Bulgarian Journal of Physics 21 Nos 3/4 (1994) 54–59

CHOKE-COIL CHARGING OF ARTIFICIAL INDUCTANCE-CAPACITANCE LINES IN PULSED OSCILLATORS

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

Received 24 June 1993

Abstract. Different operating modes are considered of choke-coil-charged artificial LC lines in view of minimizing the size of the capacitive filter (needed for eliminating the charging-current a. c. component) and increasing the overall efficiency of the system. The advantage is demonstrated of using a circuit where the charging choke-coil is sectioned and connected with capacitance cells to form a homogeneous line; during the discharge the cells are combined into one capacitor through discharge diodes.

The design of artificial LC lines-based charging devices are used for optical pumping of solid- state lasers, mostly to obtain the maximal overall efficiency. The size of the capacitive filter introduced for decoupling the charging circuit from the rectifier and smoothing (i. e., eliminating the a. c. component of) the pulsed current drawn, is a decisive factor in this respect. Optimizing the design should involve, therefore, devising such a charging-discharging circuit which would ensure equality of the effective and average values of the charging current and, consequently, minimal size of the capacitive filter.

Since the effective and average charging-current values depend on the LC-line charging mode, we shall consider the most widely used ones in order to reveal the advantage of a particular circuit design and mode of operation.

To charge an LC artificial line, one usually employs a choke-coil as a current-limiting device in the d. c. voltage circuit because it allows the use of a supply with voltage twice as low as that needed for charging the line (Fig. 1) [1, 2, 3]. In the cases of solid-state laser pumping, a negative feedback is usually implemented in order to ensure sufficient constancy of the charging voltage; it is omitted in Fig. 1 for the sake of brevity. The maximal charging-voltage value U_c^{max} in LC lines depends on the charging-circuit quality factor:

$$U_c^{max} = U_s^{av}\left[1 + \exp\left(-\frac{\pi}{Q_c}\right)\right] \qquad (1)$$

where U_s^{av} is the average value of the supply voltage; $Q_c = \frac{1}{R}\sqrt{\frac{L_c}{C_l}}$ is the quality factor of the charging circuit; R_c and L_c ($L_c = L_c^0 + \sum L_n$, n being the number of the line cells) are the resistance and inductance of the charging circuit, respectively; $C_l = \sum C_n$ is the total capacitance of the LC artificial line. Therefore, the LC-line voltage can be higher by a factor of 1.86–1.92 than the supply voltage, since Q-factors in the order of 10–20 can be easily implemented. For short discharge times, the process of charging of LC artificial lines is practically equivalent to the charging of a lumped capacitance with value equal to the sum of the capacitances of the separate cells.

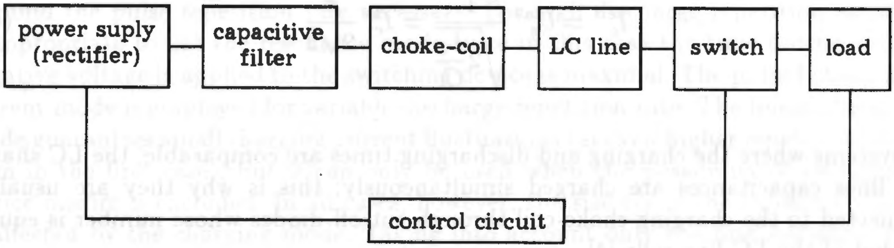

Fig. 1. Block-diagram of a choke-coil charged LC artificial line used in pulsed modulators

Some aspects of the design of pulsed modulators with charging choke-coils can be found in [5, 6]. We shall briefly discuss the following most common modes of choke-coil charging of LC lines: oscillatory, resonance, pulsed (discontinued), and linear.

The voltage of LC artificial lines depends on the load's impedance (flashlamps in the important case of solid-state lasers pumping) and on the discharge-loop matching. For ideal oscillatory charging with incomplete energy release in the load during the discharge, the charging voltage U_c can be obtained by solving the difference equation [6]

$$U_c(h+1) - aU_c(h) = 2U_s^{av} \qquad (2)$$

where h is the number of charging-discharging cycles, and $a = -\frac{U_c^{res}(h)}{U_c(h)}$ is the discharge reflection coefficient (U_c^{res} being the residual voltage).

The solution of (2) is $U_c(h) = 2U_s^{res}\frac{a^{h+1} - 1}{a - 1}$; for $h = \infty$, the established final voltage value of LC artificial lines is $U_c = \frac{2U_s^{res}}{1 - a}$. Therefore, in the case of oscillatory charging, the LC-line voltage rises with h and the output voltage becomes constant regardless the impedance value. For partial charging, the LC-line voltage approaches that of the supply so the efficiency of the choke-coil charging drops.

The resonance charging mode is characterized by equality of the LC-line discharge period T_d and the half-period $\pi\sqrt{L_c C_l}$, $C_l = \sum C_n$ $(R_c = 0)$

$$\frac{T_d}{\pi\sqrt{L_c C_l}} = \frac{1}{\pi f\sqrt{L_c C_l}} = 1\,, \qquad f = \frac{1}{T_d}\,. \tag{3}$$

The power-supply current in this case consists of half-sinusoids. The charging-current effective value I_c^{eff}, the power-supply voltage U_s^{av}, and the charging-current average value I_c^{av} are related by the following expression:

$$I_c^{\text{eff}} = U_s^{\text{av}} \frac{1}{\sqrt{2\frac{L_c}{C_l}}} = I_c^{\text{av}} \frac{\pi}{2\sqrt{2}} \tag{4}$$

In systems where the charging and discharging times are comparable, the LC shaping lines capacitances are charged simultaneously; this is why they are usually connected to the charging choke-coil through cut-off diodes whose number is equal to that of the LC-line cells [4].

When the discharge repetition rate is decreased, normal operation is only possible if a diode is present in the charging loop. The power-supply current has then discontinued character and pulsed charging mode is thus implemented. The charging-current effective value, the power-supply voltage, and the charging-current average value are related as follows:

$$I_c^{\text{eff}} = U_s^{\text{av}} \frac{\sqrt{\pi f\sqrt{L_c C_l}}}{\sqrt{2\frac{L_c}{C_l}}} = I_c^{\text{av}} \frac{\pi}{\sqrt{2\pi f\sqrt{L_c C_l}}}\,. \tag{5}$$

When the discharge repetition rate is increased, the power-supply current does not tend to zero; rather, the law of LC lines voltage-variation approaches a linear one (i.e., linear charging mode is achieved). The average value of the charging current for a constant-voltage power supply is expressed as

$$I_c^{\text{av}} = U_s^{\text{av}} C_l f \left(1 - \cos\frac{1}{f\sqrt{L_c C_l}} + \frac{\sin^2 \frac{1}{f\sqrt{L_c C_l}}}{2\sin^2 \frac{1}{2f\sqrt{L_c C_l}}} \right), \tag{6}$$

while the charging-current effective value has the form:

$$I_{\mathrm{c}}^{\mathrm{eff}} = \frac{U_{\mathrm{s}}^{\mathrm{av}}}{\sqrt{\frac{L_{\mathrm{c}}}{C_{\mathrm{l}}}}} \left[\frac{1+k^2}{2} + \frac{kf\sqrt{L_{\mathrm{c}}C_{\mathrm{l}}}}{2} \left(1 - \cos\frac{2}{f\sqrt{L_{\mathrm{c}}C_{\mathrm{l}}}}\right) + \frac{(k^2-1)f\sqrt{L_{\mathrm{c}}C_{\mathrm{l}}}}{4} \sin\frac{2}{f\sqrt{L_{\mathrm{c}}C_{\mathrm{l}}}} \right]^{\frac{1}{2}} \tag{7}$$

where

$$k = \frac{\sin\frac{1}{f\sqrt{L_{\mathrm{c}}C_{\mathrm{l}}}}}{1 - \cos\frac{1}{f\sqrt{L_{\mathrm{c}}C_{\mathrm{l}}}}} .$$

The choice of the optimal charging mode is made in each specific case bearing in mind the pulse repetition rate necessary. For high discharge repetition rates it is appropriate to use the resonance mode since in this case the time during which negative voltage is applied to the switching device is maximal. The pulsed charging-current mode is employed for variable discharge repetition rate. The linear charging mode guarantees small charging-current fluctuations (at even higher repetition rates than in the first case), but it can only be used when the possibility of switching-device misfire is excluded. In all cases, however, the size C_f of the capacitive filter is affected by the charging mode. Taking into account only the first harmonic U_{c}^{1} of the charging voltage curve, the value of the capacitive filter is determined as follows:

$$\begin{aligned} C_f &= \frac{2C_{\mathrm{l}}U_{\mathrm{s}}^{\mathrm{av}}}{\pi U_{\mathrm{c}}^{1}\left[\left(2\pi f\sqrt{L_{\mathrm{c}}C_{\mathrm{l}}}\right)^2 - 1\right]} \qquad \frac{1}{\pi f\sqrt{L_{\mathrm{c}}C_{\mathrm{l}}}} \le 1 \\ C_f &= \frac{2C_{\mathrm{l}}U_{\mathrm{s}}^{\mathrm{av}}\cos\left(\pi^2 f\sqrt{L_{\mathrm{c}}C_{\mathrm{l}}}\right)}{\pi U_{\mathrm{c}}^{1}\left[1 - \left(2\pi f\sqrt{L_{\mathrm{c}}C_{\mathrm{l}}}\right)^2\right]} \qquad \frac{1}{\pi f\sqrt{L_{\mathrm{c}}C_{\mathrm{l}}}} \ge 1 . \end{aligned} \tag{8}$$

The capacitive-filter size can thus be very large, especially when the requirements for $U_{\mathrm{s}}^{\mathrm{av}}$ constancy are strict, as in the case of charging several LC-cells simultaneously by one power supply.

To illustrate the above, we shall examine the near-linear mode since it is used extensively for high repetition rate pumping of Nd:YAG lasers with applications in the industry, laser ranging and remote environmental monitoring. Assuming $U_{\mathrm{c}}^{1} = 0.025U_{\mathrm{s}}^{\mathrm{av}}$, Eq. (8) shows that the capacitive-filter size must be one order of magnitude larger than the shaping-line capacitance; this substantially lowers the overall efficiency of the system. Using larger charging choke-coils is also undesirable due to the possible overvoltages appearing during the charging-discharging cycle. To minimize the filter size, it is interesting to consider a circuit where the choke-coil is sectioned, the storage capacitor is implemented by several equal cells C_n, and the charging and discharging processes are essentially different: during charging, the separate cells are connected to the coil sections to form a homogeneous artificial line, while during the discharge the cells are combined into one by means of discharge diodes [7] (Fig. 2). It is obvious that if the discharging and charging times are equal, and if instantaneous discharge of $\sum C_n$ and ideal line are assumed, the charging current will not contain a. c. components, i. e., the effective and average values of the charging current will be equal. For a limited C_n-cell number (n = 5–10), the separate charging-current pulses will not ensure ideal d. c. current, but even in this case the current effective value will be close to its average value. Table 1 shows a comparison between the cases of the conventional charging-discharging circuit and the one given in Fig. 2 by summarizing data calculated using expressions (6) and (7).

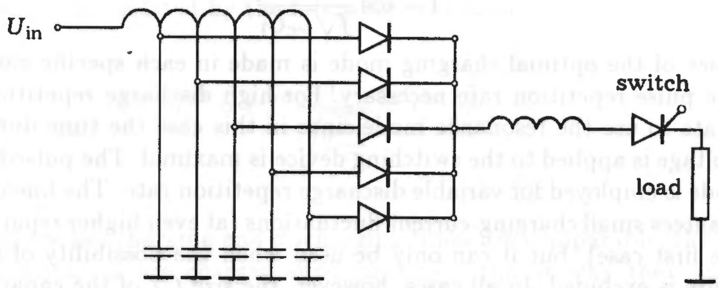

Fig. 2. Uniform artificial LC-line using a sectioned charging choke-coil

As one can see, the a. c. component is substantially reduced in the case of the circuit described; indeed, the reduction factor increases with the pulse repetition rate. The latter is significant when LC-lines are used for high repetition-rate pumping of Nd:YAG lasers.

Table 1

Charging repetition rate	Hz	33.3	38.5	45.5
Average current I_c^{av} 1)	A	9.4	11.2	13.4
Charging current a.c. component 1)	A	3.2	2.3	1.9
A.c. component relative value 1)	%	51	35	31
A. c. component relative value 2)	%	34	17	14
Factor of a.c. component reduction		1.5	1.7	2.2

1) Conventional circuit;
2) Circuit shown in Fig. 2

In conclusion, we have demonstrated that the choke-coil charging of a storage capacitor divided into separate cells combined with sections of the coil is very efficient. The a. c. component of the charging current is reduced significantly which allows one to avoid the use of large-size capacitive filters thus increasing the overall efficiently of the system.

References

1. M. S. Neiman. *Radiotransmitting Devices.* (Sovetskoe Radio, Moscow 1963) (in Russian).
2. V. M. Vakulenko, L. P. Ivanov. *Pribory i Tehnika Eksperimenta* (1970) 110 (in Russian).
3. I. V. Volkov, V. M. Vakulenko. *Laser Power Supplies.* (Tehnika, Kiev 1976).
4. I. P. Dmitriev, B. A. Prybylov. Soviet patent No 277837 MPK O3K 3/53, 22. 11. 1970.
5. V. S. Pesotskiy. In: *Increasing the Efficiency of Converters* (Kiev 1972) 259 (in Russian).
6. V. S. Pesotskiy. *Pulsed Electrical Power Engineering* (Kiev (1970) 134.
7. A. N. Goy. *Bulletin of the Leningrad Electrotechnical Institute* No 75 (1969).