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A COMPARATIVE STUDY ON AC VOLTAGE CONTROLLERS IN TERMS OF HARMONIC EFFECTIVENESS

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ABSTRACT

Currently, three basic types of AC/AC converters have been used in industrial applications. These are: AC voltage controllers, cycloconverters and matrix converters. The AC voltage controller, the simplest one and widely used, allows controlling the output voltage having the same frequency as the input voltage has. Also, the AC voltage controller itself branches into different topologies. In this study, a comparison on different types of AC voltage controllers in terms of harmonic effectiveness was done.

Key words: AC voltage controller, Harmonics, Converter

HARMONİK ETKİNLİK AÇISINDAN AC GERİLİM KONTROLCÜLERİNİ BİR KARŞILAŞTIRMA ÇALIŞMASI

ÖZET

Günümüzde, endüstriyel uygulamalarda üç temel tip AC/AC konverter kullanılmaktadır. Bunlar: AC gerilim kontrolcüleri, cyclokonverterler ve matris konverterlerdir. Bunların en basiti ve en yaygın türü olan AC gerilim kontrolcüleri, giriş frekansı ile aynı frekansta bir çıkış gerilimini kontrol etme imkanı sunmaktadır. AC gerilim kontrolcüleri de kendi arasında farklı türlere ayrılmaktadır. Bu çalışmada, harmonik etkinlik açısından farklı tip AC gerilim kontrolcülerinin bir karşılaştırması yapılmıştır.

Anahtar kelimeler: AC gerilim kontrolcüsü, Harmonikler, Konverter

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1. INTRODUCTION

There are three basic types of ac to ac converters. The simplest ones, the ac voltage controllers, allow controlling the output voltage only, while the output frequency is the same as the input frequency. The second one is the cycloconverter. In cycloconverters, the output frequency can be controlled, but it is at least one order of magnitude lower than the input frequency. In both the ac voltage controllers and cycloconverters, the maximum available output voltage approaches the input voltage. The last one is the matrix converter. Because of having no inherent limits on the output frequency, matrix converters are most versatile, but the maximum available output voltage is about 15% lower than the input voltage [1].

There are several topologies of the ac voltage controllers; the most commons of which are phase-angle controlled ac voltage controllers, section-controlled ac voltage controllers, sector-controlled ac voltage controllers and PWM-controlled ac voltage controllers.

The phase-angle control can be performed by using triacs with ease. After fired during positive and negative half-wave cycles individually, triac is switched on immediately and conducts load current until ac voltage passes zero. When triac is driven at $\alpha > 0$; the rest of positive and negative half-wave cycles, provided for the load, have correspondingly smaller root-mean-square value. Time profile of output voltage of triac, driven at $\alpha = 90°$ in public network, was shown in Fig. 1a.

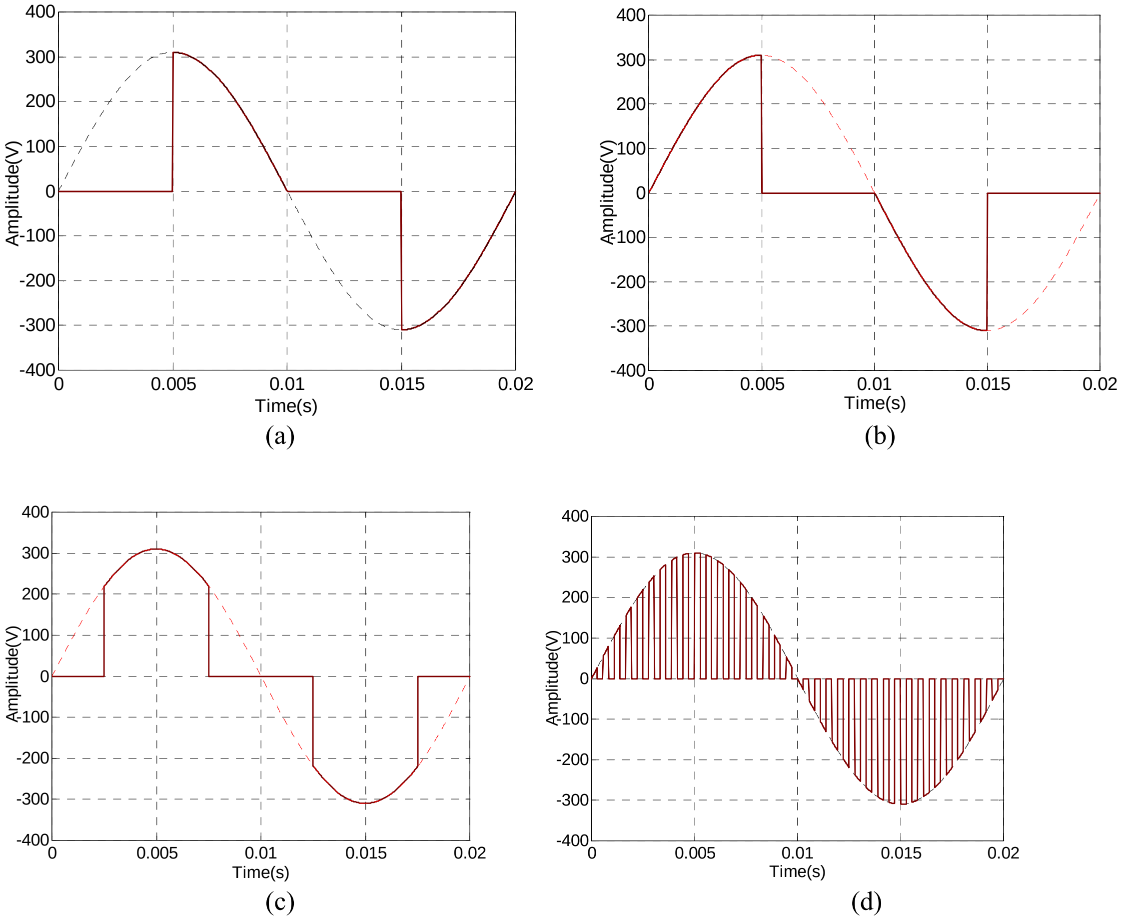
The section control, as opposed to the phase-angle control, can be performed by switching on while ac voltage passes zero and switching off at a certain angle value. As a result, the rest of the cycles are not employed. Time profile of output voltage of the section control having $0 \le \alpha \le 90°$ was shown in Fig. 1b.

The sector control uses middle sections of the positive and negative half-wave cycles, like in Fig. 1c. Positive part of this waveform is symmetric at the point of $\omega t = \pi / 2$ radians and negative part of that is symmetric at the point of $\omega t = 3\pi / 2$ radians. So, the switch must be switched on at the point of $\omega t = (\pi - \alpha) / 2$ and switched off at the point of $\omega t = (\pi + \alpha) / 2$ in positive half-wave cycle.

The PWM control, different from others totally, can be performed by cutting out numerous slices of main voltage within each switching cycle of the converter. Switching signal can be obtained by comparing an isosceles triangle carrier wave with a suitable DC voltage. The points of intersection determine the switching points of power devices. The switching frequency must be higher than the main frequency. Duty cycle (ratio) of a switch is defined as the fraction of the switching cycle during which the switch is on. Time profile of output voltage of the PWM control, operating with switching frequency of 1,8 kHz and the duty cycle of 50%, is given in Fig. 1d. The main voltage of the public network was shown by the dotted line in Fig. 1a, b, c, d.

2. ANALYSIS OF SWITCH USED IN AC VOLTAGE CONTROLLER

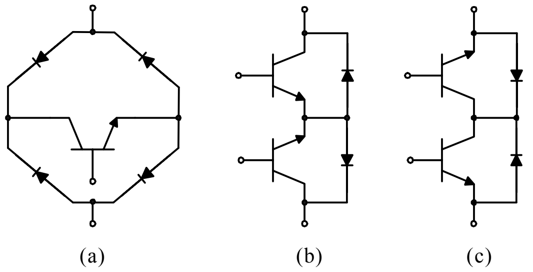
Power electronics converters can be thought as networks of semiconductor power switches. Depending on the type, the switches can be uncontrolled, semi-controlled, or fully-controlled. All controllable electrical switching devices can be used for contact-free switching or continuous control of electrical energy. Thyristors (SCRs) and triacs, semi-controlled switches, have been the traditional workhorses for bulk power conversion and control in industry. Phase-controlled converters employ pairs of SCRs or triacs. A pair of thyristors connected in anti-parallel on the same chip constitutes a triac. The device can be triggered into conduction in both positive and negative half-cycles of supply voltage by applying gate trigger pulses. A triac is more economical than a pair of thyristors in anti-parallel and its control is simpler, but its integrated construction has some disadvantages (longer turn-off time, poorer gate current sensitivity, lower dv/dt rating) [2,3]. The rest of ac voltage converters require fully controlled power switches capable of conducting current in both directions (bi-directional). Such switches can be assembled from power transistors (BJT, GTO, MOSFET, IGBT, etc.) and diodes.



(a) (b) (c) (d)

Figure 1. Time profile of output voltage of different types of AC voltage controllers, a) Phase-angle control, b) Section control, c) Sector control, d) PWM control.

There are three ways to obtain a bi-directional switch: the diode-embedded unidirectional switch (Fig. 2a), the two common-emitter unidirectional switches (Fig. 2b), and the two common-collector unidirectional switches (Fig. 2c). Though the diode-embedded switch requires only one gate driver and one active switch, it causes higher conduction losses. The two others relatively allow for lower conduction losses, but require two gate drivers.



(a) (b) (c)

Figure 2. Bi-directional switch configurations, a) the diode-embedded, b) the two common-emitter, c) the two common-collector.

3. HARMONICS AND THD

Ac voltage controllers draw distorted currents from the supply line and hence, generate harmonics, and their input power factor is also poor. The harmonic currents generated by the power electronics related-equipment flow through the utility system and cause various power quality problems. The distorted current flowing through line source inductance distorts the distribution bus voltage. The non-sinusoidal bus voltage may create a problem on sensitive loads operating on the same bus. Additionally, harmonic currents create additional loading and losses in line equipment, such as generator, transmission, and distribution lines, transformers and circuit breakers. The harmonics also give error in meter reading, protective relay malfunction, and can cause spurious line resonance with distributed inductance and capacitance parameters [2].

According to the Fourier analysis, every periodic waveform can be treated as the sum of one or several sinusoidal waveforms of different frequencies, i.e. the fundamental frequency and multiples of the fundamental frequencies. The current harmonics are non-desired by-product produced at switched operation of the switches. In electrical systems, the harmonic effectiveness of a non-linear load can be expressed with “Total Harmonic Distortion (THD)”. For distorted current waveform, THD value can be calculated with Eq.1.

$$THD(I) = \sqrt{\frac{I_2^2 + I_3^2 + I_4^2 + I_5^2 + ...}{I_1^2}} \cdot 100 \tag{1}$$

where the indices represent harmonic orders [4,5,6].

4. MATERIAL AND METHOD

In this study, Matlab is chosen as the programming tool primarily because of interactive mode of work, immediate graphics facilities, built-in functions, the possibility of adding user-written functions and simple programming. Matlab is a matrix-based software for scientific and engineering numeric computation and visualization [7].

To define and graph input-output currents and voltages of all ac voltage controllers, a total of 360 data was employed in one-period time. PWM controlled ac voltage controller has a switching frequency of 1,8 kHz. Output currents and voltages are calculated a degree interval of 10° in phase-angle, section and sector control, and a duty-cycle interval of 10% in PWM control.

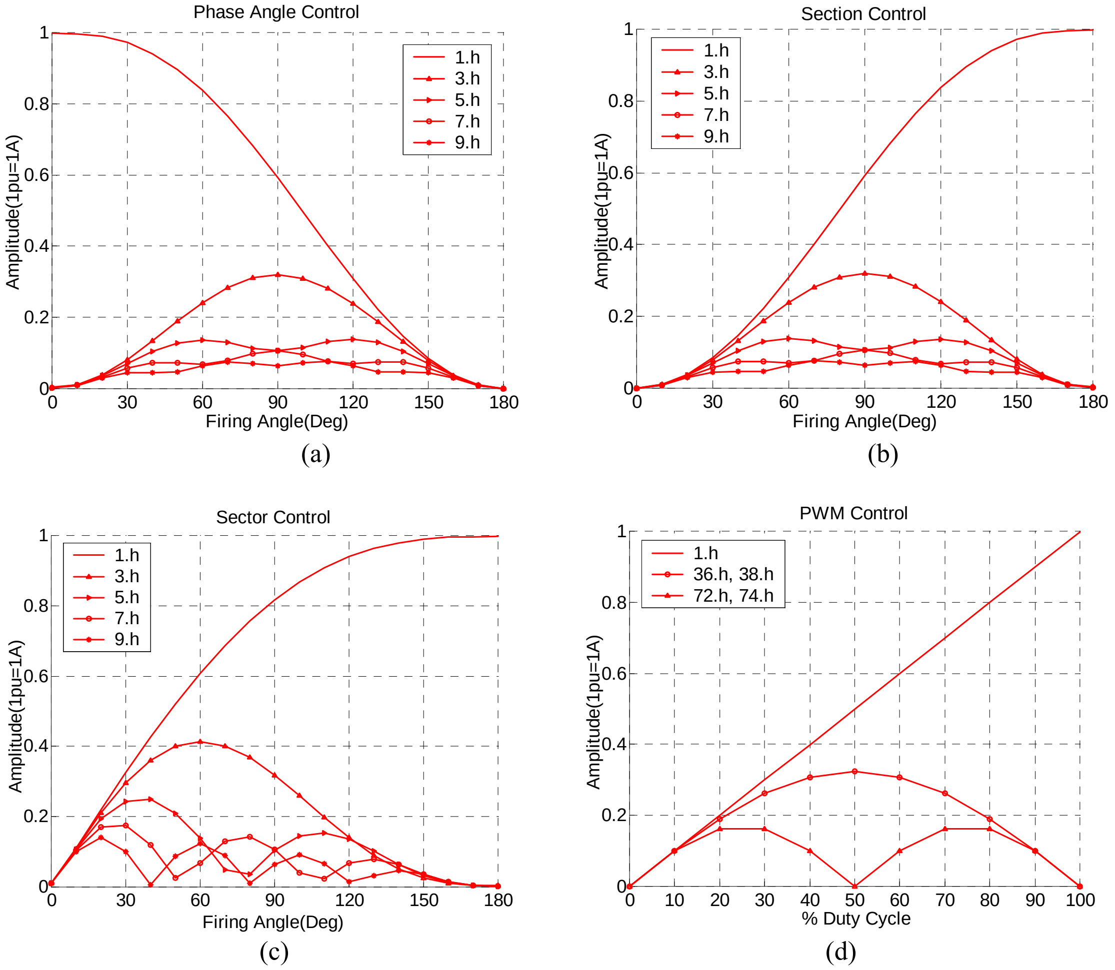
The main supply line is considered having a maximum value of 310 V, a frequency of 50Hz and not containing any harmonics. All of the ac voltage controllers in question are considered feeding a pure resistive load of 310 Ω. So, maximum value of the load current would be 1A; hence, the results obtained numerically and graphically can be compared with each other easily in per-unit system.

The Discrete Fourier Transform (DFT), used to operate on discrete (digitized) data, are employed to perform harmonic analysis. The DFT assumes the time domain waveform is a periodic function, with a period of *n* points. The normalized frequency at the first DFT point is 0 and at the last point is $2\pi(n-1)/n$ radians. The maximum frequency is $(n-1)/dt$, so the time domain sampling is normalized to $dt = n/2\pi$ [6]. To calculate THD values at different controllers and firing angles, a total of 19 harmonics is taken into account [8,9].

5. RESULTS

After attaining the data about output currents with a degree interval of 10° and a duty-cycle interval of 10%, harmonic analysis was performed by means of DFT. As a function of firing angle and duty-cycle, the amplitudes of harmonic orders are given in Fig. 3a, b, c, d graphically. The even-order harmonics are not shown in Fig. 3a, b, c because of being zero. As control strategies, both phase-angle control and section control are very similar due to using same parts of sinusoidal ac voltage. Therefore, the result of harmonic analysis must be the same. Fig. 3a and Fig. 3b verify this assumption. In according to those figures, all amplitudes of harmonics are equal symmetrically. The result of harmonic analysis of the sector control, given in Fig. 3c, are different from previous control methods in terms of amplitudes and alteration of harmonics.

With regard to PWM control, the result of harmonic analysis, given in Fig. 3d, are totally different from others because there is no low-order harmonics except first-order. High order harmonics are related to switching operation and occur around switching frequency (1800/50Hz=36) and multiples of switching frequencies. Those high-order harmonics, in contrast to low-order harmonics, can be filtered out easily by using high-pass LC filter circuitry. In according to Fig. 3d, the amplitude of first-order harmonic, fundamental frequency, changes with duty-cycle proportionally.



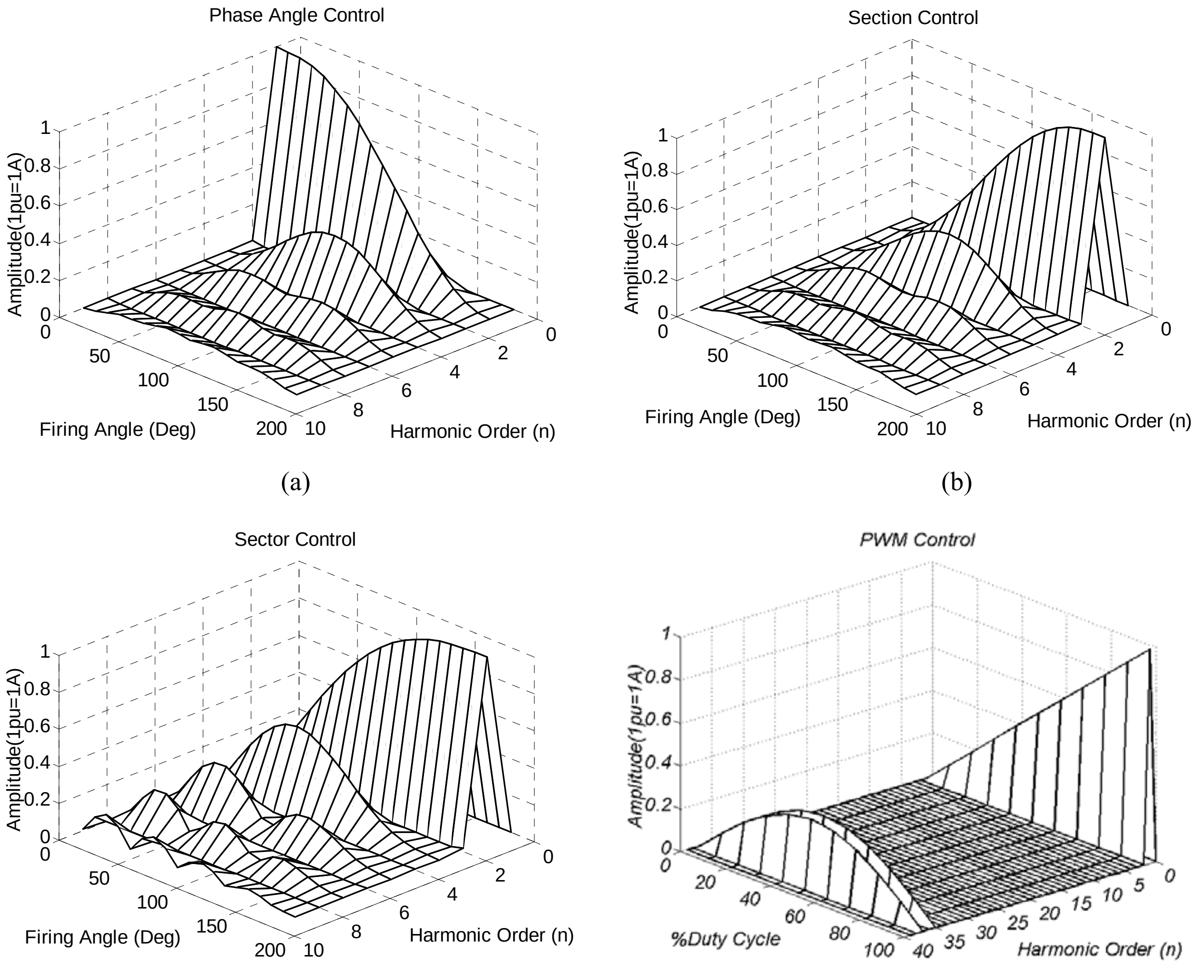
(a) (b)

(c) (d)

Figure 3. The amplitudes of harmonics versus firing angle or duty cycle, a) Phase-angle control, b) Section control, c) Sector kontrol, d) PWM control.

In contrast to showing the results of harmonic analysis conventionally (two dimentional, like in Fig. 3), the results can also be represented as a surface in 3D space for each operating point. Such an approach can express harmonic analysis more clearly than 2D can. For this reason, this method can be prefered for some applications. The three dimentions are: the firing angle (or duty-cycle) in Degree (or Percentage), the amplitudes of harmonics in Amperes and the harmonic orders.

After defining load current and precalculating the harmonics at each firing angle (or duty-cycle), a matrix containing amplitude of harmonics is constructed. Then, the second matrix, same size with the first matrix and containing harmonic order, is defined; and then, the third matrix, also same size with the first matrix and containing firing angles, is formed. The second matrix has same rows, and the third matrix has same columns. By means of those three matrixes, the results of harmonic analysis can be displayed in 3D space (Fig. 4).



(a) (b)

(c) (d)

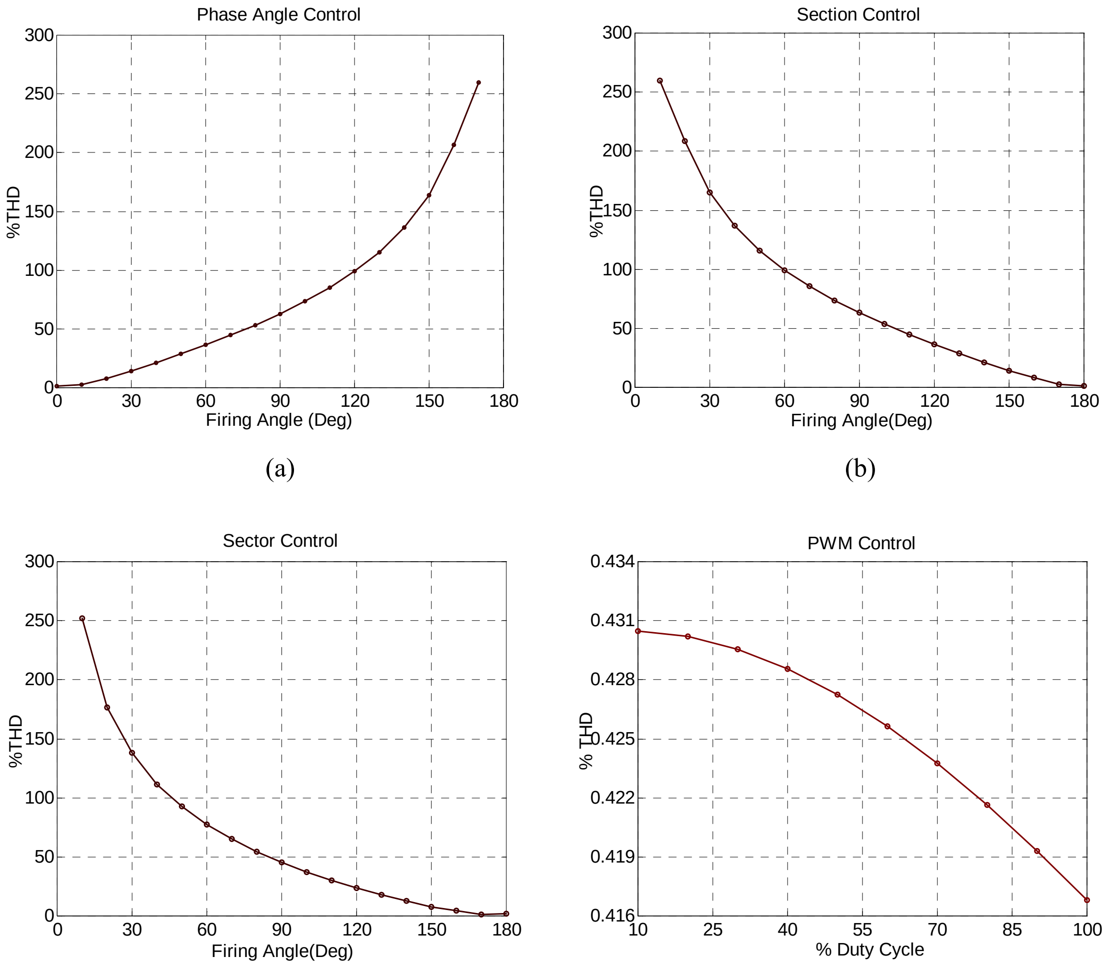
Figure 4. The 3D representation of result of harmonic analysis, a) Phase-angle control, b) Section control, c) Sector kontrol, d) PWM control.

After harmonic analysis, THD values can be calculated with the aid of Eq.1. In according to THD standards, a total of 19 harmonics is enough to obtain an acceptable THD value. The tables of THD values (Tables 1, 2, 3, 4) and their graphs (Fig. 5a, b, c, d) belong to phase-angle control, section control, sector control and PWM control, respectively. In PWM control, high order harmonics are considered being filtered out.

Table 1. THD values of the phase-angle control.

Firing(Deg)	0	10	20	30	40	50	60	70	80
%THD	0	2.617	7.9499	14.175	21.149	28.51	36.342	44.571	53.405
Firing(Deg)	90	100	110	120	130	140	150	160	170
%THD	62.901	73.424	85.191	98.932	115.26	136.11	163.57	206.37	259.58

As can be seen in Fig. 5a, b; THD alteration of the phase-angle control and section control is symmetrically the cted. THD alteration of sector control is similar to that of section control. PWM control contains asame, as expelmost non-harmonics.



(a) (b)

(c) (d)

Figure 5. THD graphs, a) Phase-angle control, b) Section control, c) Sector control, d) PWM control.

Table 2. THD values of the section control.

Firing(Deg)	10	20	30	40	50	60	70	80	90
%THD	259.59	206.37	163.57	136.1	115.26	98.932	85.191	73.424	62.9
Firing(Deg)	100	110	120	130	140	150	160	170	180
%THD	53.405	44.57	36.342	28.509	21.149	14.175	7.95	2.617	0

Table 3. THD values of the sector control.

Firing(Deg)	10	20	30	40	50	60	70	80	90
%THD	252.3	176.7	138.1	111.3	92.78	77.43	65.3	54.65	45.53
Firing(Deg)	100	110	120	130	140	150	160	170	180
%THD	37.42	30.09	23.65	17.65	12.56	7.843	4.21	1.151	0

Table 4. THD values of the PWM control.

%Duty C.	10	20	30	40	50	60	70	80	90	100
%THD	0.4305	0.4302	0.4296	0.4286	0.4273	0.4256	0.4238	0.4216	0.4193	0.4168

6. CONCLUSIONS

In this paper, four different types of ac voltage controllers were compared with each other in terms of harmonic effectiveness. Phase-angle and section controlled ac voltage controllers have same harmonic spectrum and THD values symmetrically. The sector controlled ac voltage controllers have lower THD values than phase-angle or section control have relatively (Fig. 6). PWM controlled ac voltage controllers have certainly the best results because of not containing any lower harmonics and having minimum THD values. In addition to those results, a new point of view of showing harmonic analysis results, 3D harmonic analysis, is proposed in this study.

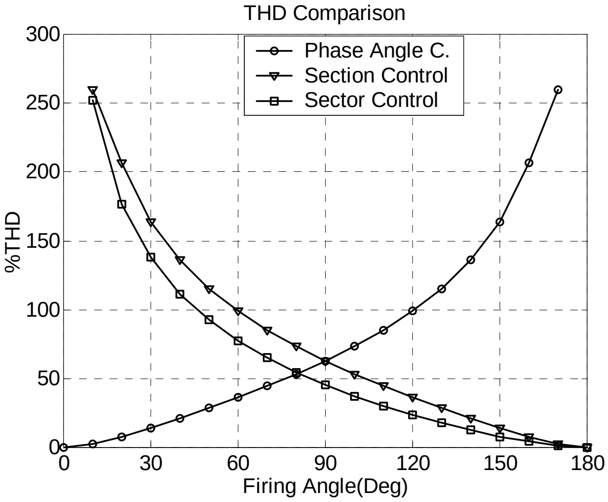


Figure 6. THD comparison of different types of AC voltage controllers.

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