A.C. Voltage Regulators

A discussion of various techniques for producing a constant a.c. supply voltage

by R. Thompson

This article looks at some methods of regulating a.c. supplies; in particular it addresses the problem of producing a constant level output at nominal value from a 50 Hz supply capable of varying ± 20% from the nominal. The methods all involve the use of thyristors (or triacs) in what may be called synchronous switching. Other forms of regulators have been, and are, used. These include motor-driven variacs, contactor transformer tap changing and ferro-resonant transformers. While these may have advantages for particular applications, they cannot compete in many instances with the speed, accuracy and low cost of the forms of regulator described here.

The most common form of thyristor circuit for a.c. voltage control is shown in Fig. 1, (the thyristors could of course be replaced by a triac). This has been widely used in applications such as lamp dimmers, where a wide control range is required for loads tolerant to high levels of distortion. The form of the load voltage raises a point to be considered in regulating a.c. voltage. What parameter of the output voltage is to remain constant? Normally this will be either its r.m.s. or mean value depending on the characteristics of the load. In some particular instances it may be required to regulate the peak value. In discussing the regulators it is assumed that the r.m.s. value is held constant, the implications of operating mean or peak sensing control circuits will generally be obvious.

The simple phase control circuit of Fig. 1 will not meet the requirement of producing a nominal output level. This will require the introduction of an auto-transformer as shown in Fig. 2. For an r.m.s. output voltage equal to the nominal supply voltage (r.m.s. value of V_0 the thyristor firings must be delayed by about 95° when the supply is at its maximum ($1.2\ V_0$). This delay reduces to zero if the supply is reduced to its lower limit ($0.8\ V_0$).

The current rating of the thyristors must be adequate to carry the full load current under delayed firing conditions. Their voltage rating must be in excess of $\sqrt{2} \times 1.5V_0$. This follows from the requirement to delay firing by more than 90°. When the supply is at 1.2 times its nominal value the auto-transformer steps the voltage up to $1.5V_0$ and the thyristors must withstand the peak value of this voltage. The transformer must have a winding volt-amp capacity of at least $0.6V_0I_L$ as shown in the following expression:

Winding VA rating is given by
AB: $1 \times 0.3\ V_0 I_L = 0.3\ V_0 I_L$
BC: $0.25 \times 1.2\ V_0 I_L = 0.3\ V_0 I_L$
Total VA rating $= 0.6\ V_0 I_L$

This form of regulator introduces considerable distortion in the output voltage. Under the worst condition, when the supply is at $1.2V_0$ and thyristor firing is held back by 95°, the total distortion is over 50%. Even if the regulation range of the regulator were reduced to ± 5% the distortion would still be over 20%.

Trigger circuits for this regulator, when feeding resistive loads, can use any of the types which have been developed for phase control of thyristors and triacs in lamp dimmers and similar applications. The only difference required is that the control of the firing angle must be operated by a circuit measuring the output voltage. Regulating the "mean" output of the regulator is straightforward since a simple mean detecting rectifier and smoothing circuit can be used. Regulating the r.m.s. output is more difficult, particularly with this type of regulator circuit where there is a large change in the form factor of the output waveform. The form factor increases as the input supply increases and the thyristor firing is retarded. This allows a simple form of compensation to be used, as illustrated in Fig. 4. If the output r.m.s. voltage is held constant then the mean and peak values of the output voltage vary as shown. A combination of the mean and peak voltages can therefore generate a resultant which can be used to give quite accurate regulation of the r.m.s. output voltage.

The effect of reactive loads will be to modify the conduction periods of the thyristors. For instance, with inductive loads the thyristors will remain conducting after the time of zero crossing of the supply. The change in load voltage waveform is unlikely to prove significant since the first 45° of control has little effect on the r.m.s. output. A more important problem is the fact that the thyristor trigger pulse may occur before conduction from the previous cycle has ceased. This could cause intermittent firing of the thyristors and a limit on the minimum firing angle or prolonged triggering pulses may have to be adopted.

Two-tap regulators

The use of two taps on the auto transformer as shown in Fig. 4 results in very significant improvements in regulator performance. Its operation when feeding

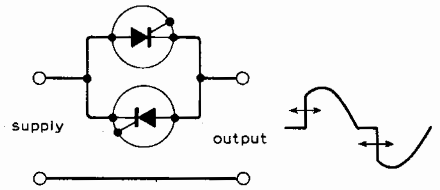

Fig. 1. Simple thyristor phase control and output waveform.

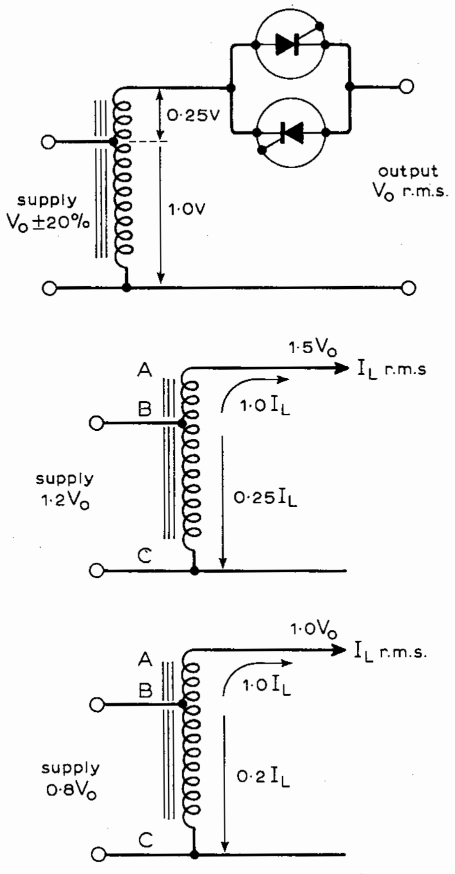

Fig. 2. Single tap regulator. Refer to text for VA *rating formulae.*

resistive loads is quite simple. At the start of each half cycle one of the lower thyristors conducts, supplying voltage to the load. Some time later in the half cycle one of the upper thyristors is triggered. This increases the voltage on the load and by so doing commutates the lower thyristor. At the end of the half cycle the upper thyristor is extinguished.

It can be seen that the output voltage can be continuously varied between the two values available at the transformer taps by altering the time of triggering the upper thyristors. The distortion is considerably lower than the single tap circuit, being zero at both extremes of input voltage and about 15% for the worst condition. There will be a proportionally lower distortion if the regulation range is reduced below ± 20%. The circuit is still quite simple and because only a fraction of the output power is handled directly by the circuit, ratings of the components are relatively low. Both pairs of thyristors must be rated for continuous full load current since the supply could be at either extreme for long periods. However they do not require as great a voltage rating as those in the single tap circuit. As the load is always connected to one or other of the transformer taps the maximum voltage seen by the thyristors is 0.5 times the nominal peak supply voltage. This is a third of that required for the single tap circuit. The transformer ratings (derived in a manner similar to that shown in Fig.2) are required to be about 25% higher than the single tap transformer, but still low in relation to the load power.

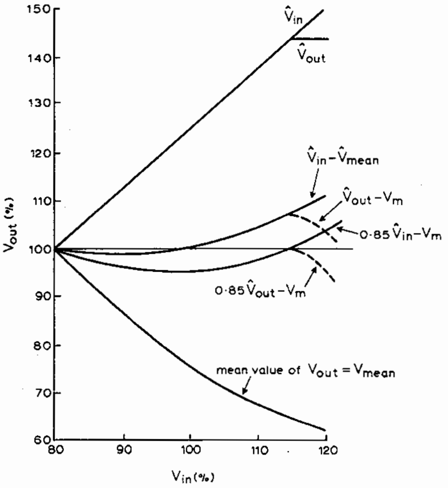

Fig. 3. The characteristics of various methods of generation of the r.m.s. control voltage. The curves are drawn for V_{out} *(r.m.s.) constant.*

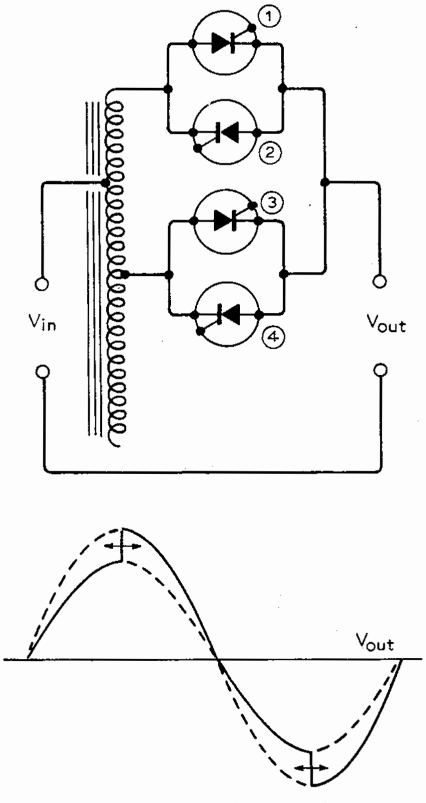

Fig. 4. Two tap regulator and output voltage waveform.

Firing requirements for the thyristors on the upper tap are basically the same as those suitable for single tap regulators. The lower thyristors require prolonged triggering in order to ensure that there is always one or other of the lower thyristors capable of conducting. Provided this prolonged triggering is generated immediately the supply is switched on only the tap-to-tap voltage will ever appear across any of the thyristors. The prolonged triggering can be obtained simply from the trigger windings added to the auto-transformer. A diode and zener clipper can be used for each thyristor as shown in Fig.5.

The problems of reactive loads poses a particular problem for the two tap regulator. This is because of the possibility of causing tap-to-tap short circuits. For instance if the load is very inductive and the input supply low, the triggering of the upper thyristors may occur before the current has reversed from the previous half cycle. The first time this occurs, current will flow only in the lower thyristor for the half cycle. If the current is still flowing in the lower thyristor at the time of triggering the upper thyristor in the next half cycle a tap-to-tap short circuit will occur. Fig.6 illustrates this point.

A typical two tap regulator circuit is shown in Fig.7. The lower thyristors are triggered via windings on the auto-transformer as explained previously. The upper thyristors are simultaneously triggered by a common pulse generated by transistor Tr_3. This transistor is driven by the Shockley diode timing circuits whose charging rate is controlled by the differential amplifier formed by Tr_1, Tr_2. At each supply voltage zero crossing the output voltage of the diode bridge (D_{1-4}) falls near to zero. When this happens C_1 is discharged through D_5 and R_1. This action resets the timing circuit every half cycle of the supply. The purpose of the zener diode in series with the Shockley diode is to ensure that the Shockley is extinguished at this time. When D_5 ceases to conduct, C_1 starts to charge at a rate determined by the collector current of Tr_2. The Shockley eventually breaks down and thyristors 3 and 4 are fired by the pulse which is generated. At the end of the pulse the Shockley may or may not cease to conduct depending on whether the collector current of Tr_2 is less or more than the diode holding current. If it does cease to conduct it may go on to produce further pulses during the same half cycle, but these will not produce any consequent change in the thyristor power circuit. The time in each half cycle when the trigger pulse is produced is determined by Tr_2 collector current. This is controlled by comparing a reference voltage, provided by D_6, with the fraction of the rectified output of the regulator which appears at the base of Tr_1. If the output voltage increases, the current in Tr_2 will be decreased. As a result the trigger pulse will move back in the half cycle, tending to reduce the regulator output. The sum of the currents taken by Tr_1 and Tr_2 remains substantially constant under all conditions and is determined primarily by the common emitter resistor and the voltage of D_6. The common emitter resistor, R_2, therefore provides a convenient method of defining a maximum collector current of Tr_2, this flowing when Tr_1 is cut off. The resistor is selected to ensure that C_1 cannot charge to the triggering level before a specified time in each half cycle. This "dead time" must be greater than the maximum time taken for the regulator load current to reverse after a voltage zero crossing. The minimum firing angle of the circuit can thus be made always greater than the lagging phase angle of the load.

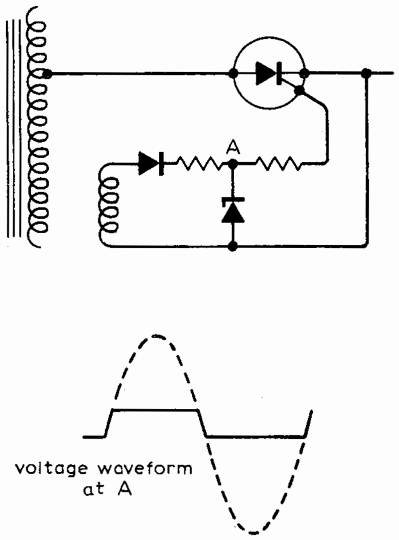

Fig. 5. Thyristor drive circuit.

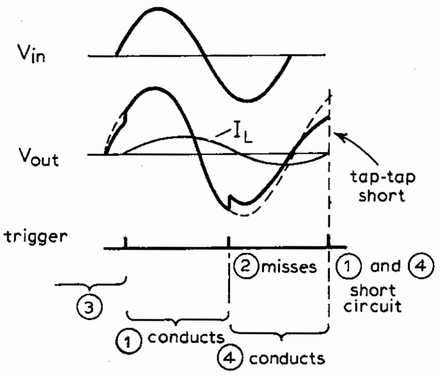

Fig. 6. Conditions under which a tap to tap short circuit can occur.

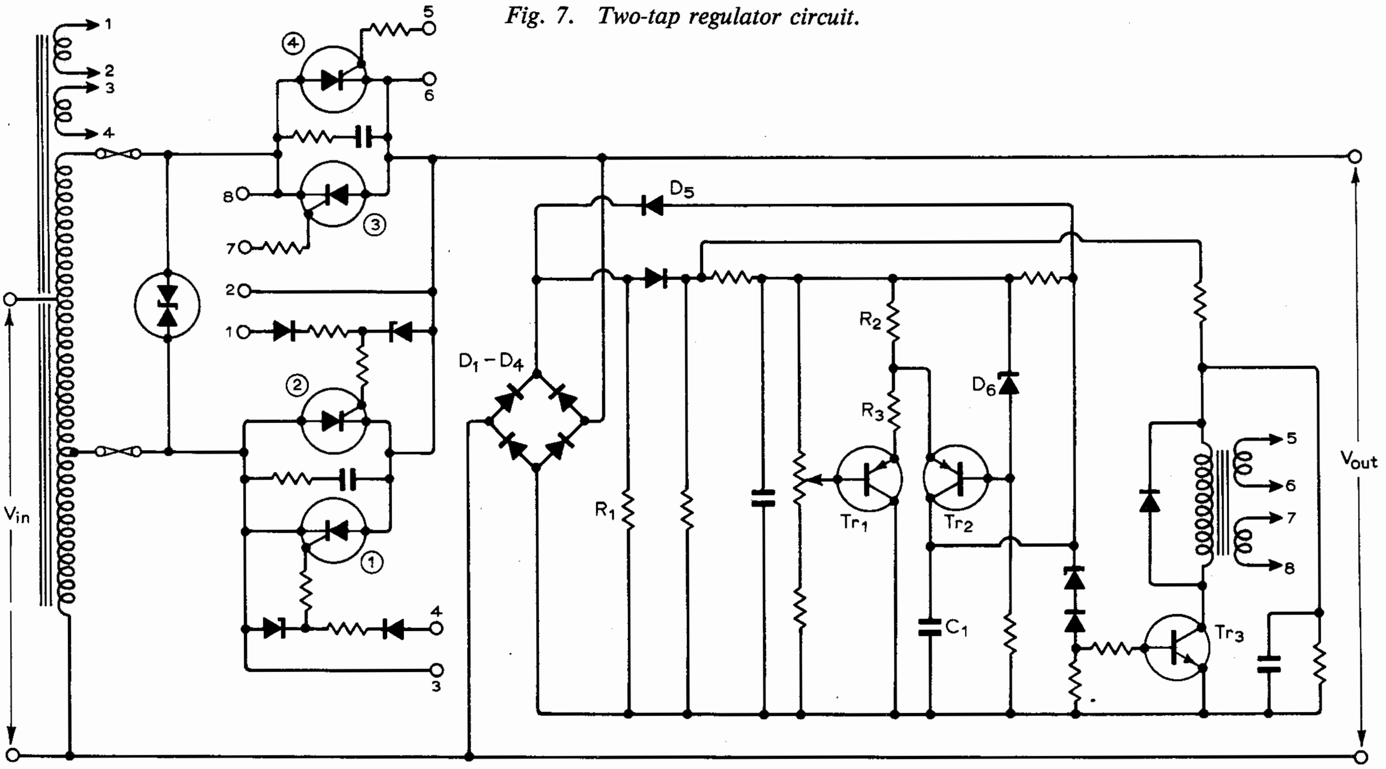

Fig. 7. Two-tap regulator circuit.

This avoids getting into a condition which could produce a tap-to-tap short circuit.

The resistor R_3 in the emitter of Tr_1 controls the regulator loop gain. This gain must be high for good regulation but loop stability consideration imposes a practical limit. The loop has a substantial lag due to the smoothing of the rectified feedback signal and in addition there is the transport delay introduced by the thyristors.

The thyristors are protected by two fast-acting fuses. Two fuses are necessary because of the possibility of tap-to-tap short circuits. If a single primary fuse were used it would be rated at approximately the same current as the secondary fuses. However, because the current in the primary is lower than in the secondary with tap-to-tap short circuits, the thyristors could experience a much higher I^2t surge. A "voltrap" suppressor is connected across the transformer taps to limit voltage transients which may occur on breaking the supply to the transformer. The suppressor will also limit voltage transients which occur in the supply voltage. A resistor capacitor network is connected across the thyristors to limit the rate of rise of forward voltage. High rates of rise may be caused by supply transients and they also occur across the lower tap thyristors due to the switching action of the regulator. If the rate of rise of forward voltage is not restricted it may cause spurious triggering of the thyristors.

An alternative form of trigger control circuit which can be used for the upper thyristors in the two-tap regulator is shown in Fig.8.

The diode bridge rectifies the output of the regulator and except for brief periods around voltage zero crossing the voltage across R_1 is defined by the zener diode voltage. The current through R_1 is therefore substantially constant. The current through R_2 is approximately proportional to the output voltage of the diode bridge and hence to the regulator output voltage. The transistor collector current is thus the difference between the "reference" current in R_1 and a current proportional to the regulator output voltage. The pulse circuit formed by C and the Shockley diode free-runs at a frequency set by the charging current. If it is initially assumed that this frequency is exactly equal to twice the supply frequency, a consideration of the circuit action will show how this exact condition is maintained. At some time during a half cycle the Shockley discharges C and triggers an upper thyristor. The Shockley extinguishes and the capacitor commences charging. As no smoothing is provided after the rectifier, the current through R_2, and hence the transistor, will vary considerably during the half cycle. However, capacitor C integrates this varying current and reaches the Shockley breakdown voltage in exactly a half cycle. By its process of integration and discharge, C averages each separate half cycle of output voltage. The exact frequency required of the oscillations can only be maintained for an exact average output voltage. If the average output voltage falls, the average charging current of C will increase causing the frequency of the capacitor-diode pulse circuit to increase. This will bring forward the firing of the upper thyristors and hence reduce the output error. As the error reduces, the pulse frequency returns to its original value. Under steady state conditions the capacitor-diode circuit is thus forced to run at exactly twice supply frequency and no permanent error is required at the regulator output. The loop gain of the system does not control the output error but merely the rate at which the circuit can correct output errors. On a half cycle to half cycle basis the gain must be less than unity, that is a given error in one half cycle must not produce overcompensation on the next, for the system to be stable.

The prolonged triggering requirement of the lower tap thyristors will normally make it inconvenient to use a triac in place of these thyristors. Prolonged triggering applied to a triac on the lower tap would lead to a tap-to-tap short circuit. It will normally be simpler to use two thyristors

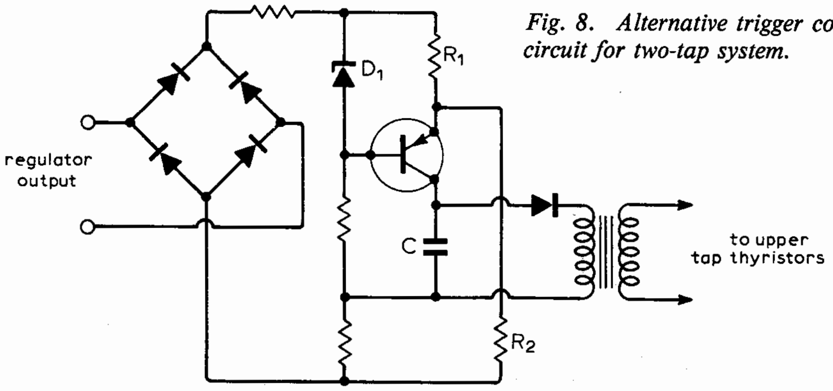

Fig. 8. Alternative trigger control circuit for two-tap system.

and only use a triac on the upper tap.

It is possible to alter the configuration of the two-tap regulator in various ways. For instance, the thyristors can be transferred to the primary of the transformer. It would be worthwhile doing this where the load operates at voltages substantially different to those of the supply. For instance the load may be heaters operating at a fraction of the supply voltage. In these situations the auto-transformer function can be included in the main transformer. It should be remembered, however, that the thyristors must withstand the transformer inrush current.

Another alternative is to rearrange the circuit so that the thyristors operate under high voltage/low current conditions. This is illustrated in Fig.9. The general operation and waveforms are identical to that for the circuit of Fig.4. However, the tap-to-tap voltage seen by the thyristors is now higher and the current lower. There are two problems with this configuration. One is that a short-circuit load will produce very high voltages across the thyristors before any fuses blow. The other is the fact that under "no load" conditions the thyristors handle the magnetizing current of the transformer. Since this could be highly inductive it could cause triggering difficulties.

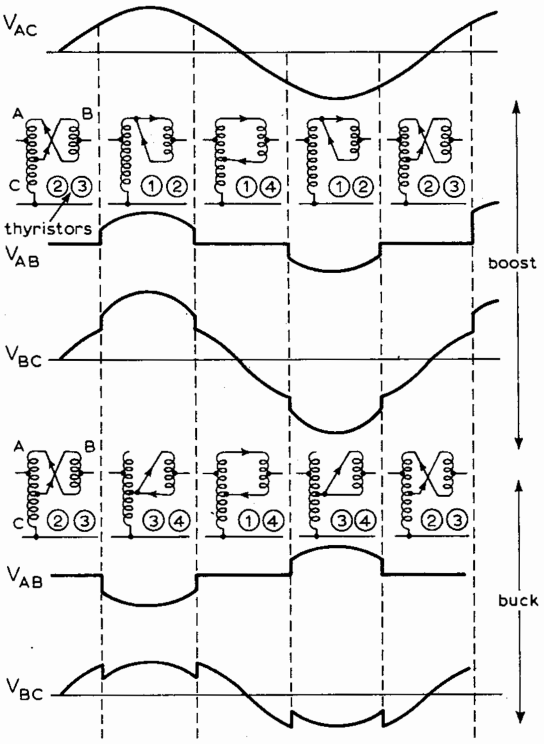

Fig. 11. Regulator switching sequence

Balanced 3-tap regulators

A regulator circuit which can operate over a very wide range of power factor loads is shown in Fig.10. A centre-tapped inductor has been included in the output circuit of the thyristors. This inductor is connected between the thyristors which could otherwise cause tap-to-tap short circuits due to faulty triggering on very reactive loads. Apart from eliminating this particular problem, the inductor also acts as an autotransformer and effectively provides a third tap on the transformer balanced between the other two. In order that the inductor should present no significant impedance in series with the supply, the current taken by the load must always be able to split evenly between the two halves of the coil. The circuit can satisfy this condition with only four thyristors if a direct current is maintained through the inductor. This current acts as a bias current through the conducting thyristors and in effect allows the load current to flow in either direction through them. Provided the direct current is greater than half the peak load current the load will never determine the time at which a thyristor is extinguished. It will be shown later that control of the circulating current and control of the output voltage are not mutually exclusive.

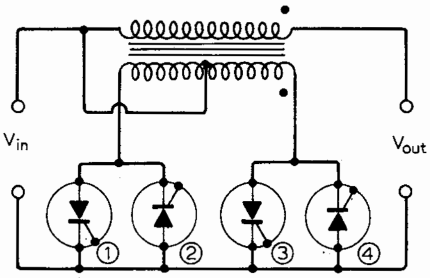

Fig. 9. Circuit arrangement to operate thyristors under high voltage and low current conditions.

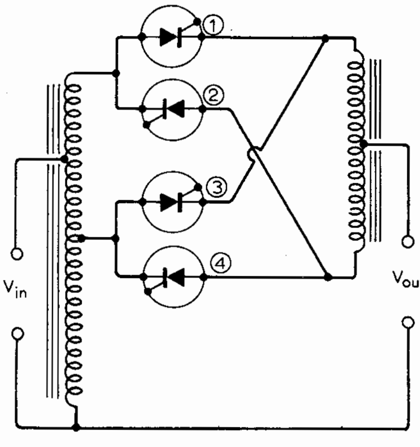

Fig. 10. Balanced three-tap regulator circuit.

Fig.11 illustrates the basic switching sequence of the regulator. The simplified circuits show how the inductor is connected at various times in the cycle (the numbers refer to which thyristors of Fig.10 are conducting). For some time around the centre of each half cycle, the inductor is short circuited and connects the load to the potential of the upper transformer tap, for boosting, or the lower tap for bucking. When the inductor is connected across the taps it behaves as an autotransformer and the output potential is the mean of the two tap voltages. This is equal to the supply voltage if the supply is connected to the transformer midway between the taps. A comparison of the switching sequence shown in Fig.11, with the circuit diagram of Fig.10, will show that commutation from one thyristor to another is obtained simply by triggering the thyristor which must be brought into conduction. For instance, the first transition shown in the boost sequence in Fig.11 involves turning on thyristor 1 and turning off 3. Triggering 1, which will be forward biased at this time, will result in reverse biasing 3. Similar action occurs at all transition in either boost or buck sequences and no additional components are necessary for commutation. It will also be seen that the difference between boosting and bucking is whether 2 is fired before or after 3 on negative half cycles and 1 before or after 4 on positive half cycles. Thyristors 1 and 2 cause transitions in the positive and negative half cycles respectively at similar points in the waveform. Thyristor 2 is already conducting (boost sequence) or reverse biased (buck sequence) when 1 is triggered. In the same way 1 is either conducting or reverse biased when 2 is triggered. Consequently, a common trigger pulse repeating every half cycle may be used for both thyristors. Similar common triggering may be used for thyristors 3 and 4.

The control of output voltage and circulated current is illustrated in Fig.12. The waveforms in (a) show typical boost and buck cycles and it can be seen that the inductor voltage has the same form for either of these conditions. The mean value of this voltage and the inductor winding resistance determine the circulated current. By moving forward both transitions in every half cycle the mean voltage across the inductor is increased, thus increasing the current. This action is shown in (b) and it can be seen that the output voltage is not substantially affected by this change. (The change in waveform symmetry has been exaggerated.) Fig.12 (c) shows the control of output voltage. For this, the two transitions are moved symmetrically about the centre of the half cycle and so do not greatly alter the mean voltage across the inductor. Circulating current and output voltage may thus be regulated with reasonably low interaction between their control loops.

When the supply voltage is near its nominal value, the two transitions coincide and little distortion will be added to the output waveform. The exact voltage at which this happens is determined by the voltage range to be regulated. As the supply voltage decreases, transitions must move further to compensate given changes in voltage. A regulator giving minimum distortion with nominal input will control larger changes in supply voltage above nominal than it can below nominal. Fig.13 shows distortion measured at the output of balanced 3-tap and 2-tap regulators (13(b) and 13(a) respectively) designed to regulate over similar voltage ranges. It can be seen that the regulation range is substantial and distortion would obviously decrease if the regulators were designed for smaller variations in supply voltage.

While the mean voltage across the inductor must be maintained reasonably constant, the alternating voltage across it varies considerably with changes in supply voltage. With a nominal input level, the inductor is continuously connected across the supply, its connections being reversed every half cycle. When the supply voltage is at either extreme of the regulator control range, the inductor will be short-circuited for a large part of each half cycle. The ripple current in the inductor will therefore alter considerably with the supply voltage, and the control circuit must ensure that the minimum instantaneous value of current is always greater than one half the peak load current. If the inductance is chosen on the basis of minimizing the peak energy in the inductor, its value is given by: $L=\frac{2V}{\Omega I_L}$ where I_L is the peak load current, V is the peak voltage across the inductor and Ω is the supply radian frequency. As the load current should always divide between the halves of the inductor winding, it will not contribute to the energy stored in this element.

The balanced 3-tap circuit provides full regulation for any load power factor and produces an output waveform substantially better than that obtained by a 2-tap regulator. The price paid for this improved performance is a reduction in the load volt-amp rating for a given thyristor and transformer cost, (or alternatively a reduced regulation range). The effect on the ratings depends on the exact nature of the load to be accommodated and the design adopted for the inductance. For a given cost, the balanced 3-tap circuit will handle about half the load volt-amps that the 2-tap circuit will.

A control circuit for the balanced 3-tap regulator must be capable of generating two separate trigger pulses in a sequence repeating every half cycle. (It was explained earlier that thyristors may be triggered in pairs.) These two pulses must move symmetrically about the centre of each half cycle to control output voltage and move asymmetrically to control circulated current. The elements of a circuit which provides this action is shown in Fig.14. The two pulses are produced by Shockley diodes D_2 and D_4 discharging ramp generators C_1R_1 and C_2R_2. The time taken for a capacitor voltage to reach the breakdown level of its associated Shockley diode is set by the time constant and aiming potential of the *CR* circuit and by the level to which the capacitor is reset after each pulse. Each time that C_1 is discharged, diode D_3 conducts and rapidly resets the capacitor to the voltage level of Tr_1 collector. D_3 then turns off and the capacitor voltage continues to rise at a rate set by the current through R_1. A synchronizing pulse occurring at supply voltage zero crossings discharges C_1 to zero each half cycle via diode D_1. The collector voltage of Tr_1, by resetting C_1 through D_3, controls the delay between the end of the synchronizing pulse and the generation of an output pulse at A. Further pulses which may be produced by D_2 before the next synchronizing pulse will not affect the regulator action since they cannot cause the firing of any thyristor. It can be seen that pulse circuit B operates in a similar manner and

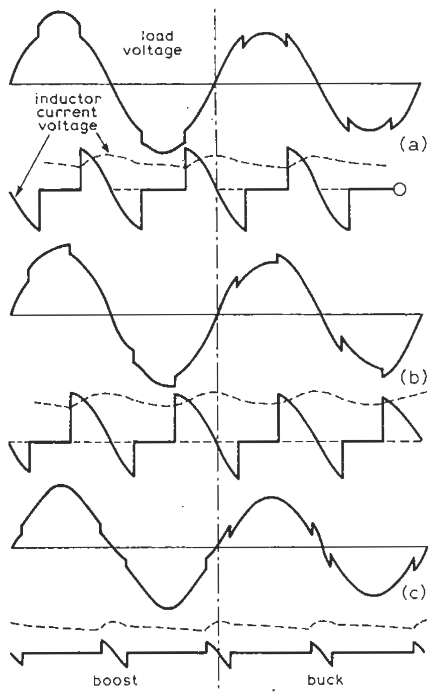

Fig. 12. Control cycle of voltage and current.

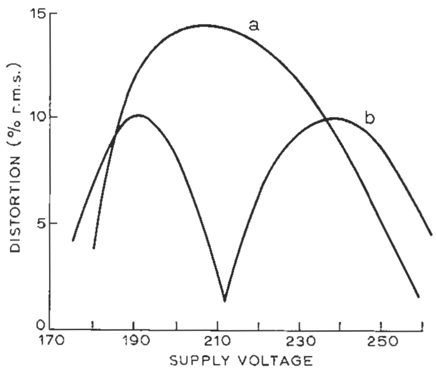

Fig. 13. Output distortion characteristic.

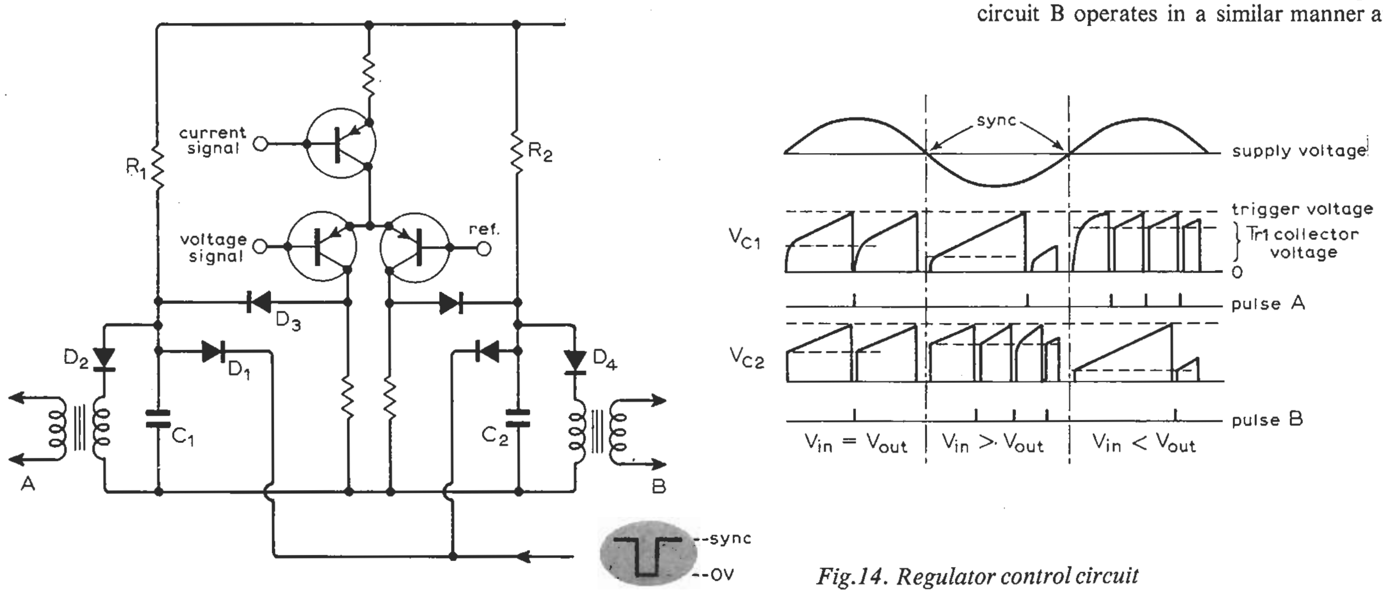

Fig.14. Regulator control circuit

is controlled by Tr_2 collector voltage. The circuit waveforms for the condition $V_{in} = V_{out}$ show that Tr_1 and Tr_2 collectors reset C_1 and C_2 to the same level and pulses at A and B both occur at the centre of each half cycle. If the "voltage" signal to the differential amplifier is altered, the voltages of the two collectors move in opposite directions causing the pulses at A and B to move in opposite directions. For $V_{in} > V_{out}$ pulse B leads A and for $V_{in} < V_{out}$, A leads B. Changes in the "voltage" signal therefore produce the symmetrical movement of pulses which is required to control the regulator output voltage. By varying the "current" signal, the amplifier tail current is altered and the two collector voltages are made to change in the same direction. This causes the two pulses to move in the same direction and alter the circulating current by unbalancing the output waveform. If the current control signal is derived by directly measuring inductor current, both halves of the winding must be monitored so that voltages due to load current can be cancelled. Alternatively, a signal may be derived from the magnetic field of the inductor which will be independent of load current.

General points on thyristor regulators

The characteristics of thyristors and triacs are normally well described in manufacturers' data. However it is worth noting a a few general points with regard to their use in a.c. voltage regulators.

High rates of rise of current through the thyristors during the time that they are being brought into conduction can lead to device failure. In the regulator circuits which have been described the leakage inductance of the transformer will normally provide adequate protection. This should be checked and it is also important to ensure a high level of trigger current during this switching time.

High rates of change of voltage across the thyristors can cause spurious triggering. Step changes of voltage occur across the devices due to the normal operation of the regulator and in addition transients on the supply can also cause sharp changes. Because of this it is advisable to shunt the thyristors by *RC* circuits as shown earlier in Fig.7. It should be remembered that such shunting increases the initial rate of rise of current through the thyristors.

The shunting of the thyristors by *RC* circuits is beneficial in two other respects. Some protection is provided against excessive voltages appearing across the thyristors due to short duration transients such as those caused by switching of the supply or load. Also the slowing of the change in voltage provides an output waveform with a much lower level of radio frequency harmonics.

The difficulty associated with radio frequency interference will of course depend on the application. A good metallic screen for the regulator housing with a balanced choke-capacitor circuit on the output will be adequate for most applications. One thyristor manufacturer recommends that for domestic situations radiated interference will be satisfactory if the rate of change of current in the supply wires is kept below 0.35 A/μs. This will normally require an inductance of a few hundred microhenries.

Finally it is worth making some comparisons between thyristor regulators and the most commonly used alternative, the ferro-resonant constant voltage transformer. Such a comparison can only be made in very approximate terms since aspects such as cost will be highly dependent on the precise requirements — see Tables below. The cost quoted for the thyristor regulator represents a likely production cost of a 2-tap circuit. It should also be remembered that although both forms of regulator carry out a similar task, that of providing a stabilized a.c. voltage, there are important differences in their detailed characteristics. In particular circumstances these detailed differences may be very important and override other considerations. For instance where it is important to minimize weight, the thyristor regulator is an almost automatic choice. Where frequent load short circuits occur the ferro-resonant transformer may have to be used.

TABLE 1
Performance characteristics

Characteristic	Thyristor Regulator	Ferro-resonant transformer
Input voltage range	± 20%	± 15%
Stability of output voltage (for full change of supply voltage and load current)	± 2%	± 3%
Overload protection	Fuse	Can handle continuous short circuit.
Output distortion	< 15%	Approximately 20%

TABLE 2
Weight and cost comparisons

Rating	Thyristor Regulator		Ferro-resonant transformer	
	Weight	Cost	Weight	Cost
500 VA	14 lbs	£25	45 lbs	£33
1000 VA	20 lbs	£35	85 lbs	£65
1500 VA	28 lbs	£50	120 lbs	£100