CHAPTER 13.5
AC REGULATORS

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CIRCUITS FOR CONTROLLING POWER FLOW IN AC LOADS

Switch configurations such as those in Fig. 13.5.1 can be used to control ac waveforms. The control may be merely *transistory*, as in soft starting an induction motor or limiting the inrush current to a transformer, or *perpetual*, as in the control of resistive heating elements, incandescent lamps, and the reactors of a static reactive volt-ampere (VAR) generator.

The basic single-phase ac regulator is depicted in Fig. 13.5.2, using a triac as the ac switch (but any of the ac switch combinations shown in Fig. 13.5.1 is applicable). The various three-phase arrangements possible are shown in Fig. 13.5.3. The first of these, the wye-connected regulator with a neutral connection (Fig. 13.5.3*a*), exhibits behavior identical to that of the single-phase regulator, since it is merely a threefold replica of the single-phase version.

The delta-connected regulator arrangement of Fig. 13.5.3*b* is also essentially similar in behavior to the single-phase regulator insofar as load voltages and currents are concerned. Because of the delta connection, however, any symmetrical zero sequence components of the load currents will not flow in the supply lines but will only circulate in the delta-connected loads.

The three-phase three-wire wye-switched regulator of Fig. 13.5.3*c* behaves differently because two switches must be closed for current to flow in any load. Shown delta-loaded, it may also have the loads wye-connected without a neutral return. In this connection, each ac switch may consist of the antiparallel combination of a thyristor and a diode. The normal wye-delta transformations apply to load voltages and currents.

The "British delta" circuit of Fig. 13.5.3*d* behaves in the same way as a wye-switched regulator in which thyristors with inverse parallel connected diodes are used as the switches and is unique in that only unidirectional current capability is required of its switches.

When the loads are essentially resistive, two methods of control are currently employed. The technique known as *integral-cycle control* operates the regulator by keeping the switch(es) closed for some number m of complete cycles of the supply and then keeping the switch(es) open for some number n of cycles. The power delivered to the load(s) is then simply $m/(m + n)$ times the power delivered if the switch(es) are kept permanently closed, for the single-phase, wye with neutral, and delta-connected regulators.

For the wye-switched (without neutral) and British delta regulators, the power delivered is slightly greater than $m/(m + n)$ times the power at full switch conduction, and dc and unbalanced ac components develop in the supply unless special control techniques are used. These phenomena arise because of the transient conditions, inevitably attending the first cycle of operation of these circuits.

An undesirable consequence of integral-cycle control is that the load voltages and currents, and hence the supply currents, contain sideband components having frequencies $f_s[1 \pm pm/(m + n)]$, where f_s is the supply frequency and p is any integer, 1 to infinity. Many of these frequencies are obviously lower than the supply frequency and may create problems for the supply system and other connected loads. The existence of this type of unwanted components in the voltage and current spectra makes integral-cycle control unsuitable for inductive loads (including loads fed by transformers). Since none of the sidebands are zero sequence, the line currents of an integral-cycle-controlled delta regulator are identical to the properly transposed load currents.

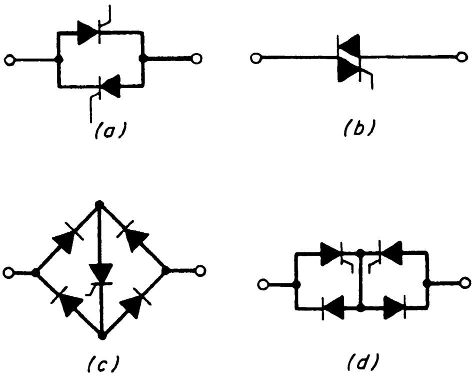

FIGURE 13.5.1 Single-phase ac switches.

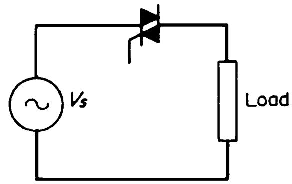

FIGURE 13.5.2 Single-phase ac regulator.

Integral-cycle control results in unity displacement factor (the cosine of the angle between the fundamental component of supply current and the supply voltage). The power factor of the burden they impose on the supply with pure resistive loads is $[m/(m + n)]^{0.5}$. This is true because any regulator that forces the load current to flow in the supply while reducing the rms voltage applied to a resistive load has a power factor equal to the rms load voltage divided by the rms supply voltage.

The other method of control commonly used is termed *phase-delay control*. It is implemented by delaying the closing of the switch(es) by an angle α (called the firing angle) from each zero crossing of the supply voltage(s) and allowing the switch(es) to open again on each succeeding current zero. The load voltages and currents in this case contain only harmonics of the supply frequency as unwanted components, and except for the regulator shown in Fig. 13.5.3*c*, using thyristor-inverse diode switches, only odd-order harmonics are present. Thus, this control technique can be used with inductive loads.

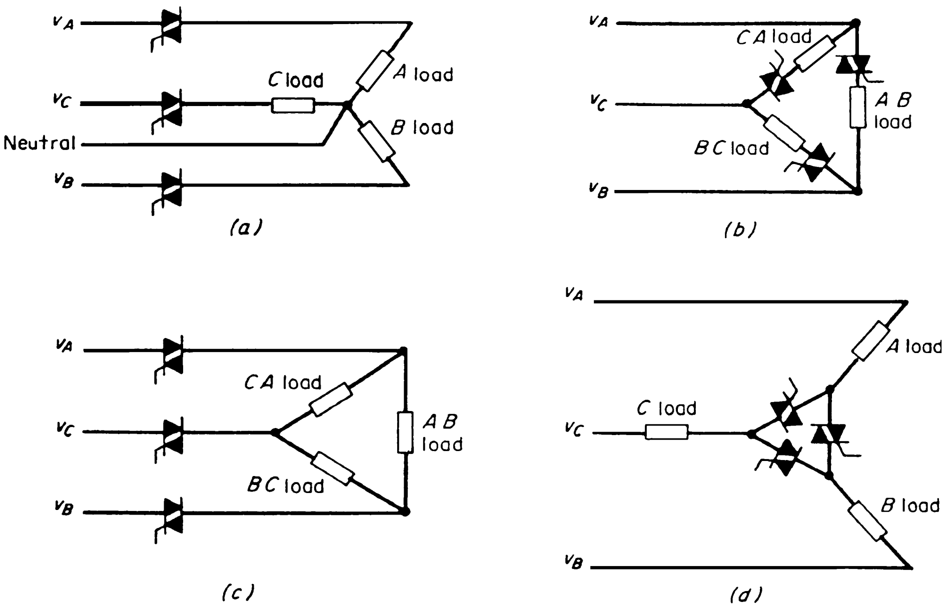

FIGURE 13.5.3 Three-phase ac regulators.

The general expressions for the load voltages and currents produced by the single-phase regulator are very cumbersome but simplify considerably for the two cases of greatest practical importance, pure resistive and pure inductive loads. For a pure resistive load with a supply voltage $V \cos \omega_s t$, the fundamental component of load voltage is given by

$$V_{DIR} = \left(1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right) V \cos \omega_s t + \frac{\sin^2 \alpha}{\pi} V \sin \omega_s t \tag{1}$$

and the total rms load voltage by

$$V_{\mathrm{RMS}R} = \frac{V}{\sqrt{2}} \left(1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right)^{1/2} \tag{2}$$

where α is the firing angle measured from the supply-voltage zero crossings. For pure inductive load it is convenient to define the firing angle $\alpha' = \alpha - \pi/2$, so that at full output $\alpha' = 0$. The fundamental voltage component is then given by

$$V_{\mathrm{DIL}} = \left(1 - \frac{2\alpha'}{\pi} - \frac{\sin 2\,\alpha'}{\pi}\right) V \cos \omega_s t \tag{3}$$

and the total rms voltage by

$$V_{\mathrm{RMS}L} = \frac{V}{\sqrt{2}} \left(1 - \frac{2\alpha'}{\pi} - \frac{\sin 2\alpha'}{\pi}\right)^{1/2} \tag{4}$$

The same relationships apply to the three-phase circuits, which are in effect triplicates of the single-phase circuit (Fig. 13.5.3*a* and 13.5.3*b*); more complex relationships exist for the remaining three-phase circuits.

The use of phase-delay control results in decreasing lagging displacement factor with increasing firing angle. Maximum displacement factor is obtained at full output, equaling the power factor of the given load. At a reduced power setting the power factor is less than the displacement factor; the ratio of the two equals the ratio of the fundamental line currents versus the total rms line currents. This ratio is less than unity because of the presence of harmonic currents.

The load voltages and currents and, more importantly, the line currents of phase-delay-controlled regulators have lower total rms distortion than those of integral-cycle-controlled regulators. Among the circuits shown, the delta regulator of Fig. 13.5.3*b* is most beneficial; since the triple *n* harmonics (those of orders which are integer multiples of 3) in its load currents are zero sequence, they do not flow in the supply lines and the circuit has both a better power factor and lower total line-current distortion than integral-cycle regulators or the phase-delay-controlled wye regulators with neutral.

For the wye regulator without neutral, the range of α is 0 to $7\pi/6$ rad, provided fully bilateral switches are used; for the British delta regulator and the wye regulator without neutral using thyristor-inverse diode switches, the range is 0 to $5\pi/6$ rad. When phase-delay regulators are used with inductive loads, the range of α used for control is reduced because current-zero crossings lag voltage-zero crossings and thus abrogate part of the delay obtained with resistive loads. The regulators most commonly used with inductive loads are the single-phase, wye with neutral and the delta, for which the range of α becomes ϕ to π, where ϕ is the load-phase angle.

STATIC VAR GENERATORS

The delta regulator with purely inductive loading finds extensive use in the *static VAR generator* (SVG) (Gyugyi et al., 1978, 1980). A basic SVG consists of three delta-connected inductors with phase-controlled switches ($\pi/2 \le \alpha \le \pi$) and three fixed capacitive branches which may be delta-or wye-connected. The capacitive branches draw a fixed current from the supply, leading the voltage by $\pi/2$ rad. The fundamental current in the inductors is lagging the voltage by $\pi/2$ rad. Its amplitude can be varied, by phase controlling the switches, from the full inductor current to zero.

Hence the net reactive volt-ampere burden on the supply can be continuously controlled from the full capacitive VAR, when $\alpha = \pi$ and the inductor currents are zero, to the difference between the capacitive- and inductive-branch VARs when $\alpha = \pi/2$ and full inductor currents flow. This difference will be zero if inductive-branch VARs are made equal to capacitive-branch VARs and become an inductive burden if inductive VARs at full conduction exceed the capacitive VARs. Since the firing angle α can be varied on a half-cycle-to-half-cycle basis, extremely rapid changes in VAR supply (capacitive burden) or demand (inductive burden) can be accomplished.

SVGs can be used to supply shunt-reactive compensation on ac transmission and distribution systems, helping system stability and voltage regulation. They can also be used to provide damping of the subsynchronous resonances, which often prove troublesome during transient disturbances on series capacitor-compensated transmission systems, and to reduce the voltage fluctuations (flicker) produced by arc-furnace loads. In the latter application, their ability to accomplish dynamic load balancing is especially valuable.

An SVG which can provide control of reactive power supply or demand can obviously compensate for an unbalanced reactive load. It can also act as a Steinmetz balancer, providing the reactive power exchange between phases necessary to transform an unbalanced resistive load into a perfectly balanced and totally active (real) power load on the supply system.

This action can be explained as follows. Suppose a single-phase resistive load is connected between lines A and B of a three-phase system. Then the current it draws will be in phase with the AB voltage, and thus the A-line current created will lead the A-phase (line-to-neutral) voltage by $\pi/6$ rad and the B-line current will lag the B-phase voltage by $\pi/6$ rad.

If equal-impedance purely reactive loads are now connected to the BC and CA line pairs, capacitance on BC and inductive on CB, they create currents with the following phase relationships to the phase voltages:

In the A line, lagging by $2\pi/3$ rad

In the B line, leading by $2\pi/3$ rad

In the C line, one leading by $\pi/3$ rad and the other lagging by $\pi/3$ rad

The result in the C line is clearly an in-phase, wholly real current. If the impedances are of appropriate magnitude, their lagging and leading quadrature contributions in the A and B lines, respectively, can be made to cancel the lagging and leading quadrature currents created therein by the single-phase resistive load. The impedance required is $\sqrt{3}$ times the resistance. Obviously an SVG capable of providing either leading or lagging line-to-line loading on any of the line pairs can be used to balance a single-phase resistive load on any one line pair; by extension, it can be used to balance any unbalanced load. It can respond rapidly to changes in the degree of imbalance existing and thus dynamically balance the load despite the fluctuating imbalance typically created by an arc furnace.

In addition to a varying reactive fundamental current, an SVG operating other than at full or zero conduction in its reactive branches generates harmonic currents. Thus at least part of the capacitive branch is usually realized in the form of tuned harmonic filters to limit harmonic injection to the ac supply system. Maximum harmonic amplitudes relative to maximum fundamental are:

Harmonic order	3d	5th	7th	9th	11th	13th
Maximum amplitude percent	13.8	5.05	2.59	1.57	1.05	0.752

with diminishing amplitudes of the higher-order components.

When the SVG is in balanced operation, the triple *n* harmonics (3d and 9th in the table above) do not flow in the supply, being zero sequence. When operation is unbalanced in order to balance an unbalanced real load, positive and negative sequence components of the triple *n* harmonics develop and of course do flow in the supply unless filtering is provided for them.

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