

A SOFTWARE FOR DETERMINING THE VARIABLES ON THYRISTOR AND TRIAC WITH DIFFERENT LOAD VARIANT AND GATE ANGLES

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ABSTRACT

Thyristors and 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 workhorses for bulk power conversion and control in industry. Currently, a lot of computer simulation software about power electronics circuits has been developed. Many of them are professional programs aimed at industry applications. In this paper, an education-aimed software package for determining the variables on thyristor and triac with different load and firing angle has been developed. The software can, also, be employed on industrial applications. With the aid of the software package developed; all variables of the load (currents, voltages, power, energy, harmonics, THD, transfer characteristics, etc.) can be displayed numerically and/or graphically.

Key words: Thyristor, Triac, Power electronics

FARKLI YÜK VE TETİKLEME AÇISINA SAHİP TRİSTÖR VE TRİYAKA AİT PARAMETRELERİ TESBİT ETMEK İÇİN BİR YAZILIM

ÖZET

Tristör ve triyaklar yüksek delinme gerilimleri ve yüksek çıkış akımlarına sahip olduklarından, anahtar ve kontrolcü olarak kullanmak için son derece uygundur. Bu yüzden endüstride, geleneksel olarak yüksek güçlü enerji dönüşümleri ve sistem kontrolü için sıkça kullanılmaktadır. Günümüzde güç elektroniği devrelerinin simülasyonu için bir çok program geliştirilmiştir. Bunlardan bir çoğu profesyonel amaçlıdır. Bu çalışmada, farklı yük ve tetikleme açısına sahip olan tristör ve triyaka ait tüm değişkenleri tespit etmek için eğitim amaçlı bir yazılım paketi geliştirilmiştir. Bu yazılım profesyonel amaçlı da kullanılabilir. Geliştirilen bu yazılım paketinin yardımı ile, yüke ait tüm değişkenler (akımlar, gerilimler, güç, enerji, harmonikler, THD, transfer karakteristiği, vb.) sayısal ve/veya grafiksel olarak görüntülenebilir.

Anahtar kelimeler: Tristör, Triyak, Güç elektroniği

1. INTRODUCTION

All controllable electrical switching devices can be used for contact-free switching or continuous control of electrical energy. However, the switching capacity of the device should be as large as possible, in order to ensure that they can be used economically in switching and control technology. Since the advent of semiconductor power switches, the control of voltage, current, power, and frequency has become cost-effective. Thyristors and triacs have been the traditional workhorses for bulk power conversion and control in industry.

Silicon Controlled Rectifiers (SCR) or Thyristors are eminently suitable for use as switches and controllers because of having extremely high peak reverse voltages and output currents. The device is turned on with a current signal to the gate, when the device is forward biased. The device can be turned off only by reverse biasing the device. During the reverse biasing, known as commutation, the device behaves like a diode. A negative voltage has to be maintained across the device for a period greater than the reverse recovery time. The device can also block negative voltages to a certain value. Beyond this certain value, the device will break down and conduct in the reverse direction [1, 2].

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). Triacs are used in light dimming, heating control, appliance-type motor drives, and solid state relays with typically 50/60 Hz supply frequency [3,4].

Simulation programs provide that the user learns whatever he wants in a short time without any physical setting up. Currently, a lot of computer simulation software about power electronics have been developed. Many of them are professional programs aimed at industry applications. Hence, to use a professional simulation program successfully necessitates having high level knowledge and experience. There are also educational programs in use.

In this study, an education-aimed software for determining all variables on thyristor and triac with different load and firing angle has been developed. The software also can be employed on industrial applications. By using the software; rms, mean and peak values of the load current-voltage, active power, power factor and power angle, extinction angle (if exist), the amplitudes of current harmonics produced from load, total harmonic distortion (THD), stored energy in L and etc. can be calculated; time profile of the load current, load voltage, blocked main voltage, instantaneous power, harmonics and etc. can be displayed; in addition to those: as a function of the firing angle, cluster of the load currents, transfer characteristics, 3D harmonic analysis results and individual harmonic variation can be obtained numerically and/or graphically.

2. DESCRIPTION OF THE LOADS AND THEORETICAL CHARACTERISTICS

Power switching devices talked about are employed for controlling resistive, inductive or capacitive loads. The two principal load types of general interest in power electronics are the resistive and the inductive loads. Turn-on and turn-off voltage and current switching waveforms depend on the type of load [5]. The resistive load represents the simplest and most easily described load variant, since the characteristic curves for voltage and current are identical in time and phase. The purely inductive load represents an ideal load. According to the law of induction, the load current varies continuously and not abruptly as in the case of resistive load. During the positive voltage half-cycle, magnetic energy is stored in the inductance. When the line voltage crosses zero, the current in the load circuit continues to flow until the inductance has been discharged. The resistive and inductive load in series is a load type frequently found in practice. Once again, the inductance of the load prevents any abrupt current changes in the load circuit.

Thyristor with resistive load: At gate angle of $\alpha=0$, the thyristor is switched on and conducts immediately after the AC voltage passes zero. In circuits with resistive load, the current is in phase with the voltage. During the negative half-wave AC voltage, the thyristor blocks. When the thyristor is driven at $\alpha>0$, it conducts as from this firing angle.

A section of the positive voltage half-wave with correspondingly smaller mean value and root-mean-square value is then present at the load resistance. This type of control is known as phase angle control. The load current function, its mean and rms value can be expressed with Eq.1, Eq.2 and Eq.3, respectively.

$$i(t) = I_m \cdot \sin(\omega t), \quad I_m = U_m / R, \quad \alpha \leq \omega t \leq 180^\circ \quad (1)$$

$$i_{mean}(\alpha) = \frac{I_m}{\pi} \cdot \frac{1 + \cos \alpha}{2} \quad (2)$$

$$i_{rms}(\alpha) = \frac{I_m}{2} \left[\frac{1}{\pi} \left(\pi - \alpha + \frac{\sin 2\alpha}{2} \right) \right]^{1/2} \quad (3)$$

Thyristor with resistive-inductive load: In the case of resistive-inductive load connected in series, the direct current can only vary continuously, since the inductance prevents any abrupt changes in the current. The direct current is equal to zero at the firing point, but then increases continuously to a maximum and drops to zero. Different resistance and inductance values have different time profile of the current because of having different time constant ($\omega L / R$), even with identical gate angles. The time profiles for purely resistive and purely inductive load represent limiting cases. Because of the storage capacity of the inductance, the direct current continues to flow after the zero transition of the AC voltage until the inductance has been completely discharged. The time profile of the DC voltage is made up of positive and negative instantaneous values. On account of the resistive load, the positive voltage/time section is larger than the corresponding negative section. The direct current decreases constantly as the gate angle increases. The time integral of the load voltage over one period is always positive. As a result, the product of the mean direct current and DC voltage values is also positive; thus, active power is absorbed by the load. The load current function, and its mean and rms value formulas are given at Eq.4, Eq.5 and Eq.6, respectively. Time profile of the load current function is given in Fig. 1 ($I_m = 1A, \varphi = 45^\circ, \alpha = 60^\circ$). But, the actual load current will be the piece between α and θ , in other words, the part above the x-axes.

With assuming $I_m = \frac{U_m}{\sqrt{R^2 + (\omega L)^2}}, \quad \varphi = \arctan \frac{\omega L}{R}$

$$i(t) = I_m \cdot (\sin(\omega t - \varphi) - \sin(\alpha - \varphi)) \cdot e^{-\frac{R}{\omega L}(\omega t - \alpha)} \quad (4)$$

$$i_{mean}(\alpha) = \frac{U_m}{R} \cdot \frac{1}{2\pi} \cdot (\cos \alpha - \cos(\alpha + \theta)) \quad (5)$$

$$i_{rms}(\alpha) = I_m \cdot \left\{ \frac{1}{2\pi} \left[\frac{\theta}{2} + \frac{1}{4 \cdot \cos \varphi} \cdot [\sin(2\alpha + \varphi) - \sin(2\alpha + 2\theta - \varphi)] \right] \right\}^{1/2} \quad (6)$$

where α, φ, θ represent firing (gating) angle, load angle, current conduction angle, respectively.

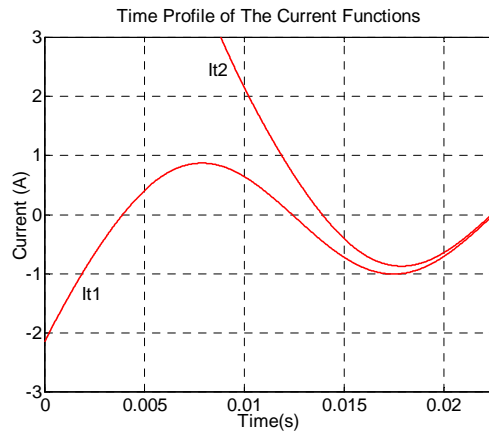
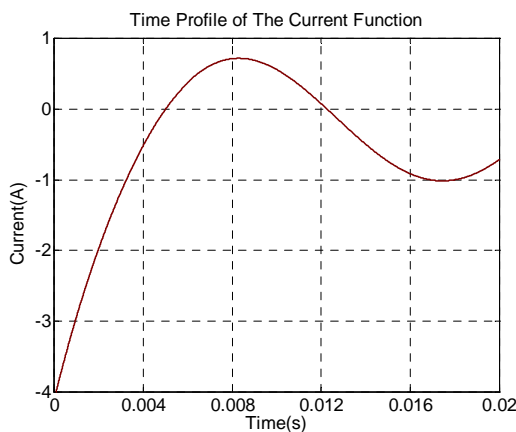


Figure1. Time profile of thyristor current function.

Figure2. Time profile of triac current functions.

Triac with resistive load: The load current is in phase with the line voltage, like thyristor with resistive load. The load current is alternatively made up of the two-thyristor current (Eq.7, Eq.8). Rms value of the load current can be calculated with the aid of Eq.9. When symmetrical firing angle is employed, mean value of the load current equals to zero.

$$it1(t) = \frac{U_m}{R} \cdot \sin(\omega t) ; \quad \alpha \leq \omega t \leq 180^\circ \quad (7)$$

$$it2(t) = \frac{U_m}{R} \cdot \sin(\omega t) ; \quad \alpha + 180^\circ \leq \omega t \leq 360^\circ \quad (8)$$

$$i_{rms}(\alpha) = \frac{U_m}{R} \cdot \left[\frac{1}{2\pi} \cdot \left(\pi - \alpha + \frac{\sin 2\alpha}{2} \right) \right]^{1/2} \quad (9)$$

Triac with resistive-inductive load: The resistive-inductive load represents a load case between resistive and purely inductive load. Full drive is obtained when $\alpha = \varphi = \arctan(\omega L / R)$. Thus, the load current can only be varied in the range between α and 180° using the gate angle. If the gate angle of the triac equals to the load phase angle, the load current will be a non-intermittent sinusoidal waveform. Eq.10 and Eq.11 express the load current made up of the two-thyristor current [2,5]. Time profiles of those current functions are given in Fig. 2 ($I_m = 1A$, $\varphi = 45^\circ$, $\alpha = 70^\circ$). Actual load current is formed with the piece of $it1(t)$ above the x-axes and the piece of $it2(t)$ under the x-axes. Rms value of the load current can be calculated with Eq.12.

$$it1(t) = \frac{U_m}{Z} \cdot \left[\sin(\omega t - \varphi) - \sin(\alpha_1 - \varphi) \cdot e^{-\frac{R}{\omega L}(\omega t - \alpha_1)} \right], \quad \alpha_1 \leq \omega t \leq \alpha_1 + \theta \quad (10)$$

$$it2(t) = \frac{U_m}{Z} \cdot \left[\sin(\omega t - \varphi) - \sin(\alpha_2 - \varphi) \cdot e^{-\frac{R}{\omega L}(\omega t - \alpha_2)} \right], \quad \alpha_2 + 180^\circ \leq \omega t \leq 180^\circ + \alpha_2 + \theta \quad (11)$$

$$i_{rms}(\alpha) = \frac{U_m}{Z} \cdot \left\{ \frac{1}{\pi} \cdot \left[\frac{\theta}{2} + \frac{1}{4 \cdot \cos \varphi} \cdot [\sin(2\alpha + \varphi) - \sin(2\alpha + 2\theta + \varphi)] \right] \right\}^{1/2} \quad (12)$$

where, $Z = R + j\omega L$ and $\varphi = \arctan(\omega L / R)$.

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 thyristors, triacs and other switches.

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 [3]. In electrical systems, the harmonic effectiveness of a non-linear load can be expressed with "Total Harmonic Distortion (THD)". THD value can be calculated with Eq.13.

$$THD(I) = \sqrt{\frac{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \dots}{I_1^2}} \cdot 100 \quad (13)$$

where the indices represent harmonic orders [6,7].

3. MATERIAL AND METHOD

Matlab is a matrix-based software for scientific and engineering numeric computation and visualization. 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, simple programming and its wide availability on computing platforms [8,9].

In this study, the developed software package can be employed for thyristor and triac with purely resistive loads (R), purely inductive loads (L) and resistive-inductive loads in series (RL). To obtain acceptable results, a total of 3600 ($360^{\circ} \cdot 10$) data was employed at calculations and time domain graphs in one-period-time. To display the loads currents and voltages, thyristor and triacs current functions given before are used in appropriate interval by using *if* conditional functions and repetitive *for* loops.

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 load condition and firing angle, a total of 19 harmonics is taken into account.

4. AN EXEMPLARY APPLICATION

Triac with resistive-inductive load is given as an example. After the program is run and both switch and load types are selected, the preferential window screen will appear (Fig. 3). In this window screen, maximum main voltage, main frequency, load values and firing angle should be entered.

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THE ANALYSIS PROGRAM OF TRIAC WITH RL LOAD
Enter the maximum value of the main voltage (Volt)?=310
Enter the main frequency (Hertz)?=50
Enter the load resistance (Ohm)?=22
Enter the load inductance (Henry)?=0.07
Enter the firing angle (Degree)?=90
  DISPLAY CALCULATION RESULTS, PRESS A
  DISPLAY LOAD CURRENT AND Vref, PRESS B
  DISPLAY TIME PROFILE OF THE MAIN AND LOAD VOLTAGE, PRESS C
  DISPLAY TIME PROFILE OF THE MAIN AND BLOCKED MAIN VOLTAGE, PRESS D
  DISPLAY TIME PROFILE OF THE LOAD RESISTANCE VOLTAGE, PRESS E
  DISPLAY TIME PROFILE OF THE LOAD INDUCTANCE VOLTAGE, PRESS F
  DISPLAY TIME PROFILE OF THE INSTANTANEOUS POWER, PRESS G
  DISPLAY AMPLITUDES OF THE HARMONICS, PRESS H
  DISPLAY 2D HARMONIC ANALYSIS, PRESS I
  DISPLAY TIME PROFILE OF THE HARMONICS, PRESS J
  DISPLAY THE LOAD CURRENTS WITH DIFFERENT FIRING ANGLES, PRESS K
  DISPLAY 3D HARMONIC ANALYSIS, PRESS L
  DISPLAY THD VALUES GRAPHICALLY, PRESS M
  DISPLAY THD VALUES NUMERICALLY, PRESS N
  DISPLAY AMPLITUDE OF INDIVIDUAL HARMONIC GRAPHICALLY, PRESS O
  DISPLAY AMPLITUDE OF INDIVIDUAL HARMONIC NUMERICALLY, PRESS P
  DISPLAY TRANSFER CHARACTERISTICS GRAPHICALLY, PRESS Q
  DISPLAY TRANSFER CHARACTERISTICS NUMERICALLY. PRESS R

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Figure 3. Preferential window screen.

When the user presses the letter A, the calculation result window appears. The calculation result window contains several variables, like in Fig. 4. In this window, mean values of the load current and voltage, which should have been zero, don't equal to zero because of using finite-digit in calculation.

When the user presses the letter B; Fig. 5, containing load current and V_{ref} , appears. V_{ref} signal, in phase with the

RMS value of the load current (A)	=	4.3877
Mean value of the load current (A)	=	-0.000015
RMS value of the load voltage (V)	=	165.37
Mean value of the load voltage (V)	=	0.000017
Peak value of the load current (A)	=	7.1538
Peak value of the load voltage (V)	=	310
Active Power (W)	=	423.16
Load Angle (Deg)	=	44.988
Power Factor	=	0.70725
%THD (1h-19h)	=	28.927
Extinction Angle (Deg)	=	220.8
Current Conduction Angle(Deg)	=	130.8
Stored Energy in L (J)	=	0.507

Figure 4. Calculation result window

main voltage, was added to graph because of observing the phase difference and firing angle. By pressing the letters C, D, E, F, respectively; the graphs of the main and load voltage (Fig. 6), the main and blocked main voltage (Fig. 7), the load resistance voltage (Fig. 8) and the load inductance voltage (Fig. 9) appear. In those figures, the main voltage was shown by the dashed line. The instantaneous power graph can be displayed on the screen by pressing the letter G (Fig. 10). Fig. 10, obtained by multiplying load current by main voltage, verifies that the load demands reactive and active power from the main.

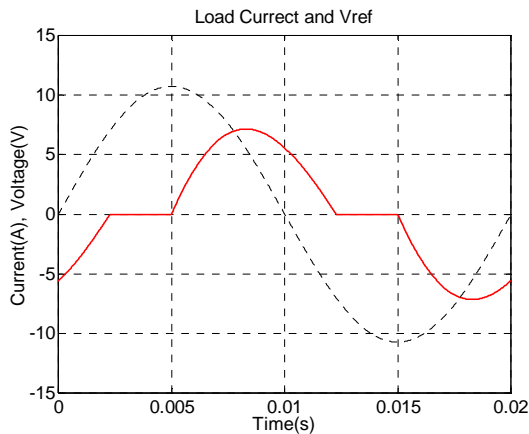


Figure 5. The load current and V_{ref} .

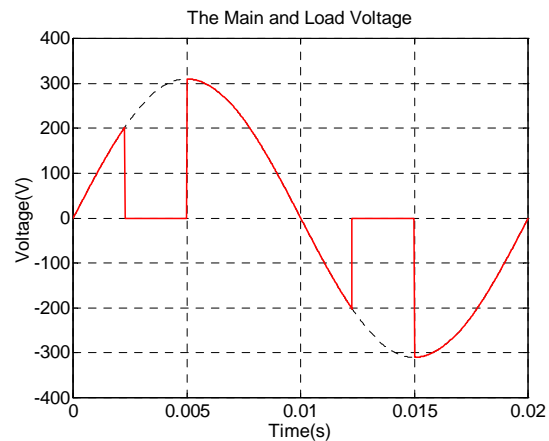


Figure 6. The main and load voltage.

By pressing the letter H; the harmonic currents, generated by the load, can be displayed numerically (Fig. 11). The harmonic number, desired to be calculated, can be chosen any number with software. Zero-order harmonic represents DC component and first-order harmonic represents fundamental component of the load current in Fig. 11.

By pressing the letter I, the harmonics in question can be displayed graphically (Fig. 12). Time profiles of the harmonics can, also, be displayed on the screen by pressing the letter J (Fig. 13). In this figure, phase differences between the harmonics are not considered.

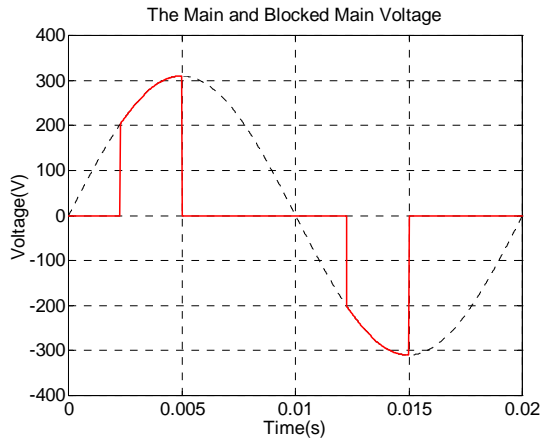


Figure 7. The main and blocked main voltage.

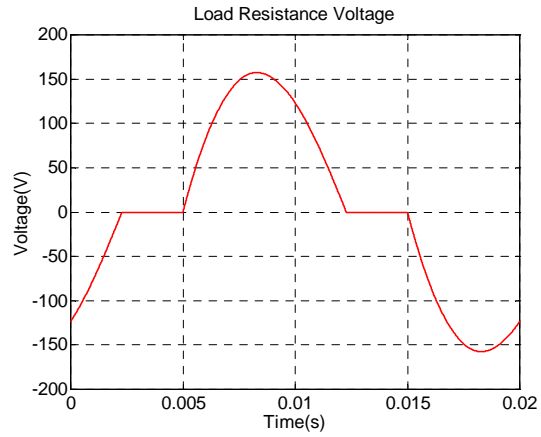


Figure 8. The load resistance voltage.

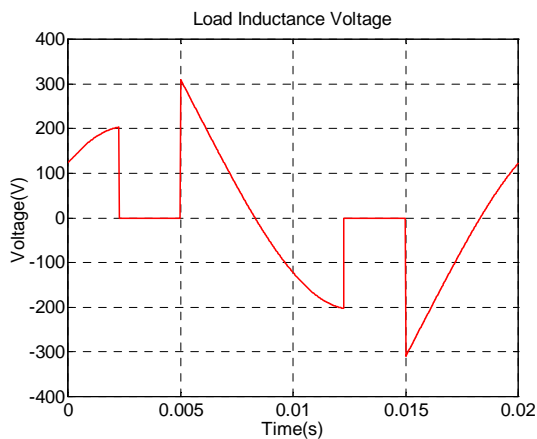


Figure 9. The load inductance voltage

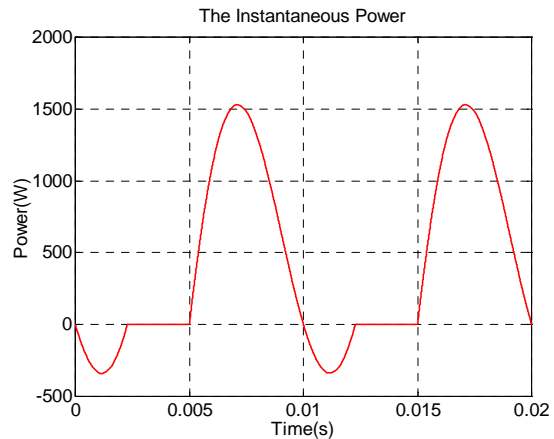


Figure 10. The instantaneous power graph

How many harmonics are desired to be calculated? = 9	
Harmonics and Their Amplitudes =	
0	0.0015532
1	5.9606
2	0.0029796
3	1.6194
4	0.0021775
5	0.55285
6	0.0013211
7	0.091403
8	0.00046147
9	0.1163

Figure 11. Harmonics displayed numerically

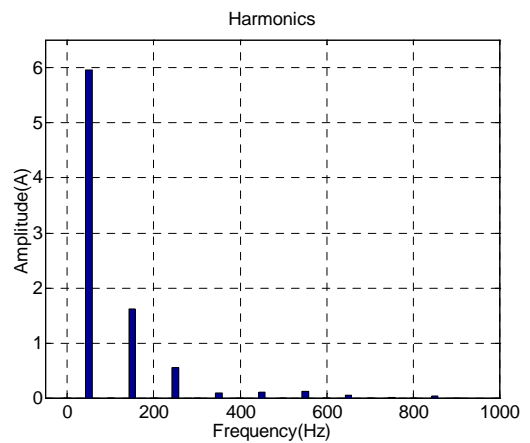


Figure 12. Harmonics displayed graphically

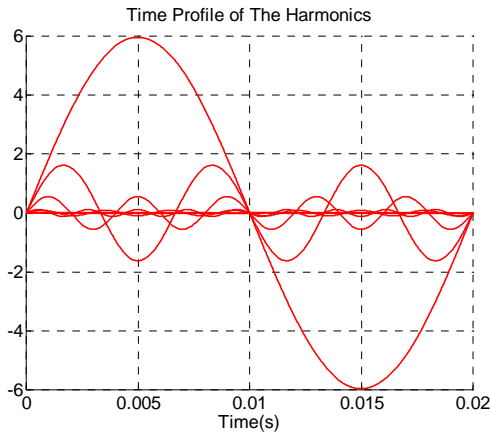


Figure 13. Time profile of the harmonics.

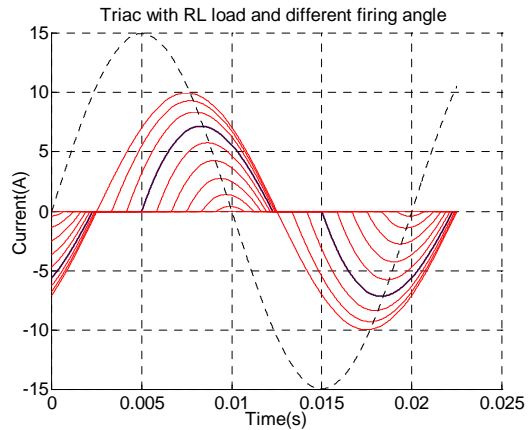


Figure 14. Cluster of the load currents.

By pressing the letter K; cluster of the load currents, obtained by changing the gating with an angle-interval of the 15 degrees, can be displayed, like in Fig. 14. The angle interval may be chosen any number. This graph also verifies that the load current has sinusoidal waveform when firing angle α equals to load angle φ . As mentioned before, the dashed line shows reference voltage V_{ref} .

By pressing the letter L, 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 amplitudes of the harmonics (Fig. 15). The three dimensions are firing angle in degree, harmonic amplitude in ampere and harmonic order. After doing 3D harmonic analysis, as a function of the firing angle, THD values and individual (let say 3rd) harmonic amplitudes can be calculated numerically (Tables 1, 2) and plotted graphically (Figs. 16, 17) with ease by pressing the letters M,N,O and P. The firing angles have been chosen in the range 45°-175° with an angle-interval of 10° at the example. The tables are performed in order to save space. Firing angles are given in degree in all the tables. According to Fig. 16, just as firing angles increases continuously so does the THD values.

Corresponding to the firing angle, transfer characteristic (I_{α} / I_{φ}) can be obtained numerically (Table 13) or graphically (Fig. 18) by pressing the letters Q, R. According to the Fig. 18, while the firing angle increases, the transfer characteristic decreases, as expected.

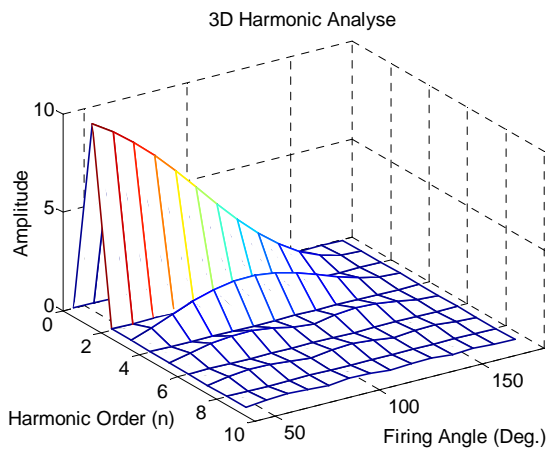


Figure 15. 3D harmonics analysis.

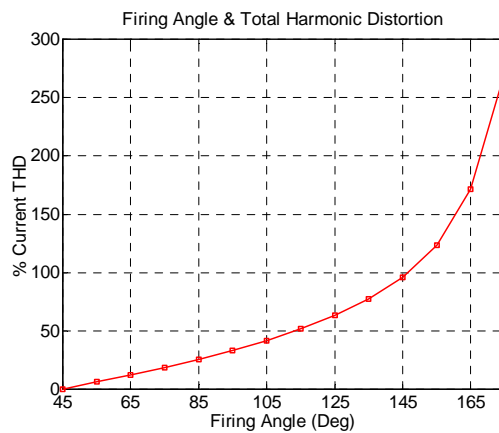


Figure 16. THD values versus firing angle.

Table 1. THD values versus firing angle

Firing	45	55	65	75	85	95	105
%THD	0	6.16	12.2	18.7	25.67	33.3	41.9
Firing	115	125	135	145	155	165	175
%THD	51.7	63.2	77.5	96.2	123.6	171	271

Table 2. Third-harmonic amplitudes versus firing angle

Firing	45	55	65	75	85	95	105
Amp.(3h)	0.037	0.43	0.843	1.227	15.34	17.19	17.53
Firing	115	125	135	145	155	165	175
Amp.(3h)	16.3	13.7	10.09	0.625	0.293	0.08	0.004

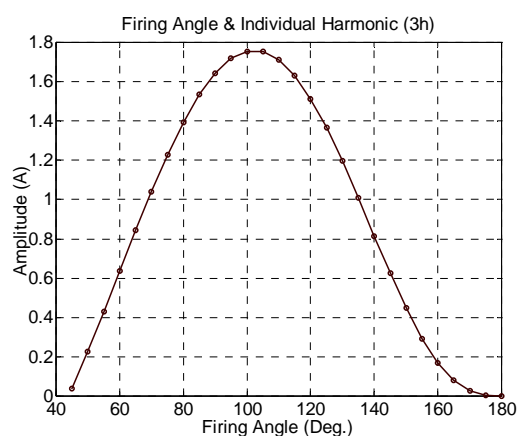


Figure 17. Third-order harmonic versus firing angle.

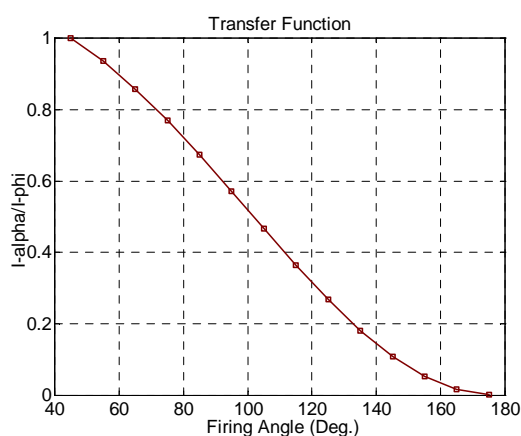
Figure 18. Transfer characteristics (I_{α} / I_{ϕ}).

Table 3. Transfer characteristic values versus firing angle.

Firing	45	55	65	75	85	95	105
I_{α} / I_{ϕ}	1	0.9	0.858	0.77	0.673	0.57	0.467
Firing	115	125	135	145	155	165	175
I_{α} / I_{ϕ}	0.4	0.27	0.18	0.109	0.05	0.017	0

5. CONCLUSION

Thyristors and triacs, power electronics switches, have been used widely since a long time in industrial applications because of having extremely high peak reverse voltages and output currents. With the education-aimed software developed in this study, most of the variables about the switches with different load and firing angle can be attained easily. The software is very useful owing to interactive mode of work and not needing any circuitry settings up on computer. The software, also, provides a convenient tool so that many scenarios can be tried with ease. Such an approach can enhance the learning process.

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