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Full Length Research Paper

A new method for power quality improvement in classical AC/AC voltage controllers using PWM technique

Ahmet Altintas

Department of Electronics and Computer Education, Dumlupinar University, Kutahya, Turkey.
E-mail: a_altintas@dumlupinar.edu.tr. Tel: 90 274 513 7917. Fax: 90 274 513 7914.

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A lot of topologies of pulse-width modulated (PWM)-AC voltage controllers for single-phase and three-phase systems are proposed up to date. PWM-AC controllers have important advantages compared with the phase-controlled AC voltage controllers using thyristors and triacs. This article presents a novel control technique for application to PWM-AC controllers with ability of generating smaller harmonics. In the proposed control method, both the traditional AC voltage controllers and the PWM-AC controllers are combined, smaller THD values are obtained and switching losses are minimized. Thus, the harmonic pollution in the power system will be reduced and the power quality will be increased. In order to investigate the proposed controller performance, computer simulations and experimental studies are performed. Obtained results are compared with those of the conventional PWM-AC controller.

Key words: Power quality, AC choppers, PWM-AC controllers, AC sector-control voltage converters.

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 (Bose, 2002).

AC voltage controllers are widely used to obtain variable AC voltage from fixed AC source. Triacs or thyristors are usually employed as the power control elements of such controllers. Such techniques offer some advantages as simplicity and ability of controlling large amount of power economically. However, delayed firing angle causes discontinuity and plentiful harmonics in load current, the size of the passive circuit becomes bulky and also a lagging power factor occurs at the AC side even though the load is completely resistive especially when the firing angle increases. Due to the waveform distortion, specifically at large delay angles or low cyclic pulsation, applications are often restricted to industrial heating, lighting control and starting or low range speed control of induction motors (Balci and Hocaoglu, 2005)

The switching mode power conversion gives high efficiency, but the main disadvantage is that harmonics are generated at both the supply and load sides due to the nonlinearity of switches. The harmonic currents generated by the power electronics related-equipment flow through the utility system and cause various power quality problems. Most of the power switches have different operating conditions; thus, they generate different order and different amplitude harmonics. These issues have motivated industry to better solutions that result in lower total harmonic current distortion (THD) to comply with IEEE Standard 519 - 1992 and lower electromagnetic interference (EMI). The harmonic limitations are very important issues so that power systems are

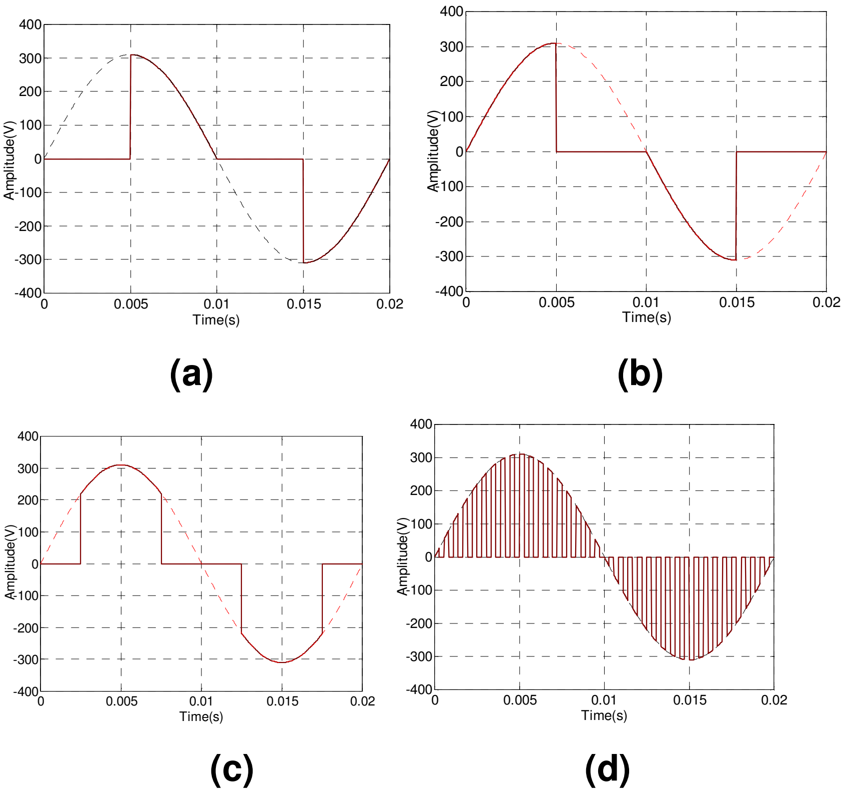


Figure 1. Time profile of output voltage of different types of AC voltage controllers, (a) phase-angle control, (b) section control, (c) sector control and (d) PWM control.

preserved from the effect of harmonic pollution (IEEE Standard (519 – 1992) 1993; Barros and Diego, 2006).

To cope with the harmonic pollution many alternative methods are proposed in the past. One of the well-known methods is the PWM control technique. The advantages of PWM technique to be gained include nearly sinusoidal input-output current/voltage waveforms, better input power factor, better transient response, elimination of the low order harmonics and consequently, smaller input-output filter parameters. On the other hand, control by switching is often accompanied by extra losses due to the switching losses (Bech, 2000; Nabil et al., 1999; Youm et al., 1999)

In this study, a novel control technique for application to PWM-AC controllers with ability of generating smaller harmonics is proposed. In the proposed control method, both the traditional AC voltage controllers and the PWM-AC controllers have been combined. As the results of this combination, smaller THD values are obtained and switching losses resulting from PWM switching are minimized. Thus, the harmonic pollution in the power system will be reduced and the power quality will be increased. The proposed method is firstly investigated by simulations and then, the experimental study is realized. Several characteristics such as the THD values, rms values and first harmonic's amplitude of the output voltage waveforms are evaluated; 3-dimensional harmonic analysis is performed. These results are compared with those of the conventional PWM method. This type of control technique is used in integral-cycle AC voltage controller before and good results have been reported in that study (Nigim and Heydt, 2002).

THEORETICAL CHARACTERISTICS OF THE TRADITIONAL AC VOLTAGE CONTROLLERS, PWM TECHNIQUE AND THD

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 and sector-controlled AC voltage controllers. The phase-angle control can be performed by using triacs with ease. 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, is shown in Figure 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. Time profile of output voltage of the section control having $0 \leq \alpha \leq 90°$ is shown in Figure 1b. The sector control uses middle sections of the positive and negative half-wave cycles, like in Figure 1c.

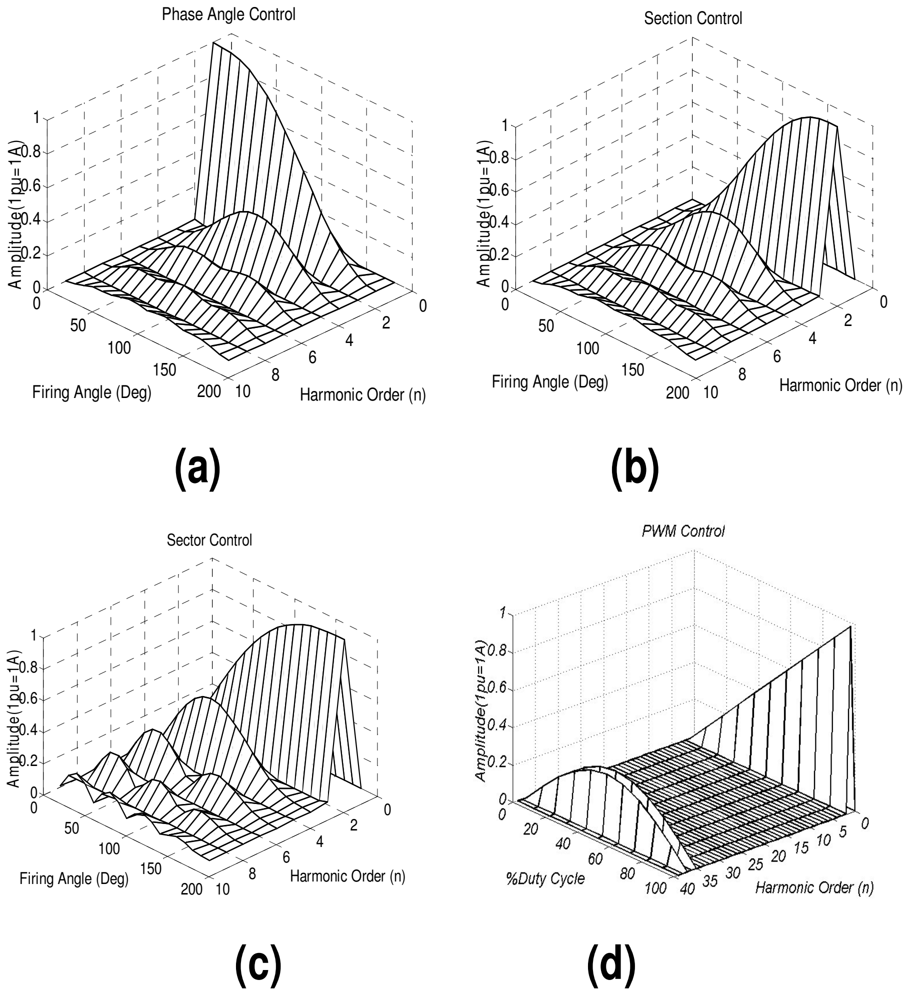


Figure 2. 3D harmonic analysis results, (a) phase-angle control, (b) section control and (c) sector control, (d) PWM control.

The PWM technique, different from other AC voltage controllers totally, can be performed by cutting out nume-rous slices of main voltage within each switching cycle of the converter. Switching signal can be obtained by com-paring 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 conventional PWM technique, operating at a switching frequency of 1.8 kHz and a duty cycle of 50%, is given in Figure 1d. The main voltage of the public network is shown by the dotted line in Figures 1a, b, c and d.

Conventionally, there are a few methods to represent harmonic analysis results. These methods use two-dimensional (2D) graphic area. For some applications with different operating conditions or parameters to be examined together, 2D graphics sometimes causes con-fusion especially when displayed too many harmonics at the same graphic area. To cope with this problem, three-dimensional (3D) graphic area representing harmonic analysis results clearly is developed in this study. 3D method represents the harmonics as a surface in 3D space. Such an approach can express harmonic analysis more clearly than 2D can. For this reason, this method can be prefered for some applications. Harmonic analysis results of the AC voltage controllers in 3D space are given in Figure 2. The three dimentions are: the triggering angle (or duty-cycle) in Degree (or Percentage), the amplitudes of harmonics in Amperes (or Voltages) and the harmonic orders (or frequencies).

Harmonic effectiveness of a non-linear load can be expressed with total-harmonic-distortion (THD). Classical AC voltage controllers have large THD values especially at small total-conduction angles. Note that the term THD used here is somewhat generalized from the usual formulation: the THD of a periodic signal is effectively the energy in the harmonics divided by the energy in the fundamental (Equation 1). The term “energy” is used as in the sense of signal processing theory.

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

where, the indices represent harmonic orders of a periodic waveforms. An extended definition of THD, given in Equation 2, can be applied in periodic or non-periodic waveforms.

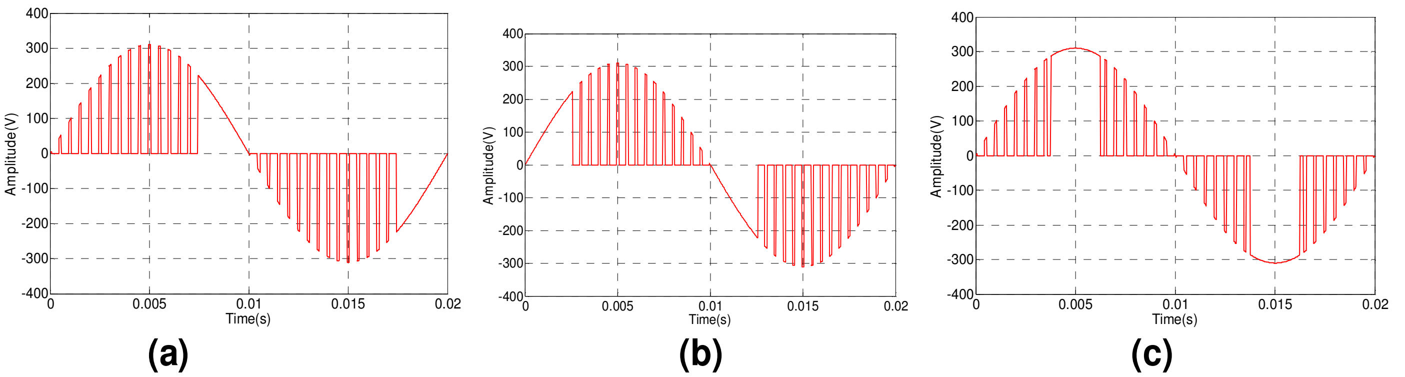


Figure 3. Output-voltage waveforms of the proposed PWM-AC controller with ohmic load ($\alpha_t = 45°$, $f_{pwm} = 2\,kHz$, duty cycle = 25%), (a) phase-angle control with PWM, (b) section control with PWM and (c) Sector control with PWM.

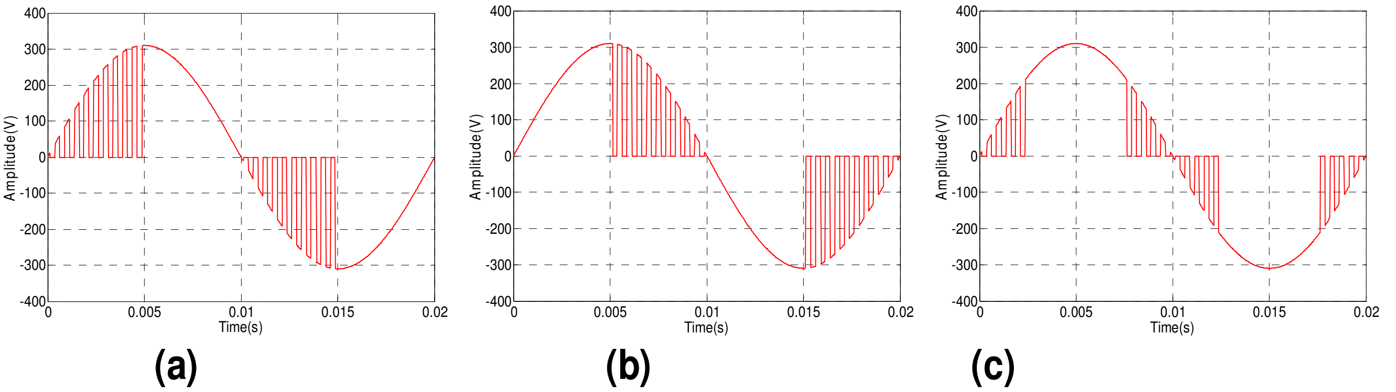


Figure 4. Output-voltage waveforms of the proposed PWM-AC controller with ohmic load ($\alpha_t = 90°$, $f_{pwm} = 2\,kHz$, duty cycle = 50%), (a) phase-angle control with PWM, (b) section control with PWM and (c) sector control with PWM.

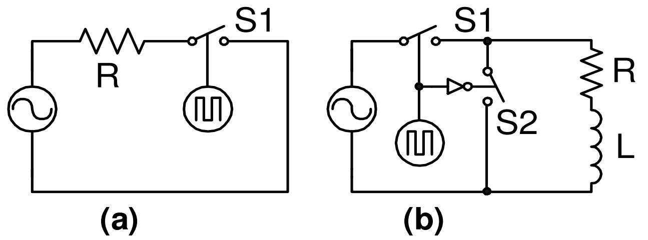


Figure 5. The schematic of power circuit used in proposed PWM-AC voltage controller, (a) resistive load power controller and (b) Inductive load power controller.

$$THD(I) = \sqrt{\frac{I_{rms}^2 - I_1^2}{I_1^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where, I_{rms} is the rms value of the load current and I_1 is the power frequency (1.harmonic) component of the current. This definition is employed for calculating THD values in this study because of simplicity.

Proposed PWM-AC controller

The main factor for harmonic producing in traditional AC voltage controllers is the discontinuity of the load voltage. In the proposed method, the discontinuity of the load voltage has been minimized by using PWM technique in the discontinuous section in which the load voltage is zero. The duty cycle of PWM is not selected as a constant value; it is directly proportional to the total conduction angle of the traditional AC voltage controllers. For example, if the total conduction angle is 45°, the duty cycle of PWM should be 25% which is calculated from 45°/180°; if the angle is 90°, the duty cycle must be 50% (90°/180°). As a result, if the conduction angle is increased from 0 to 180°, the duty cycle of PWM will be increased from 0 to 100% proportionally. Graphical representations of output-voltage waveforms of the proposed PWM-AC controller with ohmic load for total-conduction angles of 45 and 90° are given in Figures 3 and 4, respectively.

The schematic of power circuit used in the proposed PWM-AC voltage controller is given in Figure 5. The circuit topology is well known for power community. The load is connected in series with

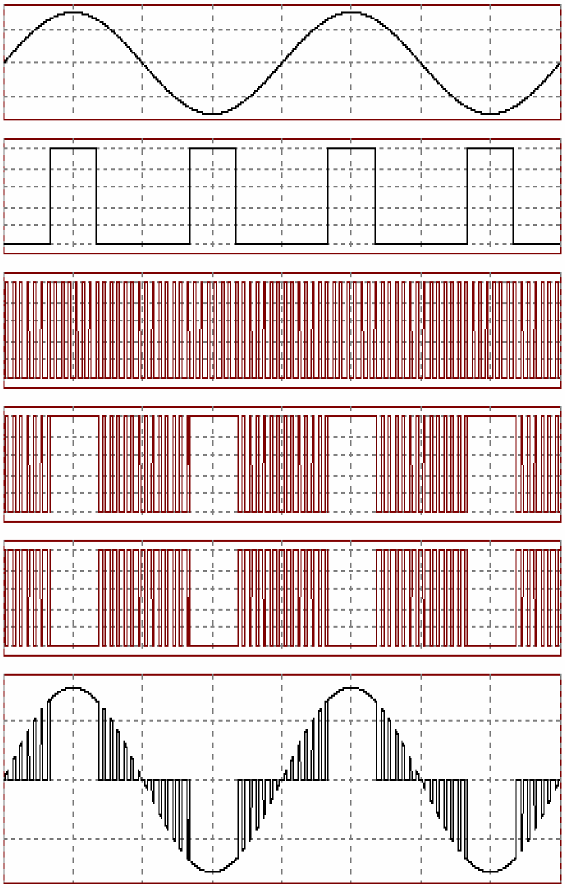


Figure 6. Basic parameters' graphs of the simulation circuit, (a) line voltage, (b) sector-control pulses only (total conduction angle = 60°), (c) PWM pulses only, (d) S1 switching pulses, (e) S2 switching pulses and (f) resultant load voltage.

the power source. The series switch S1 is used to connect or disconnect the load terminals to the supply, that is, they regulate the power delivered to the load. The parallel switch S2 provides a freewheeling path for the load current to discharge its stored energy when the series switch is turned off. The switches S1 and S2 are fully controlled power switches capable of conducting current in both directions (bi-directional). Such switches can be assembled from power transistors (BJT, MOSFET, IGBT, etc.) and diodes. There are three ways to obtain a bi-directional switch: the diode-embedded, the two-common-emitter and the two-common-collector. In this work the diode-embedded switches are employed as a power switch because it requires only one gate driver and one active switch. It also simplifies the driving circuitry.

Simulation studies are realized with SimCad package program. Basic parameters' graphs of simulation circuit of proposed method for sector control with a total-conduction angle of 60° and a PWM-frequency of 2 kHz are given in Figure 6. From top to bottom, it shows line voltage, sector-control pulses, pwm pulses, S1 switching pulses, S2 switching pulses and resultant load voltage. Naturally, if the load type is selected as purely resistive, switch-S2 can be eliminated. Sector-control strategy has less harmonic effectiveness than both phase-angle con-trol and section control have (Altintas, 2005). Therefore, the study is focused on it. Also, the circuitry used for obtaining switching signals for sector control is very simple.

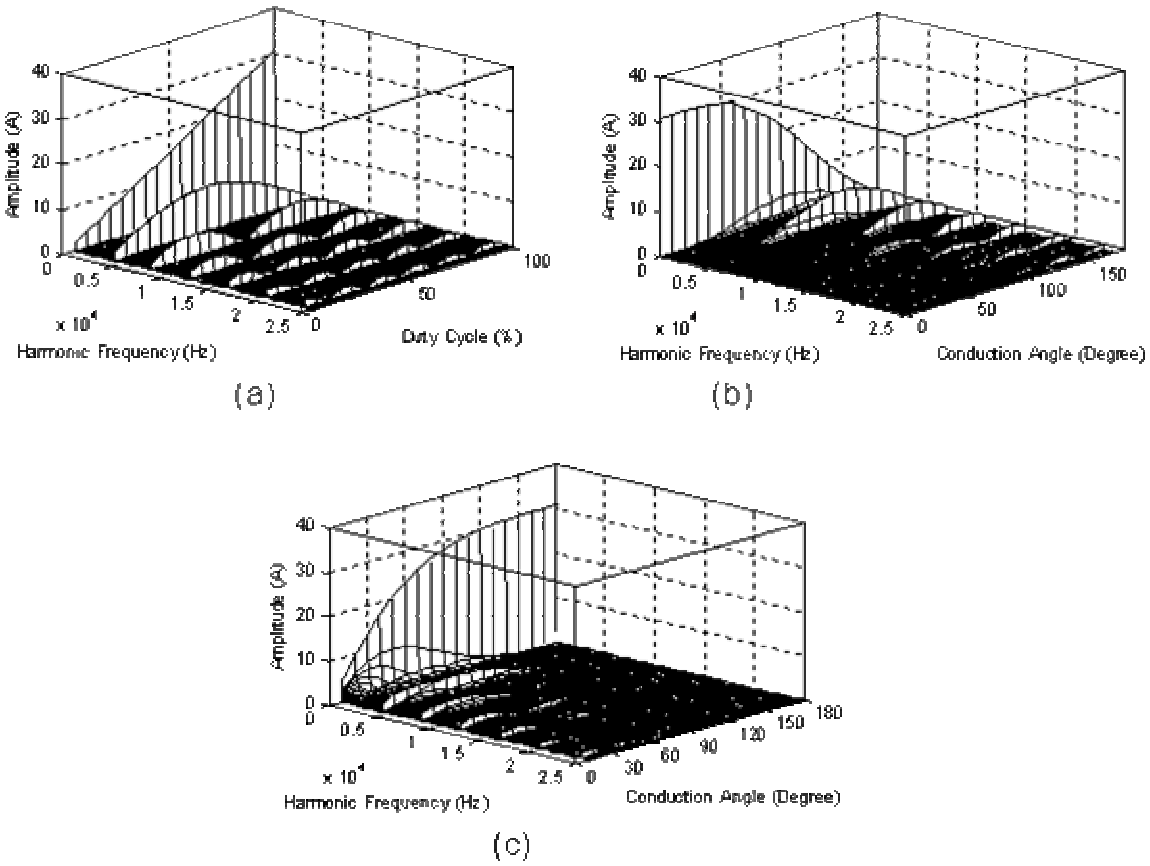
SIMULATION RESULTS

A resistive load of 10 Ω is used as a load in simulation studies. When compared to the other load types, the resistive load used with power electronics equipment produces too many harmonics due to not having energy-storage property and discontinuity of the load current. Because of waveform similarities between phase-angle control and section control, only phase-angle control has been examined. Thus, the proposed method has been applied to the phase-angle control and sector control, individually.

In simulation, the circuitry is firstly set up, the total-conduction angle and PWM frequency are adjusted and the switching patterns are obtained. And then, output-voltage waveform of the converter is measured and stored in a Dat file. This procedure is repeated for a conduction-angle interval of 10°. Finally, the stored in the Dat file are transferred to the Matlab package program. In order to represent harmonics in 3D space, a special Matlab program is developed. The developed program using FFT built-in-functions calculates the harmonics' amplitudes and expresses them in 3D space as a function of harmonic frequency and conduction angle. In addition to this, the program computes and sketches the THD value, rms value of the output-voltage waveform and amplitude of the fundamental harmonic as a function of duty cycle.

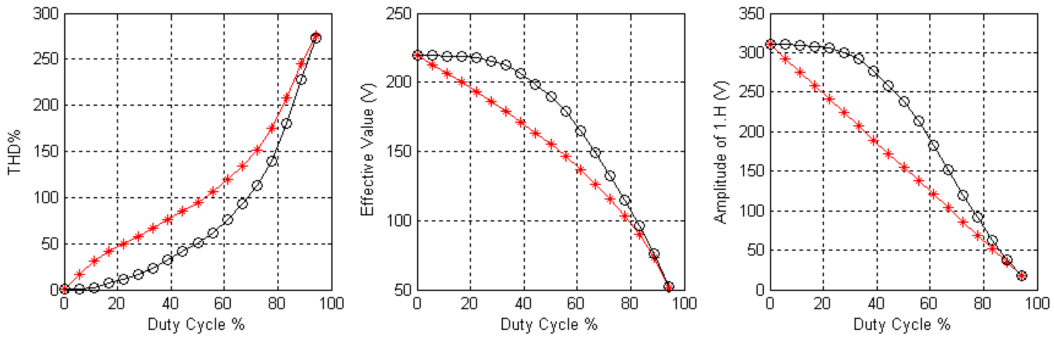
Figure 7 shows 3D harmonic-analysis results about conventional PWM technique, phase-angle control with PWM technique and sector-control with PWM technique, respectively. PWM frequency is selected as 4 kHz in all operations. As seen from Figure 7a, the conventional PWM technique produces high order harmonics; high order harmonics are related to the switching operation and occur around switching frequency and multiples of switching frequency. In the same way, the proposed method in Figures 7b and c generates high order harmonics. However, the proposed method's harmonics are smaller than that of the conventional PWM, especially at lower conduction angles in phase-angle with PWM method and at higher conduction angles in sector-control with PWM method. Figures 8a and 9a verify this inference; the proposed method has lower THD values than the conventional PWM does.

Comparison of the conventional PWM and the phase-angle control with PWM is given in Figure 8 graphically. Figure 8b shows rms values of the output voltage waveforms and Figure 8c shows amplitudes of the fundamental harmonics. A disadvantage of the proposed method is to generate a few lower order harmonics at higher conduction angles. Also, comparison of the conventional PWM and the sector-control with PWM is given in Figure 9 graphically. Figure 9b shows rms values of the output voltage waveforms and Figure 9c shows amplitudes of the fundamental harmonics. In the same manner, the disadvantage of the method is to generate a



(a) (b) (c)

Figure 7. The 3D harmonic analysis results at the switching frequency of 4 kHz, a) PWM technique only, b) Phase-angle control with PWM, c) Sector-control with PWM.



(a) (b) (c)

Figure 8. Comparison of the conventional PWM and the phase-angle control with PWM as a function of duty cycle, (a) THD values, (b) RMS values of the output voltage waveforms and (c) amplitudes of the fundamental harmonics (the lines with stars indicate the conventional PWM, the lines with circles indicate the proposed method).

few lower order harmonics at lower conduction angles.

EXPERIMENTAL RESULTS

In experimental study, only sector-control with PWM method is examined. To illustrate the performance of the method, the proposed AC voltage converter is loaded with a resistive load of 4.84 kW. A PWM frequency of 4 kHz is employed in switching operations and no capacitive filtering is employed. For a specific working condition, sector-control pulses, S1 switching pulses and

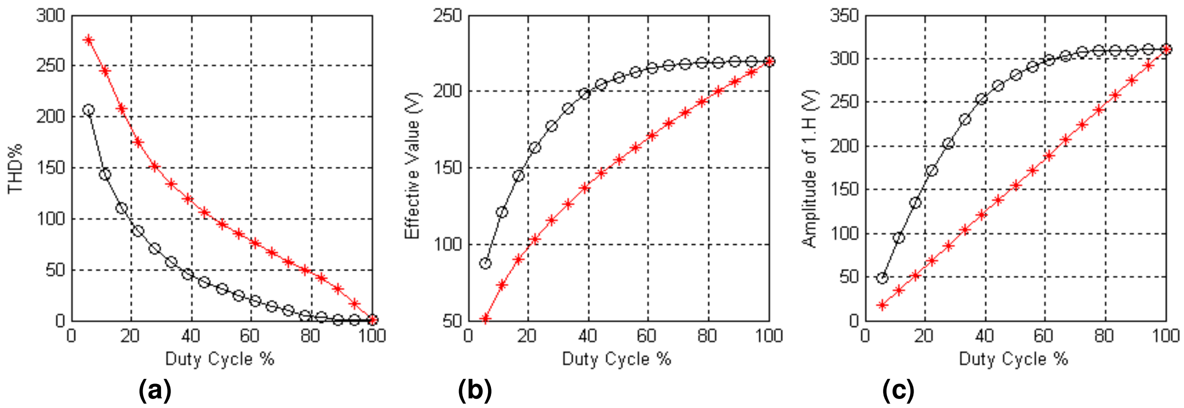


Figure 9. Comparison of the conventional PWM and the sector-control with PWM as a function of duty cycle, (a) THD values, (b) RMS values of the output voltage waveforms and (c) Amplitudes of the fundamental harmonics (the lines with stars indicate the conventional PWM, the lines with circles indicate the proposed method).

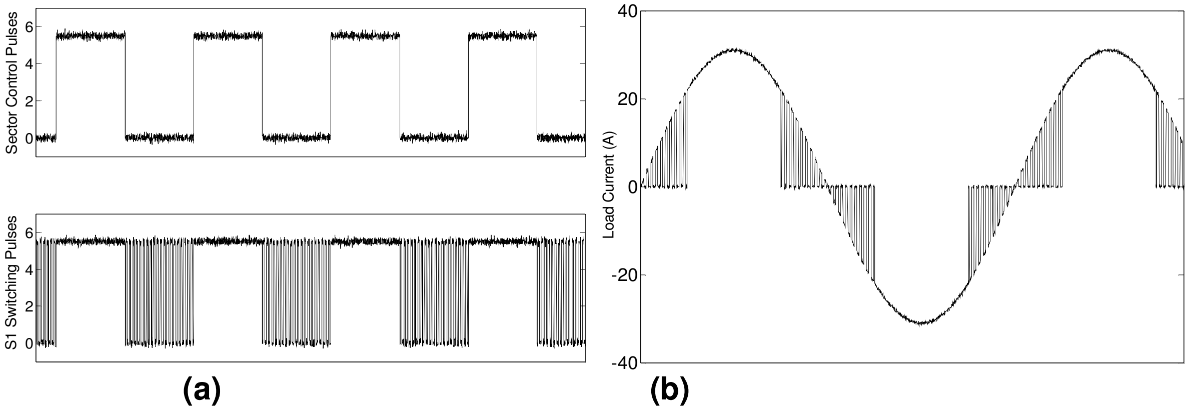


Figure 10. Measurement results, (a) sector-control pulses only; S1 switching pulses (sector-control with pwm pulses) and (b) resultant load current.

load current are shown in Figure 10. Load current is measured and stored in a Dat file and harmonic analysis is performed with built-in functions of Matlab.

Harmonic analysis results for total-conduction angles of 150 and 120° are given in Figures 11 and 12, respectively. The main observation is that higher fundamental current is supplied as compared with the classical PWM method. As seen from the figures, while the classical PWM technique has harmonics at the multiples of the switching frequencies as usual, the proposed method has suppressed these harmonics effectively. When total-conduction angle of the voltage controller is decreased up to 120°, the proposed voltage controller keeps working properly. However, switching harmonics and a few low-order harmonics come into existence slowly. A simple capacitive filter across the load will reduce the magnitude. Capacitive filtering and freewheeling the current in the proposed method is practically required to attenuate the un-wanted harmonics and to allow transient energy to pass through during the OFF period. The capacitor size is readily determined using the switching frequency and required impedance of the capacitor. A path for free-wheeling current can be easily obtained using a voltage snubber element in parallel with the switching element.

Conclusions

One of the well known and widespread methods for harmonic elimination is PWM technique. In this paper, a novel method for harmonic reduction in PWM-AC voltage controller has been proposed. In the proposed method, classical AC voltage controllers and conventional PWM-AC voltage controllers have been combined. As the results of this combination, the proposed method has its own merits and demerits. High-order harmonics are effectively suppressed, thus, smaller high-pass LC filter will be used in the filter circuitry. Smaller THD values are obtained (when compared with the conventional PWM technique); as a consequence, power quality improvement

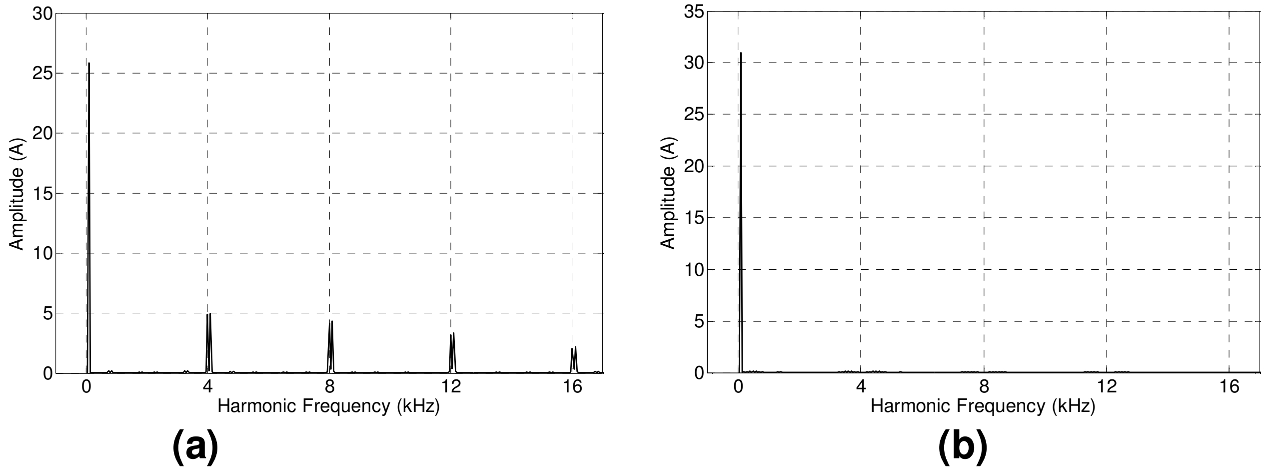


Figure 11. Harmonic analysis results of the load current, (a) classical PWM only (duty cycle: 83%) and (b) sector-control with PWM (total conduction angle:150°, duty cycle: 83%).

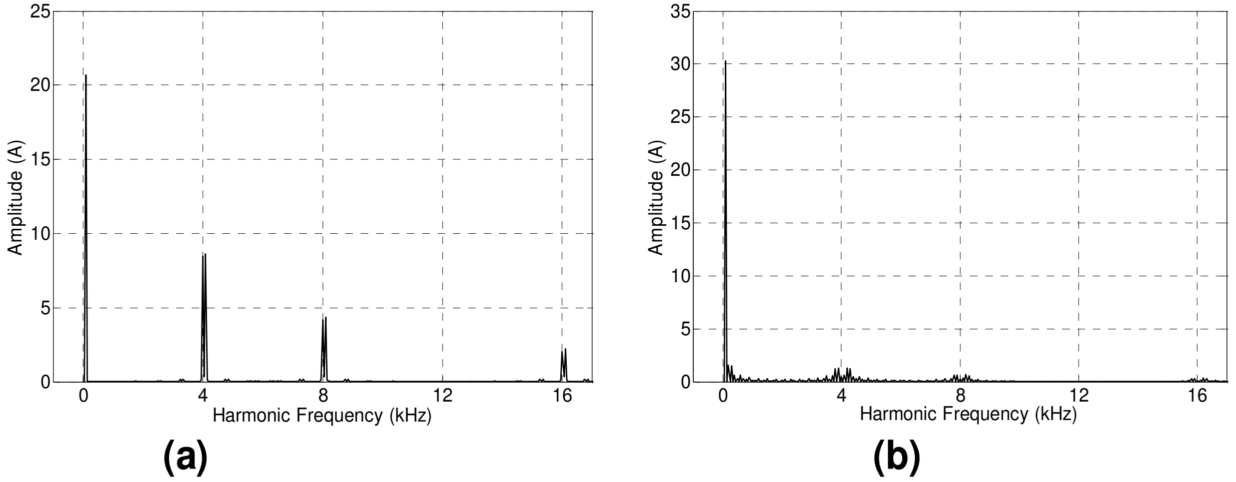


Figure 12. Harmonic analysis results of the load current, (a) classical PWM only (duty cycle: 66%) and (b) sector-control with PWM (total conduction angle:120°, duty cycle: 66%).

ment is realized. By using classical AC voltage controllers in the proposed method, the switching losses in conventional PWM method are decreased proportionally corresponding to the total-conduction angle of AC controllers. The main disadvantage of the proposed method is to generate a few lower order harmonics at higher conduction angles in phase-angle control with PWM method, at lower conduction angles in sector-control with PWM method.

According to the simulation and experimental results, sector-control with PWM method has better performance than phase-angle control with PWM method does. So, sector-control with PWM method is recommended to the power community. This method can be of practical value in replacing the conventional counterparts that are used in controlling heating elements and speed control of small fractional horsepower induction motors.

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