Method of creating equivalent circuits of capacitive batteries of pulsed power supplies of powerful technological systems

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Abstract. The article is devoted to the design aspects of pulsed power supplies of technological systems. Experiments had shown that development of such power supplies requires to take into account the resistive and inductive components of the complex impedance of capacitors batteries. The article proposes a method for finding the equivalent circuit of these batteries. The method is based on an approximation of their experimentally measured frequency characteristics. The article also shows that the obtained results for a single battery cannot be distributed to capacitor bank. Presented numerical simulation results shows that the duration of the pulse front depends on the inductive component of the resistance of capacitive elements.

1. Introduction
Efficient implementation of pulsed modes of technological systems requires power systems that provide energy storage during the pause between pulses and the release of this energy during a short time of the pulse. Almost all pulse-periodic systems use storage systems made of capacitors batteries as the main element of the power supply (PS).

When designing power supplies for pulsed technological systems, the real characteristics of capacitor bank in most cases are not taken into account [1]. However, the pulse duration, its edge and amplitude is largely determined by the properties of real capacitor bank and the way it is connected to the technological part of the installation. In paper [4], a long LC line consisting of 19 links was used to obtain rectangular pulses with a duration of 0.3-5 ms of a high-current magnetron discharge. And yet, this paper does not provide basis for the selection of the supply or its parameters.

Paper [2] shows an attempt to propose the main recommendations for choosing the circuit design of a capacitive storage of a pulsed plasma accelerator. However, these recommendations related to power systems in the form of single or multi-link capacitive pulse-forming line and did not involve the parameters of the capacitor batteries themselves. Along with that, it is well known that capacitor banks can act as resistive or inductive elements at certain frequencies [3]. So in the development of pulsed power supplies, it is necessary to take into account the fact that capacitor banks are complex systems with an extensive equivalent circuit. The determination of this circuit parameters is possible only by experimental study of the capacitor banks’ frequency characteristics.

The purpose of this work is precisely the development of methods for creating equivalent circuits for real capacitor batteries based on an experimental study of their frequency characteristics.

2. The device working principles and the order of the experiments
Despite the appearance on the market of foilless commercial capacitors of the “Maxwell Laboratories,
Inc.” with low internal impedance, foil capacitors with paper-oil insulation are still the most common ones. Typical representatives of which are capacitors K41I-7 and K75-28. In this paper, we did not go beyond studying exactly these types of capacitors and blocks made from them.

The frequency response of the K41I-7 capacitor experimentally measured using the immittance meter is shown in figure 1. Clearly, the amplitude response (AR) of the capacitor varies from almost purely capacitive nature (at frequencies up to 20 kHz) to almost inductive nature (at frequencies above 40 kHz). Therefore, we can assume that the module of complex impedance is the sum of capacitive ($Z_C$), inductive ($Z_L$) reactance and active resistances ($R_a$). The easiest thing is to determine the active resistance. It equals to the value of the complex impedance at resonance frequency ($\omega_0$). This value corresponds to the minimum of the curve in figure 1. At the same frequency $Z_C = Z_L$, i.e. $L = 1/(\omega_0^2 C)$. The total resistance calculated for the equivalent circuit of K41I-7 capacitor is shown in figure 1, as well as individual components of the resistance. A comparison of calculated and experimentally measured results indicates the adequacy of such an approach to development of an equivalent circuits. Similar results obtained for capacitor K75-28 are shown in figure 2.

**Figure 1.** The amplitude and phase responses of K41I-7 capacitor obtained experimentally (1) and calculated using the proposed equivalent circuit (2).

**Figure 2.** The amplitude and phase responses of K75-28 capacitor obtained experimentally (1) and calculated using the proposed equivalent circuit (2).

In the case of capacitor K75-28, the inductance was almost 2 times less than for capacitor K41I-7. It is obvious that with an increase in inductance in a series RLC circuit, the value of the resonance frequency decreases and the duration of the current pulse edge increases. To determine the link between the parameters of the power supply system and the duration of the current pulse edge that this system can provide, numerical experiments were carried out on a mathematical model in the NI Multisim environment. Data on parameters of the load are taken from paper [3]. The results of numerical simulation for different values of the total inductance $L_{\Sigma} = L_C + L_1 + L_2$ are shown in figure 3. These results show that the pulse edge duration is determined by the value of the resonance frequency for this circuit. Or, in other words, the duration of the pulse edge is determined by the frequency at which the capacitive resistance of the storage is equal to the total inductive load resistance and the length of the connecting cable. In the case of a properly organized energy input to the technological system, the inductance of a capacitor bank is comparable to the inductance of the current supply. It must be taken into account when developing pulsed power systems.

In terms of technology, for storing the required energy usually a capacitor bank (several capacitors connected in parallel) is used instead of one capacitor. The frequency responses of the block, made up of five parallel-connected capacitors K41I-7, are shown in figure 4. It turned out that when connected to a capacitor battery, a change occurs in the frequency at which the nature of the battery resistance changes from capacitive to inductive with 24 kHz which is characteristic of a single capacitor and at 12 kHz for
the battery and the resistance at this frequency from 24 mΩ to 5 mΩ. Also, an additional local minimum at a frequency of 24 kHz appeared on the frequency response.

![Figure 3](image1.png)

**Figure 3.** The results of numerical simulation of the current change in the technological system over time with the values of $L_1 = 0.5 \times 10^{-6}$ H, $L_2 = 1 \times 10^{-6}$ H, $L_3 = 2 \times 10^{-6}$ H.

![Figure 4](image2.png)

**Figure 4.** The amplitude and phase responses of the block, made up of five parallel-connected capacitors K411-7 obtained experimentally (1) and calculated using the proposed equivalent circuit (2).

![Figure 5](image3.png)

**Figure 5.** The equivalent circuit of the block, made up of five parallel-connected capacitors K411-7, taking into account the inductance of the tires connecting the individual capacitors.

In this case, to create a mathematical model, it is necessary to take into account the inductive reactance of the tires connecting the individual capacitors. And the equivalent circuit should take the form of a long line segment (figure 5).

3. Conclusions
1. A method of creating equivalent circuits for power supply systems that provides energy storage using capacitive storage devices has been proposed and tested.
2. The equivalent circuit of a separate capacitor can be represented as RLC elements connected in series.
3. When designing power supply systems, it is necessary to take into account both the equivalent circuit of a separate capacitor and the equivalent circuit of entire capacitor battery.

References
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