Assessment of operating modes of hybrid electromagnetic elements in the inductive-capacitive converters

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Abstract. Methods of functional integration of electromagnetic elements (EME) allow to improve the technical and economic indicators, accelerate the development process, improve manufacturability and reliability, as well as reduce the cost of secondary power sources (SPS) [1,2]. The authors suggest the use of a hybrid EME as an inductive-capacitive converter (ICC), called a "multifunctional integrated electromagnetic component" (MIEC). The authors consider various MIEC designs, in particular a two-section structure. When designing complex MIEC structures, many unresolved issues and tasks arise. The research and development of MIEC and electrotechnical devices based on them is an urgent task. The frequency and energy characteristics of the ICC are analyzed on the basis of a two-section MIEC in this article. An experimental confirmation of the adequacy of the developed mathematical model for calculating and constructing the frequency characteristics of MIEC and estimating the stabilization properties of ICCs for various design versions of MIEC is carried out. It is obtained that in the manufacture of two identical MIECs with identical electrical parameters placed on separate frames with a common magnetic circuit (with the same number of turns of each electrode, active and inductive resistance of MIEC) this circuit solution of ICC has a higher voltage gain.

1. Introduction
Methods of functional integration of electromagnetic elements (EME) allow to improve the technical and economic indicators, accelerate the development process, improve manufacturability and reliability, as well as reduce the cost of secondary power sources (SPS) [1,2]. The work on the creation of hybrid EME and electrical devices based on them has been conducted for several decades [3, 4]. There are various circuitry solutions of the power section of the SPS, implemented on the basis of hybrid EME [5, 6]. The authors suggest the use of a hybrid EME as an inductive-capacitive converter (ICC), called a "multifunctional integrated electromagnetic component" (MIEC) [7]. The authors consider various MIEC designs, in particular a two-section structure [8]. When designing complex MIEC structures, many unresolved issues and tasks arise. There are no engineering methods for calculating MIEC and algorithms for designing devices based on them. Work modes of MIEC studied insufficiently [9, 10]. In this connection, the research and development of MIEC and electrotechnical devices based on them is an urgent task.
2. Problem statement
The main objectives of the study are assessment of the operating modes, comparison the stabilization properties and frequency characteristics of the two-section MIEC structure, which has identical or different parameters of the sections operating in the ICC structure, and also an experimental confirmation of the adequacy of the developed mathematical models.

3. Theory
In this article, we consider the two-section structure of MIEC (Figure 1), which makes it possible to implement on its basis more than thirty combinations of ICC circuitry solutions that differ in the connection options of the MIEC sections and the connection scheme for the power supply and load to the MIEC sections (Table 1) [11, 12].

![Figure 1. Scheme of two-section MIEC: 1, 2 – first and second conductive electrodes, 3, 4 – first and second sections.](image)

The multifunctional integrated electromagnetic component combines the properties of the inductor and capacitor, which reduces the consumption of conductive, insulating and structural materials [13, 14]. Each section of the two-section MIEC represents two conductive electrodes, coiled and separated by a dielectric, all sections having a magnetic coupling [15, 16]. Each MIEC cover has leads at the beginning and end of the lining. There are several ways of constructive execution of the two-section structure of MIEC. In the first case, both sections are placed on one frame by winding one section onto the other (Figure 2). With the same number of turns due to the larger diameter of the winding, the second section has a large inductance and capacity. In the second case, two identical MIEC sections with identical electrical parameters are made, placed on separate frames with a common magnetic circuit (Figure 3).

![Figure 2. The scheme of a two-section MIEC with two sections placed on one skeleton by winding one section to another: 1 – the first section, 2 – the second section, 3 – the magnetic core.](image)

![Figure 3. General view of a two-section MIEC with identical electrical parameters with two sections placed on separate frames with a common magnetic circuit: 1 – first section, 2 – second section, 3 – magnetic core.](image)
4. Results of the experiment
The scheme of the experiment with a two-section MIEC is shown in Figure 4.

![Figure 4. Scheme of experiment with a two-section MIEC.](image)

The electrical parameters of MIEC laboratory samples are presented in Table 1. The indices 1 and 2 refer to the first and second sections of conductive plates, respectively. The first method of winding corresponds to the model sample code-named "MIEC 1", the second version of the winding corresponds to the model sample, code-named "MIEC 2".

| Parameter | MIEC 1 | MIEC 2 |
|-----------|--------|--------|
| R1, Ohms  | 183    | 191    |
| R2, Ohms  | 208    | 195    |
| L1, µH    | 29     | 38     |
| L2, µH    | 41     | 38     |
| C12, µF   | 0.289  | 0.218  |

The results of comparison of the stabilization properties and the frequency characteristics of the two-section MIEC structure, which have identical or different section parameters, are presented in Figures 5 to 8.

The criterion for stabilizing the load current when the load resistance varies from $Z_L = 0$ to $Z_{L,max}$ is the stabilization factor:

$$0 < \delta = \frac{(I_{in})^2}{(I_{in})^2 + Z_{L,max}} \leq 1.$$  \hspace{1cm} (1)

Figure 5 shows the dependence of the current stabilization coefficient on the relative frequency.

![Figure 5. The graph of the current stabilization coefficient as a function of the relative frequency: 1 – MIEC 1; 2 – MIEC 2.](graph)
In the resonance mode of "MIEC 2", the load current stabilization factor $\delta = 0.25$ is achieved, for "MIEC 1" the load current stabilization factor $\delta = 0.15$, i.e., less than 2 times. For the considered scheme of ICC on the basis of two-section "MIEC 2" this parameter is in the range from 0.21 to 0.25 in the frequency range from $0.75 \cdot f_{res}$ up to $1.05 \cdot f_{res}$. For the considered scheme of ICC on the basis of the two-section "MIEC 1" this parameter is in the range from 0.13 to 0.15 in the frequency range from $0.9 \cdot f_{res}$ up to $1.05 \cdot f_{res}$.

Figure 6 shows the dependence of the voltage gain on the relative frequency.

![Figure 6. The graph of the voltage gain of the relative frequency: 1 – MIEC 1; 2 – MIEC 2.](image)

In the resonance mode of MIEC 2, the maximum voltage gain is reached ($k_u = 9$), for MIEC 1 the maximum voltage gain is $k_u = 8$. The simulation results show that a 50-60-fold increase in the input voltage when using MIEC with the same parameters for the corresponding Q of the resonance LC-circuit.

For the considered circuit of the device based on the two-section "MIEC 2" this parameter is in the range from 4.5 to 9 in the frequency range from $0.85 \cdot f_{res}$ up to $1.15 \cdot f_{res}$. For the considered circuit ICC on the basis of two-section "MIEC 1" this parameter is in the range from 4 to 8 in the frequency range from $0.85 \cdot f_{res}$ up to $1.1 \cdot f_{res}$.

Figure 7 shows the dependence of the input resistance on the relative frequency.

![Figure 7. The graph of the dependence of the input resistance on the relative frequency: 1 – MIEC 1; 2 – MIEC 2.](image)

The required condition for MIEC as an ICC is to decrease the input resistance of the ICC based on MIEC with increasing frequency will be performed for "MIEC 2" and "MIEC 1" in the same frequency range from $0.75 \cdot f_{res}$ up to $1.2 \cdot f_{res}$. But the value of the input resistance of "MIEC 1" (35 Ohm $> Z_{in.1} > 15$ Ohm) is higher than "MIEC 2" (20 Ohm $> Z_{in.2} > 5$ Ohm).

Figure 8 shows the dependence of the transfer resistance on the relative frequency.
Figure 8. The graph of the dependence of the transfer resistance on the relative frequency: 1 – MIEC 1; 2 – MIEC 2.

The required condition for MIEC as an ICC is to reduce the transmission resistance of the ICC on the basis of MIEC with increasing frequency, and will be performed for "MIEC 2" and "MIEC 1" in the same frequency range from 0.75·f_{res.} up to 1.2·f_{res.}. But the value of the input resistance "MIEC 1" (15 kOhm > Z_{tr,1} > 14 kOhm) is higher than "MIEC 2" (10 kOhm > Z_{tr,2} > 8 kOhm).

The required condition of MIEC as an ICC is the entrainment of the transfer conductivity of the ICC on the basis of MIEC with increasing frequency will be performed for "MIEC 2" and "MIEC 1" in the same frequency range from 0.75·f_{res.} up to 1.15·f_{res.}. But the value of the transfer conductance of "MIEC 1" (0.01 S < Y_{tr,1} < 0.02 S) is lower than "MIEC 2" (0.02 S < Y_{tr,2} < 0.08 S).

5. Discussion
According to the simulation results, it is established that in the resonance mode of "MIEC 2" the load current stabilization factor δ = 0.25 is achieved, for "MIEC 1" the load current stabilization factor δ = 0.15, i.e. less than 2 times.

In the resonance mode of "MIEC 2" the maximum voltage gain (k_u = 9) is reached, for "MIEC 1" the maximum gain by voltage is equal to k_u = 8.

In the MIEC resonance mode, the load current of the maximum amplitude is stabilized. For the considered circuit of the device based on the two-section "MIEC 2", the current gain is equal to 0.08 in the frequency range from 0.75·f_{res.} up to 1.5·f_{res.}, and for "MIEC 1" the current gain is equal to 0.06 in the same frequency range.

The required conditions of MIEC as an ICC will be fulfilled for both design versions of the two-section MIEC structure in the same frequency range.

The experimental confirmation of the adequacy of the developed models on the MIEC model prototype has been carried out. The discrepancy between the results of the experiment and the simulation is in the range from 10% to 15% for changing the voltage gain within 50% and stabilizing the load current within ±15% of the frequency variation.

6. Conclusions
Based on the results of the study of the frequency characteristics of a two-part MIEC working as an ICC, the following conclusions can be drawn:

1. The authors carried out the study and analysis of the frequency characteristics of the ICC on the basis of a two-section MIEC using a mathematical model. The parameters describing the ICC as a current stabilizer and a voltage amplifier increasing output voltage amplitude are assessed.

2. Based on the results of the simulation, it is assessed that the maximum voltage gain (k_u = 9) is reached in the resonance mode of "MIEC 2", for "MIEC 1" the maximum voltage gain is equal to k_u = 8. Simulation results show that it is possible to achieve a 50-60-fold increase in the input voltage when using MIEC with the same parameters for the corresponding Q of the resonant LC circuit.

For the considered circuit of the device based on the two-section "MIEC 2" this parameter is in the range from 4.5 to 9 in the frequency range from 0.85·f_{res.} up to 1.15·f_{res.}. For the considered circuit ICC
on the basis of two-section "MIEC 1" this parameter is in the range from 4 to 8 in the frequency range from \(0.85\cdot f_{res}\) up to \(1.1\cdot f_{res}\).

3. The results of studies of the frequency characteristics and stabilization properties of the two-section MIEC structure of different design show that the most availability of a mutually inductive coupling allows smooth regulation of the load current due to a change in the resonant frequency over a wide range. Linear magnetic coupling between conductive plates in the hybrid design of ICC allows improving the stabilizing, power and frequency characteristics of ICC.

4. 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 results of the experiment and the simulation does not exceed 15% for changing the voltage gain by 50% and stabilizing the load current within ± 15% of the frequency variation.

7. References

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