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# Electronic Control of Electric Motors

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## Abstract

The purpose of this study was to investigate the theoretical information on electronic control of electric motors as well as the current state-of-the-art on this topic. It was also intended to carry out some of the experimental circuits discussed, for future instructional situations.

# ELECTRONIC CONTROL OF ELECTRIC MOTORS



A Research Paper for Presentation
to the Graduate Faculty
of the
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In Partial Fulfillment of the Requirements for
the Non-Thesis Master of Arts Degree

by

Armando Castillo

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# CHAPTER I. INTRODUCTION

It can be safely said that two important discoveries along the history of science marked the origin of electric motors (Bowers, 1982). One was Oersted's discovery of the production of a magnetic field when a current flows through any conductor. The other was Faraday's work on the production of continuous motion by electromagnetism.

From those early and basic experiments in the 19th century, electric motors were rapidly developed and improved to the point that they became an indispensable machine in any important factory. They are produced in a wide variety of types and sizes for specific applications ranging from thousands of horsepower to fractions of a watt.

The increased use of electric motors almost everywhere demanded the invention and production of control devices capable of governing the functioning of these machines. This was necessary because inappropriate values of certain parameters such as torque or speed may cause a product to be damaged or a process not to be completed.

In searching for the best method to control the output of electric motors, controllers evolved from crude devices based on limiting resistors or electromagnetic contactors to the sophisticated electronic drives currently used in modern industry.

These advances were possible because of the spectacular development of applied electronics. Not only has electronics evolved in an amazing way during the last decades, but it also has made possible the simplification and accuracy of many industrial processes, machines, and equipment. Indeed, many operations in industry must be carried out in a smooth manner and at predetermined speeds. Such precise functioning is not always possible with traditional electromechanical control of the electric motors used to drive specific equipment. The development of solid-state devices led to multiple applications, one of which is aimed at accurate control without using bulky and moving parts.

## Statement of the Problem

The purpose of this study was to investigate the theoretical information on electronic control of electric motors as well as the current state-of-the-art on this topic. It was also intended to carry out some of the experimental circuits discussed, for future instructional situations.

## Importance of the Study

For most consumers in today's society tasks like pushing a button or rotating a knob have become commonplace and almost automatic. Few people think about the amount of knowledge and technology involved in the simplest of the home appliances. While this is so for the general public, it is not so for personnel working in a technical field. This is particularly important because, as it was previously pointed out, motors are found in every laboratory, shop, or factory. Therefore, it seems reasonable to expect that instructors, students, and technicians in any technical occupation know the basic facts about the techniques for controlling the motors they use everyday.

With this in mind, it was believed that this study would generate important information regarding the current technology of motor control.

## Limitations of the study

This study was subject to the following limitations:

1. The technical information reflects the knowledge and technology of motor control for approximately the last two decades.

2. The emphasis was put on controls for dc or ac/dc (universal) motors, but the part on ac motors was not covered in detail.

3. Although controllers using microprocessors were mentioned, they were not discussed in their technical functioning.

4. The industrial information included was limited to that

provided by those companies which responded to the request (see letter in appendix A).

## Methodology of the Study

In order to carry out this study, the following activities were accomplished:

1. A search and review of literature were conducted to identify and use the most recent sources on this topic.

2. Letters were sent to nineteen selected companies in the United States asking for current literature on motor controllers produced by each one. Three of these companies responded and a summary of their information was included in a chapter of the study.

3. A laboratory experience was developed using some of the circuits discussed and the experimental results were reported in a special chapter.

# CHAPTER II. HISTORICAL BACKGROUND

One of the characteristic features of today's technology is the amazing rate of development of electronics during the last twenty-five years. In the following sections a brief chronological description of some special devices with specific applications to motor control is offered.

## Evolution of Solid-State Devices

### Transistor

Although the basic facts about semiconductors date back to the experiments of Hertz and Boze in the 1860s (Kuecken, 1978), the beginning of the era of solid-state electronics came with the development of the transistor in the late 1950s. Early experimental work began at the Bell Telephone Laboratories "to study and relate the known facts of solid-state physics to the anticipated needs of the communications technology" (Davis, 1985,p. 44). As a result, the junction transistor was invented by William Shockley in 1945. Three years later, John Bardeen and Walter Brattain made the first practical transistor.

### Silicon Controlled Rectifier (SCR)

This special type of rectifier, having a gate to control the firing point, was developed by the General Electric Laboratories in 1957. However, practical SCRs appeared on the market only about 1962 (Davis, 1985). One of their first applications was in the Whirlpool clothes dryer to provide a continuously variable rotation speed. Since then, many uses have been found for SCRs. They are used in many consumer products, industrial processes, motor control, and power circuits handling high currents. In fact, SCRs have replaced transistors whenever high levels of current are needed.

## Triode ac (Triac)

According to Davis (1985), the triac or solid-state ac switch was developed by General Electric Company in 1965 as a result of a navy contract calling for "the development and evaluation of a bilateral switching device capable of carrying 25 amperes." Triacs have come to be used as substitutes for SCRs in applications where ac loads are fed from an ac supply.

## Integrated Circuits

The first idea of replacing discrete components by integrated circuits was presented by George W.A. Dummer (Great Britain) in May, 1952, at the annual Electronic Components Symposium in Washington, D.C.(Davis, 1985). Later on, in February 1959, Jack Kilby of Texas Instruments patented a device consisting of two circuits including transistors, resistors, and capacitors formed within a chip of germanium (Ryder, 1984). Six months later, Robert Noice of Fairchild Instruments invented the arrangement of planar elements on a chip of germanium interconnected by deposited aluminum strips. This technique is still used in the production of integrated circuits (Ryder, 1984).

## Evolution of Electric Motor Controls

While in many cases motors were controlled simply by switching them ON or OFF, many applications required high power over a wide range of speeds. Historically, a dc motor and the Ward-Leonard control were used in these cases (Bowers, 1982). In this method, invented about 1890 by the American H. Ward Leonard, the controlled output of a generator is fed to the armature of the motor being controlled, thus changing the rotor speed.

The advent of power transistors and SCRs made it possible to overcome the drawbacks of the Ward-Leonard technique, replacing it by more efficient, reliable, and small variable speed dc drives.

Regarding the ac induction motor, traditionally a constant-speed machine, the development of special devices based on semiconductor components or integrated circuits also introduced many changes in speed control. By about 1960, thyristors were available to generate a variable-frequency ac voltage for the above purpose.

Finally, the fact that universal motors (ac/dc) can run much faster than induction motors, led to their use in many home and shop appliances where a continuous control of the speed under different load conditions is required.

The latest advance in motor control seems to be a computer-based system. Microprocessors can perform the same functions as the present analog methods, but in a more accurate and faster way. It is expected that this new development in motor control will become more and more popular within the next decade.

# CHAPTER III. TECHNICAL INFORMATION

## Basic Motor Control Concepts

The advent of mass production in today's industry was only possible due to the increasing use of electric motors in almost every machine in the factory. The systems or techniques devised to govern or regulate the functions of these motors or machines are included in the generic term of "motor control". The most important functions to be accomplished by any motor controller in a predetermined sequence are starting, acceleration, speed, braking, reversing, and stopping.

The above operations can be carried out in one of three possible ways (McIntyre, 1974). The least sophisticated is a manual controller. This is the simplest and least expensive control system, but it has the disadvantage that any action must be decided and initiated by the human operator of the motor or machine. Another is the semiautomatic control, which uses one or more manual devices in combination with magnetic starters. In this case, the operator has more freedom as to the location from where to start the system. Finally, in an automatic controller the sequential operations are controlled by one or more pilot or sensing devices after the initial start. It should be noted that the three methods differ basically in the flexibility of the system and the extent of human decisions that are required.

In the past, the most popular devices were of the electromagnetic type, using magnetic starters to energize the motors. The use of these devices presented many problems in the factory. First, the magnetic coils required large current to operate and, therefore, were subject to burn out. Second, the contacts of any unit were exposed to dirt, grease, moisture, etc., which caused frequent failures. Third, the switching action of these contacts was rather slow and not suitable for certain applications. Finally, the components required a large space for installation.

The evolution of electronics led to the development of what was called "electronic control", "static control" or "solid-state control". Whatever the name, it refers to the fact that this control has no moving parts or contacts. Because of this, the static controls provide substantial advantages over magnetic controls, such as longer life, higher speed of operation, smaller size and weight, less maintenance, and lower costs. All these factors contribute to a high reliability of the system to the point where static control has almost completely replaced the magnetic control in modern industry.

## Solid-State Discrete Components

The number and type of solid-state components has grown at such a phenomenal rate that it is almost impossible for the technician to keep pace with this development. For example, Buchsbaum (1973) listed some of the semiconductor devices used at that time together with their applications (Table 1).

Table 1.

Semiconductors Devices and Applications

| Device | Junction Configuration or Type | Material | Application |
|---|---|---|---|
| Rectifiers (diodes) | pn junction | Silicon | Low fwd. voltage drop, signal and power rectification |
| | pn junction | Germanium | High rectification ratio, high inverse breakdown, high temperature, signal and power rectification |
| | Dry disc | Selenium | Power rectifier, low-frequency diode, self-healing |
| | Dry disc | Copper oxide | Meter rectifier, low voltage power rectifier |
| | Dry disc | Copper sulfide | Low voltage power rectifier |
| Transistors | pnp or npn | Germanium | Low saturation voltage, general purpose to $75^{\circ}$ C |
| | pnp or npn | Silicon | High temp. use to $175^{\circ}$ C, higher voltage |
| Field Effect Transistors (FET) | n or p channel types | Silicon | High input impedance, resistive, bidirectional output impedance |
| Unijunction Transistors | n-type bar with p-junction between ends of bar | Silicon | Relaxation oscillator, timing, trigger circuits, neg. res. device |

Table 1. Continued.

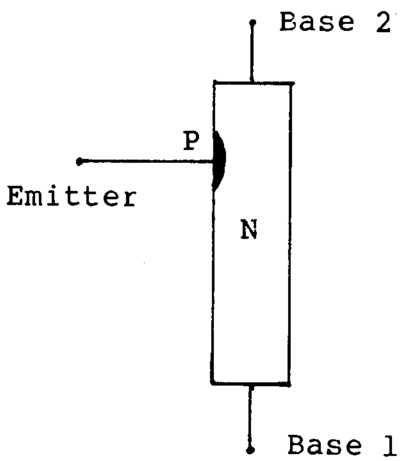
| Device | Junction Configuration or Type | Material | Application |
|---|---|---|---|
| Photo-diodes<br>Photo-transistors | pn<br>npn | Germanium<br>Silicon | Photo-conduction and photovoltaic for control applications |
| Photoelectric Cells | photoresistive<br>photoresistive<br>photovoltaic<br>photovoltaic | Lead sulf.<br>Lead telur.<br>Cadmium sul.<br>Selenium | Infrared detector<br>Infrared detector<br>Light meter<br>Light meter |
| Varistors | Fired<br>Dry disc | Silicon car.<br>Selenium | Surge suppresors<br>Contact protector |
| Thermistors | Fired | Mixed metal oxides | Temperature sensing, control, compensating |
| Zener Diodes | pn junction reverse biased to Zener breakdown | Silicon | Reverse biased voltage regulator, voltage reference |
| Varactor Diode (varicap) | pn junction reverse biased, no current flow | Silicon | Voltage controlled capacitor, parametric amplifier, multipliers |
| Light Emitting Diode(LED) | pn junction | Gallium arsenide Phosphide | Visible, infrared, light emitting, displays |
| Thyristors Silicon Controlled Rectifier(SCR) | pnpn | Silicon | Phase controlled rectifier, similar to thyratron tube |
| Triac | Two SCRs in parallel and opposite orient. | Silicon | Bidirectional control of AC, light dimmers, power tool speed control |
| Tunnel Diode | Heavely doped pn junction | Germanium Gallium arsenide | Negative resistance, microwave amplifier oscillators, converters |

Note: From Buchsbaum's Complete Handbook of Practical Electronic Data by W.H. Buchsbaum, 1973, Englewood Cliffs, NJ: Prentice Hall, Inc.

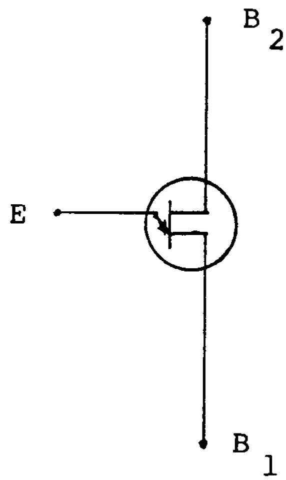
In the following sections, it is intended to describe only those specific devices (from the above list) that have application in the electronic control of electric motors.

## Unijunction Transistor

The unijunction transistor (UJT) is a three-terminal device consisting of an N-type silicon bar with a single PN junction usually formed at a point approximately two-thirds of its length. Its terminals are called emitter, base 1 and base 2, as shown in Fig. 1.




(a) Structure




(b) Symbol

Figure 1. Unijunction Transistor

Base 1 is taken as the reference terminal, while Base 2 is the more positive terminal. With a positive voltage applied at the emitter, the UJT is in OFF condition until a specific voltage called the "peak voltage" Vp is slightly exceeded. When this happens, the UJT turns ON, which means that for a short period of time a high emitter current flows due to the discharge of the external capacitor providing the peak voltage. Then this current decreases to the point where the UJT reverts to the OFF state.

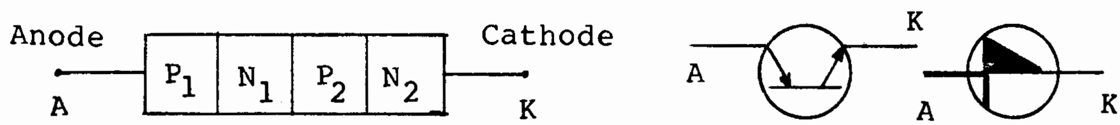
## Thyristors

The generic name of thyristors is applied to those solid-state components used specifically for switching purposes. Thyristors are preferred to transistors in applications where low frequency and/or high power are required. They can be classified into two- and three-terminal devices.

### Two-Terminal Thyristors

#### Shockley diode.

A Shockley diode is a four-layer, two-terminal device, as illustrated in Fig. 2 (Cirovic, 1974).




(a) Structure (b) Symbols

Figure 2. Shockley Diode

As can be seen, the structure of a Shockley diode is equivalent to that of two transistors, $P_1N_1P_2$ and $N_1P_2N_2$ connected as shown in Fig. 3.

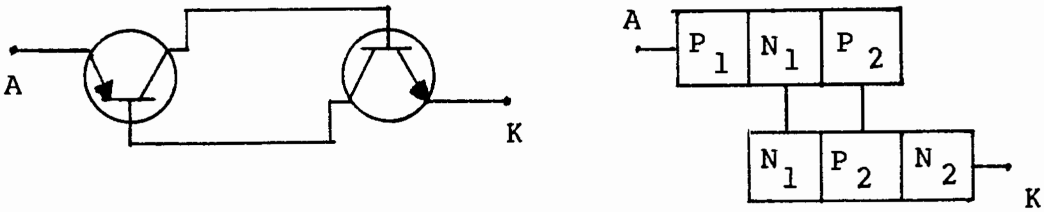



Figure 3. Equivalent Circuit for a Shockley Diode

With a forward voltage across the diode there is no conduction because the $N_1P_2$ junction is reverse biased. The forward voltage can be increased up to a certain value, the "breakover voltage" Vbo, and at this point the $N_1P_2$ junction breaks down and the diode starts conducting. This conduction remains, even though the voltage across the diode decreases. The Shockley diode is, therefore, a unilateral or unidirectional device.

Diac.

The diac or "diode ac" switch is a three-layer, bidirectional device, i.e., can conduct current in either direction (Fig. 4) (Kaiser, 1982).


(a) Structure

(b) Symbols

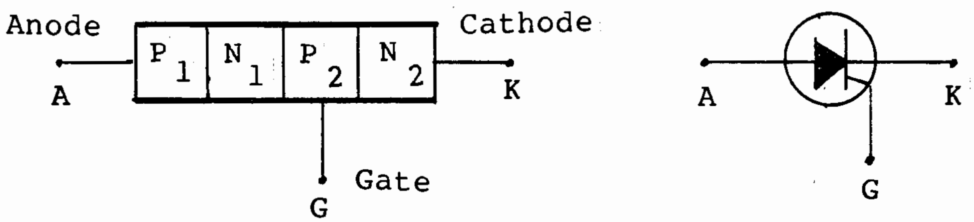
Figure 4. Diac

If a voltage is applied to the diac, one of the junctions is reverse biased and the diac does not conduct. By increasing the voltage, the breakover voltage is reached and the diac begins to conduct. After this, the voltage can be reduced to an operating value. To turn the diac OFF, the voltage must be reduced to zero or nearly zero volts.

Three-Terminal Thyristors

Silicon controlled rectifier(SCR).

This is a four-layer device similar in construction to the Shockley diode, but it has a third terminal, the gate, connected to the P layer (Cirovic, 1974). The other two terminals are called "anode" (A) and "cathode" (K), as shown in Fig. 5.




(a) Structure

(b) Symbol

Figure 5. SCR

Like the Shockley diode, the SCR acts like an open switch when no voltage is applied to the gate, unless the breakover voltage is reached. However, with the SCR forward biased, if a positive voltage is applied to the gate, the $P_2N_1$ junction becomes forward biased aand the SCR goes into conduction. Once this happens, the voltage applied to the gate is no longer needed for control purposes. To turn the SCR OFF its anode voltage must drop to zero or change polarity.

One variation of the SCR is the light-activated SCR (LASCR) which is turned ON by light shining on the gate-to-cathode junction. Another variation is the complimentary SCR (CSCR), whose gate is connected at the inner negative layer (Davis, 1973).

SCRs are used extensively in motor control due to their small size, low cost, and capability to handle high voltages and currents. This last feature is shown in Fig. 6, which compares SCRs vs. transistors (Murphy & Gilmore, 1984).

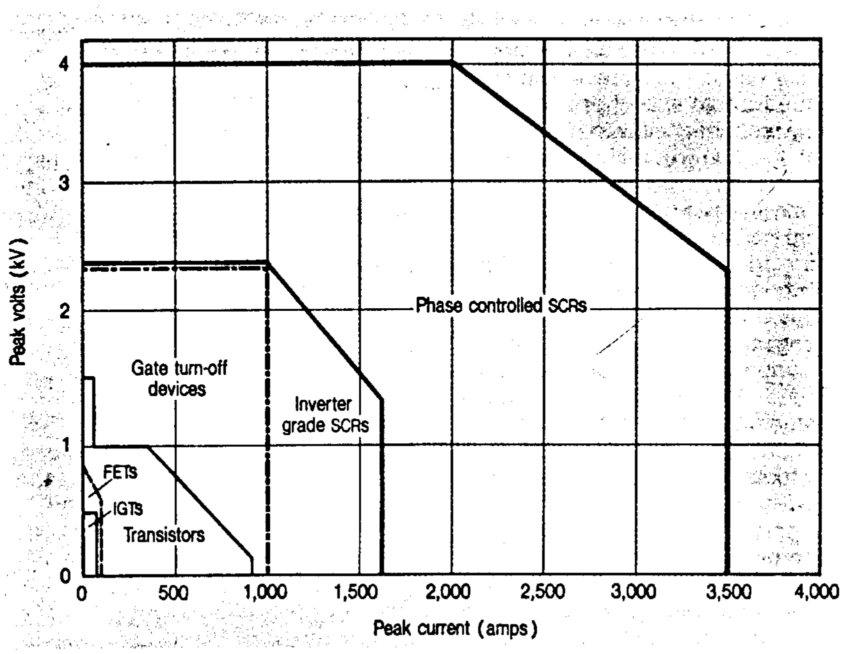



Figure 6. SCRs vs. Transistors

Triode ac (Triac).

This name is applied to a bidirectional triode comprised of five layers and a small sixth region under part of the gate contact. This arrangement allows the triac to be triggered by gate current moving in either direction (Fig. 7) (Texas Instruments, 1972).

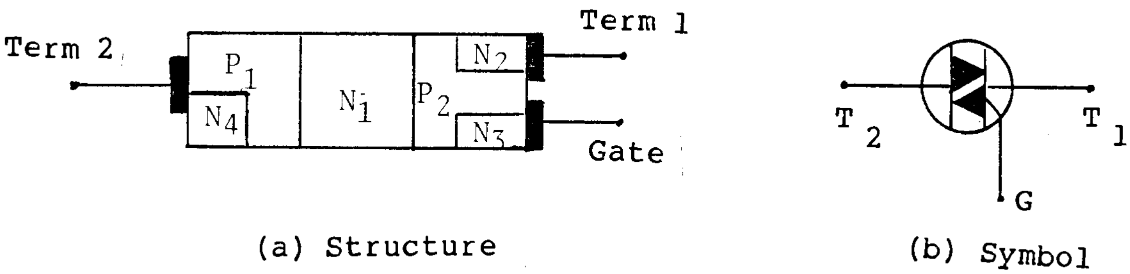



Figure 7. Triac

A triac behaves like a pair of SCRs connected in inverse parallel, as seen in Fig. 8.

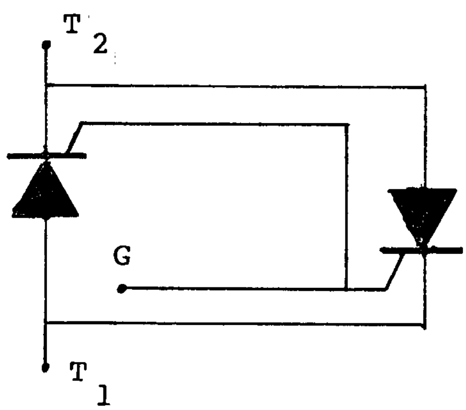



Figure 8. Equivalent Circuit for a Triac

The triac can be turned OFF by either interrupting or lowering the current below the holding value of the $T_1T_2$ current. It should be pointed out that the triac is designed for ac circuits, whereas the SCR is used in circuits with dc loads.

## Basic Operation of Electronic Motor Controls

Like any electrical system, an electric motor and its controlling devices is comprised of three basic stages: sense, decide, and act, which in a more technical language are called input, process, and output (Texas Instruments, 1972).

In the "sense" or "input" stage a certain amount of information is fed into the system. This information is analyzed in the "decide" or "process" stage where it is decided the appropriate actions to be taken. Finally, the "act" or "output" stage interprets the decision and produces the expected result.

There are two basic methods for sending information through the input portion of electrical systems to the other stages. One method is called "digital" and involves sending information through an electrical circuit by switching the current ON and OFF. On the other hand, the so called "analog method" implies sending information by regulating the current or voltage in an electrical circuit.

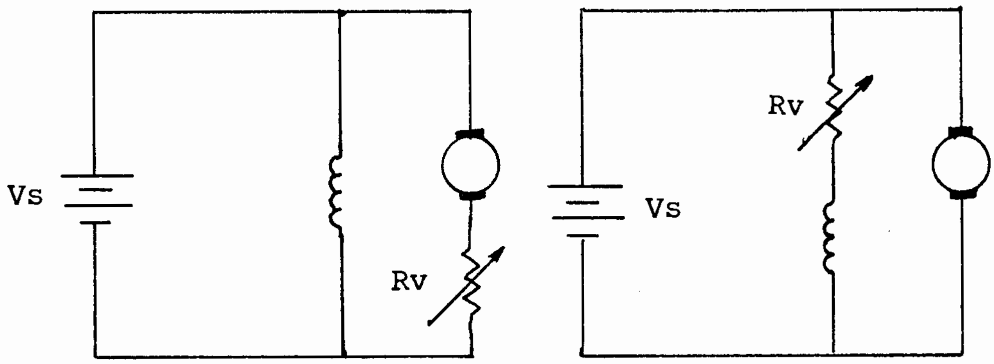
The early devices to carry out either one of the above methods were slow, unreliable, bulky, and subject to wear, as pointed out in previous sections. The invention of vaccuum tubes and later on of solid-state devices made it possible to design highly sophisticated equipment to perform the switching and regulating functions in a very fast, reliable, and lasting way within a very small space.

Each one of the three stages within a particular system is made up of building blocks called "circuits", which in turn are made up of "components" like those described in the preceding section.

The ultimate purpose of any control system of electric motors is to regulate their functioning by controlling some parameter, such as voltage, current, or frequency. Many industrial and commercial applications require that the speed of the motor attached to specific equipment can be adjusted in accordance with the mechanical load connected to the motor's shaft. A discussion of the basic methods of control for dc and ac motors follows.

## DC Motor Controls

The workhorse of industry as far as adjustable speed motors is concerned is the dc shunt-wound motor. In this motor, speed is conveniently controlled by varying the armature voltage or the field current, as shown in Fig. 9 (Maloney, 1979).




(a) Varying the Armature Voltage (b) Varying the Field Current

Figure 9. DC Motor Speed Control

In method "a", as the armature voltage is increased, the motor speeds up because the armature current also increases and in order to limit this increase, the motor has to produce a greater counter emf which is accomplished by the motor spinning faster.

On the other hand, method "b" causes the motor to slow down as the field voltage is increased because a greater current results in a stronger magnetic field, which in turn induces a greater counter emf in the armature winding. This reaction reduces the dc applied voltage and thus reduces the armature current. The net result is a reduction in the motor speed.

Generally speaking, the armature voltage is varied for speed control up to the rated speed, whereas the field current is varied to control speed above the rated speed of the motor.

In either case, but particularly with the armature control, the rheostat must handle a relatively large current, which tends to overheat it, wasting a considerable amount of energy. This is why these components are usually large and expensive. Currently, most rheostat functions can be performed with solid-state components.

The basic elements of most electronic dc motor controls include: (a) a reference signal to set the desired speed, (b) a control device to vary the armature or field voltage, and (c) a feedback mechanism to compare the actual motor speed to the reference setting.

The simplest and most economical design is the SCR control illustrated in Fig. 10 (Davis, 1973).

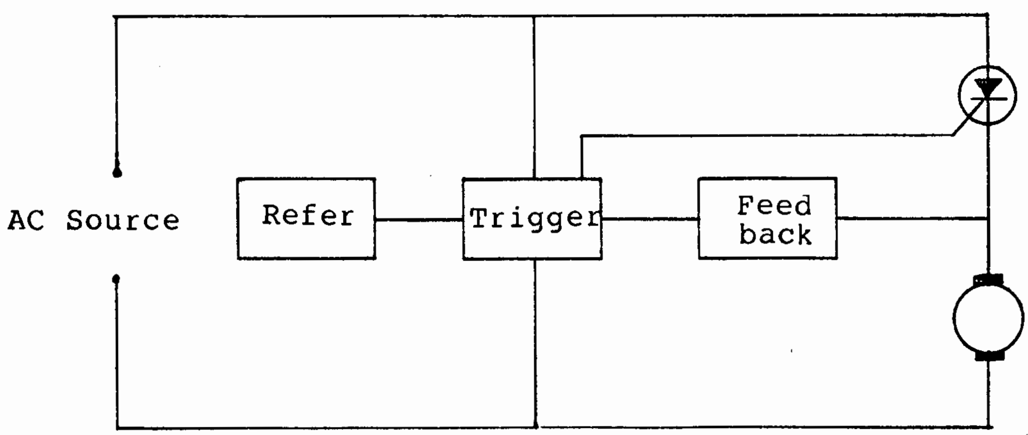



Figure 10. Basic SCR Motor Controller

In this basic arrangement the trigger circuit turns ON the SCR once during each ac cycle at a time called "phase" and previously determined in accordance with the desired speed. If the control were set at half power the waveform at the load would look like that shown in Fig. 11 a).

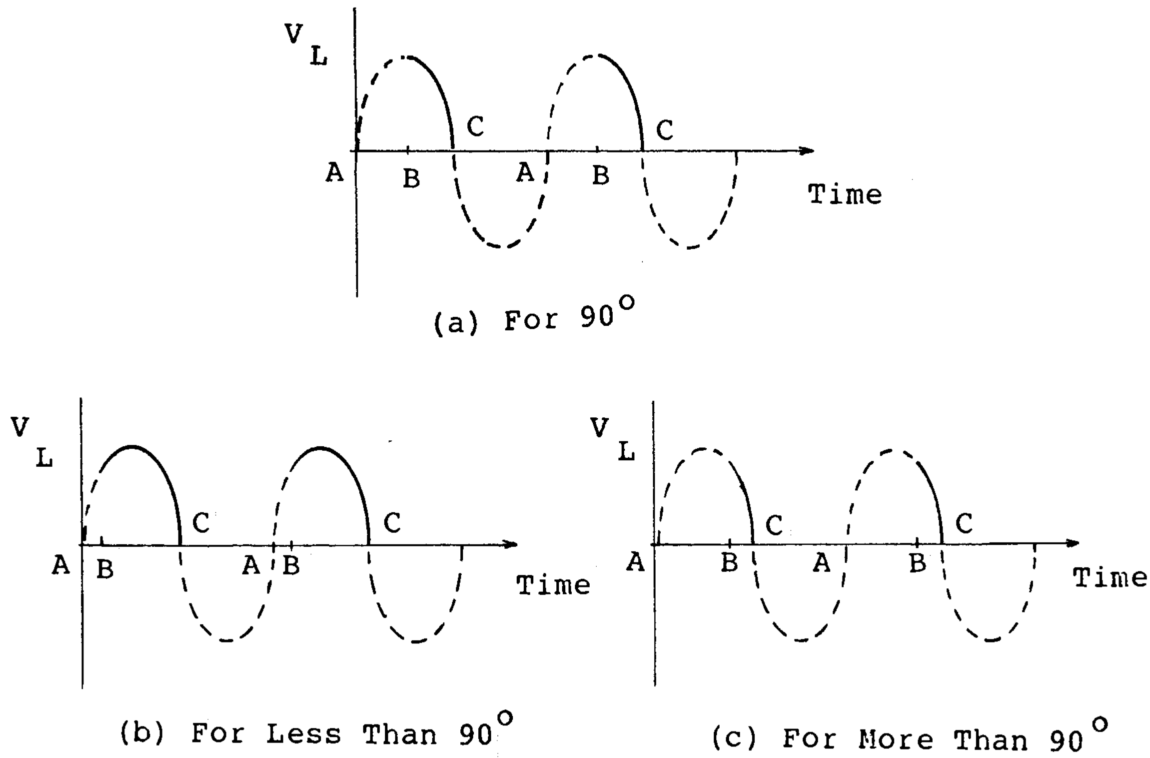



Figure 11. Load Waveform for Circuit of Fig. 10.

At point A in each cycle current tries to pass forward, but it is blocked because the SCR is still turned OFF. At the phase of the cycle (point B) the trigger circuit turns ON the SCR and current flows. At point C the SCR is turned OFF again because the forward current has decreased to zero. By varying the trigger-pulse timing to any point between A and C in the cycle, the average current supplied to the motor is also varied from zero to complete forward half-waves.

By firing the SCR early (Fig. 11 b), the average armature current is increased and the motor can run faster. By firing it later (Fig. 11 c), the average armature current is decreased and the motor runs slower.

The counter emf generated by the motor serves as the feedback mechanism. The SCR trigger timing is dependent on the difference between the reference setting and the feedback signal. Therefore, the motor speed is held constant under changing loads.

The circuit of Fig. 10 provides only half-wave rectification and control to the armature winding. Other arrangements may provide full-wave power control, which in most cases is preferable. An example of these circuits, using two SCRs, is shown in Fig. 12 (Moore & Elonka, 1977).

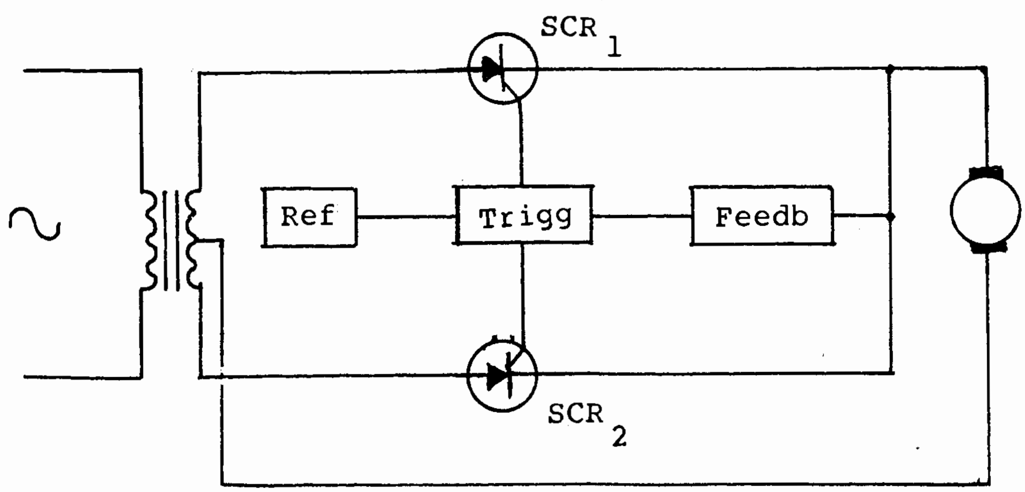



Figure 12. Full-Wave Power Control for DC Motors

The corresponding waveform for a trigger angle of about 45 with a full-wave power control can be seen in Fig. 13.

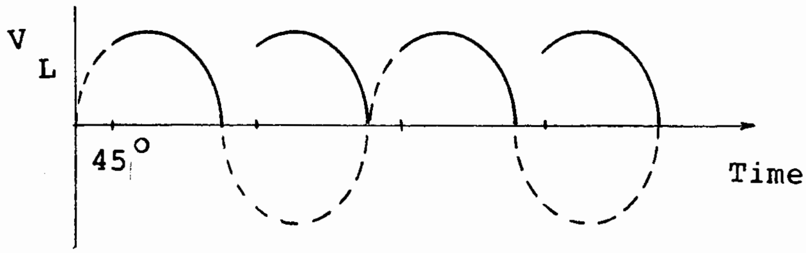



Figure 13. Waveform for a Full-Wave Power Control

It should be noted that even though the SCR is used as a switching device it performs the function of an ac regulating device, instead of a rheostat.

There are many possible triggering circuits used to fire the SCRs in a control system. The simplest type of gate control circuit uses the same voltage supply to power both the gate of the SCR and the motor, as shown in Fig. 14 (Davis, 1973).

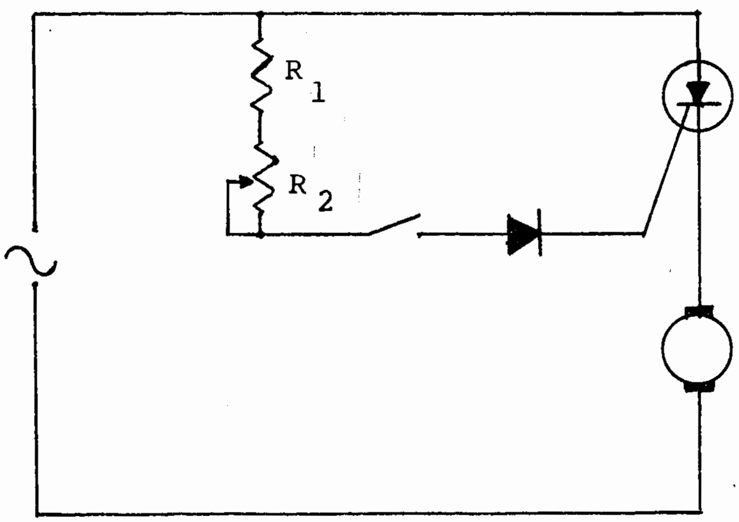



Figure 14. A Simple Triggering Circuit for SCR

When the switch is closed there will be current into the gate during the positive half wave. The phase or firing angle is determined by the setting of the rheostat $R_2$. If $R_2$ is low, the gate current will be sufficiently large to fire the SCR when the supply voltage is low. As a result, the firing angle will be small, the average armature current will be large, and the speed of the motor will increase. For high values of $R_2$, the process reverses. The purpose of $R_1$ is two-fold: (a) it maintains a fixed resistance in the gate lead, even when $R_2$ = 0; and (b) it determines the minimum firing angle. The diode in series with the gate protects the gate-cathode junction against high reverse voltages.

One disadvantage of the above method is that the firing angle is adjustable only from about $0^o$ to $90^o$. This shortcoming can be overcome by adding a capacitor at the bottom of the gate lead resistance, as shown in Fig. 15.

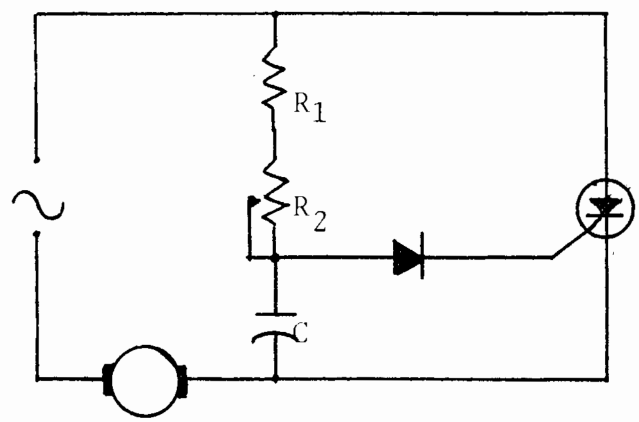



Figure 15. An Improved Triggering Circuit for SCR

In this circuit, during the negative alternation of the cycle the reverse voltage across the SCR is applied to the RC triggering circuit, charging the capacitor negative on the top plate and positive on the bottom plate. During the positive half cycle the forward voltage tends to charge the capacitor in the opposite direction. This phenomenon, however, is delayed until the negative charge is removed from the capacitor plates. This delay in applying positive voltage at the gate can be extended past the 90° point. The larger the potentiometer resistance, the longer it takes to charge C positive on the top plate and the later the SCR fires. Triggering can be further delayed by inserting a resistor into the gate lead (Fig. 16), which constitutes an RC network for gate control.

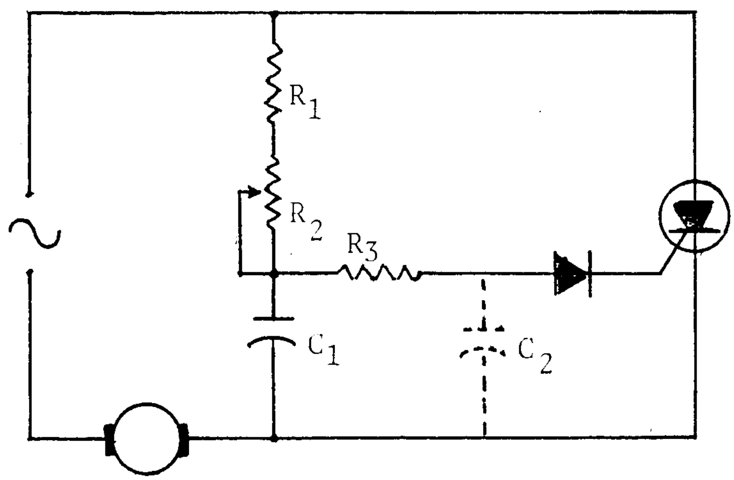



Figure 16. A Triggering Circuit with an Extended Range

With $R_3$ in place, the capacitor voltage must reach a higher value to force sufficient current through the resistor and into the gate terminal. Therefore, a greater range of adjustment of the firing angle can be obtained. If capacitor $C_2$

is included, the delayed voltage across $C_1$ is used to charge $C_2$ resulting in even further delay.

One disadvantage of the above method is what is called "temperature dependence". This means that an SCR tends to fire at a lower gate current when its temperature is higher. This condition is unacceptable in many industrial applications.

New developments in this area led to the use of breakover devices in gate control circuits, improving by this means the temperature stability of the drive. A Shockley diode used with this purpose is illustrated in Fig. 17 (Davis, 1973).

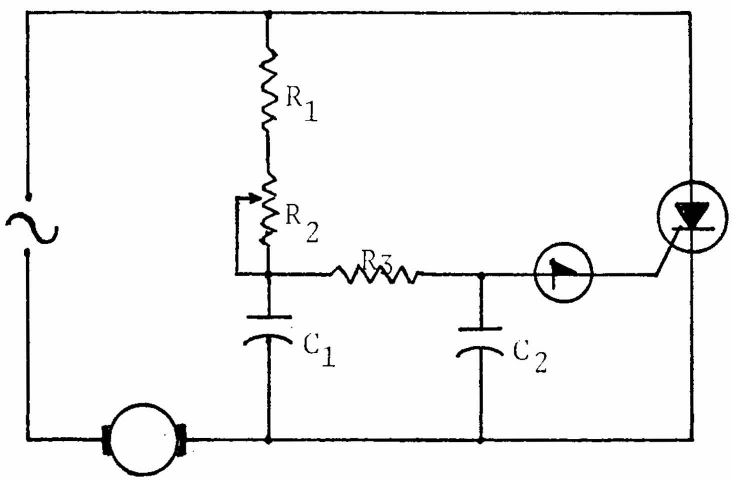



Figure 17. Shockley Diode in Gate Terminal

The circuit of Fig. 17 is essentially the same as that of Fig. 16, but in this case when the voltage across $C_2$ rises to the breakover value of the Shockley diode, this device begins to conduct, which in turn provides triggering to the SCR.

The unijunction transistor (UJT) is another device frequently used to fire the SCR without the inconveniences of the RC controls. Fig. 18 shows a typical UJT control circuit (Davis, 1973).

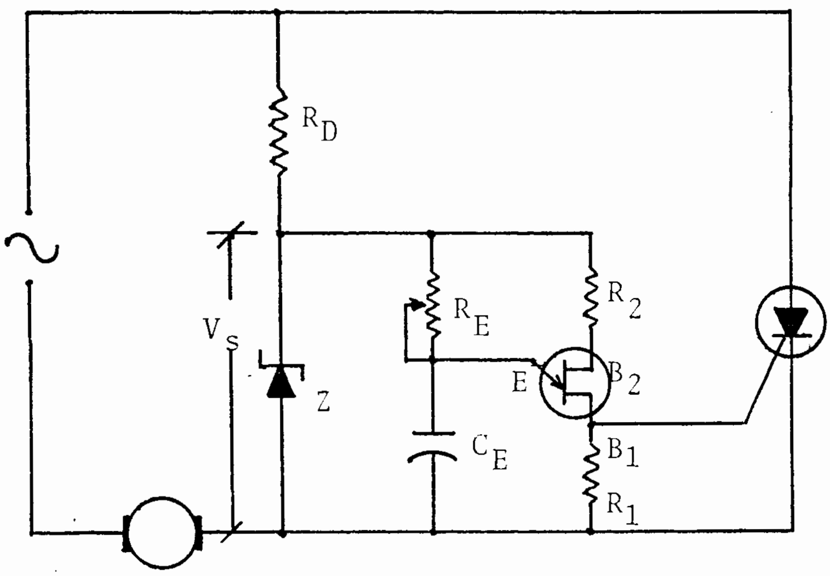



Figure 18. Triggering Circuit with UJT

In this circuit, the zener diode Z clips the $V_s$ waveform at the zener voltage during the positive half cycle. During the negative half cycle, Z is forward biased and holds $V_s$ near zero. The voltage $V_s$ begins charging $C_E$ through $R_E$. When $C_E$ reaches the peak voltage of the UJT, the UJT fires, creating a voltage pulse across $R_1$. This fires the SCR, thus allowing current to flow through the load for the remainder of the positive alternation. The firing angle, and consequently the load power, is controlled by the potentiometer $R_E$ in the same way as explained in previous circuits with RC control.

## AC Motor Controls

When the load is ac instead of dc, two SCRs connected back-to-back can be used to control the flow of current in both directions. However, for low and medium power, these two SCRs are currently substituted by a triac (Fig. 19) (Maloney, 1979).

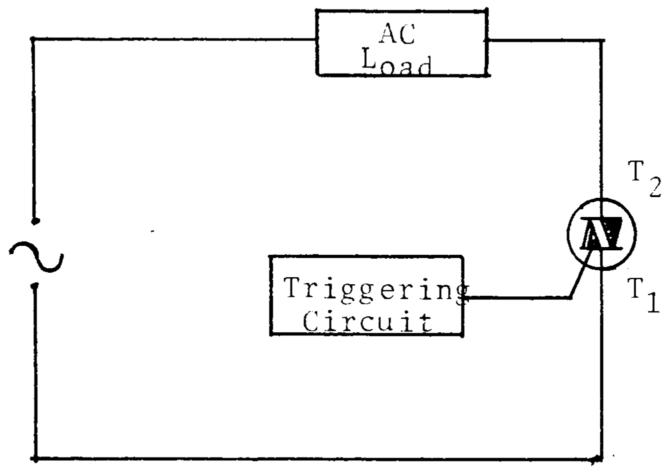



Figure 19. Basic AC Controller

In this circuit, when the triac is turned OFF no current can flow between the main terminals 1 and 2, regardless of the polarity of the applied voltage. When the triac is turned ON, current starts flowing in a direction dependent upon the polarity of the applied voltage. The firing angle can be adjusted in the same way as in the SCR control, but in this case the triac is also turned ON during each negative alternation, as shown in Fig. 20, for an approximate firing angle of 30 $^{\circ}$.

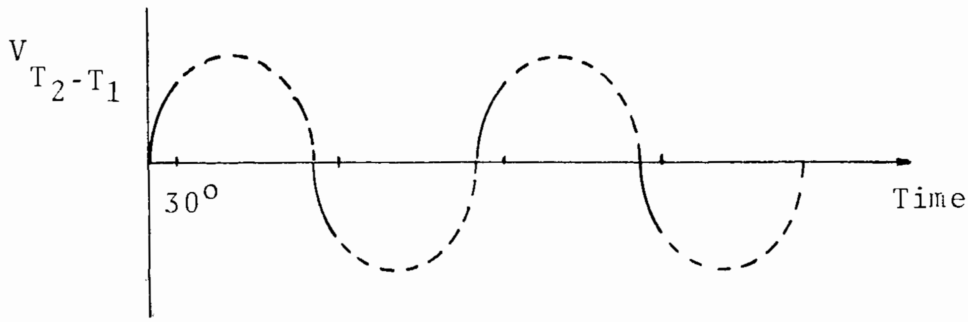



Figure 20. Waveform for a Triac

The triggering methods discussed for dc motors can be used for ac loads, but a diac (diode ac) is used in series with the gate lead of the triac, instead of the Shockley diode used with SCRs. Fig. 21 shows a simple circuit using this arrangement for a universal motor.

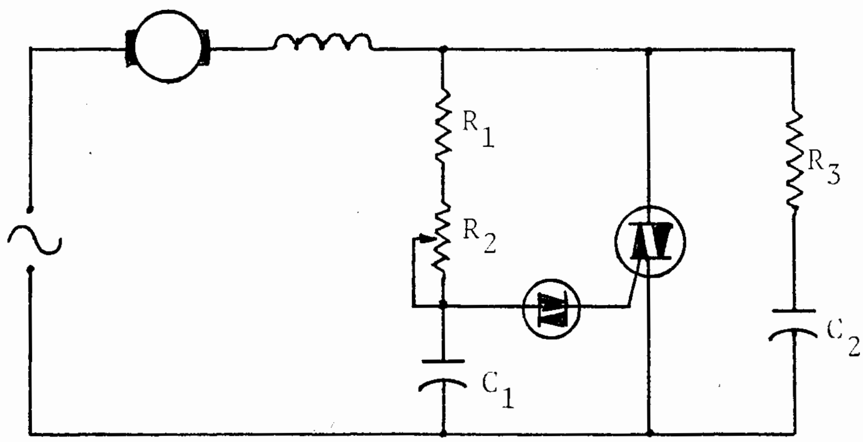



Figure 21. A Simple Control for a Universal Motor

The only new element in this circuit is the RC network comprised of $R_3$ and $C_2$ in series. Its purpose is to prevent the triac from conducting because of a countervoltage surge from the motor winding. This circuit provides a path for the inductive kickback voltage around the triac.

This method can be used with universal motors as ac loads because the speed of this type of motor is directly proportional to the voltage applied to it: the higher the voltage, the higher the speed. These motors find widespread use in many consumer appliances, such as sewing machines, vaccuum cleaners, mixers, blenders, hand drills, floor polishers, etc.

This method, however, is not appropriate for most ac induction motors because the speed for these motors is dependent on the frequency of the line and the number of poles of the stator winding.

The electronic technique most commonly used to obtain variable speed for an ac motor is to change the frequency of the applied voltage. This can be realized by changing dc power into variable ac frequency. Such a circuit is called an inverter. The variable dc power is normally obtained by rectification of the ac supply. One of these circuits for an industrial three-phase motor is shown in the block diagram of Fig. 22 (Kaiser, 1982).

The power supply is single-phase ac, usually 230 V. This voltage is rectified through a standard SCR full-wave bridge of the type discussed for dc motors. After filtering the output, the adjustable dc voltage is fed to the dc bus and from here to the inverter. This device contains three transistorized switching modules, one for each phase. An oscillator circuit distributes firing pulses to the transistor in such an order

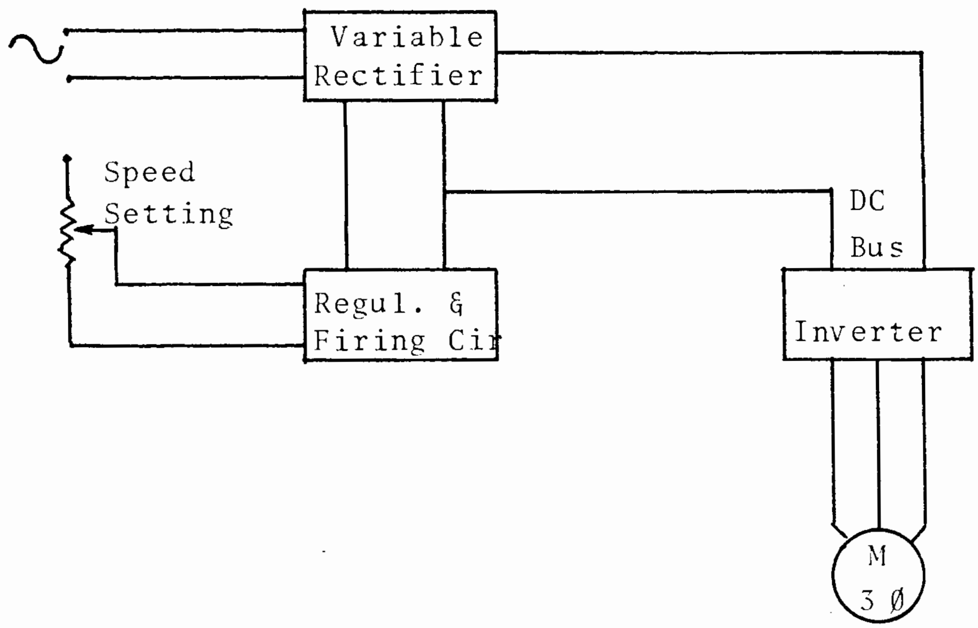



Figure 22. Solid-State Control for 3Ø Motors

that three wave forms 120 electrical degrees apart are produced.

One of the problems of this method of changing the frequency is that for a low frequency, the inductive reactance of the stator windings is also low. This means higher motor current, which can result in overheating. For this reason, when this technique is used it is also necessary to vary the applied voltage. Voltage must be reduced as frequency goes down so that the ratio between these two factors stays constant, as does the current. In the example just described (Fig. 22), both the output voltage and the frequency of the oscillator are controlled by the speed adjustment.

Another type of inverter is built with SCRs instead of power transistors mainly because the former are available with much more power-handling capability than transistors. Fig. 23 illustrates a circuit of this type (Maloney, 1979).

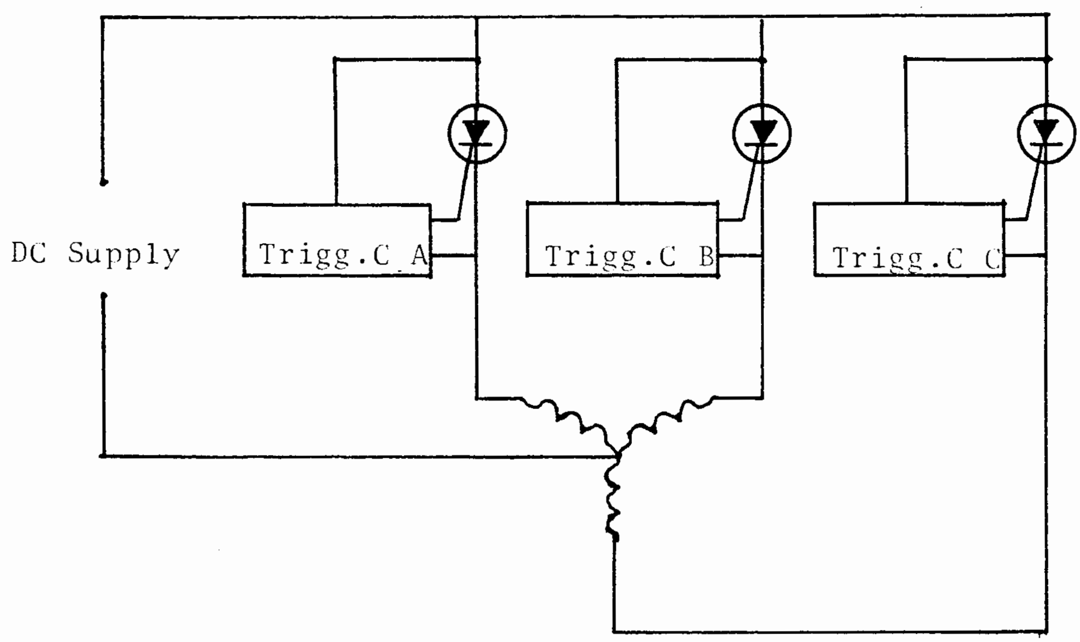



Figure 23. Three-Phase Motor Control with SCRs

In this circuit the three SCRs are fired in sequence, one immediately following the other, but only after the preceding one has been turned OFF. In this way, the longer the SCRs remain ON, the lower the stator frequency and, consequently, the lower the speed.

# CHAPTER IV. CURRENT TECHNOLOGY ON CONTROLLERS

The increasing automation of industrial processes has made the market of motor control very competitive. Manufacturing companies try to keep pace and to develop better systems in this field. The information provided in the following sections is based on the printed materials sent to the researcher by the companies cited.

## General Electric Company

As a pioneer in this field, General Electric has launched the microprocessor-based motor control, especially designed for those applications requiring a precise control of motor speed or position, such as transfer lines and machine tools. The company claims that a microprocessor drive has the following advantages over the current analog drive: (a) it eliminates the need to adjust potentiometers and change fixed components; (b) the drive can be tuned-up by an external computer in a faster and more accurate way than by human operators; (c) it is less sensitive to noise, aging, and temperature errors; and (d) the system is more flexible since the drive can be quickly reprogrammed for many tasks.

To date, the most advanced microprocessor-based drive produced by GE is a DC integral horsepower unit. It is produced in two versions, the DC-200 SCR control (5-60 HP) and the DC-300 SCR control (5-75 HP). Specifications for these drives can be found in appendix C.

### Hampton Products Co., Inc.

This company provides industry with the conventional variable speed SCR controls for DC motors in different models ranging from 1/8 to 5 HP (See Appendix D). It also offers adjustable frequency controls for AC motors from 1 to 30 HP (Appendix E)

### Quantem Corporation

The related product manufactured by this company is a temperature modulating fan speed control. This solid-state, single phase variable motor speed controller is used to ventilate automatically industrial, commercial and agricultural facilities. The controller varies motor speed in response to temperature changes by delivering pulses to a triac early or late in each half cycle. Specifications for this type of control can be found in appendix F.

# CHAPTER V. FUTURE DEVELOPMENTS

The possibilities for improvements of current motor controllers or for new advances in this field seem to be promising for the near future. Some of the predicted areas of future development are briefly discussed in the following sections.

## Capability and Cost

Some knowledgeable writers (Stokes, 1984; Shrivastava, 1985) predict that future controllers will be designed for higher voltage capabilities. This will be possible due to the increasing use of high powered, self-commutating power devices, such as the gate turn-off thyristor (gto) and the phase controlled SCR. Since these advances imply a simplification in the design, it is expected that the current costs will decrease for many packages of motor control.

## Microprocessors

The use of microprocessor-based controllers will increase during the next few years (Shrivastava, 1985; Murphy & Gilmore, 1984). The system will provide more control options on a single control board, such as better protection, increased user flexibility, and better self-diagnostic capabilities.

## Motors

DC motors will continue in use, although the ac induction motor will continue to prevail as the rotating component in ac drives (Murphy & Gilmore, 1984). However, those types of motors built as simple and inexpensive as possible and with a minimum connections to the outside world will be the most widely used within the years to come (Stokes, 1984).

# CHAPTER VI. LABORATORY EXPERIENCES

In order to have some hands-on experiences with regard to actual motor controls, three circuits were set up in the laboratory and some experimental results were obtained (see appendix G). The circuits used (Malloney, 1979, pp. 141, 186) represent the fundamental theory on speed control of universal motors as discussed in previous chapters.

The devices used and their electrical characteristics were the following:

Load

| | |
|---|---|
| Type | : Sewing machine motor |
| Make | : Premier |
| Volts | : 115 V DC & AC |
| Amperes | : 1.5 A |
| Frequency | : 25-60 Hz |
| Model | : UV-625 |

SCR

| | |
|---|---|
| Type | : Radio Shack Cat. 276-1067 |
| DC gate trigger current | : Typ. 6 mA |
| DC gate trigger current | : Max. 12 mA |
| On-state current, Tc 80 C Max. | : 6A (RMS) |
| Repetitive peak off-state and peak reverse voltage | : Max. 200 V |
| DC holding current | : Max. 30 mA at RT |

| | | |
|---|---|---|
| Peak reverse gate voltage | : | Max. 10 V |
| Peak gate power dissipation | : | Max. 5 W |
| Average gate power dissipation | : | Max. 0.5 W |

Quadrac (triac with built-in diac)

| | | |
|---|---|---|
| V | : | 400 V |
| I | : | 6 A |
| I | : | $\geq$ 10 mA |
| V | : | 32 V |

# CHAPTER VII.SUMMMARY, CONCLUSIONS, AND RECOMMENDATIONS

## Summary

The invention and constant improvement of solid-state devices revolutionized the field of electric motor control, providing industry with components of high reliability, low cost, and long life. SCRs, diacs, triacs, and similar devices are widely used in many applications ranging from a variety of low-power home appliances to industrial machinery requiring high voltages and currents.

Although many variations of motor control have been developed, most of them use switching devices to vary the voltage fed to the motor by either turning it ON and OFF at a very fast rate (RC or phase shift method) or changing the frequency at which power is delivered (pulse-width-modulation).

The method to be chosen is dependent on the type of motor to be controlled and the amount of power required. For dc motors, it is appropriate to use RC control, in a half- or full-wave arrangement and from a single- or three-phase source. AC motors, on the other hand, require a change in frequency in order to vary their speed. In these cases, an inverter of the pulse-width-modulation type is necessary.

The search for improvements in this field seems to be endless. The years to come will witness the increasing use of computer-based methods aimed at controlling the many functions of electric motors, especially in those applications involving complex and precise operations.

## Conclusions

The review of literature and the practical experiences carried out through this study showed that the field of solid-state controllers is an expanding and complex area of today's technology. Although the study was conducted at a basic level, it was very beneficial for the researcher to gain a better understanding of the theory and processes involved.

It is hoped that the insight gained through this research can be applied in future educational practice.

## Recommendations

Since this study was not exhaustive in the sense of covering all the possible aspects on the topic, it is recommended that future researchers investigate the following areas:

1. Controllers for ac induction motors.
2. Microprocessor-based controllers.

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# APPENDICES

# Appendix A

## Letter to Controller Manufacturers

**University of Northern Iowa**

**Department of Industrial Technology**

Industrial Technology Center
Cedar Falls, Iowa 50614
Phone

September 12, 1985

Dear Sir or Madam:

I am a graduate student at the University of Northern Iowa working on my Master's degree in Industrial Arts.

I intend to write my research paper on electronic control of electric motors, which I consider an important development within the latest technological advances.

In order to carry out the above purpose, I would appreciate if you forward to me any current state-of-the-art information on the control equipment produced by your company: solid-state control devices, electronic motor controllers and their industrial and commercial applications.

Additional information on historical development and future trends on this technology will also be welcomed.

The name of your company will be credited for the corresponding data included in this research.

Thank you very much for your cooperation.

Sincerely yours,

Armando Castillo
Department of Industrial Technology
University of Northern Iowa
Cedar Falls, IA 50614

Dr. Rex W. Pershing
Associate Professor of Industrial Technology

# Appendix B

## Addresses of Selected Controller Manufacturers

# MANUFACTURERS OF ELECTRONIC CONTROLS

Allied Electronic Components
P.O Box 1013R-T
Morristown, NJ 07960 (201)455-2000

Baldor Co.
P.O. Box 2400-T
Fort Smith, AR 72902 (501)646-4711

Bodine Electric Company
2500 West Bradley Place
Chicago, IL 60618 (312)478-3515

Borg-Warner Electronics Corporation
702-T S. Aurora St.
Ithaca, NY 14850 (607)272-5050

Eaton Corporation, Industrial Control Division
4201 North 27th Street
Milwaukee, WI 53216 (414)449-6000

Ebbert Engineering Co.
1925-T W Maple Rd.
Troy, MI 48084 (313)649-9410

Electro-Craft Corporation
1602 Second Street South
Hopkins, MN 55343 (800)328-3983

Electrol Co., Inc.
P.O. Box 29-T
York, PA 17404 (717)848-1722

Electro-Devices, Inc.
2 Godwin Ave.
Paterson, NJ 07509 (201)345-1344

Firing Circuits, Inc.
10 Muller Ave., P.O. Box 2007
Norwalk, CT 06852 (203)846-1633

General Electric Co.
1100 Lawrence Parkway
Erie, PA 16531 (814)875-2663

Hampton Products Co., Inc.
2995 Eastrock Dr.
Rockford, IL 61109 (800)435-8870

Parametrics Co.
284 Racebrook Rd.
Orange, CT 06477 (203)795-0811

Plant Specialties, Inc.
P.O. Box 1097-T
Carrollton, TX 75006 (214)245-9673

Quantem Corporation
P.O. Box 7599
Trenton, NJ 08628 ( )

Ranco Electronics Division,
Teccor Electronics Inc.
P.O. Box 619009-T
Dallas, TX 75261 (214)659-0678

Rockwell International Corp.
4311 Jamboree Rd., P.O. Box C
Newport Beach, CA 92658 (714)833-4600

Square D Co.
252-T N Tippecanoe
Peru, IN 46970 (317)472-3381

SSAC, Inc.
P.O. Box 395-A
Liverpool, NY 13088 (315)622-1000

Westinghouse Electric Corporation
Industrial Control Division
P.O. Box 819-W
Oldsmar, FL 33557 (813)855-4621

# Appendix C

## General Electric DC-200 and DC-300 SCR Controls

# Appendix D

## Specifications for Hampton DC Motor Controls

# Appendix E

## Specifications for Hampton AC Motor Controls

# Appendix F

# Specifications for Quantem Series 50 Controllers

# Appendix G

## Experiments

# Experiment No. 1. An SCR Power Control Circuit

## Purposes

1. To observe the operation and waveform of an SCR driving an inductive load.

2. To determine the range of operation (minimum and maximum firing delay angle).

3. To determine the gate and load current at minimum and maximum speed.

## Circuit

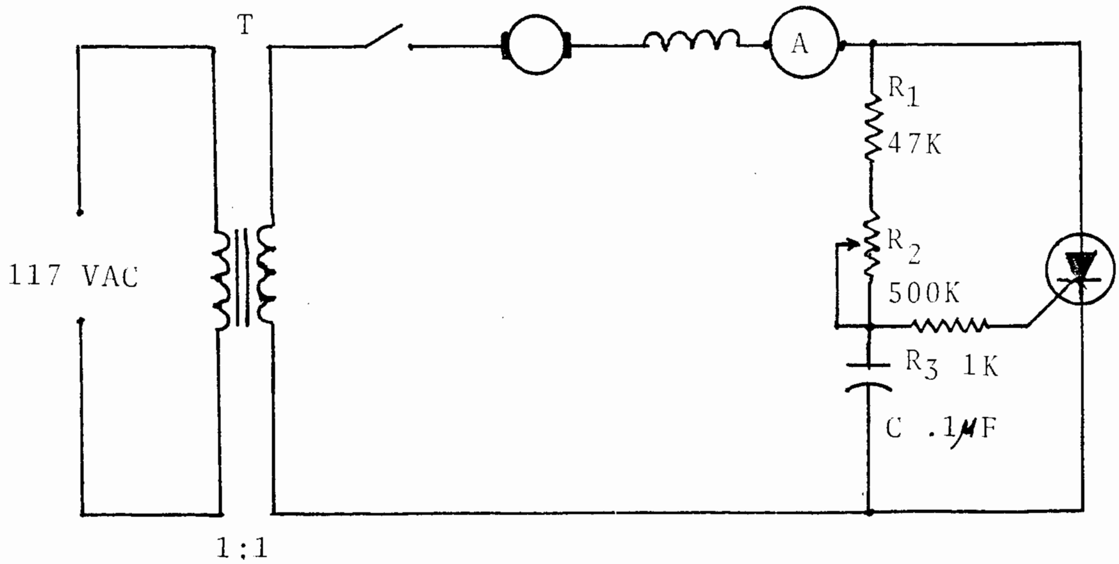


Figure 24. SCR Power Control Circuit

## Experimental Results

The circuit was connected using the values shown in Fig. 24, but it did not work. Therefore, the values of $R_1$ and $R_2$

were changed in order to decrease the value of the RC time constant, as follows: (a) $R_1 = 4.7K$, instead of 47K; and (b) $R_2 = 100K$, instead of 500K.

After these changes the circuit worked satisfactorily and the following results were obtained:

Range of control.

Minimum firing angle : $45^{\circ}$ (maximum speed)

Maximum firing angle : $90^{\circ}$ (minimum speed)

Waveform.

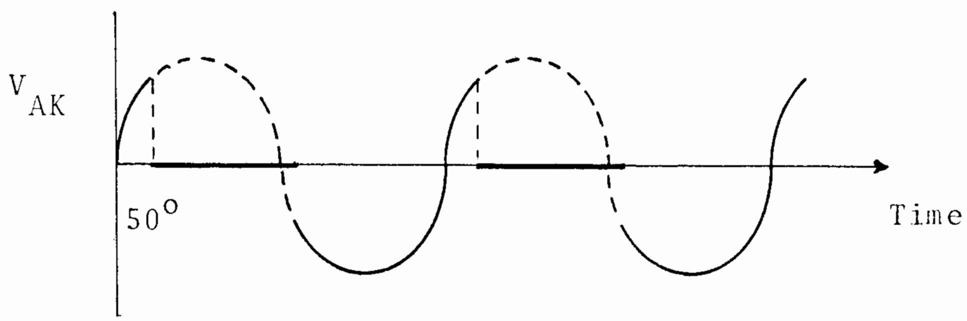


Figure 25. Waveform for $V_{AK}$ in Circuit of Fig. 24

Triggering current.

Measured : $I_G$ = 5 mA

Calculated ($E_{R_3}/R_3$) : $I_G$ = 5.3 mA

Load current.

$I_L$ at minimum speed : $I_L$ = 200 mA

$I_L$ at maximum speed : $I_L$ = 380 mA

Comments.

1. The speed control was not very good and it was possible only at the end of the potentiometer $R_2$ (near zero ohms). Lower values for $R_2$ were tried, with similar results.

2. It was difficult to read $I_{L(min)}$ because of the instability of the current at low speed.

3. The range of operation was rather limited since the triggering angle extended only from 45° to 90°.

Experiment No. 2. SCR Control with a Double RC Gate Trigger Circuit

Purposes

1. To observe the operation and waveform of an SCR driving an inductive load with a double RC gate control circuit.

2. To determine the characteristic parameters of the circuit.

Circuit

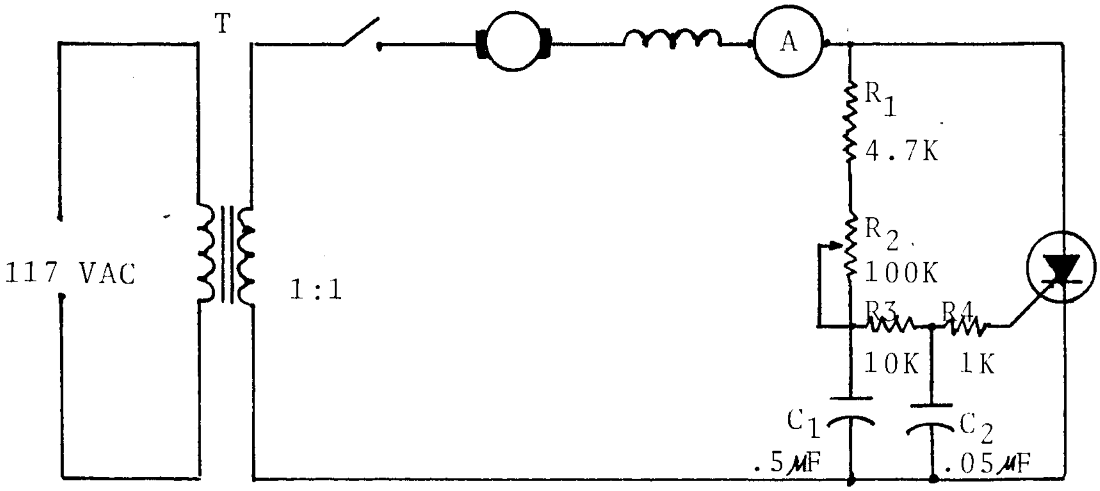


Figure 26. Double RC Trigger Circuit

## Experimental Results

Range of control.

Minimum firing angle : $110^{\circ}$ (maximum speed)

Maximum firing angle : $130^{\circ}$ (minimum speed)

Waveform.

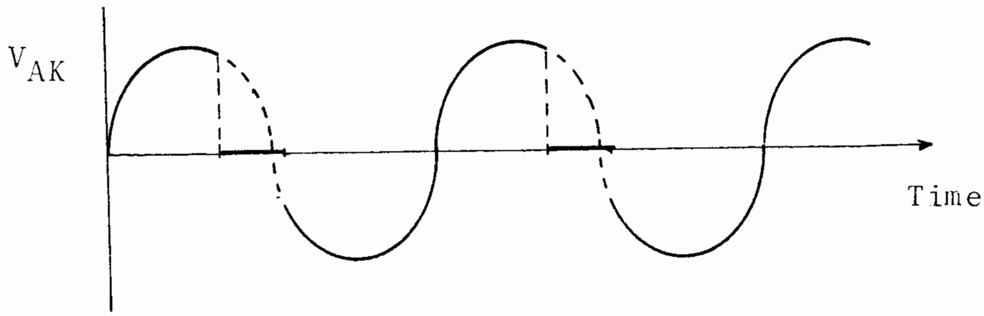


Figure 27. Waveform for $V_{AK}$ in Circuit of Fig. 26

Triggering current.

$I_G$ , measured and calculated : 5 mA

Load current.

$I_L$ at minimum speed : 230 mA

$I_L$ at maximum speed : 280 mA

Comments.

1. Although the delay angle was increased with this circuit, the range of control was still very narrow ($110^{\circ}$ to $130^{\circ}$ ). By decreasing the value of $C_1$ from 0.5 $\mu$F to 0.1 $\mu$F a wider range was obtained but at lower limits than before, as

follows: $70^{o}$ to $110^{o}$ with $I_L$ ranging from 150 mA to 340 mA.

Like the preceding circuit, this one only could be controlled at the end portion of the potentiometer, i.e., where $R_2$ approaches zero. Again, different values for $R_2$ were tried with no improved results.

## Experiment No. 3. Triggering Circuit for a Triac

### Purpose

To determine the parameters in the functioning of an RC gate control circuit using a triac with built-in diac (quadrac).

### Circuit

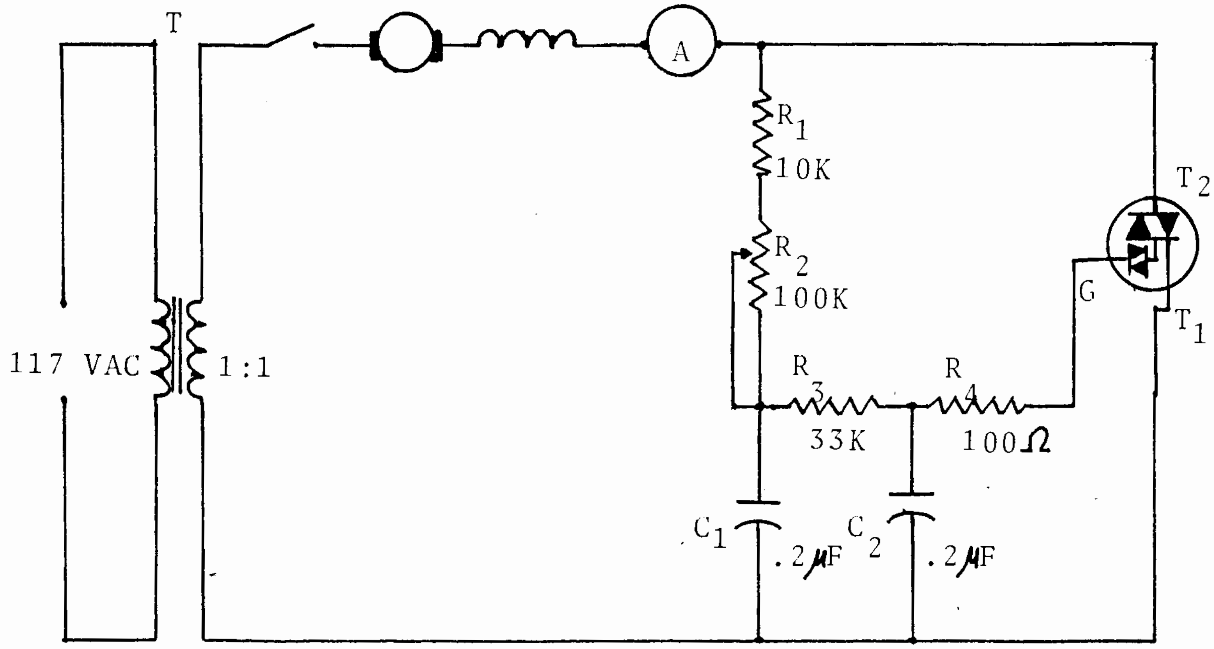


Figure 28. Triggering Circuit for a Triac

## Experimental Results

Range of control.

From $70^{\circ}$ (maximum speed) to $100^{\circ}$ (minimum speed)

Waveform.

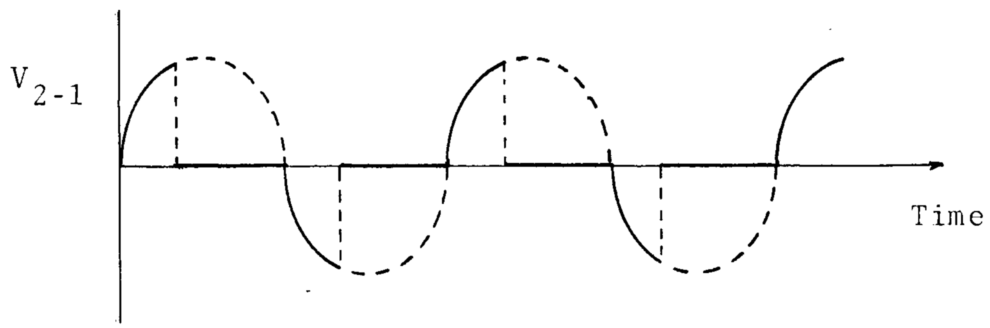


Figure 29. Waveform for $V_{2-1}$ in Circuit of Fig. 28

Triggering current.

| | | |
|---|---|---|
| $I_G$ measured | : | 2.4 mA |
| $I_G$ calculated | : | 2.0 mA |

Load current.

| | | |
|---|---|---|
| $I_L$ at minimum speed | : | 250 mA |
| $I_L$ at maximum speed | : | 330 mA |

Comments.

Although the triggering current specified for this triac was 10 mA or more, in this experiment the triac was triggered with a gate current of about 2 mA. The difference could be due to a defective device or to an error in the manufacturer's specifications.