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GÜÇ ELEKTRONİĞİ UYGULAMALARINDA HARMONİK ANALİZ SONUÇLARININ YÜZEY UYDURMA İLE ÜÇ BOYUTLU GÖSTERİMİ

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ÖZET

Yarı iletken malzemeler modern güç elektroniği cihazların temelini oluşturmaktadır. Bunlar, açık-kapalı anahtarların matrissel bir formundaki güç elektroniği konvertörlerinde kullanılır, ve ac'den dc'ye (doğrultucu), dc'den dc'ye (kıyıcı), dc'den ac'ye (inverter) ve ac'den ac'ye (ac kontrolcü, siklokonverter, matris konverter) enerji dönüşümüne yardım ederler. Anahtarlama modlu enerji dönüşümü yüksek bir verimlilik sağlamaktadır, fakat anahtarların non-lineer bir özelliğe sahip olmalarından dolayı yük ve kaynak tarafında harmonik üretmeleri onların bir dezavantajıdır. Güç anahtarlama elemanlı cihazlar tarafında üretilen harmonikler şehir elektrik şebekesine doğru akarlar ve ciddi enerji kalite problemlerine sebep olurlar. Güç anahtarlarının çoğu farklı çalışma karakteristiklerine sahiptir; bu yüzden onlar farklı mertebe ve farklı genlikli harmonikler üretirler. Harmonikler, harmonik analizi yardımıyla tespit edilebilir. Harmonik analiz sonuçları geleneksel olarak sadece bir çalışma durumundaki harmoniklerin özelliklerini gösterir. Eğer, farklı çalışma durumundaki harmonik analiz sonuçları aynı grafik alanında gösterilecek olursa, bazı karışıklıklar oluşabilir. Bu çalışmada, oluşan karışıklığı engellemek için, harmonik analiz sonuçlarını göstermek amacıyla yeni bir yöntem tanıtılmıştır. Sunulan bu yöntem, harmonikleri 3B ortamda göstermektedir.

Anahtar kelimeler: *Harmonik analizi, Güç elektroniği, Yüzey uydurma*

THREE DIMENSIONAL REPRESENTATION OF HARMONIC ANALYSIS RESULTS WITH SURFACE FITTING IN POWER ELECTRONICS APPLICATIONS

ABSTRACT

Power semiconductor devices constitute the base of modern power electronics apparatus. They are used in power electronics converters in the form of a matrix of on-off switches, and help to convert power from ac-to-dc (rectifier), dc-to-dc (chopper), dc-to-ac (inverter), and ac-to-ac (ac controller, cycloconverter, matrix converter). The switching mode power conversion gives high efficiency; but the disadvantage is that harmonics are generated at both the supply and load sides due to the nonlinearty 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. Harmonics can be determined by harmonic analysis. Harmonic analysis result conventionally shows all harmonics' features just for one operating condition. If harmonic analysis results at different operating conditions are displayed in same graphic, some confusion may occur. In this study, to prevent this confusion, a new method to represent harmonic analysis results is introduced. The proposed method shows harmonics in 3D space.

Key words: *Harmonic analysis, Power electronics, Surface fitting*

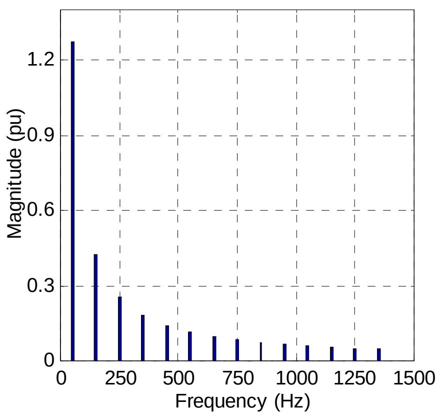
1. INTRODUCTION

All power electronic switching devices can be used for contact-free switching or continuous control of electrical energy. Since the advent of semiconductor power switches, the control of voltage, current, power, and frequency has become cost-effective. Power electronic converters (dc-dc, dc-ac, ac-ac and ac-dc) can be thought of as networks of semiconductor power switches. Depending on the type, the switches can be uncontrolled, semicontrolled or fully controlled. Power converters are widely used in applications such as heating and lighting control, power supplies, electrochemical processes, motor drives, static VAR generation, active filtering, etc. On the other hand, the main disadvantage of the power electronic converter is harmonics. The current/voltage harmonics are non-desired by-product produced at switched operation of power electronic switches [1].

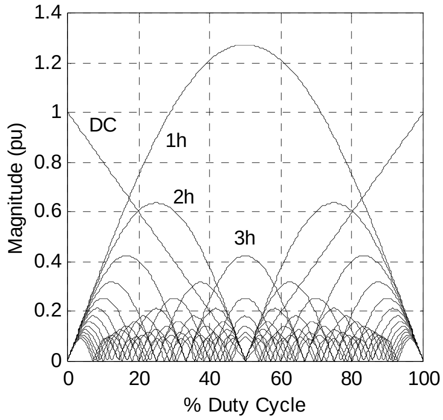
Power converters draw distorted currents from the supply and hence generate harmonics, and their input power factor is also poor. The harmonic currents generated by the power electronic related-equipment flow through the utility system and cause various power quality problems. The distorted current flowing 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 [2,3].

In electrical systems, the harmonic effectiveness of a non-linear load can be expressed with "Total Harmonic Distortion" (THD). When power electronic related-loads are a considerable part of the total load in the facility (more than 20%), there is a chance of a harmonic problem. Therefore, THD value of the power system must be checked at periodic intervals; and harmonic currents are to be filtered out in the facility. Since the harmonic patterns are very complex due to the different operating conditions of power switches, it is difficult to make an analysis graphically or mathematically. The most convenient method to study harmonics is to make a computer simulation study and analyze the waveforms by FFT [4,5]. In application, a digital oscilloscope is needed to be measured the waveform, THD and amplitude of each harmonic. However, if we simply want to measure the RMS value of the waveform, a "True-RMS" multimeter will be sufficient.

Conventionally, there are a few methods to represent harmonic analysis results. The simplest one is formed by using two parameters: harmonic order (or frequency) and harmonic amplitude (Fig. 1.a); second one is formed by using three parameters: harmonic order, harmonic amplitude and operating conditions (Fig. 1.b). Operating conditions depend on some system parameters such as firing angles at thyristors and triacs, duty ratio in square and sawtooth signals used in control circuitry, load types such as battery charger, modulation index in PWM control, power transfer ratio (*n*/*N*) in integral cycle control. Although the second method is overall and illustrative, it sometimes causes confusion especially when displayed too many harmonics at the same graphic area. These two representation methods can be briefly called "two dimensional (2D) representation" because of using 2D graphic area.



(a)



(b)

Figure 1. Two dimensional harmonic analysis results of square wave with, a) a fixed duty cycle (50%), b) a variety of duty cycles.

In this paper, a new method to display harmonic analysis results is introduced; the new method shows harmonics in three dimensional (3D) space; by doing so, it was intended to prevent confusion occurring in second 2D representation. Because of using 3D graphic volume, the new method can be called "3D representation". Such an approach can express harmonic analysis result more clearly than 2D can. For this reason, this method can be prefered for some applications such as active filtering and power quality conditioning.

2. 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 and the possibility of adding user-written functions. Matlab is a matrix-based software for scientific and engineering numeric computation and visualization. Its integrated graphic capabilities make this program a powerful tool for data analysis operating on both acquired and simulated data. Matlab can handle both real and complex data, which is very important in Fourier transforms [6,7]. Matlab/Simulink can perform 2D FFT directly, but does not perform 3D FFT.

Currently, there are huge varieties of waveform processing techniques. Undoubtedly, Fourier transforms are among the most popular signal processing techniques in use today. According to the Fourier series, 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. In essence, the Fourier transform is used to convert from a time domain waveform to a frequency domain waveform. For signal processing applications, a special Fourier transform is used to operate on discrete, finite functions. This is called the discrete Fourier transform (DFT). In this study, the DFT are employed to perform all harmonic analyses [8,9].

Surfaces and their description play a critical role in design and manufacturing. The design and manufacture of automobile bodies, aircraft wings, fan blades, turbine, bottles and shoes are obvious examples. Surface shape or geometry is essence of design for either functional or aesthetic reasons. Surface description also plays an important role in the representation of data obtained from medical, geological, physical, electrical and other natural phenomena. In design and engineering the traditional way of representing a surface is to use multiple orthogonal projections. In effect, the surface is defined by a net or mesh of orthogonal plane curves lying in plane sections plus multiple orthogonal projections of certain three-dimensional feature lines. In computer graphics and computer aided design, it is advantageous to develop a true three-dimensional mathematical model of a surface. Such a model allows early and relatively easy analysis of surface characteristics [10]. In the developed matlab program, the built-in function of *griddata* is used to realize surface fitting. Griddata function fits a surface of the form $z = f(x, y)$ to the data in the (usually) nonuniformly-spaced vectors. This function interpolates the surface at the specified points. The surface always goes through the data points. Griddata function has a few methods to fit surface such as *linear*, *nearest*, *cubic* and *v*4. The *cubic* and *v*4 methods produce smooth surfaces while *linear* and *nearest* have discontinuities in the first and zero-th derivative respectively. Since the harmonic orders are always discontinuous (higher harmonics, such as 2^{nd}, 3^{rd}, 4^{th} and so on, are simply integer multiples of the 1^{st} harmonic in terms of their periods), *linear* surface fitting method has been used in the program. Griddata function can produce 3D harmonic analysis result not only graphically but also numerically; thus, one can obtain harmonic amplitude for specified harmonic order and operating condition.

Simplified flowchart of the developed matlab program, performing the 3D-harmonic analysis, is given in Fig. 2. According to the flowchart, load type is selected and curcuit parameter are defined firstly. After defining source current and precalculating the harmonics at each operating condition, a matrix containing harmonic amplitudes is constructed; then, the second matrix, same size with the first matrix and containing harmonic orders, is defined; and then, the third matrix, also same size with the first matrix and containing operating condition, is formed. The second matrix has the same rows, and the third matrix has the same columns. By means of these three matrixes and surface fitting operation, harmonic analysis results are represented in 3D space.

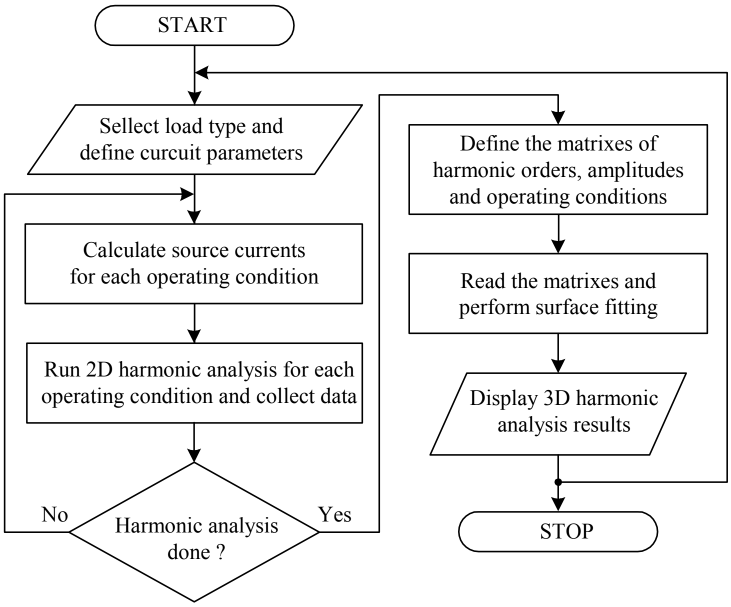


Figure 2. Simplified flowchart of the developed matlab program.

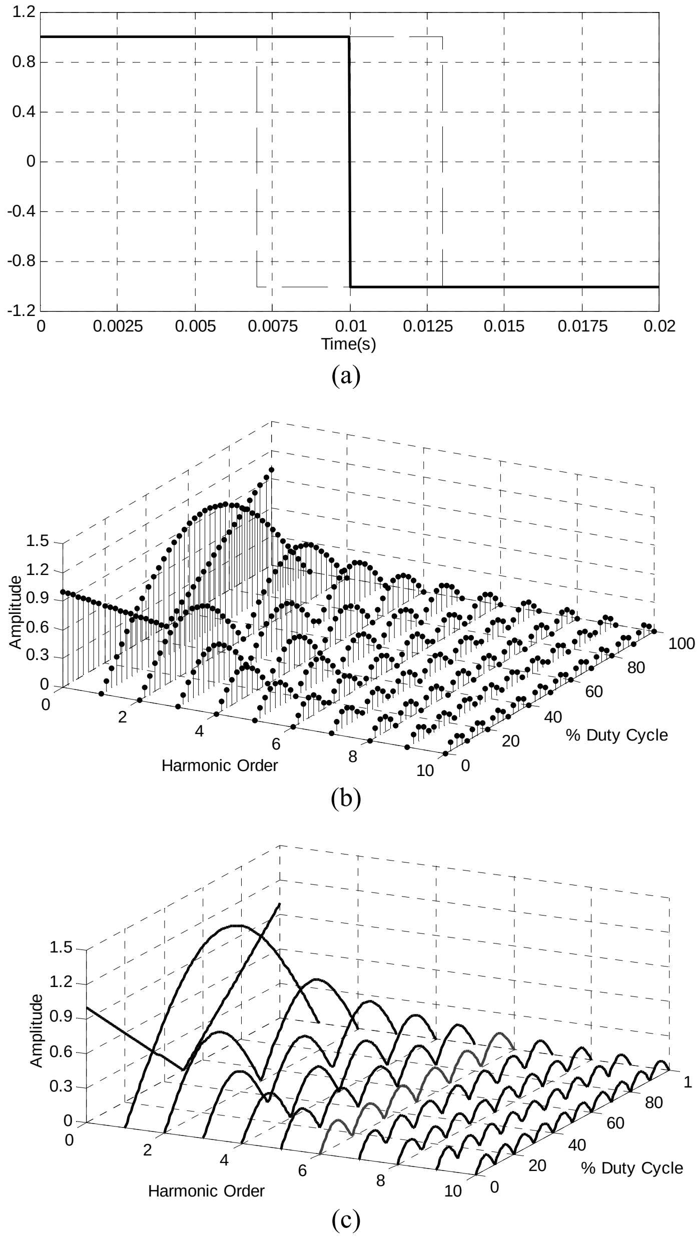
Every power electronics circuit has own its circuit parameters, load types and operating condition. Although this flowchart is valid for all circuitry, the developed matlab program is just valid for exemplary applications given in section 3. Also, the circuit parameters and the operating condition related to exemplary applications are given in relevant topic.

3. EXEMPLARY APPLICATIONS

3.1. Square Wave with Different Duty Cycles

All books, containing Fourier series/analysis, initially mention a square wave because it is the easiest signal type for performing harmonic analysis analytically, and, is frequently encountered in many applications. That's why, a square wave has been chosen as a first example. A square wave with 50% duty cycle contains only odd harmonics. These odd ordered harmonics are displayed in Fig. 1.a. If the duty cycle of a square wave is changed sequentially at the range 0-100 an interval of 2.5%, harmonic analysis result would be like in Fig. 1.b. While low ordered harmonics can be seen easily, some difficulties arise at identifying high ordered harmonics in Fig. 1.b.

In this example, the frequency and amplitude of the square wave are choosen as the circuit parameters; and, the duty cycle of the square wave is defined as the operating condition. The data, obtained from 2D harmonic analysis for each duty cycle, are collected properly and expressed as a bar graph in 3D space (Fig. 3.b). After converting 3D-bar graph to 3D-line graph (Fig. 3.c), surface fitting operation is realized. As a result, the fitted surface is shown in Fig. 3.d. Numerical results of harmonic analysis of square wave with a duty cycle interval of 10% are given in Table 1. In all tables, except Table 3, the harmonics between 1^{st} and 9^{th} are only given due to saving space.


1.2
0.8
0.4
0
-0.4
-0.8
-1.2
0
0.0025
0.005
0.0075
0.01
0.0125
0.015
0.0175
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Time(s)
(a)
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% Duty Cycle
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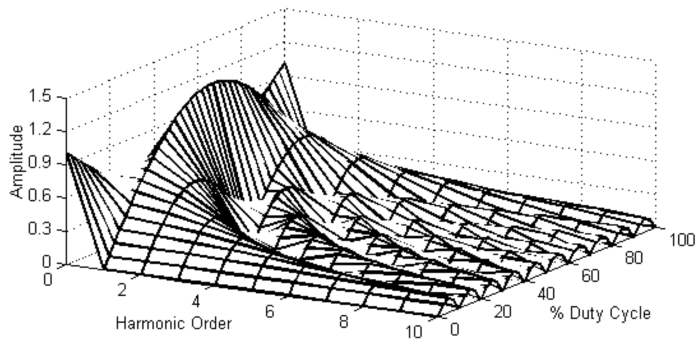
% Duty Cycle
(c)



(d)

Figure 3.a) Description of the square wave with different duty cycles, b, c, d) Three dimensional representations of harmonic analysis results of the square wave with bar graph, line graph and fitted surface respectively.

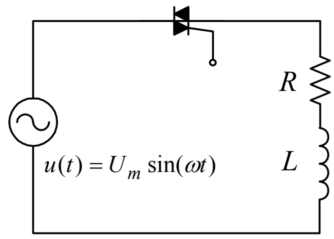
Table 1. Harmonic amplitudes of the square wave with different duty cycles.

D. Cycle ⇨ H. Order ⇩	0	10	20	30	40	50	60	70	80	90	100
dc	1.00	0.80	0.60	0.40	0.20	0	0.20	0.40	0.60	0.80	1.00
1	0	0.39	0.75	1.03	1.21	1.27	1.21	1.03	0.75	0.39	0
2	0	0.37	0.61	0.61	0.37	0	0.37	0.61	0.61	0.37	0
3	0	0.34	0.40	0.13	0.25	0.42	0.25	0.13	0.40	0.34	0
4	0	0.30	0.19	0.19	0.30	0	0.30	0.19	0.19	0.30	0
5	0	0.25	0	0.25	0	0.25	0	0.25	0	0.25	0
6	0	0.20	0.12	0.12	0.20	0	0.20	0.12	0.12	0.20	0
7	0	0.15	0.17	0.06	0.11	0.18	0.11	0.06	0.17	0.15	0
8	0	0.09	0.15	0.15	0.09	0	0.09	0.15	0.15	0.09	0
9	0	0.04	0.08	0.11	0.13	0.14	0.13	0.11	0.08	0.04	0

3.2. Triac Controlled Ohmic-Inductive Load

Triacs are eminently suitable for use as switches and controllers because of having extremely high peak reverse voltages and output currents. Therefore, they have been the traditional equipment for bulk power conversion and control in industry. 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. When triac is driven at $\alpha > 0$; the rest of positive and negative half-wave cycles have correspondingly smaller root-mean-square (RMS) value. In the case of an ohmic-inductive load, the load current can only be controlled in the range between the load phase angle φ and 180° using the firing angle [3,11,12]. Time profiles of input current of triac, driven at $\alpha = 60°, 90°$ in public network, are shown in Fig. 4a. In the case of triac controlled ohmic-inductive load, the line voltage and the load values (R,L) are choosen as the circuit parameters; and, the firing angle of triac is taken into account as the operating condition.

3D harmonic analysis can be performed automatically by means of applying harmonic analysis to each load current obtained at different firing angles, and collecting the harmonic amplitudes. The three dimensions consist of the firing angle given in *Degree*, the harmonic amplitude given in *Ampere* and the harmonic order. To define the graph of output current of triac controlled RL load with the power factor of 0.7, a total of 360 data is employed in one-period time. Output currents and voltages are calculated a degree interval of 10° for 3D representation. After getting harmonic analysis results properly, the data are demonsrated in 3D space by the method under consideration (Fig. 4.c,d). Numerical results of harmonic analysis of triac controlled RL load with a firing angle interval of 15° are given in Table 2.



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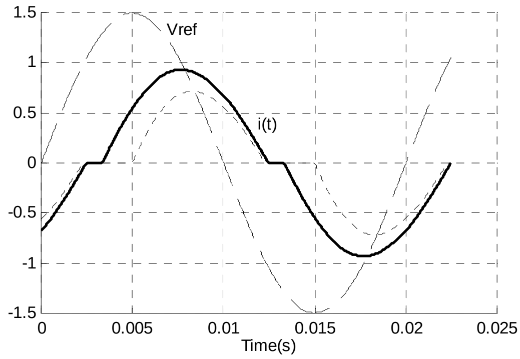

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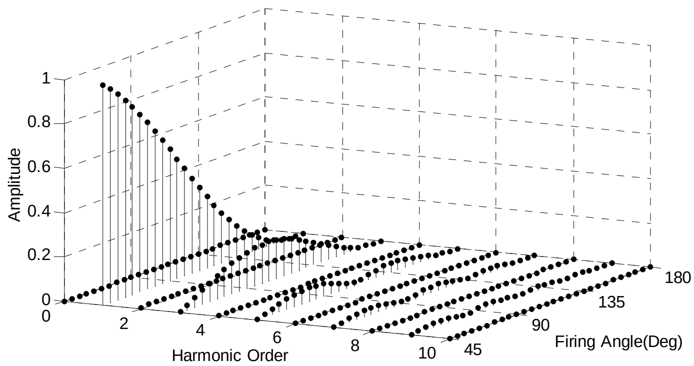

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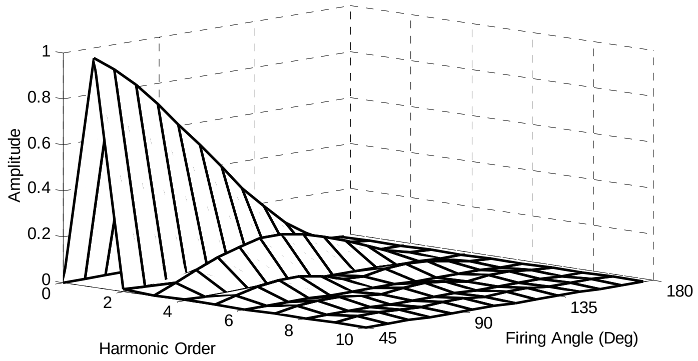


(d)

Figure 4.a) Shematic representation of triac controlled RL load, b) Time profiles of source currents and reference source voltage (V_{ref}) for $\alpha = 60° - 90°$, c, d) Three dimensional representations of triac harmonics with bar graph and fitted surface respectively.

Table 2. Harmonic amplitudes of the triac controlled ohmic-inductive load at different firing angles.

F. Angle ⇨ H. Order ⇩	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°
dc	0	0	0	0	0	0	0	0	0	0
1	9.94	8.89	7.52	5.94	4.29	2.73	1.43	0.53	0.08	0
2	0	0	0	0	0	0	0	0	0	0
3	0.04	0.64	1.23	1.64	1.75	1.51	1.01	0.45	0.08	0
4	0	0	0	0	0	0	0	0	0	0
5	0.02	0.37	0.60	0.55	0.23	0.24	0.43	0.31	0.07	0
6	0	0	0	0	0	0	0	0	0	0
7	0.01	0.24	0.29	0.08	0.23	0.25	0.04	0.16	0.06	0
8	0	0	0	0	0	0	0	0	0	0
9	0.01	0.17	0.11	0.12	0.16	0.07	0.13	0.04	0.05	0

3.3. PWM Control Of Voltage Source Inverter with Ohmic Load

PWM control 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 or sinusoidal signal. 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 sinusoidal PWM, operating with switching frequency of 0.5 *kHz* and modulation index of 1, is given in Fig. 5.b. In the case of PWM controlled inverter with ohmic load (Fig. 5.a), the frequencies of the sinusoidal and triangle carrier wave signal are choosen as the circuit parameters; and, the modulation index is taken into account as the operating condition. Output currents of PWM controlled voltage source inverter are calculated a modulation index interval of 0.1 in the range 0-1.2 for 3D representation. As a result, Fig.

5.c,d are obtained. Numerical results of harmonic analysis of the voltage sorce inverter with a modulation index interval of 0.1 are given in Table 3.

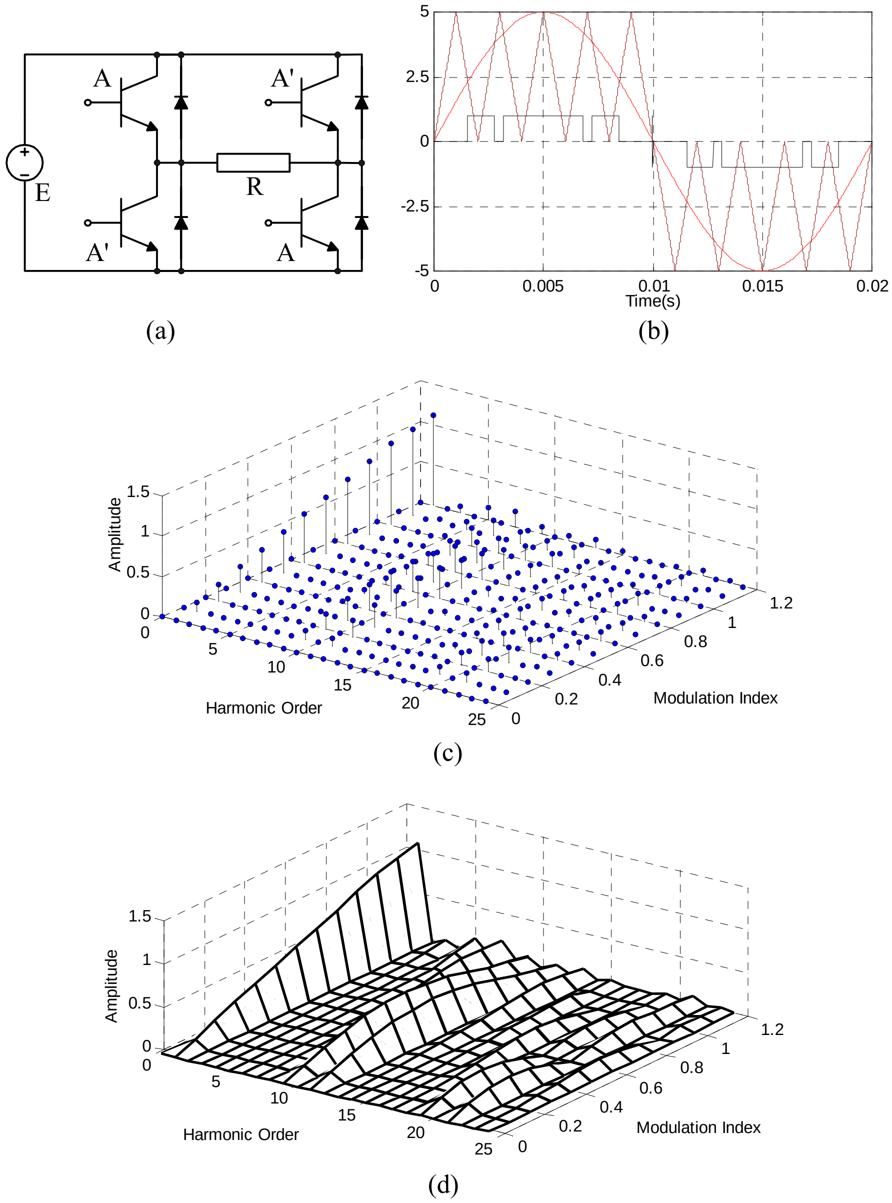


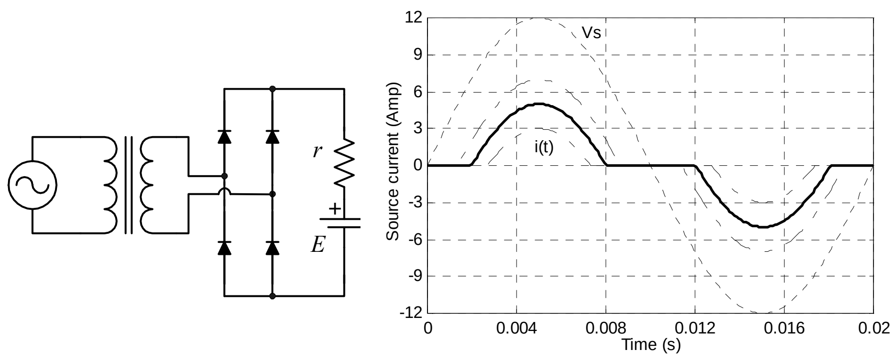
Figure 5.a) An application circuitry of PWM control: Single-phase, full-bridge, voltage source inverter with ohmic load, b) The time profile of output voltage of sinusoidal PWM with modulation index of 1, c, d) Three dimensional representations of the inverter harmonics with bar graph and fitted surface respectively.

Table 3. Harmonic amplitudes of the PWM-controlled voltage source inverter with a modulation index interval of 0.1.

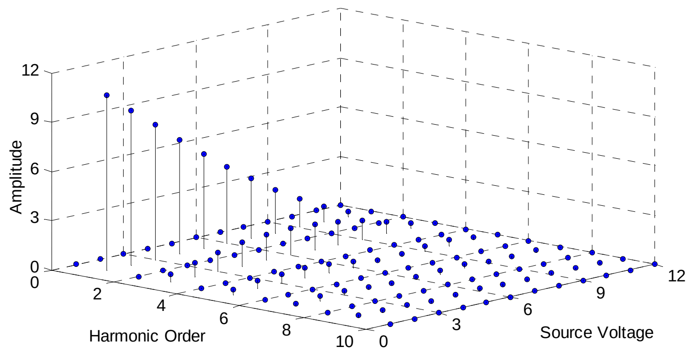
M. Index ⇨ H. Order ⇩	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
dc	0	0	0	0	0	0	0	0	0	0	0	0
1	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	1.06	1.12
9	0.10	0.19	0.27	0.33	0.36	0.37	0.35	0.32	0.25	0.18	0.14	0.09
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0.10	0.19	0.27	0.33	0.36	0.37	0.36	0.31	0.25	0.18	0.12	0.06
19	0.10	0.16	0.18	0.15	0.09	0.01	0.07	0.10	0.10	0.05	0.02	0.03
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0.10	0.17	0.19	0.16	0.09	0	0.07	0.12	0.14	0.12	0.11	0.08
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0.01	0.04	0.07	0.10	0.11	0.10	0.05	0	0.05	0.04	0.03

3.4. Full-Bridge Battery Charger

The fourth example is about battery charger. While battery voltage is increasing with time, battery charger current will also decrease. As a result, the current, provided to battery from the public network, is distorted and generates harmonics. The main currents of the public network for different battery voltages are shown in Fig. 6.b; the dotted line (Vs) denotes input voltage of the battery charger; output voltage/current of the battery charger will be fullwave dc. In the case of single-phase uncontrolled full-bridge rectifier with a battery (counter emk) and an ohmic load, the output voltage of the rectifier and the ohmic load value are choosen as the circuit parameters; and, the battery voltage is taken into account as the operating condition. Input currents of battery charger are calculated a battery voltage interval of 1. Numerical results of harmonic analysis of the battery charger with a voltage interval of 1 are given in Table 4.



(a) (b)



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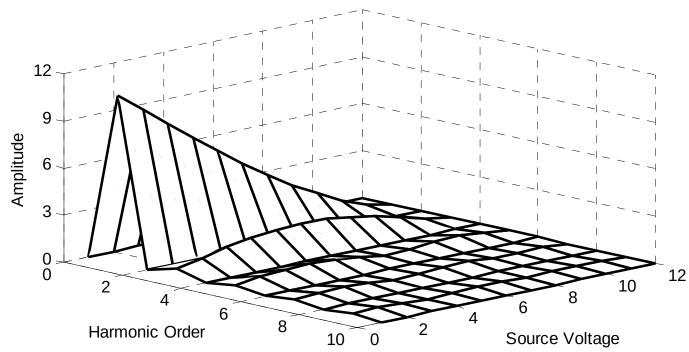

(d)

Figure 6.a) Single-phase, uncontrolled, full-bridge battery charger circuitry, b) Time profiles of input currents of battery charger, c, d) Three dimensional representations of battery charger harmonics with bar graph and fitted surface respectively.

Table 4. Harmonic amplitudes of the battery charger with a voltage interval of 1.

B. Voltage ⇨ H. Order ⇩	1	2	3	4	5	6	7	8	9	10	11
dc	0	0	0	0	0	0	0	0	0	0	0
1	10.70	9.44	8.20	6.98	5.80	4.68	3.61	2.62	1.72	0.95	0.34
2	0	0	0	0	0	0	0	0	0	0	0
3	0.46	0.85	1.19	1.45	1.61	1.67	1.60	1.41	1.11	0.72	0.30
4	0	0	0	0	0	0	0	0	0	0	0
5	0.27	0.47	0.59	0.60	0.51	0.32	0.08	0.17	0.34	0.37	0.22
6	0	0	0	0	0	0	0	0	0	0	0
7	0.18	0.29	0.30	0.21	0.05	0.13	0.24	0.23	0.10	0.07	0.13
8	0	0	0	0	0	0	0	0	0	0	0
9	0.14	0.19	0.14	0.01	0.12	0.17	0.10	0.03	0.12	0.07	0.06

4. CONCLUSIONS

This paper deals with a new method to represent harmonic analysis results. As mentioned before, harmonic analysis result is conventionally expressed in 2D space. The new method, detailed in this paper, shows harmonics in 3D space. The 3D representation of harmonics is overall and very illustrative; thus, the amplitude of each harmonic current for all operating conditions can be determined graphically and numerically. Additionally, a comparison on harmonics produced at different operating conditions can be made easily. An important parameter of the non-linear load is THD values; THD values for each operating condition can be, also, calculated by using data obtained numerically.

In order to simulate the waveform of load or source current and to get the data on harmonics can be sometimes very difficult. In case of this circumstance, the data can be obtain from other computer simulation programs such as OrCad, SimCad, and so on; another way to get the data is to use a digital storage oscilloscope or a data acquisition system, if possible; this method can be very effective and realistic in laboratory and industrial applications. After getting appropriate data with one of these methods, 2D or 3D harmonic analysis can be, also, performed by using the developed software package.

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