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SPEED CONTROL OF A SEPARATELY-EXCITED DC MOTOR

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Abstract

This paper proposes two methods of speed controlling for separately excited dc motor. The methods are provided with their schematics and block diagram, the construction of each scheme was made in breadboard at the first. This eases the testing and troubleshooting of the circuit, and each scheme was constructed in separate breadboard. The results was obtained by using the oscilloscope and the digital multimeter, after assuring of the results obtained, the next step was to fabricate the PCB and demonstrate it in separate boards and jumper wires were used to route the connectors. It was found that the results obtained after fabricating the PCB is similar to that while testing on the breadboard. Afterwards testing the motor was done for the both schemes. The two methods are contributed to the same major factor on controlling the speed of the dc motor, and it was achieved by varying the firing angle, and hence triggers the SCR. Regardless the construction of each scheme, the results obtained proves the theoretical part, and scheme 2 is considered cost effective than scheme 1 and on the other hand it is more reliable in term of size, construction and components availability and accessibility.

Keywords*:* Thyristor, Firing angle, Half wave controlled rectifier.

1.0 Introduction

An electric motor is an electromechanical device that converts electrical energy to mechanical energy. Electric motors are mainly divided into two types namely, DC motors and AC motors. However, the general working mechanism is the same for all motors. Speed control of an electric motor is very important in many systems and applications such as fans and washing machines. Systems used for motion control are called drives. Hence, drives that use electric motors to control motion are called electric derive [1]. Because they are easy to control, DC motors are widely used in applications where the speed of the motor is to be controlled. DC motors are, in turn, divided into several sub-categories, namely, series motors, long-shunt compound motors, short-shunt compound motors and separately excited DC motors. Two methods of speed control of separately excited DC motors are applicable when the separately excited DC motor is supplied by a constant voltage, namely, armature control method and field control method [2].

In armature control method, a resistor can be installed in series with the armature to vary the voltage supplied to the armature. Using this method we can have a speed that is less than the nominal speed of the motor. However, lot of power lost in the series resistor makes this method inefficient.

In field control method, the idea is in controlling the supplied voltage to the field winding. The main concept used in this method is the inverse proportionality between the motor's speed and the amount of flux. When the supply voltage is small, amount of flux is small as well, and hence the motor's speed is high [2]. Using this method, a speed higher than motor's nominal speed can be achieved.

Some important applications of DC motors speed control are rolling mills, paper mills, mine winders, hoists, machine tools, traction, printing presses, textile mills, excavators, and cranes. Fractional horsepower dc motors are widely used as servo motors for positioning and tracking [3] [4].

2.0 A separately-excited DC motor circuit components and its operation

2.1 Controlled rectifier

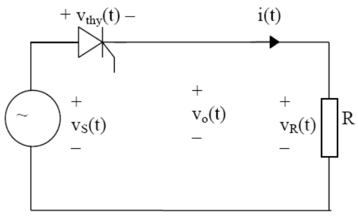

Figure 1: Half-wave controlled rectifier

A single phase half controlled rectifier as shown in Figure 1 above is used in our paper. Thyristor is a controlled rectifier in the circuit. It has two main terminals which is anode, cathode and a controlling gate terminal. A thyristor can only forward bias; therefore the current can only flow in the forward direction, which is from anode to cathode [4]. A thyristor will conduct in the forward direction when a gate current is applied to the gate terminal. However, it will block the forward current when a smaller current pulse enters the gate terminal. Therefore, the gate terminal plays an important role to switch on or off the thyristor. With that, a thyristor is different compared to a diode, and works as a controlled rectifier [3].

Furthermore, when we increase the gate pulse, it will reach a “latching” level. At this state, even if we remove the gate pulse, but the thyristor will still remain on. Once established, the anode-cathode current cannot be interrupted by any gate signal. We can only switch off the thyristor with an external switch. In other words, the non-conducting state can only be restored after the current flowing through the thyristor is reduced to zero. For example, to switch off the thyristor, we must switch off the power supply. Moreover, a thyristor acts as a close switch when conducting. It only has a forward voltage drop of 1V or 2V over wide range or current. Despite the low volt drop in the “on” state, heat is dissipated. Therefore an efficient heat sink is required, to cool down and protect the thyristor.

Power transistors such as power BJT can control the current flow through by adjusting the base current; therefore it is better than thyristors. However, we use thyristor instead of power transistor because a few reasons. Among the reasons is because the thyristor is **lower cost compare to power BJT**. On the other hand, the thyristor has the **higher power capability** compare to BJT. Thyristors allows a very larger current and power to flow through. Furthermore, thyristors have a **low triggering power**. In other words, a thyristor needs a low gate pulse to switch on. Besides that, a thyristor also have a **low on-state voltage drop [5]**.

2.1.1 Single Phase Half-Wave Controlled Rectifier

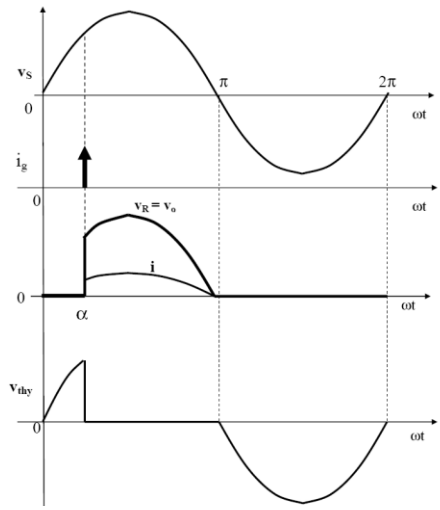

Figure 2: Waveforms for the single-phase half wave circuit

In figure 3, the first waveform shows the voltage input, the second waveform shows the output current from the thyristor and the 3rd waveform shows the load voltage of the circuit. We can observe that there are only the positive half-cycles of the AC supply voltage to the load. However, it is not smooth, but is DC in the sense that it has a positive mean value. By changing the firing angle (α), which measured from the zero crossing of the supply voltage, the mean voltage can be controlled. The circuit is Figure II is called "single-pulse" or half-wave circuit because of the output waveform shown in the Figure III gives only one peak in the rectified output for each complete cycle of the source [6] .

2.1.2 Calculation:

a. Half wave controlled rectifier:

$$V_R = \frac{1}{2\pi}\int_0^{\pi} Vm\sin\theta\delta\theta$$
$$= \frac{1}{2\pi}Vm[-\cos\theta]_0^{\pi}$$
$$= \frac{2Vm}{2\pi}$$
$$= \frac{Vm}{\pi} \quad (1)$$

Since $V_m = \sqrt{2}Vrms$,

Therefore,

$$V_R = \frac{\sqrt{2}}{\pi}Vrms \quad (2)$$

b. Half wave controlled rectifier with firing angle α:

$$
\begin{aligned}
V_R &= \frac{1}{2\pi}\int_{\alpha}^{\pi} Vm \sin\theta\delta\theta \\
&= \frac{1}{2\pi} Vm[-\cos\theta]_{\alpha}^{\pi} \\
&= \frac{Vm}{2\pi}(1+\cos\alpha) \\
&= \frac{Vrms}{\sqrt{2}\pi}(1+\cos\alpha) \qquad (3)
\end{aligned}
$$

2.2 Basic structure and operation of thyristor

Thyristors are usually three-terminal devices that have four layers of alternating p-type and n-type material (i.e. three p–n junctions) comprising its main power handling section. The thyristor circuit symbol is shown in figure 3(a). Generally, the operation of thyristors is as follows; when a positive voltage is applied to the anode (with respect to cathode), the thyristor is in its forward-blocking state. The center junction, J2 (see Figure 3(b)) is reverse biased. In this operating mode the gate current is held to zero (open circuit). In practice, the gate electrode is biased to a small negative voltage (with respect to the cathode) to reverse bias the GK-junction J3 and prevent charge-carriers from being injected into the p-base. In this condition only thermally generated leakage current flows through the device and can often be approximated as zero in value (the actual value of the leakage current is typically many orders of magnitude lower than the conducted current in the on-state). As long as the forward applied voltage does not exceed the value necessary to cause excessive carrier multiplication in the depletion region around J2 (avalanche breakdown), the thyristor remains in an off-state (forward-blocking). If the applied voltage exceeds the maximum forward-blocking voltage of the thyristor, it will switch to its on-state. However, this mode of turn-on cause non-uniformity in the current flow, is generally destructive, and should be avoided. When a positive gate current is injected into the device, J3 becomes forward biased and electrons are injected from the n-emitter into the p-base. Some of these electrons diffuse across the p-base and get collected in the n-base. This collected charge causes a change in the bias condition of J1. The change in bias of J1 causes holes to be injected from the p-emitter into the n-base. These holes diffuse across the n-base and are collected in the p-base. The addition of these collected holes in the p-base acts the same as gate current [7]. The entire process is regenerative and will cause the increase in charge carriers until J2 also becomes forward biased and the thyristor is latched in its on-state (forward-conduction) [5] [6]. The regenerative action will take place as long as the gate current is applied in sufficient amount and for a sufficient length of time. This mode of turn on is considered to be the desired one as it is controlled by the gate signal.

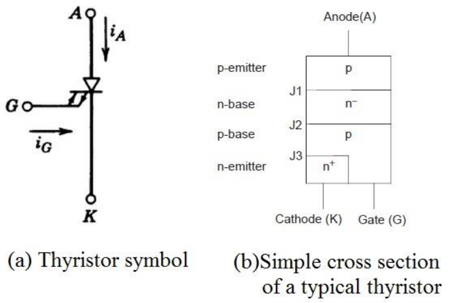

Figure 3: Circuit symbol and cross section of thyristor

The uniqueness of the thyristor lies principally in its Volt-Amp characteristic, which shown in Figure 4. In the reverse direction the thyristor appears similar to a reverse- biased diode, which conducts very little current until avalanche breakdown occurs. Besides that, SCR can exhibit very high internal impedance, with perhaps a slight reverse blocking current. However, if the reverse breakdown voltage is exceeded, the reverse current rapidly increases to a large value and may destroy the SCR. In the forward bias condition (gate is grounded), the internal impedance of the SCR is very high with a small current flowing called the forward blocking current. When the forward voltage ($+V_F$) is increased beyond the forward break over voltage point, an avalanche breakdown occurs and the current from the cathode to anode increases rapidly. A regenerative action occurs with the conduction of p-n junctions and the internal impedance of the SCR decreases. If the gate current is allowed to flow, the forward break over point will be smaller. The larger the gate current flows, the lower the point at which forward break over will occur as illustrated in Figure 4 bellow. Normally, SCRs operated with applied voltage lower than the forward break over voltage point (with no gate current flowing) and the gate triggering current is made sufficiently large to ensure complete turn on. Figure 4 bellow illustrates the volt-ampere characteristics curve of an SCR. The vertical axis (+I) represents the device current, and the horizontal axis (+V) is the voltage applied across the device anode to cathode. The parameter I_F defines the RMS forward current that the SCR can carry in the ON state, while V_R defines the amount of voltage the unit can block in the OFF state [7] [8].

The holding current I_H, for more details, represents the minimum current that can flow through the thyristor and still maintain the device in the ON state. This current value and the accompanying voltage across the device, termed the holding voltage $V_{H'}$ represent the lowest possible extension of the ON-state portion of the Volt-Amp characteristic.

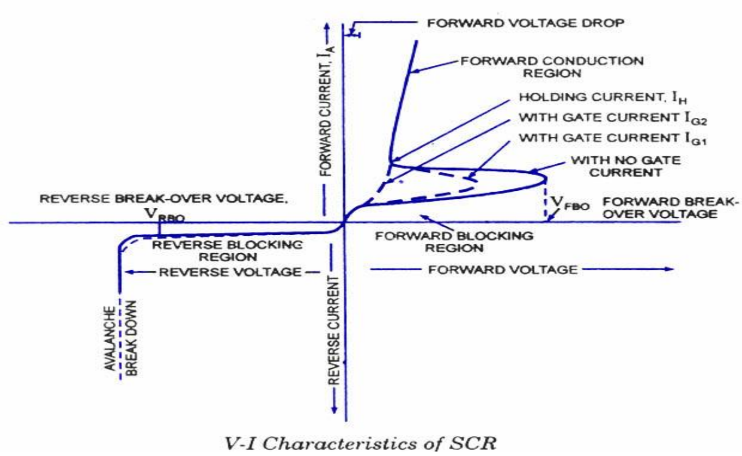

Figure 4: Volt-Amp Characteristics of SCR

2.3 Phase Control

In SCR Phase Control, the firing angle which the SCR is triggered, determines the amount of current which flows through the device during the half-cycle. It acts as a high-speed switch which is open for the first part of the cycle, and then closes to allow power flow after the trigger pulse is applied. Figure 2.5.1, shows the AC voltage waveform being applied with a gating pulse at 45 degrees. There are 360 electrical degrees in a cycle; 180 degrees in a half-cycle. The number of degrees from the beginning of the cycle until the SCR is gated ON is referred to as the firing angle, and the number of degrees that the SCR remains conducting is known as the conduction angle. The earlier in the cycle the SCR is gated ON, the greater will be the voltage applied to the load. Figure 5 shows a comparison between the average output voltages for an SCR being gated on at 30 degrees as compared with one which has a firing angle of 90 degrees. Note that the earlier the SCR is fired, the higher the output voltage applied to the load. For accurate SCR gating, the Firing Circuit must be synchronized with the AC line voltage being applied anode to- cathode across the device. Without synchronization, the SCR firing would be random in nature and the system response variable. In closed-loop systems, such as motor control, an Error Detector Circuit or/ Zero crossing detector Unit computes the required firing angle based on the system set-point and the actual system output [6] [9]. The firing circuit is able to sense the start of the cycle, and, based on an input from the Error Detector, delaying the firing pulse until proper time in the cycle will provide desired output voltage.

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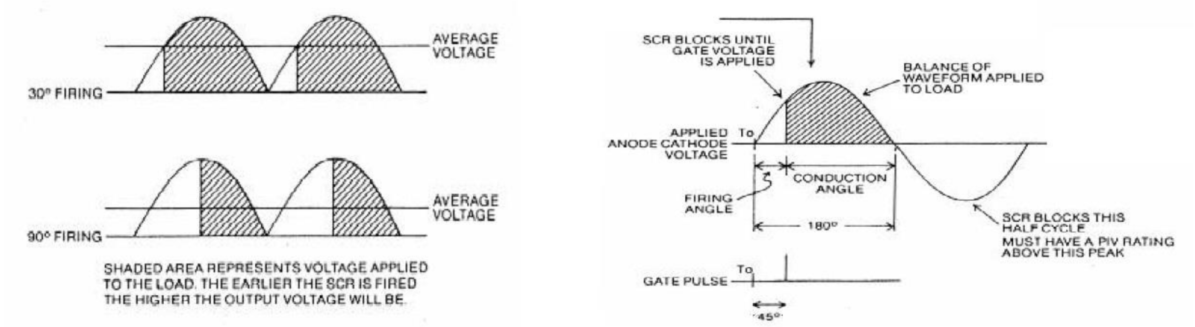


a. Voltage waveform at 45 degrees

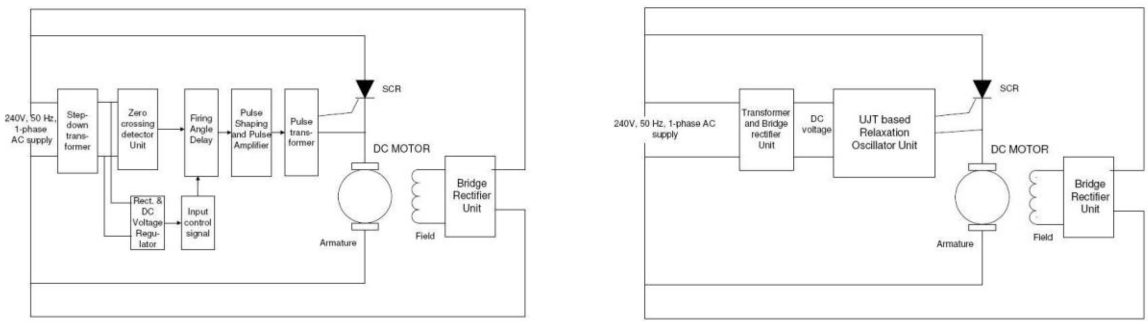
b. Voltage waveform at 30 and 90 degrees

Figure 5: A comparison between the average output voltages for an SCR being gated on at 30 and 90 degrees firing angle.

3.0 Details of the design

3.1 Circuit construction

For the firing angle control, information of zero crossing point of an AC input is vital. This project requires student to design circuit for each blocks as shown in figure 6 (i.e. Zero crossing detector, firing angle circuit and pulse shaping). The firing angle can be varied from 0 to 180 degree through a potentiometer. The block diagram of the overall drives system to be developed under this project is shown in figure 6 scheme 1.



Scheme 1

Scheme 2

Figure 6: The two schemes for speed control of DC separately excited motor

UJT based Relaxation Oscillator can be used for providing triggering pulses to the gate of the SCR as shown in figure V above. Depending upon the delay angle, the speed of the DC motor varies. We then design and construct the complete circuit including dc power supplies as shown if figure 6 scheme 2 above. Next we will go in detail to explain each block in block diagrams above.

3.2 Transformer and bridge rectifier unit

This section is consisting of the step down transformer, half wave rectifier circuit and the DC voltage regulator unit. The step down transformer rating as, primary of: 230V and the Secondary: 12V-0-12V (AC), the secondary winding of the transformer is connected to rectifier unit, A transformer rectifier unit (TRU) is used to convert AC into relatively smooth DC. This device takes the mains 240 V-AC and converts it to approximately 12 V-DC to supply the main circuit. This is achieved by a transformer, which first steps down the AC voltage to a reasonable level. Then converts it via a bridge rectifier and regulate it via the voltage regulator LM7812 assembly into DC. Diodes in their basic forms are used for rectification (or conversion) of AC into DC, the diodes offer an easy path for current to flow in one direction and offer a high resistance path in the opposite direction. The (LM7812) Linear IC Voltage Regulator, used to maintain the output voltage from the dc supply over a wide range of load and line variations. One of the popular positive fixed three-terminal voltage regulators is known from the first two digits **78**XX series and the other two digits XX**12** represent the regulated output voltage [10]. Figure 7 represents the DC voltage regulator schematic circuit.

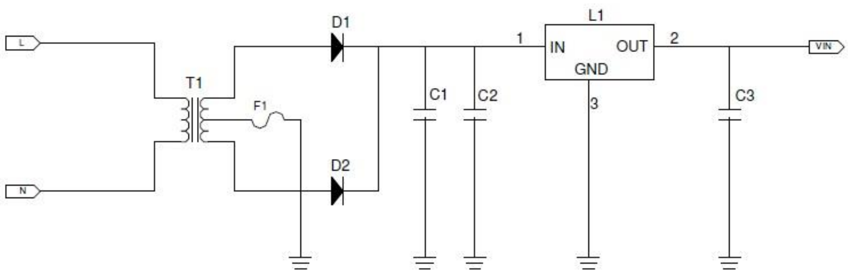


Figure 7: The DC voltage regulator schematic circuit

The two capacitors C1 and C2 in (Figure 7) act as a filters, C1 is used to smooth the dc voltage and remove the unwanted lower frequency noise to the unregulated power supply while C2 is used to provide rejection of transients in the input of the unregulated supply. Capacitor C3 is commonly used to provide improved output impedance, rejection of transients and shorting any very high frequency to ground and preventing it from getting back into the power supply line and travelling to other circuits. For simple explain on the system of the bridge rectification unit, Figure 8 shows a simple block diagram of a regulated power supply system.

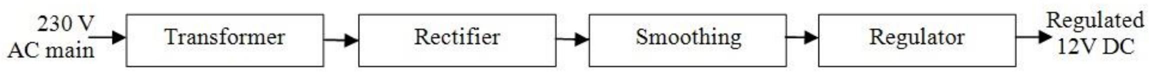


Figure 8: Block diagram of a regulated power supply system

3.3 Zero crossing detector & pulse generator circuit

This part considered as the important part of Scheme 1, where mainly the design require to put in considerations the design criterion of the zero crossing detector unit, the firing angle delay and the input control signal. The IC used is the phase control IC (TCA785) which is shown in figure 9. The synchronization signal is obtained via a high-ohmic resistance (R_5: 220k) from the line voltage (voltage V_5: 230V AC). A zero voltage detector evaluates the zero passages and transfers them to the synchronization register. This synchronization register controls a ramp generator, the capacitor C_{10} of which is charged by a constant current (determined by R_9). If the ramp voltage V_{10} exceeds the control voltage V_{11} (triggering angle α), a signal is processed to the logic. Dependent on the magnitude of the control voltage V_{11}, the triggering angle α can be shifted within a phase angle of 0 deg to 180 deg, and this can be fulfilled by using a potentiometer. For every half wave, a positive pulse of approximate 30ms duration appears at the outputs Q1 and Q2. The pulse duration can be prolonged up to 180 deg via a capacitor C_{12}. If pin 12 is connected to ground, pulses with duration between α and 180 deg will result the outputs Q1' and Q2' supply the inverse signals of Q1 and Q2. A signal of α +180 deg which can be used for controlling an external logic is available at pin 3. A signal which corresponds to the NOR link of Q1 and Q2 is available at output QZ (pin 7). The inhibit input can be used to disable outputs Q1, Q2 and Q1', Q2'. Pin 13 is used to extend the outputs Q1'and Q2'to full the pulse length (180 deg ~ α).

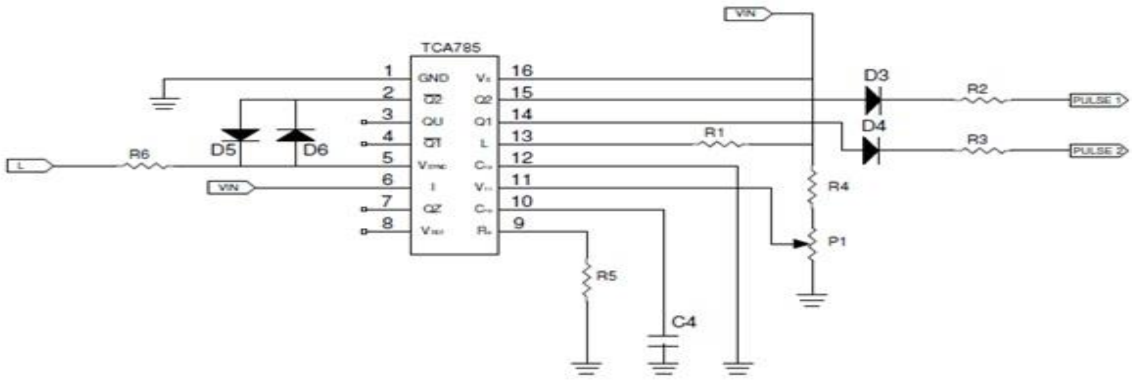


Figure 9: Pulse generator circuit

The anti-parallel diodes D5 and D6 are used to measure the two output inverters using only two pins, as at the first, the circuit will sources current through diode D6, since diode D5 is reverse biased after the current passes through D6, the D6/D5 selection signal will switch the direction of the current and force it to pass through diode D5 with D6 now is as reverse biased. This technique reduces board routing complexity, while maintains high accuracy and minimizing pin count.

3.3.1 Zero crossing detector:

These points below explain the function of the Zero Crossing Detector :

- A zero crossing detector gives a pulse when the voltage reaches 0V.
- It detects the zero voltage at pin 5, therefore whenever there is a zero voltage at pin 5, a pulse is then transferred to synchronization register.
- The synchronization register controls a ramp generator, which a ramp capacitor (C4) charges a constant current. The constant current is determined by a ramp resistor (R5).
- If the voltage of pin 10 is larger than the voltage in pin 11, the triggering angle can be shifted within a phase angle of 0° to 180°.

Figure 10 shows the zero crossing waveform signals.

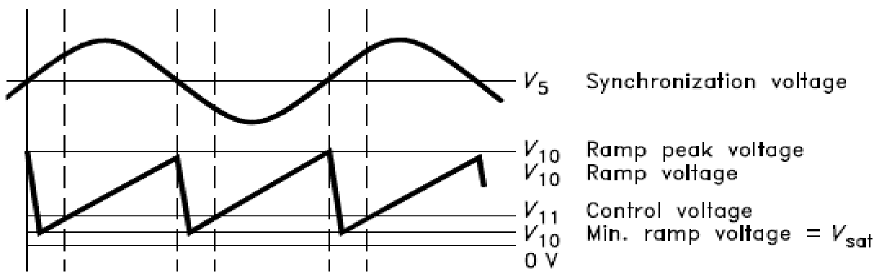


Figure 10: Zero crossing waveform signals

3.4 Pulse Transformer Circuit

Pulse transformers are used to couple a trigger-pulse generator to a thyristor in order to obtain electrical isolation between the two circuits, and also their applications in triggering considered as an excellent application. Figure 11 is illustrates the complete circuit of the pulse transformer.

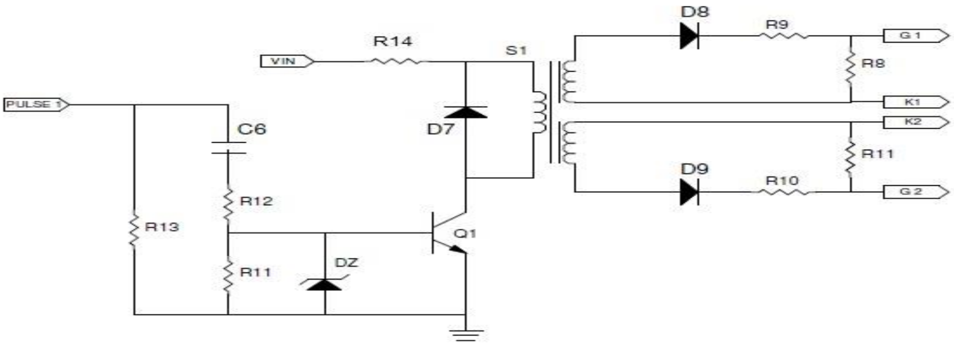


Figure 11: Pulse transformer circuit

3.5 UJT circuit for thyristor firing

The uni-junction transistor (2N2646), abbreviated UJT, is a three–terminal, single–junction device. The three terminals are: Emitter (E), Base-one (B_1) and Base-two (B_2). Between B_1 and B_2 the uni-junction has the characteristics of an ordinary resistance. This resistance is the inner-base resistance (R_{BB}) and at 25^0 C has values in the range from 4.7 k to 9.1 k. In general, R_{B1} is limited to a value below 100 ohms, and the resistor R is limited to a value between 3 k and 3 Meg. The lower limit and the upper limit of the resistor R is set by using the equation 4:

$$\frac{V_{BB} - V_v}{I_v} \prec R \prec \frac{V_{BB} - V_p}{I_p} \qquad (4)$$

These limits on the resistor R are set by the requirements that the load formed by the resistor R and V_{BB} intersect the emitter characteristic curve of Figure 12, hence the emitter peak point must be greater or smaller than I_p for the UJT to turn ON and to turn OFF respectively. In fact the value of R_{B1} is not important for the purpose of the design, provided that it is within the limits required for the UJT to oscillate. The recommended range of the supply voltage V_{BB} is 10 V to 35 V. For the design criterion of UJT, it is recommended to use a resistance of 100 ohms or greater and with large value of Wattage in series with either the power supply or in series with Base two (B_2) for a purpose of protection to the UJT from possible thermal runaway.

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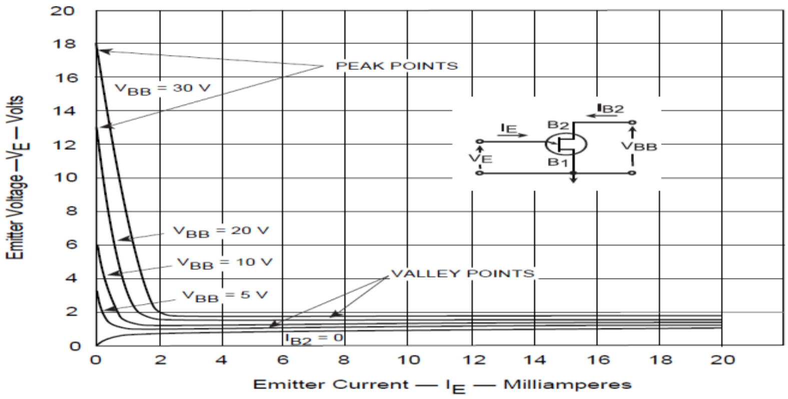


Figure 12: The emitter characteristic curve

Normally the value of the resistance R_{B2} is depending on the temperature range of the UJT, as if an extreme temperature composition is not essential, it is recommended to choose $R_{B2} \geq 100$ ohms. In addition of that, an important design consideration in this type of circuit concerns on the premature triggering of the SCR. The voltage at Base one (B1) when the UJT is turned OFF can be calculated by equation 5:

$$V_{B1}(off) = \frac{V_{BB} - R_1}{(R_{BB} + R_1 + R_2)} \qquad (5)$$

3.6 Separately- excited dc motor (Power Circuit):

This circuit is the final circuit considered as the load, it contain the bridge rectifier unit, the thyristor SCR and a 300W separately-excited dc motor. The armature winding must be connected as in figure 13.

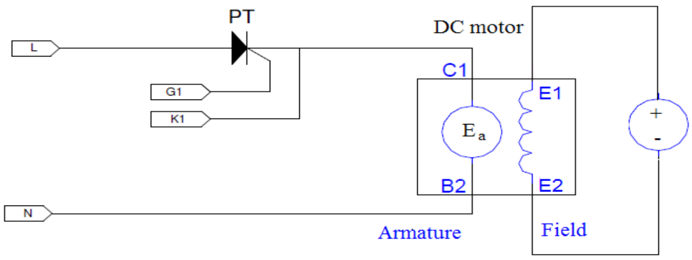


Figure 13: Power circuit of the dc motor

As C1 and B2 represent the armature winding of the motor and E1 and E2 show the connection of the field winding with the bridge rectifier unit. G1 and K1 are the outputs of the pulse transformer (secondary winding) as they represent the gate and the cathode terminals respectively. In general the field windings are used to excite the field flux, while the armature current is mainly supplied to the rotor via commutator and brush for the mechanical operation. When a separately excited motor is excited by a field current of I_f and an armature current of I_a flows in the circuit, the motor will develop a back EMF and a torque to balance the load torque at a particular speed. Normally the field current I_f is much less than the armature current of I_a. The speed control of the motor can be obtained from the firing angle α, by changing the firing angle; variable dc output voltage can be obtained. The firing angle can be varied from 0 deg to 180 deg through a potentiometer.

4.0 Experimental and test results:

Voltage Regulator output voltage using experimental calculation is 12V while output voltage during testing is 11.79V. The test result is slightly different from the experimental result mainly is because there is a voltage caused by the internal resistance of the voltage regulator device.

Pulse 1 and Pulse 2 output voltage:

- **Experimental result:**

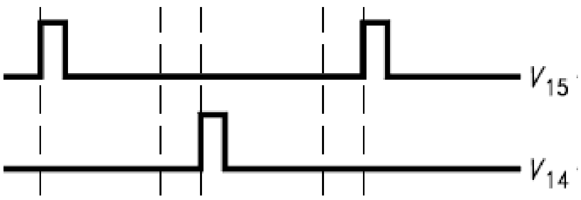
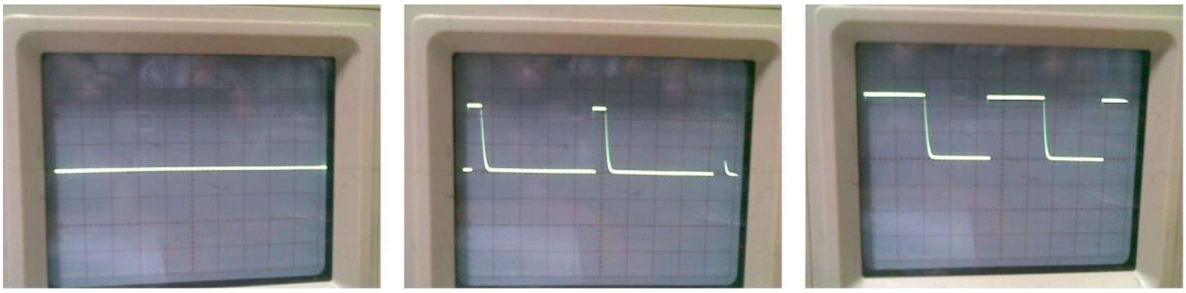


Figure 14: Expected 'pulse 1' (V15) and 'pulse 2' (V14) output waveform

- **Test result:**



(a) Neutral line (b) Pulse 1 (c) Pulse 2

Figure 15: The actual pulse 1and pulse 2 output waveforms

For the pulse transformer, the results was obtained for the gate current for each secondary winding, and the correspond waveform. This was obtained by using the oscilloscope. For the output voltage waveform of the pulse transformer, G_1 is illustrated bellow in figure 16 (a), and the waveform of the gate after connecting the thyristor SCR, in figure 16 (b).

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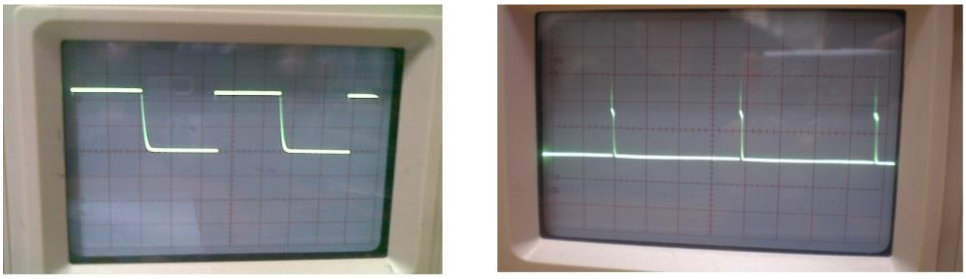

(a) Output voltage of G_1 (b)Output voltage of G_1 after connecting the SCR

Figure 16: Output voltages

5.0 The temperature controlled fan for cooling

The design of an **8051 based controlled fan** to control the speed of a fan and it has two modes, one to control the speed manually and the other is Auto in which the speed will depend on the temperature of the surrounding environment.

The system contains a sensor, ADC, Microcontroller, common cathode LED display, switches, fan and some other electronic components and the circuit was constructed as shown:

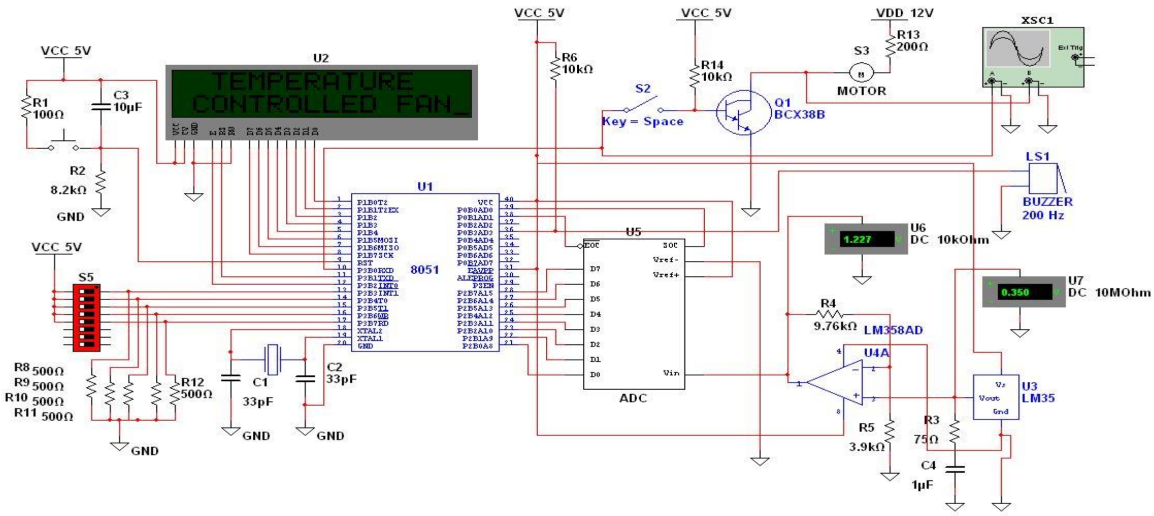

Figure 17: The temperature controlled fan schematic diagram

The sensor will detect the temperature and send it to the ADC as an analog signal. The ADC will convert the analog signal into digital signal that will be the input data of the microcontroller. This data is converted to BCD to be displayed in the LCD display as the temperature in degree Celsius. This operation will be done in both modes.

There are four switches connected to the microcontroller excluding the reset switch SW1. The switch SW2 is used to switch the system to Auto mode. The switches SW3 & SW4 are used to control the speed of the fan manually, where SW3 is to set the status of the fan to high speed while SW4 is to set it to low speed. Finally, the switch SW5 is used to switch off the fan.

In the Auto mode, the data fetched from the ADC is converted to hexadecimal data. The microcontroller then will check the temperature and change the status of the fan depending on the temperature:

Table 1: Temperature ranges and mode of operation

Mode	OFF	Low speed	High speed
Temperature range	Temperature<30˚C	30˚C ≤ Temperature <40˚C	Temperature ≥ 40˚C

6.0 Conclusion

It can be concluded that, the speed of dc motors can be controlled by using a thyristors, which is recognized as the full controlled rectifier and the design of our project meets the requirements in term of size and cost effectiveness. Moreover, some additional enhancements were made to the main circuit. Although what was done previously, some of the obstacles were faced during the designing and the construction of the circuit, such as:

- Time management.
- Technical faults (short circuit) & burning some components.
- Lake of components provided at the beginning.
- Connecting the circuit and verifying from the results.

Taking all these points into account, the overall output was a full build circuit with its own enhancement, which achieved the objectives of the project.

References

[1] Muhammad H. Rashid, 2003 ,Power Electronics: Circuits, Devices, and Applications, 3nd Edition, Prentice Hall, USA.

[2] Kothari. D P and I J Nagrath, 2004, “Electric Machines”, 3rd edn, Tata McGraw-Hill, New Delhi, page no. 375 (7.14 – Speed Control of DC Motors).

[3] P.M.Balasubramaniam , 2011, “Implementation of High Power Dc-Dc Converter and Speed Control of Dc Motor Using DSP”, Kalaignar Karunanidhi Institute of Technology, Computer Engineering and Intelligent Systems, Vol 2, No4.

[4] Dr.Bimbhra.P.S. and Khanna Publishers, 1998, “Power Electronics”, New Delhi, 2nd Edition.

[5] Moleykutty George, 2008, Speed Control of Separately Excited DC Motor, *American Journal of Applied Sciences*, Volume 5, Issue 3, Pages 227-233.

[6] Liu, Kwang-Hwa and Lee, F. C, 1990, “Zero Voltage Switching technique in DC/DC Converters”, IEEE Transactions on Power Electronics, page no. 293 – 304.

[7] G. Rajeshkanna, 2013, “Modern Speed Control of Separately Excited DC Motor by Boost Converter Fed Field Control Method”, International Conference on Computer Communication and Informatics, Pages 1 – 7.

[8] Jianguo Zhou, et al., 2001, “Global speed control of separately excited DC motor” , IEEE CONFERENCE PUBLICATIONS, Volume: 3, Pages 1425 – 1430.

[9] R.Krishnan, 2005, “Electric Motor drives modeling, Analysis and control”, Prentice-Hall of India Private Limited, New Delhi.

[10] Data sheet catalog Homepage, Function and Industrial ICs - Phase Control IC (TCA785) [online]. Available: http://www.datasheetcatalog.com/datasheets_pdf/T/C/A/7/TCA785.shtml.

[11] T.C. Burg, D. M. Dason, J. Hu, P. Vedagarbba, 1994, “Velocity tracking for a separately excited dc motor without velocity measurement”, Proceeding of the American Control Conference, pages 1051-1055.

[12] Hsu, Yuan-Yih, Chan, Wah-Chun, 1984, “Optimal variable-structure controller for DC motor speed control”, IET JOURNALS & MAGAZINES, Volume: 131 , Issue 6 , Pages 233 – 237.