IEEE TRANSACTIONS ON INDUSTRY AND GENERAL APPLICATIONS VOL. IGA-2, NO. 2 MAR/APR 1966

Voltage Control by Means of Power Thyristors

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***Abstract*—This paper is presented as a tutorial informative survey on the subject of voltage control. Voltage control is discussed from several viewpoints: 1) control of direct voltage from an ac source, 2) control of alternating voltage from an ac source, 3) control of direct voltage from a dc source, and 4) control of alternating voltage from a dc source. Such various control modes as 1) phase control, 2) switching control, 3) pulse burst modulation control, and 4) chopper control are discussed. Many circuit possibilities are tabulated together with typical transfer characteristics and notes concerning optimum matching of application and circuit. Also discussed are such allied control subjects as 1) the function of free-wheeling diodes, 2) interphase transformers, 3) power factor effects, 4) capacitive and counter-EMF loads, 5) firing-pulse requirements, and 6) zero voltage switching. Comprehensive listings of circuits and control and application methods are included. These are sufficiently complete to suggest to those skilled in rectifier art other variations which may be useful in solving specific problems.**

INTRODUCTION

BY UTILIZING the gate of a thyristor to initiate conduction of load current at any desired instant, it is possible to control the flow of ac or dc power, thus reducing the load voltage essentially to zero, or to adjust the voltage smoothly from maximum available to zero. This action is in contrast to that of the transistor which can exert control over circuit voltage equivalent to that obtained using a variable resistor.

A number of circuit configurations may be used to adjust both direct and alternating voltage with thyristors; it is the purpose of this paper to review these possibilities, stressing circuit action and means for calculating the voltage control characteristic in each case.

Phase controlled biphase (single phase, full wave) and polyphase rectifier circuits provide smooth control of output voltage. (Figure 4 relates output voltage to angle of phase retard α for such circuits when supplying resistive and inductive loads. This figure also discloses the performance of hybrid bridge (double-way) circuits, where half the thyristors are replaced by rectifier diodes, and of rectifier circuits feeding loads shunted by a free-wheeling diode.)

Phase controlled thyristors may be used to control alternating voltage; circuit configurations are given in Table I. The relationship of output voltage to phase control angle, for the resistive load case, is shown in curve *E* of Fig. 4. In addition to using phase control, alternating voltage may be controlled by OFF-ON switching, or by switching from full alternating voltage to a partial voltage provided by a transformer tap. For this type of operation, pulse-burst modulation is frequently used and found to lend itself well to loads having thermal or mechanical inertia. Radio frequency interference, encountered in both the phase control and switching modes of voltage control, may be reduced greatly in the case of the switching mode if zero voltage switching is used.

Chopper control of direct voltage makes possible the control of dc power more efficiently than by a control method employing a variable resistor or a transistor regulator. The chopper may be used to reduce input voltage or to increase it. Two basic circuits are recognized, the series chopper and the parallel chopper. Control may be accomplished by varying the repetition rate of the ON periods, keeping the duration of the ON periods constant, or the frequency may be held constant and the duration of the ON periods changed. Control characteristics may be modified by tapping the inductance which is a part of the circuit. (Control characteristics are shown in Figs. 16, 17, 21, and 22. More complex systems using thyristors will provide control of voltage; one such system is depicted by the block diagram of Fig. 23.) In addition, circuits which are selected to provide some other function, such as cycloconverters used for frequency changing, may be controlled in such a manner that the output voltage is adjustable over a desired range or may be regulated at a desired value.

CONTROL OF DIRECT VOLTAGE BY PHASE CONTROL

Phase Controlled Rectifiers

Probably the most common method of adjusting direct voltage by phase control is by using reverse blocking thyristors (silicon controlled rectifiers) in a conventional rectifier circuit and delaying the start of current conduction through them. By this means, known as phase control, the direct voltage can be reduced from the value obtained without phase control to some other desired value. If the start of conduction is delayed sufficiently, the average output voltage will be reduced to zero.

The average voltage which will appear across the load for a given phase control angle depends upon the rectifier circuit and the type of load. Performance with a purely resistive and also with a highly inductive load can easily be analyzed, and in this way insight is provided with respect to circuit performance when the load is partly resistive and partly inductive. It is also useful to consider performance when the load is capacitative, has a large counter-EMF, or is provided with a free-wheeling diode.

Approved by the Industrial Power Rectifier Committee for presentation at the IEEE Industrial Static Power Conversion Conf., Philadelphia, Pa., November 1–3, 1965.

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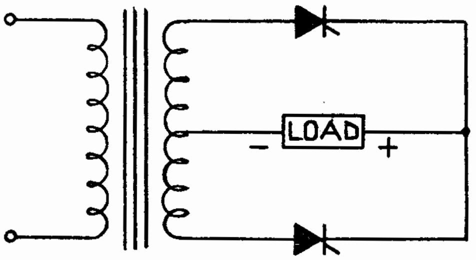
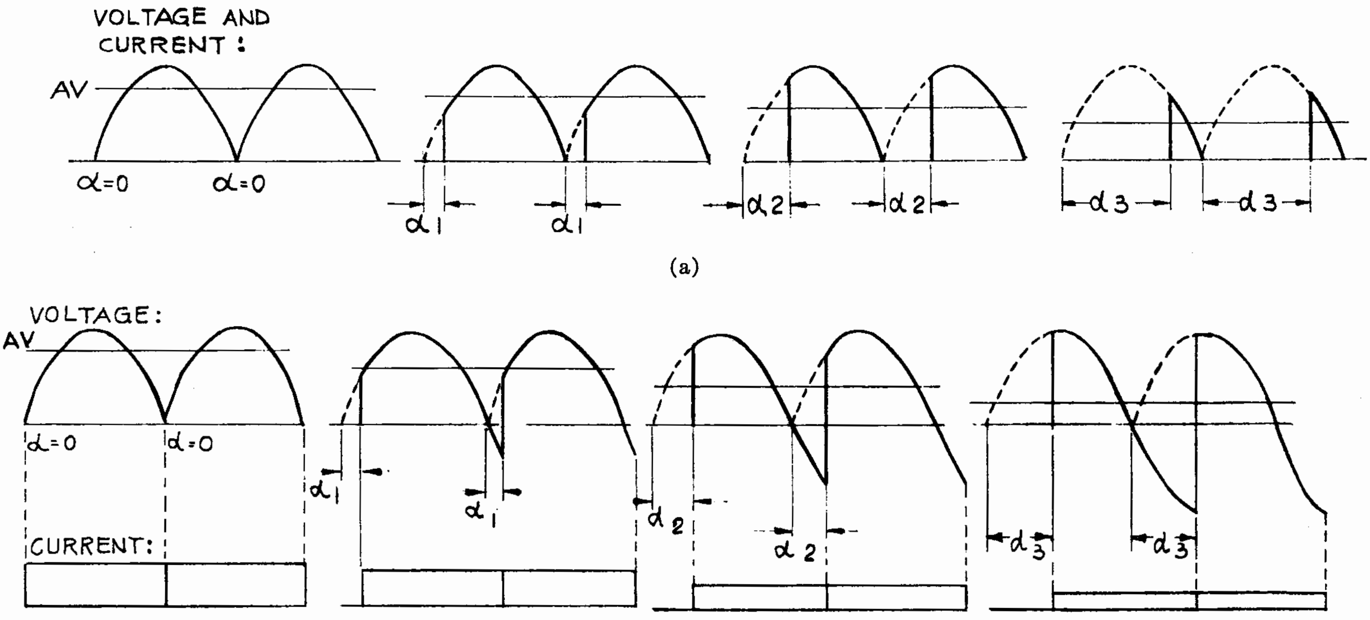


Fig. 1. Biphase single-way (single-phase full-wave center-tap) rectifier circuit.



(a)

(b)

Fig. 2. Output voltage and current waveforms, biphase circuit, various angles of phase retard α. (a) Resistive load. (b) Inductive load

In some circuits, half of the thyristors are replaced by rectifier diodes that operate without phase control. In these hybrid or half-controlled circuits the voltage reduction for a given phase control angle, or angle of retard, will be different than in conventional circuits where all the rectifying devices are thyristors.

Biphase (Single Phase, Full Wave) Circuit, Resistive and Inductive Loads

As a simple example of a phase controlled rectifier circuit, consider the single phase, full wave, center tap circuit (more correctly known as the biphase circuit) shown in Fig. 1. Output direct voltage waveforms for several angles of delay, or phase retard α are shown in Fig. 2 for the cases of resistive load and highly inductive load. Angle of phase retard α is measured from the point where current conduction through the rectifying device would naturally begin if an unrestrained rectifying device (i.e., a rectifier diode) were being used. A thyristor may be made to operate in the same manner as a diode by pulsing the gate so that the thyristor conducts the instant that anode voltage becomes positive with respect to the cathode (anode is forward biased). By delaying the firing pulse, the thyristor blocks the more positive ac phase so that the preceding phase, although it is at a lower potential, remains connected to the load. When the delayed firing pulse finally appears, load current is commutated (or switched) to the thyristor fired, and this connects the load to the ac phase having the highest voltage at that instant. However, during the time when the firing pulse is delayed by the angle α, the voltage across the load is less than if conduction had occurred at the earliest possible moment. In this way, the average voltage across the load is reduced by phase control.

When the load is purely resistive, load current will be a faithful reproduction of load voltage; this is illustrated in Fig. 2(a). When phase control is introduced, the voltage across the load is seen to be discontinuous, and current flows through the thyristor for some interval less than

TABLE I
THYRISTOR CIRCUITS TO CONTROL A-C LOADS

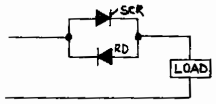
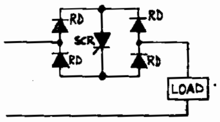
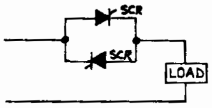
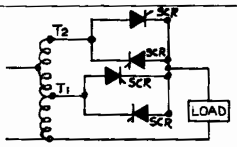
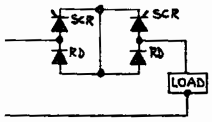
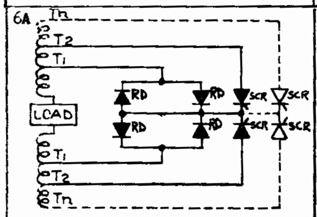
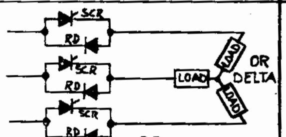
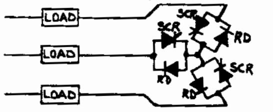
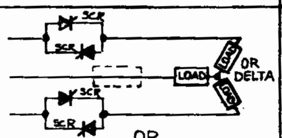
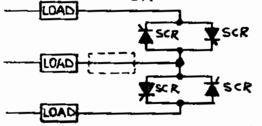
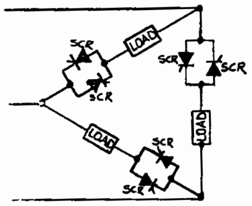
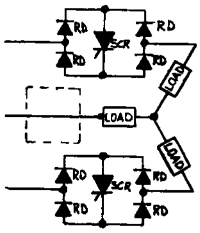
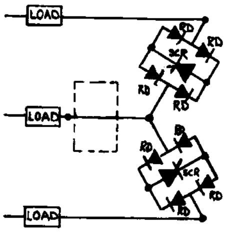
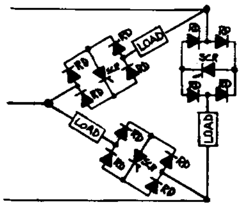
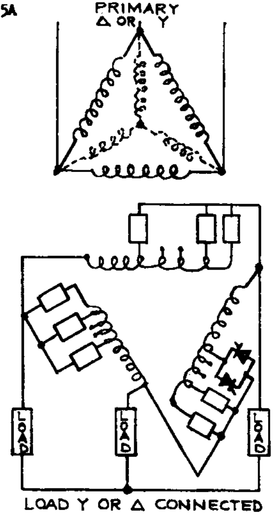
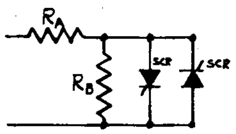
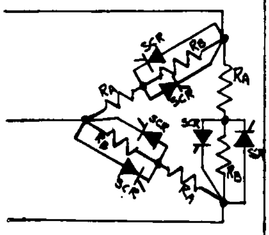
CIRCUIT	RELATIVE POWER OUTPUT	TYPE OF LOAD	CONTROL RANGE %	TYPICAL USES	APPLICABLE MODES OF CONTROL	SEE NOTES
1A 	1	Resistive only	50 to 100	Low Power Heater Loads Lamp Intensity Control	SWC PC PBM	1 2 3 4
2A 	0.7	Resistive or with low inductance	0 to 100	Heater Control Lamp Intensity Control Motor Speed Control (Induction or Universal)	SWC PC PBM	2 3 4
3A 	1	Resistive or Inductive	0 to 100	Heater Control Lamp Intensity Control Motor Speed Control (Induction or Universal) Transformer Primary Control Solenoid Pull Control AC Magnet Control	SWC PC PBM	3 4
4A 	1	Resistive or Inductive	% T1 to 100	Heater Control Lamp Intensity Control Motor Speed Control (Induction or Universal) Solenoid Pull Control AC Magnet Control On Load Tap Changing	SWC PC PBM	3 4 5 6
5A 	1	Resistive or Inductive	0 to 100	Heater Control Lamp Intensity Control Motor Speed Control (Induction or Universal) Transformer Primary Control Solenoid Pull Control AC Magnet Control	SWC PC PBM	3 4
6A 	1	Resistive or Inductive	% T1 to 100	Heater Control Lamp Intensity Control Motor Speed Control (Induction or Universal) Solenoid Pull Control AC Magnet Control On Load Tap Changing	SWC PC PBM	3 4 5 6
7A  OR 8A 	1.73 1.73	Resistive or Inductive	0 to 100	Heater Control Lamp Intensity Control Motor Speed Control (Induction) Transformer Primary Control Solenoid Pull Control AC Magnet Control	SWC PC PBM	3 4 7
9A  OR 10A 	1.73 1.73	Resistive or Inductive	0 to 100	Heater Control Lamp Intensity Contol Motor Speed Control (Induction) Transformer Primary Control Solenoid Pull Control AC Magnet Control	SWC PC PBM	2 3 4 7 8
11A 	3	Resistive or Inductive	0 to 100	Heater Control Lamp Intensity Control Motor Speed Control (Induction) Transformer Primary Control Solenoid Pull Control AC Magnet Control	SWC PC PBM	3 4 10

TABLE I (CONT.)

CIRCUIT	RELATIVE POWER OUTPUT	TYPE OF LOAD	CONTROL RANGE %	TYPICAL USES	APPLICABLE MODES OF CONTROL	SEE NOTES
12A 	1.21	Resistive or Slightly Inductive	0 to 100	Heater Control Lamp Intensity Control Transformer Primary Control (when load has high power factor) Note: If load is connected Δ, a third diode-thyristor control unit is required in the third line.	SWC PC PBM	3 4 8 11
13A 	1.21	Resistive or Slightly Inductive	0 to 100	Heater Control Lamp Intensity Control Transformer Primary Control (when load has high power factor) Note: If load is connected Δ, a third diode-thyristor control unit is required in the third line.	SWC PC PBM	3 4 8 11
14A 	2.1	Resistive or Slightly Inductive	0 to 100	Heater Control Lamp Intensity Control Transformer Primary Control (when load has high power factor)	SWC PC PBM	3 4 10
15A 	2.1	Resistive or Inductive	$\%\ T_1$ to 100	Heater Control Motor Speed Control (Induction) On Load Tap Changing	SWC PC PBM	3 4 5 6 10 for Y Conn. Load 7 11
16A 	1	Resistive or Inductive (Inductance in R_A only)	Depends on Ratio R_A:R_B	Heater Control Lamp Intensity Control Transformer Primary Control (Transf. Winding replaces R_A) Induction Motor Speed Control	SWC PC PBM	3 4 18
17A 	3	Resistive or Inductive (Inductance in R_A only)	Depends on Ratio R_A:R_B	Heater Control Lamp Intensity Control Transformer Primary Control (Transf. Winding replaces R_A) Induction Motor Speed Control Wound Rotor Induction Motor Speed Control	SWC PC PBM	3 4 11 18

the full 180 electrical degrees that it flows when there is no phase control. The time that current flows under these conditions is known as the conduction angle. Energy is stored in the inductance of the transformer each time current increases and is returned to the load as current decreases, so that there is essentially no reactive voltage drop with a purely resistive load as long as load current is discontinuous.

On the other hand, when the load is highly inductive, the load current remains continuous for all angles of phase retard. In this case, the duration of current flow through the rectifying devices remains the same as the phase retard angle is varied, but it is displaced with respect to the alternating supply voltage wave by the phase retard angle α as shown in Fig. 2(b). With an inductive load, the angle of conduction is determined by the circuit used and not by the angle of phase retard, and is often referred to as the conduction period.

It will be seen that, with an inductive load, the flow of current through each thyristor is essentially rectangular. Inductance in the ac supply (due to rectifier transformer leakage reactance, ac supply reactance, etc.) prevents the load current from commutating instantaneously from one thyristor to the next thyristor when the latter is fired. For a brief interval both thyristors conduct, one dropping current and the other picking it up. This interval is known as the angle of overlap μ.

The currents through two thyristors which are undergoing commutation are shown in Fig. 3. It can be seen that the total current remains constant, due to the inductive nature of the load. The length of the angle of overlap μ depends upon the magnitude of the load current and of the inductive reactance of the circuit which carries that commutating current, i.e., the circuit comprising the two diodes and the transformer windings which feed them. The inductive reactance of this circuit is known as the commutating reactance.

During the angle of overlap, the direct output voltage of the rectifier is the average of the voltage applied to each thyristor by the transformer windings which feed them. This is a lower voltage than would be present if the angle of overlap were zero, and so the overlap phenomenon introduces a voltage drop E_x, the value of which is a function of the angle of overlap. Hence, in a given rectifier unit, it is a function of load current, proportional to I_cX_c, the product of current commutated and commutating reactance.

In a rectifier feeding an inductive load and operated with phase retard, the angle of overlap will be present immediately following the angle of phase retard. As phase retard is increased, the angle of overlap μ will decrease because there is a greater voltage difference between phases when commutation begins, and this speeds up the transfer of current from one phase to the next. However, the voltage drop due to overlap remains the same whether phase control is present or not.

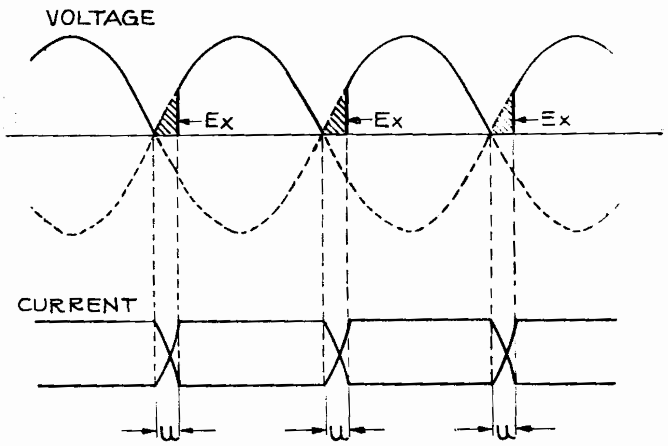


Fig. 3. Output voltage and current waveforms, biphase circuit, inductive load, with commutating reactance present.

In the inductive load case it is evident that although the alternating component of voltage appears across the load at large angles of phase retard, the average voltage can be reduced to zero. It can also be seen that in order to obtain zero voltage across the load when it is resistive, the angle of phase retard must be 180 degrees, whereas with an inductive load zero average output voltage is obtained when it is 90 degrees.

Expressions that give the output voltage at no load for any angle of phase retard are

For resistive loads:

$$E_D = E_{DO}\,\frac{1 - \sin(\alpha - 90^\circ)}{2}. \tag{1}$$

For inductive loads:

$$E_D = E_{DO} \cos \alpha. \tag{2}$$

In these expressions E_D is the direct output voltage, E_{DO} is the output voltage without phase control (rectifying devices operated without constraint), and α is the angle of phase retard in electrical degrees.

It is often convenient to express the above relationships in terms of E_{DO} and the voltage reduction E_α.

For resistive loads:

$$\frac{E_{DO} - E_\alpha}{E_{DO}} = \frac{1 - \sin(\alpha - 90^\circ)}{2}. \tag{1a}$$

For inductive loads:

$$\frac{E_{DO} - E_\alpha}{E_{DO}} = \cos \alpha. \tag{2a}$$

These two expressions are plotted on linear coordinates in Fig. 4 as curves D and A, respectively.

Single-Phase, Half-Wave Circuit: As was mentioned previously, the single-phase, center tap circuit is actually a biphase circuit since it is in reality two single-phase circuits displaced by 180 degrees. The single-phase, half-wave circuit, where the number of phases is one, is not considered

Operation with Free-Wheeling Diode

Where the load is inductive, and the large amount of ripple obtained in the usual circuits with a large angle of phase retard is not desired, one or more rectifier diodes may be used as free-wheeling diodes and placed across the load in the direction to block the flow of current from the rectifier, but to provide a path for the current flowing in the load inductance during the intervals when the rectifier output voltage is negative, as shown in Fig. 5. This occurs at angles of α between α_1 and α_2; the values for these are given for several rectifier circuits in the previous tabulation. The action of the free-wheeling diode reduces the ripple voltage across the load; it also causes the rectifier output current to become discontinuous although the load current is continuous.

When a free-wheeling diode is present, a rectifier behaves very much as if it were supplying a resistive load, and the curve of output voltage vs. angle of phase retard is the one shown in Fig. 4 for the same rectifier circuit when it is feeding a resistive load.

Operation with Capacitive or Counter-EMF Load

A rectifier, when supplying either a capacitive or a counter-EMF load, will tend to deliver output current in a discontinuous manner, because current can flow only near the peak of each ac wave. For current to flow, the rectifier output voltage must exceed the voltage across the capacitor, which will be more or less fully charged depending upon the magnitude of the resistive component of the load. Other loads presenting a counter-EMF, such as electrolytic cells, batteries, and lightly loaded dc motors, will cause the same circuit action.

If the load includes some inductance, which is usually the case, this inductance will store energy while the current is rising to its peak value, and current will continue to flow until this stored energy is delivered to the load. This means that the rectifier output current will persist for a longer time than just the interval when rectifier voltage exceeds the counter-EMF, which is the case when there is no inductance. Waveforms to illustrate current flow with and without load circuit inductance are shown in Fig. 6.

When phase control is applied, the output voltage will be reduced if the thyristors are fired at some instant later than when the rectifier phase voltages exceed the counter-EMF. At the same time, the energy absorbed in the inductance of the load will be less, so that the conduction angle is further reduced, causing the additional loss in voltage output. Because of this interaction, there is no simple relationship between angle of phase retard and reduction of output voltage, as is the case when the load on a rectifier is purely resistive or inductive.

It is clear from the preceding discussion that, when the load exhibits a counter-EMF, the earliest instant a given rectifying device can be fired depends upon the ratio of the load voltage to the peak voltage supplied by the transformer. This ratio will vary with changes in load current, which could be caused by changes in load resistance; or it will vary because of changes in the alternating supply voltage. In the designing of the firing circuit, this effect must be recognized; long firing pulses are desirable, so that if the thyristor is fired before load current can flow, it will remain turned ON by the firing pulse until some instant later when current can flow to the load. If this is not done, the rectifier may fail to deliver any power to the load when it is phased ahead in an effort to obtain maximum output!

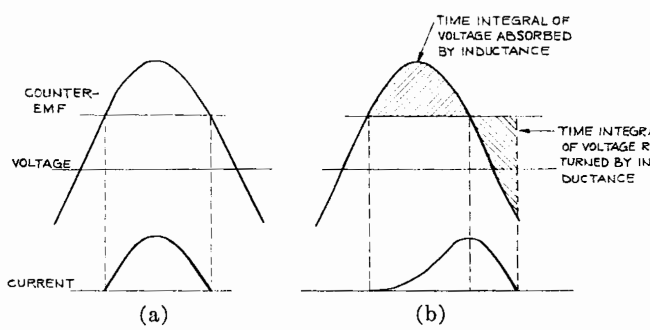


Fig. 6. Voltage and current waveforms, biphase circuit feeding counter-EMF load. (a) Without load circuit inductance. (b) With load circuit inductance.

Hybrid Circuits

In the single-phase and polyphase bridge circuits, half the rectifying devices can be made rectifier diodes, the others remaining thyristors, and the output voltage can be controlled by phase shifting the firing pulses for the thyristors. The performance of these hybrid or half-controlled circuits, where the thyristors have a common cathode (or common anode) connection, can be analyzed by considering them as a phase controlled rectifier in series with one which is not. In this group of bridge circuits (including all hybrid circuits except one of the single-phase bridge circuits), when the angle of retard at which the thyristors are operated exceeds 90 degrees, the thyristors must invert or pump back some of the power delivered by the rectifier diodes. It is theoretically possible for this action to take place all the way down to zero voltage output, at which point the angle of phase retard required is 180 degrees. In practice, it will be found that with a large amount of phase retard the current may not completely commutate to the next phase before the phase which is commutating out becomes positive again. In this event, the thyristor which was supposed to commutate to the next phase will instead conduct full ON, and control of output by phase control will be lost. This is sometimes referred to as the "mouse trap" effect or as "half waving" [2].

All hybrid circuits can be thought of as having an action similar to that provided by a free-wheeling diode. For this reason, the control characteristic shown by curve *D* in Fig. 4 applies.

Single-Phase Hybrid Bridge: In the case of the single-phase hybrid bridge, two circuit configurations are possible;

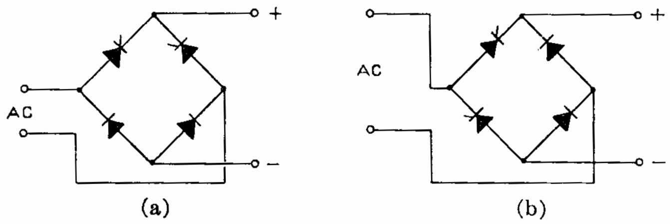


Fig. 7. Single-phase hybrid bridge circuits. (a) Thyristors in common cathode configuration. (b) Thyristors in doubler configuration.

in one, the two thyristors are connected with the cathodes (or anodes) tied to a common point, as in the center tap rectifier circuit, and in the other configuration the two thyristors are connected in series, as in the doubler rectifier circuit; refer to Figs. 7(a) and (b). Circuit action is similar but not the same in both cases.

With the common cathode configuration, the conduction angle through all the rectifying devices remains the same as the angle of phase retard is increased. With the other circuit the conduction angle through the rectifier diodes increases with increasing phase retard; the rectifier diodes used must be large enough to handle this increased current flow.

A disadvantage of the common cathode configuration is that, for large angles of phase retard, "half waving" may occur. Where the thyristors are connected in the doubler configuration this effect is not present.

Ripple from Hybrid Circuits: Because hybrid circuits behave as if a free-wheeling diode were present, the ripple voltage they exhibit, as output voltage is reduced by phase control, is less. This can be illustrated by comparing the action of the single-phase bridge having four thyristors with that of the hybrid single-phase bridge. In the first circuit, with an inductive load, zero output voltage will be obtained with a phase retard angle of 90 degrees. Under this condition, the peak of the alternating input voltage will appear across the load [see Fig. 2(b), waveforms for α_3] although the average voltage across the load will be zero. On the other hand, with the hybrid circuit phased by 180 degrees, the average and peak voltage both will be essentially zero. This difference in ripple voltage can be significant if part of the load is purely resistive, since with the hybrid circuit there will be less power dissipated in the resistive part of the load when the voltage is reduced by phase retard. For instance, with the hybrid circuit, an indicating lamp across the load will give a measure of the average voltage across the load; with the regular circuit having four thyristors, the lamp intensity will hardly change over the full range of average output voltage.

On the other hand, in the polyphase hybrid bridge circuits the ripple frequency will assume a lower value as phase retard is introduced. For instance, in the regular 3-phase bridge circuit, the fundamental ripple frequency is six times the supply frequency for all values of phase retard. In the hybrid 3-phase bridge circuit, a ripple frequency component which is three times the line frequency appears when phase retard is introduced. This action must be considered when the load is adversely affected by lower ripple frequencies; for example, in some dc motors.

Inversion of Inductive Energy: If it is desired to quickly reduce the voltage across an inductive load, this can be done by operating the rectifier as an inverter and pumping the energy stores in the load reductance back into the ac system. This is done by adjusting the angle of phase retard to be greater than 90 degrees. When a hybrid rectifier circuit is used, this mode of voltage control cannot be used, since the half of the rectifier circuit which is made up of diodes cannot be made to function as an inverter.

Firing Pulses for Bridge Circuits

In certain bridge rectifier circuits precautions must be taken when designing the thyristor firing circuit to be certain that the desired rectifier circuit action can take place. For example, in the conventional 3-phase bridge circuit having six thyristors, current flow through the load will not start if each thyristor is simply given a short gate pulse at the instant when current flow in each thyristor normally would start. This is the consequence of the fact that this circuit behaves as two 3-phase circuits in cascade and displaced by 30 degrees. To initiate current flow, thyristors in both halves of the circuit must be pulsed simultaneously. Under operating conditions were current flow becomes discontinuous, this simultaneous pulsing must occur six times a cycle.

Two solutions are possible. One is to provide each thyristor with a long gate pulse, more than 60 degrees in duration. The other solution is to double pulse each thyristor; once, when initiation of current flow is desired, and once again 60 degrees later.

In hybrid bridge circuits, where circuit action similar to that provided by a free-wheeling diode is obtained (and also in all-thyristor circuits which feed a load having a free-wheeling diode), the discontinuous nature of the current through the thyristors must be considered when designing the firing circuit. Since the interval of current discontinuity varies with load current and also with angle of phase retard, a firing circuit which provides a long firing pulse is desirable to assure proper circuit action from the thyristors.

FULL-WAVE CONTROL OF OUTPUT OF SINGLE-PHASE BRIDGE

A circuit of particular interest for use with thyristors is the single-phase bridge rectifier with a thyristor in series in the dc output. If conditions are such that the thyristor can regain forward blocking ability at the end of each voltage pulse in the output of the bridge rectifier, phase control may be applied to the thyristor and it will control the average voltage applied to the load. This circuit is most successful when the load has a counter-EMF, as in the case of a storage battery. It also can be made to work successfully with a resistive load and with a 3-c motor armature as the load when a free-wheeling diode is connected across the armature.

In this circuit the diodes in the single-phase bridge help to provide a short interval at the end of each half-cycle when flow is zero and during which the thyristor can turn OFF. Nevertheless, when feeding a resistive load or a dc motor, thyristors which have fast turn-OFF times are needed, which is the major reason why this circuit has never been used with thyratron tubes. Conventional mercury vapor thyratrons simply do not turn OFF (deionize) fast enough to operate in this circuit at supply frequencies of 50 or 60 c/s.

If the load is resistive or is provided with a free-wheeling diode, the voltage output will follow curve D of Fig. 4 as α is varied. It should be understood that α in this case is the angle of retard of each pulse applied to the thyristor in series with the load.

CONTROL OF ALTERNATING VOLTAGE BY PHASE CONTROL

A number of circuits are available for controlling alternating voltage with thyristors. Reverse blocking thyristors (semiconductor controlled rectifiers) may be connected in antiparallel, or a single-phase bridge may be used to rectify the ac line current so that one thyristor can control both halves of the ac wave; this circuit is the same as discussed under "Full-Wave Control of Output of Single-Phase Bridge" with the exception that the dc load is replaced by a short circuit and the load is located in the ac line. In some polyphase circuits the same control of voltage can be obtained when one thyristor is replaced with a rectifier diode, and this arrangement is, of course, more economical. A number of possible circuit configurations are shown in Table I.

In addition, the same kind of control can be provided by a bidirectional thyristor, since this can be triggered into conduction during either half of the ac wave. In Table I a bilateral thyristor may be used in place of any of the all-thyristor and thyristor-diode control circuits shown.

When using one of the configurations mentioned to adjust the alternating voltage applied to a load, it is evident that the average value of each half-cycle of current is controlled in the same manner as for the single-phase (biphase) rectifier circuit feeding a resistive load and that the control characteristic for average voltage follows curve D of Fig. 4. As a rule, the rms value of the voltage wave applied to an ac load is of greater interest than the average value; for a resistive load, the rms voltage is given as a function of the angle of phase retard by curve E of Fig. 4.

When the load is inductive, current flows as a sine wave which lags the supply voltage by θ, the angle which determines the power-factor. If each thyristor is fired at this angle, load current will be unaffected. If the firing angle is made to lag behind θ, the load current will flow as a series of nonsinusoidal pulses of less than 180 degrees duration.

As the angle of phase retard is increased, these pulses become increasingly shorter until, at 180 degrees retard, they cease to exist and the voltage across the load is zero. Thus, the voltage across the load will be reduced by phase retard in much the same manner as with a resistive load, except that voltage control will take place over a narrower range of firing angles; from θ to 180 degrees. At all firing angles the power-factor of the load does not depart significantly from the value observed with no phase control [3], [4].

Firing Pulses

As explained previously, with an inductive load, current will not flow the instant the voltage across the thyristor becomes positive from anode to cathode. For such loads, firing the thyristor full ON can result in no output if the firing pulse is so short that it disappears and the thyristor regains its forward blocking ability before current can flow in the load circuit. To avoid this it is necessary to make the firing pulses long enough so that the thyristor will always be able to conduct whenever circuit conditions are right for conduction, once it has been fired.

VOLTAGE CONTROL USING THYRISTORS IN SWITCHING MODE

There are numerous types of equipment or systems which can be controlled readily and advantageously by the use of thyristors as switches (as opposed to using them in the phase control mode for continuous variability of voltage). Of course, many of the switching mode circuits may be readily modified so that they incorporate phase control to provide a fine voltage adjustment to supplement the switching mode of control.

Advantages of the Switching Mode

Some of the advantages of the switching mode of operation of thyristors for controlling voltage are as follows:

1) Switching of load voltage (either from zero to full voltage or from partial to full voltage) is accomplished without mechanical contacts, thus eliminating common maintenance problems which result from burning, pitting, and welding of contacts. "Contact bounce" is also eliminated, thereby reducing radio frequency interference caused by the repetitive shock excitation of reactive circuit elements.

2) "Zero voltage switching" may be used to essentially eliminate radio frequency interference often encountered when voltage is controlled by phase control.

3) The use of the switching mode of voltage control eliminates the reduction in power-factor which inherently occurs when voltage is reduced by phase control.

Switching Mode Circuits and Applications

Table I shows a variety of switching mode circuits which are capable of controlling the voltage applied to ac loads. Table II shows a similar group of circuits for controlling dc voltage. The Appendix is a tabulation of notes which describes and amplifies the uses for the various circuits shown in Tables I and II.

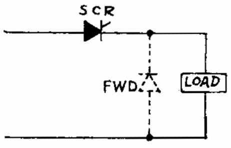
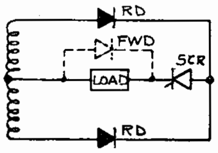
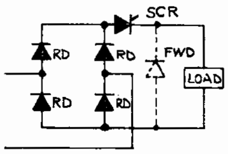
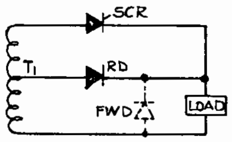
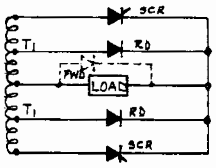
Many of these switching control circuits will find use in controlling heating elements for ovens, furnaces, hot plates, crucibles, and space heaters. Of equal importance, they may also be used for speed controls of squirrel cage and wound rotor induction motors and also dc motors, where the motor and/or load inertia is high. Still other types of load, for example 1) resistance welders, 2) stud welders, 3) flashers and flashing beacons, and 4) magnetic hammers or pulsers, demand this type of control as an inherent element in their mode of operation.

Most heating elements have a high thermal inertia and are easily adaptable to control by the switching mode, either by being switched from zero to full voltage (circuits 1*A*, 2*A*, 3*A*, 5*A*, 7*A*, 14*A*, and 1*D* through 3*D*), or from a low voltage tap to full voltage (circuits 4*A*, 6*A*, 15*A*, and 4*D* through 9*D*). Where the heating elements can be tapped at a midpoint, the circuits of 16*A* and 17*A* are also useful.

When the circuits with a tapped transformer winding are compared to those with a tapped load, it will be seen that the final control result is very similar for both. However, where the transformer is tapped, the load voltage is initially low and is switched to a higher value. In the tapped load circuit, the initial voltage is high across one section of the load and zero across the other section. After switching, the voltage decreases across one section while increasing across the other. This tapped load "shunt controller" performs equally well for resistive loads (such as heating elements) and for speed control of wound rotor induction motors, by varying the resistance in the rotor circuit.

In the cases of flashers and beacons it often becomes possible to substantially lengthen filament life of the lamps by switching from full voltage to a lower transformer tap (reducing the voltage below the incandescent level), thus minimizing the range of filament temperature excursion. A similar improvement in the life of heating elements may also be expected when they are controlled in this way for the same reason.

TABLE II
Thyristor Circuits to Control D-C Loads

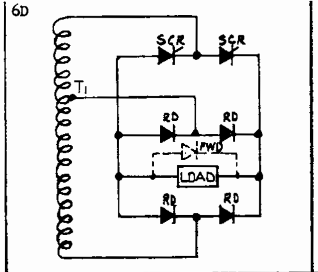
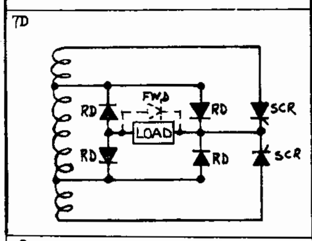
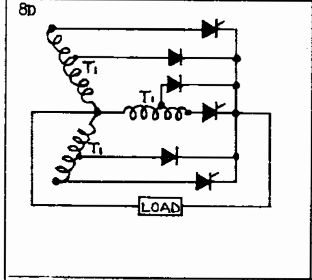
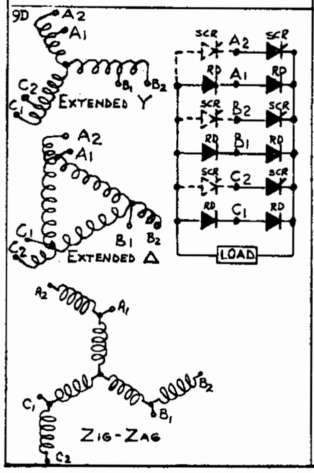
CIRCUIT	RELATIVE POWER OUTPUT	TYPE OF LOAD	CONTROL RANGE %	TYPICAL USES	APPLICABLE MODES OF CONTROL	SEE NOTES
1D 	1	Resistive or Capacitive Inductive i if free wheeling diode is used.	0 to 100	Heating Element (Small) Battery Charging (Small) Universal Motor Speed Control	SWC PC PBM PC	1 2 3 4 12
2D 	1.4	Resistive or Capacitive Inductive if free wheeling diode is used.	0 to 100	Heating Elements Lamp Intensity Control Adjustable & Regulated Power Supplies Motor Speed Controls	SWC PC PBM PC	3 4 12
3D 	1.4	Resistive or Capacitive Inductive if free wheeling diode is used.	0 to 100	Heating Elements Lamp Intensity Control Adjustable & Regulated Power Supplies Motor Speed Controls	SWC PC PBM	3 4 12
4D 	1	Resistive or Capacitive Inductive if free wheeling diode is used.	% T_1 to 100	Heating Element (small) Lamp Intensity Control (limited range) Battery Charging Universal Motor Speed Control	SWC PC	1 2 3 4 5 12 13 14 16
5D 	2	All	% T_1 to 100	Heating Elements Lamp Intensity Control Adjustable & Regulated Power Supplies Motor Speed Controls Magnet Strength Control	SWC PC PBM	3 4 5 14 16

Pulse-Burst Modulation: To obtain good temperature regulation, or speed regulation, with the switching mode of control, the control system usually employs pulse-burst modulation. This mode of control is usually based on a fixed time period, for example, 20 cycles at power frequency. The number of cycles during this period when the thyristor switch is in conduction is made variable and is adjusted by temperature feedback controls. The switch always conducts for essentially an integral number of cycles, and either is OFF, or conducts at a reduced voltage level, for the balance of each period, Figs. 8 and 9.

Pulse-burst modulation can be applied to the control of most heating systems and motor drives due to the high thermal or mechanical inertia of these systems. Systems with very high inertia can tolerate relatively long control periods, whereas systems with lower inertia, or requiring a fine control resolution, will demand a short control period.

Zero Voltage Switching: As mentioned earlier, the use of thyristor switches will minimize radio frequency interference, but this by itself will not completely eliminate it. The fast turn-ON of a thyristor when the supply voltage is at any value other than zero still causes one pulse of shock excitation each time the thyristor is turned ON to carry a burst of pulses. However, with thyristor switches it is possible and desirable to incorporate zero voltage switching. When controlled in this mode, the thyristors are always turned ON at zero voltage (they inherently always

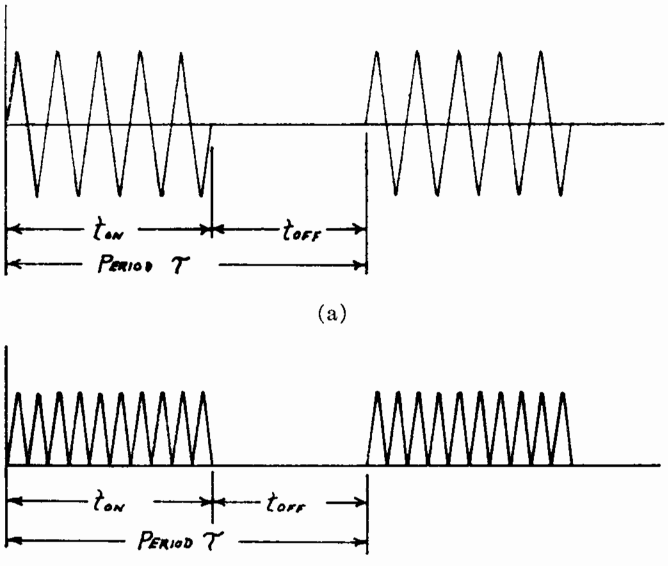
TABLE II (Cont.)

6D 	2	All	% T_1 to 100	Heating Elements Lamp Intensity Control Adjustable & Regulated Power Supplies Motor Speed Controls Magnet Strength Control	SWC PC PBM	3 4 5 14 16
7D 	2	All	% T_1 to 100	Heating Elements Lamp Intensity Control Adjustable & Regulated Power Supplies Motor Speed Controls Magnet Strength Control	SWC PC PBM	3 4 5 14 16
8D 	2.7	All	% T_1 to 100	Heating Elements Lamp Intensity Control Adjustable & Regulated Power Supplies Motor Speed Controls Magnet Strength Control	SWC PC PBM	3 4 5 14 16
9D 	2.7	All	% T_1 to 100	Heating Elements Lamp Intensity Control Adjustable & Regulated Power Supplies Motor Speed Controls Magnet Strength Control	SWC PC PBM	3 4 5 14 15 16

turn OFF at zero current), thus eliminating the interference caused by fast switching of heavy currents.

Examples of temperature control circuits using pulse-burst modulation only (in Fig. 10) and combining zero voltage switching with pulse-burst modulation (in Fig. 11) are shown for illustrative purposes.

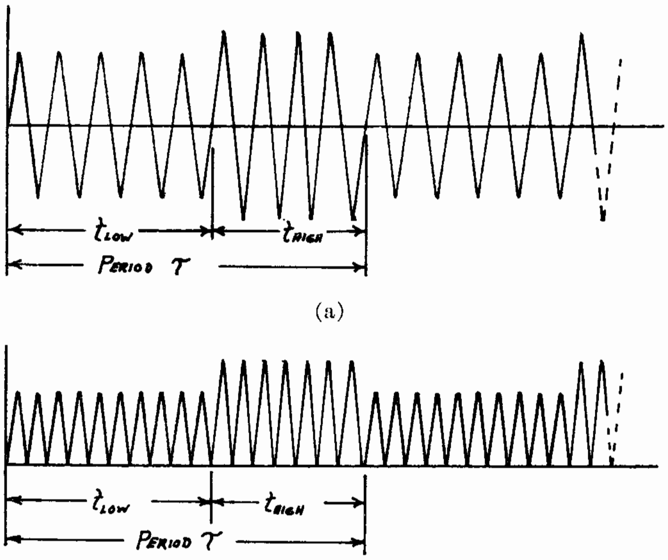
Phase Control: All of the circuits which switch from one tap to another (either tapped transformer or tapped load) may incorporate phase control to supplement the switching type of control to obtain voltage or current regulation of power supplies. Methods of applying phase control have been discussed earlier in the paper. It is, of course, possible to achieve such regulation by phase control alone. However, where only a limited range of adjustability is required, the combination of phase control with switching mode operation greatly reduces the peak-to-rms current ratio in ac power supplies. For instance, output voltage can be smoothly varied between the voltages obtained from



(a)

(b)

Fig. 8. Example of OFF-ON switching control combining PBM and ZVS. (a) Control of ac load (circuits 1*A* through 3*A*, 5*A*, and 7*A* through 13*A*. (b) Control of dc load (circuits 1*A* through 3*A*, 5*A*, 7*A* through 13*A*, and 1*D* through 3*D*.



(a)

(b)

Fig. 9. Example of transformer tap switching control combined as in Fig. 8. (a) Control of ac load (circuits 4*A*, 6*A*, and 15*A*). (b) Control of dc load (circuits 4*D* through 9*D*).

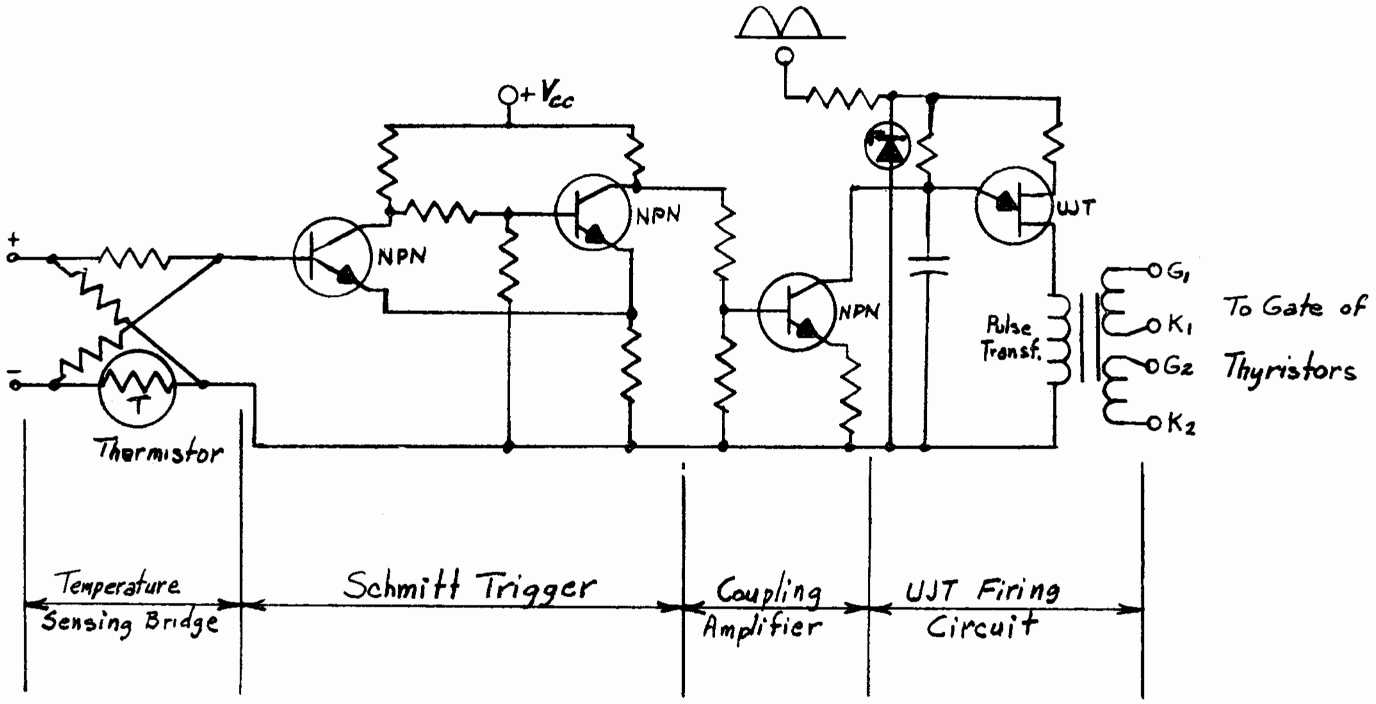


Fig. 10. Example of firing circuit for temperature control utilizing PBM, via Schmitt trigger action.

any two transformer taps by first firing a thyristor connected to the lower voltage tap, and then later in the cycle firing a thyristor connected to the higher voltage tap. This type of voltage control reduces the peak-to-average current ratio and the ripple in dc power supplies. It also minimizes the change in power-factor as voltage is varied. Filtering of dc supplies, when using the combination of switching, phase control, and rectification, is substantially less difficult than when phase control alone is employed.

Phase control is also very effective (although radio frequency interference filtering may be necessary) using the shunt mode of control. Figures 12(a) and (b) illustrate the

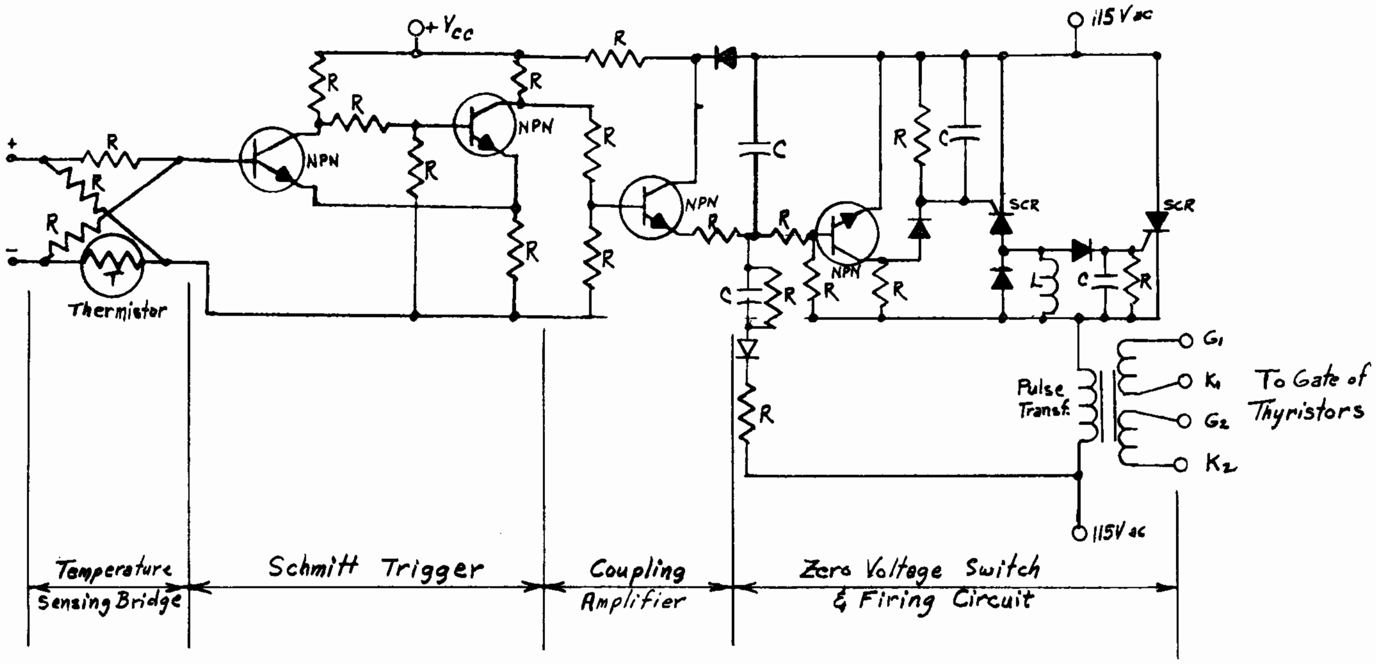
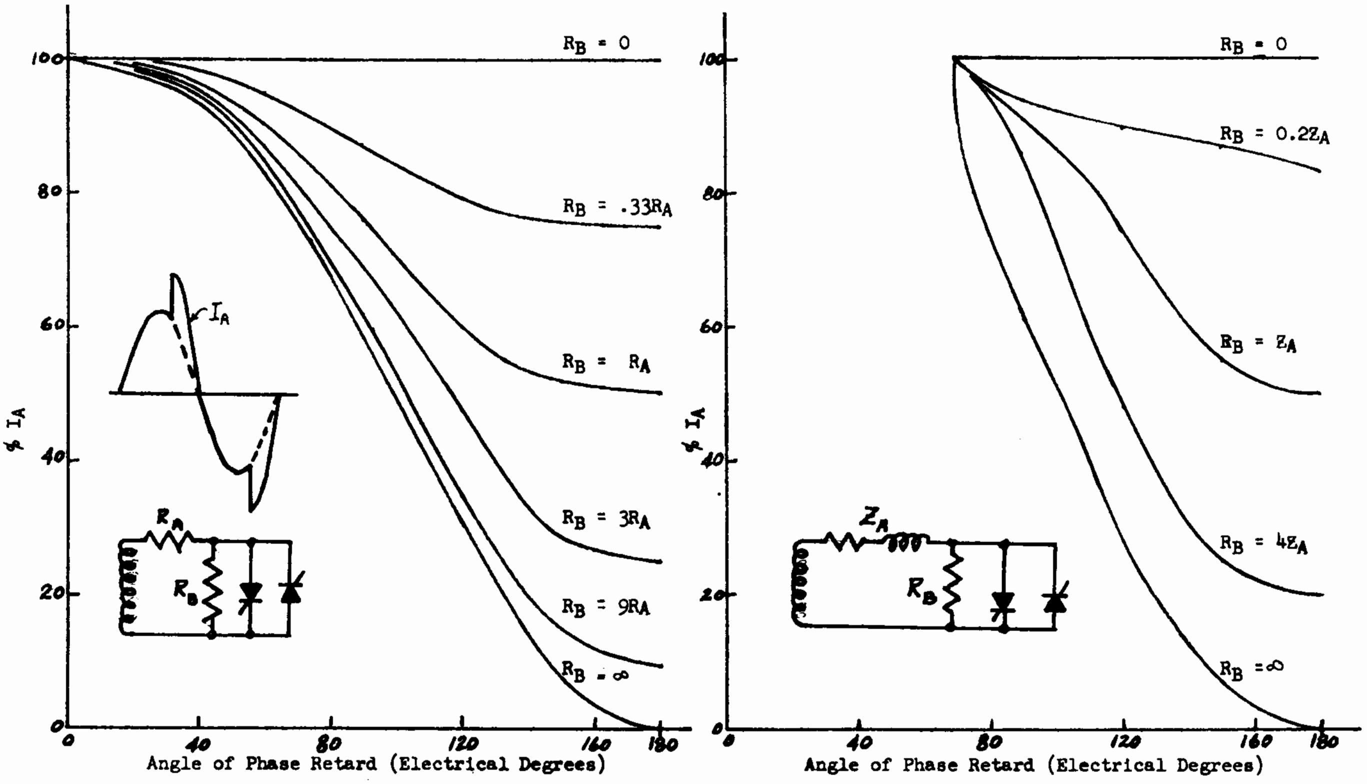


Fig. 11. Example same as in Fig. 10, plus ZVS to eliminate RI.



(a) (b)

Fig. 12. Thyristor shunt mode of ac control. (a) Resistive load. (b) Inductive load.

control characteristic for both a resistive load and an inductive (70-degree lagging) load. When R_B is small compared to R_A, the range of load current variation is small, but precision of adjustment is very good. When R_B is large compared to R_A, the swing in load current can be very large, but with a reduction in adjustment precision. In either case the voltage is smoothly adjustable over the design range, and is readily adaptable to automatic control.

Firing the Thyristor Switches

When the thyristor switch is used to control resistive loads, almost any of the varied forms of firing circuits may be used with satisfactory results. Synchronization of the firing pulses may be accomplished from either the line voltage or the voltage across the thyristor.

However, when the load is inductive, several precautions must be observed in order to achieve optimum performance.

1) If a firing circuit is used which produces a narrow spike of gate signal, the charge injected into the thyristor may not be sufficient to maintain the thyristor in the conducting state until the load current has built up to a magnitude larger than the latching current. This may result in misfiring and erratic control, or no load current whatever. One solution is to shunt the inductive load with a small resistive load drawing a current somewhat larger than the maximum value of thyristor holding current. An alternate (and usually more satisfactory) solution is to provide a firing circuit which produces a square-wave gate signal which lasts from the time at which firing is initiated until the time thyristor conducts a significant amount of current.

2) For inductive loads it is mandatory to obtain line synchronization for the firing circuit from the line voltage, *not* from across the thyristor. If the synchronizing signal is obtained from across the thyristor, large unbalance between the positive and negative half cycles of current is probable. The result may be overloading of one thyristor, saturation of the transformer core (if a transformer is being controlled), and unstable control.

DC CHOPPER CONTROL

Voltage and power control can be achieved with the dc chopper, in which the thyristor is the switch. A chopper alternatingly interrupts a direct current to form a unidirectional current varying between a constant flat-top peak and zero. This method of voltage and power control is also designated in the literature by several other terms, such as

1) time ratio control (TRC) [5]–[7]
2) pulse control [8]
3) pulse modulation control.

These terms relate to the same method, in which a dc source is connected to a dc load by a rapidly operated switch; i.e., the switching rate, as compared to the changes of current in either the source or the load, is infinitely high.

The old mechanical chopper, or vibrator, operating off a storage battery, generates a "chopped" direct current which can be transformed, similarly to an alternating current. However, due to mechanical limitations, it does not lend itself to output control by varying either the frequency or the closing time of the contact. The use of thyristors (combined with transistor firing circuits, saturable switching reactors, free-wheeling diodes, and filtering) affords a very great flexibility and precision of control. These new techniques are far beyond the limited capabilities of the mechanical chopper, so that the introduction of new terminologies is warranted.

The term time ratio control (TRC), used by R. E. Morgan [6] is both descriptive and appropriate; however, it is used not only for "control by interrupted direct current" but also for other means of control, for example, by conducting or suppressing full cycles of an ac wave. The historic term "dc chopper," however, appears to be not only more specific but also the one which is in more general use.

The thyristor choppers discussed herein control a major flow of direct power, without resorting to full inversion followed by rectification. Choppers operate also without introducing a significant amount of resistance into the switching path as in a transistor dc control. Although not part of the fundamental principle, chopper controls usually include filtering means, so that input and output currents are not only unidirectional but do not have a significant ripple.

This discussion is limited to the essentials of voltage control. We refer to the thorough treatment in the literature [6], [7], [9]–[11] for the many ingenious turn-OFF circuits (including methods to improve commutation or economize on components), firing circuits with special compensation methods for varying source voltage, and protective circuits to prevent firing too shortly after turn-OFF (lockout).

Regulation

Similarly to circuits which embody voltage control by phase retard, the dc chopper exhibits a voltage drop (regulation) which is load dependent. The regulation of a phase controlled rectifier can be determined by applying a simple equation using known circuit constants. On the other hand, this is not possible for chopper circuits. The voltage drop of a chopper is much more complex and, for example, is determined by

1) Reduction of output due to slow rise of current in the switch (similar to the overlap of rectifiers), which is determined by the dynamic properties (inductance, capacitance, damping) of the circuit elements which participate in this current rise (e.g., filter elements and switching devices).

2) Reduction of output due to finite rise time of current and finite decay of forward voltage in the thyristor itself (note these two effects are also influenced by the above circuit constants). These specific thyristor switching losses increase with the chopping frequency and determine the upper frequency limit for these choppers, independently from the characteristic response of other elements such as turn-OFF and firing circuits.

3) Reduction of output due to backswing or overswing of turn-OFF current pulses initiated by the turn-OFF circuitry. This is sometimes compounded by the energy drain required to charge these reset components, unless they are supplied directly from the source.

4) Reduction of output in the filter. This may be aggravated by energy losses due to high internal pulses, circulating currents in free-wheeling diodes or other ripple current (ac) losses.

Because no general statements on regulation can be made, the following discussion assumes that the chopper has a negligible internal voltage drop, hence, that it displays only a controllable voltage change between input and output. The major advance in the state of the art of the thyristor chopper was the invention of circuits which do have a predictable high-efficiency performance; for these circuits, the following voltage relationships are essentially correct. On the other hand, in any radically new application of choppers, serious consideration must be given to dynamic output voltage loss effects; otherwise the performance may not be as expected.

Influence of Thyristor Characteristics

Dc chopper controls were developed to use the properties of thyristors to best advantage. The control is effected by turning a direct current ON and OFF, yet thyristors are not directly able to turn OFF a major direct current flowing in an inductive circuit. This has been overcome by the invention of several turn-OFF circuits, using

1) a special turn-OFF thyristor [10]
2) saturable reactors [12]
3) a combination of these and other components [9].

These circuits replace the forcible circuit interruption of the mechanical and transistor choppers (with the associated problems of transient overvoltages, severe energy losses, and destructive side effects due to resistive arc quenching) by a harmless commutating effect.

The advantages of the thyristor device itself are found in the combination of high-efficiency, fast-switching ability and high amplification.

High Efficiency: The high efficiency (very high ratios of blocking voltage over forward voltage drop and load current over leakage current) is assured because the thyristor by nature is either blocking or conducting; i.e., it cannot remain in an intermediate stage. Another factor is that the forward voltage drop of the thyristor is in the order of magnitude of 1 volt, whereas the usual input and output direct voltages are in the order of magnitude of tens to hundreds of volts. Thus, the resistive voltage loss of the thyristor, although low, may not be negligible in all cases; but it is not prohibitive as it would be with thyratrons operating at the same voltage levels. The high blocking voltage capabilities of some thyristors lend new interest to chopper circuits with tapped chokes in which the switching voltage is a multiple of the source or load dc voltage and which offer control characteristics which have unusually advantageous properties and are now economically realizable.

Fast Switching Ability: The very fast switching ability of the thyristor is the result of a total switching-energy dissipation time of a few microseconds and full recovery of forward blocking ability (turn-OFF time) in less than 50 μs. In the proper circuitry the entire switching process required to turn a load fully ON and OFF and thus effect full power control requires a time which is in the order of magnitude of one thousandth of the duration of 1 cycle of the power frequency.

High Amplification: Firing the thyristor with pulses derived from a resistor-capacitor-transistor relaxation circuit affords control of a major amount of output power with a negligible amount of control power. Thus the need to satisfy special control conditions is not tied to excessive power demands or narrow limits for control current and voltage (amplification or pulse transformation are performed at low power levels).

Properties of the Chopper Control

Chopper circuits are very efficient, compared to variable resistance control. They are used preferably when the output voltage (at full load) is commensurate with the input voltage.

The chopping frequency (and size of filtering means) are not tied to the line frequency, hence they can be selected for optimum performance. This makes it possible, also, to increase the speed of response of servosystems.

For precise dc control of power taken from an ac system with widely varying voltage and frequency, it is usually preferable to use a phase controlled, coarsely regulated rectifier (with output filter and capacitor buffer if desired) feeding a dc chopper control which is then independent of changes in the primary system.

There are many different chopper circuits available which can be controlled in various ways. The basic time control methods are

1) Variable-frequency control: Control is accomplished by keeping the ON time of the thyristor constant and varying the OFF time. This method is usually simpler and less expensive than the others.

2) Constant-frequency control: Control is provided by using a constant repetition rate but varying the ratio of ON TIME over OFF TIME. This method is preferable if special filtering exists. The constant frequency permits the use of tuned filters.

It is conceivable that other principles could be used, e.g., constant OFF TIME (or variable frequency and ON TIME). Basically there is no difficulty in creating such systems; they are not discussed because they are not generally in use. For the variable frequency control, the constant ON TIME is usually held constant by saturable reactor reset time (Morgan [6], [12]–[14]). Otherwise almost all the time intervals, be they constant or controllable, are determined by the timing of relaxation circuits (resistor-capacitor-transistor) actuating the gate of a thyristor.

There are two basic connections for chopper control:

1) the series or step-down circuit
2) the parallel or step-up circuit.

These may be combined with the various time-control methods.

Series Chopper

The basic circuit is shown in Fig. 13. The main switching element appears as a thyristor in series with the flow of power current; it is shown inside a dashed rectangle, to indicate that a substantial number of accessory components (including other thyristors, diodes, and saturable reactors) must be provided for turn-OFF and firing control.

Series chopper circuits provide an output voltage which is always less than the input, controllable down to zero output voltage without the drawback of increased ripple and voltage reversal encountered in phase controlled rectifiers. Zero output corresponds to SWITCH OFF, i.e., the circuit is essentially open. The circuit contains an integral output filter, with an inductive termination (important for subsequent filtering). The input may require an ac bypass capacitor, depending on the operating frequency and the impedance of the source.

Figure 14 shows a modification of the basic circuit by extending the winding on the filter coil. This increases the current capacity of the chopper at reduced voltage without additionally loading the switching circuitry (approaching the condition of constant output power). However, the circuit is only applicable when a reduced control range is acceptable, i.e., for output voltage ranging downward from the input voltage but not to zero. This modification also reduces the internal regulation.

For increased pull-down of the output voltage the circuit connection is altered as shown in Fig. 15. This allows operation at a very high ratio of input over output voltage, without resorting to poor utilization of the thyristor (e.g., very short, very high pulses). Deviations of the tap ratio of the filter choke from unity increase the output ripple. This may require additional filtering, introducing additional losses.

Variable Frequency Control (Morgan Circuit): The ratio of output direct voltage over input voltage is given by

$$\frac{e_1}{e_d} = \frac{1}{1 + n\,T_2/T_1}. \tag{6}$$

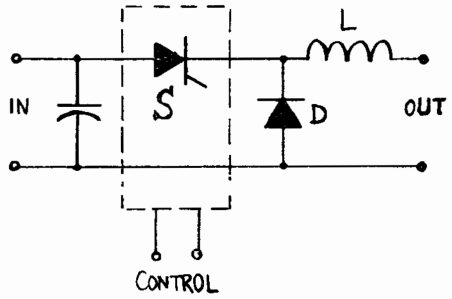


Fig. 13. Series chopper circuit. Dashed rectangle *S*, containing switching thyristor, also assumed to contain turn-OFF circuitry, firing control, and other accessories, not shown. Chopper operates by interrupting, intermittently, the main current path between input and output. Choke *L* maintains steady output current, alternatingly supplied by switching thyristor or FWD, section *D* of diagram.

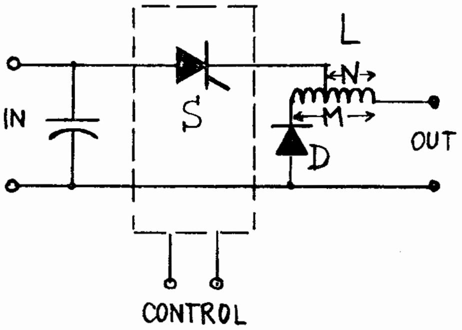


Fig. 14. Series chopper circuit, similar to Fig. 13, except output choke has extended winding, resulting in increased current capacity at expense of reduced control range.

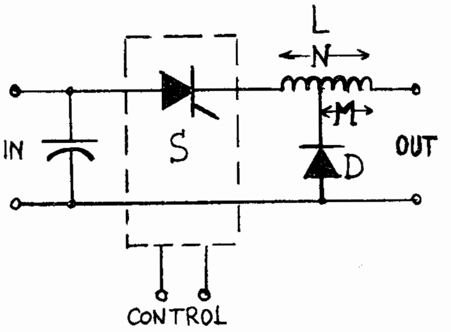


Fig. 15. Series chopper circuit, similar to Fig. 13, except output choke has partial tap for FWD, resulting in higher ratio input-output voltage.

e_1 = direct voltage across the load
e_d = direct voltage of source
T_1 = time interval during which the series switch is closed
T_2 = time interval during which the series switch is open
T = $T_1 + T_2$, time of one complete cycle
$n = \dfrac{N}{M}$ = ratio of number of turns on tapped reactor.

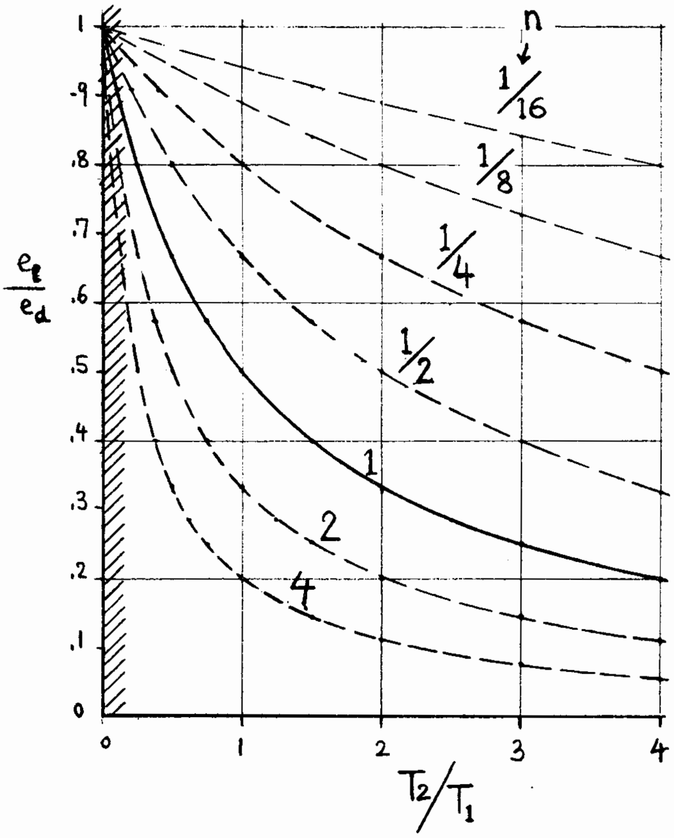


Fig. 16. Series chopper wi h variable frequency control and ratio of output-to-input voltage vs. ratio of open-to-closed time. Each curve is for a given tap ratio on output choke. Operation in shaded area is to be avoided as chopper tends to lock in.

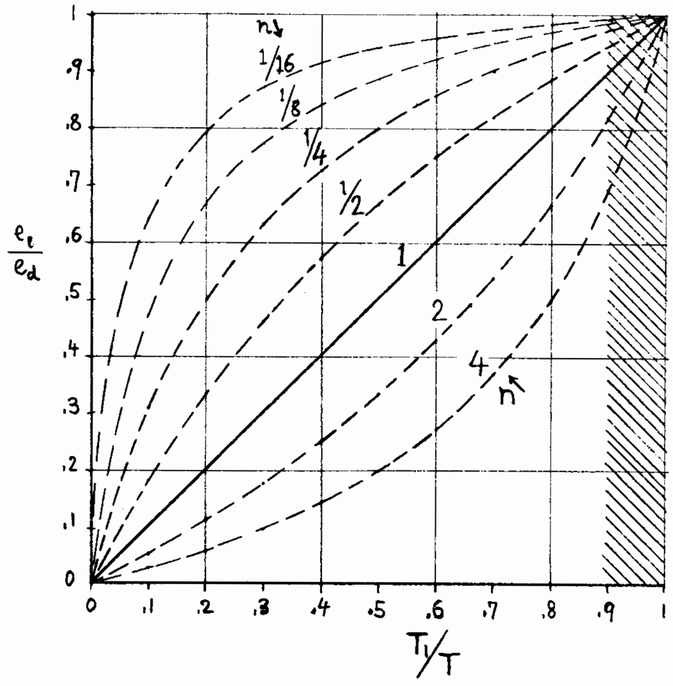


Fig. 17. Series chopper with constant frequency control. Voltage vs. time ratio, (closed-to-cycle duration). Curves shown for various tap ratios on output choke. Operation in shaded area must be avoided.

Figure 16 shows this voltage ratio as a function of the ratio of "open over closed" time. The solid curve for $n = 1$ applies to the basic circuit of Fig. 13. Within the shaded area the chopper is in danger of being continuously ON; it is not advisable to operate in this range (lockout zone).

The upper curves for $n < 1$ apply to reduced range taps of Fig. 14. As seen in the figure, this allows fine voltage control close to the input voltage, without entering the danger zone.

The lower curves for $n > 1$ apply to the connection of Fig. 12. As seen from the curves, the voltage may be reduced to almost zero with a control characteristic which is suitable for fine control at low values.

Constant-Frequency Control (Series Chopper): Using the preceding terminology, the ratio of output over input voltage is derived as

$$\frac{e_1}{e_d} = \frac{1}{1 - n + n\,T/T_1} \tag{7}$$

in which the duration of the cycle T is constant. Figure 17 shows the voltage ratio as a function of the ratio closing time over cycle time. As discussed above, the reduced or increased tap ranges are useful either for partial control (close to 100 percent) or for extended operation near zero voltage.

Parallel Chopper

This basic circuit is shown in Fig. 18. The main switching element is in parallel with the output; it short-circuits the input to a choke. A current flows in the choke, storing energy. When the switching element is turned OFF, the choke forces the current through the diode into the output capacitor. The voltage of the input is increased by this forcing voltage of the choke. The output diode prevents current from flowing back when the switch is closed again. The dashed rectangle around the thyristor indicates the need for accessory circuit elements for turn-OFF, gate control, lockout, etc.

Parallel choppers provide an output voltage which is higher than the input voltage (disregarding the internal regulation voltage drop), except when the switching thyristor is completely turned OFF; then the input and output voltage are equal (lowest output level).

The circuit, in order to operate at all, requires an output filter capacitor. Other filtering elements may be required, both on input and output, depending on the ac impedances of source and load and on the output ripple which can be tolerated.

Figure 19 shows a modification of the basic circuit by adding a tap to the energy storing choke. This reduces the voltage boost obtainable from the chopper, but at the same time it reduces the power demand on the switching circuit. It also reduces the regulation voltage drop. This circuit, therefore, is particularly useful in obtaining a constant output voltage at various loads by time ratio control.

Variable Frequency Control (Parallel Chopper): The ratio

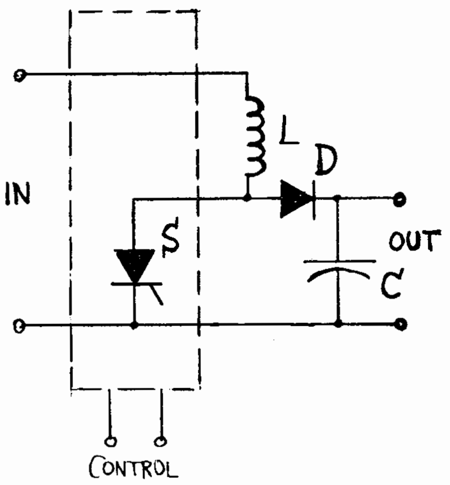


Fig. 18. Parallel chopper circuit. Dashed rectangle *S*, containing switching SCR, is also assumed to contain turn-OFF circuitry, firing control, and other accessories not shown. Chopper operates by intermittent short-circuiting of input voltage over choke at *L*; opening switch at *S* delivering "inductive kick" through charging diode at *D* into output capacitor at *C*.

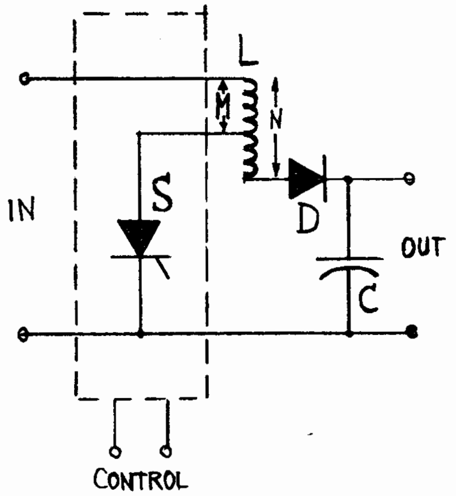


Fig. 20. Parallel chopper is same as Fig. 18, except for increased output tap on switching choke and increased voltage boost at reduced power capacity.

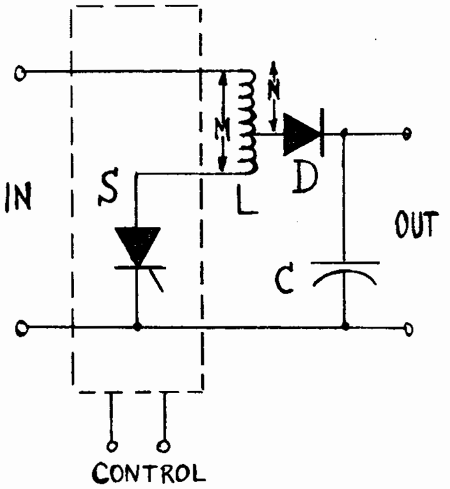


Fig. 19. Parallel chopper is same as in Fig. 18, except for reduced output tap on switching choke and increased power capacity at reduced voltage boosting range.

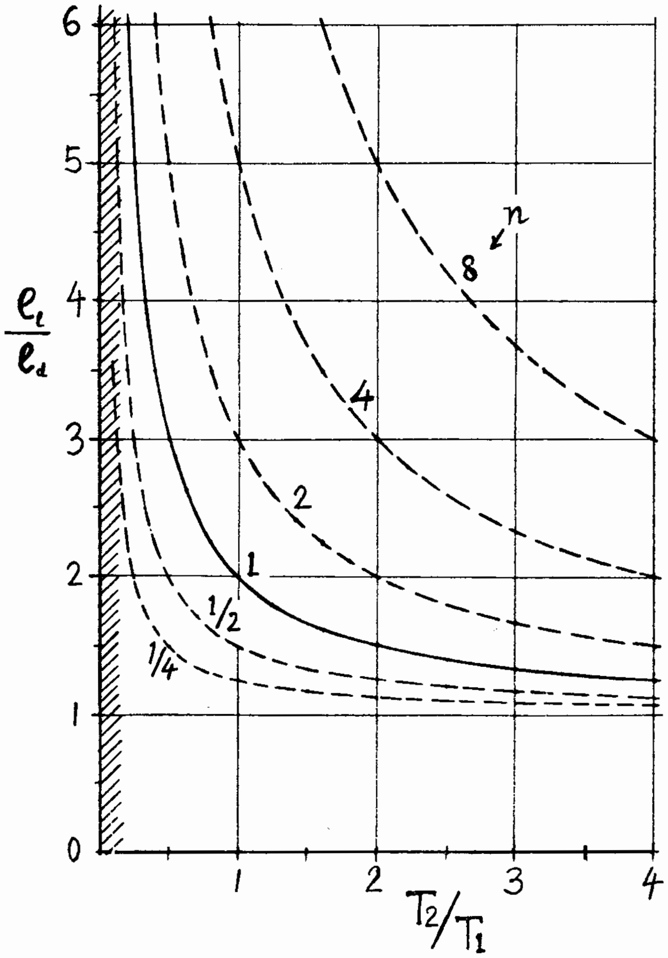


Fig. 21. Parallel chopper with variable frequency control and ratio of output-to-input voltage vs. ratio of open-to-closed time. Each curve represents a given tap ratio on the choke. Operation in shaded area must be avoided.

of output over input voltage is given by

$$\frac{e_1}{e_d} = 1 + n\, T_1/T_2. \tag{8}$$

The nomenclature is the same as before. Specifically, the open time T_2 and the closed time T_1 refer now to the parallel switch. The turns ratio is defined as

$$n = N/M$$

as shown in Figs. 19 and 20.

Figure 21 shows the voltage ratio (output over input) as

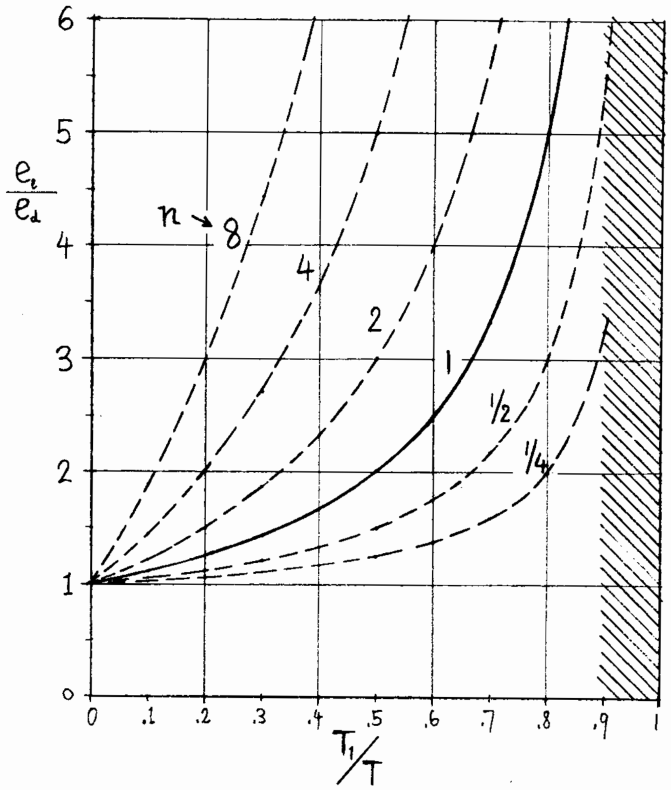


Fig. 22. Parallel chopper with constant frequency control and voltage vs. time ratio (closed-to-cycle duration). Curves represent tap ratios on switching choke. Shaded area must be avoided.

a function of the ratio of open over closed time. The solid curve applies for the simple coil of Fig. 18. For equal opening and closing time it doubles the output voltage.

The lower curves, in which n is less than unity, correspond to the circuit of Fig. 19.

The upper curves, in which n is higher than unity, correspond to the circuit of Fig. 20. For high ratios of voltage boost it is particularly important to consider the effects of internal voltage drop in the chopper; these could not be shown in the figure. The shaded area corresponds to the range within which the chopper is in danger of not turning off; it should be avoided.

Constant Frequency Control (*Parallel Chopper*): The ratio of voltage output over input is given by:

$$\frac{e_1}{e_d} = 1 + \frac{n}{T/T_1 - 1} \tag{9}$$

in which the cycle duration T is constant.

Figure 22 shows this voltage ratio as a function of the relative closing time. The values of tap ratio n are the same as for the preceding figure. It is apparent how the proper selection of tap ratio and control range afford many ways of voltage control. The shaded area represents again the danger zone of having the thyristor permanently turned on. By selecting the proper turns ratio it is possible to avoid this range by a wide margin.

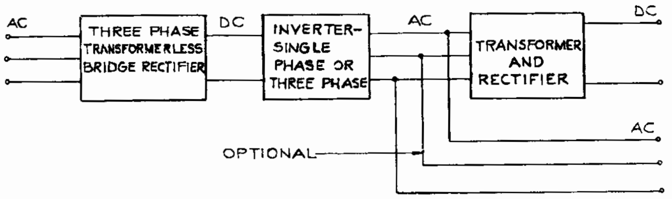


Fig. 23. Block diagram shows rectifier-inverter system which will provide control of output alternating or direct voltage.

VOLTAGE CONTROL WITH MORE COMPLEX SYSTEMS

In complex systems which make use of rectifying devices, one of the results achieved may be voltage control. For instance, referring to Fig. 23, one way to build an adjustable voltage power supply is to create a system consisting of

1) Rectifier, to obtain dc from the ac line
2) Inverter, to obtain a frequency much higher than line frequency
3) Transformer and rectifier, to obtain dc output at the desired voltage.

A major advantage of such a system would be a reduction in weight and size over a conventional transformer-rectifier power supply. The rectifier could be a 3-phase bridge connected directly to the ac supply. By selecting a high inverter frequency, the transformer size and weight can be drastically reduced.

The voltage output of the second rectifier can be controlled by varying the output of the first rectifier by means of phase control. This would work best over a narrow voltage range; a large reduction in the direct voltage applied to the inverter would impair its operation. Output voltage also could be varied by controlling the width of the ac waves generated by the inverter, using the principle of forced commutation. A third point of control would be phase control of the rectifying devices fed by the inverter. Control at this point would permit adjustment of output voltage from 100 percent to zero.

If the second rectifier is omitted from this system, the result is a frequency changer. Output voltage, in this case alternating, can be controlled by adjusting the voltage delivered by the rectifier, using phase control, or by pulse width modulation of the inverter, as before. This can be done with the inverter operating at a constant frequency to achieve a regulated output voltage, or it can be done with the inverter operated over a wide frequency range. In this case, it is often desired that the output voltage be proportional to frequency, to provide constant volt-seconds per output pulse which is needed when driving ac motors and other magnetic loads.

Another controlled rectifier frequency changer is the cycloconverter, which is a composite frequency changer in which the rectifying devices directly interconnect the two ac systems and there is no dc line, as was present in the rectifier-inverter system first described. The output voltage of a cycloconverter may be varied by controlling the instant of firing of each rectifying device.

The cycloconverter provides a reduction in frequency, generally a reduction of 3 to 1 or greater. By controlling the angle of firing of each thyristor, the envelope of the output waveform may be made to approach a sine wave. Logic circuitry is required to produce this essentially sinusoidal output; reduction of output voltage can be achieved by causing this circuitry to introduce an additional delay of each firing pulse. The cycloconverter offers a means of providing constant output frequency and voltage from a variable frequency source (variable speed constant frequency, VSCF) in which case control of the output voltage to maintain it within narrow limits is a most desirable feature.

The cycloinverter is another composite frequency changing circuit; in this case the output frequency is higher than the input frequency. Output voltage control is again made possible by varying the position of the firing pulses applied to the thyristors in the circuit.

APPENDIX

NOTES FOR SWITCHING MODE OPERATION WITH CIRCUIT REFERENCES AFTER EACH NUMBER

1) All circuits. PBM is applicable only to the control of heating element loads where substantial thermal inertia exists.
2) All circuits. ZVS may be employed advantageously to supplement PBM control and eliminate RFI resulting from steep wavefronts common to PC modes.
3) Circuits 1A, 1D, 4D. Used only for 10-ampere power loads, operating directly from distribution system where unbalance between positive and negative half-cycles is not detrimental.
4) Circuits 1A, 1D. Can be used also to control speed of small universal motors.
5) Circuits 4A, 6A, 14A, and 4D through 9D. The switching mode between two transformer taps is useful for both PC and PBM control, especially for heating elements. Tap T_1 is selected to provide slightly less than the minimum required power input; then, either PC or PBM adds the necessary incremental extra power to obtain fine control and with a minimum fluctuation of heater element temperature, resulting in longer element life. In addition, less waveform distortion is introduced than when either type of control switches from zero to full voltage (as in Circuits 2A, 3A, 4A, and 6A through 12A).
6) Circuits 4A, 6A, 14A, and 4D through 9D. In circuits similar to 4A, additional taps between T_1 and T_2 may be used also, provided that an antiparallel pair of thyristors is added for each tap. This mode of operation permits tap changing under load, either by switching from tap to tap or, when PC is also provided, to provide a smooth variation of voltage between each two taps.
7) Circuits 7A, 8A. In circuits 7A and 8A where an antiparallel diode-thyristor pair is used, either in each line or between load and neutral of a polyphase Y circuit, it is NOT permissible to connect the neutral to a 4-wire system. Where a 4-wire system is necessary, see circuits 9A, 10A, and 12A.
8) Circuits 9A, 10A, 12A 13A. In circuits 9A, 10A, 12A, and 13A, the 3-phase Y circuits will operate with full control in a 3-wire system with only two antiparallel thyristor sets, or bridge-thyristor sets. When 4-wire systems are necessary, a third set of either type is required in the location indicated by the phantom box.
9) Circuits 9A, 10A. For 3-phase delta circuits, it is practical to use circuits 9A, 10A, 12A, and 13A with only two antiparallel thyristor sets, or two bridge-thyristor sets in two of the three supply lines. The addition of the third set, however, provides added insurance against misfiring due to a voltage transient, since with three sets the transient must fire two devices before conduction can commence.
10) Circuits 11A, 14A, 15A. Placing the 2-thyristor sets or the bridge-thyristor sets inside the delta instead of in the line always requires three sets. However, this location of the sets results in the ability to control 73-percent higher line current for the same thyristor rating. It also requires a 73-percent higher peak reverse voltage/forward breakover voltage rating as compared to the Y circuits with three sets.
11) Circuits 9A, 10A, 12A, 13A. In all Y-connected circuits, it is necessary to provide a gate firing supply which supplies either: a) double pulsing at 60-degree phase displacement, instead of 120 degrees, or b) a square-wave firing pulse that is maintained for a time interval which exceeds 60 degrees to assure that the two thyristors which are in cascade, line-to-line, both conduct at the same time.

12) Circuits 1*D* through 7*D*. In circuits which use only one thyristor in series with the load, an FWD is necessary whenever the load is inductive (such as a magnet, solenoid, or dc motor) to allow the thyristor to regain control. Other special circuit considerations may be necessary.

13) Circuit 4*D*. Circuit 4*D* is useful only for low power applications where the unidirectional current will not cause saturation of the transformer core.

14) Circuits 4*D* through 9*D*. Where a limited range of control is all that is necessary, the circuits of 4*D* through 9*D* provide a rectified voltage and current waveforms with substantially less ripple than those where PC switching from zero to full voltage is used.

15) Circuit 9*D*. In circuit 9*D*, a phase shift occurs when current is switched from tap 1 to tap 2. Depending on transformer connections and phase rotation, the voltage of tap 2 can be made to either lead or lag that of tap 1. The amount of shift is a function of the voltage ratio for the extended Y or delta, but is 30 degrees for the zig-zag connection.

16) Circuits 4*A*, 6*A*, and 4*D* through 9*D*. Where definite maximum- and minimum-duty cycles are known or are determinable for the circuits which switch from one voltage level to another (as opposed to zero to full-voltage switching) it may be practical to utilize devices with lower rated current (thyristors and/or diodes) than where PC of thyristors only is the control means.

17) Circuit 9*D*. The rectifier circuit of 9*D* in Fig. 9 will operate with six RDs and three thyristors. This connection, however, introduces a substantial 3-phase 180-c/s ripple component. The addition of three more SCRs (shown in phantom) retains the characteristic 6-phase 360-c/s ripple of a 3-phase bridge as well as permitting improved control.

18) Circuits 16*A*, 17*A*. The shunt-control circuits 16*A* and 17*A* provide a similar mode of control to those of the transformer tap switching control (circuits 4*A*, 6*A*, 14*A*, and 15*A*), and are useful where transformers with taps are not available, but where taps can be obtained on heater elements, or they are useful to control a resistor in the rotor circuit of a wound-rotor motor.

NOMENCLATURE

SCR = thyristor
RD = rectifier diode
FWD = free wheeling diode
SWC = switching control
PC = phase control
PBM = pulse burst modulation
RFI = radio frequency interference
ZVS = zero voltage switching

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