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Increase of the efficiency of self-oscillating push-pull power converter

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Space applications of small-current supply often require improvement of the routine electric circuitry in order to ensure higher reliability. This paper examines the improvement of the energy parameters of the classical converter cell.

The theory and practice of small-current sources broadly imply self-oscillating converters with saturated converting transformers [1]. They are used as driving generators or power transformers of low energy. The block diagram is shown in Fig. 1.

The operating frequency is determined with the following expression:

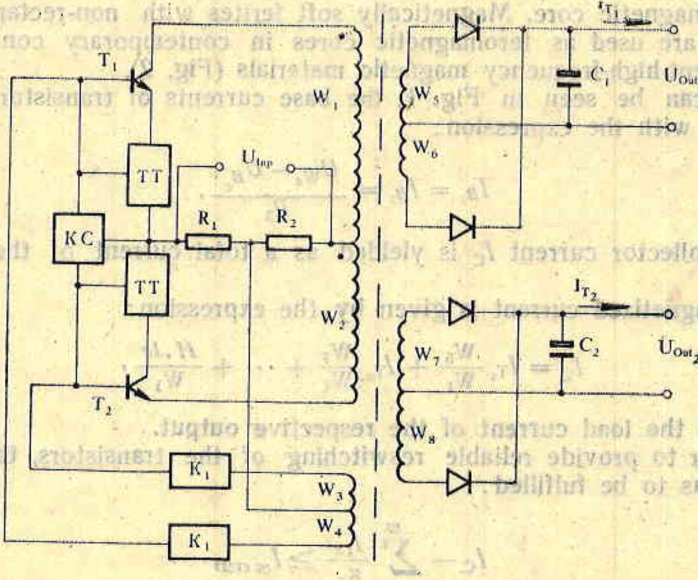

Fig. 1. Standard push-pull self-oscillating converter

$$\frac{dB}{dt} = \frac{(E - U_{\mathrm{CE\,SAt}}) \cdot 10^4}{\mathrm{W}_1 \cdot Ac}, \qquad (1)$$

or where

$$f = \frac{1}{T} = \frac{(E - U_{\mathrm{CE\,SAt}}) \cdot 10^4}{4\, B_{\max} \cdot \mathrm{W}_1 \cdot A_{\mathrm{E}}}.$$

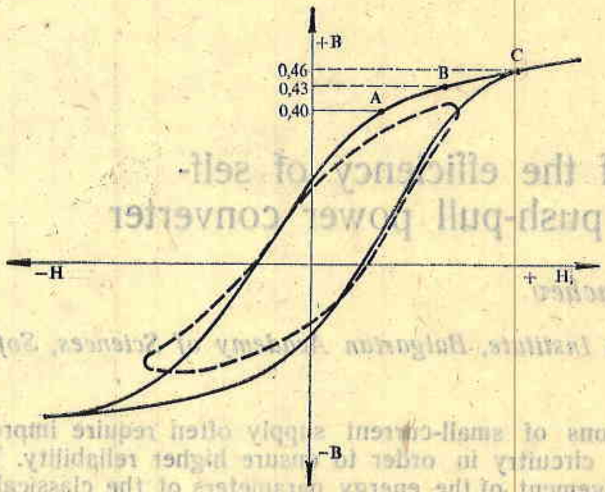

Fig. 2. Histeretic curve for soft magnetic ferrites: at low frequencies (solid line); at high frequencies (dashed line)

This converter is specified with poor efficiency, low load and great losses in the feromagnetic core. Magnetically soft ferites with non-rectangular histeretic curve are used as feromagnetic cores in contemporary converters, i. e. they represent high-frequency magnetic materials (Fig. 2).

As it can be seen in Fig. 1, the base currents of transistors T_1 and T_2 are defined with the expression:

$$I_{B_1} = I_{B_2} = \frac{U_{\mathrm{W}_8} - U_{B_e}}{R_3},$$

while the collector current I_{C} is yielded as a total current of the secondary wiring.

The magnetized current is given by the expression:

$$I_{\mathrm{C}} = I_{\mathrm{T}_1} \frac{\mathrm{W}_5}{\mathrm{W}_1} + I_{\mathrm{T}_2} \frac{\mathrm{W}_7}{\mathrm{W}_1} + \cdots + \frac{H \cdot le}{\mathrm{W}_1}, \qquad (2)$$

where I_{tx} is the load current of the respective output.

In order to provide reliable reswitching of the transistors, the following condition has to be fulfilled:

$$I_{\mathrm{C}} - \sum_{x=1}^{m} \frac{I_{tx}}{\pi_x} \geq I_{m\,\mathrm{crit}}, \qquad (3)$$

where $I_{m\text{crit}}$ is the minimum magnetized current of intensity H at the point of change in the histeretic curve slope. Since $I_{m\,\text{crit}}$ is high for such type of converters and a strain of $H \geq 80$ A/m has to be achieved for the most frequently used types [2], then the maximum collector current at weak loading

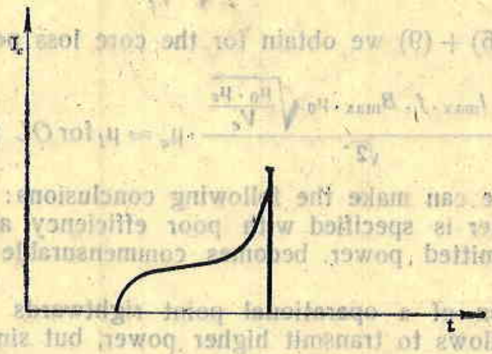

Fig. 3. Collector current shape for saturated transformer converter

of the converter is determined exclusively by the second term of equation (2). The shape of the collector current is shown in Fig. 3.

The maximum value of the collector current is defined with the base current and the amplification index $h_{21\,e}$ for bipolar transistors, and by the gate-source voltage and the preliminary characteristics for the power FET transistor. In addition, in order to obtain great power, the switching-off position is selected rightwards from the histeretic curve (point B and point C), in Fig. 2 which results in a greater increase of losses in the magnetic core, field keys, etc.

The losses in the ferrite core are given with

$$P_c = P_{\text{hist}} + P_{\text{sec}} + P_{\text{suppl}}, \tag{4}$$

where $P_{\text{hist}} = \frac{f \,.\, \Phi H \,.\, dB}{\gamma}$ [W/kg] are the histeretic losses; γ is the density of the material; $P_{\text{sec}} \approx 0$ are the losses of the eddy currents. This component for frequencies up to the critical one is negligibly small in ferrites.

$P_{\text{suppl.}}$ are the supplementary losses effective only for weak fields $H \leq 10$ A/m.

Usually the "angle of losses" parameter is used for the quantitative determination of the losses

$$\operatorname{tg}\delta = \frac{R_s}{\omega L_s} = \delta_{\text{hist}},\, h + \delta_{\text{sec}}.\, f + \delta_{\text{suppl}}, \tag{5}$$

which in agreement with (3) is:

$$\operatorname{tg}\delta = \eta_B \cdot \mu_e \,.\, B_{\max}/h, \tag{6}$$

where h — histeretic coefficient of the material; η_B — material histeresis constant

The total loss of power in the core may be expressed with

$$P_c = I^2 \,.\, l_{\max} \,.\, R_S = I^2 \,.\, l_{\max} \,.\, \omega L \,.\, \operatorname{tg}\delta. \tag{7}$$

We substitute $\operatorname{tg}\delta$ into (7) with its value from (6) and obtain

$$P_c = \frac{I^2 \,.\, l_{\max} \,.\, f \,.\, \mu_e \,.\, B_{\max}}{\sqrt{2} \,.\, \mu^2} \text{ [W/kg]}. \tag{8}$$

The core histeresis constant is used to introduce its parameters as related to its geometric size

$$\eta_1 = \mu_e \cdot \mu_B \sqrt{\frac{\mu_0 \cdot \mu_e}{V_e}}. \tag{9}$$

From expressions (6) + (9) we obtain for the core loss power

$$P_c = \frac{I^2 \cdot l_{\max} \cdot f \cdot B_{\max} \cdot \mu_0 \sqrt{\frac{\mu_0 \cdot \mu_e}{V_e}}}{\sqrt{2}}, \mu_e \approx \mu_i \text{ for } OL \text{ type core.} \tag{10}$$

In summary we can make the following conclusions:

— The converter is specified with poor efficiency at low loading since the usefully transmitted power becomes commensurable with the circuitry losses;

— The selection of a operational point rightwards the point A of the histeretic curve allows to transmit higher power, but simultaneously abruptly increases the losses of the transformer core;

— The field keys are used in a capacity less than complete by current and are subject to overload at the point of switch-off.

The efficiency/output power characteristics may be improved and linearized significantly with proportional current control of the field keys in dependence on the output power of the converter. A method of increasing the real efficiency of such converters is suggested in [5]. Their general block diagram is given in Fig. 4.

The proportional control is made in agreement with the expression

$$I_b = k . I_k + K_1, \tag{11}$$

where $k = \frac{S}{h_{21e\,\min}}$ and $K_1 = \frac{I_m}{h_{21e\,\min}} = \frac{H_{\text{crit}} \cdot l_e}{W_1 \cdot h_{21e\,\min}}$.

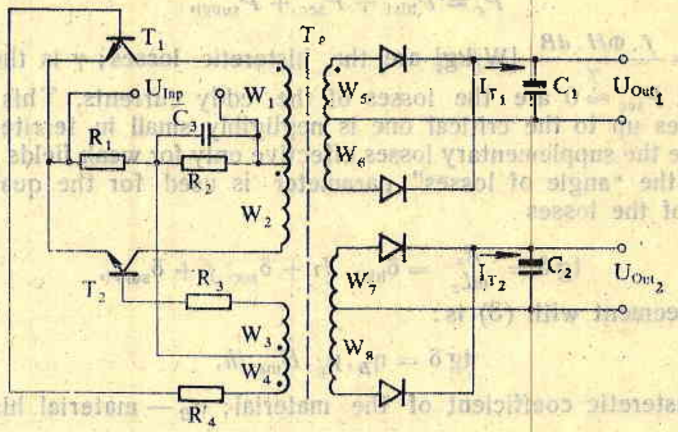

Fig. 4. Generalized block diagram of improved push-pull self-oscillating converter

The proportional feeding of the base is provided with k coefficient, while K_1 determines the minimum strain of field H, in order to safeguard the regenerative operational cycle.

When using advanced MOS transistors, the circuitry is transformed by replacing current transformers with current-to-voltage converters. Expression (11) takes the form of

$$E_{GS} = T_k/g_m + E_{GS\ init}, \tag{12}$$

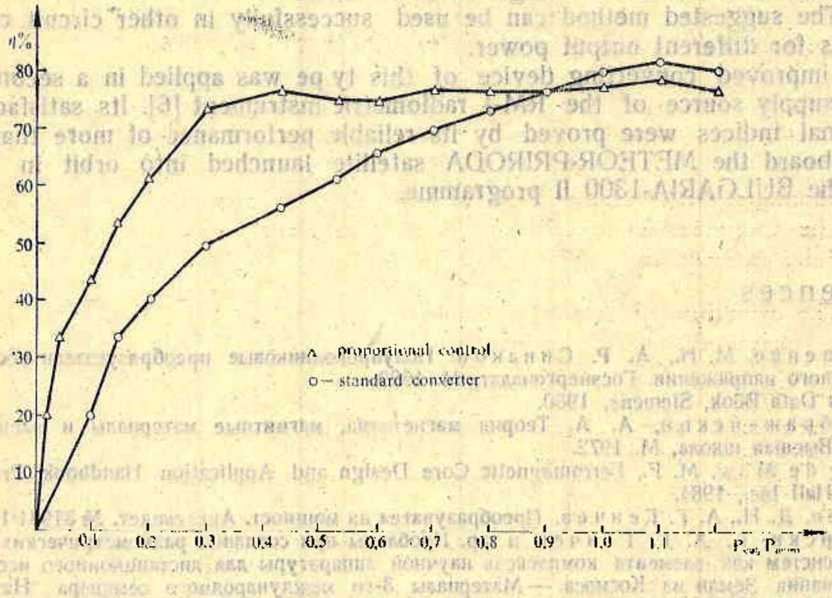

Fig. 5. Experimentally obtained curve, reflecting the efficiency of both converter types in dependence on the normalized output power

where g_m — transistor transadmittance, $E_{GS\ init}$ — prevoltage applied to the gate in order to ensure the required drain current, corresponding to field H_{min}.

We have to apply a thermal compensation of the gate voltage E_{GS} too, since it has a negative temperature coefficient (usually 20-25 mV/C°).

Additionally, for both modifications we have to ensure signal integration proportional to the collector (drain) current at the end of its switched-on position, so as to avoid introduction of a supplementary coefficient in equations (11) and (12) and an avalanche-like current amplification via the transistor.

The advantage of the method described was experimentally verified with the use of a small 15 W inverter. For power transistors, the bipolar 2N5038 and MOS FET VN64GA types were used. In order to provide a correct set-up and to take four reliable measurements, one and the same converting transformer was used: the ferrite core type 30 X 19, T 26, Al 6200, V_e 6100 mm^3

The results from these measurements are shown in Fig. 5 for a bipolar power transistor.

On the basis of theoretical and experimental evidence, we can make the following more important conclusions:

1. The method suggested for the loss decrease in converter with saturated transformer allows to improve by simple means the efficiency coefficient at an average 20%, when operating with normalized power $P_{out}/P_{norm} < 0{,}5$.
2. At low output power, a converter implemented on powerful MOS transistors has an efficiency $2 \div 4\%$ higher than the similar converter on bipo-

lar transistors. This is due to the drop of the base power, necessary for the control of the bipolar transistors.

3. Vice versa, at high power the efficiency of the powerful MOS transistors modification is lower, due to the effect of the higher voltage of saturation in these instruments at high drain currents.

4. The suggested method can be used successfully in other circuit configurations for different output power.

An improved converting device of this type was applied in a secondary current supply source of the RM-1 radiometric instrument [6]. Its satisfactory operational indices were proved by its reliable performance of more than 36 month aboard the METEOR-PRIRODA satellite launched into orbit in 1981 within the BULGARIA-1300 II programme.

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Повышение коэффициента полезного действия самоосциллирующего двухтактного преобразователя мощности

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(Резюме)

В работе рассматриваются метод и устройство для повышения коэффициента полезного действия стандартного самовозбуждающегося двухтактного преобразователя мощности с насыщаемым трансформатором. Обсуждаются причины, вызывающие ухудшение эффективности преобразователя при низкой нагрузке. Применено техническое решение, позволяющее повысить его эффективность при низкой нагрузке, и представлены экспериментальные результаты.