Design and Implementation of Firing Circuit for Single-Phase Converter

Tirtharaj Sen, Pijush Kanti Bhattacharjee, *Member, IACSIT*, Manjima Bhattacharya

***Abstract*—The theme of the paper is to design and implement the firing circuit for a converter. The necessity of getting synchronized firing pulses for the gate of the thyristor is discussed. Out of many variety of firing circuits available, the ideas behind are the two most popularly used control circuits that are namely using ramp signal and using cosine signal. It shows how a cosine controls scheme work. Detail description and functioning of each block is explained along with the waveforms at the output of the blocks. Experimental results obtained from oscillographic displays at important points of the circuits are included. In this paper, we fabricate a hardware circuit which implements the cosine control technique, test the circuit and also check that desired gate pulses for the thyristors.**

***Index Terms*—Thyristors or Silicon Controlled Rectifiers (SCRs), Bipolar Junction Transistors (BJTs), Metal Oxide Semiconductor Field Effect Transistors (MOSFETs), Insulated Gate Bipolar Transistors (IGBTs), Single Phase Converter, Comparator, Monoshot, Exclusive Or gate, SR Flip Flop, 555 Timer.**

I. Introduction

Thyristors or Silicon Controlled Rectifiers (SCRs) [1]-[5] are widely used as a switching device in the medium and large power levels starting from few kilowatts to several mega watts at voltage levels of few hundred to several kilo volt levels. Bipolar Junction Transistors (BJTs) and Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) although have very fast switching characteristics compared to SCRs, their uses are limited to medium power levels at few hundred volts.

Insulated Gate Bipolar Transistors (IGBTs) are switching devices which have positive points over the MOSFETs and thyristors. However, their higher cost and inability to work at very high voltages makes SCR a better choice even today, so far as line commutated converters are concerned. In this paper we have designed to implement low cost firing circuit for a single phase line commuted converters.

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A. Thyristor & its conduction

A thyristor or SCR is a four layer device having three junctions J1, J2 and J3. Essentially three terminals named anode, cathode and gate are available as shown in Fig. 1 (below) for external connections. Under the conditions a thyristor either conduct or not conduct, i.e., it allows current either to flow or not, is pictorially depicted in Fig. 1. A thyristor will be in reverse blocking mode if $V_{AK} < 0$, irrespective of the fact that a gate pulse is present or not. On the other hand the thyristor is said to be in the forward blocking mode, when $V_{AK} > 0$ in absence of any gate pulse, some current will flow through the thyristor. In case of the thyristor is turning on either by exceeding the forward break-over voltage or by applying a gate pulse between gate and cathode, called forward conduction mode.

Therefore if we want to use a SCR as a switching device [1]-[5], we must ensure that appropriate gate pulse is supplied between gate and cathode at desired instant of time.

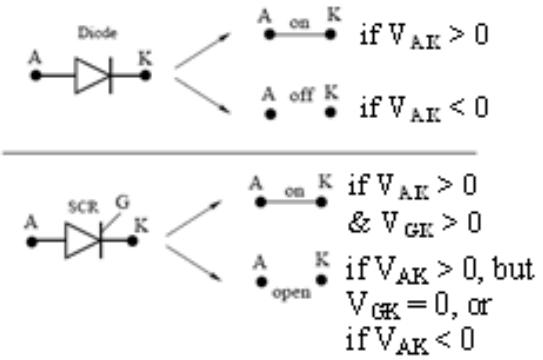


Fig. 1. Symbols for Diode and Thyristor

Some important values of a thyristor is given below:
Voltage rating- 230 V
Current rating- 20 A
Turn on time (T_{ON}) - 1 to 2 μsec
Turn off time (T_{OFF}) - about 70 mA to 100 mA current
Pulse of duration > TON
Conduction voltage drop- about 1.2V

The number of degrees from the beginning of the cycle when the SCR is gated or switched on is referred to as the firing angle, symbol as α, and the number of degrees that the SCR remains conducting is known as the conduction angle.

B. Line Commutated Converters

Conversion of line frequency (50 Hz) a.c. to d.c. [1]-[5] is carried out either by using a single phase bridge converter using four thyristors or 3-phase converter using six thyristors. A single phase fully controlled bridge with four

thyristors is shown in Fig. 2. Appropriate pulses between the gates and cathodes of the thyristors T1 to T2 are to be supplied with a provision to vary the firing angle α.

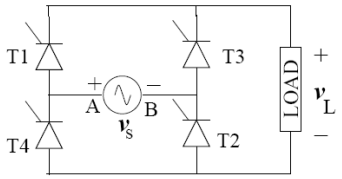


Fig. 2. Fully Controlled Converter

With reference to the single phase converter circuit shown in Fig. 2, we note that when $V_{AB} > 0$ or positive, two diagonally opposite thyristors T1 and T2 are forward biased and other two thyristors T3 and T4 are reversed biased. Therefore during intervals (i.e. 0^0 to 180^0) gate pulses are simultaneously applies to T1 and T2, both start conducting and load voltage $V_L = V_{AB}$ and also T3 and T4 are reversed biased and cannot conduct at that period of time and vice versa (When T3 and T4 are switched on, $V_L = V_{BA}$).

C. Necessity of getting synchronizing pulses

Typical waveform of the supply voltage, gate pulses necessary are shown in Fig. 3. From the Fig. 3, it is quite clear how the firing angle α is to be fixed and measured.

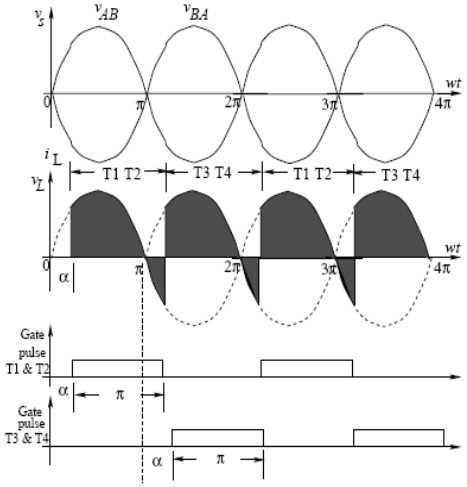


Fig.3. Typical waveforms of a single phase converter

For T1 and T2, α is to be measured from the instant when V_{AB} is zero and going towards positive. Similarly T3 and T4, α is to be measured from the instant V_{BA} is zero and going towards positive. Thus we see that for successful operation of the fully controlled bridge, the gate pulses to be properly synchronized with the a.c. power supply. It is noted that each thyristor conducts for 180^0 only.

D. Expression for the output voltage

Assuming the rms value of the supply voltage to be V_s, the output voltage V_0 can be obtained below. The output current has been assumed to be continuous which is true for most of the cases. ω is the angular frequency of supply a.c. voltage.

$$\begin{aligned} V_o &= \frac{1}{\pi}\int_{\alpha}^{\alpha+\pi} \sqrt{2}V_s \sin\omega t\, d(\omega t) \\ &= \frac{2\sqrt{2}}{\pi}V_s \cos\alpha \\ \therefore\ V_o &= 0.9\, V_s \cos\alpha \end{aligned} \quad (1)$$

E. Popular methods of generating firing pulses

1) Using ramp signal: In this scheme a ramp signal is generated in synchronism with the a.c. supply. Vs by using two comparators and an approximate ramp generator circuit using a transistor and capacitors as described in Fig. 4.

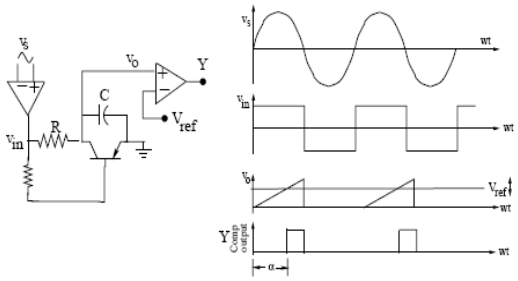


Fig.4. Basic idea of ramp scheme.

The first comparator translates the input sinusoidal voltage into a square wave voltage. When the square wave voltage is high, the transistor (P-N-P type) collector-base junction is forward biased; the transistor is non conducting stage (off) and the capacitor charges exponentially giving ramp rise of the voltage at the output. However, as soon as the square voltage is negative, transistor becomes on due to collector-base junction is reverse biased and the capacitor discharges sharply giving a saw tooth like waveform as shown in Fig. 4. This triangular voltage can now be compared by the second comparator with a variable reference d.c. voltage (V_{ref}) to get the firing pulse signal at Y. The value of α can be varied in the range $0^0 \le \alpha \le 180^0$ by changing the value of the reference voltage (V_{ref}).

2) Using cosine control: In this interesting scheme, the supply voltage V_s is first integrated to obtain a cosine wave as shown in Fig. 5. The cosine wave so obtained is compared with a reference d.c. voltage (V_{ref}). Therefore square pulses will be generated at the output terminal Y of the comparator. The signal at Y is synchronized with the pulse and is delayed from the supply zero crossing by an angle α. Obviously, the value of α can be varied a range of $0^0 \le \alpha \le 180^0$.

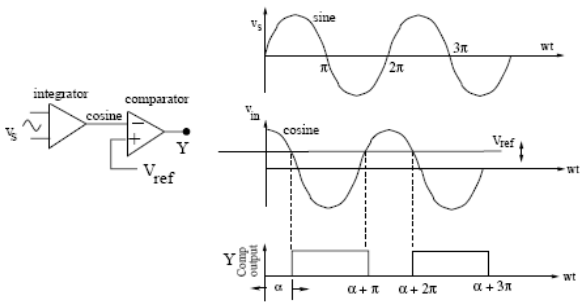


Fig. 5. Basic idea of cosine control scheme.

F. Basic building blocks

Basic blocks which will be necessary to implement any firing control scheme in a converter circuit are shown in Fig. 6. The figure demonstrates with the help of a single line diagram, the major blocks necessary to generate *firing* pulses for any scheme. The converter is organized from a.c. power. Since the firing pulses must be synchronized with the a.c. supply, a.c. power also goes to the *isolation and synchronizing* blocks. Isolation is essential as because the

control circuit uses very low power devices such as various chips, logic gates etc. The logic circuit block uses few logic gates to implement a particular firing scheme. The strength of the pulse obtained from logic gates may not be sufficient to drive the gate of a thyristor, so amplification of the pulse along with isolation is used at final stage as shown Fig. 6.

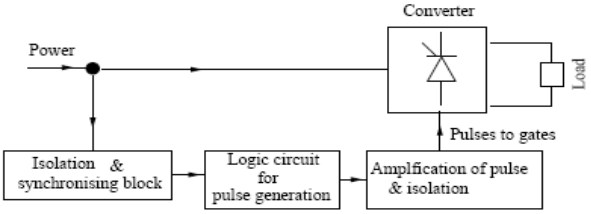


Fig. 6. Basic block of firing control circuit.

II. Block Diagram Representation Of The Cosine Control Scheme

The emphasis of this paper is the implementation of cosine control scheme. We shall first outline the scheme in terms of block diagram and then explain each block in detail. Let V_{ab} be the supply voltage feeding the converter for which the control pulses are to be generated. With the help of a step down centre tapped transformer, V_{ab} is transformed into two power level voltage V_{a0} and V_{b0}. For obvious reason V_{a0} and V_{b0} will be 180^0 out of phase as shown in Fig. 7.

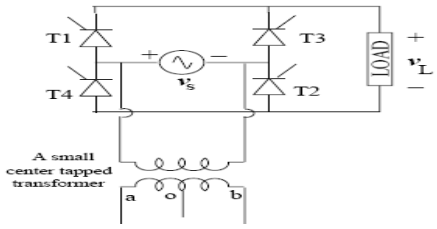


Fig. 7. Generating V_{a0} and V_{b0}

T1 & T2 are to be fired when V_{a0} is positive and T3 & T4 are to be fired when V_{b0} is positive. For T1 & T2 the firing angle α is to be measured from the instant when V_{a0} is zero and increasing in the positive direction. The range of variation of α is 0^0 to 180^0. Similarly for T3 & T4 the firing angle α is to be measured from the instant when V_{b0} is zero and increasing in the positive direction. Basic idea for generating necessary pulses for T1 & T2 and T3 & T4 can be understood by referring figures 7, 8 and 9.

With reference to Fig. 8 the signal V_{a0} is integrated with the help of Integrator -1 and a cosine wave will be obtained. This cosine wave is compared with a variable d.c. voltage V_r using a comparator-1.

Noting that V_r is connected to the +ve terminal of the comparator-1, the output of the comp-1 will be square wave and it goes to high state from the instant when V_r becomes greater than the cosine voltage value. However the width of the pulse will vary as V_r is varied. Our first aim will be to make the width of the pulse to be 180^0. This is achieved in the following way. The output of the Comp-1 is fed to a block mono-1. Output of the mono will be a pulse of small width at positive going edge of the input square wave. The output of mono-1 will thus give small pulses separated by 360^0.

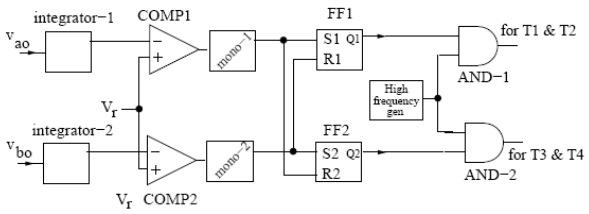


Fig. 8. Basic blocks for cosine control scheme

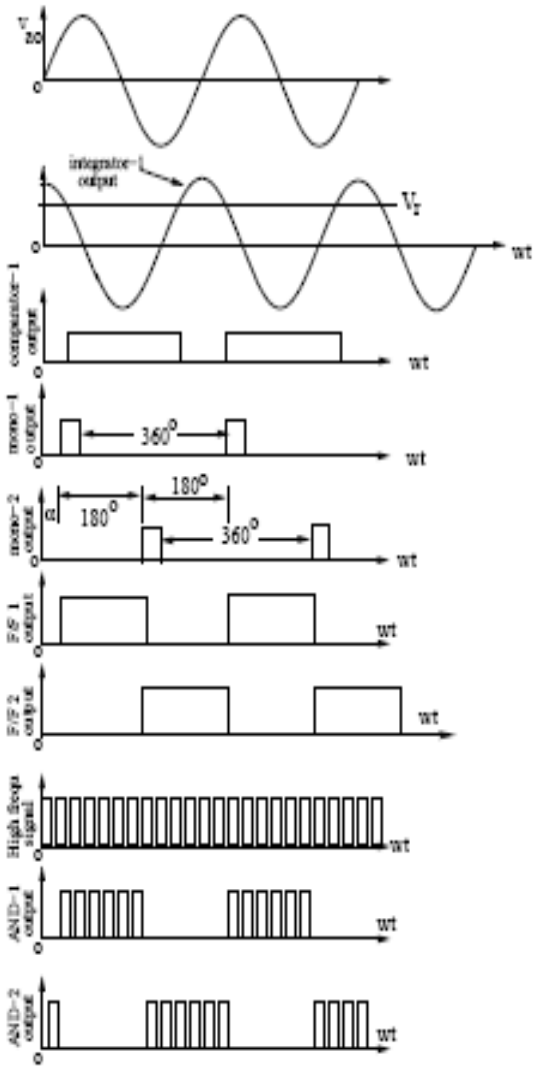


Fig. 9. Waveforms at different points in the circuit of Fig.8

The voltage V_{b0} is similarly processed, i.e., it is integrated then compared with the same variable d.c. with the help of comparator-2, output of COMP-2 will be a square wave and will be shifted by 180^0 from the output square wave of COMP-1. This is because of the fact that V_{b0} lags V_{a0} by 180^0. The output of the COMP-2 is now fed to a block mono-2. Output of mono-2 will be a pulse of small width at positive going edge of the input square wave.

The output of MONO-2 will thus give small pulses separated by 360^0. This is important to know that the fixed width pulse waveforms at the output of mono-1 and mono-2 are shifted by 180^0 as shown in Fig. 9. The outputs of mono-1 and mono-2 can be used in conjunction with to two S-R flip flops so as to generate two square waves each having a fixed width of 180^0 and mutually separated by 180^0.

III. Description Of The Each Block

In this section detail of each block will discussed separately. The type of components used and their connections will also be explained.

A. Input transformer to get V_{a0} and V_{b0}

A 220/6-0-6 V 50 Hz control transformer is selected for the purpose of stepping down the 220 V supply to a level of 6-0-6 V with the help of the centre tapped secondary as shown in Fig. 10.

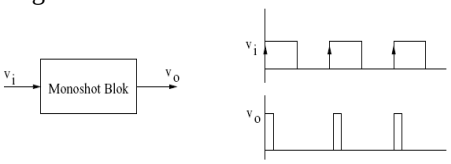


Fig. 10. Input transformer for the control circuit.

B. Integrator to get cosine wave

Popular IC 741 is used along with some resistor and capacitor to realize integrator function out of it. The values of different circuit parameters are shown in Fig. 11. ±12 V d.c. supply required for the chip is obtained from a separate d.c. source. The ground point of the d.c. supply is connected to the common ground point zero (0) of the center tapped transformer. Signal V_2 $v_2 = \int v_{ao}\, dt.$ will be obtained as integration of small V_1, i.e., For our purpose we will get small V_2. $v_2 = \int v_1\, dt.$

Another identical integrator is used to integrate V_{b0} as explained earlier.

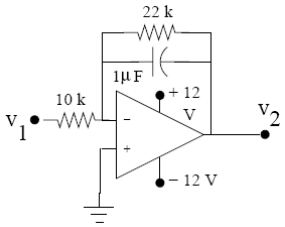


Fig. 11. Integrator using OP AMP 741.

C. Comparator producing variable width pulse

An OP AMP (741 IC) is used to realize the comparator block by inverting terminal IC 741, the variable d.c. voltage V_r is applied to the non inverting terminal or positive terminal, the cosine signal is obtained from the output of the integrator block as connected. V_r is fed from the output of a 10 KΩ variable resistor terminal. The input to the pot is the ±12 V supply as shown in Fig 12.

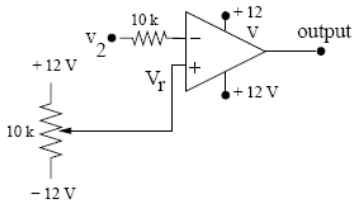


Fig. 12. Comparator using OP AMP IC 741.

D. Monoshot block using Exclusive OR Gate

A Monoshot block is supposed to produce thin pulses when the input rectangular input signal V_i changes state from 0 to 1 as shown in Fig. 13, a Monoshot block is shown with input signal V_i and with the desired output signal V_0.

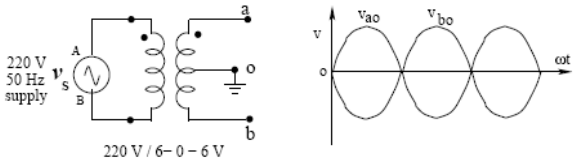
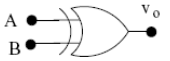


Fig. 13. Characteristics of a Monoshot

In this project work under this paper, the Monoshot is implemented in an interesting way by using Exclusive OR Gate. The truth table and representation of Exclusive OR Gate is shown in Fig. 14. In Exclusive OR gate, the output is high or 1 when one of the inputs is high (1) or odd matching with the others and the output is low or 0 when both the inputs are same or even nature.



A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

Fig. 14. Exclusive OR Gate & its Truth Table

E. SR Flip flops to get 1800 width pulse

In the previous section we have seen that the variable width pulse obtain from the comparator output is converted into a train of thin pulses separated by 360^0 at the output of the Monoshot in Fig. 15.

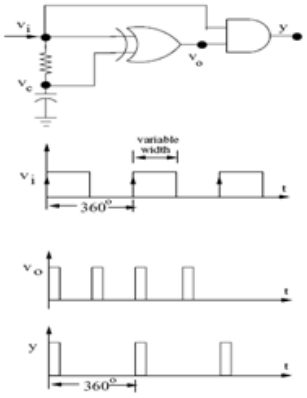


Fig. 15. Final circuit for Monoshot

F. ANDing the rectangular pulse with frequency using 555 timer

The rectangular voltage signals obtain from the flip flops 1 and 2 are complementary which means separated by 180^0 as desired. In our case where the supply frequency is 50 Hz, the time period of the signals will be 20 ms and for 10 ms it will remain high and for rest of the 10 ms it will be low. Outputs of the flip flops cannot however, be connected directly to between the gate and cathode of a thyristor, and because the output from a TTL (Transistor-Transistor-Logic) chip will not be able to supply the necessary current required by the gate circuit of a thyristor. Apart from this, we require isolation between the control circuit and power circuit. Therefore with the help of a transistor and a pulse transformer these two objectives of strengthening the pulse and providing the isolation are met. The idea is depicted in

Fig. 16.

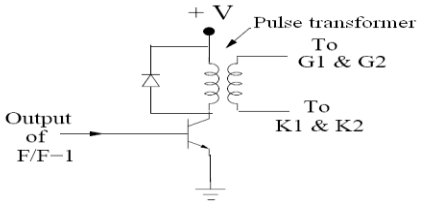


Fig. 16. Showing amplification & isolation circuit.

G. Complete circuit diagram

Putting all the blocks together, the complete connection with circuit diagram of the circuit is shown in Fig. 29 at the end.

H. ±12 V Power supply circuit

As seen from the circuit shown in Fig. 17 a ±12 V d.c. power supply is required for supplying various chips used. To make the set up self content, standard power supply chips of numbers IC 7812 and IC 7912 are used in conjunction with a centre tapped transformer, diode bridge rectifier and filter capacitors as shown in Fig. 17.

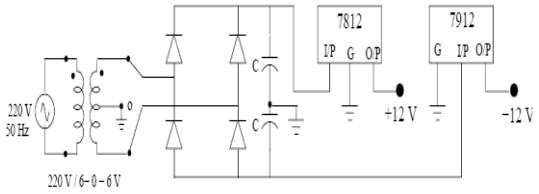


Fig. 17. Circuit for ± 12 V Power supply.

IV. Methodology For The Proposed Work

A. Description for IC chips used:

The following things are elaborated for the method using:

i. IC 4043 is used for realizing SR flip flop. In this chip 4 separate SR flip flops are available. This chip works with a d. c. supply of + 3 V to + 15 V. In our case power supply used is + 12 V. The chip has 16 pins as shown in Fig 18.

ii. IC 4081 is used for realizing AND gate. In this chip 4 separate AND gates are available. This chip works with a d.c. supply range of + 3 V to +15 V. In our case power supply used is +12V. The chip has 14 pins as shown in Fig. 19.

iii. IC 4070 is used for realizing Ex-OR gates. In this 4 separate Ex-OR gates are available. This chip works with a d.c. supply range of + 3V to + 15 V. In our case power supply used is +12 V. The chip has 14 pins as shown in Fig 20.

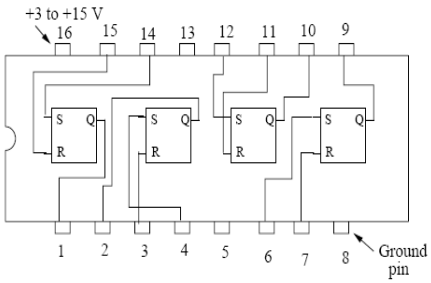


Fig- 18 Pin description of IC 4043

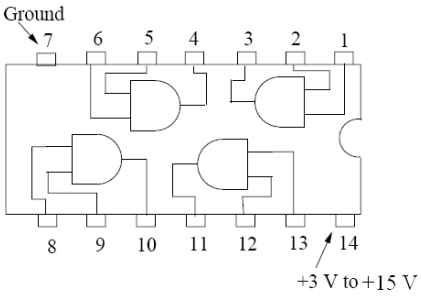


Fig. 19. Pin descriptions IC 4081

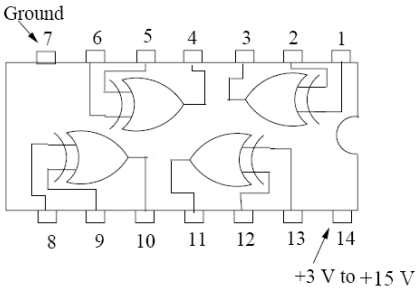


Fig. 20. Pin descriptions IC 4070

B. Components used

The followings components are used for the circuit:

i. Two centre tapped transformer: 220 V/ 6-0-6 V.

ii. Two IC 741 OP AMP for two integrators one corresponding to V_{a0} and the other corresponding to V_{b0}.

iii. Two IC 741 OP AMP for two comparators.

iv. One IC 4070 which houses 4 EX-OR gates.

v. One IC 4081 which houses 4 AND gates.

vi. One IC 4043 which houses 4 SR flip flops gates.

vii. One 555 timer for generating high frequency pulses.

viii. Number of resistors and capacitors of various values as detailed shown in the circuit.

ix. Few diodes for making the ± 12 V power supply and also to clip the negative half of rectangular pulse obtained at the output of the comparator.

x. One 10 KΩ pot for having variable d.c. voltage V_r .

xi. Two rectangular power supply chips numbered IC 7812 and IC 7912 for ± 12 V supply.

V. Experimental Results

The circuit fabricated is tested for important waveforms at various points. The primary of the input isolation transformer is energized with 220 V, 50 Hz source. The secondary output voltages of V_{a0} and V_{b0} are recorded in an oscilloscope and shown in Fig. 21.

As told earlier the signal V_{a0} is integrated to obtain $\int V_{a0}\, dt$ with the help of an IC 741 op amp, i.e., if $V_{a0} = V_{max} \cos \omega t$. The obtained waveforms at the input and output of the integrator are shown in Fig. 22. In Fig. 23 the output waveforms of comparator and Exclusive OR gates are shown.

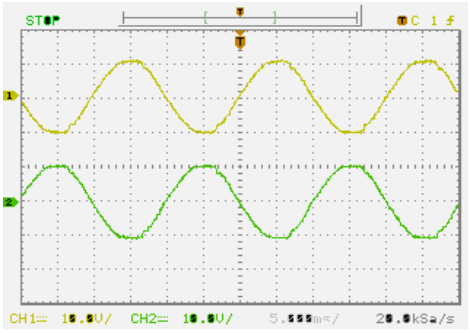


Fig. 21. Waveforms of Va0 and Vb0

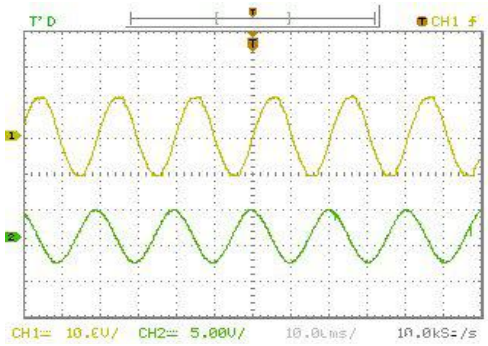


Fig. 22. Waveforms V_{a0} and $\int V_{a0}\,dt$

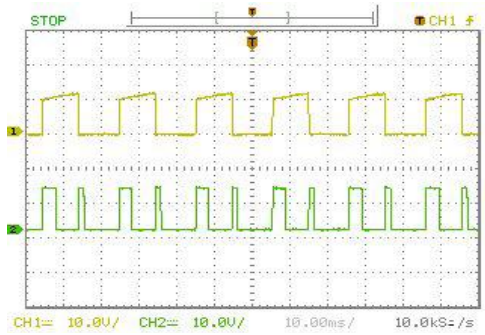


Fig. 23. Output of Comparator and EX-OR gate

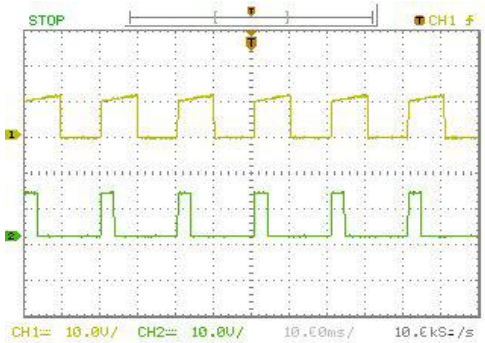


Fig. 24. Output of Comparator and first AND gate.

It can be noted that we get train of thin pulses both at the positive and negative edge of the comparator square wave output as explained. Since our intention is to obtain thin pulses only at the positive edges, output of the XOR gate is ANDed with the comparator output voltage as detailed in earlier sections which is given in Fig. 24.

We know the output of the SR Flip Flop will give square pulses of width 180^0, i.e., 10 ms. However such a wide pulse is not suitable for a pulse transformer as explained. So this wide width continuous pulse is converted into chopped pulses by ANDing the output of SR Flip Flop and the output of 555 timer chip connected in astable mode. In Fig. 25 the output of the SR Flip Flop and the output of 555 timer chip are shown. In Fig. 26 output of the SR Flip Flops are ANDed with the output of 555 timer chips. It can easily be seen that after ANDing the continuous wide pulse become thin pulse in nature.

The final waveforms of getting two complementary separated by 180^0 widths chopped pulses one corresponding to V_{a0} and another to V_{b0} are shown in Fig. 26. In fact these two complementary signals are the gate signals of the thyristors.

To demonstrate at what firing angle α the bridge is operating, the waveforms of V_{a0} and the final pulses synchronized with V_{a0} are shown in Fig 27.

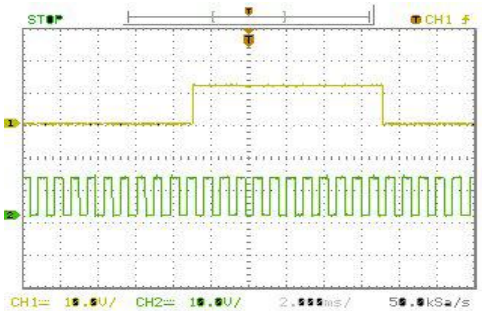


Fig. 25. Output of SR Flip Flop and 555 timer chip

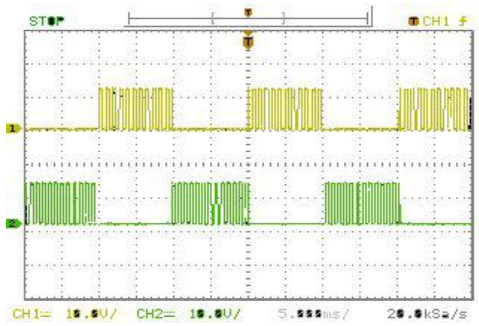


Fig. 26. Final gate pulses for thyristors.

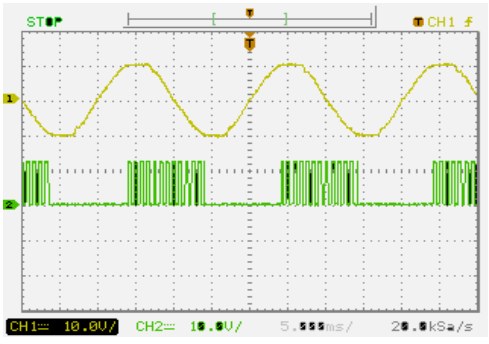


Fig. 27. Waveforms of the measuring angle α.

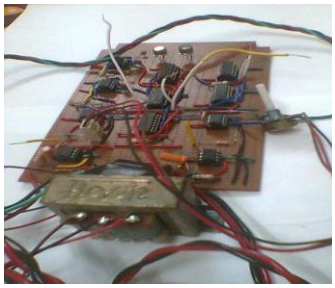


Fig. 28. Practical firing circuit

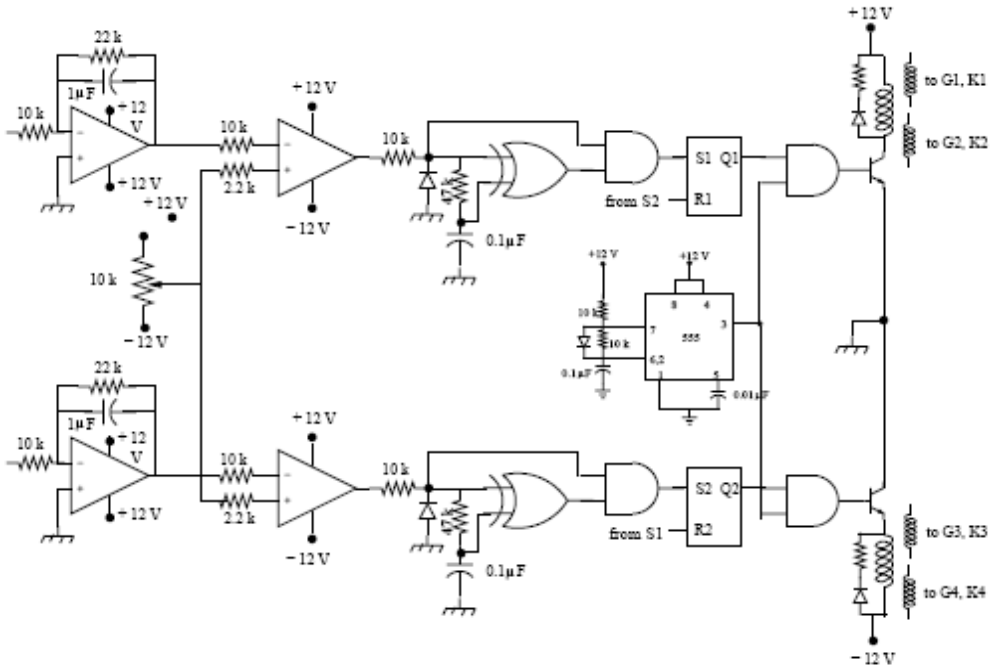


Fig. 29. Complete circuit diagram of cosine control scheme for firing circuit of single-phase converter.

VI. Conclusion

In this project work an attempt has been made to implement and test a firing circuit for a fully controlled single phase converter. The circuit is fabricated using components such as resistors, capacitors and some standard IC chips. The circuit is first fabricated on bread board and then tested. Now from all of this, following conclusions can be drawn that cosine control scheme for firing circuit is studied and understood. Various blocks necessary to implement the scheme are decided. We procure the relevant ICs and electronics components. This is done in a correct way for implementing in the circuit. The circuit successfully generated complementary pulses as desired and the waveforms recorded for future realistic studies.

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