BULETINUL Universităţii Petrol – Gaze din Ploieşti	Vol. LX No. 3B/2008	175 - 182	Seria Tehnică

Analysis of Electrical Processes in Converters for Capacitive Energy Accumulation

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ABSTRACT

Many technological processes are related to the form of periodic discharge pulses and assume the presence of systems (converters) for capacitive energy accumulation. The dependency of the discharge pulses parameters from the structure of the converter and the supply network parameters necessitates the modeling of such circuits and analysis of the electrical processes in them, which present the object of this article. The results from the analysis give a possibility for designing such converters with compliance to certain application demands.

KEYWORDS: *systems for capacitive energy accumulation, rectifier sections with a current-limiting rectifier load, stabilizers in high voltage circuits with a possibility to work in a short circuit regime.*

The periodic pulse discharges are connected with different technological processes. A number of requirements are often set to the apparatuses, which ensure the form of the discharge pulse:

- Wide range of frequency alteration of the pulse repetition;
- Wide range of pulse energy variation;
- Repetition of the pulse parameters;
- Relatively uniformly loading of the supply network during the period of energy accumulation.

The circuit for energy accumulation can be represented as a converter with an input and output. It should be emphasized that in [1, 2, 3] it is missing an analysis which includes the structure of the converter (**Figure 1**) when revealing the relations between the input and output parameters.

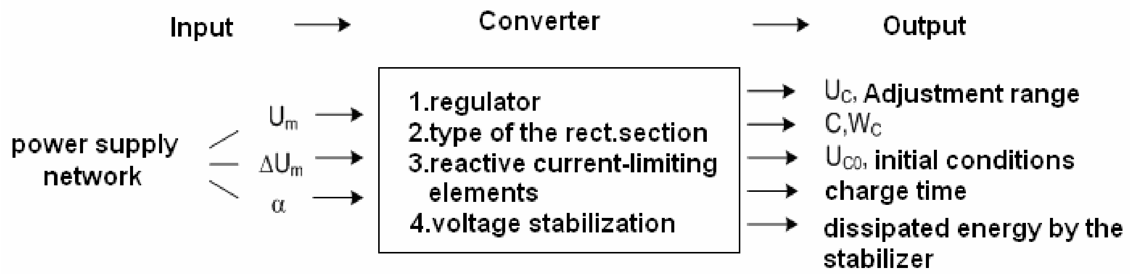

Figure 1

where:

- U_m, ΔU_m – amplitude and change of the input voltage;
- α – angle of the regulator conductivity;
- C, W_C – capacitance and energy of the capacitor battery;
- ΔU_{C0} – initial charge voltage.

The purpose of the current work is development of a model for analysis of the electrical processes including the structure of the converting section, its input parameters – amplitude and change of the input supply voltage and the angle of AC regulator conductivity. This model will also provide possibilities for:

- Definition of the controlled parameters as charge time for the corresponding supply voltage in the regulation range, dissipated energy by the parallel stabilizer, instability of the supply voltage.
- Definition of the loading of the converter elements.

A possible model of the converter is shown in **Figure 2.**

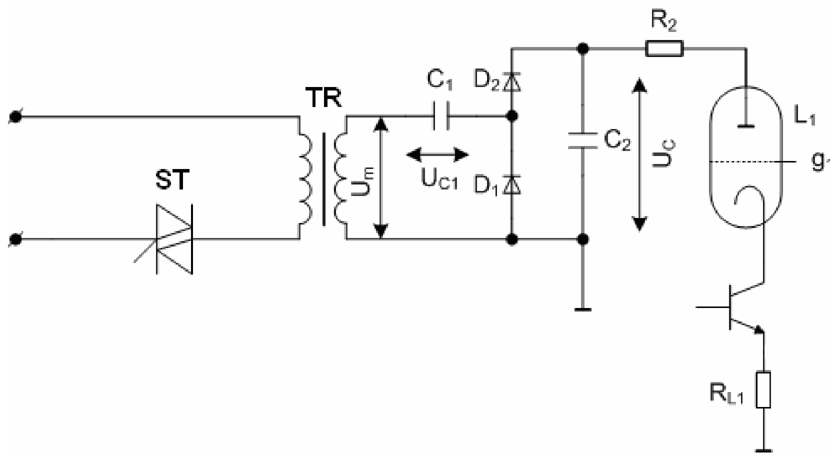

Figure 2

The operation of the parallel stabilizer L_1, T_1 has been discussed in [4,6].

The equivalent scheme of the circuit from **Figure 2** is shown on **Figure 3.**

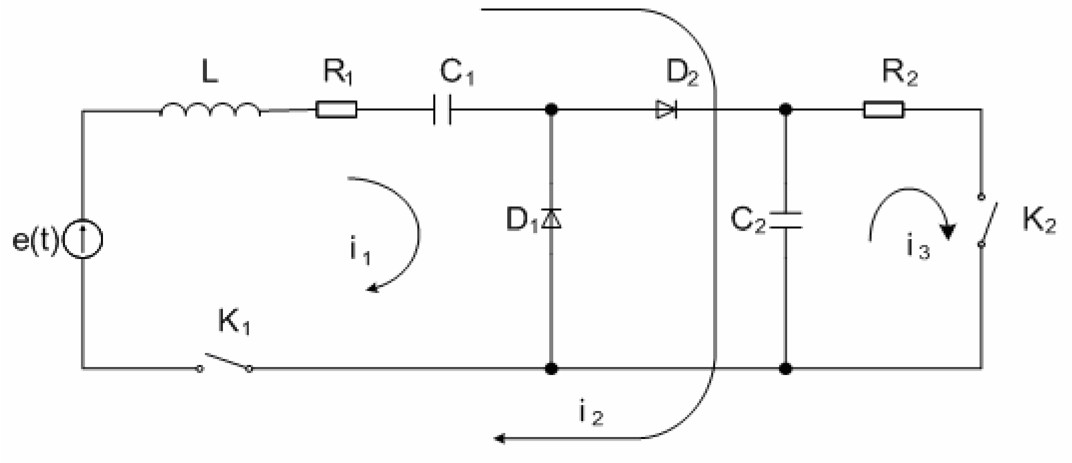

Figure 3

- e(t) – voltage on the secondary side of the input transformer.
- L and R_1 are the adjusted inductivity and resistance of the secondary winding of the transformer..
- K_1 – a switch for representing a simistor or a thyristor switch
- R_2, K_2 – parallel stabilizer

It is assumed that the transformer can be replaced only with a e(t), L and R_1 i.e. the losses in the steel are not considered; the switches in the AC and DC circuits are ideal and the time constant in the control circuit of the simistor is sufficiently high, i.e. the control angle α remains constant during the charge process.

The circuit on **Figure 3** can be analyzed with the method of condition variables.

In the time domain can be formed several intervals:

- Interval 1 – beginning of the charge process – D_1 is conductive (**Figure 3**) and C_1 is charging. The interval is shown on Figure 4 in the limits $t_1 \le t \le t_2 + \varepsilon_1$, where t_1 is the moment when the simistor is triggered into the forward conduction zone/switched on/, represented with the switch K_1, and $t_2 + \varepsilon_1$ is the moment of commutation of the simistor when the currents becomes 0.
- Interval 2 - $t_3 \le t \le t_4 + \varepsilon_2$ - The diode D_2 is conductive and C_2 is charging.- **Figure 3.**

  Intervals 1 and 2 are repeating in a cycle and the capacitor C_2 is charging.

- Interval "n" - $t_3^n \le t \le t_4^n + \varepsilon_2^n$. During this interval at a moment t_e ($t_3^n \le t_e \le t_4^n + \varepsilon_2^n$), C_2 is charging to a previously set voltage, the switch K_2 – Fig.3 closes and C_2 starts to discharge through R_2 and K_2, which compensates the overcharge for the time interval $t_e \div t_4^n + \varepsilon_2^n$.

The time intervals are shown on **Figure 4**.

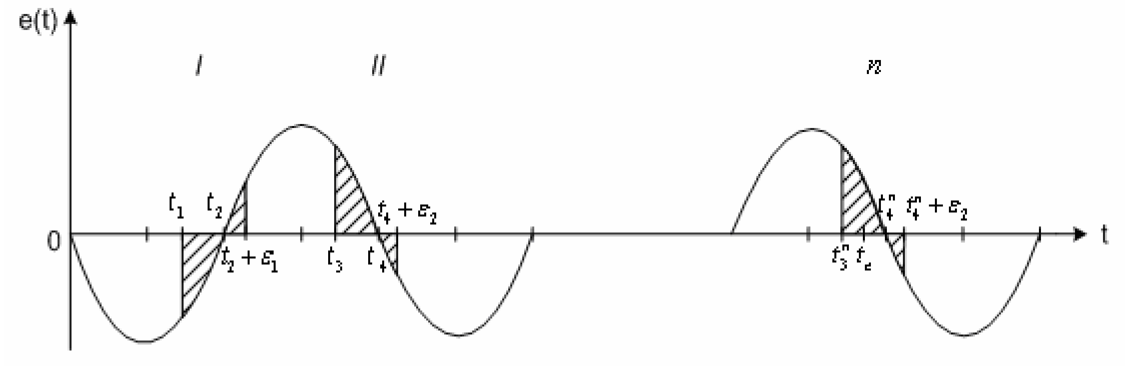

Figure 4

Interval 1: $t_1 \le t \le t_2 + \varepsilon_1$; K_1 – closed, K_2 – open. The scheme from **Figure 3** is transformed into **Figure 5.**

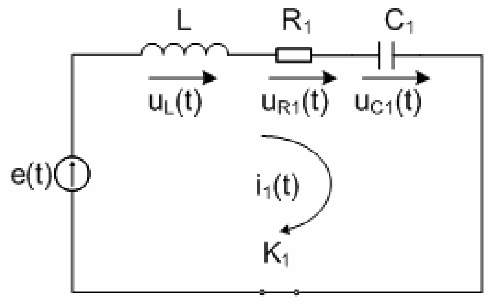

Figure 5

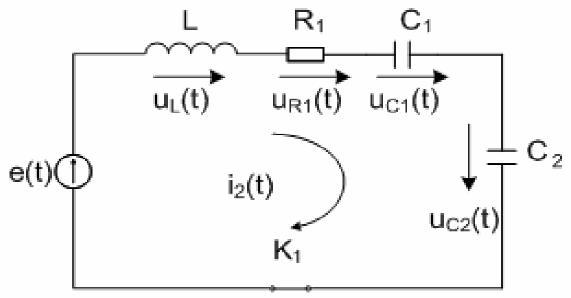

Figure 6

The circuit on **Figure 5** is described with equations (1) and (2):

$$\frac{d}{dt}\begin{bmatrix} u_{C_1}(t) \\ i_1(t) \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{C_1} \\ -\frac{1}{L} & -\frac{R_1}{L} \end{bmatrix} \begin{bmatrix} u_{C_1}(t) \\ i_1(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} . \left[e(t) \right] \tag{1}$$

$$\left[x_1(t) \right] = \begin{bmatrix} u_{C1}(t) \\ i_1(t) \end{bmatrix} = e^{[A_1].(t-t_1)} \left[x_1(t_1+) \right] + e^{[A_1].t} . \int_{t_1}^{t} e^{-[A_1].\tau} . [B_1] \left[f(\tau) \right] d\tau \tag{2}$$

where:

$$\left[A_1 \right] = \begin{bmatrix} 0 & \frac{1}{C_1} \\ -\frac{1}{L} & -\frac{R_1}{L} \end{bmatrix}; \quad \left[B_1 \right] = \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix}; \quad \left[f(\tau) \right] = \left[e(t) \right]$$

The precise solution is according to the formula of Cauchy. The final conditions i.e. $u_{C_1}(t)$ and $i_1(t)$ at the moment $t = t_2 + \varepsilon_1$ are as follows:

$$\left[x_1(t_2+\varepsilon_1)\right] = \begin{bmatrix} u_{C_1}(t_2+\varepsilon_1) \\ i_1(t_2+\varepsilon_1) \end{bmatrix} = \begin{bmatrix} u_{C_1}(t_2+\varepsilon_1) \\ 0 \end{bmatrix} \tag{3}$$

Interval 2: $t_3 \le t \le t_4 + \varepsilon_2$. The equivalent scheme on **Figure 3** is transformed into **Figure 6.** For the circuit on **Figure 6** is the valid equation (4).

$$\frac{d}{dt}\begin{bmatrix} u_{C_2}(t) \\ u_{C_1}(t) \\ i_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{C_2} \\ 0 & 0 & \frac{1}{C_1} \\ -\frac{1}{L} & -\frac{1}{L} & -\frac{R_1}{L} \end{bmatrix} \begin{bmatrix} u_{C_2}(t) \\ u_{C_1}(t) \\ i_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} \left[e(t)\right] \tag{4}$$

The solution of equation (4) looks like:

$$\left[x_2(t)\right] = \begin{bmatrix} u_{C2}(t) \\ u_{C1}(t) \\ i_2(t) \end{bmatrix} = e^{\left[A_2\right].(t-t_3)}\left[x_2(t_3+)\right] + e^{\left[A_2\right].t}.\int_{t_3}^{t} e^{-\left[A_2\right].\tau}.\left[B_2\right]\left[f(\tau)\right]d\tau \tag{5}$$

where:

$$\left[A_2\right] = \begin{bmatrix} 0 & 0 & \frac{1}{C_2} \\ 0 & 0 & \frac{1}{C_1} \\ -\frac{1}{L} & -\frac{1}{L} & -\frac{R_1}{L} \end{bmatrix}; \quad \left[B_2\right] = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix}; \quad \left[f(\tau)\right] = \left[e(t)\right]$$

$$\left[x_2(t_3+)\right] = \begin{bmatrix} u_{C_2}(t_2+\varepsilon_1) \\ u_{C_1}(t_2+\varepsilon_1) \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ u_{C_1}(t_2+\varepsilon_1) \\ 0 \end{bmatrix} \tag{6}$$

At moment $t = t_4 + \varepsilon_2$ the current $i_2(t)$ becomes equal to 0. The final conditions i.e. the values of $u_{C_2}(t)$, $u_{C_1}(t)$ and $i_2(t)$ when $t = t_4 + \varepsilon_2$ are the following:

$$\left[x_2\left(t_4+\varepsilon_2\right)\right]=\begin{bmatrix} u_{C_2}\left(t_4+\varepsilon_2\right) \\ u_{C_1}\left(t_4+\varepsilon_2\right) \\ i_2\left(t_4+\varepsilon_2\right) \end{bmatrix}=\begin{bmatrix} u_{C_2}\left(t_4+\varepsilon_2\right) \\ u_{C_1}\left(t_4+\varepsilon_2\right) \\ 0 \end{bmatrix} \tag{7}$$

We accept that at moment t_e from the n[th] interval capacitor C_2 charges to the defined voltage. Then, the switch K_2 closes and it begins compensation of the overvoltage of C_2 after the moment t_e i.e. the discharge through the switch K_2 and the resistor R_2 – Figure 3. Hence, the n[th] interval can be divided into two parts:

- $t_3^n \le t \le t_e$;
- $t_e \le t \le t_4^n + \varepsilon_2^n$.

For the interval $t_3^n \le t \le t_e$ is valid equation (6), which initial conditions are set with equation (8).

$$\left[x_2\left(t_3^n+\right)\right]=\begin{bmatrix} u_{C_2}\left(t_3^n+\right) \\ u_{C_1}\left(t_3^n+\right) \\ i_2\left(t_3^n+\right) \end{bmatrix}=\begin{bmatrix} u_{C_2}\left(t_4^{n-1}+\varepsilon_2^{n-1}\right) \\ u_{C_1}\left(t_2^n+\varepsilon_1^n\right) \\ 0 \end{bmatrix} \tag{8}$$

The final conditions are defined at a moment $t = t_e -$:

$$\left[x_2\left(t_e-\right)\right]=\begin{bmatrix} u_{C_2}\left(t_e-\right) \\ u_{C_1}\left(t_e-\right) \\ i_2\left(t_e-\right) \end{bmatrix}=\left[x_2\left(t_e+\right)\right]=\begin{bmatrix} u_{C_2}\left(t_e+\right) \\ u_{C_1}\left(t_e+\right) \\ i_2\left(t_e+\right) \end{bmatrix} \tag{9}$$

For the interval $t_e \le t \le t_4^n + \varepsilon_2^n$ the equivalent scheme in **Figure 3** looks like the circuit in **Figure 7.**

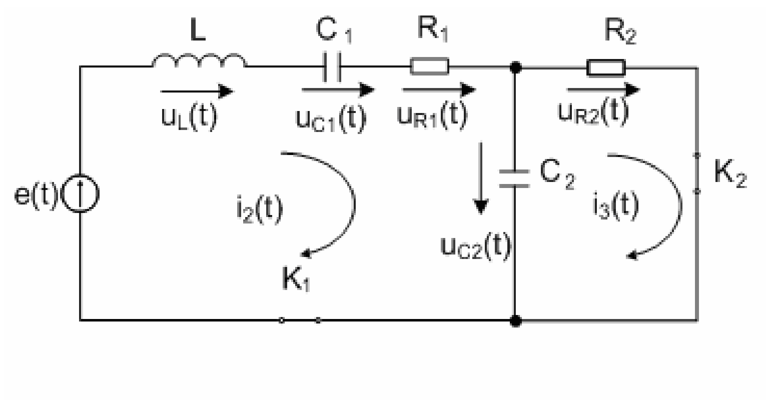

Figure 7

For the circuit in **Figure 7** $i_3\left(t\right)=\dfrac{u_{C_2}\left(t\right)}{R_2}$ and equation (10) is in force:

$$\frac{d}{dt}\begin{bmatrix} u_{C_2}(t) \\ u_{C_1}(t) \\ i_2(t) \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_2 C_2} & 0 & \frac{1}{C_2} \\ 0 & 0 & \frac{1}{C_1} \\ -\frac{1}{L} & -\frac{1}{L} & -\frac{R_1}{L_1} \end{bmatrix} \begin{bmatrix} u_{C_2}(t) \\ u_{C_1}(t) \\ i_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} [e(t)]. \tag{10}$$

Its solution looks like:

$$[x_2(t)] = \begin{bmatrix} u_{C2}(t) \\ u_{C1}(t) \\ i_2(t) \end{bmatrix} = e^{[A_3].(t-t_e)}[x_2(t_e+)] + e^{[A_3].t}.\int_{t_e}^{t} e^{-[A_3].\tau}.[B_3][f(\tau)]d\tau\,, \tag{11}$$

where:

$$[A_3] = \begin{bmatrix} -\frac{1}{R_2 C_2} & 0 & \frac{1}{C_2} \\ 0 & 0 & \frac{1}{C_1} \\ -\frac{1}{L} & -\frac{1}{L} & -\frac{R_1}{L} \end{bmatrix}; \quad [B_3] = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix}; \quad [f(\tau)] = [e(t)]$$

The solution is according to the Cauchy equation.

The beginning and the end of the charge process are shown on **Figure 8** using MATLAB to visualize the conductivity angle $\alpha = 1,9 rad; L = 50H; R_1 = 3k\Omega; C_1 = 0,25\mu F; C_2 = 1\mu F$ and $R_2 = 30k\Omega$.

The method of description of the charge circuit allows introduction of non-zero initial conditions.

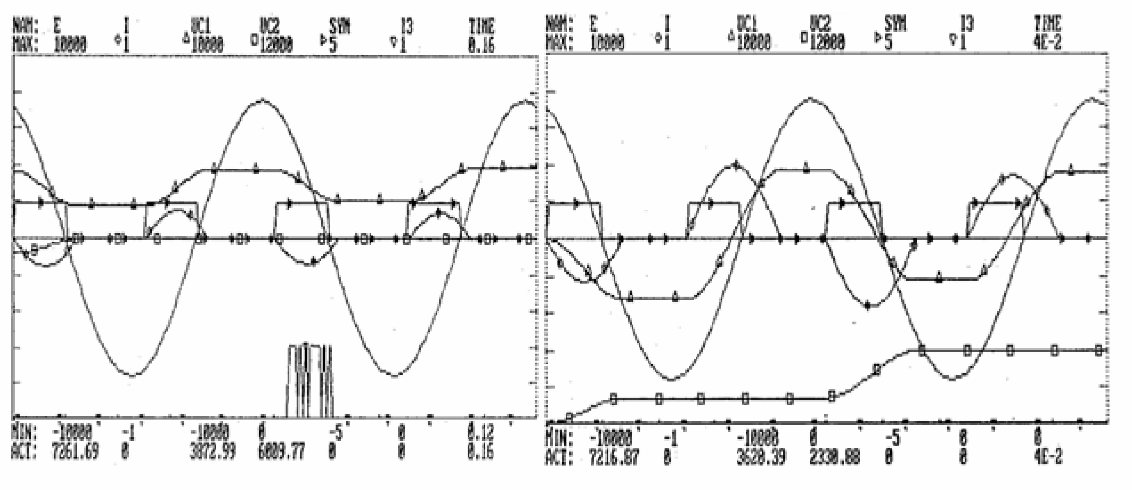

Figure 8

Consequently, for the certain charge circuit and regime (charge time and charge voltage) can be defined a suitable conductivity angle of the simistor, which will ensure the regime and the reduced loading of the elements in the charge circuit. The conductivity angle follows to decrease when a parallel stabilizer is switched. Along with this, the dissipated power by the parallel stabilizer decreases.

The discussed process can be divided into two periods:

- $U_{C2} < U_{C0}$ - capacitive energy accumulation;

- $U_{C2} \geq U_{C0}$ - stabilization process.

It is considered that the circuit is non-linear and $t_3 = t_3(C_2, U_{C2}, U_m, \Delta U_m, \alpha)$, $i_{ch,\max} = i_{ch,\max}(C_2, U_m, \Delta U_m, \alpha)$ and $P = P(C_2, U_{C2}, U_{C0}, U_m, \Delta U_m, \alpha)$.

The analyzed schematic solution for the converter (includes regulator for alternating voltage, step up transformer with dissipation; rectifying section with capacitive current-limiting element and parallel stabilizer) gives possibility for reduced current loading in the interval $U_{C2} < U_{C0}$ with a suitable choice of U_m and α and at the same time insures the controlled parameters t_3 and U_{C2}. In the period when $U_{C2} \geq U_{C0}$, the dissipated power is reduced with the change of α.

Conclusions

For the non-linear circuit of the converter, it is suggested a model – system of differential equations. Software based on MATLAB is used to solve this system, which also allows visualization of the processes of capacitive energy accumulation. By this analysis:

- more parameters and specifics of the charge circuits are used for more accurate defining of the controlled parameters (charge time, charge voltage and its stability) as well as more precise defining of the requirements to the elements in the converter circuit.
- the proposed model follows to be accepted as a method for design. Its application in the design of certain devices for pulse periodic discharges and the compliance between the designed and experimentally assessed parameters is an evaluation for the reliability of the suggested model.

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