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ELECTRICAL ENGINEERING

Time Ratio Controlled Three-phase AC Chopper

Khaled E. Addoweesh
Electrical Engineering Department, King Saud University
Riyadh, Saudi Arabia

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Abstract. A general switching method suitable to control three-phase AC chopper circuit is presented. Such a method can be used with different circuit configurations of the AC chopper. Detailed harmonic analysis of the AC chopper when controlled by the time ratio control (TRC) strategy is given. TRC has the advantages of linear control of the fundamental component of the output voltage and elimination of all harmonics of order less than the frequency ratio by two. Also, the control signal can be generated easily. Experimental results verifying the analysis are presented.

Introduction

Phase-angle control technique was traditionally used for AC voltage control [1]. This technique has a simple circuit structure. Besides its advantages it generates low-order harmonics and its response speed is limited to the frequency of the mains. The performance of the AC voltage controllers can be improved by chopping techniques. AC choppers are capable of achieving flexible voltage control while preventing low harmonic injection to the system as compared to the conventional AC voltage controllers. The response of the AC chopper is significantly faster than its counterpart. Also, filtering requirements are less as a result of its high switching frequency. Many chopping techniques for the single-phase circuits have been discussed [2-5]. Design of a three-phase transistorized AC chopper is given in [5].

This paper presents different circuit configurations of the three-phase AC chopper. The switches are controlled using only one signal and its complement. The output of the AC chopper is controlled by time ratio control (TRC) technique. TRC is an easy implemented technique. Detailed harmonic performance of the AC chopper under this technique is presented. TRC technique gives the following advantages:

- linear control of output voltage,
- no low order harmonics, and
- simple electronic circuit could be used to generate TRC signals

Experimental results are provided to verify the proposed technique.

Circuit Configuration and Principle of Operation

Figure 1 shows different circuit configurations where the main AC switches (S_n) are used to connect the load with the supply while the fly-wheeling switches (F_n) are used to give path for energy stored in the inductances of the load when the main switches open. In the proposed technique all the main switches are controlled by one switching signal. In the circuit configuration a and b shown in Fig.1, it is adequate to use two fly-wheeling switches. To keep symmetry between the output phases of the chopper the frequency of the switching signal should be multiples of 3 times the supply frequency as shown in Fig.2.

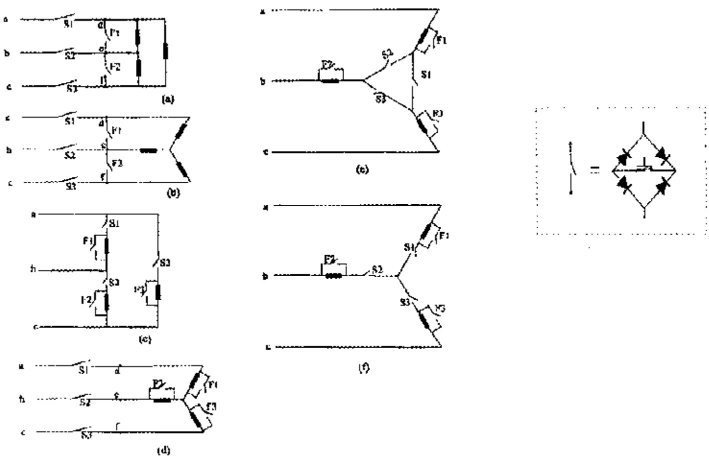

Fig. 1. Different configurations of the three phase AC chopper circuit.

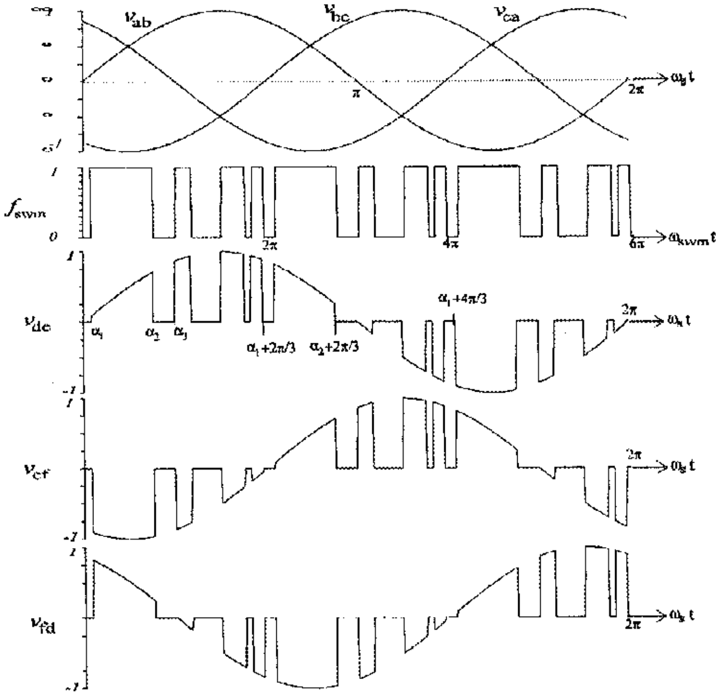

Fig. 2. Output voltage of the 3 phase AC chopper.

Two switching signals: f_{swm} and f_{swf} are used to control the switches of the three phase AC chopper circuit. Switching signal f_{swm} controls main switches while f_{swf} controls fly-wheeling ones as follows:

When $f_{swm} = 1$ S_1, S_2 and S_3 are closed and F_1, F_2 and F_3 are open (1)

When $f_{swm} = 0$ S_1, S_2 and S_3 are open F_1, F_2 and F_3 are closed (2)

$$f_{swf} = \overline{f_{swm}} \tag{3}$$

Analysis

Supply voltages are given by

$$V_{ab} = \sin(\omega t) \quad \text{pu} \tag{4}$$

$$V_{bc} = \sin\left(\omega t - \frac{2\pi}{3}\right) \quad \text{pu} \tag{5}$$

$$V_{ca} = \sin\left(\omega t + \frac{2\pi}{3}\right) \quad \text{pu} \tag{6}$$

Load is assumed to be balanced series resistive-inductive having a per phase impedance of $1 \angle \Phi$ for star connection and $3 \angle \Phi$ for delta connection.

Output voltage of the AC chopper can be expressed in Fourier series as

$$V_{de} = A_o + \sum_{n=1}^{\infty} A_n \cos n\omega_s t + B_n \sin n\omega_s t \tag{7}$$

where

$$A_o = \frac{1}{2\pi} \int_{\alpha_1, \alpha_3 \ldots, \alpha_1 + \frac{2\pi}{3}, \ldots, \alpha_1 + \frac{4\pi}{3}}^{\alpha_2, \alpha_4 \ldots, \alpha_2 + \frac{2\pi}{3}, \ldots, \alpha_2 + \frac{4\pi}{3}} \sin\theta \, d\theta$$

$$= \frac{1}{2\pi} \sum_{m=1}^{P} (-1)^{m+1} \left(\cos\alpha + \cos\left(\alpha + \frac{2\pi}{3}\right) + \cos\left(\alpha + \frac{4\pi}{3}\right) \right) \tag{8}$$

where P = no. of switching angles per 1/3 cycle
As,

$$\cos\alpha + \cos\left(\alpha + \frac{2\pi}{3}\right) + \left(\alpha + \frac{4\pi}{3}\right) = 0$$

Hence

$$A_o = 0 \tag{9}$$

The fundamental cosine component is

$$A_1 = \frac{1}{\pi}\int_{\alpha_1, \alpha_3, \ldots, \alpha_1 + \frac{2\pi}{3}, \ldots, \alpha_1 + \frac{4\pi}{3}}^{\alpha_2, \alpha_4, \ldots, \alpha_2 + \frac{2\pi}{3}, \ldots, \alpha_2 + \frac{4\pi}{3}} \sin\theta\cos\theta\, d\theta \tag{10}$$

$$= \frac{1}{4\pi}\sum_{m=1}^{P}(-1)^{m+1}\left[\cos 2\alpha_m + \cos 2\left(\alpha_m + \frac{2\pi}{3}\right) + \cos 2\left(\alpha_m + \frac{4\pi}{3}\right)\right]$$

As

$$\cos 2\alpha + \cos 2\left(\alpha + \frac{2\pi}{3}\right) + \cos 2\left(\alpha + \frac{4\pi}{3}\right) = 0$$

thus

$$A1 = 0 \tag{11}$$

The fundamental sine component is

$$B_1 = \frac{1}{\pi}\int_{\alpha_1, \alpha_3, \ldots, \alpha_1 + \frac{2\pi}{3}, \ldots, a_1 + \frac{4\pi}{3}}^{\alpha_2, \alpha_4, \ldots, \alpha_2 + \frac{2\pi}{3}, \ldots, \alpha_2 + \frac{4\pi}{3}} \sin^2\theta\, d\theta$$

$$= \frac{1}{2\pi}\sum_{m=1}^{P}(-1)^{m}\left[3\alpha_m - \frac{1}{2}\left[\sin 2\alpha_m + \sin 2\left(\alpha_m + \frac{2\pi}{3}\right) + \sin 2\left(\alpha_m + \frac{4\pi}{3}\right)\right]\right] \tag{12}$$

$$= \frac{3}{2\pi}\sum_{m=1}^{P}(-1)^{m}\alpha_m$$

Cosine component of the nth harmonic is

$$A_n = \frac{1}{\pi}\int_{a_1, a_3, \ldots, a_1 + \frac{4\pi}{3}}^{a_2, a_4, \ldots, a_2 + \frac{4\pi}{3}} \sin\theta\cos n\theta\, d\theta$$

$$= \frac{1}{2\pi}\sum_{m=1}^{P}(-1)^{m+1}\left[\frac{1}{1-n}\left\{\cos(1-n)\alpha_m + \cos(1-n)\left(\alpha_m + \frac{2\pi}{3}\right) + \cos(1-n)\left(\alpha_m + \frac{4\pi}{3}\right)\right\}\right. \tag{13}$$

$$\left. + \frac{1}{1+n}\left\{\cos(1+n)\alpha_m + \cos(1+n)\left(\alpha_m + \frac{2\pi}{3}\right) + \cos(1+n)\left(\alpha_m + \frac{4\pi}{3}\right)\right\}\right]$$

By simplifying gives

$$A_n = \frac{3}{2\pi}\sum_{m=1}^{P}(-1)^{m+1}\left[\frac{1}{1-n}\cos(1-n)\alpha_m \cdot \frac{(n+1) \bmod 3}{2} + \frac{1}{1+n}\cos(1+n)\alpha_m \cdot (n-1) \bmod 3\right]$$

$$\text{for } n = 3i \pm 1 \qquad i = 1, 2, 3, \ldots \tag{14}$$

$$A_n = 0 \qquad \text{for } n = 3i$$

In similar way sine component of the nth harmonic can be expressed as

$$B_n = \frac{3}{2\pi}\sum_{m=1}^{p}(-1)^m \left[\frac{1}{1-n}\sin(n-1)\alpha_m \cdot \frac{(n+1)\bmod 3}{2} + \frac{1}{1+n}\sin(1+n)\alpha_m \cdot (n-1)\bmod 3\right]$$

$B_n = 0$ for $n = 3i \pm 1$

for $n = 3i$ (15)

Time Ratio Control

In this technique the switching function f_{swm} is generated by comparing control signal v_c with the saw tooth signal v_t as shown in Fig.3.

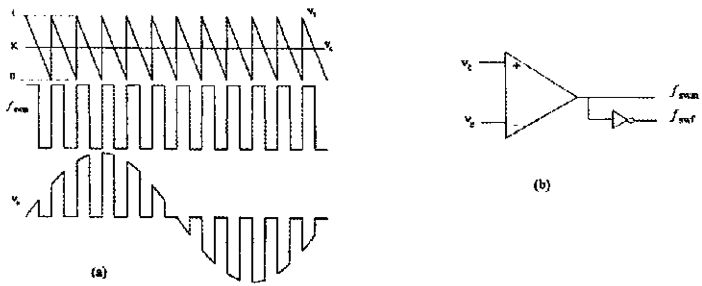

Fig. 3. Time ratio control switching signal.
(a) waveforms (b) model

To fulfill the requirement of symmetry the frequency of f_{swm} should be

$\omega_{swm} = 3i\,\omega_s$ where i is a positive integer

The output voltage may be expressed as

$$v_{de} = f_{swm}\, v_{ab} \quad (16)$$

$$v_{cf} = f_{swm}\, v_{bc} \quad (17)$$

$$v_{fd} = f_{swm}\, v_{ca} \quad (18)$$

F_{swm} may be expressed in Fourier series [6]

$$f_{swm} = K + \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\sin(nk\pi)\cos(nr\omega_s t - nk\pi) \quad (19)$$

where,

K is the time ratio

$r = \omega_C/\omega_S$ = frequency ratio

Therefore, from (4) and (19) the output voltage is

$$V_{dc} = K\sin(\omega_s t) + \frac{1}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\sin(nk\pi) \left[\sin((nr+1)\omega_s t - nk\pi) - \sin((nr-1)\ \omega_s t - nk\pi)\right] \quad (20)$$

$$V_{ef} = K\sin\left(\omega_S t - \frac{2\pi}{3}\right) + \frac{1}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\sin(nk\pi) \left[\sin\left((nr+1)\left(\omega_S t - \frac{2\pi}{3}\right) - nk\pi\right) - \sin\left((nr-1)\left(\omega_S t - \frac{2\pi}{3}\right) - nk\pi\right)\right] \quad (21)$$

$$V_{fd} = K\sin\left(\omega_S + \frac{2\pi}{3}\right) + \frac{1}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\sin(nk\pi) \left[\sin\left((nr+1)\left(\omega_S t + \frac{2\pi}{3}\right) - nk\pi\right) - \sin\left((nr-1)\left(\omega_S t + \frac{2\pi}{3}\right) - nk\pi\right)\right] \quad (22)$$

Equations (20-22) reveal the following features of this technique.

i) The fundamental component of output voltage is in phase with the input voltage.
ii) The amplitude of the fundamental component of output voltage depends only on K with linear relation between them.
iii) Harmonics are of order = $ir \pm 1$, with peak value $-(\sin nk\pi)/i$.
iv) Increasing r shifts the lowest harmonics far from the fundamental, making it easy to filter the output current.

The rms value of the output voltage can be expressed as

$$V_{ms} = \left[\frac{1}{2\pi}\int_0^{2\pi} v^2\ de\, d\theta\right] \qquad pu \quad (23)$$

$$= \left[\frac{1}{2\pi}\int_{\alpha_1,\alpha_3,\ldots}^{\alpha_2,\alpha_4,\ldots} 2\sin^2\theta\, d\theta\right]^{0.5}$$

from (12) and (23)

$$V_{rms} = \sqrt{b_1} = \sqrt{K} \qquad \text{pu} \tag{24}$$

Also the harmonic voltage is

$$V_h = \sqrt{V_{rms}^2 - V_1^2} = \sqrt{K(1-K)} \qquad \text{pu} \tag{25}$$

Load current in the case of delta connection may be expressed as

$$i_{de} = \frac{K}{Z}\sin(\omega_s t - \phi) + \frac{1}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\sin(nk\pi)\left[\frac{\sin(m\omega_s t - \alpha_m)}{Z_m} - \frac{\sin(j\omega_s t - \alpha_j)}{Z_j}\right] \tag{26}$$

$$i_{ef} = i_{de}(\omega_s t - 2\pi/3)$$
$$i_{fd} = i_{de}(\omega_s t - 4\pi/3)$$

where

$$Z_j = Z[\cos^2\Phi + (j\sin\Phi)^2]^{0.5}$$
$$\Phi_j = \tan^{-1} j\sin\Phi/\cos\Phi = \tan^{-1}(j\tan\Phi)$$
$$m = nr + 1\ ;\ j = nr - 1\ ;\ \alpha_m = nK\pi + \Phi_m\ ;\ \alpha_j = nK\pi + \Phi_j$$

In the case of star connection, phase voltages should be derived from line voltage expressions. Then, phase currents can derived.

Output line current in the case of delta connection is

$$i_d = i_{de} - i_{fd} \tag{27}$$

Also, the supply line current may be found from

$$i_a = f_{swm}\, i_d \tag{28}$$
$$i_b = f_{swn}\, i_e \tag{29}$$
$$i_c = f_{swm}\, i_f \tag{30}$$

Output Characteristics

Harmonic contents of the output voltage of the AC chopper operating under TRC technique can be calculated using (20). The first harmonics are of the order r-1,r+1,2r-1 and 2r+1 as shown in Fig. 4. The first two harmonics reach to their maximum value of 0.38 pu at K=0.5. The harmonic factor of output voltage is

$$HF_v = \frac{V_h}{V_i} \tag{31}$$

From (24-25) and (31)

$$HF_v = \sqrt{\frac{1}{K} - 1} \tag{32}$$

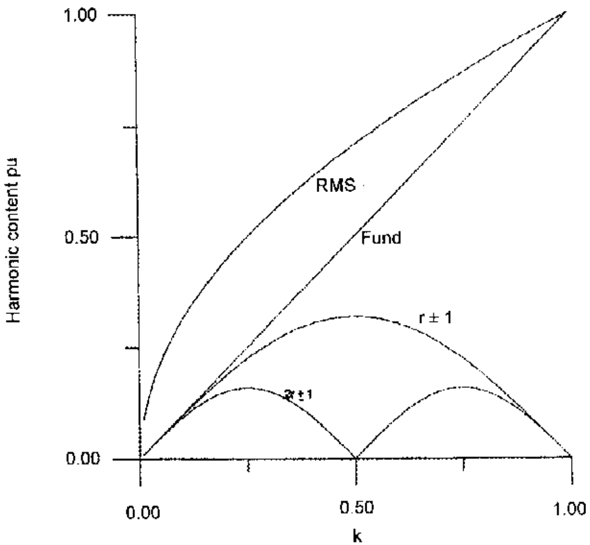

Fig. 4. Harmonic contents of the output voltage.

Output current harmonics are reduced when the AC chopper is connected to an R-L load. As the rms value of harmonics decrease hence the rms value of the output current approaches the fundamental as shown in Fig.5. Increasing the load angle makes more suppression on the harmonics of the output current and hence leads to decrease in the HF as shown in Fig. 6.

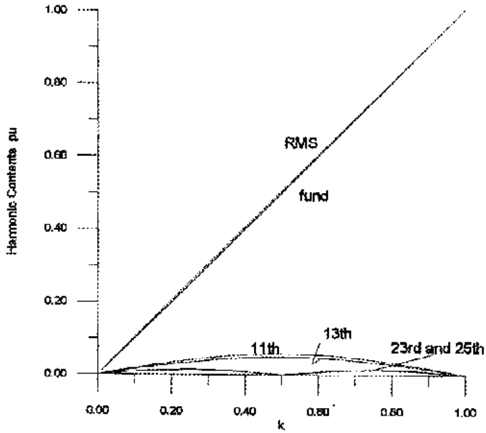

Fig. 5. Harmonic contents of output current for inductive load with phase angle = 30°.

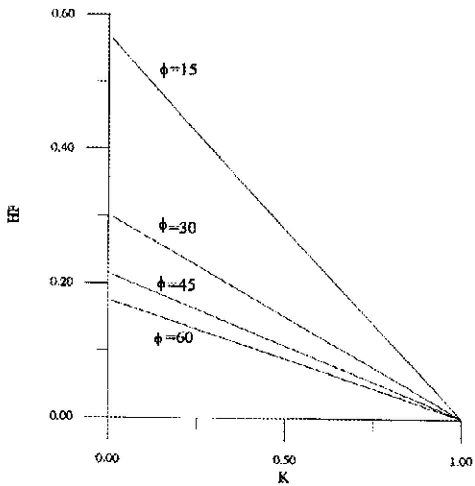

Fig. 6. HF of output current.

Input Characteristics

The harmonic contents of the supply current are shown in Fig.7. Dominant harmonics are of order r ± 1. Relations between the dominant harmonics and K for different load angles are shown in Figs. 8 and 9. It could be noted that the value of the harmonics decreases with increasing the load angle. The rms value of the supply current increases with decrease in the load angle as shown in Fig.10. As a result the HF is better in the case of lower load angles as shown in Fig.11.

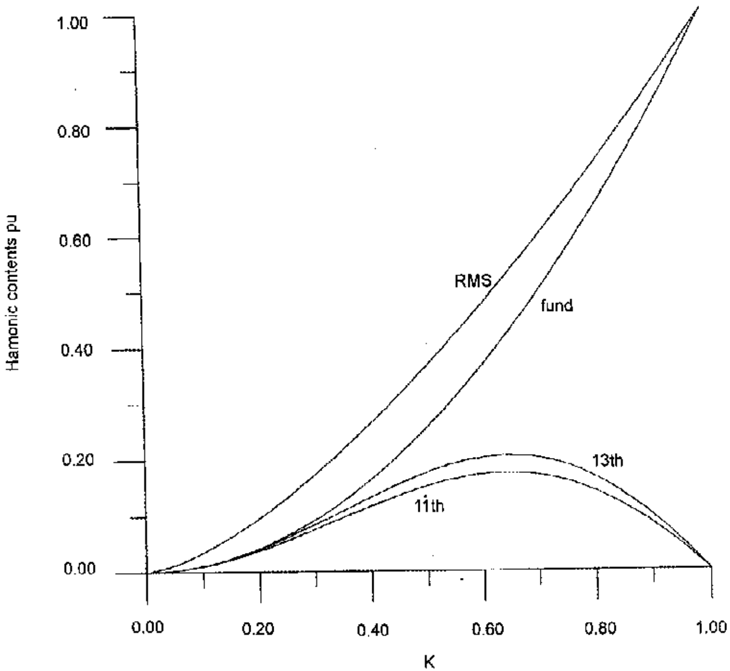

Fig. 7. Harmonic contents of supply current for inductive load with phase angle = 30°.

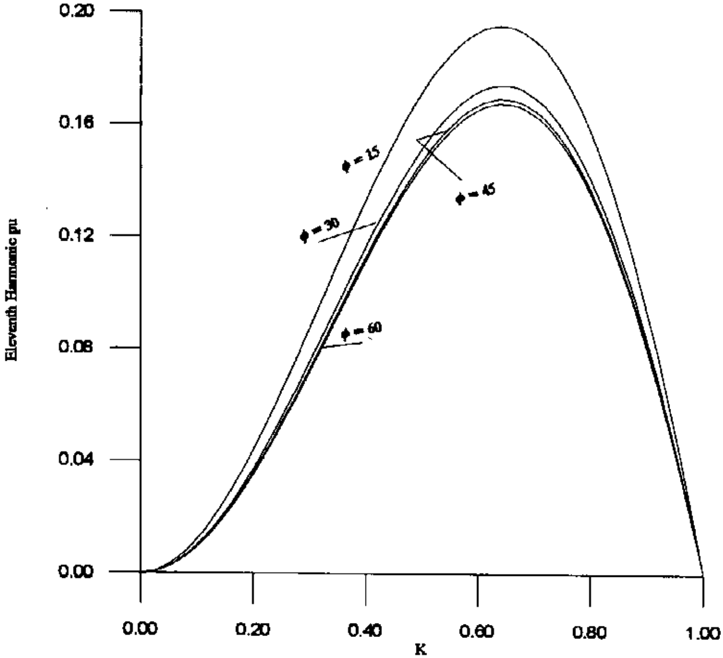

Fig. 8. RMS value of the 11th harmonic in supply current.

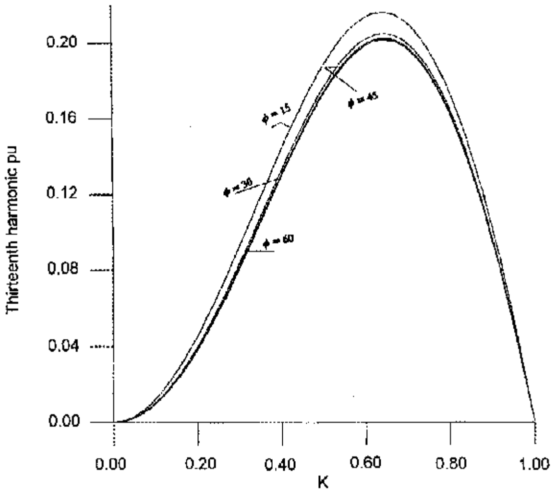

Fig. 9. RMS value of the 13th harmonic in supply current.

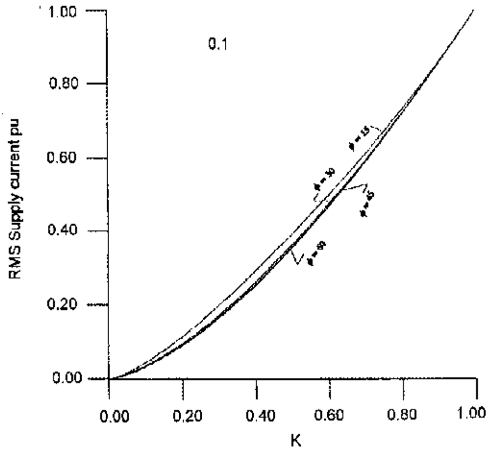

Fig. 10. RMS of the supply current.

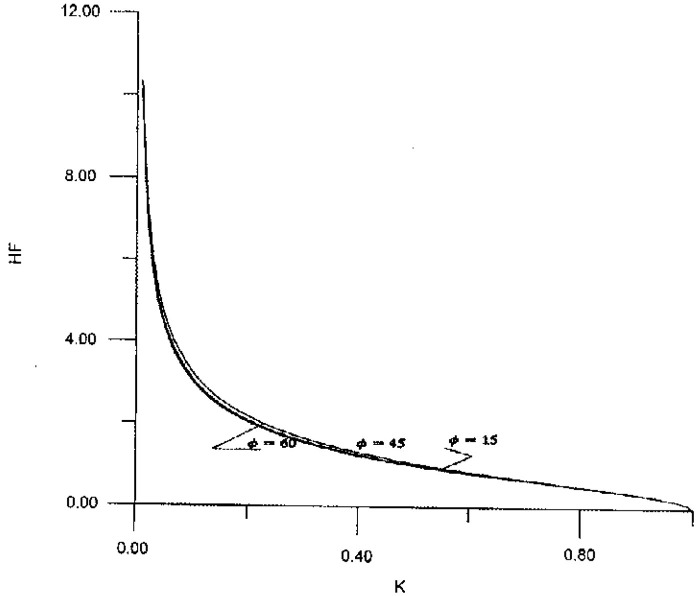

Fig. 11. HF of the supply current.

The power factor (PF) of the supply current, which is defined as

$$PF = \frac{3V_s I_{s1} Cos(\psi_1)}{3\,V_s I_{rms}} \tag{33}$$

where

V_s is the value of the supply phase voltage

I_{s1} is the fundamental component of the supply current

I_{rms} is the rms value of the supply current

ψ_1 is the phase angle of the fundamental component of the supply current

Relation between PF and K at different loads is shown in Fig. 12.

Experimental Results

To check the validity of the computed results, the three-phase AC chopper circuit has been tested. Power MOSFETs were used as the AC switches of the three-phase AC chopper. The gate of the MOSFET is driven by the emitter-follower circuit as shown in Fig. 12. Simulated and experimental results are shown in Fig. 13 which show good agreement between computed and experimental results.

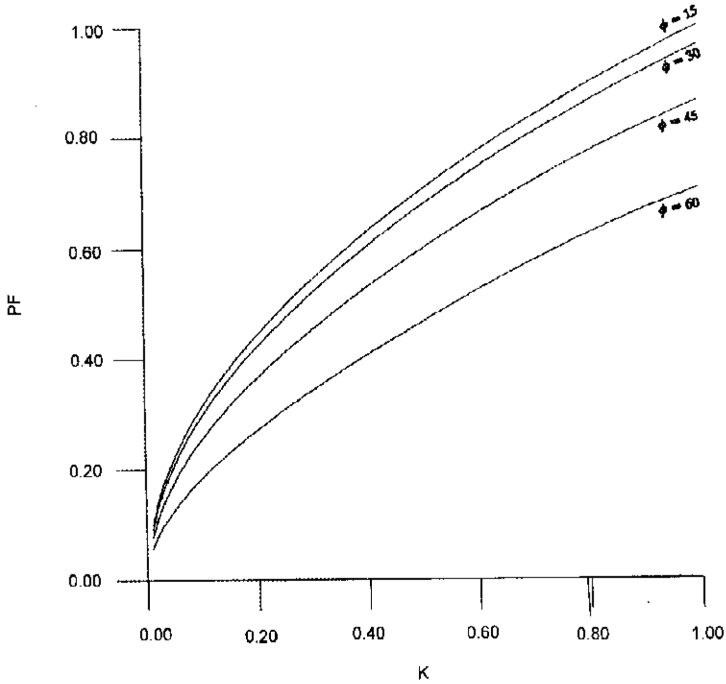

Fig. 12. PF of the supply current.

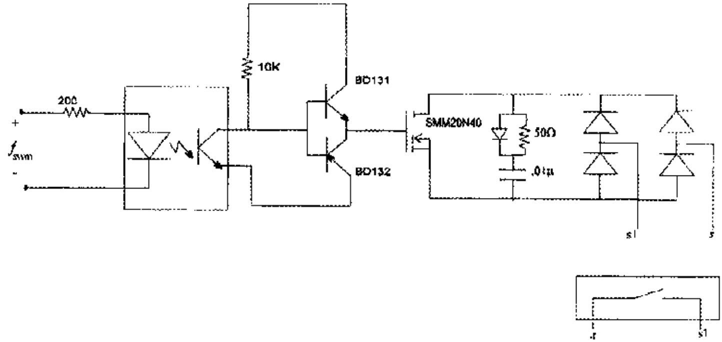

Fig. 13. AC power switch.

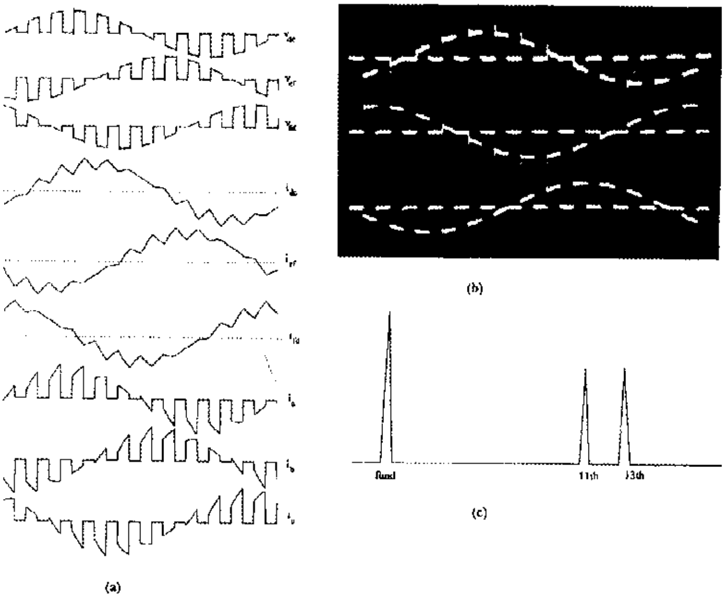

Fig. 14. Simulated and experimental results for r = 12 and K = 0.5: (a) simulated results; (b) experimental output voltage; (c) spectrum of experimental output voltage.

Conclusion

In this paper a general technique to control different configurations of the three phase AC chopper circuits is presented. In this technique two control signals are used to control the switches of the circuit. Harmonic analysis of the chopper performance is presented. Time ratio control (TRC) technique with a multiple of 3 frequency ratio is proposed. TRC technique has been found to give linear relation between the fundamental component of the output voltage and K also the low order harmonics are eliminated. Detailed analysis of the performance of the AC chopper under this control strategy has been given.

Experimental tests on the AC chopper circuit with the power MOSFETs used as the power switches were performed. Test results were observed to be in good agreement with relevant simulated ones.

Acknowledgment. The author acknowledges the assistance of Dr. A. S. Ahmed.

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مقطّع جهد ثلاثي الطور محكوم نسبةِ الوقت

خالد بن إبراهيم الدويش

قسم الهندسة الكهربائية ، كلية الهندسة ، جامعة الملك سعود ، ص ب ٨٠٠ ،
الرياض ١١٤٢١ ، المملكة العربية السعودية

(استلم في ١٩٩٨/٣/٢٣م ، وقبل للنشر في ١٩٩٨/٦/١٦م)

ملخص البحث. يعرض هذا البحث طريقة قفلٍ للتحكم بدائرة مقطّع الجهد ثلاثي الطور. تلك الطريقة يمكن استخدامها مع هيئات مختلفة من دوائر مقطّع الجهد المتردد. كما يقدم هذا البحث بالتفصيل تحليل التوافقيات لمقطّع الجهد المتردد حين التحكم بنسبة الوقت. تعطي استراتيجية التحكم بنسبة الوقت مزية العلاقة الخطّية لمركّبة الجهد الأساسية مع إلغاء كافة التوافقيات ذات الرتبة الأقل من نسبة التردد باثنين. إضافة إلى سهولة توليد نبضات القفل. و يعطي هذا البحث نتائج معملية للتحقق من النتائج التحليلية.