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A FAST-CHARGING POWER SUPPLY FOR THE DELAY LINES OF THE KICKER MAGNET PULSERS

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SUMMARY

A power supply of the resonant-charging type can charge the delay lines of the kicker magnet in a short time and with high precision. The principle is discussed and formulae are given which enable to calculate the relevant circuit parameters. Such a power supply can charge the line several times per machine cycle to different voltages and polarities.

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CONTENTS

1. INTRODUCTION

The purpose of this report is to suggest a possible solution to the problem of charging the delay lines of the kicker magnet to high voltages, with a precision better than 1%. This is realized by means of a bank of electrolytical capacitors which are discharged into a pulse transformer with a high secondary-to-primary-voltage ratio. The principle was developed and realized elsewhere[1)], but here general formulae are proposed which extend the design to a greater number of cases.

2. THE CIRCUIT

The circuit is described in Fig. 1, and the corresponding waveforms in Fig. 2. The hysteresis cycle of the transformer is drawn in Fig. 3.

We suppose that C_0 is charged to the maximum allowable value V_0, and that all calculations will be done with this maximum value. The circuit will then work satisfactorily for all values of charge.

3. THE EQUIVALENT CIRCUIT

Figure 4 gives the equivalent charge transfer circuit, seen from the secondary side of the transformer. Diode D and switch S simulate the thyristor TH1. The switch S closes at $t = t_1$, and at that moment $v_0' = V_0'$ and $v_L = 0$.

During the charging period $t_1 < t < t_2$, the main inductance of the transformer can be neglected and the charge transfer circuit then simplifies to Fig. 5.

4. CHARGE TRANSFER TO C_L

4.1 Definitions

- Capacitance ratio α:

$$\alpha = C_0'/C_L \; . \qquad (1)$$

- Quality factor Q:

$$Q = \frac{1}{R_\sigma}\sqrt{\left(\frac{1+\alpha}{\alpha}\right)\left(\frac{L_\sigma}{C_L}\right)} \; . \qquad (2)$$

- Charge-transfer time T_1:

$$T_1 = \pi \sqrt{\frac{\alpha}{1+\alpha} \cdot \frac{4Q^2}{4Q^2-1} \cdot L_\sigma \cdot C_L} \quad . \tag{3}$$

- Critical damping resistor:

$$R_K = 2 \sqrt{\frac{1+\alpha}{\alpha} \; \frac{L_\sigma}{C_L}} = 2Q \, R_\sigma \; . \tag{4}$$

4.2 Calculations

After some manipulations we find that C_L charges to a maximum of $v_L = V_L$ at time $t = t_2$

$$\boxed{V_L = \frac{\alpha}{1+\alpha} \, \rho \; V_0'} \tag{5}$$

with

$$\rho = 1 + \exp\left(- \frac{\pi}{\sqrt{4Q^2 - 1}}\right) \; ; \tag{6}$$

ρ, as a function of the quality factor, is given by the following table:

Q	1	2	3	4	5	6	7	8	9	10
ρ	1.18	1.45	1.59	1.68	1.73	1.77	1.80	1.82	1.84	1.86

5. MEAN VALUE OF v_T DURING THE CHARGE TRANSFER

After some long but straightforward calculations, we find:

$$\bar{v}_T = \frac{1}{T_1} \int_{t_1}^{t_2} v_T \, dt = \varphi \, V_L \tag{7}$$

with

$$\varphi = \frac{1}{\rho} - \frac{\sqrt{4Q^2-1}}{2\pi Q^2} \left(1 - \frac{1+\alpha}{\alpha} \; \frac{R_2}{R_1 + R_2}\right) . \tag{8}$$

$\bar{v}_T$ is minimum when:

- the quality factor is high;
- α is great;
- the resistance in the secondary circuit is small.

6. EFFECTIVE CURRENT IN THE TRANSFORMER

The effective current is the continuous current which would have the same thermal effect in the transformer as would the real current. It consists mainly of the transfer current to C_L. The thermal effect of the polarizing currents is usually less than 5% of this value and will be neglected here.

If the mean pulse repetition frequency is A pulses per second, then:

$$I_{eff} = \left[A \int_{t_1}^{t_2} i^2 \, dt \right]^{1/2} = 1.1 \sqrt{A} \; \frac{C_L \cdot V_L}{\sqrt{T_1}} \qquad (9)$$

7. CALCULATION OF THE TRANSFORMER PARAMETERS

It is possible to use a normal 50 Hz power transformer for the charge transfer. In this paragraph we will calculate the main characteristics of this transformer.

7.1 Definitions

$n = n_2/n_1$	:	ratio of sec. to prim. turns
V_N	:	nominal sec. voltage
I_N	:	nominal sec. current
P_N	:	nominal power
I_0	:	primary exciting current
ℓ	:	% short circuit reactance
r	:	% short circuit resistance

7.2 Nominal secondary voltage

When we specify a nominal voltage V_N, the transformer is insulated for the peak value $\sqrt{2}\, V_N$. The peak value of the pulse is V_L. So it is logical to put:

$$\boxed{V_N = \frac{V_L}{\sqrt{2}}} \qquad (10)$$

7.3 Nominal secondary current

In normal use, the losses in the windings and the losses in the core of a transformer are about equal. In our case, however, the losses in the iron are very small because of the low duty-cycle, and we can double the losses in the windings. From formula (9) we calculate

$$I_N = \frac{I_{eff}}{\sqrt{2}} = 0.8\sqrt{A}\,\frac{C_L \cdot V_L}{\sqrt{T_1}} \qquad (11)$$

There is, however, a second limit: when the current is too high, mechanical damage may be done to the windings. It is safe to observe the following limit:

$$I_N \geq \text{Peak current}/14 \ .$$

This limit is observed when $A \geq 1/64 \cdot T_1$. Consequently, we have to calculate the transformer for a minimum pulse repetition rate of about 3 per second, even if the actual mean rate is lower. We shall see below that there can be a second reason to raise A above the actual value.

7.4 Nominal power

$$P_N = I_N \cdot V_N = \frac{1.1\sqrt{A}}{\sqrt{T_1}} \cdot E_L \qquad (12)$$

where $E_L = (C_L \cdot V_L^2)/2$ is the energy stored on the line.

7.5 Ratio of secondary to primary turns

From Eq. (5) we calculate:

$$n = \frac{1+\alpha}{\alpha} \cdot \frac{1}{\rho} \cdot \frac{V_L}{V_0} \qquad (13)$$

7.6 Exciting current

The exact value of the exciting current is not important if it is not excessively high. If we take the polarizing current 2 to 4 times I_0, we are sure that the transformer is saturated.

7.7 Per cent short circuit reactance and resistance

These parameters are dependent on the other parameters of the transformer for a given design. In order to get a good quality factor, r should not be too high; ℓ determines T_1 and also should not be too high, in order to get a reasonable "flat top" (see below).

8. FLAT TOP

By "flat top" we mean the region between t_2 and t_4 where the line voltage is constant (see Fig. 2). A large flat top gives more tolerance on the timing and on component changes.

A normal power transformer goes from $-B_{max}$ to $+B_{max}$ during the positive half-cycle of the mains voltage. In our case the core goes from $-B_{max}$ to $+B_{max}$ between t_1 and t_4 (Fig. 3), and this under influence of v_T. Thus we find the following relation:

$$\int_{t_1}^{t_4} v_T \, dt = \int_{0}^{10^{-2}} \sqrt{2} \cdot V_N \sin 314t \cdot dt = 6.4 \times 10^{-3} \, V_L \, . \qquad (14)$$

But, with Eq. (7):

$$\int_{t_1}^{t_4} v_T \, dt = \int_{t_1}^{t_2} v_T \, dt + \int_{t_2}^{t_4} v_T \, dt = V_L(\varphi \, T_1 + T_2) \, , \qquad (15)$$

from Eqs. (14) and (15):

$$\boxed{\varphi \, T_1 + T_2 = 6.4 \text{ msec}} \qquad (16)$$

φ depends little on α or on R_1/R_2. For normal values ($\alpha = 2.5$; $R_1 = R_2$) it depends on Q as follows:

Q	2	3	4	5
φ	0.65	0.60	0.58	0.57

For the worst case: Q = 2 and the flat top only 2 msec, we find:

$$T_1 \lesssim 6.8 \text{ msec.}$$

8.1 Dependence of the flat top on ℓ

The stray inductance of the transformer is:

$$L_\sigma = \frac{\ell}{100} \cdot \frac{V_N}{314\ I_N} ,$$

and the charging time [Eq. (3)]:

$$T_1 = 10^{-2} \sqrt{\frac{1+\alpha}{\alpha} \cdot \frac{4Q^2}{4Q^2-1} \cdot \pi \ell \cdot \frac{E_L}{P_N}} , \tag{17}$$

and, with Eq. (12):

$$T_1 = 4.4 \times 10^{-3} \left(\frac{\alpha}{1+\alpha} \cdot \frac{4Q^2}{4Q^2-1} \cdot \frac{\ell}{\sqrt{\Lambda}}\right)^{2/3} . \tag{18}$$

For: $\alpha = 2.5$; $Q = 2$; $T_1 = 6.8$ msec, we find the following relationship between ℓ and the minimum value of Λ to be put in Eqs. (11) and (12):

ℓ	4	5	6	7
Λ_{min}	2.5	3.9	5.6	7.7

We see that when ℓ becomes large (for large transformers), we have to raise Λ to the minimum value given by the table, even if the actual mean pulse rate is lower, in order to get a reasonable flat top.

9. POLARIZATION

The principle is explained in Fig. 1. Figure 2 gives the waveforms and Fig. 3 the transformer cycle.

As the polarization time is also the dead-time between two pulses, it is of interest to calculate it.

For economical reasons we limit the polarizing voltage V_P to 20% of V_L. R_S is chosen to limit the charging current to the nominal current of the transformer. Then:

$$T_3 \cong 40 \text{ msec}$$
$$T_4 \cong 6 \text{ msec}$$
$$T_5 \cong 14 \text{ msec} .$$

Together with T_1 and T_2, the total time between two pulses is about 70 msec.

10. MULTIPLE SHOT FACILITY

The dead-time between two charges is less than 100 msec; it is difficult to charge a large capacitor bank in this time. When multiple charges are necessary in a small time interval, several capacitor banks C, C_1, ..., C_n can be put in parallel, each with its own thyristor switch. These banks can be charged to different voltages.

The line can also be charged to both polarities consecutively by means of a thyristor bridge, as shown in Fig. 6.

Acknowledgements

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REFERENCE

1) A. Brückner and J.F. Labeye: "A Resonant Charging Pulsed High-Voltage Power Supply". SI/Int. MAE/68-6, 27.6.68.

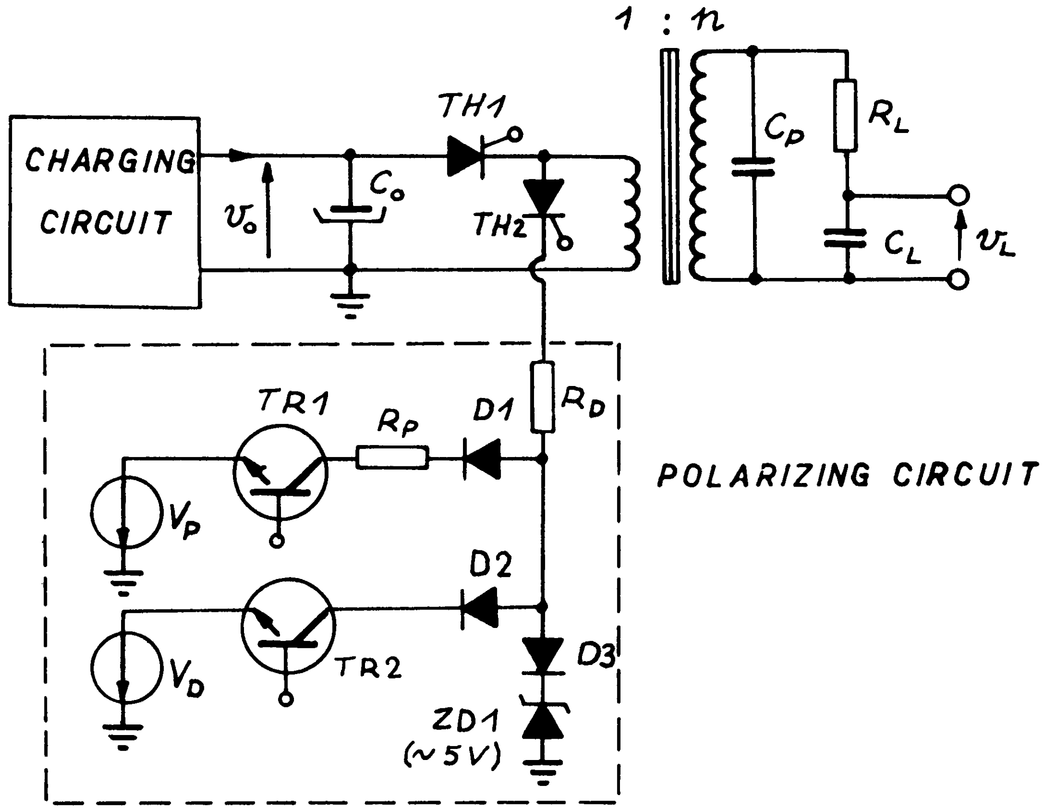

Fig. 1 : Simplified circuit diagram

The electrolytical capacitor bank C_0 is charged to the required voltage V_0. Thyristor 1 is triggered and the charge of C_0 is transferred to the line capacitance C_L by means of the resonant circuit formed by C_0, C_L, and the stray inductance of the transformer. The back-swing is prevented because TH1 opens. The voltage on the line then stays constant until the transformer saturates, but the line is discharged externally before this moment. R_L and C_p prevent damage to the transformer when the line is discharged.

After the discharge of the line, the transformer is prepared for the next charge by polarizing it in the opposite direction. TH2 is fired , and via transistor 1 and resistor R_p, the line is charged to a negative voltage V_p. When the transformer saturates at $-B_{max}$, C_L discharges through the transformer. TR1 opens and TR2 closes. The line voltage is now brought to zero by means of the critical damping resistor R_D. V_D maintains the necessary polarizing current.

Meanwhile C_0 is charged again. Just before triggering TH1, transistor 2 opens and TH2 extinguishes, and we are back where we started.

Diodes D1 and D2 protect the transistors against negative voltages, and D3 protects the transistors when TH1 and TH2 accidentally fire together. ZD1 provides the voltage necessary to extinguish TH2 rapidly.

Just before discharging the line, the line voltage can be measured and this measurement can serve to correct V_0 for the next pulse.

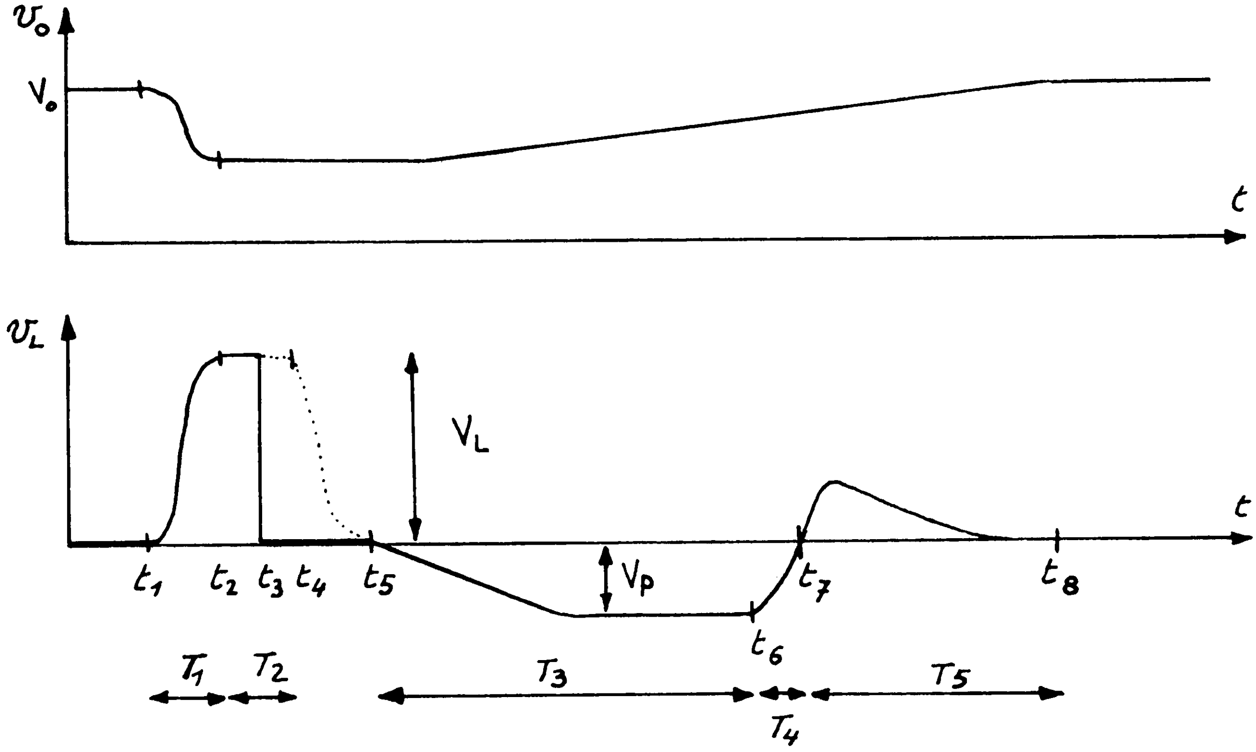

Fig. 2 : Waveforms of v_o and v_L

t_1	:	thyristor 1 is triggered
t_2	:	thyristor 1 extinguishes
t_3	:	the line is discharged
t_4	:	the transformer saturates (when the line is not discharged)
t_5	:	TH2 is fired; TR1 closed
t_6	:	the transformer saturates in the opposite direction
t_7	:	TR1 is opened; TR2 is closed
t_8	:	The circuit is ready for the next pulse.

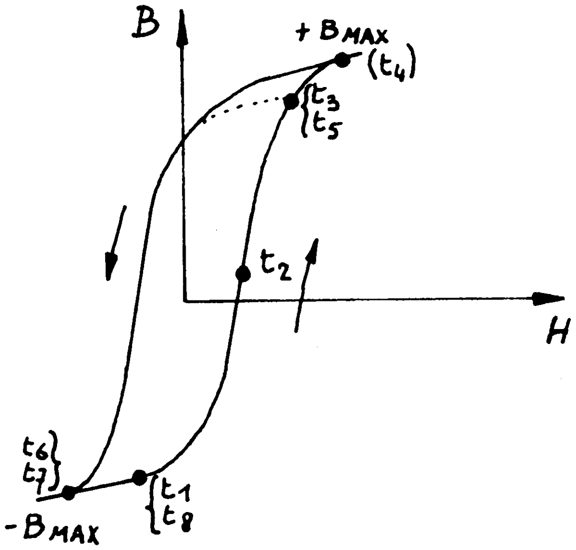

Fig. 3 : Transformer hysteresis cycle

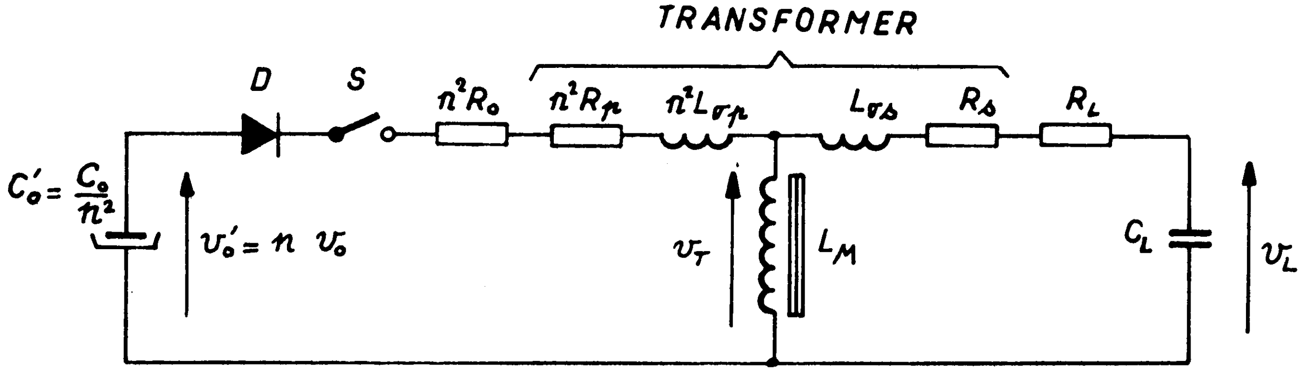

Fig. 4 : Equivalent circuit

R_p : resistance of the primary winding of the transformer

$L_{\sigma p}$: stray inductance of the primary

R_s : resistance of the secondary

$L_{\sigma s}$: stray inductance of the secondary

L_M : main inductance

R_o : resistance in the primary circuit (mainly series resistance of C_o)

R_L : resistance in the secondary circuit.

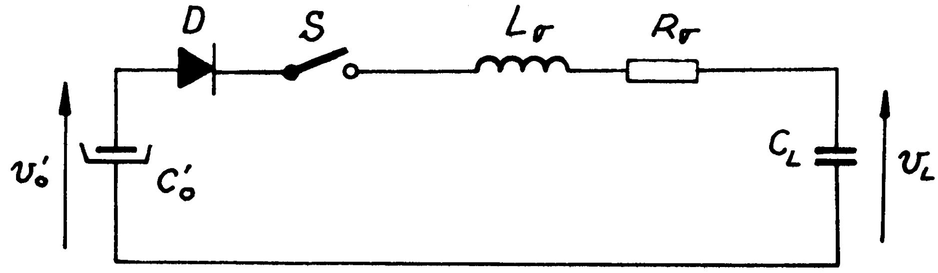

Fig. 5 : Simplified equivalent circuit

$$R_\sigma = n^2 R_o + n^2 R_p + R_s + R_L$$

$$L_\sigma = n^2 L_{\sigma p} + L_{\sigma s}$$

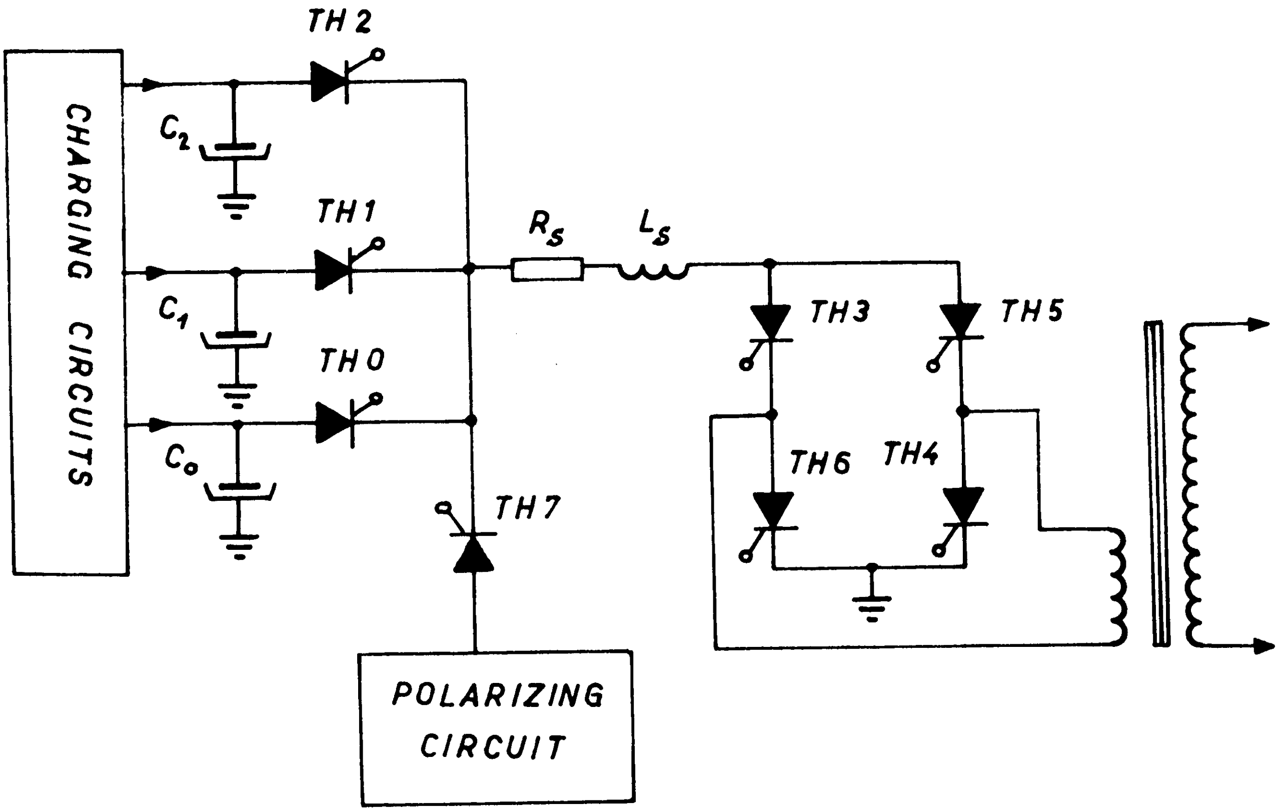

Fig. 6 : Bidirectional power supply

C_0, C_1, and C_2 can be discharged consecutively in a short time. By firing TH5 and TH6 the line charges positively, and by firing TH3 and TH4 the line charges negatively.

The transformer can be polarized in both directions by means of the polarizing circuit and the thyristor bridge. This polarizing circuit is the same as in Fig. 1 except for inverted polarities.

R_S and L_S limit the current to acceptable values for the thyristors, when TH3 and TH6 or TH5 and TH4 accidentally fire together.