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原著論文

Performance of Medium Frequency Supplying System for Plasma Reactor

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There are certain requirements of the supplying system which need to be satisfied to obtain the good performance of a plasma reactor. Thus the system should ensure the high-voltage output, increased frequency and current limiting facility. This paper shows some example results of analysis of a magnetic frequency quintupler and a short description of used method. Presented supplying system seems to fulfill the requirements given by a plasma reactor of considered type.

Key Words : Magnetic frequency quintupler, Plasma generators, Harmonic balance technique, Galerkin procedure, Newton-Raphson method

1. Introduction

Low temperature plasma makes it possible to conduct some chemical processes like ozone synthesis and industrial gases utilization. Most often an electric discharge method is used to produce plasma. The productivity of chemical processes is mostly dependent on a set of electrodes and electrical parameters like voltage, frequency, current, and waveform. The basic and most important elements of a plasma reactor are: discharge chamber and electrical supplying system. The discharge chamber is a nonlinear electrical energy receiver of R or RC character, which needs to be supplied by alternating voltage. with value from several to several teens kilovolts.

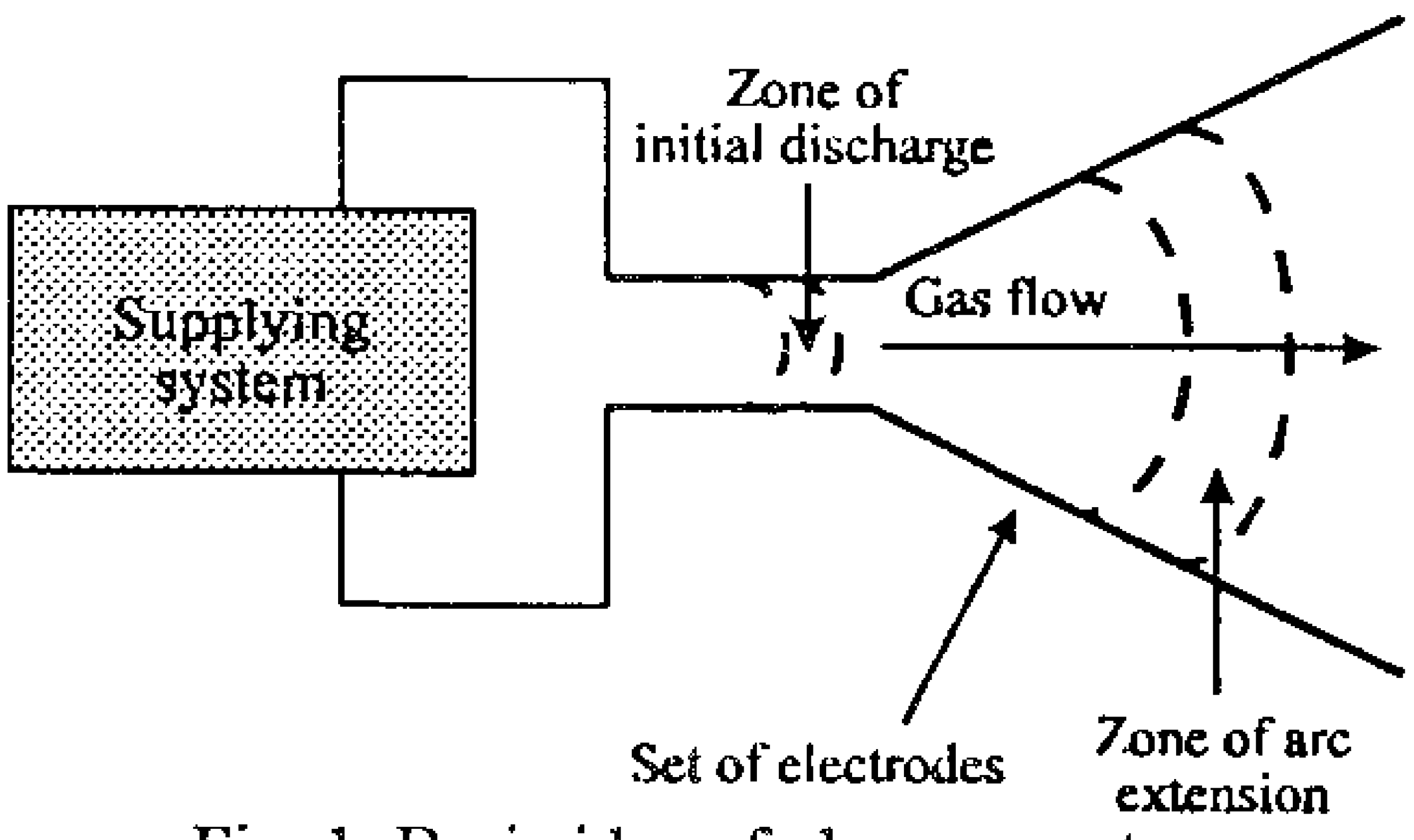

Fig. 1. Basic idea of plasma reactor.

The impedance of space between electrodes is a highly nonlinear one; its value comparatively big before a discharge happens decreases when discharges continue. Maximum efficiency is obtained from a reactor when supplied with frequency of several hundreds Hz and the power of reactors used in industry is about hundreds of kW. The basic idea of considered plasma reactor is shown on Fig. 1.

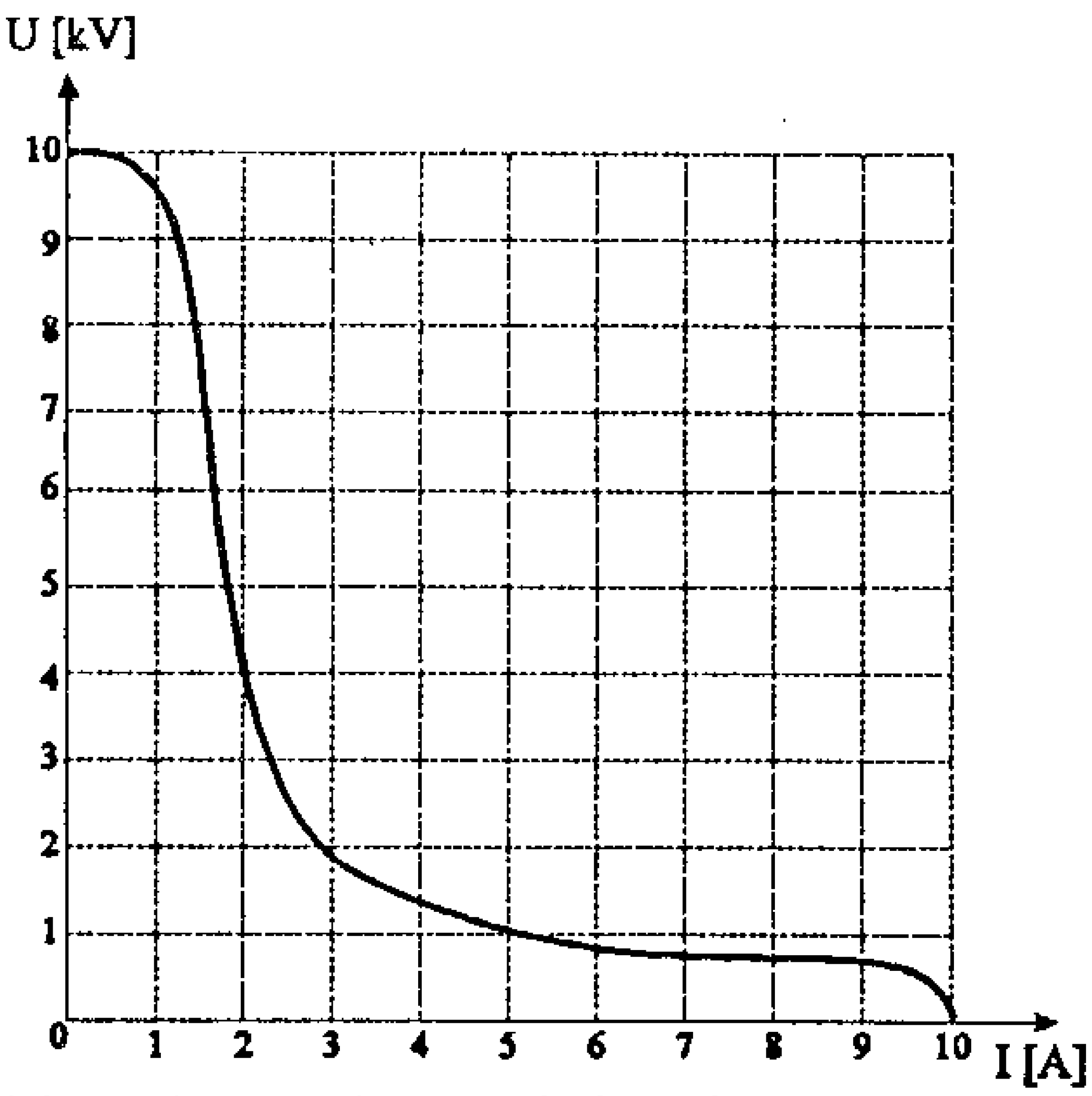

Fig.2. Output characteristics of plasma reactor.

A transformer seems to be the most basic supplying system, but it needs current limiting elements such as a choke applied in secondary circuit and reactive, capacitive power compensators. In addition the frequency should be increased to several hundreds Hz to improve the

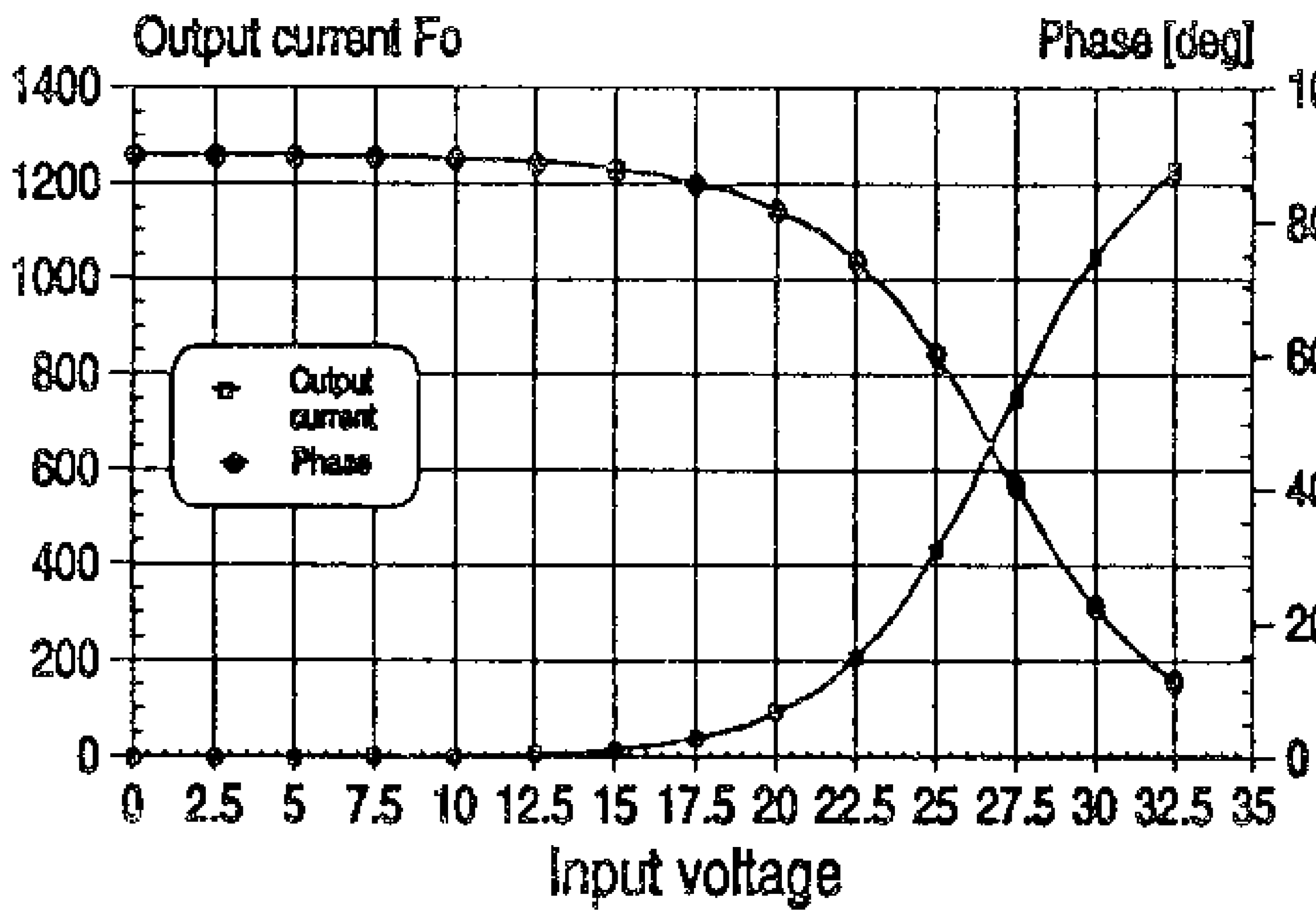

Fig. 5. Fifth harmonic of output current.

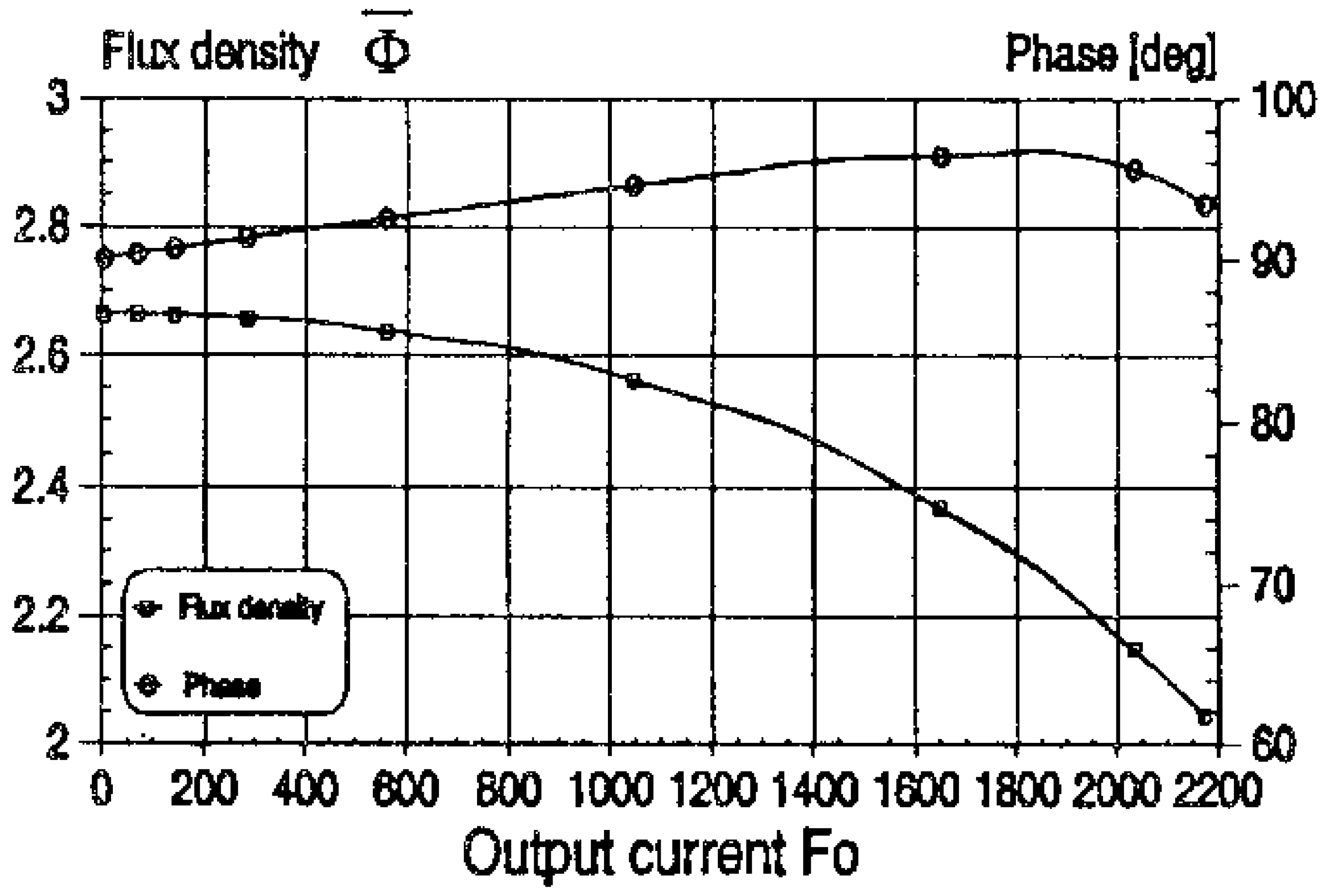

Fig. 6. Third harmonic of flux density.

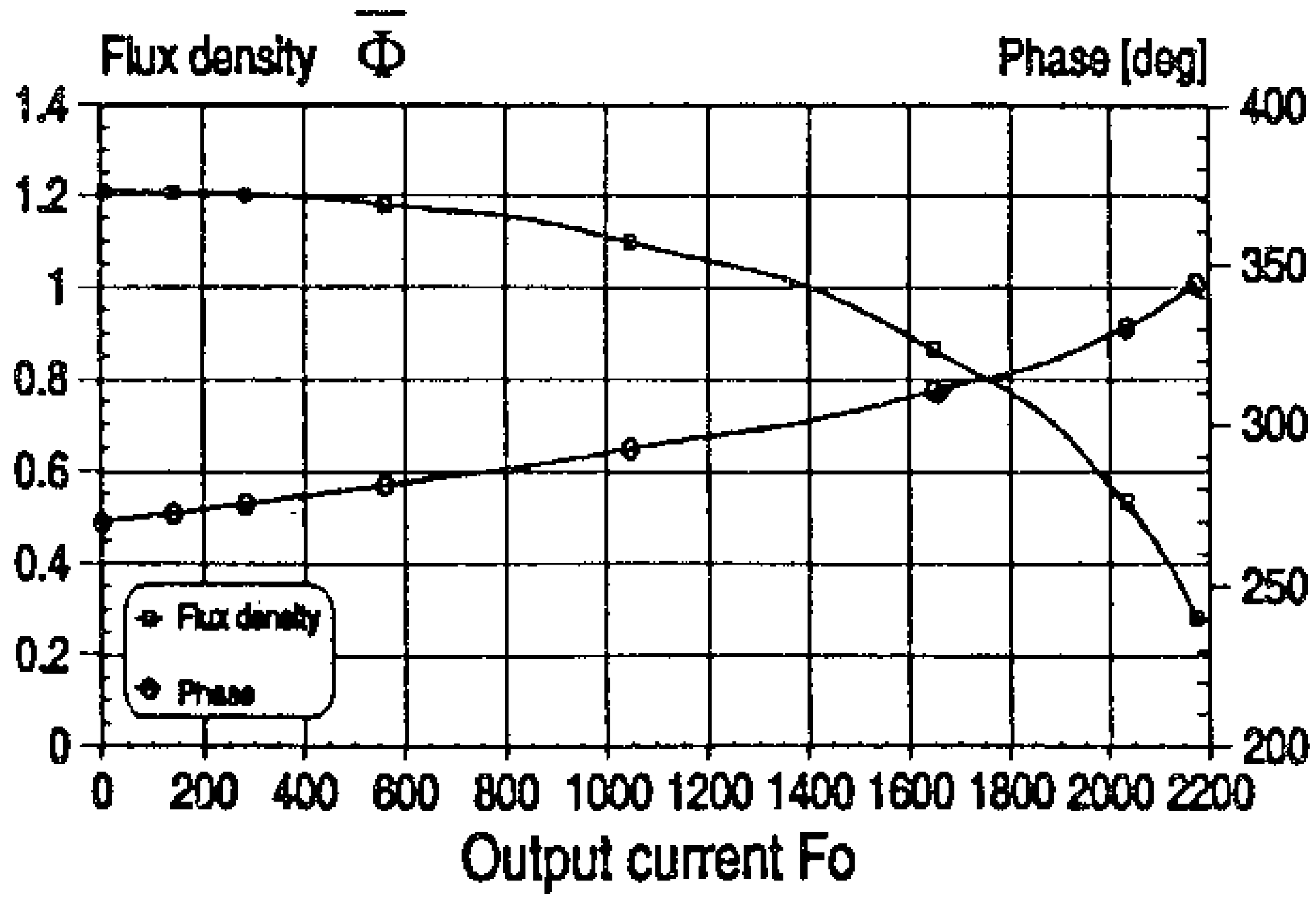

Fig. 7. Fifth harmonic of flux density.

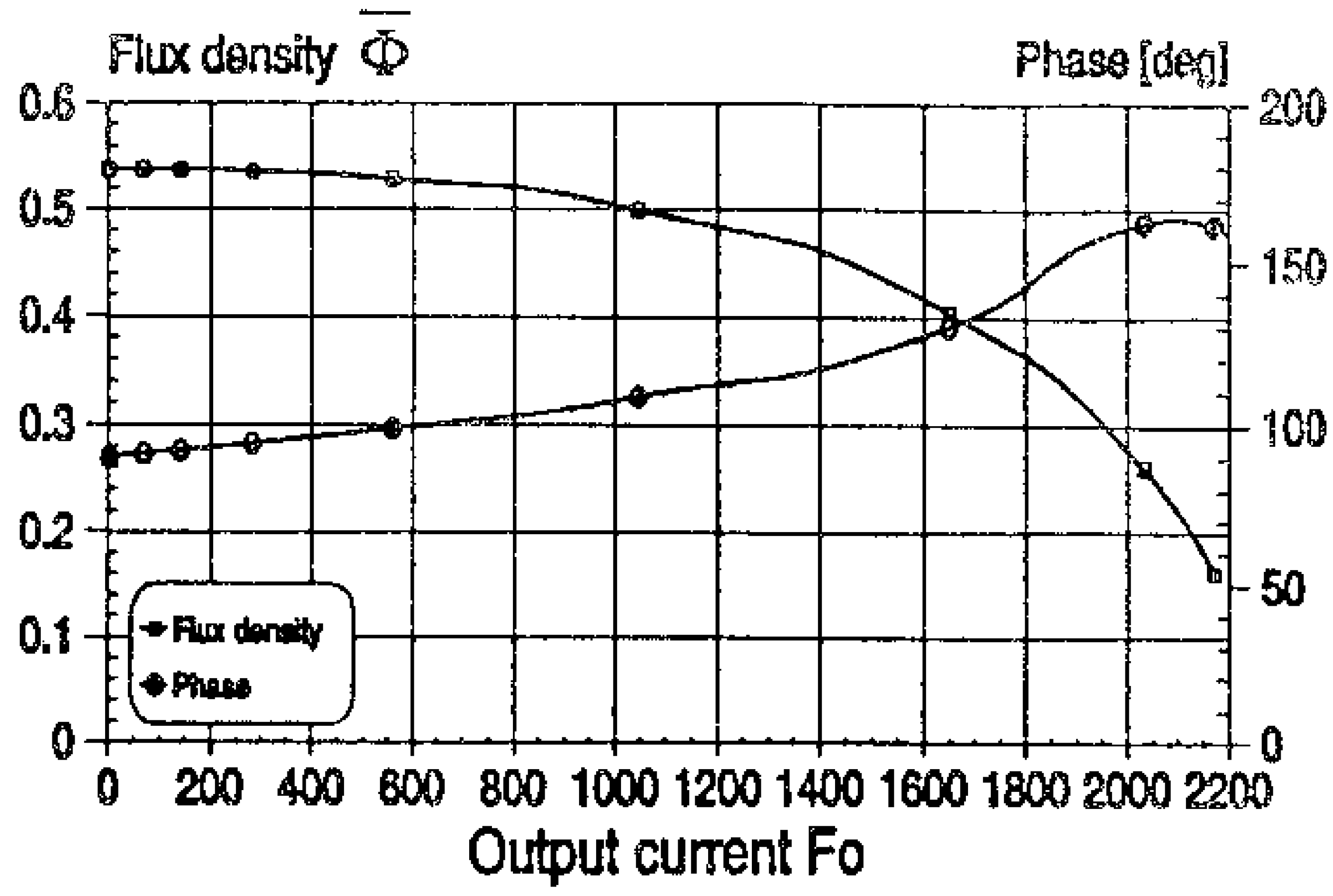

Fig. 8. Seventh harmonic of flux density.

a discharge chamber. The figure below shows the steady-state performances of third, seventh harmonic and fifth harmonic of flux density, which is directly proportional to the output voltage and fifth harmonic of output current.

4. Conclusion

The quintupler seems to satisfy the requirements of a plasma reactor by having the possibility to increase the frequency and limit the output current as the performances show. Although the ordinary transformer combined with the semiconductor converter and set of chokes is probably more simple, the supplying system with the quintupler seems to be more compacted one.

（1993年3月15日受付）

5. References

[1] Jan Guz: "Analytical calculations of voltages and currents of a magnetic frequency multiplier" - Ph.D. Thesis of Lublin Technical University (1984). (in Polish)

[2] A. Nafalski, J. Guz, M. Wojtowicz: "Numerical solving of chosen problems of theoretical electrotechnics." Lublin Technical University publishing office (1988). (in Polish)

$$\overline{H} = \sinh \overline{B}, \quad \text{- magnetizing curve,} \qquad (1d)$$

$$\overline{R} = \frac{R \cdot \alpha \cdot \beta \cdot l}{\omega \cdot z^2 \cdot s}, \quad \text{- resistance,} \qquad (1e)$$

$$\overline{X}_L = \frac{L \cdot \alpha \cdot \beta \cdot l}{z^2 \cdot s}, \quad \text{- inductive reactance,} \qquad (1f)$$

$$\overline{X}_C = \frac{\alpha \cdot \beta \cdot l}{\omega^2 \cdot z^2 \cdot s \cdot C}, \quad \text{- capacitive reactance,} \qquad (1g)$$

$$\overline{\Phi} = \overline{B} = \frac{\Phi \cdot \beta}{s}, \quad \text{- flux, flux density,} \qquad (1h)$$

The circuit shown on Fig. 4 satisfies the equations given below.

$$u = F \cdot R + \dot{B} \qquad (2a)$$

$$F_5 = F_0 + G \cdot \dot{B} \qquad (2b)$$

$$F_0 = \frac{1}{L_0} / B /^{(5)} + G_0 / \dot{B} /^{(5)} + C_0 / \ddot{B} /^{(5)} \qquad (2c)$$

$$u_0 = 5 / \dot{B} /^{(5)} \qquad (2d)$$

$$\sinh B = F - F_5 \qquad (2e)$$

Only third, fifth and seventh harmonic of flux density is considered, so the instantaneous value of flux density can be described by the formula:

$$B = \hat{B}_1 \cdot \sin t + \sum_{n=1}^{3} \{ Y_{2n-1} \cdot \sin[(2n+1) \cdot t] + Y_{2n} \cdot \cos[(2n+1) \cdot t] \} \qquad (3)$$

where Y_{2n-1} and Y_{2n} are undetermined amplitudes of each considered harmonic, and $\hat{B}_1$ is the amplitude of the fundamental harmonic of flux density. Applying the Harmonic Balance technique and using Galerkin procedure the following system of nonlinear equations is obtained:

$$-3GY_2 + \frac{1}{\pi} \int_0^{2\pi} \{ (\sinh B) \sin 3t \} dt = 0 \qquad (4a)$$

$$3GY_1 + \frac{1}{\pi} \int_0^{2\pi} \{ (\sinh B) \cos 3t \} dt = 0 \qquad (4b)$$

$$Y_3 (L_0^{-1} - 25C_0) - 5Y_4 (G + G_0) + \frac{1}{\pi} \int_0^{2\pi} \{ (\sinh B) \sin 5t \} dt = 0 \qquad (4c)$$

$$Y_4 (L_0^{-1} - 25C_0) + 5Y_3 (G + G_0) + \frac{1}{\pi} \int_0^{2\pi} \{ (\sinh B) \cos 5t \} dt = 0 \qquad (4d)$$

$$-7GY_6 + \frac{1}{\pi} \int_0^{2\pi} \{ (\sinh B) \sin 7t \} dt = 0 \qquad (4e)$$

$$7GY_5 + \frac{1}{\pi} \int_0^{2\pi} \{ (\sinh B) \cos 7t \} dt = 0 \qquad (4f)$$

This system can be easily solved using basic Newton-Raphson procedure [2]. The calculations were carried out for varying value of output current and input voltage. Load applied in the secondary circuit was of R -character and small value which corresponds to the small impedance of stability of the discharge. This is usually done by applying a thyristor or transistor converter to the circuit, but all these demands can be satisfied by using a magnetic frequency multiplier.

2. Supplying system with magnetic frequency quintupler

Magnetic frequency quintupler consists of a set of five single-phase transformers with identical cores and with their windings connected together in a specific way so as to make the first harmonics of flux a symmetric five-phase system. Voltage of frequency f_2 equal $5f_1$ will be obtained on the terminals of secondary windings connected in series. Basic scheme of connections is shown on Fig. 3, the parameters of windings are shown in table 1, and table 2 shows basic specifications identical for all quintupler's transformers.

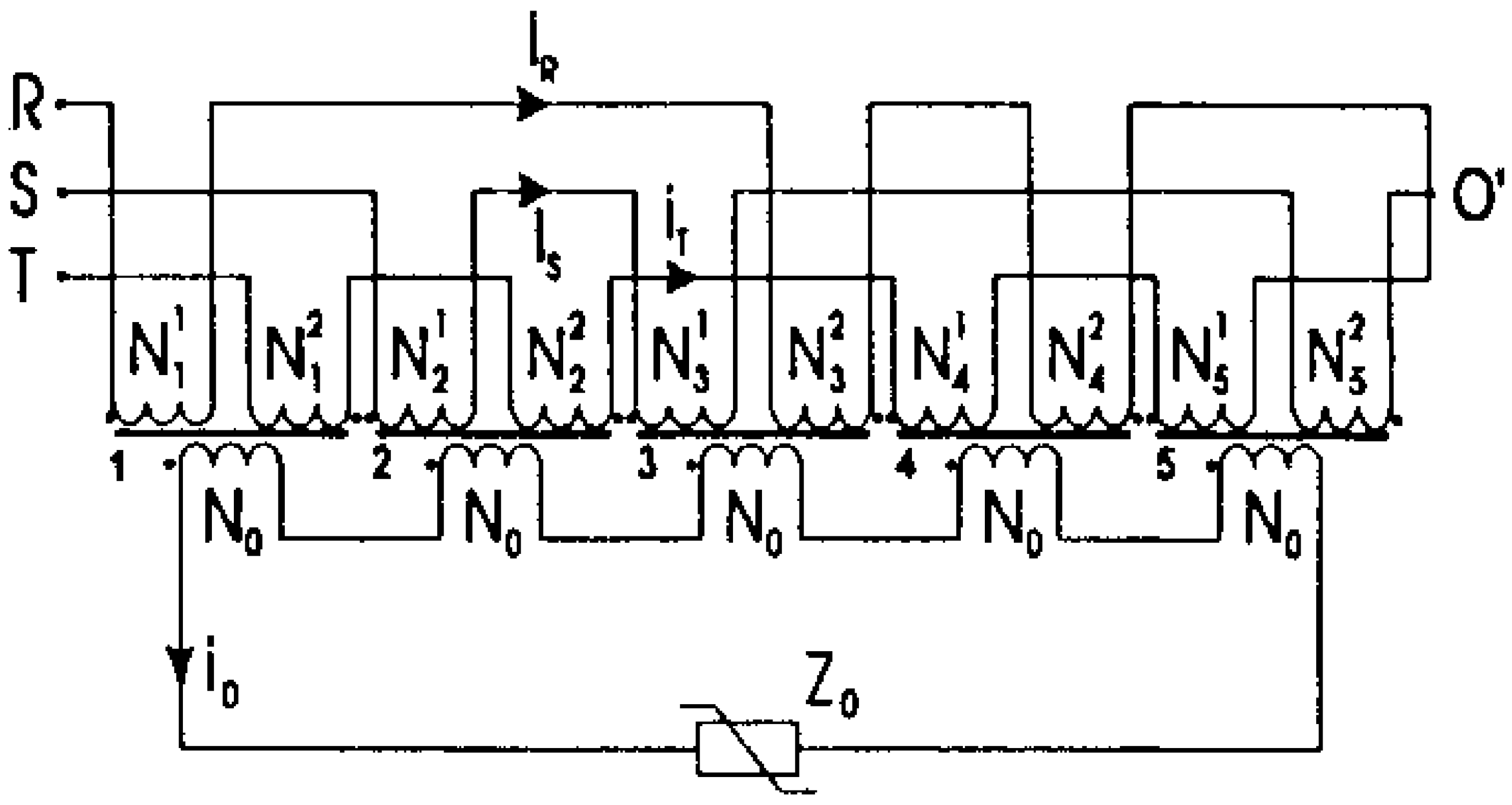

Fig. 3. Basic circuit of quintupler.

Table 1. Numbers of turns of primary windings.

	N^1	N^2
N_1	170	146
N_2	41	140
N_3	115	80
N_4	115	80
N_5	41	146

Table 2. Specifications of quintupler's transformers

No	Specification	Unit	Value
1	Cross-section of magnetic core	m²	12.2·10⁻⁴
2	Length of magnetic circuit	m	0.72
3	Core sheet thickness	mm	0.35
4	Cross-section of primary winding	mm²	10
5	Number of turns of secondary winding	-	3000
6	Diameter of winding wire	mm	0.4
7	Resistance of secondary winding	Ω	228

3. Quintupler analysis

To simplify the analysis the single-transformer equivalent circuit was used [1].

In secondary circuit of this transformer an ideal filter is applied passing only the fifth

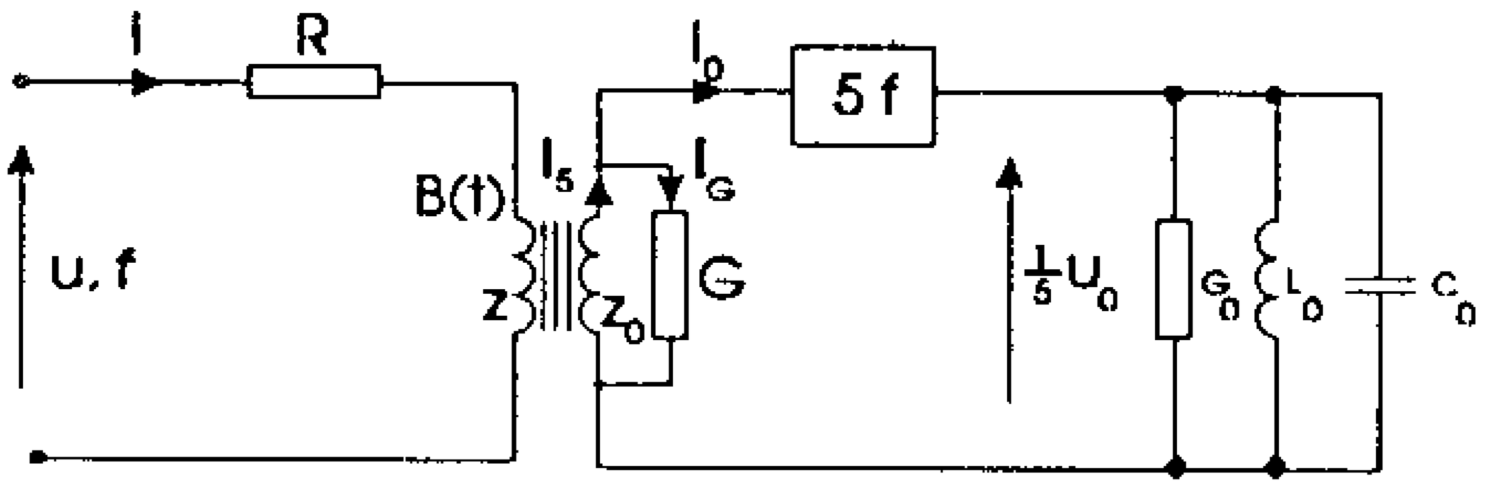

Fig. 4. Single transformer circuit.

harmonics, a mark $[]^{(5)}$ is used in the equations to notify this fact. To generalize the results and to make them independent on frequency, numbers of turns and parameters of magnetizing curve, the calculations were carried out by using dimensionless related system of units. This allows to obtain results which are true for every quntupler having the magnetizing curve given by hyperbolic sine approximation. The normalization of values was made by the use of the following formulas in which the basic quantities are prameters of magnetizing curve approximations (α, β). The stroke over each symbol means the undetermined value. In further calculations all values are undetermined, so this mark was neglected to simplify the notation.

$$\bar{u} = \frac{\beta \cdot u}{\omega \cdot z \cdot s} \quad \text{- voltage,} \qquad (1a)$$

$$\bar{i} = \bar{H} = \bar{F} = \frac{i \cdot z}{\alpha \cdot l} \quad \text{- current,magnetic field,} \qquad (1b)$$

$$\bar{t} = \omega \cdot t \quad \text{- time,} \qquad (1c)$$