig. 8. Graph of transfer conductivity versus relative frequency.
V. THE DISCUSSION OF THE RESULTS

Theoretical studies have shown that:

- in the MIEC resonance mode, the maximum voltage gain \((k_i = 10)\) is reached, the value of which depends on the quality factor of the resonant LC-circuit and can reach a considerable value. For the investigated scheme the voltage gain is within acceptable limits (from 5 to 10) when the frequency is adjusted from \(0.85 f_{\text{res}}\) up to \(1.15 f_{\text{res}}\);

- the maximum value of stabilization factor of the load current is observed in the resonant mode. Stabilization factor varies from 0.55 to 0.75 when the frequency changes from \(0.7 f_{\text{res}}\) up to \(1.5 f_{\text{res}}\); of the input and into account the nature of the load

- the efficiency of MIEC as an ICC increases with decreasing ICC input and transfer resistances as the frequency increases \((10 \,\text{Ohm} > Z_{eg} > 1.5 \,\text{Ohm} \text{ and } 5000 \,\text{Ohm} > Z_{egp} > 3500 \,\text{Ohm})\). In the frequency range from \(0.7 f_{\text{res}}\) to \(1.15 f_{\text{res}}\) and from \(0.5 f_{\text{res}}\) to \(1.5 f_{\text{res}}\) this is exactly what happens, this condition is satisfied;

- the performance of MIEC as an ICC increases with an increase in the transfer conductivity of the ICC \((0.05 < \gamma_{\text{transfer}} < 0.074)\) as the frequency increases \((0.05 < \gamma_{\text{transfer}} < 0.074)\).

Theoretical studies have established that when the frequency of free oscillations of the oscillating circuit formed by MIEC coincides with the switching frequency, the maximum voltage gain is achieved. The discrepancy between the results of the experiment and the simulation is in the range from 6% to 15%.

VI. CONCLUSION

According to the results of the study, the following conclusions can be drawn:

1. The mathematical model of ICC on the basis of MIEC, proposed by the authors, made it possible to estimate the stabilization parameters, amplification parameters, frequency characteristics and stabilization properties.

2. It is established that the maximum voltage gain and stabilization of the load current of maximum amplitude is achieved when MIEC operates in the resonance mode. The required frequency dependence of the input and transfer resistances of the ICC is provided in the frequency range from \(0.7 f_{\text{res}}\) to \(1.15 f_{\text{res}}\) and from \(0.5 f_{\text{res}}\) to \(1.5 f_{\text{res}}\) respectively.

It is shown that the investigated structure of MIEC has a high voltage gain and is recommended for use in high voltage sources of secondary power supply with the function of current stabilization.

3. Theoretical studies have established that when the frequency of free oscillations of the oscillating circuit formed by MIEC coincides with the switching frequency, the maximum voltage gain is achieved. The discrepancy between the results of the experiment and the simulation is in the range from 6% to 15%.

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