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Insulated-Gate Bipolar Transistor Controlled Reactor

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Abstract – *In this paper a controlled reactor using insulated-gate bipolar transistor (IGBT) is presented. Controlled reactors are usually implemented by using thyristors since the mid-1970's and they are usually referred to as thyristor-controlled reactors. A thyristor-controlled reactor (TCR) is simply two anti-parallel thyristors connected in series with a fixed inductor or reactor. In TCR, it is only required to specify the instants at which its thyristors must start conduction. Once a thyristor conducts, its current keeps on flowing as long as its magnitude is above holding limit and hence no trigger is required after starting of conduction. In addition, a thyristor will be naturally commutated as soon as its current decays below holding limit. For IGBT, the instant at which the device must start conduction and the conduction period must be both identified because maintaining conduction requires keeping on activating the device gate as long its current is still greater than zero. The problem is how long should the IGBT conduct and when it will be turned off? In this paper a reliable control strategy is adopted for presenting the IGBT as a good replacement of thyristor in controlled reactors. A demonstrating system is designed and implemented on the computer program PSpice.*

Keywords: *Controlled Reactor, Power Quality, Reactive Power Control, Static VAR, TCR*

Nomenclature

TCR	Thyristor controlled reactor
IGBT	Insulated gate bipolar transistor capacitor bank
V	The ac supply voltage
V_m	Ac voltage amplitude
ω	Ac voltage angular frequency
L	TCR or IGBT reactor
i_{TCR}	The TCR actual current
σ	Thyristor controlled reactor firing angle
IGCR	The IGBT controlled reactor
i_{IGCR}	IGCR actual current
I_1	TCR fundamental current component
I_k	TCR kth harmonic current component
i_{T1}	The actual current of the thyristor T1
i_{T2}	The actual current of the thyristor T2
i_{Z1}	The actual current of the IGBT (Z1)
i_{Z2}	The actual current of the IGBT Z2
V_{in}	An analog voltage proportional to the inductive reactive current demand
γ_1	Conduction angle of the IGBT Z1
γ_2	Conduction angleof the IGBT Z2
$T_1\&T_2$	The TCR thyristors
$Z_1\&Z_2$	The IGCR switching devices (IGBTs)
V_F	The IGCR function circuit output

I. Introduction

Thyristor-controlled reactors (TCRs) are productive tools amongst reactive power control techniques employed for power factor correction, power system voltage control, and load balancing purposes [1]-[8]. The TCR is constructed of two anti-parallel thyristors connected in series with a fixed reactor. The fundamental component of the TCR current can be controlled continuously by varying the conduction angles of its thyristors symmetrically [1].

The TCR releases odd harmonics in the power system network. These harmonics depend upon the TCR firing angle and are directly proportional to its rating [9]-[12]. They are usually treated by using harmonic filtering techniques in order to avoid disturbance in the power system network voltage profile and transmission losses. The TCR can also be employed in applications different from those dealing with static VAR compensation. Basing on its fast switching behavior, the TCR can be used as a current limiter.

This property presents the TCR as a good protector during fault conditions [13]. The thyristor controlled reactors as its name indicates, employs thyristors only in its construction since it appeared to existence in the mid-1970's. Here is in this paper, the insulated-gate bipolar transistor (IGBT) is presented as a good and reliable replacement of thyristor in TCR design circuitry. The new configuration is referred to as IGBT-controlled reactor (IGCR).

II. The TCR Concept

The conventional TCR is shown in Fig. 1(a). When the TCR is fired at a certain angle σ, its current will be as

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shown in Fig. 1(b). Each thyristor will be naturally commutated as its current approaches zero. The TCR current (i_{TCR}) fundamental component (I_1) is given by [1]:

$$I_1 = \frac{V_m}{\pi \omega L}\left(\pi - 2\sigma - sin(2\sigma)\right) \tag{1}$$

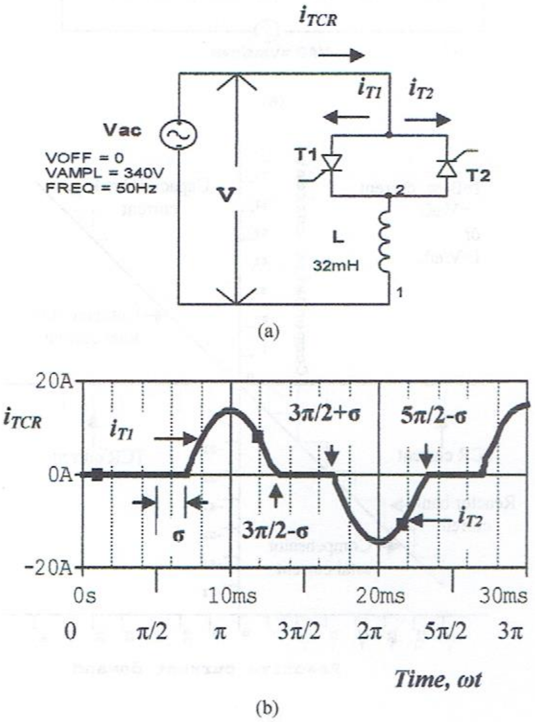
where σ is the TCR firing angle in radians, V_m is the amplitude of the ac applied voltage (V) in volts, ω is the ac supply angular frequency in radians per seconds, and L is the reactor inductances in Henries. σ varies in the range $0 \leq \sigma \leq \pi/2$. Note that $\sigma=0$ at $\omega t=\pi/2$ and $\sigma=\pi/2$ at $\omega t=\pi$.

The thyristor T_1 starts conduction at $\omega t=(\pi/2+\sigma)$ and turns off naturally at $\omega t=(3\pi/2-\sigma)$, while T_2 starts conduction at $\omega t=(3\pi/2+\sigma)$ and turns off naturally at $\omega t=(5\pi/2-\sigma)$. Note that each thyristor conducts for an angle of $(\pi-2\sigma)$.

When σ is set zero, the TCR current will be a pure sinusoid. The TCR current contains odd harmonics only. The k_{th} order harmonic is given by [1]:

$$I_k = \frac{V_m}{\omega L}\left(\frac{4}{\pi}\right)\left[\frac{sin(\sigma)cos(k\sigma) - k\,cos(\sigma)sin(k\sigma)}{k\left(k^2-1\right)}\right] \tag{2}$$

where k is a positive odd integer greater than unity.



Figs. 1. The TCR, (a) configuration, (b) current waveforms

III. The IGBT-Controlled Reactor

The configuration of the IGBT-controlled reactor (IGCR) is shown in Fig. 2. It is similar to the TCR configuration except that thyristors are replaced by IGBTs.

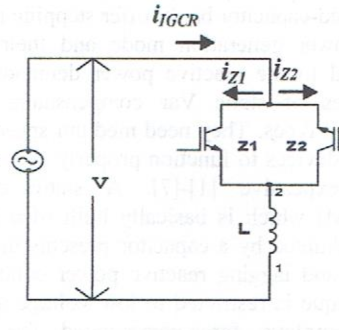
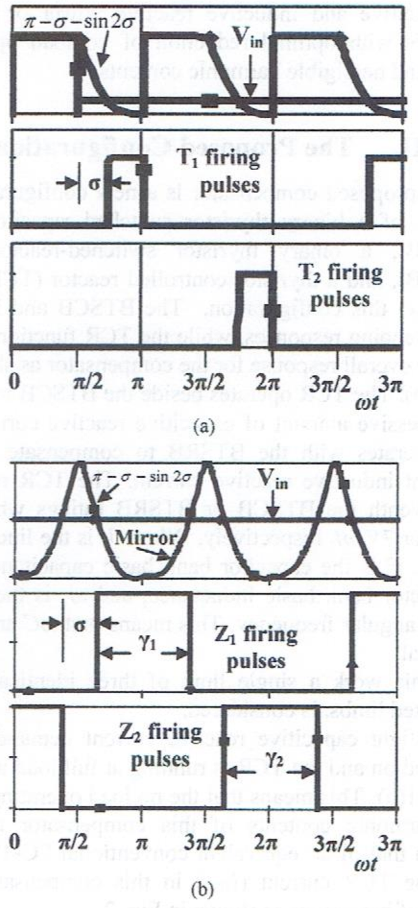


Fig. 2. The insulated-gate bipolar transistor controlled reactor configuration

To make the TCR conducts according to Fig. 1(b), a suitable technique must be devised to determine its firing angle **σ** as shown in Fig. 3(a).



Figs. 3. (a) The TCR firing angle determination technique, (b) the IGCR firing and conduction angles determination technique

The above technique complies with Equation (1) which consists of the constant part ($V_m/\pi\omega L$) and the variable part (π-2σ-$sin2\sigma$). If the latter is analogously simulated in the range $(\pi/2+k\pi)\leq\omega t\leq(1+k)\pi$, where k=0,1,2, 3, .., then the TCR or IGCR firing angle will be easily determined by comparing the simulated function with an analogue voltage (V_{in}) proportional to the inductive reactive current demand as shown in Fig. 3(a). Determining the instants at which firing must be started is sufficient for thyristors due to their properties of conduction, but this is not sufficient for IGBTs since they stop conduction as soon as their triggers disappear. Note that the IGBT conducts when its anode-to-cathode voltage is positive and its gate-to-cathode capacitance is positively charged to a value depending on its type.

In order that the IGCR responds like the TCR in Fig. 1(b), the conduction angles of the IGBTs (Z_1 and Z_2) must be identified. The technique stated in Fig. 3(b) is devised to solve this problem. In this technique, the expression (π-2σ-$sin2\sigma$) and its mirror are analogously simulated. The conduction angle for each IGBT is easily determined by comparing the simulated waveform with V_{in} which is directly proportional to the inductive reactive current demand. In Fig. 3(b), γ_1 and γ_2 are the conduction angles of Z_1 and Z_2 respectively.

IV. The IGCR Circuit Design

The electronic circuit of this system is implemented using the computer program PSpice. The datasheets of electronic parts and relating supportive literatures were taken into account during design process [14]-[16]. Fig. 4 shows the circuit diagram of this system. It consists of the IGCR function, triggering, driving, and power circuits.

The IGCR function circuit in Fig. 4 generates the waveform that represents the analogue simulation of the expression (π-2σ-$sin2\sigma$) and its mirror. The sequential stages of simulation process are shown in Fig. 5. The IGCR triggering circuit compares an analogue input voltage V_{in} (proportional the inductive reactive current demand) with the output of the function circuit to determine the conduction angles for Z_1 and Z_2 as shown in Fig. 3(b).

The driving circuit offers the suitable context for the operation of Z_1 and Z_2. During the conduction period of each IGBT, the gate-to-cathode capacitance is charged to about +15 volts. At the end of conduction period, the gate-to-cathode capacitance of each IGBT discharges to zero rapidly.

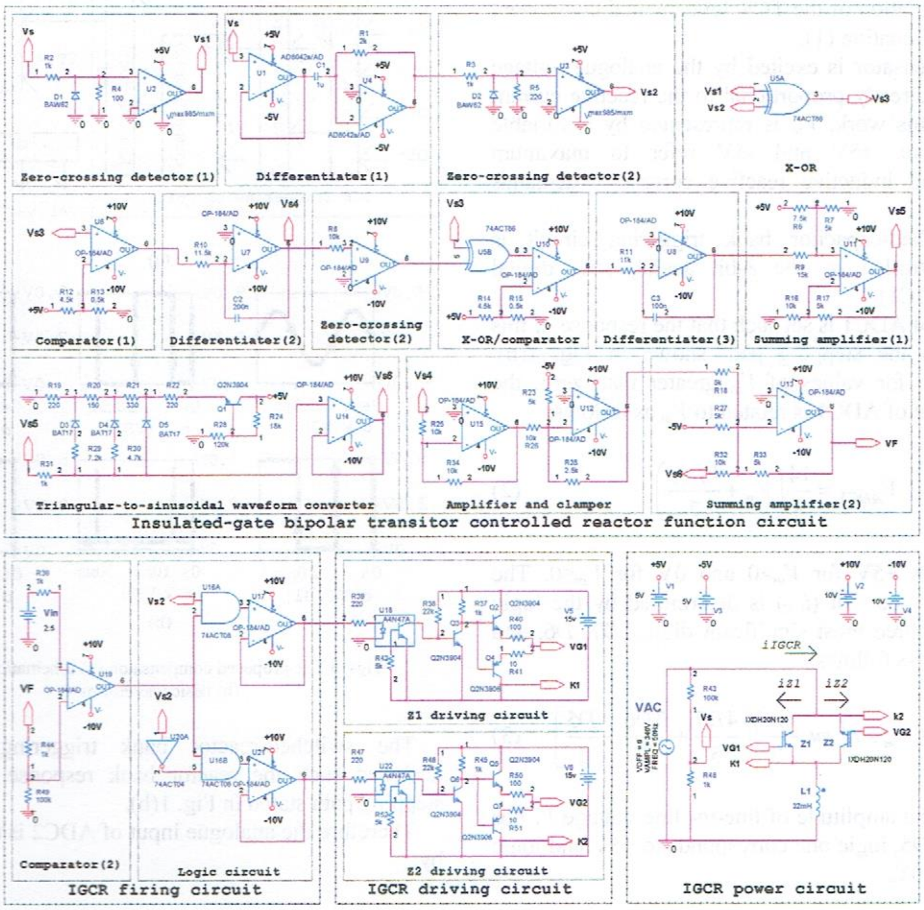


Fig. 4. The IGCR circuit diagram

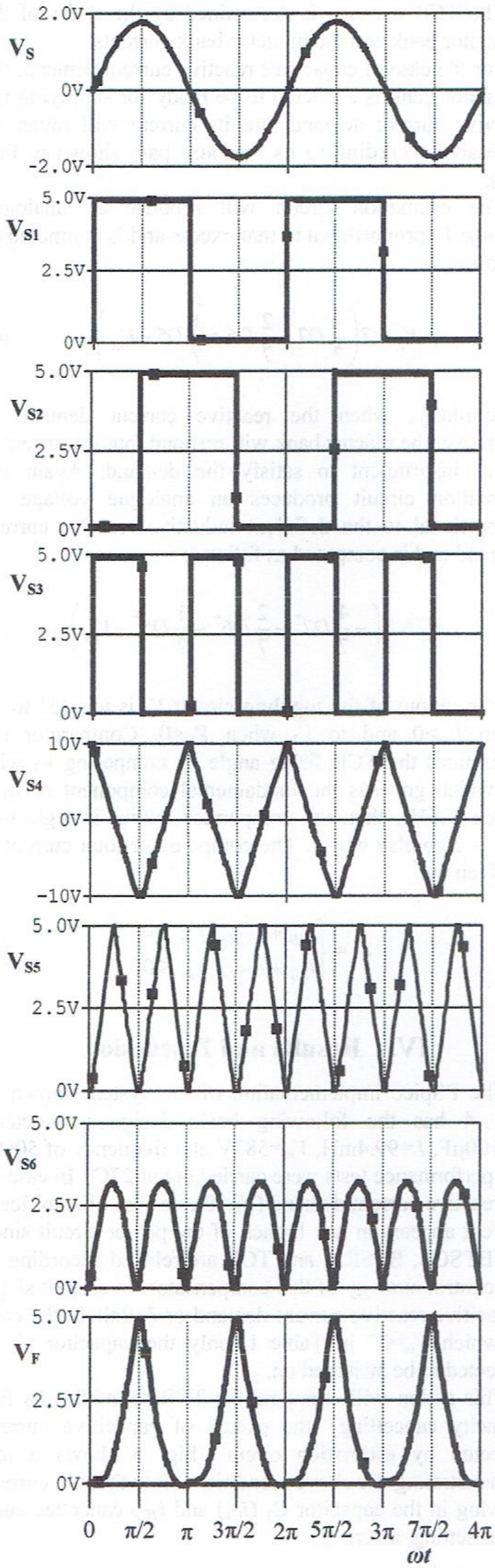


Fig. 5. The IGBT-controlled reactor function circuit waveforms

V. Results and Discussion

The circuit of Fig. 4 was tested on PSpice using an ac voltage of 240 volts at a frequency of 50Hz. The IGCR firing angle σ was varied from 0° to 90° by adjusting V_{in}. Figs. 6 to 11 shows tests at which σ=0°, 18°, 27°, 36°, 45°, and 81°. It is obvious that the fundamental component (I_1) of IGCR current is varied from 100% to 20% of its rated value as σ varies from 0° to 45° respectively. Table I presents a comparison between the theoretical values of I_1 obtained from Equation (1) and the practical results obtained by tests. It is obvious that theoretical and practical results are almost coinciding with each other. Fig. 12 and Fig. 13 show the variations of the IGCR current fundamental component and its most significant odd harmonic contents respectively as the firing angle σ varies from 0° to 90° with a step of 9°. The third, fifth, seventh, and ninth harmonics are the most significant harmonics in TCR and IGCR currents.

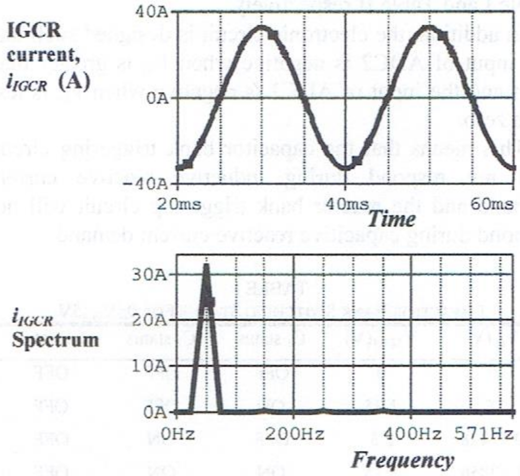


Fig. 6. The IGCR current and its frequency spectrum at σ=0°

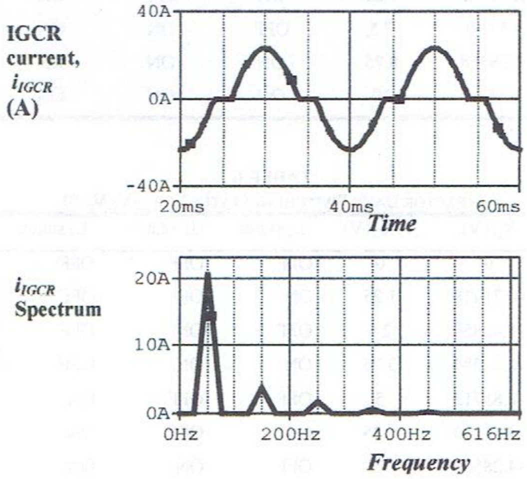


Fig. 7. The IGCR current and its frequency spectrum at σ=18°

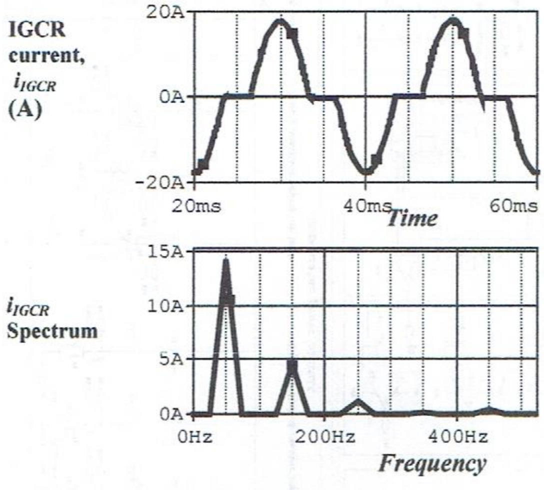


Fig. 8. The IGCR current and its frequency spectrum at σ=27°

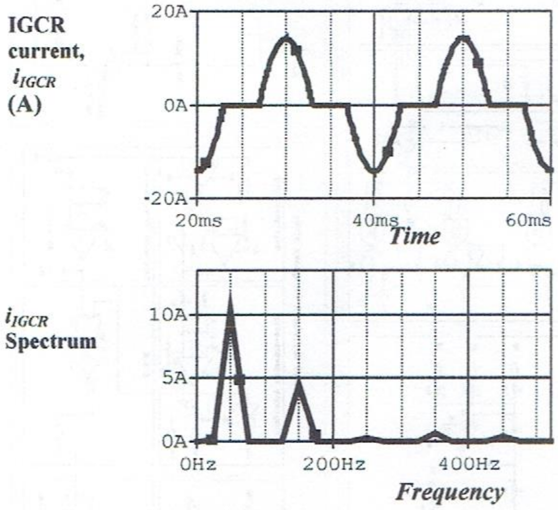


Fig. 9. The IGCR current and its frequency spectrum at σ=36°

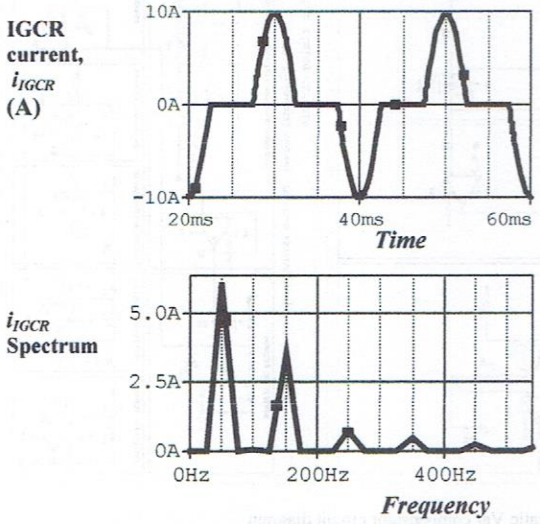


Fig. 10. The IGCR current and its frequency spectrum at σ=45°

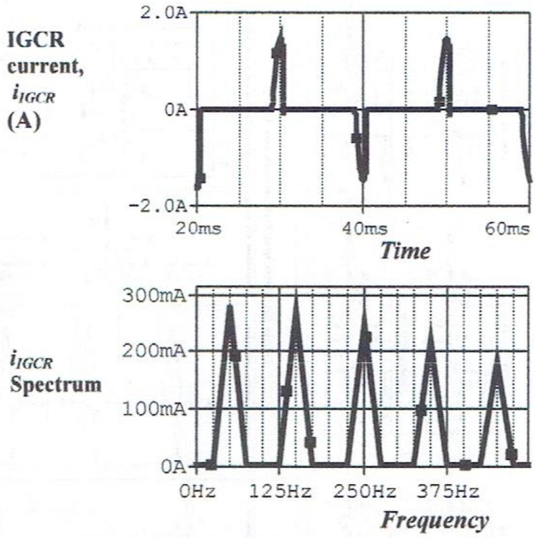


Fig. 11. The IGCR current and its frequency spectrum at σ=81°

TABLE I
THEORETICAL AND PRACTICAL IGCR FUNDAMENTAL CURRENT AS Σ VARIES FROM 0° TO 90° WITH A STEP OF 9°

σ (degrees)	Vin (volts)	I_1 (amperes) Practical values	I_1 (amperes) Theoretical values
0	5	32.9	33.8
9	4.6	26.625	26.645
18	3.57	20.75	20.72
27	2.45	14.5	14.95
36	1.8	10.35	10.06
45	1.1	6.11	6.16
54	0.6	3.25	3.3
63	0.2	1.5	1.44
72	0.06	0.55	0.436
81	0.02	0.2	0.06
90	0	0	0

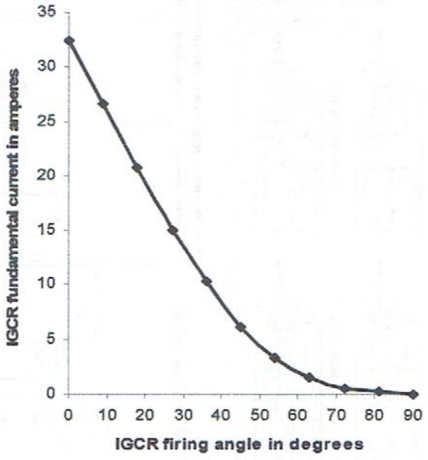


Fig. 12. The IGCR fundamental current as its firing angle (σ) varies from 0° to 90° with a step of 9°

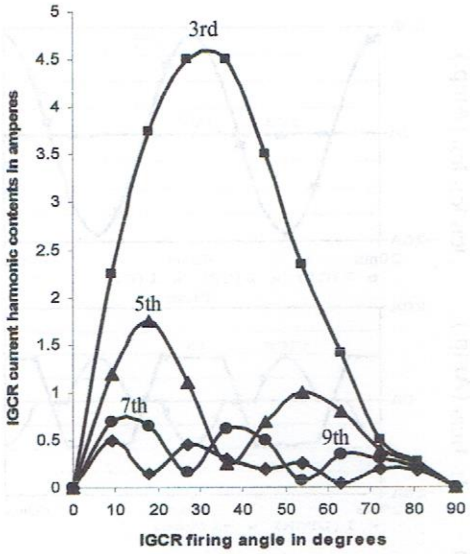


Fig. 13. The IGCR harmonic current components as its firing angle (σ) varies from 0° to 90° with a step of 9°

VI. Conclusion

The IGBT is demonstrated as a good and reliable replacement of thyristor in controlled reactors. The IGCR operation coincides with controlled reactor criterion specified by Equation (1). Since the IGBT can be easily turned on and off, the IGCR offers the feasibility of being conditioned for reducing or eliminating harmonics released throughout its operation. The IGBT has large safe operating area than thyristor so it will be more reliable. The switching losses of the IGBT can be optimized by using suitable gate drive techniques. In addition most IGBTs are equipped with an additional terminal used for detecting its current for protection purposes.

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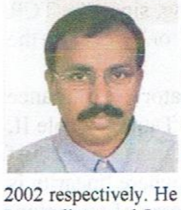

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