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GENERATION OF PULSED MAGNETIC FIELDS USING REACTIVE SHAPING CIRCUITS

N. I. MIHAILOV, O. I. VANKOV, CH. GHELEV
Institute of Electronics, Bulgarian Academy of Sciences
72 Tsarigradsko Chaussée Blvd, 1784 Sofia, Bulgaria

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Abstract. Theoretical considerations are given concerning the use of bi- quadri- and multipolar reactive circuits for formation of current pulses with an arbitrary predefined shape. Different practical cases are considered, and the use of particular circuits is recommended in view of simplifying the circuit design.

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High-intensity pulsed magnetic fields find uses in physical experiments, e-beam accelerator design, as well as in various electrical and technological equipment. The type of the physical investigation, or requirements of the technological process, often impose severe constraints on the shape and duration of the magnetic pulse, i. e. on the current pulse dissipated on the inductance (coil) used to generate the magnetic field.

To implement generators of current pulses with a complex shape, one ordinarily employs nonlinear multi-switch circuits that are too complicated to design and adjust, and, consequently, not sufficiently reliable. The application of reactive shaping circuits not only eliminates some of the design difficulties and increases the reliability of the equipment, but also improves such important parameters as the current transfer coefficient K_i and the overall energy efficiency K_W. The present paper is a logical continuation of previous works of the authors devoted to formation of current pulses with pre-defined shape using bi- and quadripolar passive circuits [1, 2].

A shaping circuit with an inductive load L_L is shown schematically in Fig. 1. If one considers L_L as being an element of the shaping loop, the circuit can be mathematically treated as being of the short-circuited output type. To obtain a positive half-wave current pulse at the output, one has to use a switch with unidirectional conductance (e. g., thyristor, thyratron). When the switch is open, the storage elements are recharged through L_L for a time $t = T/2$, where T is the period of the function $i_1(t)$. At $t = T/2$, the input current must change its sign simultaneously with i_2 — the diode switch then breaks the circuit and the shaping cycle is completed. The energy remaining in the storage elements can be used to form the subsequent pulses if one implements the circuit shown in Fig. 2, or other similar energy-recuperating techniques [1].

Thus the problem of implementing the shaping circuit is reduced to synthesizing a short-circuited reactive loop with an inductive output element. In addition, for one half-period, the current of the short-circuited loop should coincide with the current through the load, i. e.

$$i_2(t) = i_L(t), \quad \text{for } t = 0 \text{ to } \frac{T}{2}.$$

To construct the circuit, it is necessary to know the transfer function

$$H(p) = \frac{I_2(p)}{U_1(p)}$$

where $I = I(p)$ and $U = U(p)$ are the Laplace representations of the current and the voltage.

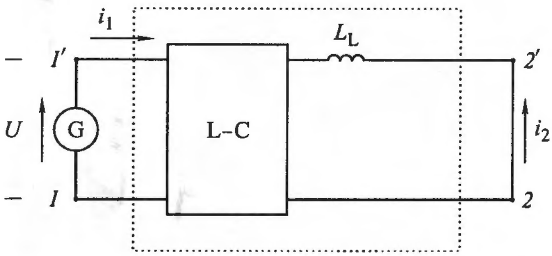

Fig. 1. Schematic representation of a shaping circuit with an inductive load

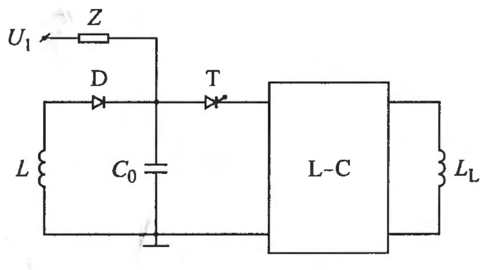

Fig. 2. An example of energy-recuperation shaping circuit with an inductive load

With this objective, the current $i_2(t)$, obtained through periodical odd continuation of the pre- defined current $i_L(t)$, is expanded in a Fourier series. Assuming that the first n terms provide the necessary accuracy, is written as

$$i_2(t) \approx \sum_{k=1}^{n} B_k \sin \omega kt$$

where B_k are the coefficients and $\omega = 2\pi/T$.

In the case of applying a step-like voltage-jump at the input, the transfer function has the form [e. g. 1]

$$H(p) = pI_2(p)\frac{p(a_{2m}p^{2m} + a_{2(m-1)}p^{2(m-1)} + \cdots + a_0)}{p^{2n} + b_{2(n-1)}p^{2(n-1)} + \cdots + b_0} = p\frac{M(p)}{N(p)}\,.$$

Here $N(p)$ is an even polynomial of $2n$-th degree with positive coefficients ($b > 0$) and zeros on the imaginary axis, and $M(p)$ is also an even polynomial of a degree less than $2n$, whose order $2m$, sign of the coefficients a, and location of zeros on the imaginary plane are determined by the expansion coefficients B_k.

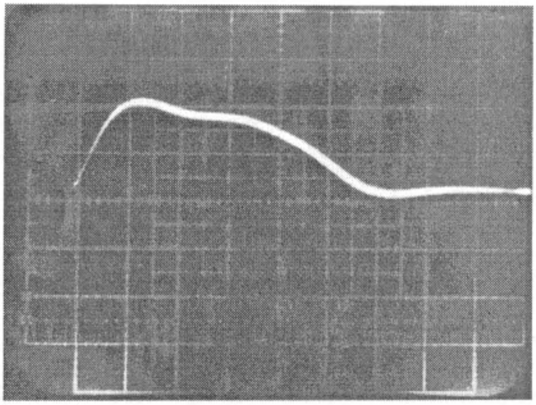

Fig. 3. Typical current pulse shaped using a bopole circuit
Tektronix 466 DM 44 storage oscilloscope, horizontal sweep 200 μs/div, vertical sweep 5 kA/div

The type of circuit implemented depends on the type of the transfer function, i. e., on the type of $M(p)$. When analyzing this polynomial, depending on the coefficients B_k for 3 and 4 terms of the Fourier series, one arrives at the following conclusions.

A. If the degree of $M(p)$ is $2m = 2(n-1), a > 0$, and its zeros are purely imaginary and alternate with those of $N(p)$, then the transfer function is represented by the input admittance of a bipolar circuit

$$H(p) = y(p)\,,$$

which has a zero at $p = \infty$. In this case, one can easily implement such a bipole with an inductive element at the output using well-known techniques, such as described in [3]. Fig. 3 illustrates a current shaped by a bipole circuit making use of the technique discussed above.

B. If the degree of $M(p)$ is $2m = 2(n-i), i < n, a > 0$, and its zeros are purely imaginary but do not alternate with those of $N(p)$, then the transfer function is the transfer admittance $y_{21}(p)$ of a short-circuited quadripolar circuit. To implement such a circuit in accordance with a known procedures [4], one has to know one more parameter of the short circuit, such as the input or output admittance. Since the cases with energy recuperation (Fig. 2) imply the presence of diode switches and a separate storage element, it is easier to construct the circuit not by using the latter as usual but rather the former [5]

$$I_1 = y_{11}U_1 + y_{12}U_2$$
$$I_2 = y_{21}U_1 + y_{22}U_2$$

where y_{11} and y_{22} are the input or output admittances, respectively.
When one uses $y_{11}(p)$, and also has to define the input current $i_1(t)$ — the choice of its shape is determined by additional conditions, such as minimal number of elements in the circuit, maximal values of K_W and K_i, etc. The function $i_1(t)$ can also be approximated by means of a sine Fourier series — this ensures that $y_{21}(p)$ and $y_{11}(p)$ have common zeros at $p = 0$ and $p = \infty$ and guarantees that one can place a storage capacitor C_0 at the input and an inductance L_L at the output.

C. If the coefficients in $M(p)$ $a < 0$, or it has complex conjugate zeros, then the transfer function will correspond to a parallel-chain circuit. The negative coefficients can be avoided by means of additional multipliers [1]. These circuits, however, possess a number of considerable drawbacks, such as:
   - an increase of the degree of $H(p)$ and of the number of necessary elements,
   - a low-current transfer coefficient,
   - a lack of control on the input current shape and no guarantee that diode switches can be used in implementing the circuit.

   These usually make one avoid their use.

The above discussion led us to consider multipolar circuits, the simplest case being the hexapole that consists of two bipolar circuits connected in opposite with a common inductive load (Fig. 4).

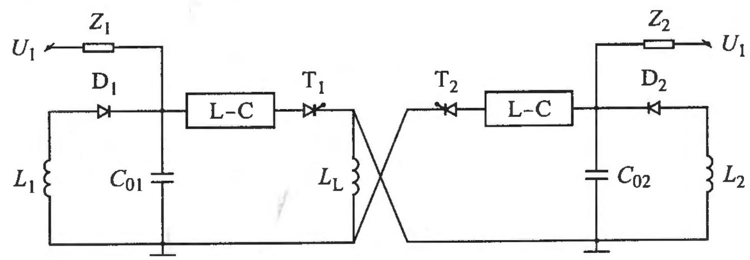

Fig. 4. A six-pole circuit with common inductive load

This circuit is implemented on the basis of the assumption that its transfer function can be represented as the difference of the admittances of the two bipoles [6]

$$H(p) = y_{21}(p) = y_1(p) - y_2(p)\,.$$

The calculations begin with a partial separation of the common zero at $p = \infty$. The remainder $y'_{22}(p)$ is presented as sum of components calculated using the remaining zeros of $y_1(p)$ and $y_2(p)$.

In conclusion, summarizing the above discussion, we have shown that one can always construct a reactive circuit that forms a current pulse with an arbitrary predefined shape on an inductive load; moreover, the pulse shape corresponds strictly to the circuit type. As demonstrated in cases A, B, C, one can select the expansion coefficients of the function $i_2(t)$ within the limits of the accuracy desired (i. e. depending on pulse-shape needed) so as to simplify significantly the structure of the shaping circuit — especially in the case of a hexapolar reactive circuit. This possibility eases considerably the design of pulsed magnetic field generators based on the use of reactive shaping circuits.

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