Performance and analysis of an advanced type magnetic frequency tripler with three three-legged cores

PERFORMANCE AND ANALYSIS OF AN ADVANCED TYPE MAGNETIC FREQUENCY TRIPLER WITH THREE THREE-LEGGED CORES

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ABSTRACT

A new magnetic frequency tripler employing three 3-legged transformers connected in delta is proposed. The device has very little input current distortion and which only changes very little with the fluctuations of the input voltage and the load. In addition, the volume of iron and copper is about the same as in traditional star-connected circuit. Properties of a three-legged transformer and tripler are shown with and without filters. Fundamental analysis based on single-phase equivalent circuit is conducted. Results of experiments and analysis show improved performance of the new tripler.

INTRODUCTION

The star-connected magnetic frequency tripler (Fig.1a), prevalent both in industrial applications and as a research topic [1], has reached an output power of several MW per unit [2]. Recently, a new tripler has been reported [3],[4],[5] which consists of three

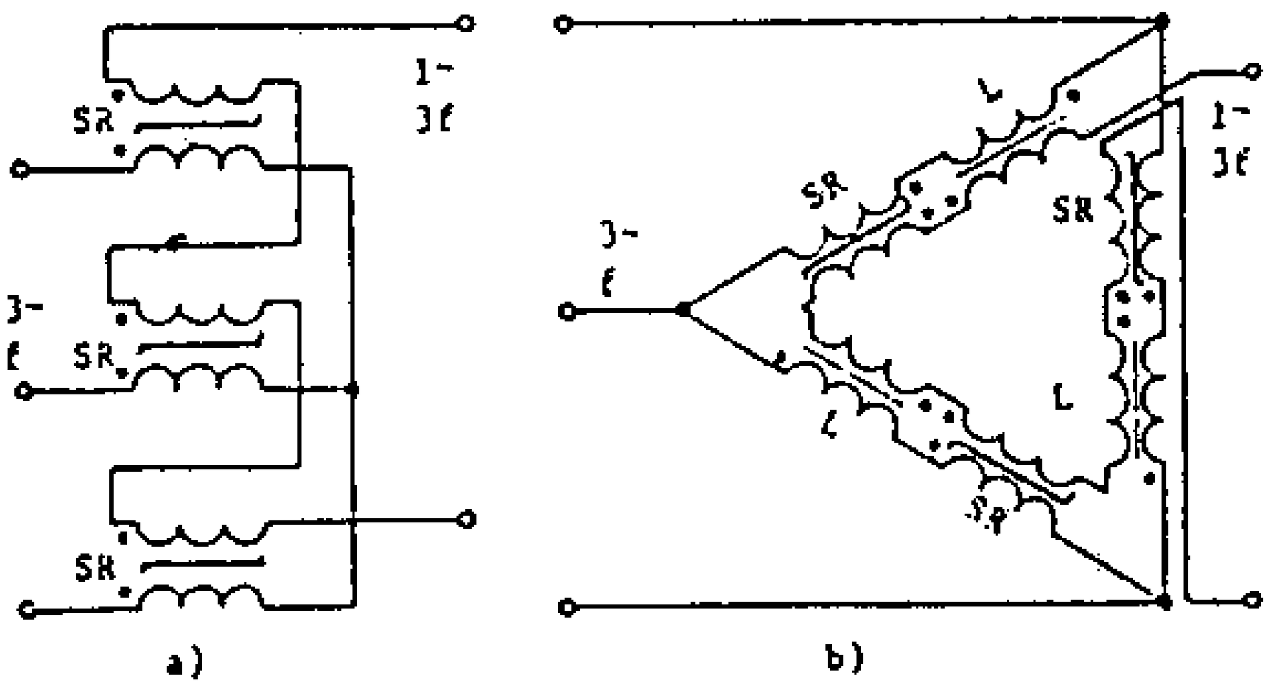

Fig.1. Basic structures of magnetic frequency triplers a) star-connected type b) delta-connected type

series-connected reactor circuits coupled in delta, (Fig.1b). The advantages of this device include little input current distortion and a small dependence of its effective value upon fluctuations of the input voltage and load. The disadvantages include larger amounts of iron and copper compared with the star-connected tripler (about 50% more). While working on improvement of the structure (Fig.1b) the authors discovered very interesting properties of the three-legged transformer.

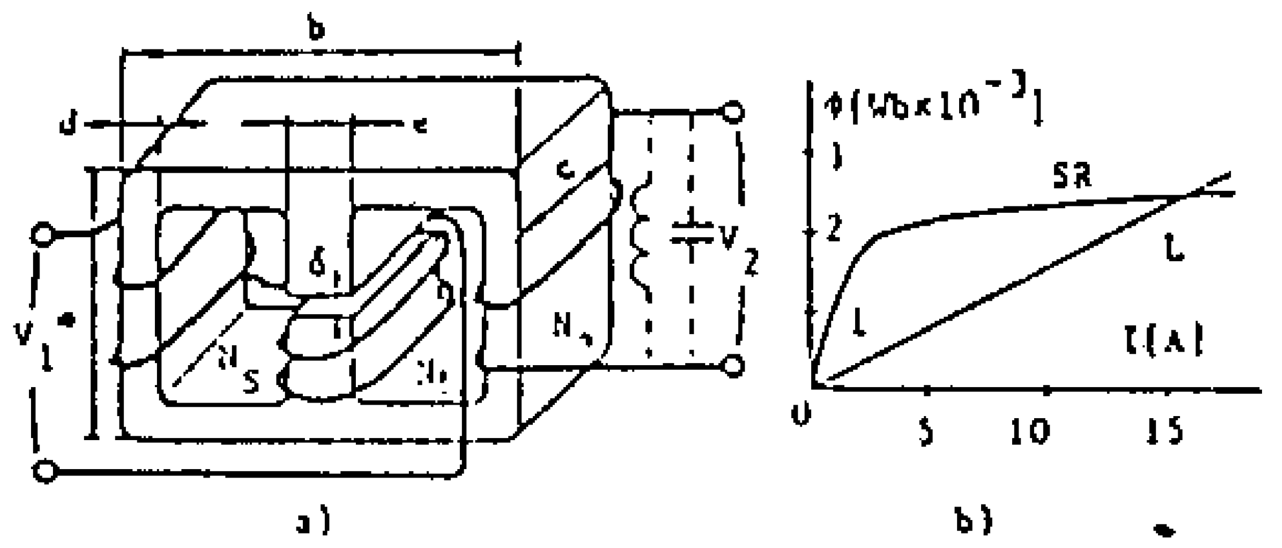

Fig.2. Three-legged transformer : a) structure b) magnetization curves

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THREE-LEGGED TRANSFORMER

The core of the three-legged transformer with an air-gap in the central leg carries two sections of the primary windings N_S and N_L and the secondary winding N_2 (Fig.2a). The magnetization curve of the linear L and the saturable path SR are shown in Fig.2b. Due to the nonlinearity, the output voltage of the transformer (Fig.2a) fed from a sine-wave source contains higher odd harmonics (Fig.3), with the third

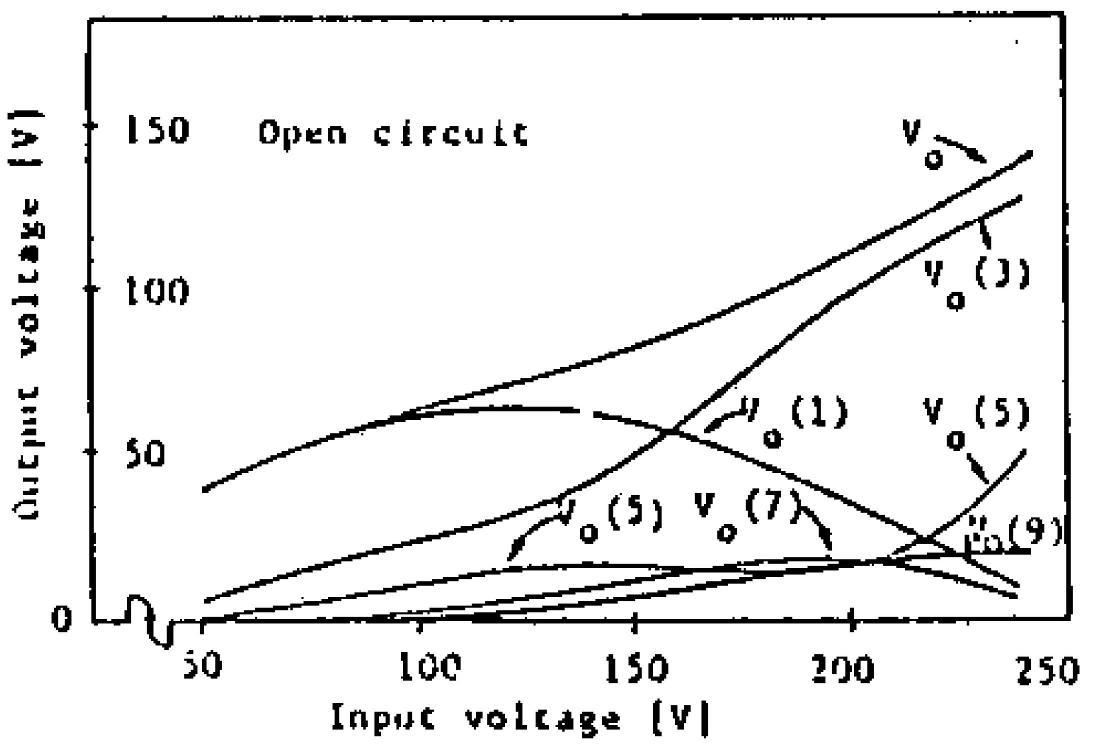

Fig.3. Harmonics of output voltage of three-legged transformer in open-circuit condition

being largest. The device is well-suited to operate as a frequency tripler either with single-phase or with three-phase input. It should be mentioned, however, that a proper choice of the output ferroresonant circuit (indicated in Fig.2a with dashed line) or structure changes can amplify the desired harmonic, so that a higher order multiplier can be obtained (quintupler etc.). Harmonic analysis of the input current of three-legged transformer (Tab.I) shows

Table I Harmonics of the input current 3-legged transformer V_1=220 V

Harmonic order k		1	3	5	7	9	11	13	15
$I_1(k)/I_1$	Open-circ.	96.0	27.9	2.1	1.9	< 1	1.1	< 1	< 1
[%]	Short-cir.	93.2	32.3	15.2	3.4	1.9	1.7	< 1	< 1

relatively low harmonic distortion with the increased presence of the first and the third harmonics. Because functions of the circuit are based on only one standard type magnetic core, the performance qualifies the three-legged transformer as a powerful harmonic generator. All quoted trials were carried out on three-legged transformer with following parameters of windings and core: N_S=N_L=N_2=170^T, a=132mm, b=136mm, c=50mm, d=23mm, e=30mm. Strip wound cut cores silicon-iron laminations Z-11, 0.35mm, with milled gap σ=3mm were employed.

STRUCTURE OF NEW TRIPLER

The tripler works with the structure of three equally rated three-legged transformers (Fig.2a) connected in delta. The primary side of the filtered frequency tripler includes reactors L_1 and condensers C_1, both provided for input power compensation. In addition, they stabilize the voltage supplying tripler and to some extend filter the input current. Across the secondary terminals a ferroresonant filter L_oC_o is placed to stabilize the output voltage.

The part of the primary winding on the linear path of transformer acts as a filter of phase current (Tab.I). Further, due to the delta connection, the three-phase line current is devoid of the third

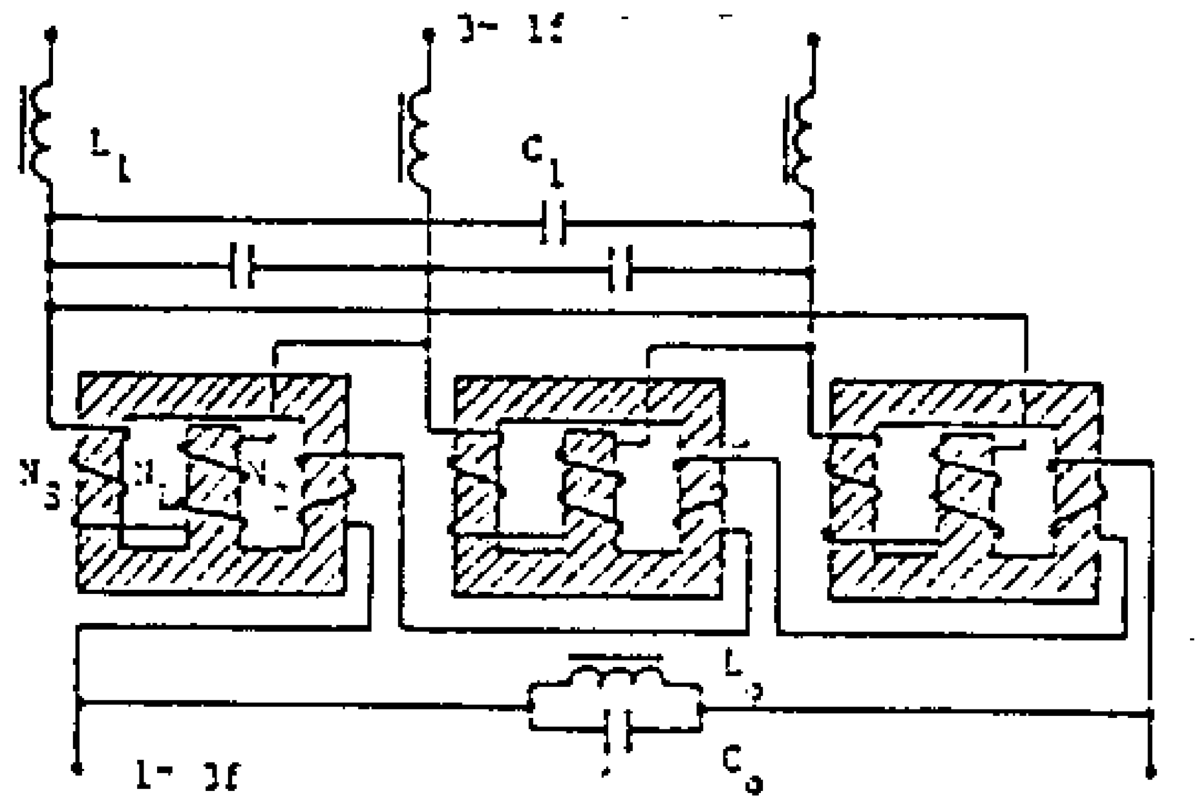

Fig.4. Filtered magnetic frequency tripler of new type

harmonic, so the new tripler has little input current distortion by nature. The secondaries of the tripler (Fig.4) connected in series eliminate all harmonic voltage components but the third and other divisible be three.

PERFORMANCE OF TRIPLER

The examination of non-filtered tripler in open-circuit and short-circuit operation confirmed the expectations with respect to the small harmonic content in the input current (Tab.II). The harmonic content,

Table II Harmonics of the input current fundamental tripler V_1=220 V

Harmonic order k		1	3	5	7	9	11	13	15
$I_1(k)/I_1$ [%]	Open-circ.	99.9	2.0	1.7	1.6	< 1	1.3	< 1	< 1
	Short-cir.	99.2	3.2	10.9	3.7	< 1	< 1	< 1	< 1

which depends on conditions, is only 3-12%, and is at least two to five times less than in case of traditional star-connected tripler. The short-circuit occurs rarely under normal operation, so under normal load the results are likely to be near the lower boundary of distortion, making the input filters unnecessary.

Table III Harmonics of the output voltage; V_1=220 V fundamental tripler in open-circuit

Harmonic order k	1	3	5	7	9	11	13	15
$V_o(k)/V_o$ [%]	2.9	98.8	1.7	< 1	14.6	1.2	< 1	1.9

Results of harmonic analysis of the open-circuit output voltage (Tab.III) indicate that only the third and nineth harmonic are significant, similar to other

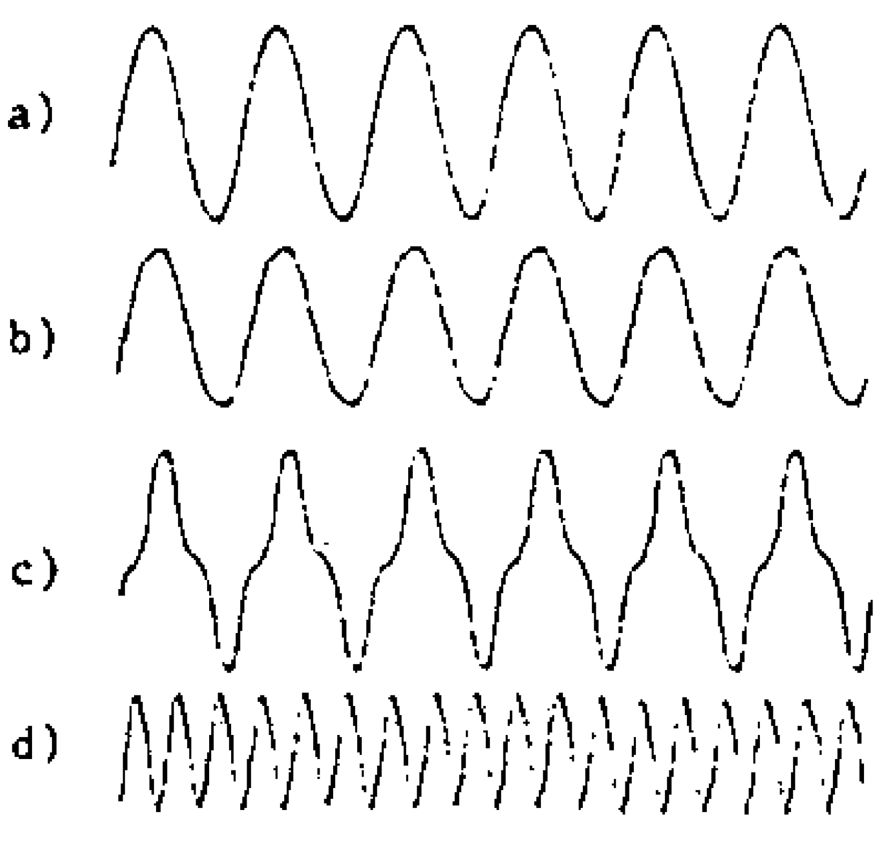

Fig.5. Waveforms of basic tripler in open-circuit
a) input voltage b) line current
c) phase current d) output voltage

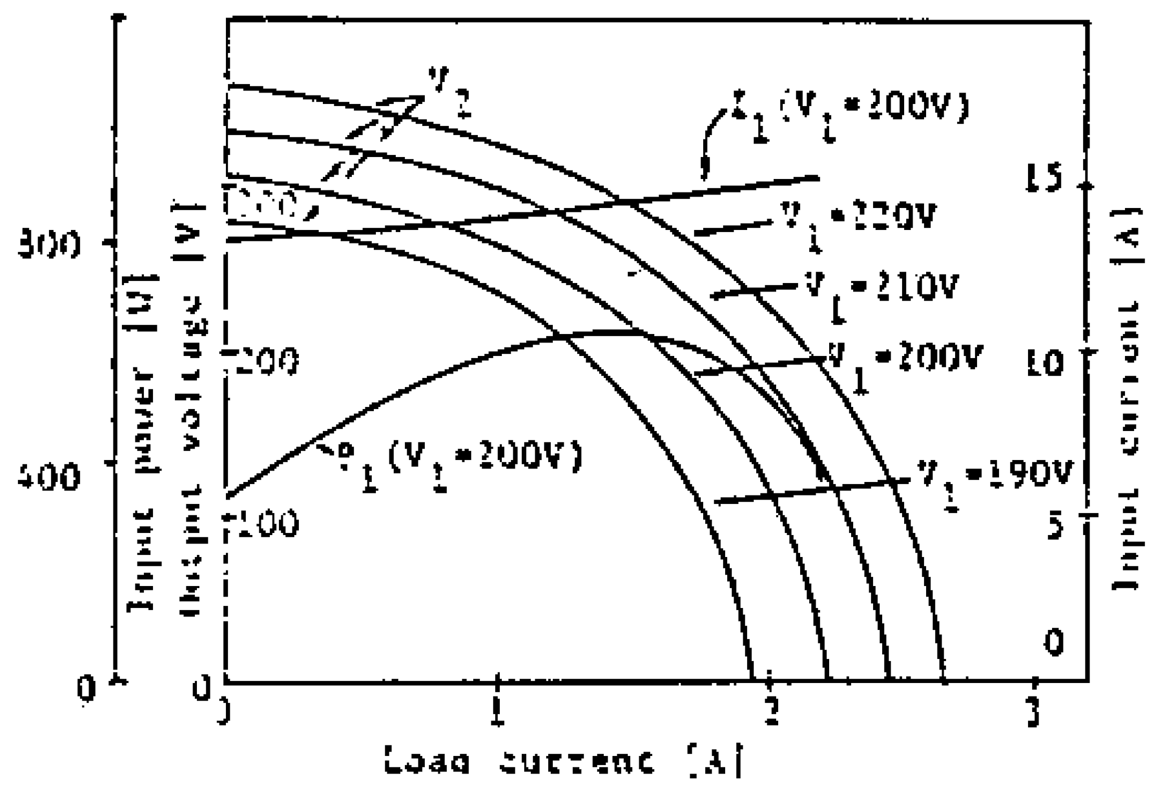

Fig.6. Load characteristics of the tripler without input and output filters

triplers [7]. Tripler waveforms are shown in Fig.5.

The input current under resistive load scarcely varies in course of loading (Fig.6). Between open- and short-circuit conditions there is only about 13-15% difference in current, which is distinctively different from the star-connected tripler [8].

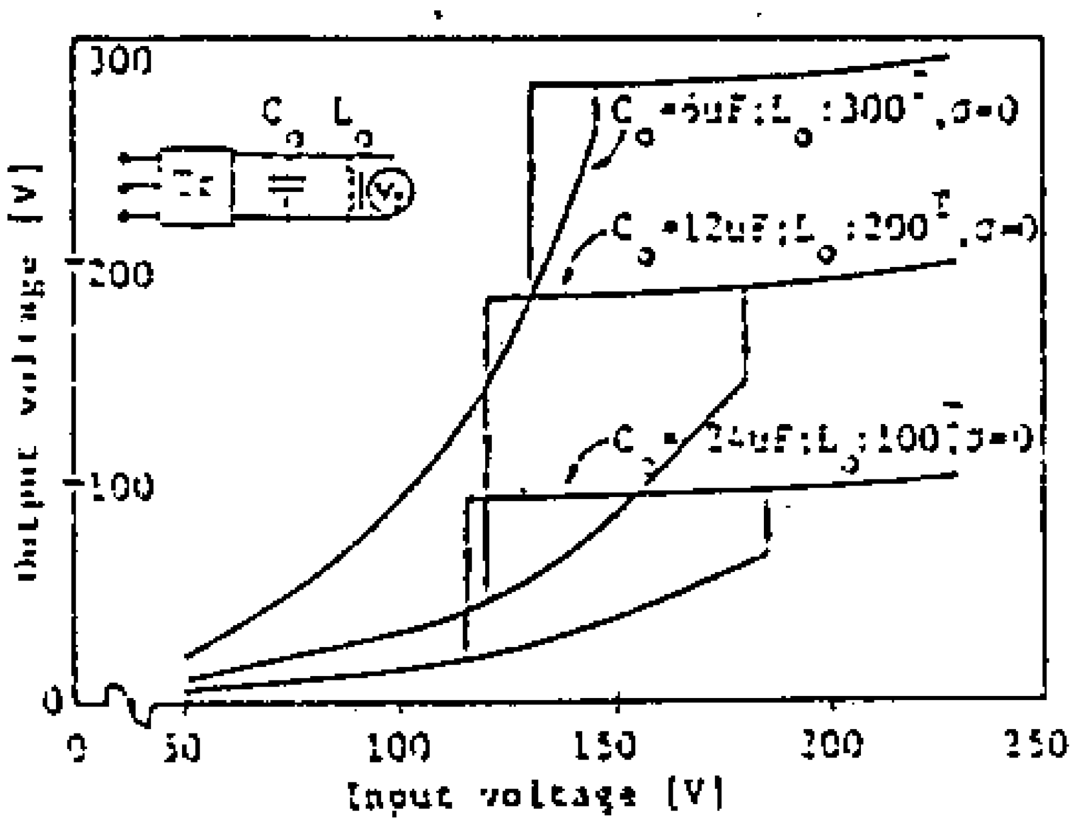

Fig.7. Voltage characteristics of tripler with output ferroresonant circuit L_oC_o (no-load)

The task of the output ferroresonant filter L_oC_o is to obtain constant voltage characteristics as shown in Fig.7. In order to achieve maximum output power the selection of resonance voltage is similar to that discussed in [3].

The input power factor of the fully-filtered tripler (Fig.4) is increased. The load characteristics (Fig.8) show further improved performance of the device.

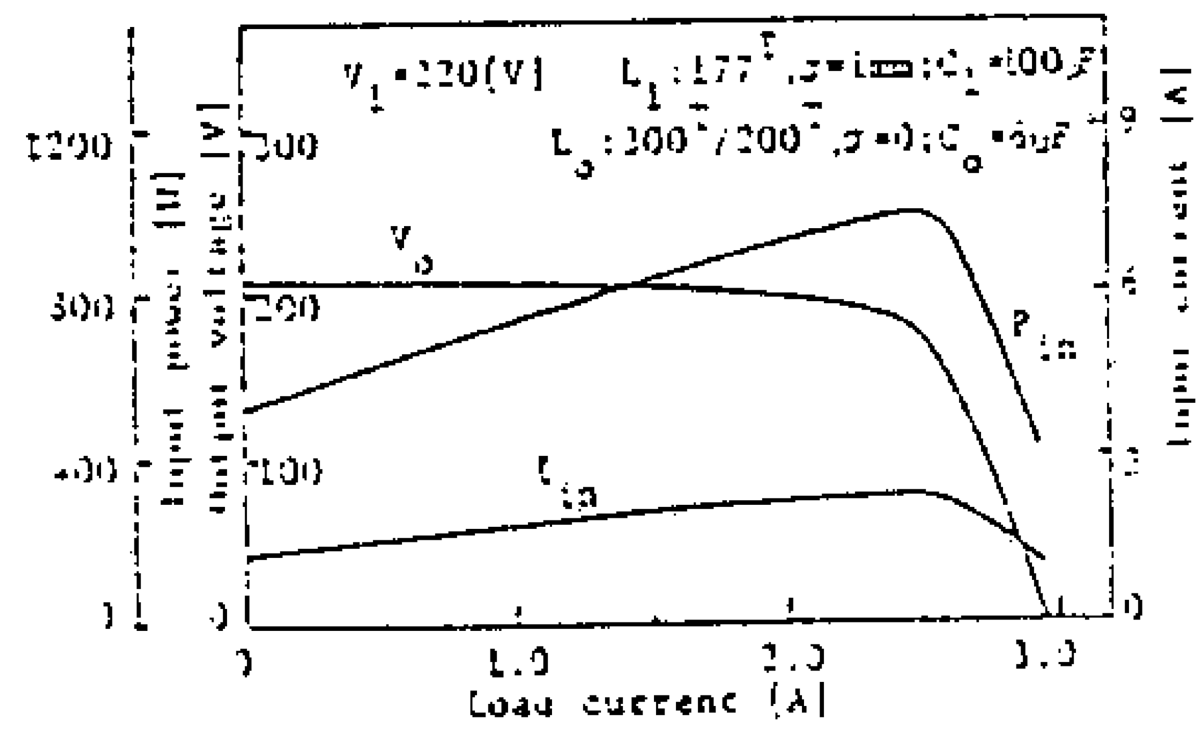

Fig.8. Load characteristics of tripler with input (L_1C_1) and output filters (L_oC_o)

ANALYTICAL APPROACH

During the experimental trials the following observations has been made which created basis for steady-state numerical analysis: (1) Linear and saturable paths of the three-legged transformer (Fig.2a) act relatively independently from each other. (2) Three-phases of the tripler (Fig.4) contribute equally to the load. (3) Performance of single three-legged transformer decides about the operation of the whole tripler. (4) All harmonics except for the fundamental and the third are of little importance in normal steady-state. Conclusion (1) permits us to separate two paths of transformer into a saturable and a linear reactor. Relative independence of the phases, clearly visible in case of open-circuit condition, authorizes us to analyse in steady-state only one phase (similar to [9], although for star-connection it was less obvious). Taking into consideration one phase of the tripler we can apply a similar model for both tripler and three-legged transformer with some modification of parameter values and imposing necessary constraints to the tripler. Finally, in normal steady-state, consideration of only the first and third harmonics seems permissible. The afore-mentioned assumptions are materialized in form of single-phase equivalent circuit of the filtered tripler (3-legged transformer) shown in Fig.9. Beside the symbols used

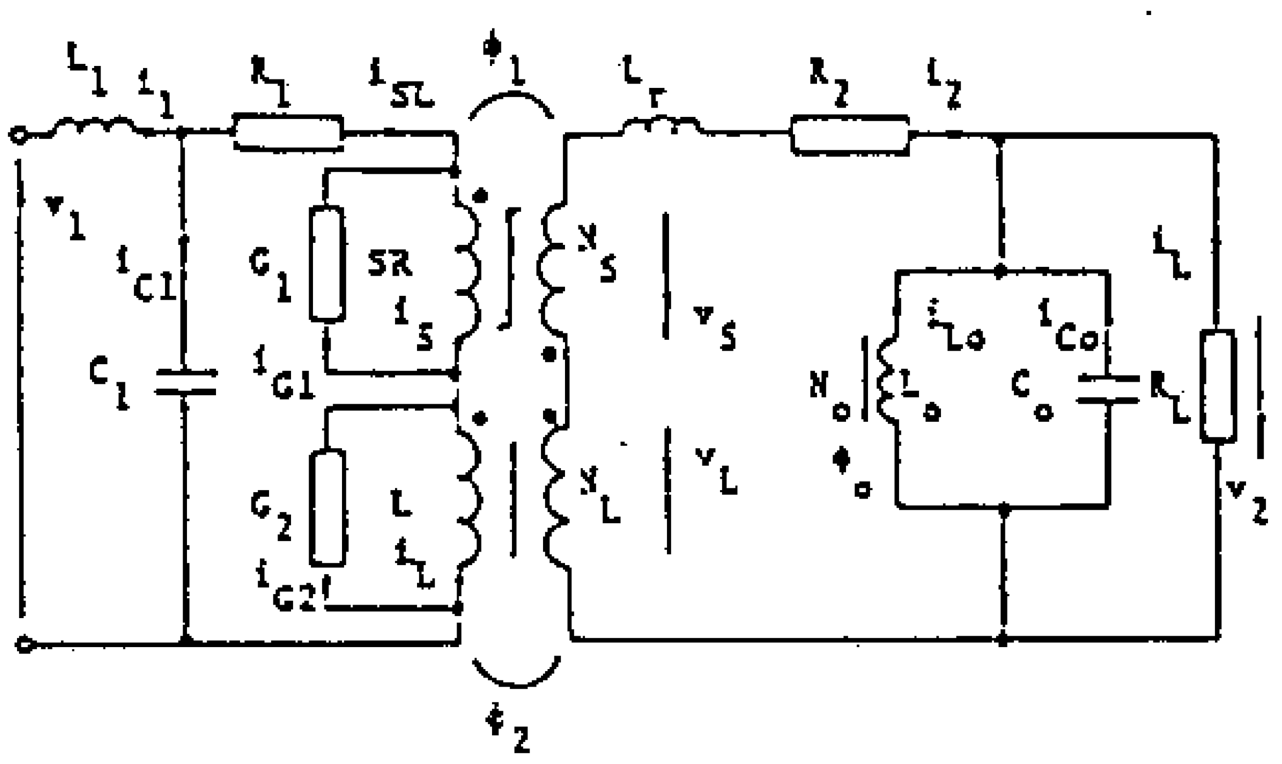

Fig.9. Single-phase equivalent circuit of new tripler

in Fig.4, R_1 and R_2 are winding resistances, G_1 and G_2 are equivalences of core loss resistances and L_r is leakage inductance. To analyse the circuit (Fig.9) we have chosen the method of Harmonic Balance and Newton-Raphson (N-R) algorithm applied successfully in [4]. The method permits to use nonlinear differential equation system in the form given below:

$$f\left(\frac{d^i y}{dt^i}, \frac{d^{i-1}y}{dt^{i-1}}, \ . \ . \ . \ , \frac{dy}{dt}, y\right) = 0 \qquad (1)$$

Magnetization curves of reactors are approximated as follows:

$$f(\phi_1)=\alpha_1\phi_1+\beta_1\phi_1^3+\gamma_1\phi_1^5 \qquad (2)$$

$$f(\phi_2)=\alpha_2\phi_2 \qquad (3)$$

$$f(\phi_o)=\alpha_o\phi_o+\beta_o\phi_o^3+\gamma_o\phi_o^5 \qquad (4)$$

We expect solution in form of the Fourier series with sinus and cosinus terms:

$$\phi_o=\sum_{n=1}^{2}\sum_{m=1}^{2}A_{(2n-1,m)}\sin\left\{(2n-1)\omega t+\frac{(m-1)\pi}{2}\right\} \qquad (5)$$

$$\phi_1=\sum_{n=1}^{2}\sum_{m=1}^{2}B_{(2n-1,m)}\sin\left\{(2n-1)\omega t+\frac{(m-1)\pi}{2}\right\} \qquad (6)$$

$$\phi_2=\sum_{n=1}\sum_{m=1}C_{(2n-1,m)}\sin\left\{(2n-1)\omega t+\frac{(m-1)\pi}{2}\right\} \qquad (7)$$

System of nonlinear algebraic equations was solved by means of N-R iteration with evaluation of initial guess for the fluxes explained below. We used Runge-Kutta integration for simplified circuit (no filters, losses and leakage flux) to obtain a periodic solution. Although system was ligtly damped we could get the solution for fluxes already after several periods by direct application of Fourier analysis. It was possible due to negligence of the aperiodic component of solution (N-R iteration started from small input voltages so the system was yet linear). Such results were enough accurate to obtain proper

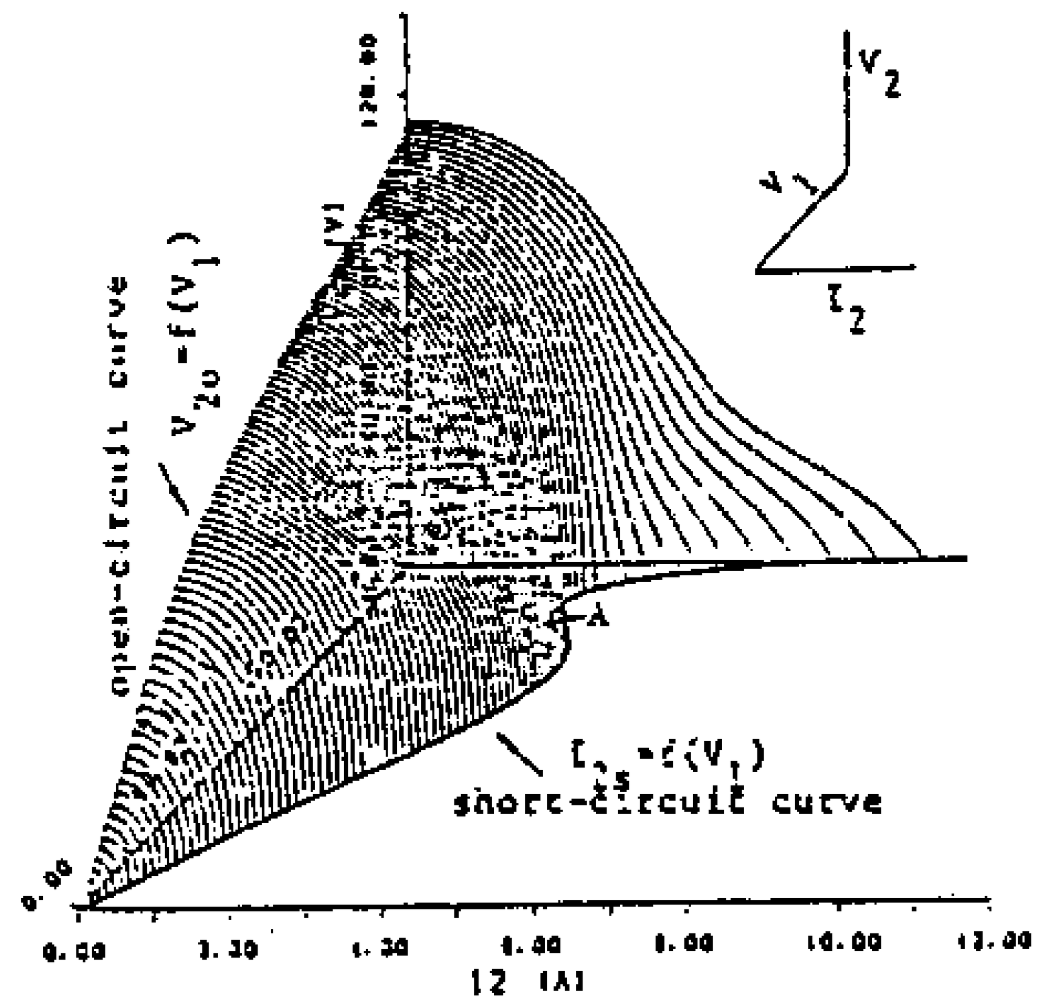

Fig.10. Total load characteristics of three-legged transformer $V_2=f(I_2,V_1)$

convergence of N-R method. The initial values of fluxes for each next input voltage or load resistance were taken from the previous iteration step.

In Fig.10 a "total" load characteristic of the three-legged transformer in a "load space" limited by boundary conditions: open-circuit and short-circuit curves, is given. Point A indicates the minimum in short-circuit curve which estimates value of the rated input voltage (securing the best power factor and load characteristics [11]). In addition, product of the short-circuit current and open-circuit voltage informs us about the minimum output power. Such results can be calculated from the magnetization curves of SR and L, therefore very easily. It was found that the model (Fig.9) is very helpful as a design aid.

CONCLUSIONS

The magnetic frequency tripler composed of three three-legged transformers has been proven to be very promising for high output power applications. This new device can be favourably compared to existing star-connected tripler. Input current harmonic distortion is up to five times smaller, while copper and iron volumes are about the same. To other advantages counts almost constant current consumption in course of load changes. Simple construction, economy and very good operational characteristics make the new tripler noteworthy in family of frequency multipliers.

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