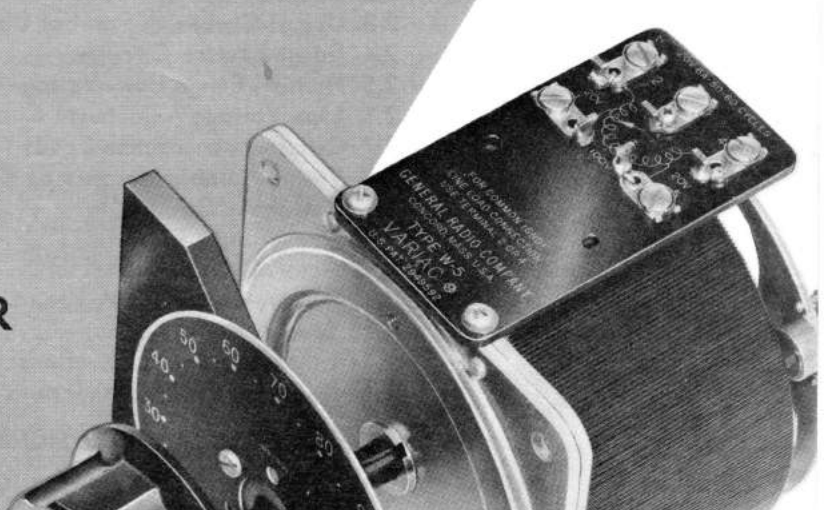
HANDBOOK OF

Voltage Control

with the

VARIAC®

AUTOTRANSFORMER



GENERAL RADIO COMPANY
WEST CONCORD, MASSACHUSETTS

TABLE OF CONTENTS

West Concord, Massachusetts, USA

Form 3080-A January, 1963 Printed in U.S.A.

FOREWORD

Variac® is the registered trade name for the continuously adjustable autotransformers, originally designed, patented, introduced, and manufactured by General Radio Company. Covered by patents[1] under which other manufacturers were licensed, this invention now embodies many electrical and mechanical improvements in the original design, the result of a continuous development program carried on since 1933. Among these is the patented[2] Duratrak ® contact surface, an improvement that makes the adjustable autotransformer as reliable as a fixed-ratio transformer. The single winding of a Variac autotransformer is common to both line and load circuits. For a given rating, Variac autotransformers are usually smaller than reactive controls and have a better power factor. Unlike resistive controls, Variac autotransformers cannot operate on direct current. They are, however, considerably more efficient.

Variac autotransformers are used to control voltage and thus to regulate other quantities such as current, power, light, and heat, which are sensitive to voltage change. (See Figure 1.1). Some typical loads, with the function that is subject to voltage variation for each, are listed on the following page.

Variac autotransformers are designed for 120-, 240-, or (in combinations) 480-volt input. Series-W models can be operated at rated current and voltage from 50 to 400 cps. For 350- to 1200-cycle service, the Series-M models are available. Either type may be connected to provide voltage control from zero to 17 percent above line voltage or to line voltage only. Models are available in 2-, 5-, 8-, 10-, 20-, 30-, and 50-ampere sizes. These size designations are the approximate current values for 120-volt models. The rated current (which may be drawn at any brush setting) is specified in our catalogs for each model. A maximum current rating is also given which is the current that may be drawn at or near line or zero voltage. A constant-impedance load which draws maximum current at line voltage may safely be controlled downward to zero.

The Variac® brand of adjustable transformers offers many important advantages to the user. Designed to accepted standards for electrical apparatus, all models are ruggedly constructed of high-quality materials and are rigidly inspected and tested before shipment.

The Duratrak contact surface assures long life, even under overload conditions. Prices are competitive with, and often lower than, others of comparable quality.

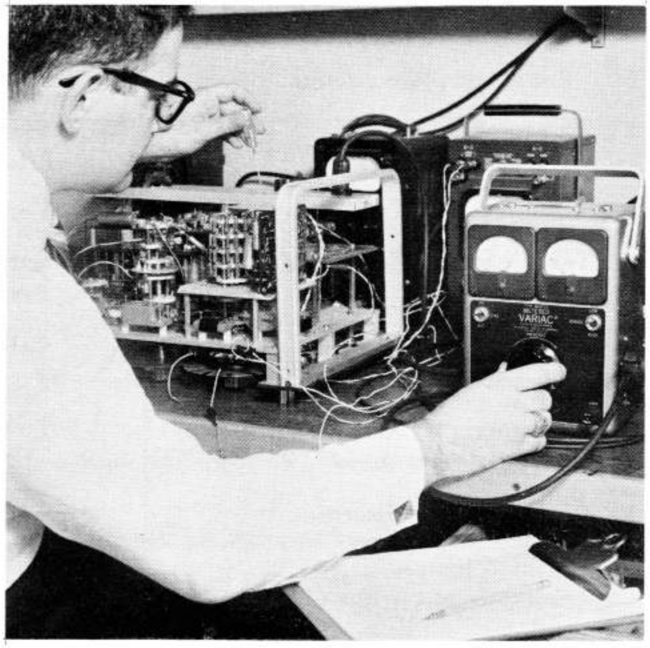


Figure 1.1.
Voltage control with a metered Variac autotransformer.

---

[1] U.S. Patent No. 2,009,013.

[2] U.S. Patent No. 2,949,592.

Many Variac autotransformer models are listed under the Re-examination Service of the Underwriter's Laboratory, Inc. and Canadian Standards Association.

This manual presents the theory and practice of Variac autotransformer design and operation. Specifications and information for ordering are included in our catalogs. While a complete compilation of their uses is probably impossible, it is hoped that this information will be of value to those whose work is in any way concerned with Variac autotransformers.

TYPE OF LOAD	FUNCTION CONTROLLED
A. Incandescent Lamps.	Brilliance and color temperature.
B. Fluorescent lamps (both hot- and cold-cathode types).	Brilliance.
C. Heating devices. Resistive heaters and infra-red lamps.	Temperature.
D. Motors.	Speed and torque.
AC Motors.	
Universal.	
Series.	
Repulsion.	Use only on fan loads, or where torque is proportional to speed.
Two-phase.	
Shaded-pole.	
Split-phase induction.	
Capacitor split-phase.	
DC Motors.	Use with rectifier, as in the Variac Motor Speed Control.
E. Rectifiers.	
Electroplating.	Current.
Power and plate circuits.	Voltage.
F. Electron Tubes.	Plate voltage.
Transmitting tubes.	Filament current.
G. Solenoids.	Force.
H. Test Loads.	Over- and under-voltage testing. Breakdown tests.
I. Voltmeters, ammeters, wattmeters, watthour meters.	Calibrating voltage and current.
J. Magnetrons, klystrons, traveling-wave tubes.	Power and frequency.
K. Development equipment.	Gradual line-voltage application, to detect defects without burnouts.
L. Laboratory power lines.	Line-voltage correction. (See also General Radio Type 1570-A Automatic Voltage Regulator.)
M. Servo systems.	Voltage.
N. Remote control of any of the above.	

SECTION 1

THEORY AND PRINCIPLES

1.1 BASIC DESCRIPTION.

An autotransformer is simply a transformer with a single winding, all or part of which is common to both the primary and the secondary circuits. Autotransformers can have lower leakage reactance, lower losses, smaller exciting current, and usually lower cost than two-winding transformers. They differ from potentiometers in that they have an induced voltage in each turn and will not operate on dc, or at low frequencies without a reduction in voltage.

Basically, an adjustable autotransformer consists of a single layer of wire, wound on a toroidal core, and an electrographitic ("carbon") brush which traverses this winding. The brush track or commutator is made by removing a portion of the insulation from each turn of the winding, thus forming a series of commutator elements. The basic principle is that of a tap-changing transformer. The brush is always in contact with one or more wires, and continuously taps off any desired fraction of the winding voltage. It is possible, therefore, to move the contact under load without interrupting the circuit. This feature distinguishes the continuously variable autotransformer from tapped transformers that cannot be switched under load.

1.2 TRANSFORMER OPERATION.

An autotransformer serves as a common magnetic circuit to link two or more electrical circuits. When the primary winding is connected to an alternating-voltage source, an alternating magnetic flux will be produced. The magnitude of this flux, which is analogous to electrical current, depends on the voltage applied to the primary and on the number of primary turns. All the turns on the transformer are linked by the mutual magnetic field. The mutual flux in this field induces the same voltage per turn throughout the winding. The magnitude of the voltage induced in the secondary portion of the winding depends, therefore, on the number of turns in the secondary circuit.

In order to make the transformer action most effective, all of the flux should be confined to a definate path linking all turns in the winding. This is approximated by the use of a core of iron or other ferromagnetic material which has a much higher permeability than air. Variac autotransformers use spirally wound cores of strip stock, grain-oriented, so that the flux path is along the axis of maximum permeability.

The direction of the flux in a magnetic circuit is described by flux lines. The number of flux lines in a given area indicates the intensity of the magnetic effect, or the flux density. This quantity (usually expressed in flux lines per square centimeter, or gausses) is calculated from the equation:

$$B_{max} = \frac{10^8 \, E}{4.44 \, A_c \, fSN} \tag{1}$$

where B_{max} = flux density in gausses
E = rms volts applied to the winding
A_c = cross section area of the core in square centimeters

f = frequency of E in cycles per second
S = stacking factor of the core (usually 0.90 to 0.98)
N = number of winding turns to which E is applied.

It will be observed that the flux density, B_{max}, is directly proportional to E and inversely proportional to A_c, f, and N. $B_{maximum}$ is used because of the nonlinearity of iron-core materials and because factors such as core loss and magnetizing current are more dependent upon maximum than upon average or rms values.

The core loss (power absorbed by hysteresis and eddy current losses), in watts per pound, and the core excitation, in volt-amperes per pound, are complex functions of the flux density, B_{max}. These factors increase rapidly as saturation is approached (the point at which further ferro-magnetization is impossible); thus, in order to avoid excessive core loss and excitation, B_{max} must be limited. The core loss for a given flux density decreases with decreasing frequency. However, for a given winding, core, and voltage, the flux density is inversely proportional to frequency.

Copper loss (I^2R loss in the winding) is also a dominant design factor. Wire size is closely fixed by the current rating and the maximum allowable temperature rise. Small transformers (including Variac autotransformers) cannot be operated at a flux density sufficiently high to equalize core and copper losses without excessive magnetizing current. In an adjustable autotransformer, with the input voltage applied across the entire winding, copper loss at a constant output current varies with brush setting from a maximum at mid-point, decreasing gradually, and then abruptly, to zero at the winding end. Were it not for the poor thermal conductivity of the necessary insulation, the load could be increased as the brush approached the end of the winding, and, theoretically, could reach infinity if the brush losses were ignored. Because of these brush and thermal limitations, the current increase must be held to a modest 30 to 50 percent.

To set up the flux, a wattless component of current, I_x, traverses the primary winding, accompanied by a real component, I_{CL}, that supplies the hysteresis and eddy current losses in the core. The vector sum of these two currents is the magnetizing current, I_m. For a given transformer and winding, I_m is constant for constant applied voltage and frequency. In most transformers I_m is small (a few percent) with respect to the load current components, and can therefore be neglected in generalized computations. However, it is always present and is substantially independent of load conditions. It is I_m, and only I_m, that excites the core and supplies its losses.

The magnetizing ampere-turns (the product of I_m times the number of turns that it traverses) are the only unbalanced ampere-turns in any transformer. All other ampere-turns, due to load circuits, are completely balanced. Let us see why this is so.

Figure 1.2 represents a typical two-winding transformer, with a primary, P, wound for 120 volts, and a secondary, S, wound for 360 volts. The two windings, electrically insulated from each other, surround a common iron core. They are wound in the same "sense" so that when the top of P is positive the top of S is also positive (as shown by the dots in the figure).

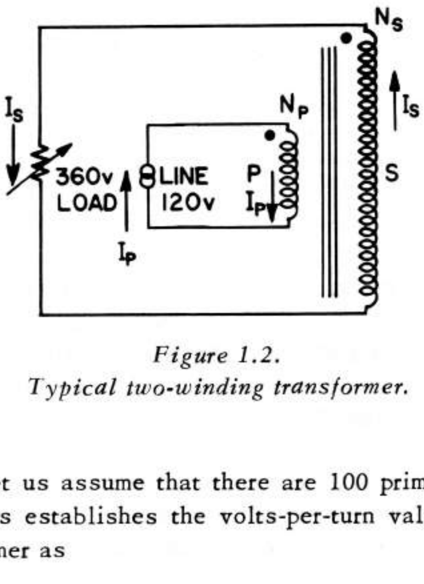


Figure 1.2.
Typical two-winding transformer.

Let us assume that there are 100 primary turns, N_P. This establishes the volts-per-turn value for the transformer as

$$\frac{E}{N_P} = \frac{120}{100} = 1.2 \tag{2}$$

Note that this is a basic ratio, appearing in equation (1). It establishes the value of B_{max} in that equation. Conversely, B_{max} determines the value of E/N, so that every turn surrounding the transformer core will have an induced voltage of E/N volts. Neglecting regulation, the secondary turns for 360 volts will be given by

$$N_S = \frac{360}{1.2} = 300$$

In Figure 1.2, the directions of the primary and secondary currents, I_P and I_S, are indicated by the arrows. At any given instant these currents flow in opposite directions. This can be readily understood by considering the line source as a generator which pumps the current "up," after which it flows "down" through the primary. However, the secondary, with its induced voltage, acts like a generator to the load. The secondary current, then, flows "up" through the secondary and "down" through the load.

In a transformer, the product of primary voltage and current (neglecting I_m) is equal to the product of secondary voltage and current. If, as in Figure 1.2, the secondary voltage is three times the primary voltage, then the secondary current must be one-third of the primary current.

$$E_S = 3\ E_P \tag{3}$$

$$I_S = \frac{I_P}{3} \tag{4}$$

$$E_S I_S = \frac{3\ E_P\ I_P}{3} = E_P I_P \tag{5}$$

Since the primary-to-secondary turns ratio is the same as the voltage ratio, then

$$I_P N_P = I_S\ N_S = \frac{I_P}{3}\ (3\ N_P) \tag{6}$$

The primary and secondary load-related ampere-turns are equal in magnitude and opposite in effect on the core. Thus there are no net load-related ampere-turns (referred to the core) in a transformer (except when it is operated as a choke).

Let us assume that the transformer of Figure 1.2 is capable of delivering one ampere to the load, for a rating of 360 volt-amperes. From equation 4, the primary current will be 3 amperes. Now let us reconnect the transformer as in Figure 1.3, with the primary and secondary windings in series, aiding. The line voltage will be the sum of the primary and secondary voltages, 120 plus 360, or 480 volts. The load voltage will remain at 360, but the primary and secondary currents will add at point X, yielding a permissible load current of 4 amperes (3 + 1), and a volt-ampere rating of 4 x 360, or 1440. This simple change of connections has converted the transformer of Figure 1.2 to an autotransformer; its volt-ampere rating has been quadrupled, with no change in primary winding, secondary winding, or core. However, the magnetizing current, I_m, will now traverse both primary and secondary windings and, since the number of turns has now been increased by a factor of four, I_m will be one-fourth as large. But with the line voltage now four times as great, $\frac{480}{120}$, the magnetizing volt-amperes will remain unchanged, as expected, since the core is being excited by the same number of volts per turn.

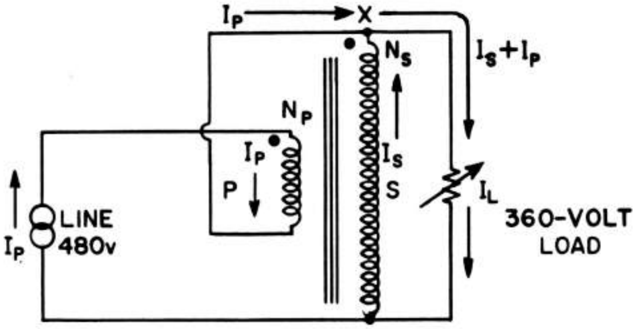


Figure 1.3.
Primary and secondary of transformer connected in series.

The conventional autotransformer diagram, with the current paths, is shown in Figure 1.4.* Note that I_m adds *vectorially* to I_P and subtracts *vectorially* from I_S. Also I_P and I_S are opposing, and

$$N_P I_P = N\ I_P = 3\ N\ I_S = N_S I_S \tag{7}$$

---

*The terminology of Figure 1.3 for primary and secondary will be used throughout this discussion.

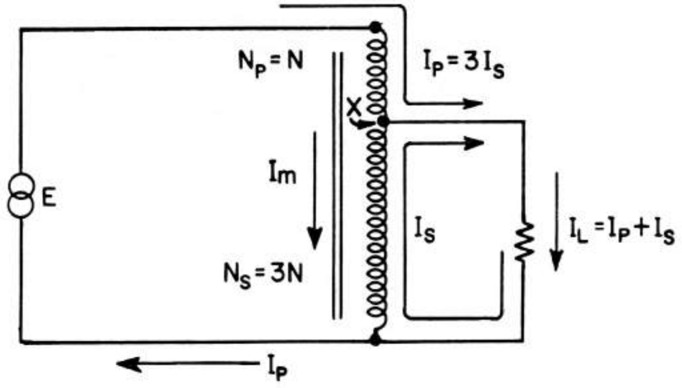


Figure 1.4.
Circuit of fixed autotransformer.

1.3 VARIAC AUTOTRANSFORMER PRINCIPLES.

Let us now consider the continuously adjustable autotransformer. The circuit of Figure 1.5 differs from the transformer-autotransformer circuits of Figures 1.2, 1.3, and 1.4 in that the number of turns in the primary and in the secondary may be continuously adjusted by means of a sliding brush. Also, the winding usually consists of a single wire size from beginning to end, whereas, in a fixed autotransformer (Figure 1.4), the two sections often employ different wire sizes, to minimize copper losses.

(The theory of the Variac autotransformer brush has been fully covered in the Karplus-Tuttle patent #2,009,013 and in other literature.)

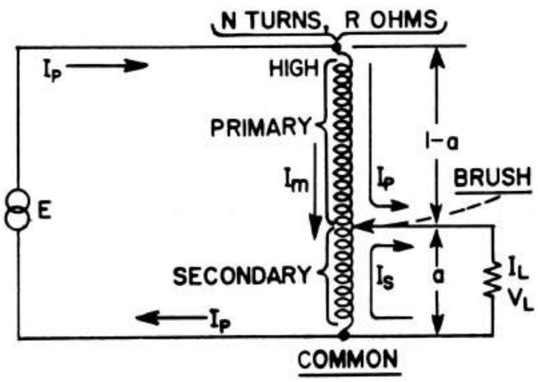


Figure 1.5.
Basic Variac autotransformer circuit.

In Figure 1.5, let a represent any number between zero and unity. Thus with the brush as shown, there will be aN turns and aR ohms in the secondary winding, and $(1 - a)\ N$ turns and $(1 - a)\ R$ ohms in the primary winding.

Then the load voltage is

$$V_L = aE \tag{8}$$

Volt-amperes of the load $= (VA)_L = aE\ I_L$ (9)

$$I_P = \frac{(VA)_L}{E} = \frac{aE\ I_L}{E} = aI_L \tag{10}$$

Primary ampere-turns $= I_P N_P = aI_L\ (1 - a)\ N$
$= (a - a^2)\ NI_L$ (11)

$$I_S = I_P \frac{N_P}{N_S} = aI_L \frac{(1 - a)\ N}{aN} = (1 - a)\ I_L \tag{12}$$

Secondary ampere-turns $= I_S N_S = (1 - a)\ I_L\ a\ N$
$= (a - a^2)\ N\ I_L$ (13)

From (11) and (13), $I_S N_S = I_P N_P$ (14)

Copper loss $= \Sigma W = I_P^2 R_P + I_S^2 R_S$

$$\begin{aligned} &= a^2 I_L^2\ (1 - a)\ R + (1 - a)^2\ I_L^2\ aR \\ &= I_L^2 R\ [a^2 - a^3 + a - 2a^2 + a^3] \\ &= I_L^2 R\ [a - a^2] \end{aligned} \tag{15}$$

Differentiating, $\frac{d}{da}\ [a - a^2] = 1 - 2a = 0$ (16)

$$2a = 1$$

$$a = \tfrac{1}{2} \tag{17}$$

$$\text{Maximum } \Sigma W = I_L^2\ R \left[\frac{1}{2} - \frac{1}{4}\right] = \frac{I_L^2\ R}{4} \tag{18}$$

Therefore the maximum copper loss for a constant-current load occurs when the brush is at the mid-point. The rated current can be determined by assigning a value to I_L that will keep the mid-point-brush-setting temperature rise below the permissible limit.

At any other brush setting, the constant-current copper loss is less, which means the current can be increased while the copper loss remains constant.

Let the current at the mid-point setting be I_R. Then

$$I_L^2 R \; [a - a^2] = I_R^2 \left(\frac{R}{4}\right) \tag{19}$$

$$I_L^2 = \frac{I_R^2}{4\;[a - a^2]} \tag{20}$$

$$I_L = \frac{I_R}{2\sqrt{a - a^2}} \tag{21}$$

The solution of this equation gives the curve of Figure 1.6. As a approaches zero or unity, I_L approaches infinity. Problems of thermal conductivity and brush heating make the usual limit of I_L either 1.3 or 1.5 times I_R.

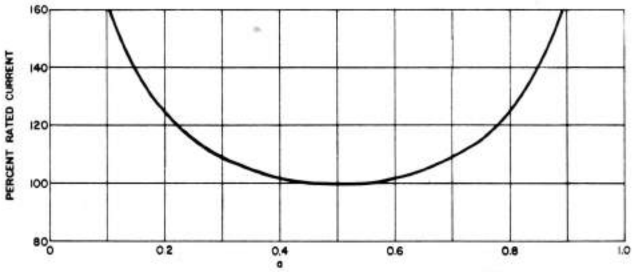


Figure 1.6.
Constant copper-loss current versus output voltage.

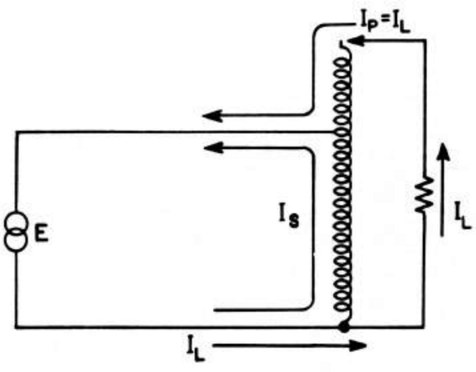


Figure 1.7.
Autotransformer step-up connection.

In Figure 1.7, the roles of the line and load, as shown in Figure 1.5, have been reversed. The line current is now equal to the original load current, etc.

In equation (10), $I_P = aI_L$

$$= aI_R \frac{1}{2\sqrt{a - a^2}}$$

$$= \frac{I_R}{2\sqrt{\frac{1}{a} - 1}} \tag{22}$$

which yields the curve of Figure 1.8. Combining the curves of Figures 1.6 and 1.8, we obtain the familiar form shown in Figure 1.9.

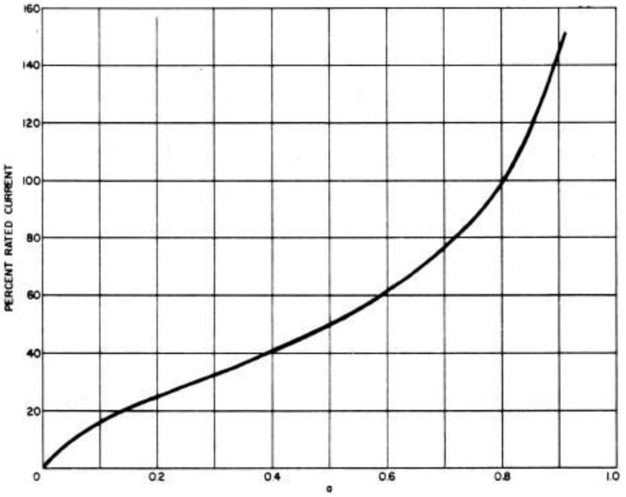


Figure 1.8.
Load current versus ratio of input to output voltage.

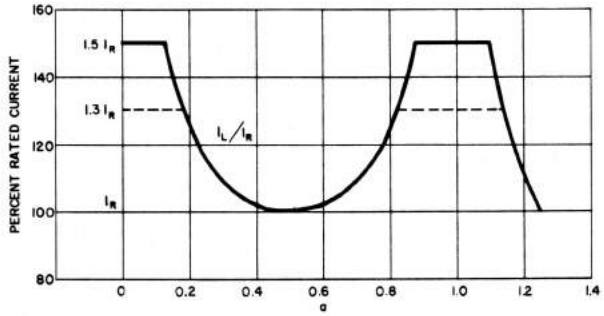


Figure 1.9.
Output current versus transformation ratio.

1.4 MAGNETIC CIRCUIT.

As mentioned in Section 1.2, the core magnetic flux, B_{max}, is limited to avoid excessive core loss and excitation. The limit for Variac autotransformers is approximately 18,000 gausses at low power frequencies (25, 50, and 60 cps). This limit is based on a magnetizing current not to exceed 10% of the rated current, (that may be drawn at any brush setting,) based on temperature rise with the unit operating at the lowest recommended frequency. The curves in Figure 1.10 show the core loss in watts per pound of core material versus flux density in maximum kilogausses (thousands of flux lines per square centimeter). Curves are given for the three most common power frequencies, 60, 50, and 25 cps, with a portion of the 400-cps curve for comparison.

Most of the Series W Variac Autotransformers are designed for flux densities of between 14 and 15 kilogausses (at 60 cps). A good average figure is 14.5. This refers to the normal connection (over-voltage for standard models), 120-volt input for 0 to 140-volt output, and 120- or 240-volt input for 0 to 280-volt output. For other voltages, v, at the normal input terminals, the flux density will be 14.5 (v/120) = 0.121v for 120 volts, or 14.5 (v/240) = 0.06v for 240-volt models operating on 240 volts.

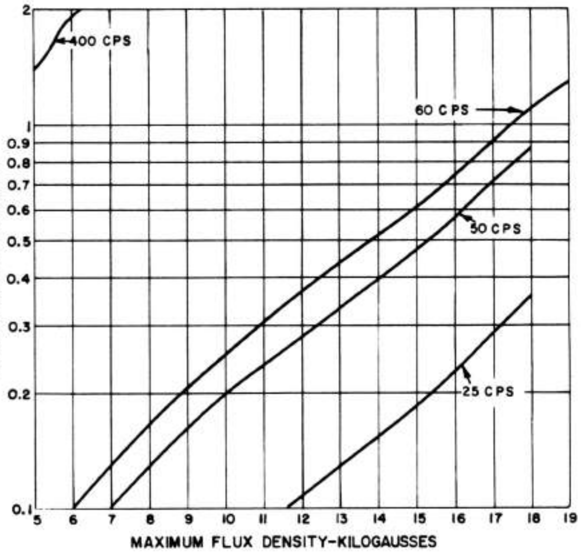
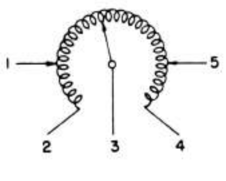


Figure 1.10.
Typical curves of core loss versus flux density for Variac autotransformer cores.

A unit designed for 14.5 kilogausses at 120 v, 60 cps, will operate at 14.5 (60/50) = 17.4 kilogausses at 120 v, 50 cps. The 60-cycle loss will be 0.56 watt per pound; the 50-cycle loss, 0.77 watt per pound. When 240-volt, 50- to 60-cycle units are operated at 120 volts, 25 cps, the flux density is the same as for 240-volt, 50-cycle operation; i.e. 17.4 kilogausses. The 25-cycle loss is 0.32 watt per pound. Since B_{max} decreases with increasing frequency, the losses actually go down, so that it is possible to reduce the core section for operation at frequencies between 350 and

TABLE 1.1
Varıac Autotransformer Constants.



*Terminal Connections

Variac Autotransformer Terminals Used*	2 - 5 or 1 - 4	2 - 4	2 - 5 or 1 - 4	2 - 4	2 - 5 or 1 - 4	2 - 4	2 - 5 or 1 - 4	2 - 4	2 - 5 or 1 - 4	2 - 4
Model	K (see text)		Z (ohms)		R (ohms)		L (henrys)		I_Z (amperes)	
W2	7.67	9.00	7650	10520	9000	12400	37.7	52.0	0.823	0.700
W5	7.67	9.00	4130	5700	4930	6800	20.5	28.2	1.52	1.29
W5H	15.34	18.00	16520	22800	19720	27200	82.0	112.8	0.76	0.65
W5L	—	7.15	—	3600	—	4300	—	17.8	—	2.04
W8	7.53	8.85	3370	4660	3950	5570	16.8	23.1	1.86	1.58
W8L	—	6.86	—	2780	—	3320	10.0	14.3	—	2.64
W10	7.93	9.32	2590	3560	3080	4240	12.9	17.8	2.48	2.21
W10H	15.86	18.64	10360	14240	12320	16960	51.5	71.0	1.24	1.11
W20	7.88	9.26	1570	2160	1860	2560	7.73	10.65	4.1	3.5
W20H	15.76	18.52	6280	8640	7440	10240	30.9	42.6	2.1	1.75
W30	7.87	9.25	2650	3630	3140	4330	13.1	18.0	2.39	2.03
W30H	15.74	18.50	10600	14520	12560	17320	52.4	72.0	1.20	1.02
W50	8.23	9.65	845	1165	1000	1380	4.1	5.65	6.66	5.67
W50H	17.25	22.40	3380	4650	4030	5550	22.40	36.0	4.20	3.05

1200 cps, as used in many military power supplies. This explains the "squat" design of the Series M autotransformer models. The reduction in core-section area permits a reduction in over-all size.

The parallel resistance, reactance, and impedance of Variac autotransformers can be derived from the curves of watts per pound and volt-amperes per pound versus flux density. Since all Series W models are wound on grade M6W core material or better, the performance for a given value of flux density per pound of core is the same for all models in this series. Figure 1.11 shows the variation of *R*, *Z*, and *L* versus B_{max}. A magnetization-current (I_Z) curve is also included. The maximum values of these factors for all Series W models are tabulated in Table 1.1.

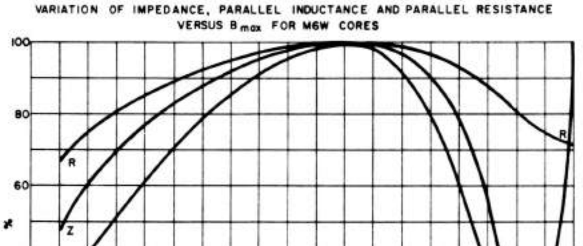


Figure 1.11.
Variation of impedance, parallel inductance, and parallel resistance versus B_{max} for M6W cores.

Figure 1.12 is the equivalent circuit showing a representation of the factors that are plotted in Figure 1.11. The series resistance of the winding is negligible for no-load data.

In order to use the table and the plot, first find the core magnetization by dividing the applied voltage (*E*) by the appropriate value of *K* from the table. Refer to the appropriate curve of Figure 1.11, at the value of B that is $\frac{E}{K}$. Read the percentage values of *R*, *L*, *Z*, and I_Z. Multiply the listed value in Table 1.1 by this percentage to obtain the correct value.

1.5 CURRENT RATINGS.

As already mentioned, the load current increase at the end of the winding cannot be infinity (the theoretical value), but is limited to 30 - 50% by brush and thermal limitations. Maximum current ratings are derived from this permissible increase. A constant-impedance load that draws maximum current at line voltage may be controlled downward to zero without exceeding a safe temperature rise. Rated current is based on the temperature rise at the mid-point brush setting. Rated current can be drawn at any brush setting; maximum current can be drawn only at or near line or zero voltage.

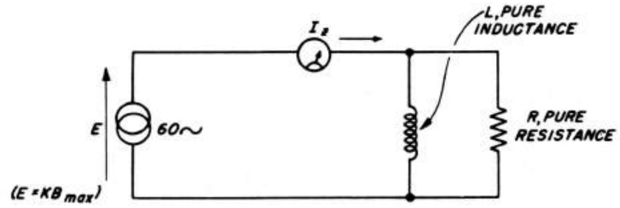


Figure 1.12.
Equivalent circuit of an unloaded Variac autotransformer.

1.6 CORE.

The laminated, toroidal core used in Variac autotransformers is formed by winding grain-oriented strip steel, much as one would spool ribbon. It is then given a carefully controlled heat treatment in a protective atmosphere to improve its magnetic properties. Because the flux paths are always parallel to the preferred longitudinal grain orientation, wound cores of this construction have inherently lower losses than cores formed from stacked washers stamped from sheet stock, in which the flux paths cannot everywhere parallel the grain of the material. Wound cores also permit closer packing of the magnetic material into the available space, with a corresponding gain in the stacking factor (ratio of useful magnetic material volume to total available volume). Full advantage of improved core material has been utilized in the design of Variac autotransformers. Today's more compact models use less core material and copper than earlier models because of the permissible increase in flux density.

1.7 WINDING.

1.7.1 GENERAL

The winding of a Variac autotransformer surrounds the core and is insulated from it. Most commonly, it is a toroid which permits rotary brush traverse, double-banked inside to conserve space, with a single layer outside for consecutive-turn brush access. Wire size is closely fixed by the current rating and the maximum allowable temperature rise. The wire used is always insulated. A very high grade of insulation is required to withstand high operating temperatures. Enough insulation and wire are removed from the brush track to offer an adequately large contact surface to the brush.

The number of turns in the winding is determined by the operating voltage, frequency, brush loss, required resolution, most favorable copper-to-core ratio, and wire size.

1.7.2 DURATRAK® CONTACT SURFACE[1]

All Variac autotransformers have the patented Duratrak contact surface, developed in the General Radio laboratories. Because of its superior conducrivity (exceeded only by silver) and reasonable price, copper is usually employed in transformer windings. Unfortunately, bare copper tends to oxidize when heated. Below 150 C, oxidation is gradual and is limited to a relatively thin, medium-conductivity film of cuprous oxide, which does no particular harm. Above 150 C, however, a thick, black, poorly conductive film of cupric oxide forms rapidly. The cupric film, interposed between brush and winding, causes severe heating under load, initiating a vicious cycle of more heat, more oxide, more heat, etc. Since Variac autotransformers are conservatively rated, it may be difficult to understand how an initial temperature of 150 C is reached, to start the cycle. Usual causes are unintentional overload, abnormal ambient temperature, or corrosion or contamination of the brush track. Once started, the cycle will continue until the unit is ruined, even if subsequent operation does not exceed rated current.

This difficulty is avoided by coating the brush track with a precious-metal alloy to produce the Duratrak contact surface. The coating resists oxidation and does not corrode easily. The contact resistance between brush and track is greatly influenced by the coating material, and optimum brush parameters will differ for different coatings if the optimum no-load-to-full-load brush-loss compromise is to be realized.

1.8 BRUSHES.

1.8.1 DESCRIPTION

Variac autotransformers use electrographitic brushes (contacts) to connect the load to the individual turns of the winding. Resistance characteristics, mechanical design, and thermal properties of the contact are most important for proper operation of the autotransformer.

The contact resistance between an electrographitic brush and a metallic surface varies with the current passing through the surface, and the resistance of the brush itself depends to a large degree on the current density. The resistance of the brush varies with the current passing through it in a manner that maintains a substantially constant voltage drop. This voltage drop varies with the composition of the brush and with the pressure applied, and is used by brush manufacturers in the rating of their product. A definite relation between this voltage drop and the volts-per-turn of the unit must be maintained to prevent excessive heating of the short-circuited turn and of the contact.

Variac autotransformer brushes do not "wear in" with use, so the current density and specific pressure can be varied within wide limits and can hardly be compared with the values recommended by carbon manufacturers for rotating-machine brushes. Each brush is positioned in a slot in a metal radiator; springs press the brush against the winding. The radiator absorbs about half the heat of the contact (primarily by conduction) and transmits it to the surrounding air. Electrical connections to brushes are made with flexible leads.

1.8.2 OPERATION OF THE BRUSH.

In traversing the track, the brush often bridges more than one turn. As the brush loses contact with one turn and makes contact with another, a voltage-dividing action occurs which allows the selection of voltage increments less than the voltage difference between turns. As a result, the resolution or incremental adjustment of a Variac autotransformer is actually better than would be indicated by the number of turns alone.

Figure 1.13a is a "picture diagram" of a brush as it bridges one turn; Figure 1.13b is the equivalent circuit diagram. R_1 and R_2 represent the brush-to-winding interface resistances. Experience shows that brush-to-body, brush-to-holder, and turn resistances are all negligible in a properly designed Variac autotransformer. The load current, I_L, is the algebraic sum

---

[1] U. S. Patent No. 2,949,592.

of the currents, I_1 and I_2, traversing R_1 and R_2, respectively; E_T is the voltage induced in the bridged turn. As the brush traverses the winding, R_1 and R_2 vary inversely as their respective areas of contact. We have seen that maximum loss, for a given brush and load current, occurs at the mid-point of the traverse, where $R_1 = R_2$. Furthermore, at this maximum-loss point, the loss will be a minimum when $R_1 = R_2 = \frac{E_T}{I_L}$. Under these conditions $I_L = I_1$, $I_2 = 0$ and brush-loss watts $= E_T \times I_L$. If the load current is reduced to zero, the bridging brush-loss watts $= \frac{E_T I_L}{2}$ The original variable-autotransformer patent, U. S. No. 2,009,013 to E. Karplus and W. N. Tuttle, of the General Radio Company, was issued on the basis of this analysis. To realize this optimum condition, it is important to control the brush track, brush composition, and brush pressure. For this reason, Variac autotransformers should never be operated with brushes other than those recommended for the particular model in question. Any attempt to use a substitute brush may result in a burned-out unit.

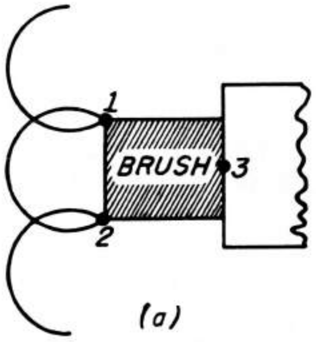


Figure 1.13.
a. One turn is bridged by the brush.

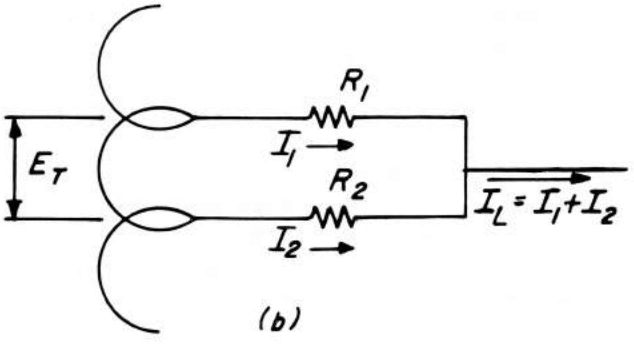


Figure 1.13.
b. Equivalent circuit of the Variac autotransformer brush.

1.9 REGULATION AND EFFICIENCY.

Regulation varies with brush setting. As noted under Section 1.3, copper loss is a function of setting. Expressed as an equivalent resistance traversed by the load current, copper loss is the dominant factor in the regulation curves of Figures 1.14 and 1.15. It will be noted that, at zero and line voltage settings, there is some inherent regulation attributable to the finite brush resistance. Regulation is due in part to leakage reactance caused by stray flux that does not link all the turns. While this is a minor factor at low frequencies, it becomes dominant at some higher frequency, and actually imposes an upper-frequency limit on the operation. This limit depends upon the load conditions.

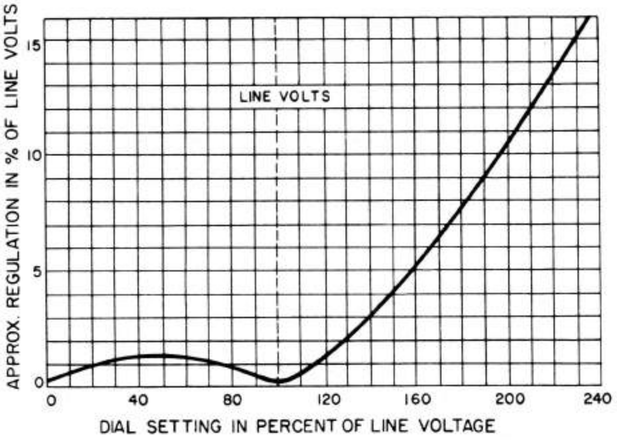


Figure 1.14.
Regulation curve for step-up connection at half normal rated current.

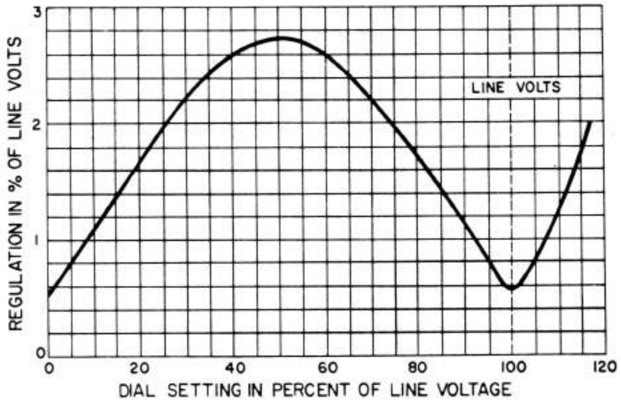


Figure 1.15.
Regulation curve with normal rated current.

Regulation is defined as the change in output voltage from no load to full load, with constant input; it is expressed as a percentage of the line voltage.

Efficiency is defined by the following equation, with all values expressed in watts:

$$\text{Percent efficiency} = \frac{\text{Output}}{\text{Output} + \text{Losses}} \times 100$$

$$= \frac{\text{Input} - \text{Losses}}{\text{Input}} \times 100$$

Since the output starts at zero at a zero setting, the efficiency starts at zero, rises rapidly with increasing setting, and then levels off, as line voltage is approached, at a value close to 99.5%. Losses are the sum of brush, copper, and core losses. Copper loss disappears at zero and line voltage, but it is dominant over most of the range.

1.10 LOADS.

Loads are subject to two types of control: The load function may be varied by altering the output voltage, or the load function may be stabilized by maintaining the output voltage at some desired value, independent of supply fluctuations. Not all loads are subject to successful control by voltage variation. Notable among these are single or polyphase induction motors that try to maintain a constant speed, despite reduced voltage, until the torque suddenly breaks down, resulting in a stall.

Figure 1.16 illustrates why a Variac autotransformer may be used with a constant-impedance load that draws maximum current at line voltage. Note that, as the voltage is reduced, the current is similarly reduced, and, at all points, is below the permissible current level. (The permissible current is limited over most of the range by the copper loss, which is maximum at the mid-point brush setting. Near line and zero voltages, however, the permissible current is limited by the brush loss. Refer to Sections 1.2 and 1.4.)

This is not true with a tungsten-lamp load. Here the current does not vary directly with line voltage, so the current-versus-voltage curve is above the permissible current level by a substantial amount. This leads to overheating, with subsequent insulation deterioration if operation is prolonged in the region between 26% and 82% of line voltage. For this reason, tungsten-lamp loads should be confined to the rated current of the Variac autotransformer.

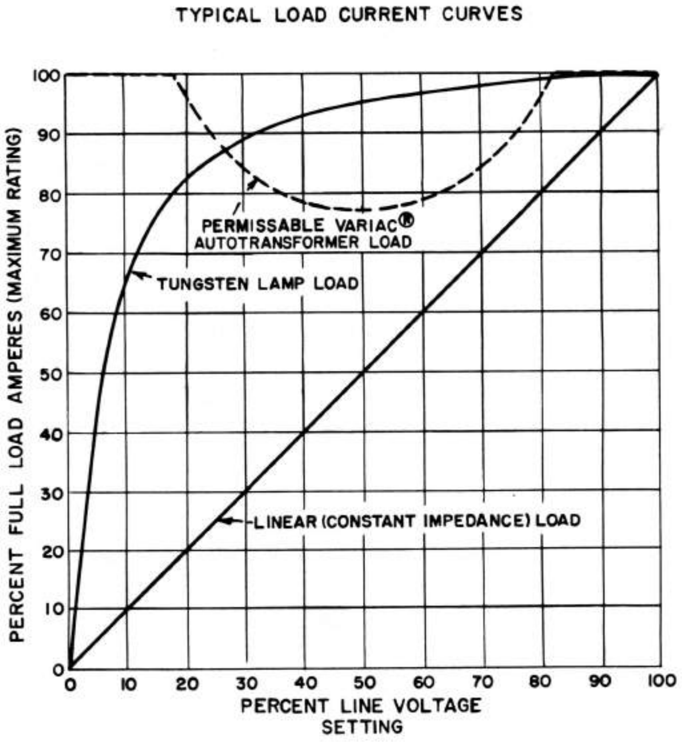


Figure 1.16.
Typical load current curves.

1.11 OVERLOAD PROTECTION–FUSES–CIRCUIT BREAKERS.

Today's improved core materials permit the use of higher flux densities than were formerly practical. Under certain conditions of core magnetization and line-voltage phase, an inrush transient or surge having an initial value up to ten times the rated current of the unit may occur. This does no harm except to ordinary "quick-blow" fuses. For this reason, time-current integrating circuit breakers or "slow-blow" fuses are recommended for primary protection. They will hold during transients, but will protect against sustained and potentially damaging overloads.

CAUTION

Under no circumstances should Variac autotransformers be operated above rated input voltage. Even though core losses and excitation figures are not exceeded, the higher voltage per turn will unduly increase brush losses and may result in damage to the winding.

Overload Protection for variable-ratio transformers differs from that used with fixed-ratio transformers, where safe primary and secondary currents are related by the ratio of secondary to primary turns. In a fixed-ratio transformer having 100 primary turns and 20 secondary-turns, if the safe secondary current is 10 amperes, the safe primary current will be $10 \times \frac{20}{100} = 2$ amperes. The transformer secondary wire will have 5 times the cross section of the primary wire. The amount of copper in each winding will be approximately the same. Equal protection will be provided by a 10-ampere secondary fuse or a 2-ampere primary fuse.

This is not true with Variac autotransformers. As the brush traverses the winding, the transformation ratio continually changes, without a corresponding change in wire size. The safe current over most of the ratio range is set by the wire size, not by the transformation ratio, and, with the exception noted under Section 1.3, cannot be appreciably exceeded. Under these conditions, primary protection is of little or no assistance, but output protection is all-important, since it is the output current that must be held within safe limits. For this reason a Variac autotransformer should be protected by a fuse or circuit breaker in the brush lead, where the load is normally connected.

Primary-circuit fusing may be added as a refinement to protect against accidental connection to a supply line of too high a voltage or too low a frequency. This can be particularly valuable with portable units that might be accidentally plugged into a direct-current line.

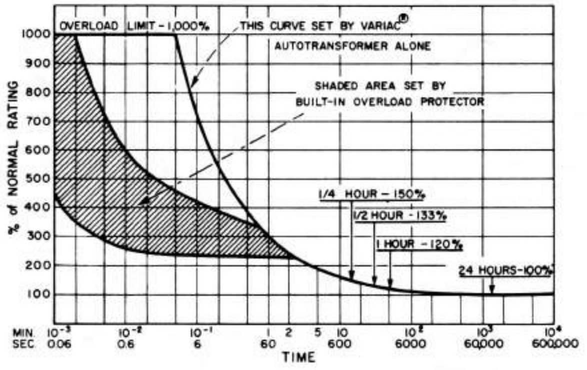


Figure 1.17.
Short-time overload characteristic of Variac autotransformers with line-voltage connection.

The nature of the protective devices should be partially determined by the service requirements. Variac autotransformers have an inherently high short-time overload capacity, since temperature is dependent upon time for a given rise. Figure 1.17 illustrates the short-time overload characteristics of units containing Duratrak. They can safely absorb relatively infrequent overloads (due to motor starting or lamp inrush) without derating. The upper curve applies to units without built-in fuse protection. Models with built-in protection in the brush arm (Models W5L, W20H, W30, W30H, W50, and W50H) have overload characteristics corresponding to the shaded area on the curve. This fusible link is purposely made inaccessible to guard against careless replacement with fuses of the wrong value and it is not intended to serve as the sole protective device for the unit. The shaded portion shown indicates the area of uncertainty due to fuse tolerance (+20%, -0%) and the fact that larger-value fuses, due to their greater thermal inertia, tend to hold longer against a given percentage of over-load. The lower limit of the shaded area applies to a Type W5L model with a zero-tolerance fuse, and the upper limit applies to a Type W50 model with a +20%-tolerance fuse.

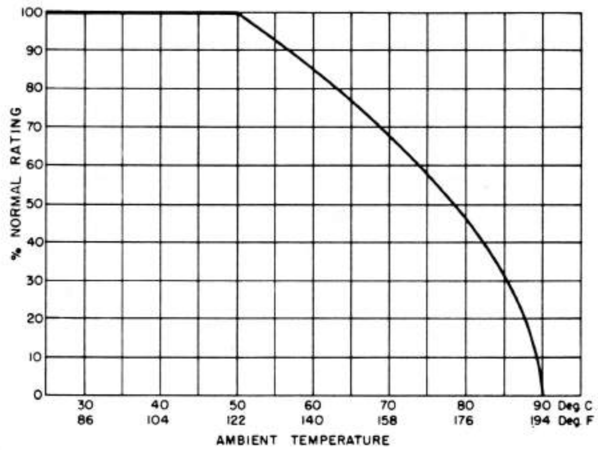


Figure 1.18.
Variac autotransformer derating versus ambient temperature.

To benefit fully from the short-term overload characteristic, the overload capacity must not be unduly limited by the protective device. Since quick-blow fuses (already discussed as unsuitable for primary protection, under Section 1.2) cannot withstand surges, their use is discouraged except for loads not subject to inrush. Slow-blow fuses are better; time-current integrating circuit breakers are better still. Thermal breakers are to be preferred, since they automatically derate with increasing ambient temperature. They most nearly conform to the requirements of Figure 1.18, which shows derating versus ambient temperature. This type of protector is standard in the Type MT (portable, cased) models of the W series Variac autotransformers. When operation is intermittent, a further increase in rating is permissible, depending upon the duty-cycle ratio. If the total number of duty cycles comprises only relatively short operating periods, the current can be further increased to that determined by the short-time rating factor shown in Figure 1.17.

1.12 EFFECT OF DUTY CYCLE.

When duty-cycle operation is continuous, the rating should be determined in the following manner: If the duty-cycle ratio is defined as the ratio of "off-plus-on" time to "on" time, the rated current can be multiplied by the square root of this ratio to obtain the allowable uprated current. The following examples will illustrate the calculation of permissible overloads for the Type W5 model, whose current is 6 amperes.

Example 1.

(a) Duty cycle: 15 seconds on, out of every 4 minutes (240 seconds).

$$\sqrt{\text{duty-cycle ratio}} = \sqrt{\frac{240}{15}} = 4$$

Up-rated current = 6 x 4 = 24 amperes.

(b) 15-second short-time overload (Figure 1.17*) = 500% = 30 amperes.

Since the duty-cycle calculation gives the smaller value, the permissible current is 24 amperes.

Example 2.

(a) Duty cycle: 30 seconds on, 8 minutes off.

$$\sqrt{\text{duty-cycle ratio}} = \sqrt{\frac{510}{30}} = 4.1$$

Up-rated current = 4.1 x 6 = 24.6 amperes.

(b) 30-second short-time overload from Figure 1.17 = 380% = 22.8 amperes. This figure is the limiting value, because it is lower than that calculated from the duty-cycle ratio. Therefore the permissible current is 22.8 amperes.

Example 3.

(a) Duty cycle: 6 seconds on, each minute; repeated for one-half hour, maximum.

$$\sqrt{\text{duty-cycle ratio}} = \sqrt{\frac{60}{6}} = 3.16$$

Short-time rating (Figure 1.17) for 30 minutes = 133%.

Up-rated current = 6 x 3.16 x 1.33 = 24.6 amperes.

(b) 6-second short-time overload (Figure 1.17) = 725% = 42.7 amperes.

Permissible current is 24.6 amperes.

1.13 RATINGS FOR SPECIAL CASES.

The organic insulation used in Variac autotransformers has a life-expectancy versus operating-temperature characteristic that may be closely approximated by a straight-line plot on log-log, time-temperature coordinates (see Figure 1.19). Notice that life expectancy is halved for each ten degrees Centigrade increase in temperature, and, conversely, it is doubled for each ten degrees decrease. The ten-degree interval is approximately correct for Variac autotransformer insulations; other insulations, such as the silicone organics, may have steeper curves of 7 or 8 degrees for a life factor of two-to-one. The curve has been purposely extended to the 7-hour, 265-degree point which is specified in the Underwriters' Laboratories, Inc., for the three-times-rated-current "burn-out" test.

The operating temperature in Figure 1.19 is the absolute hot-spot temperature, which is the sum of the ambient (environmental) temperature and the temperature rise resulting from losses. This hot-spot temperature usually occurs directly under the brush in Variac autotransformers.

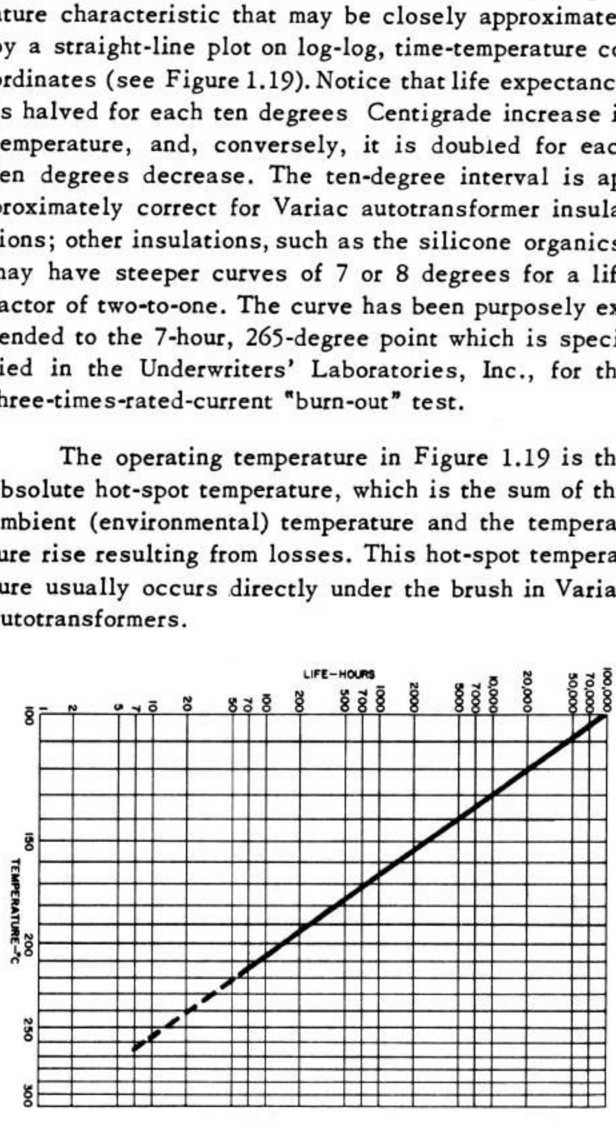


Figure 1.19.
Insulation life versus temperature.

---

*For models with built-in fuses, use the lower curve in Figure 1.17 for autotransformer and fuse.

The losses in an autotransformer include core loss (constant for a given voltage and frequency), copper loss (varies as the square of the load current), and brush loss (although not closely predictable, seems to vary as the three-halves power of the load current). Under steady-state conditions, these losses produce a temperature rise sufficient to dissipate the power loss by conduction, convection, and radiation. Since the ambient temperature is not subject to the designer's control, he must assume some arbitary, "normal," maximum temperature and design the unit for a temperature rise that will not exceed his hot-spot limit at this ambient. Variac autotransformers are designed for a minimum hot-spot temperature that will allow a minimum life of seven years with continuous operation, under full load, with maximum-loss brush setting, in a 50 C ambient. A change in any one of these conditions will change one, several, or all of the other conditions.

Certain of these changes were discussed in Section 1.12 which deals with uprating for short-term or intermittent duty-cycle operation, and with derating for ambient increases above 50 C. The derating curve of Figure 1.18 could be continued above the rating for ambients below 50 C. It is, however, both conventional and convenient to establish a fixed rating, here based on 50 C maximum ambient. Also, full-load operation is possible above a 50 C ambient if reduced life is acceptable, or below 50 C if increased life is desirable.

The minimum life-rating-ambient relationship is given in Figure 1.20 (an extension of Figure 1.18 plus the information yielded by Figure 1.19). To obtain the rated curve, the following equation was used:

$$T\,^\circ C = \underset{\textit{Core}}{15^\circ} + \underset{\textit{Copper}}{25^\circ \times (I/I_R)^2} + \underset{\textit{Brush}}{15^\circ \times (I/I_R)^{\frac{3}{2}}} \qquad (23)$$

For a minimum seven-year life, the hot-spot temperature is:

$$105\,^\circ C = \underset{\textit{Ambient}}{50^\circ} + \underset{\textit{Core}}{15^\circ} + \underset{\textit{Copper}}{25^\circ} + \underset{\textit{Brush}}{15^\circ} \qquad (24)$$

Knowing this, it is a simple matter to assign life-ambient scales to the load curve. If the 61,320 hours in 7 years is rounded off to 64,000 hours, the departure in degrees C from the "normal" curve is given by:

$$T\,^\circ C = \log_2 \frac{64{,}000}{\textit{Hours Specified}} \times 10\,^\circ C$$

$$= \log_2 \frac{7}{\textit{Years Specified}} \times 10\,^\circ C \qquad (25)$$

If the number of specified hours or years exceeds 64,000 or 7, respectively, T is negative; if not, T is positive.

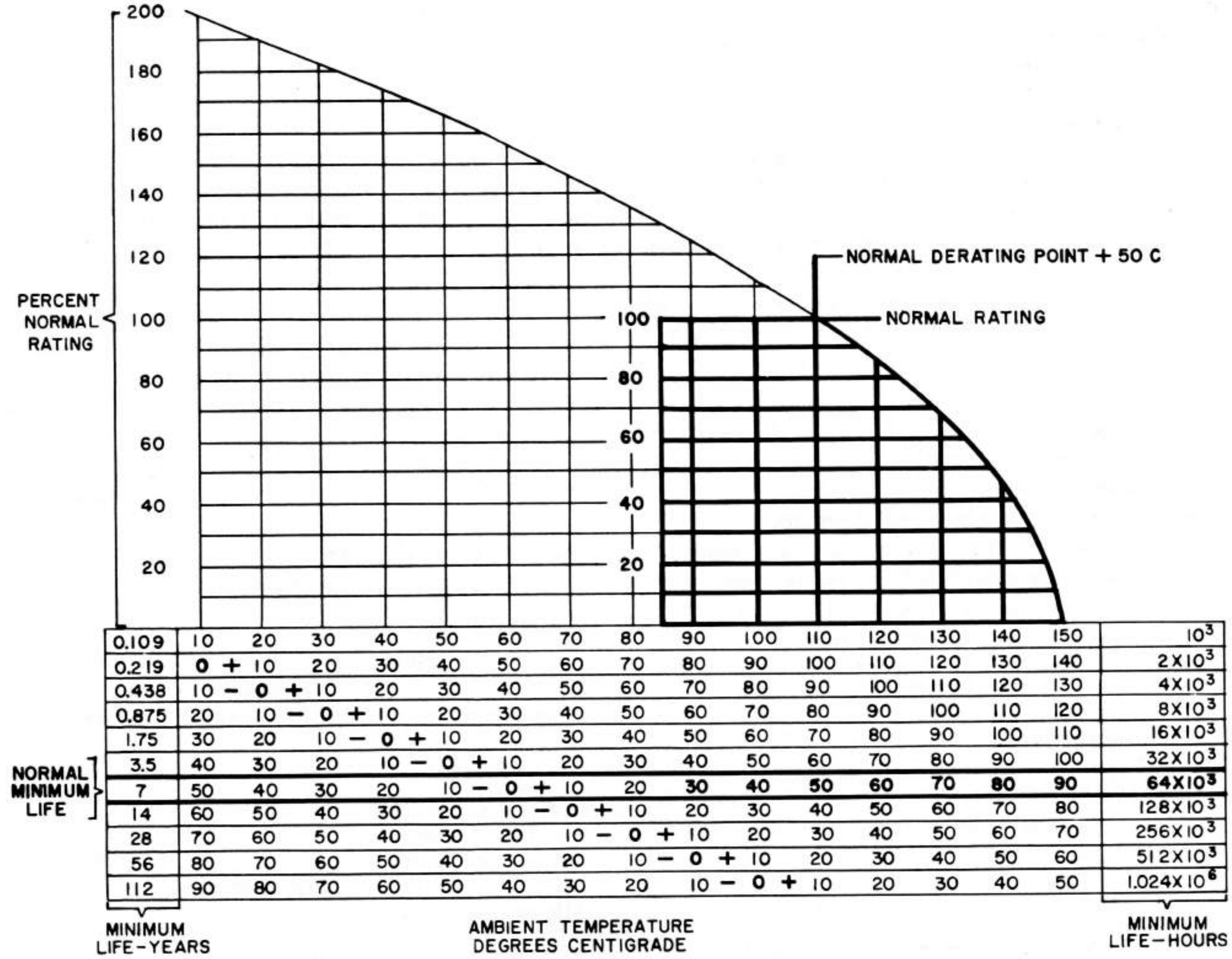
Except for reference to Section 1.12, we have been concerned primarily with steady-state, twenty-four-hour-a-day operation. It should be realized that the short-term overload curve and the duty-cycle formula are also based on a 105 C hot-spot. Here, too, minimum life may be traded for increased rating or vice-versa. Simply apply the "life-rating-ambient" curve to these problems and uprate or derate as indicated, except that the limit of ten times rated current should never, under any circumstances, be exceeded.

For example, consider the Type W5 unit in Example 1, Section 1.12, in this case further modified by requirements of a 4000-hour minimum life, at a 30 C ambient temperature.

Uprating for 30 C ambient, 4000-hour life (Figure 1.20) = 1.65
Duty-cycle factor = 4
Resultant uprating factor (product of above) = 6.60
Allowable current = 6 x 6.60 = 39.6 amp

Uprating for 30 C and 4000-hour life (Figure 1.20) = 1.65
15-second short-term overload factor (Figure 1.17) = 5
Resultant uprating factor (product of above) = 8.25
Allowable current = 6 x 8.25 = 49.5 amp

Since 39.6 is the smaller, it is the limiting value, and the allowable current is 39.6 amperes.



MINIMUM LIFE–YEARS	AMBIENT TEMPERATURE DEGREES CENTIGRADE															MINIMUM LIFE–HOURS
0.109	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	10^3
0.219	0 +	10	20	30	40	50	60	70	80	90	100	110	120	130	140	2×10^3
0.438	10	– 0 +	10	20	30	40	50	60	70	80	90	100	110	120	130	4×10^3
0.875	20	10	– 0 +	10	20	30	40	50	60	70	80	90	100	110	120	8×10^3
1.75	30	20	10	– 0 +	10	20	30	40	50	60	70	80	90	100	110	16×10^3
3.5	40	30	20	10	– 0 +	10	20	30	40	50	60	70	80	90	100	32×10^3
7	50	40	30	20	10	– 0 +	10	20	**30**	**40**	**50**	**60**	**70**	**80**	**90**	$\mathbf{64 \times 10^3}$
14	60	50	40	30	20	10	– 0 +	10	20	30	40	50	60	70	80	128×10^3
28	70	60	50	40	30	20	10	– 0 +	10	20	30	40	50	60	70	256×10^3
56	80	70	60	50	40	30	20	10	– 0 +	10	20	30	40	50	60	512×10^3
112	90	80	70	60	50	40	30	20	10	– 0 +	10	20	30	40	50	1.024×10^6

Figure 1.20. Life-load-ambient curve.

SECTION **2**

CIRCUITS

2.1 BASIC CIRCUITS.

Variac autotransformer circuits are almost as numerous as the people who use them. As previously noted, it is both impractical and impossible to include them all. The following circuits are those with the most widespread and basic utility.

The circuit in Figure 2.1, called the line-voltage connection, is used for the control of a load between zero and line voltage. Points a, b, and c are protective locations, in order of importance. Load protection, at point b, or points b and c, is optional. Off-on switching, if used, should break both sides of the line (b and c), positively disconnecting both the autotransformer and the load from dangerous potentials. Except as noted, the same switch and load locations apply to all other circuits.

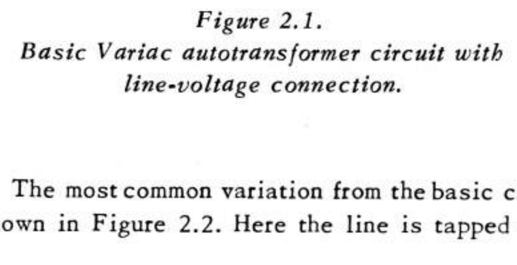


Figure 2.1.
Basic Variac autotransformer circuit with line-voltage connection.

The most common variation from the basic circuit is shown in Figure 2.2. Here the line is tapped down on the coil, allowing the brush to traverse above line voltage by virtue of transformer action. This is called the over-voltage connection. The step-up may be small (17%), as with an output of 140 volts from a 120-volt source, or large (133%) for an output of 0 to 280 volts from a 120-volt source. In the former case, rated current can be drawn at any setting; in the latter, output is limited to one-half rated current.

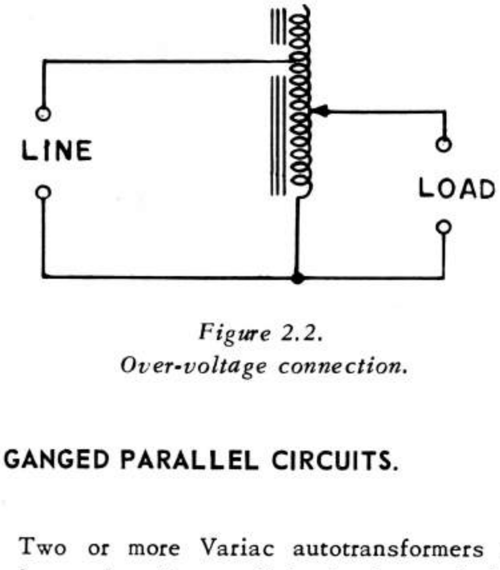


Figure 2.2.
Over-voltage connection.

2.2 GANGED PARALLEL CIRCUITS.

Two or more Variac autotransformers can be ganged together for parallel circuits and then can supply a single-phase load greater than a single unit can accomodate. The load rating of two identical units in parallel is twice that of a single unit; for three in parallel, it is three times that of a single unit. Parallel operation is usually recommended only for the large models (Type W20, W30, or W50), because it is more economical to handle any load within the capacity of a single unit with a single unit, rather than by the use of ganged, smaller models.

Figures 2.3 and 2.4 show two- and three-gang parallel assemblies, respectively. A four-gang, series-parallel combination is illustrated in Figure 2.5. The Type 50-P1 Chokes in these circuits are used to prevent high interchange currents between the parallel-connected units. (Refer to paragraph 2.3.)

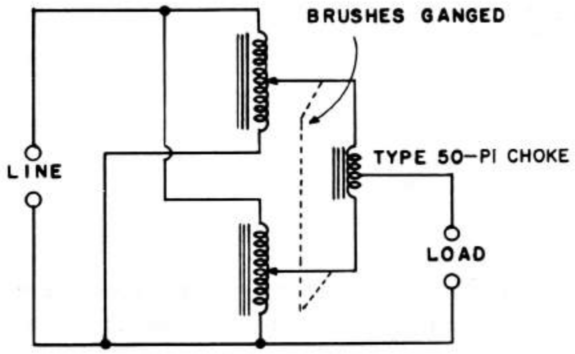


Figure 2.3.
Ganged assembly, two units in parallel.

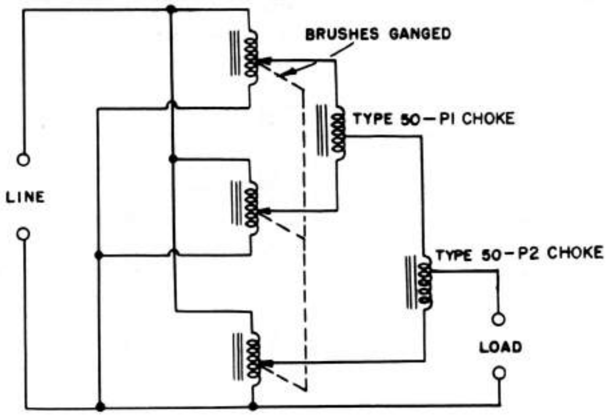


Figure 2.4.
Ganged assembly, three units in parallel.

2.3 USE OF CHOKES IN PARALLEL CIRCUITS.

Two or more parallel Variac autotransformers, the brushes of which are slightly out of step, will normally exchange a large circulating current. To prevent this, one or more fixed autotransformers (chokes) are used. Consider Figure 2.6, which shows two units with their brushes connected to the ends of a center-tapped autotransformer (Type 50-P1 Choke). Any small difference in the brush voltages will appear across the choke. As long as this voltage does not exceed a value that approaches saturation of the choke core, the current exchanged between the two Variac autotransformers is limited to the magnetizing current of the choke. This is the only unbalanced component that can be present. Also I_1 and I_2 traverse equal turns in opposite sense. Therefore I_1 and I_2 must be equal and the two units are loaded equally except for this negligible magnetizing current of the choke.

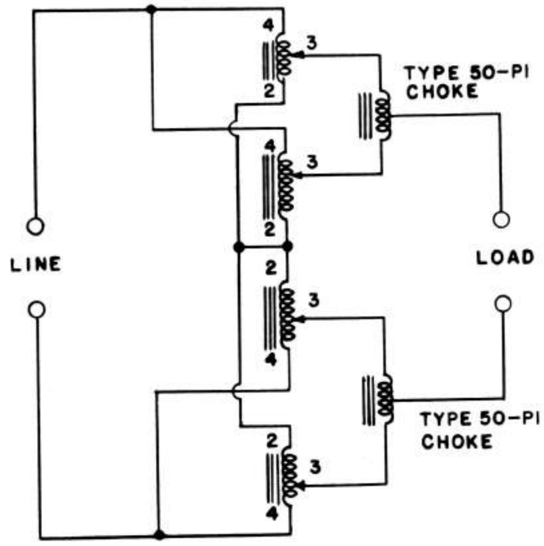


Figure 2.5.
Four-gang, series-parallel combination.

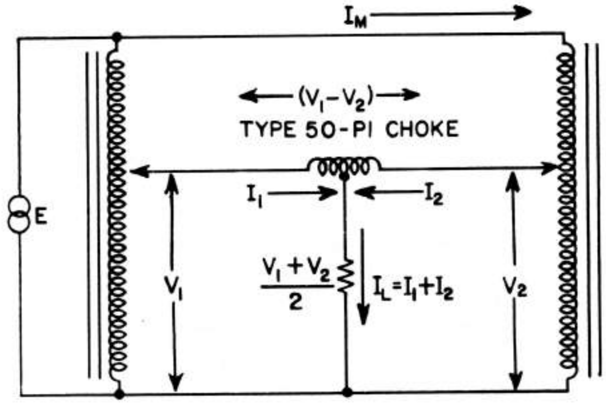


Figure 2.6.
Choke limits circulating current.

Similarly, when two Variac autotransformers are to be paralleled with a single, third unit, a choke tapped at one-third of the winding is used. The current from the single unit traverses two-thirds of the choke winding, and that from the two units traverses one-third only. Again the ampere-turns relationship is satisfied. (Of course, in this case the two units are, in turn, paralleled through a center-tapped choke, as in Figure 2.6.)

This principle can be extended to a greater number of units. For instance, three Variac autotransformers can be paralleled with two, using a choke with a two-fifths tap, etc.

The use of three Type 50-P1 Chokes with a six-gang assembly in a three-phase circuit is shown in Figure 2.7.

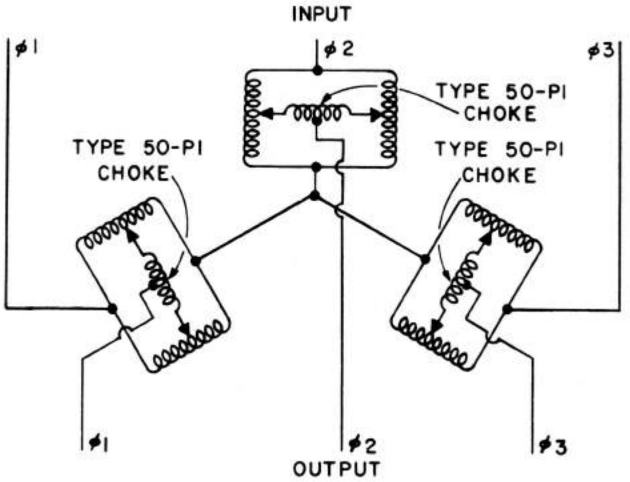


Figure 2.7.
Connection for a six-gang assembly in a three-phase circuit.

2.4 GANGED SERIES CIRCUITS.

Figure 2.8 shows the basic circuit for the series connection. The two brushes move simultaneously toward or away from the line terminals of the units. The currents as shown satisfy the no-net-ampere-turns requirement for both units. However, the load is "floating" on the brushes, and therefore it cannot be grounded. The modified circuit of Figure 2.9 shows a single-phase, three-wire system such as the conventional residential supply, with the neutral lead shown dotted. When all elements and settings in branch 1 are equal to those in branch 2, no current will flow in the neutral line and it can be removed to produce the circuit of Figure 2.8.

CAUTION

Occasionally an attempt is made to use two units connected as shown in Figure 2.10. Note that the I_S circuit includes unit #2. Since the two autotransformers do not have a common core, I_S cannot circulate through unit #2 except by setting up a tremendous current in the turn or turns which are shorted by the brush in unit #1. This, of course, results in a burned-out unit. Therefore, the circuit of Figure 2.10 should never be used.

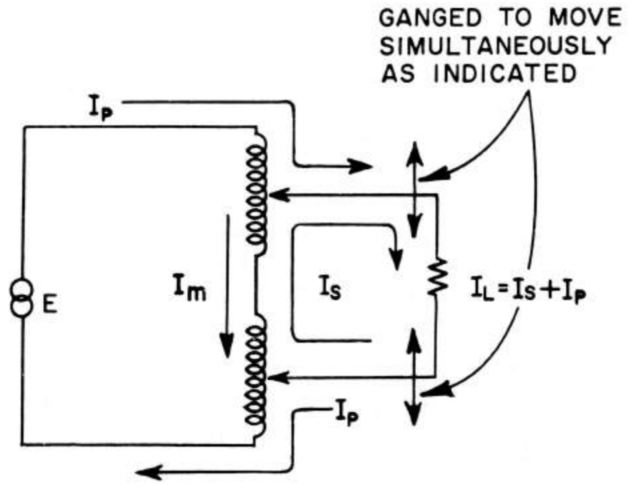


Figure 2.8.
Basic circuit for two-gang connection.

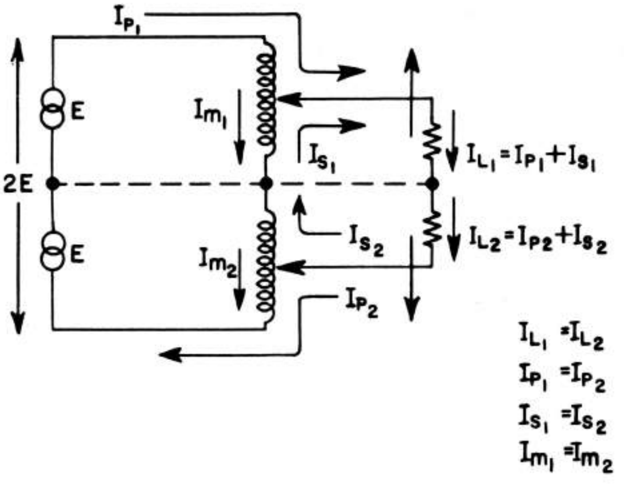


Figure 2.9.
Connections for a single-phase, three-wire system.

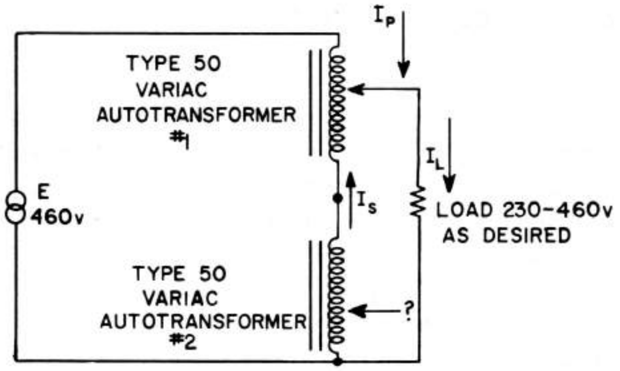


Figure 2.10.
DON'T DO THIS!

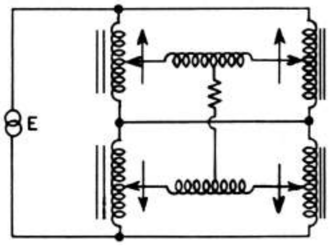


Figure 2.11.
Series-parallel connection.

Any number of units can be series-parallel connected, as indicated in Figure 2.11, if there are never more than two equal, parallel groups in series. However, the fundamental ampere-turns relationship must be kept in mind. Figure 2.12 is an example of the improper extension of this principle. The secondary component of current, I_S, cannot circulate through the middle unit without causing one or both of the other units to burn out. The use of a fixed autotransformer to supply the Variac autotransformer eliminates the trouble, as shown in Figure 2.13. The value of a can vary between a minimum of 1/3 and a maximum of 1.

$$b = \frac{3}{2}\left(a - \frac{1}{3}\right)$$

$$1 - b = \frac{3}{2}(1 - a)$$

$$a - b = \frac{1}{2}(1 - a) = \frac{1}{3}(1 - b)$$

$$(1 - b)\, I_L = 2\,(a - b)\, I_L + (a - b)\, I_L$$

$$(1\text{-}b)\, I_L = \frac{3}{2}(1\text{-}a)\, I_L = 2 \times \frac{1}{2}(1\text{-}a)\, I_L + \frac{1}{2}(1\text{-}a)\, I_L$$

$$(1 - b)\, I_L = \frac{3}{2}(1 - a)\, I_L$$

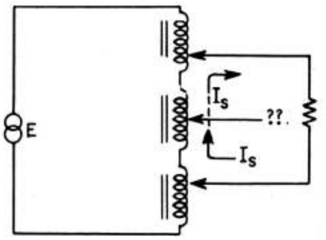


Figure 2.12.
DON'T DO THIS EITHER!
(See Figure 2.13)

Thus all the current relationships are satisfied for both the fixed and the Variac autotransformers. The volt-ampere rating of the fixed unit is determined by the maximum value of

$$\frac{E}{3} \times 2\,(a - b)\, I_L = \frac{E}{3}(1 - a)\, I_L = VA_F$$

and occurs when the value of a is at its minimum, or $\frac{1}{3}$. Then

$$VA_{F max} = \frac{EI_L}{3}\left(\frac{2}{3}\right) = \frac{2}{9}\, EI_L \tag{26}$$

The rating for each Variac autotransformer is

$$VA_{V max} = \frac{E}{3} I_L = \frac{EI_L}{3} \tag{27}$$

and the total volt-ampere requirements for the circuit are

$$\Sigma\, VA = \frac{2}{9}\, EI_L + 2\left(\frac{EI_L}{3}\right) = \frac{8}{9} EI_L \tag{28}$$

However, the total volt-ampere rating is EI_L. The

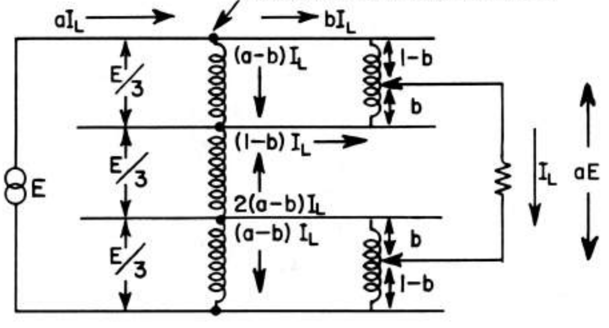


Figure 2.13.
The addition of a fixed autotransformer eliminates the trouble with the circuit of Figure 2.12.

difference of $\frac{1}{9} EI_L$ is due to the fact that control extends over only two-thirds of the E range.

Figure 2.14 details an extension of the series connection principle. As shown, two separate, equal loads must be used. These can be two primaries of a transformer (as indicated by the dotted lines) which then connect to the load as a single unit through the transformer secondary. Note that the transformer is not connected between E and the Variac autotransformers, as in the conventional circuit. This is because it is often desirable to feed a transformer, such as a high- or low-voltage rectifier, which has two appropriate primaries. The circuit of Figure 2.14 eliminates the need of a second transformer.

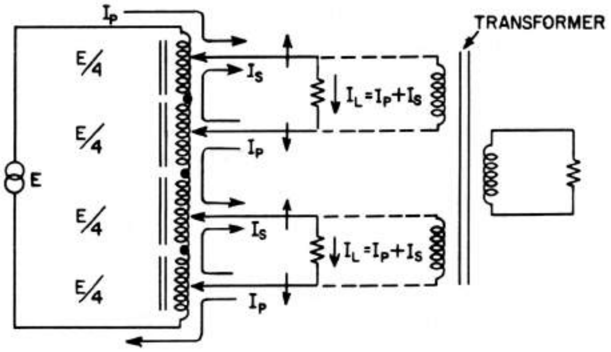


Figure 2.14.
Use of the series connection with two separate, equal loads.

Variac autotransformers may be connected for overvoltage (as shown in Figure 2.15; also see Figure 2.2), or for line voltage (Figure 2.9). Because 120-volt models usually carry a higher kva rating than comparable 240-volt units, and because no choke is required, this circuit usually yields more rating per dollar than paralleled 240-volt units for 240-volt service. Two 240-volt units can be series connected for 480-volt service. Note, however, that the load cannot be grounded with this circuit, because there is no common line connection between input and output.

2.5 NARROW-RANGE LOW-VOLTAGE ADJUSTMENT CIRCUITS.

The Variac autotransformer is inherently a wide-range device. If the required range of voltage adjustment is narrow, it can most effectively be used with a supplementary transformer having a ratio determined by the ratio of the normal Variac autotransformer range to the required range of adjustment. In this way the whole traverse is used to effect the necessary adjustment, improving resolution and multiplying the available current by the transformation ratio of the supplementary transformer. Such narrow range operation generally falls into one of two classifications: low-voltage, as for tube heaters or plating rectifiers, or high-voltage, as for line-voltage regulation.

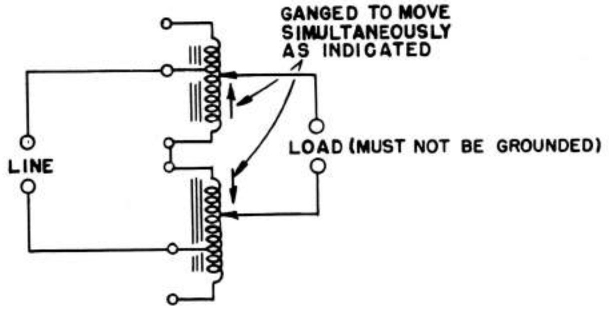


Figure 2.15.
Two-gang series connection with overvoltage.

In the low-voltage case, either an isolation transformer, or a fixed-ratio autotransformer can be used, as shown in Figure 2.16, a and b. It is interesting to note that the supplementary transformer in

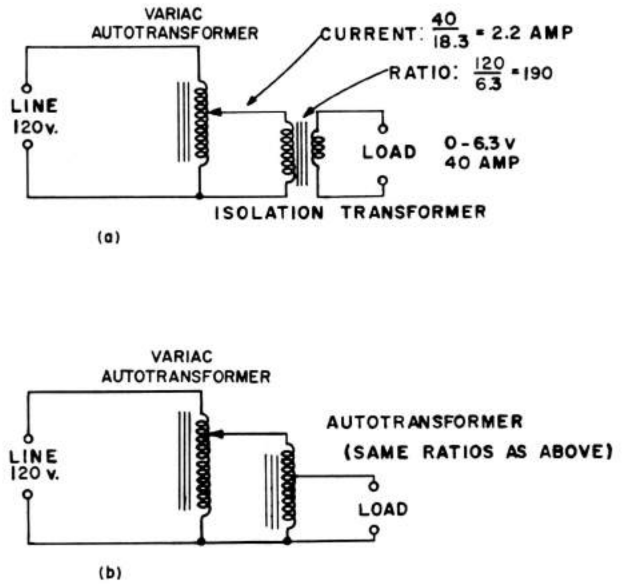


Figure 2.16a. and b.
Low-voltage, narrow-range, adjustment circuit.

both of these cases allows the use of a unit of about 1/20th the rating that would be required where the load operated directly from the Variac autotransformer. Furthermore, the resolution or fineness of adjustment is greatly improved by two factors—the control range is spread over the whole traverse, and the smaller unit has more turns per volt.

2.6 LINE-VOLTAGE ADJUSTMENT CIRCUITS.

The use of supplementary transformers for line-voltage adjustment may take several circuit variants. Figure 2.17 shows a simple circuit for line-voltage adjustment purposes. Depending upon the position of the reversing switch, the circuit will either buck or boost the line voltage. The design of this buck-or-boost circuit can best be shown in the solution of a typical problem:

Problem: What size transformer is necessary to handle a 50-ampere load when the line voltage varies from 96 to 120 volts?

Solution: 120
-96
24 volts

24/120 = 1/5 = turns ratio of transformer

The rating is determined by the load current and the turns ratio of the transformer:

50 amperes x 1/5 = 10 amperes.

Hence, the primary rating of the transformer is 120 volts at 10 amperes. The secondary voltage is 120 x 1/5 or 24 volts and the secondary current is 10 x 5 or 50 amperes.

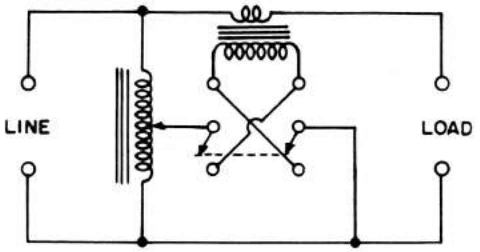


Figure 2.17.
Buck or boost line-voltage adjustment circuit.

Where the regulated line is always high or always low, an autotransformer may also be used, as shown in Figures 2.18, a and 2.18, b. In the step-down case, the transformation ratio allows a 6-ampere unit to control a load of 6 x 13 x 120 = 9.4 KVA; in the step-up case, 6 x 11 x 120 = 7.9 KVA.

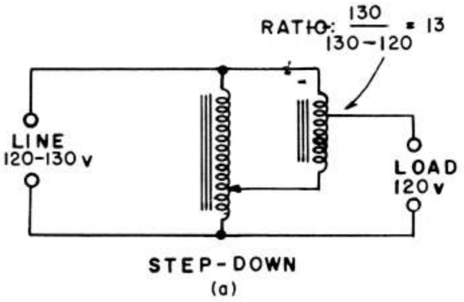


Figure 2.18a.
Step-down circuit for high line voltage.

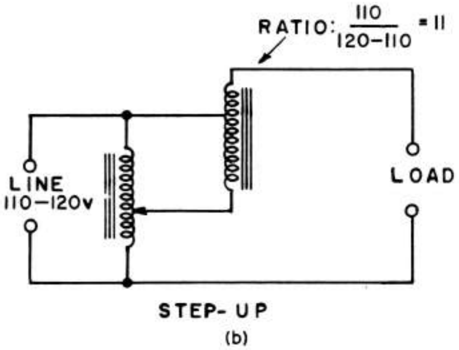


Figure 2.18b.
Step-up circuit for low line voltage.

Where buck-and-boost regulation is required, the circuit becomes the one shown in Figure 2.19. Here the ratio is reduced because the buck-boost connection

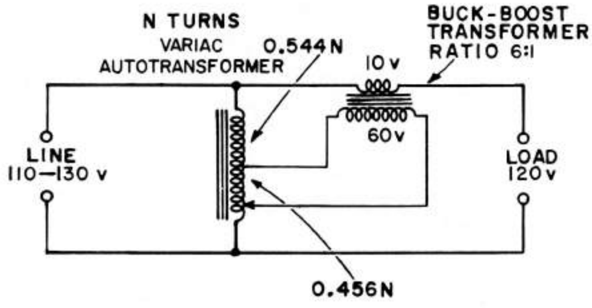


Figure 2.19.
Buck-boost circuit for line-voltage adjustment.

requires a tap on the autotransformer. The tap location (tapped units can be furnished on special order) is determined by the condition that the turns times the line voltage should be equal for the two conditions of maximum buck or boost. However, as shown, there is a current gain of 6 to 1, which means a 6-ampere unit can control a 6 x 6 x 120 = 4.3-KVA load.

Other variations of this scheme are possible. In Figure 2.20 the unit is connected to primary taps on, say, a plate supply transformer. The brush is moved up to compensate for high line voltage and down for low line voltage. The input current must conform to the unit current rating.

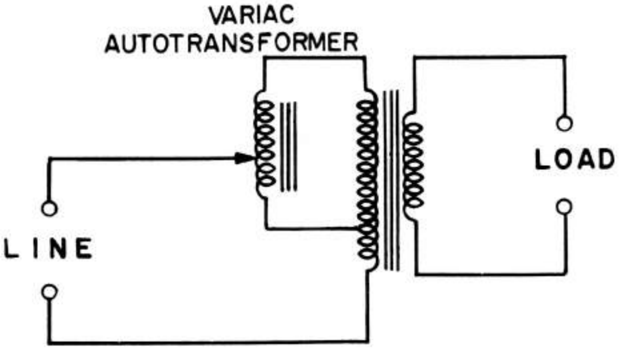


Figure 2.20.
Primary circuit compensation for line-voltage adjustment.

Where the line and load voltages are vastly dissimilar from the operating voltage, a Variac unit or assembly may be inserted between transformers as shown in Figure 2.21. The transformers may be either isolation transformers, as shown, or autotransformers.

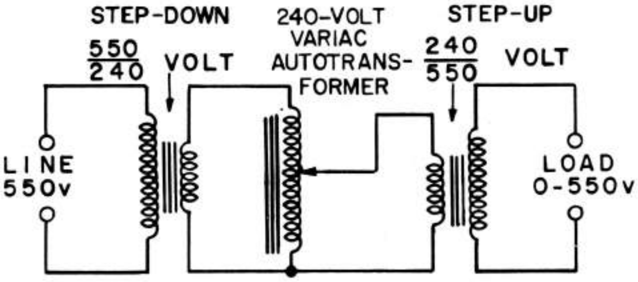


Figure 2.21.
Line-voltage adjustment circuit when line and load voltages are beyond the range of the Variac autotransformer.

There is, of course, no current gain in this case. In fact, current rating of the Variac autotransformers must be $\frac{55}{24}$ of the load current requirement.

Still another variation is shown in Figure 2.22. Note that a 110-volt unit controls a 550-volt load in this case. The KVA rating is 6 x 110 x 5 = 3.3 KVA. The disadvantage lies in the need for switching, which introduces a discontinuity between sections.

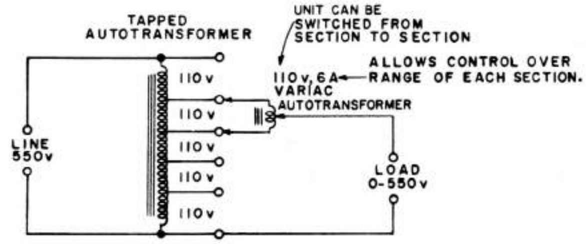


Figure 2.22.
A tap-switching circuit for line-voltage adjustment.

Two Variac autotransformers can be combined with a supplementary transformer to give a coarse/fine control as shown in Figure 2.23. The 2-ampere model and supplementary transformer make an effective vernier adjustment.

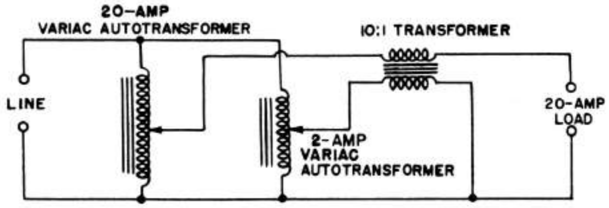


Figure 2.23.
Line-voltage adjustment with a coarse/fine control.

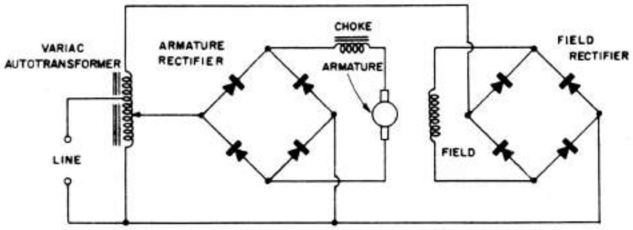


Figure 2.24.
Basic circuit of Variac autotransformer motor speed control.

Often the Variac autotransformer is used as both a fixed and variable transformer at the same time. Figure 2.24 shows the basic circuit in the General Radio Speed Controls. Here the step-up ratio of the Variac autotransformer is used to secure high excitation for the field.

2.7 CONSTANT-IMPEDANCE LOADS.

We have been concerned to this point only with constant-current (or substantially so) circuits. In practice, most loads have a constant impedance and draw a current that is proportional to the applied voltage. (Some notorious non-linear exceptions are incandescent lamps, "Globar" heating elements, and dc rectifier-motor combinations.) The constant-impedance load readily lends itself to a straightforward mathematical analysis.

Again refer to Figure 1.5. Let $I_L = a\, I_{max}$. Then

$$I_P = a I_L = a^2 I_{max}$$

and $I_S = (1 - a)\, I_L = (a - a^2)\, I_{max}$

The copper loss $= \Sigma W = I_P^2 (1 - a) R + I_S^2\ a R$

$$= a^4 I_{max}^2 (1 - a) R + (a - a^2)^2 I_{max}^2\, a R$$

$$= I_{max}^2 R\, (a^3 - a^4)$$

$$\frac{d}{da}(a^3 - a^4) = 3a^2 - 4a^3 = 0$$

$$a = \frac{3}{4}$$

$$Max\ \Sigma W = I_{max}^2 R \left(\frac{27}{64} - \frac{81}{256}\right) = \frac{27}{256} I_{max}^2 R$$

To determine the value of I_{max} that can be regulated to zero without crossing the I_L curve of Figure 1.6, locate the point of tangency of the straight line with the curve. This, naturally, occurs where the two values are equal, as are the two slopes. Let the constant-impedance current be $I_{ZC} = a\, I_{max}$.

$$I_L = \frac{I_R}{2\sqrt{a - a^2}} = I_{ZC}$$

$$I_{max} = \frac{I_R}{2a\sqrt{a - a^2}}$$

$$\frac{d}{da} I_{ZC} = \frac{d}{da}\, a\, I_{max} = I_{max}$$

$$\frac{d}{da} I_L = \frac{I_R}{2}\, \frac{1}{\left(a - a^2\right)^{\frac{3}{2}}} \left(-\frac{1}{2}\right)(1 - 2a)$$

$$I_{max} = \frac{I_R}{2a\left(a - a^2\right)^{\frac{1}{2}}} = \frac{1 - 2a}{2\,(a - a^2)}$$

Then $2a - 2a^2 = 2a^2 - a$

$$a = \frac{3}{4}$$

and $I_{max} = I_R \left(\frac{1}{1.5\sqrt{3/4 - 9/16}}\right) = 1.54\ I_R$

This is shown in Figure 2.25. Also note that a constant-impedance load which draws respectively 1.5 and 1.3 times the rated current will fall below the permissible current curve, I_L.

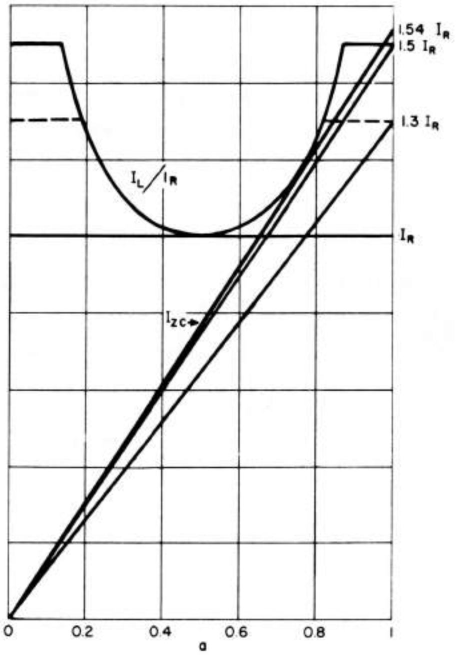


Figure 2.25. Load curves.

2.8 VARIAC AUTOTRANSFORMERS AS EQUIVALENT CIRCUITS.

A Variac autotransformer and a fixed resistance can be substituted for a variable resistor in alternating current circuits, Figures 2.26 a and 2.26 b. Values should be selected to keep the brush current within the unit rating. With the resistance as the brush load, Figure 2.26(a), the limiting impedance will be the input impedance of the autotransformer. Somewhat the same technique can be applied to a capacitance substitued for the resistance.

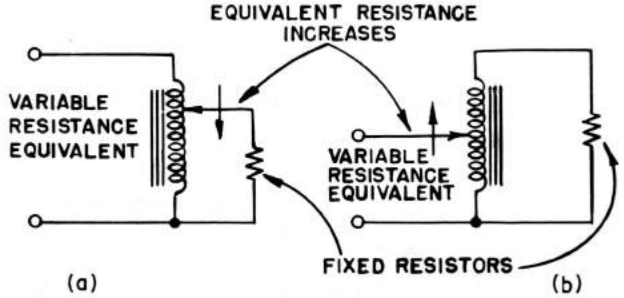


Figure 2.26a. and b.
Variable resistance equivalent.

A load of specified power factor is often required for the testing of switches and circuit breakers at power frequencies. Since the required load is usually inductive, an adjustable inductor is needed. Conventional adjustable inductors for high inductance values and high currents are often considered difficult and expensive to build. A standard Variac autotransformer used with a small, fixed inductor can produce effective inductance values continuously variable from one to several hundred times the value of the fixed inductor, for currents up to 180 amperes. The circuit is shown in Figure 2.27.

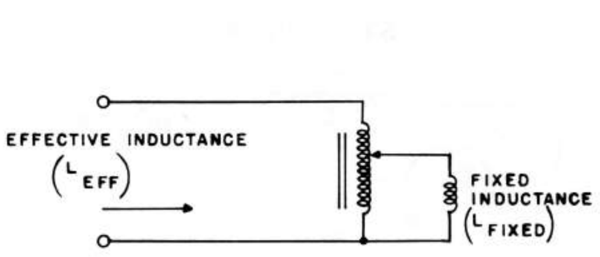


Figure 2.27.
Inductance-multiplier circuit.

The unit in this circuit is functioning as a continuously variable impedance transformer, multiplying impedance and inductance by the square of its turns ratio.

Inductance Range: When the unit is set for zero voltage applied to the fixed inductor ($K = \infty$), the effective inductance is actually that of the winding, L_{Variac}, rather than the infinite value predicted by the formula $L_{eff} = K^2 L_{fixed}$, where K is the turns ratio. Thus the range of obtainable inductance values has L_{fixed} as a lower limit and L_{Variac} as an upper limit. A more accurate formula for effective inductance, taking into account the parallel inductance of the winding, is:

$$L_{eff} = \frac{K^2 L_{fixed}}{1 + \dfrac{(K^2 L_{fixed})}{(L_{Variac})}}$$

which reduces to the earlier simplified formula when K is not too great. Typical inductance values for windings are given in Table 1.1, page 6.

Numerical Example: Taking arbitrarily a Type W10 model, which has a total winding inductance of approximately 6 henrys with 120 volts, 60 cps applied, and a small fixed inductor of 25 mh, we obtain the curve of effective inductance versus dial setting shown in Figure 2.28, calculated from the above formula. The range of inductance variation is 240 to 1. The maximum voltage that can be applied is 140 volts, and maximum current is 13 amperes for the Type W10.

Special Comments: No inductor is entirely free from losses, and Variac autotransformers and any fixed inductors that might be used with them are no exceptions. As a result, the effective inductance will be shunted by an effective parallel resistance that should be taken into account in some applications. Typical parallel resistance values for windings are given in Table 1.1. Another factor is the inrush current or momentary surge when voltage is applied. This may be significant in some instances. The surge magnitude is a variable, dependent upon the last previous magnetic history of the core and the phase of the line voltage.

The circuit in Figure 2.29, which provides a variable-power-factor and variable-current load for testing applications, is based on these principles. The Variac autotransformer can be made to produce a lagging power factor with an inductor across it, or a leading power factor when the inductor is replaced with a capacitor. The current can be set to the desired value with the rheostat.

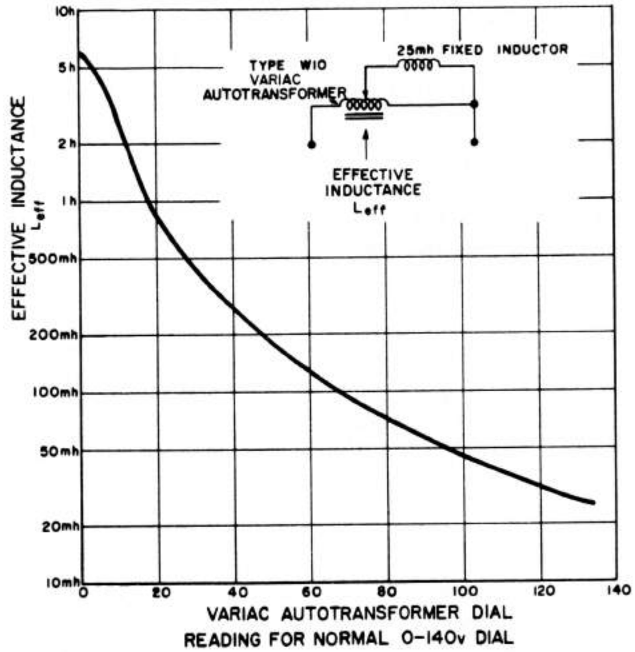


Figure 2.28.
Curve of effective inductance versus dial reading (calculated).

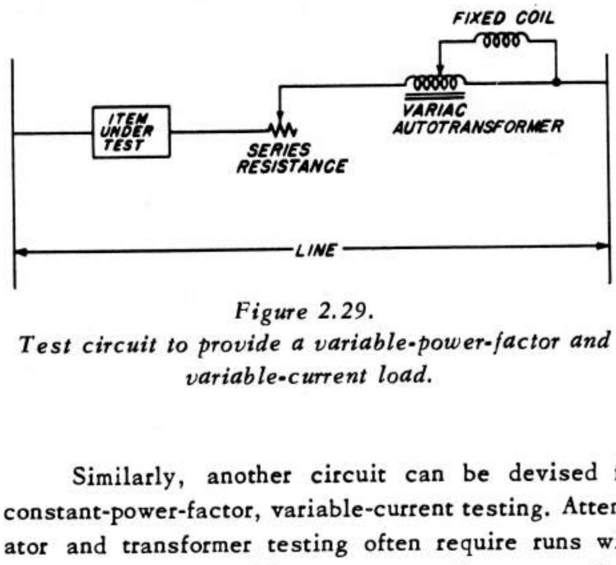


Figure 2.29.
Test circuit to provide a variable-power-factor and variable-current load.

Similarly, another circuit can be devised for constant-power-factor, variable-current testing. Attenuator and transformer testing often require runs with this type of loading. These tests are, by nature, time-consuming and tedious, since many adjustments of resistive and reactive elements are required to produce a satisfactory plot of conditions. A circuit which eliminates much of this tedium is shown in Figure 2.30. With this circuit, load variations with constant power factor can be obtained quickly and easily. The necessary power factor is obtained by selecting the proper values of R and X. When the Variac autotransformer is adjusted to a 1:1 turns ratio, the resistive and reactive elements draw full load current at the desired power factor. For other currents, the unit is adjusted to produce other ratios. The load will appear as $\left(\frac{N_1}{N_2}\right)^2 (R + jX)$ where N_1 and N_2 are the respective primary and secondary turns. The parallel inductance and resistance of the unit should be taken into account for high transformation ratios (refer to Table 1.1). For most uses, the simple expression is adequate.

This single-phase case can be extended to three-phase testing with a three-phase Variac autotransformer assembly.

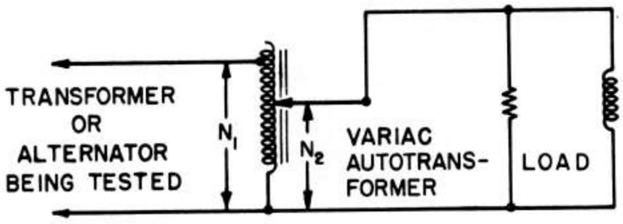


Figure 2.30.
Constant-power-factor, variable-current test circuit.

How Not To Do It: One may reasonably ask why it would not be simpler to obtain variable inductance using a Variac autotransformer alone, making connections to the brush and to one end of the winding and leaving the other end of the winding free, as in Figure 2.31. Actually, this practice is apt to result in a burned-out autotransformer. Under certain conditions of load and line voltage, the volts per turn

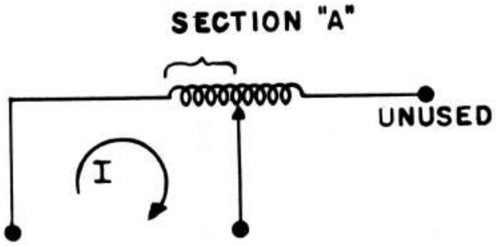


Figure 2.31.
HOW NOT TO DO IT!

applied to the unit may easily exceed safe limits, resulting in excessive current in the turn or turns bridged by the brush, with consequent overheating of such turn or turns, even to the point of burnout.

Other Applications: In addition to producing variable inductance from a fixed inductor, a Variac autotransformer can also be used to produce variable capacitance or resistance (as in Figure 2.26) from a fixed resistor. Depending on the application, the effect of the inductance or effective parallel resistance of the winding may or may not have to be taken into account. In particular, resonance effects may be obtained when capacitors are used.

Along the same lines, it is possible to construct an element having independently adjustable phase angle and impedance (Figure 2.32). The theoretical phase-angle range is from +90° to -90° as R varies from infinity to zero. This will be limited by finite resistance in the inductors.

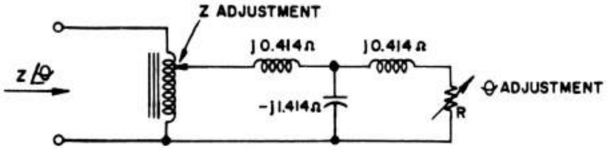


Figure 2.32.
Phase angle and impedance independently adjustable.

2.9 POLYPHASE CIRCUITS.

Each Variac autotransformer of a polyphase system can be assumed to be operating as a single-phase device, with the same limitations as for single-phase circuits. The series circuit, however, does not lend itself conveniently to polyphase operation. For either wye or delta circuits, series operation usually requires separate isolation transformers.

The similarity of Figure 2.33 to the series circuit (Figure 2.15) can be noted. The connections can be made for line or overvoltage (as in Figure 2.1 or 2.2). The KVA rating is the sum of the two ratings multiplied by $\frac{\sqrt{3}}{2}$ or 0.866 (or 1.732 times that of a single unit, if identical) due to the phase angle between the Variac autotransformer voltage and load current. Open-delta circuits may also be comprised of parallel units in each leg (see Figures 2.3 and 2.4).

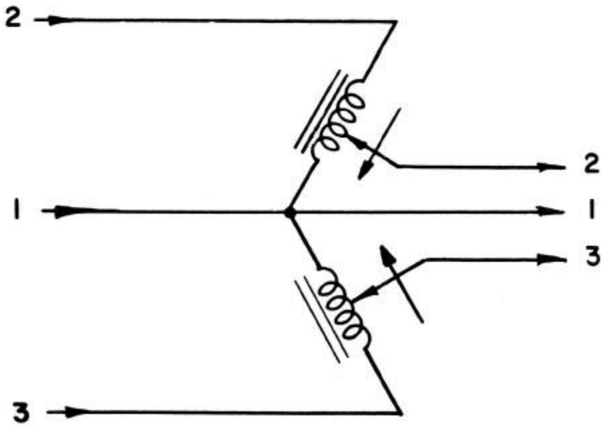
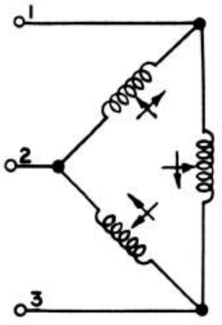


Figure 2.33.
Open-delta circuit.

It is well to note here that a closed-delta assembly is impractical. This is shown in Figure 2.34. As indicated by the arrows, the brushes simply move from line to line. The voltage between brushes drops to one-half of line voltage at the midpoint and then increases again. This circuit is a good phase-shifter, but a poor voltage controller.



INCLUDED TO DEMONSTATE IMPRACTIBILITY

Figure 2.34.
Closed-delta circuit - DO NOT USE.

The circuit in Figure 2.35 takes advantage of the fact that the delta (Δ) and wye (Y) voltages in a three-phase network are in the ratio of the $\sqrt{3}$ or 1.732. Thus, if the voltage between 1 and 2 is 240, the voltage between 1 and J is $\frac{240}{1.732} = 138$. Since 120-volt units are wound for 140 volts across the whole winding, three 120-volt units can be wye connected, as shown, in a 240-volt, three-phase system without exceeding the volts-per-turn limitation. The overvoltage feature must be omitted with a wye connection. However, the

KVA ratio is increased by a factor of 138/120. The load rating of a wye-connected assembly is 3.47 times that of a single unit. Similarly, 240-volt units may be used on 480-volt, three-phase systems.

Note that if only one three-phase voltage is given, it usually refers to the line-to-line, or delta, voltage. If two voltages are given, as 208/120, the larger voltage is the delta voltage; the smaller is the wye, or line-to-neutral voltage. In four-wire systems, the neutral may be connected to junction J.

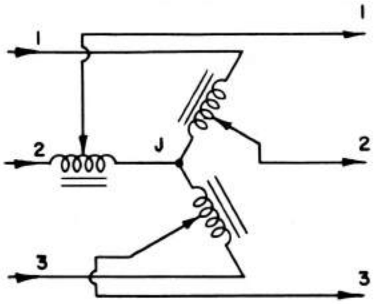


Figure 2.35.
Three-phase wye circuit.

Three-phase loads may be either wye or delta connected. In all cases, the limiting current is the brush current, just as in single-phase operation. Since a wye-load element connects directly to the brush in either open-delta or wye wiring, the wye phase current must not exceed the Variac autotransformer current limitation. Figure 2.36 (a and b) shows the relation between wye- and delta-load resistance, current, and voltage.

As an example, consider a three-gang, 120-volt, 6-ampere assembly, wye connected for 240 volts.

Maximum current is 7.8 amperes.

Wye voltage is $\frac{240}{1.732}$ = 138 volts.

R_Y is $\frac{138}{7.8}$ = 17.7 ohms, minimum.

$R_\triangle = 3 \times 17.7 = 53.1$ ohms, minimum.

$i_\triangle = \frac{240}{53.1} = \frac{7.8}{\sqrt{3}} = 4.5$ amperes, maximum.

$KVA = 7.8 \times 138 \times 3 = 3.24$ or
$= 4.5 \times 240 \times 3 = 3.24$

Obviously, a two-gang assembly can be used to control each phase of a two-phase circuit separately. No circuit diagram of this is shown, since each phase is treated in the same manner as a single-phase circuit (Figure 2.1 or 2.2).

Numerous tricks are possible with polyphase circuits. Many of these have appeared in the GENERAL RADIO EXPERIMENTER from time to time. Only those circuits which are most frequently used are included here.

$$V_\Delta = \sqrt{3}\, V_y ; \quad R_\Delta = 3R_y ; \quad i_\Delta = \frac{i_y}{\sqrt{3}}$$

Figure 2.36a. and b.
Wye-to-delta transformation.

A most ingenious circuit is shown in Figure 2.37. Here the delta load can be separated into three discrete single-phase loads. The circuit permits a 3:1 variation in power. Note that the brush on the unit connected to line 1 moves between points 1 and J. The load connected to this brush terminates on line 3.

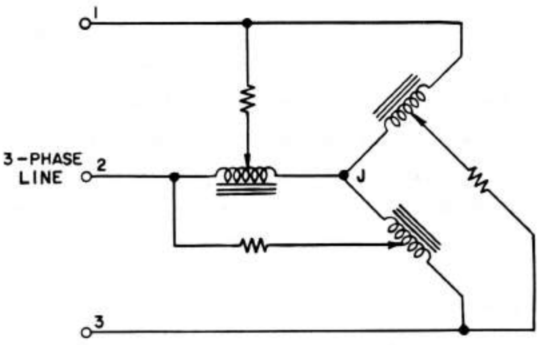


Figure 2.37.
Special limited-range three-phase circuit.

The voltage across the load is changed from delta to wye voltage as the brush traverses the winding. Since the delta-to-wye transformation ratio is $\sqrt{3}$, and since power $= \frac{(\text{volts})^2}{\text{resistance}}$, the power range is $(\sqrt{3})^2 = 3$. Using this circuit, the rating, which would be 3.24 KVA, (Figure 2.36) increases to 7.8 x 240 x 3 = 5.6 KVA, an increase of $(\sqrt{3}-1)\ 100 = 73.2\%$. In effect, by limiting the control range as described, the delta load current is increased to the wye load current.

Rectifier circuits are particularly suited for three-phase operation. The most popular is the three-phase full-wave, or six-phase, rectifier circuit (Figure 2.38). Not only does it deliver a relatively high voltage, but the overlapping effect of the three phases reduces inherent ripple.

Never operate half-wave rectifiers from Variac autotransformers unless an isolation transformer capable of handling the unbalanced dc component is used between the autotransformer and the rectifier. Variac autotransformers are not designed to handle any appreciable direct current and will almost certainly fail if so used!

It should be remembered that, for maximum power and efficiency, the three legs of a delta or wye load must be equal. With a four-wire system, a balanced load reduces the current in the neutral wire to zero.

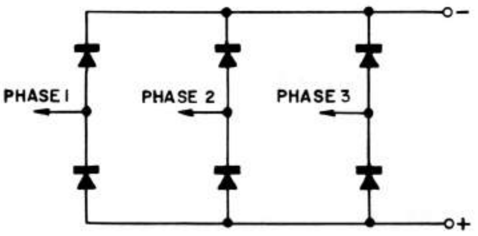


Figure 2.38.
Use of rectifier circuits for three-phase operation.

2.10 PHASE-SHIFT CIRCUITS.

Three-phase circuits with bridging Variac autotransformers make excellent phase-shifters (see Figure 2.34). About the most useful of these circuits is shown in Figure 2.39. Here, V is output voltage that is shifted in phase as the brush traverses from line 1 to line 2. The fixed terminal of V may be line 3 or the neutral, line 4. If line 3 is the fixed terminal, Figure 2.39 (a), the maximum phase shift is 60°, and V varies in magnitude from the delta voltage E to $\frac{\sqrt{3}}{2}E$ at 50% dial rotation. If the neutral, line 4, is the fixed terminal, Figure 2.39 (b), the maximum phase shift is 120°, and V varies from the wye voltage $\frac{E}{\sqrt{3}}$ to $\frac{E}{2\sqrt{3}}$ at 50% dial rotation. These circuits are useful in calibrating wattmeters and in measuring values of phase angles by comparison methods. A second unit may be connected across the variable-phase output to maintain a constant voltage.

In addition, the single-phase circuits for parallel operation (Figures 2.3 and 2.4), step-down (Figure 2.16), buck-boost (Figures 2.17, 2.18, 2.19), and special cases (Figures 2.21, 2.22, 2.23, 2.26), may be applied to either open-delta or wye circuits by treating each phase arm as a single-phase circuit.

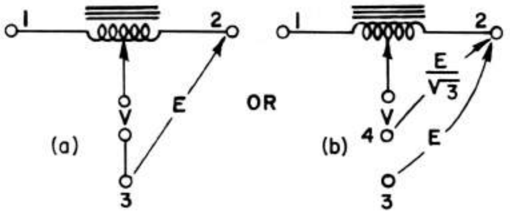


Figure 2.39a. and b.
Phase-shift circuits.

2.11 MOTOR-DRIVEN MODELS.

Motor-driven models offer a convenient assembly for either remote positioning (by push-button or switch), or for servo applications (as in the GR Type 1570-A Automatic Voltage Regulator). As shown in Figure 2.40, a geared, two-phase, reversible motor is connected to a Variac assembly in the same manner in which another ganged assembly would be added.

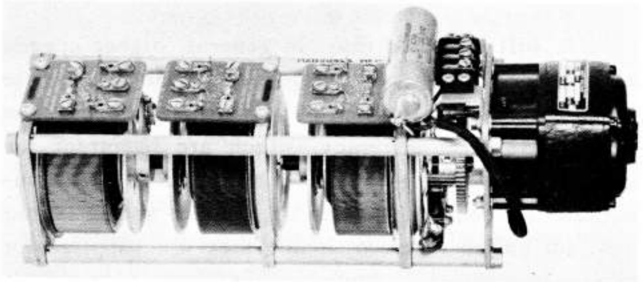


Figure 2.40.
Motor-driven 3-gang Variac autotransformer.

Various combinations of gearing and stops are available to yield wide ranges of torques and speeds. In general, larger Variac assemblies will require slower speeds and higher-torque drives. Mechanical stops, which relieve the radiator of stopping stresses, are used for the higher speeds. For lower speeds, where the motor gearing is inadequate to withstand the strain of a mechanical stop, electrical limit switches are employed.

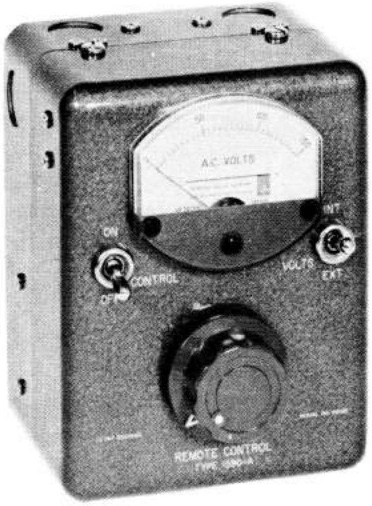


Figure 2.41.
General Radio Type 1590-A Remote Control for use with motor-driven Variac autotransformers.

The two-phase motor supply may be derived either from a servo amplifier, or from the 120-volt mains, using a capacitor to secure the necessary phase shift. Standard motors are supplied for 120 volts, 50-60 cps. Table 2.1 lists torques, speeds, and standard accessories and shows the relationship between these and the various standard Variac autotransformer assemblies. All motor-driven models are supplied with ball bearings in the interest of long life and constant torque.

It will be noted that, in general, higher speeds are provided for servo applications than for remote positioning. This is done to provide greater response speed and better accuracy, which are important for servo work. The high-speed units are considered unsuitable for remote positioning, as the speed is too great for human reaction; hence they are supplied for servo operation only. Since the high-speed, low-torque motors are offered for servo operation only, mechanical limit stops are provided. On the low-speed, high-torque units, limit switches are mandatory. At intermediate speeds, the choice is optional.

2.12 REMOTE CONTROL OF VOLTAGE SETTING.

Motor-driven Variac autotransformers can be controlled from a remote point by the Type 1590-A Remote Control shown in Figure 2.41. This device is a closed-loop servo mechanism, whose elementary circuit is shown in Figure 2.42.

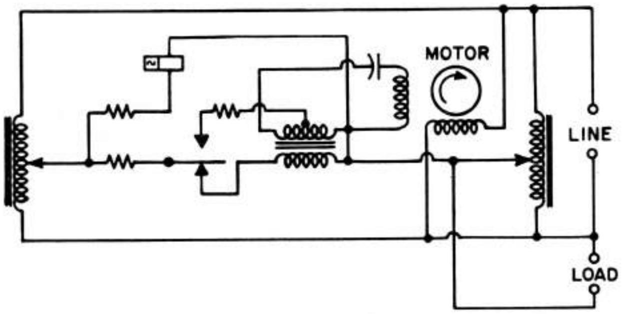


Figure 2.42.
Elementary schematic diagram of Type 1590-A Remote Control.

2.13 SPECIAL MODELS.

2.13.1 GENERAL.

General Radio Company welcomes inquiries concerning special models and we are glad to furnish them when the quantities involved are sufficient to make production economically practicable. Series W models are designed so that many modifications are possible at some increase in cost and with longer delivery schedule.

Some simple modifications are:

- shifting or addition of a tap;
- inclusion of a traverse-limiting stop;
- changing of shaft length;
- use of fungiciding treatments;
- inclusion of ball bearings.

Some of the more complex modifications are:

- changing of wire size, to adjust voltage and current ratings to a different set of limits;
- inclusion of locking devices;

TABLE 2.1

Available motors for motor-driven models.

MOTOR	STANDARD EXTERNAL GEAR RATIOS							
ALL MOTORS SHOWN ARE 60-CYCLE A	2:1	4:1						
B			2:1	4:1	8:1			
C						2:1	4:1	8:1
SECONDS FOR 320° TRAVERSE	2	4	8	16	32	32	64	128
TORQUE–OUNCE-INCHES	30	60	120	240	480	240	480	960
TYPE								
M2	O	O	OR	OR		R	R	S
M2G2	O	O	OR	OR		R	R	S
M2G3		O	OR	OR		R	R	S
M5	O	O	OR	OR		R	R	S
M5G2	O	O	OR	OR		R	R	S
M5G3		O	OR	OR		R	R	S
M10	O	O	OR	OR	OR		R	R
M10G2		O	OR	OR	OR		R	R
M10G3			OR	OR	OR		R	R
M20	S	O	OR	OR	OR		R	R
M20G2	S	S	OR	OR	OR		R	R
M20G3		S	OR	OR	OR		R	R
W2	O	O	OR	OR		R	R	S
W2G2	O	O	OR	OR		R	R	S
W2G3		O	OR	OR		R	R	S
W5	O	O	OR	OR		R	R	S
W5G2	O	O	OR	OR		R	R	S
W5G3		O	OR	OR		R	R	S
W5L	O	O	OR	OR		R	R	S
W5LG2	O	O	OR	OR		R	R	S
W5LG3		O	OR	OR		R	R	S
W5H	O	O	OR	OR		R	R	S
W5HG2	O	O	OR	OR		R	R	S
W5HG3		O	OR	OR		R	R	S
W8	O	O	OR	OR		R	R	S
W8G2	O	O	OR	OR		R	R	S
W8G3		O	OR	OR		R	R	S
W8L	O	O	OR	OR		R	R	S
W8LG2	O	O	OR	OR		R	R	S
W8LG3		O	OR	OR		R	R	S
W10	O	O	OR	OR	OR		R	R
W10G2		O	OR	OR	OR		R	R
W10G3			OR	OR	OR		R	R
W10H	O	O	OR	OR	OR		R	R
W10HG2		O	OR	OR	OR		R	R
W10HG3			OR	OR	OR		R	R
W20	S	O	OR	OR	OR		R	R
W20G2	S	S	OR	OR	OR		R	R
W20G3		S	OR	OR	OR		R	R
W20H	S	O	OR	OR	OR		R	R
W20HG2	S	S	OR	OR	OR		R	R
W20HG3		S	OR	OR	OR		R	R
W30	S	O	OR	OR	OR		R	R
W30G2		S	S	OR	OR		R	R
W30G3			S	S	OR		R	R
W30H	S	O	OR	OR	OR		R	R
W30HG2		S	S	OR	OR		R	R
W30HG3			S	S	OR		R	R
W50		S	S	OR	OR		R	R
W50G2			S	S	OR		R	R
W50G3			S	S	OR		R	R
W50G4				S	S		S	R
W50G6					S		S	R
W50H		S	S	OR	OR		R	R
W50HG2			S	S	OR		R	R
W50HG3			S	S	OR		R	R
W50HG4				S	S		S	R
W50HG6					S		S	R

NOTES:

O	- Servo applications only.
R	- Remote positioning only.
OR	- Either servo or remote positioning.
S	- Requires a special motor (see below); column headings for torque and gearing do not apply.

M models have 60-cycle motor on 400-cycle Variac autotransformer.

Motor A is intended for servo operation only. Microswitches are optional; capacitor is supplied.

Motor B may be servo or manually operated. Microswitches are optional; capacitor is supplied.

Motor C is intended for remote positioning only. The torque exceeds the limits of the mechanical stop; microswitches are necessary; capacitor is supplied.

Motors in the S series are high-torque motors and are available on special order. They are intended for remote positioning only. Microswitches are necessary; capacitor is supplied.

addition of one or more independently controlled brushes (refer to Section 2.13.2);
inclusion of overload protectors;
provision for 360-degree rotation;
militarization for operation in humid, tropical conditions.

Models can (on special order) be supplied less knob, dial, etc., at lower net prices. Explosion-proof housings for Variac autotransformers can be purchased from Crouse-Hinds Company, Syracuse, New York.

2.13.2 MULTIPLE BRUSH CIRCUITS.

The ball-bearing and wire-size modifications require no discussion; their purposes are obvious. With the multiple-brush modification, the uses may not be apparent at first. It is possible on most models to supply an extra brush track as, for example, on the end of the coil opposite the existing brush track. With suitable switching, a two-brush model can be used to provide adjustable "stand-by" and "operate" settings for electronic equipment, or a double-brush model can supply two independently adjustable voltages.

When the loads on the several brushes of a multiple unit all return to the same side of the supply mains, the sum of the brush currents must not exceed the rated current of the autotransformer. No gain in power output is possible. The multiple brushes merely yield a more flexible control device.

One double-brush application that deserves special notice is shown in Figure 2.43. Here the loads are returned to opposite sides of the line. Under these conditions, each load can draw full current without overloading the unit. The power output is doubled. Of course, only one load can be grounded, but in many cases this is unimportant. The case is somewhat analogous to Figure 3.3, for when the load currents are equal and both brushes are together, the unit will carry no load.

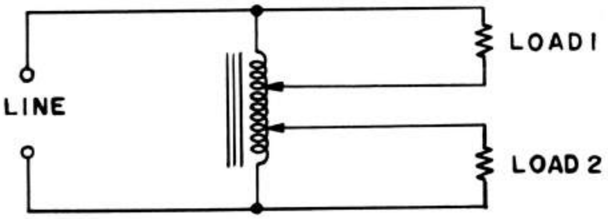


Figure 2.43.
Power-doubling circuit.

If the two brushes are geared so that they travel equal and opposite amounts, and they are used to feed two equal primaries of a supplementary transformer, the output of the transformer will be doubled over the values possible in Figures 2.16, 2.19, 2.21, 2.23. The circuit is shown in Figure 2.44.

Each primary of the supplementary transformer will have wire of 1/2 the cross section of a single primary, and will contain the same number of turns. If, for example, a 12-ampere, single-brush unit is required, a 6-ampere, double-brush model will do as well.

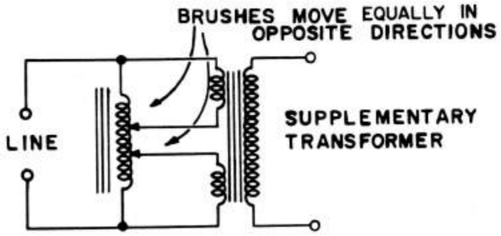
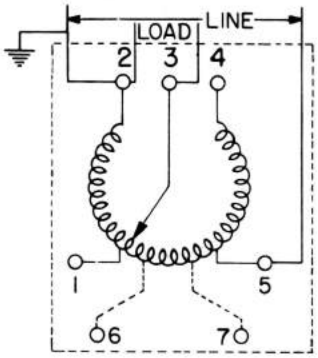


Figure 2.44.
Transformer power doubler.

2.14 LINE AND LOAD CONNECTIONS.

The following diagrams show the proper connections for stated line and load voltages, with the Variac autotransformer models that may be used. The type of mounting for clockwise increasing voltage is also given. If counterclockwise increasing voltage is desired, use the surface-mounting connections for back-of-panel mounting and the back-of-panel-mounting connection for surface mounting.

TERMINAL BOARD CONNECTIONS FOR CLOCKWISE INCREASING VOLTAGE.*



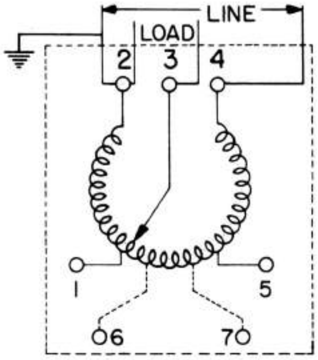
Types M2, M5,
W2, W5, W8

Line 120 v.
Load 0 - 140 v.

Type W5H

Line 240 v.
Load 0 - 280 v.

SURFACE MOUNTING



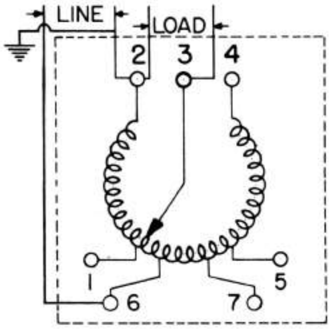
Types M2, M5,
W2, W5, W8

Line 120 v.
Load 0 - 120 v.

Type W5H

Line 240 v.
Load 0 - 240 v.

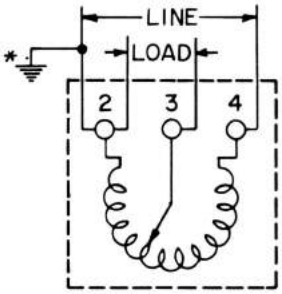
SURFACE MOUNTING



Type W5H

Line 120 v.
Load 0 - 280 v.

SURFACE MOUNTING



Types W5L, W8L

Line 120 v.
Load 0 - 120 v.

SURFACE MOUNTING

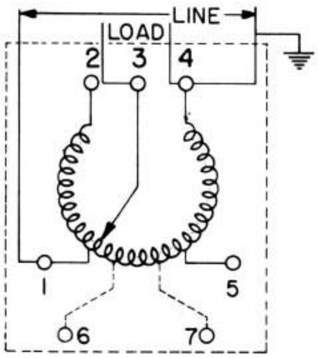
Types M2, M5,
W2, W5, W8

Line 120 v.
Load 0 - 140 v.

Type W5H

Line 240 v.
Load 0 - 280 v.

BACK-OF-PANEL MOUNTING



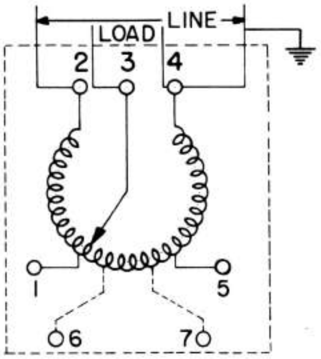
Types M2, M5,
W2, W5, W8

Line 120 v.
Load 0 - 120 v.

Type W5H

Line 240 v.
Load 0 - 240 v.

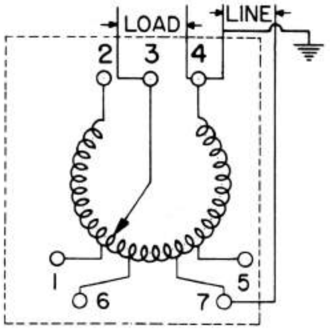
BACK-OF-PANEL MOUNTING



Type W5H

Line 120 v.
Load 0 - 280 v.

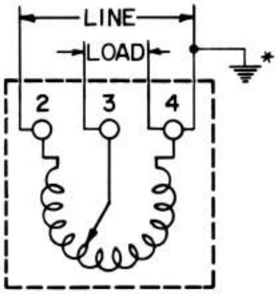
BACK-OF-PANEL MOUNTING



Types W5L, W8L

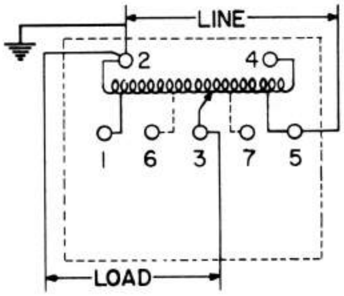
Line 120 v.
Load 0 - 120 v.

BACK-OF-PANEL MOUNTING



(continued on following page)

(continued from previous page)



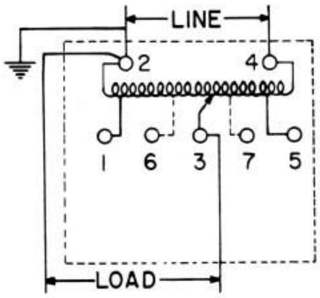
Types M10, M20, W10, W20, W30, W50

Line 120 v.
Load 0 - 140 v.

Types W10H, W20H, W30H, W50H

Line 240 v.
Load 0 - 280 v.

SURFACE MOUNTING



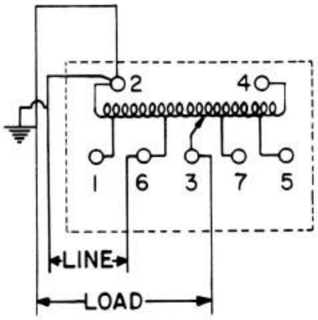
Types M10, M20, W10, W20, W30, W50

Line 120 v.
Load 0 - 120 v.

Types W10H, W20H, W30H, W50H

Line 240 v.
Load 0 - 240 v.

SURFACE MOUNTING



Type W10H, W20H, W30H, W50H

Line 120 v.
Load 0 - 280 v.

SURFACE MOUNTING

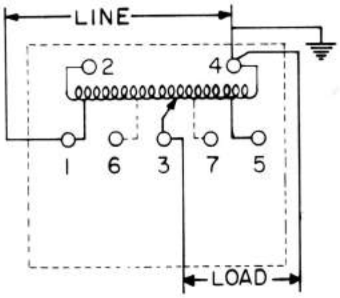
Types M10, M20, W10, W20, W30, W50

Line 120 v.
Load 0 - 140 v.

Types W10H, W20H, W30H, W50H

Line 240 v.
Load 0 - 280 v.

BACK-OF-PANEL MOUNTING



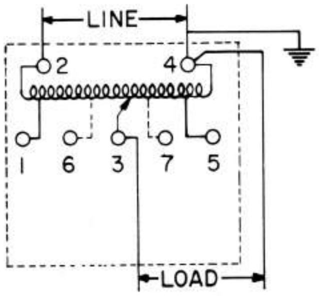
Types M10, M20, W10, W2[illegible] W30, W50

Line 120 v.
Load 0 - 120 v.

Types W10H, W20H, W30H, W50H

Line 240 v.
Load 0 - 240 v.

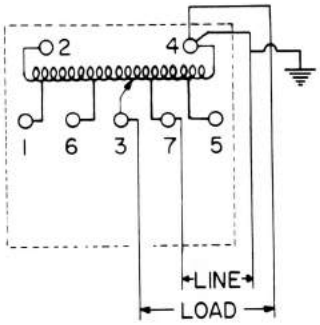
BACK-OF-PANEL MOUNTING



Types W10H, W20H, W30H, W50H

Line 120 v.
Load 0 - 280 v.

BACK-OF-PANEL MOUNTING



*If counter-clockwise increasing voltage is desired, use the above surface-mounting connections for back-of-panel mounting and the above back-of-panel-mounting connections for surface mounting.

Series M models are designed for 350 to 1200 cps.

Series W models are designed for 50 to 60 cps.

Models designed for 240–volt, 50– to 60–cycle service can be used on a 25–cycle supply at full current rating, but at one-half their voltage and kva ratings.

SECTION **3**

SOME SPECIFIC APPLICATIONS

3.1 INCANDESCENT DIMMING.

Variac autotransformers are excellent for controlling illumination levels. Their "built-in" features provide many desirable qualities that are not often found in other types of illumination controls. Smooth, silent and continuous control, low maintenance costs, cool running, and small size are a few of these features.

Another important feature, which is inherent in the design of the Variac autotransformer, is its ability to withstand temporary current surges up to ten times the nominal rating (see Figure 1.5). This feature protects the unit against high inrush currents that are drawn by incandescent lamps when their tungsten filaments are cold. The tabulation given in Table 3.1 will give some idea of the magnitude of inrush currents.

TABLE 3.1
Values of inrush currents drawn by incandescent lamps.

Lamp Wattage	120-V Normal Current	Theoretical Inrush Current	Actual Max. Current by Test	Time for Current to	
				Reach Max. Value	Fall to Normal Value
Watts	Amperes	Amperes	Amperes	Seconds	Seconds
75	0.625	9.38	7.2	.0004	.07
100	0.835	13.0	9.0	.0007	.10
200	1.67	26.2	17.2	.0008	.10
300	2.50	40.0	26.2	.0011	.13
500	4.17	67.9	45.7	.0014	.15
750	6.25	101.9	51.7	.0021	.17
1000	8.33	142.4	65.2	.0031	.23

When a heavy lamp load is to be dimmed by means of a Variac autotransformer, the inrush current should be calculated to determine if it will be within the handling capabilities of the unit. When high initial surges are possible, the pointer should always first be set to zero. A further protection would be to incorporate a switching circuit which would shunt out the unit during periods of initial inrush current flow. When the current reaches its nominal value, the autotransformer could then be switched back into the circuit. Surge protection should always be used with both resistive and reactive loads that can produce high inrush currents.

However, certain applications often preclude the use of switching circuits and the setting of the pointer to zero for protective purposes. In these cases, a choke coil may be inserted in series with the load to limit the inrush current to a safe value.

The inductance of current-limiting chokes can be calculated from the following formula:

$$L = \frac{\text{Load Voltage}}{31.4\, f I_R} \tag{29}$$

where L = inductance in henrys
f = line frequency in cps and
I_R = rated current of the Variac autotransformer in amperes.

The choke should be large enough to maintain its inductance at ten times the rated current and should be capable of carrying the load current continuously. The choke will not seriously reduce the load voltage. Under the worst possible conditions, the voltage drop across the choke will never exceed 4 percent of the operating voltage, and the choke will still effectively limit the surge.

The wiring of a dimming circuit that utilizes autotransformer control without a choke is a straightforward matter, as can be seen from Figure 3.1. Figure 3.2 shows the circuit with a choke to limit the inrush current.

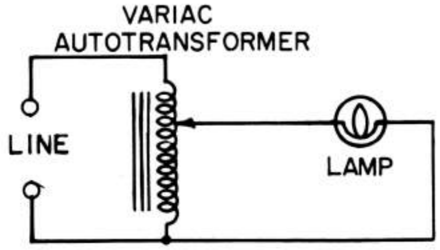


Figure 3.1.
Dimming circuit with autotransformer control.

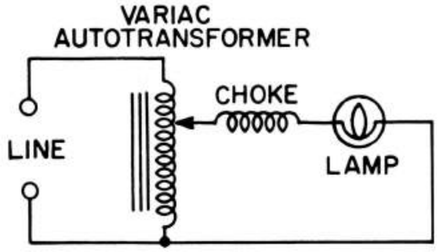


Figure 3.2.
Addition of a choke to the dimming circuit limits the inrush current.

A clever variation of this circuit which provides simultaneous dimming and brightening is shown in Figure 3.3. With both switches closed, one lamp will dim while the other brightens as the brush is moved. If one switch is opened, only one lamp circuit will function. If both lamps have equal voltage ratings, the autotransformer will carry no load when the brush is in the center position, since the lamp currents are equal. Note that Underwriters' specifications require that one side of a lamp circuit must be grounded. This circuit should not be used in the wiring of buildings.

3.2 FLUORESCENT DIMMING.

Dimming of fluorescent lamps by a simple reduction of the applied voltage yields a very limited range. Unlike the incandescent lamp, the fluorescent lamp requires a constant, relatively high voltage across it to maintain the arc discharge necessary for illumination. Only a limited decrease in illumination level (about 50% of normal) can be accomplished before the circuit becomes unstable, and the lamps go out. Fluorescent dimming at present is quite restricted and is limited in use to only the 40-watt, rapid-start, Type T-12, hot-cathode, fluorescent lamp. In addition, a special ballast is required that is designed to maintain constant heat on the lamp electrodes. Currently, there are two types of variable-reactance fluorescent dimming systems on the market. The basic difference in the two systems lies in the method of connecting the autotransformer into the dimming circuit.

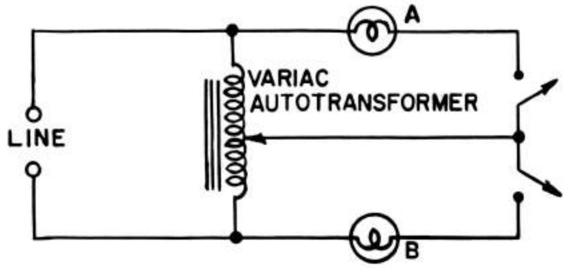


Figure 3.3.
Circuit for simultaneous dimming and brightening.

In the system used by the Ward Leonard Electric Company, the autotransformer is connected across the line as shown in Figure 3.4. This system is designed for operation on a 120-volt, 60-cycle, 2-wire line to the dimmer. A single ballast is required for each lamp. The Varistat autotransformer dimmer, as supplied by Ward Leonard, is capable of handling up to forty, 40-watt, Type T-12 lamps. Additional capacity can be obtained with ganged autotransformers connected to separate lighting circuits. A dimming range of 500 to 1, that is, down to 0.20 percent of maximum light output, can be obtained with this circuit.

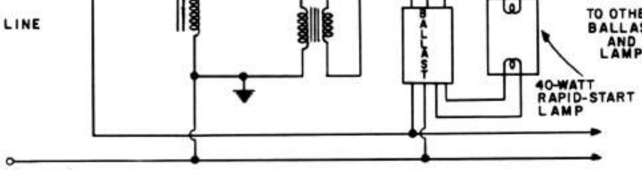


Figure 3.4.
Ward-Leonard dimming system.
The transformer can be omitted if a 146-volt output is available from the Variac autotransformer.

In the variable-reactance dimming method developed by General Electric Company, the autotransformer winding is connected in series with the line. The wiring diagram is shown in Figure 3.5. This circuit permits dimming down to 2 percent of full brightness (dimming range of 50 to 1). Since the autotransformer is in series with the line, a compensating reactor is needed to keep the volts-per-turn ratio on the autotransformer from becoming excessive. In addition, if the lamps are not connected into metal fixtures, a grounded, one-inch-wide, metal strip should be placed behind each lamp.

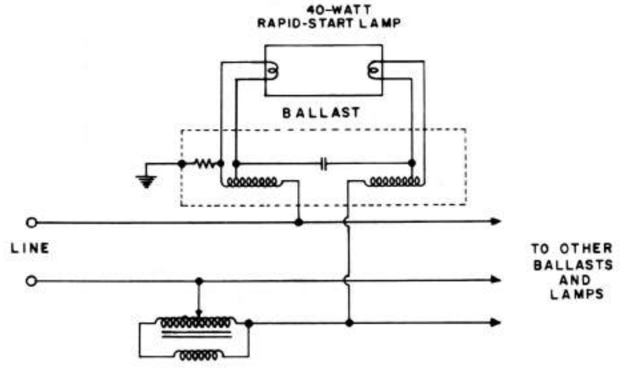


Figure 3.5.
General Electric dimming system.

3.3 COLD-CATHODE LAMPS AND DIMMING.

One type of fluorescent lamp which can be dimmed directly with a Variac autotransformer is the cold-cathode type. This type of lamp does not have the usual heated filaments; but instead has thimble-shaped, cylindrical electrodes at each end. The cold-cathode lamp utilizes electrical field emission. The most common type of cold-cathode lamp is the neon sign. These same principles of high field emission have also been extended to general-purpose lighting. The lamps are not generally available, as are the hot-cathode types, and often must be custom made. The usual operating voltages encountered run from 2000 to 15,000 volts, depending upon the size and number of lamps used. The primary of this step-up transformer can be controlled directly by a Variac autotransformer.

Figure 3.6 shows a plot of the dimming characteristics of cold-cathode lamps. Shown are the variations in light output from a single-lamp circuit up to an eight-lamp, parallel-connected circuit. It can be noted from the plot that, at illumination levels below 10 percent of total light output, lamp flicker is likely to take place. The boundaries of this zone are not definite since lamp characteristics, lamp age, and line-voltage regulation all vary. In general, the greater the lamp load in the circuit, the more pronounced is the tendency to flicker.

3.4 PHOTOGRAPHY.

Maintenance of proper color temperature in studio lighting poses problems when the available line voltage is below the rated value of the photolamps. Such a situation can easily occur when high-wattage studio-lights create severe loads, which cause corresponding drops in line voltage. Illumination that is not at the correct value of Kelvin temperature (a measure of the actinic quality of light) can cause serious color unbalance to appear on the film. These effects are not important in black and white photography, but do create a problem with color film rated for a specific Kelvin temperature. The curves shown in Figure 3.6 show the variability of photo-lamp color temperature with voltage. When the Kelvin temperature of the illumination is below the film's requirements, the film will register an overabundance of reds and yellows. Conversely, when the temperature is too high, there will be an increase in the blues, and the resulting photograph will have a "cool" quality.

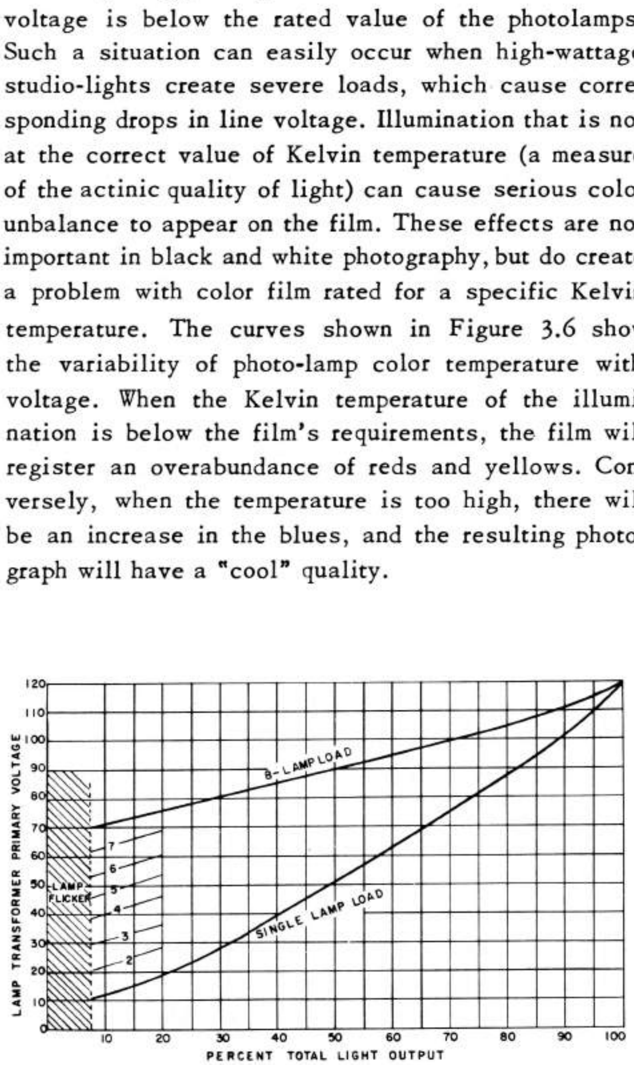


Figure 3.6.
Dimming characteristics of cold-cathode lamps.

Color films for artificial lighting are rated in two types: those for use with 3200° Kelvin lamps, that are designated as Type B (commonly used by professionals) and those for use with "photoflood" lamps, rated at approximately 3400° Kelvin. The latter are designated as Type A.

To adjust for color temperature, make a voltage measurement at the lamp terminals. This gives an indication of the color temperature (see Figure 3.7). The voltage can be conveniently adjusted by a Variac autotransformer.

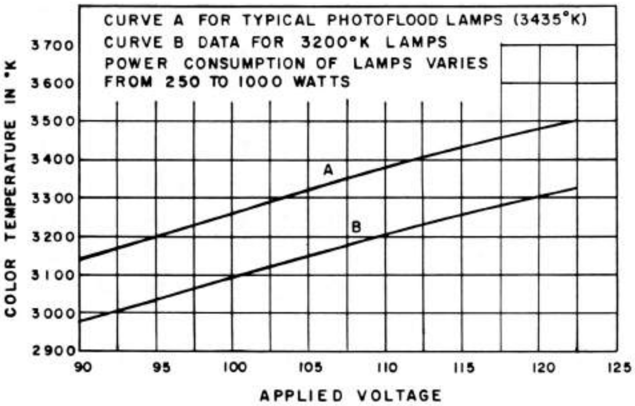


Figure 3.7.
Variability of photoflood color temperature with voltage.

Variable line voltage also presents problems in color-photo printing.* The printing operation requires separate red, green, and blue exposures. The color correction filters which are used are based on the color temperature of the enlarger lamp when it is operating at correct line voltage. Any shift in this voltage will cause a change in the color temperature. This change in temperature causes a change in the relative qualities of primary colors present in the white light. With a drop in line voltage, the white light is no longer white, but shifts toward a yellow hue. This can be explained from the curve in Figure 3.8. It can be seen that, as the illumination (voltage) falls, there is a drop in the intensity of the red, green, and blue components. The drop in intensity level is different for each color. If uncorrected, the variable rate of intensity will cause serious unbalances in the color print. For this reason, the line voltage must be kept at the lamp rating.

Prior to making a final color print, two determinations must be made: (1) the exposure that will result in satisfactory color density and (2) the proper combination of filters to give good color balance. This is accomplished by a series of trial exposures taken with various sets of filters. In order to achieve any sort of accurate test information, it is necessary that the voltage supplying the enlarger lamp be held at its rated value. Here a Metered Variac autotransformer or a Type 1570 Automatic Voltage Regulator is most useful.

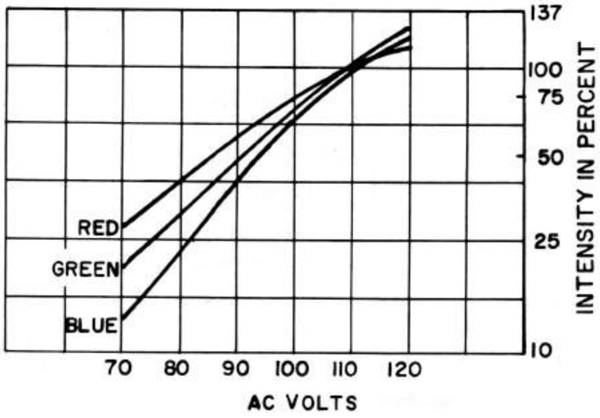


Figure 3.8.
Variability of primary colors in white light versus lamp voltage.

3.5 THE VARIAC AUTOTRANSFORMER AS A LABORATORY TOOL.

The most common use of Variac autotransformers in the laboratory is as a source of variable ac voltage. In this connection, they offer a means of calibrating ac voltmeters and ammeters. Simply connect the voltmeter to be calibrated and a standard voltmeter across the secondary side of the autotransformer, as shown in Figure 3.9.

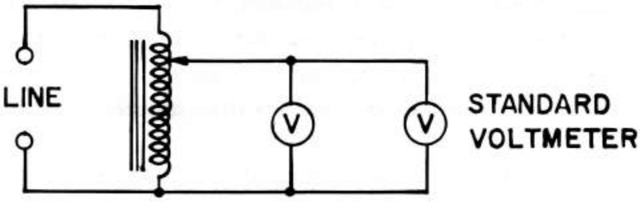


Figure 3.9.
Circuit for calibration of an ac voltmeter.

---

*This text is based on color printing techniques using Kodak Color Print Material, Type C and Type R. (Refer to "Kodak Color Handbook".)

As a further refinement for calibrating high or low meter ranges, a step-up or step-down transformer, or one with a multi-tapped secondary, can be used to improve the adjustment range. See Figure 3.10.

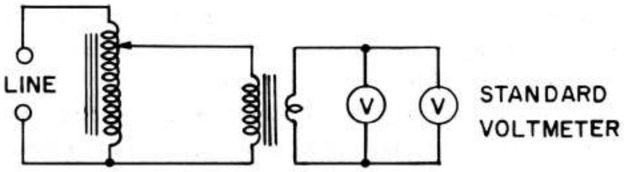


Figure 3.10.
Use of a transformer for calibration of high or low meter ranges.

By the insertion of series resistors of appropriate values into the secondary circuit, ammeters can also be calibrated. The step-down transformer allows the use of Variac autotransformers which have current ratings below that of the ammeters. See Figure 3.11.

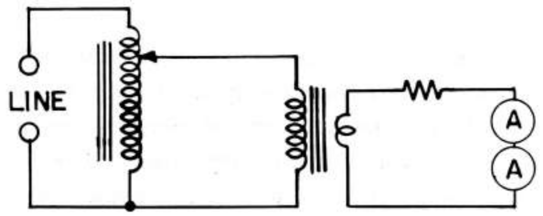


Figure 3.11.
Insertion of appropriate resistance values in this circuit permits calibration of an ammeter.

A Variac autotransformer can also be employed as an adjustable-ratio current transformer, to increase the effective range of an ammeter. In this setup, it is necessary to calibrate the Variac-autotransformer and meter combination prior to use. See Figure 3.12.

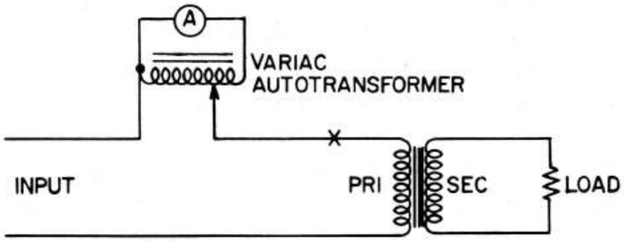


Figure 3.12.
Use of a Variac autotransformer as an adjustable-ratio current transformer.

The circuit in Figure 3.13 can be used to provide a voltage source of zero to 260 volts for testing purposes.

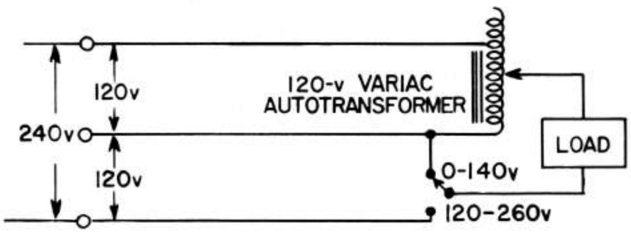


Figure 3.13.
Circuit for a voltage source of 0 to 260 volts.

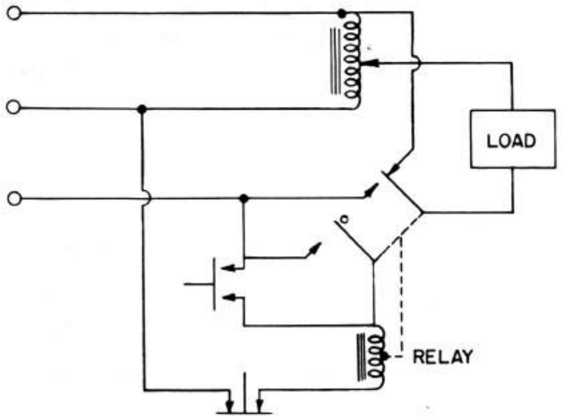


Figure 3.14.
Circuit of Figure 3.13 with push buttons and relay for switching.

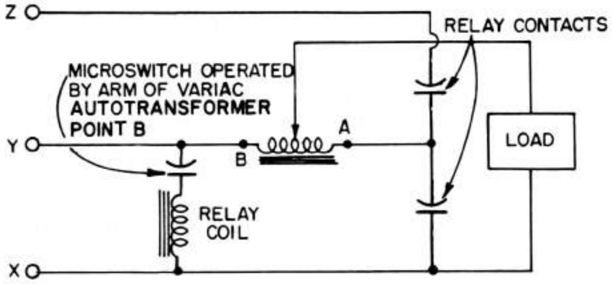


Figure 3.15.
Circuit of Figure 3.13 with automatic switching.

Another arrangement is shown in Figure 3.14. The switching from one range to the other is performed by push buttons and a relay. Figure 3.15 shows a similar circuit which has automatic, rather than manual, switching. This involves mounting a limit switch on the unit in such a way that the switch is operated by the brush arm just as it reaches the end of its travel in the increasing-voltage (clockwise) direction. This actuates a latching-type transfer relay which transfers end *A* of the winding from point *X* to *Z*. In this position, counter-clockwise rotation of the knob increases the voltage up to 240 volts. The voltage is reduced in the same manner by going through two rotations in the opposite direction. The interrupting duty on the contacts of the transfer relay is not severe, because the transfer is made when only the magnetizing current is flowing through the winding.

An easily constructed high-voltage insulation tester that can be made using a Variac autotransformer is shown in Figure 3.16. The lamp glows brightly when the insulation under test fails. The lamp also acts as an effective current limiter. The meter reading times the turns ratio of the step-up transformer indicates the breakdown voltage.

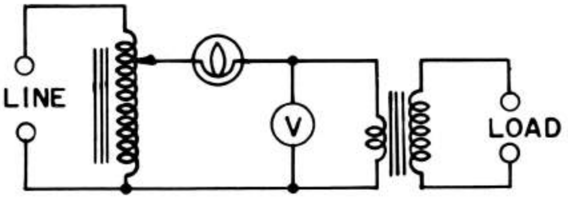


Figure 3.16.
Circuit for insulation-breakdown testing.

3.6 HEATING APPLICATIONS.

Many of the preceding circuits can be used to control the temperatures in electrically heated devices. Variac autotransformers possess many advantages over resistance-type controls. They are smaller in size. Resistive controls dissipate and waste power which is not used in the actual heating process. As a result of this power dissipation, resistive controls run at higher operating temperatures than Variac autotransformers.

A high-efficiency heater and controller for laboratory use can be made by using a reflector-type, infrared lamp and a Variac autotransformer. This type of heating is very useful in the distillation or evaporation of flammable materials. Should vessel breakage occur, there is no danger of the material coming in contact with an open flame. Also, this type of heating can be accurately controlled, since there is no significant heat retention in the lamp. In addition, the heat can be turned off almost instantly. Conversely, since there is not significant warm-up time, heat can be applied almost instantaneously.

An application of Variac autotransformers to heat control in the medical field can be found in the use of thermocauters, small-size surgical probes with heated-wire ends. They are used to cauterize internal wounds. Accurate heat control is essential – too much heat injures healthy tissue adjacent to the wound, while too little heat fails to cauterize the wound sufficiently. Thermocauters generally operate in the 0-to-10-volt range, with a current demand of about 30 amperes.

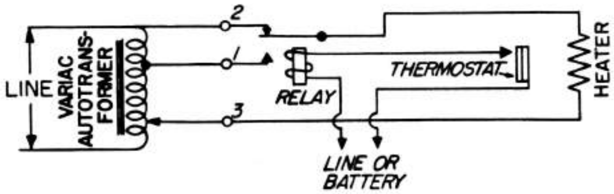


Figure 3.17.
Thermostatic control for multiple temperature settings.

Figure 3.17 shows a circuit that can be used to maintain constant heater temperature at a variety of settings. The thermostat is the adjustable type and is initially set to the desired temperature. The Variac autotransformer, which has been precalibrated in terms of temperature, is also adjusted to the same setting.

Another important use is controlling the heat of a soldering iron. With a Variac autotransformer, it is possible to let the iron "idle" at low temperatures when it is not in use. This is not only worthwhile as an economy measure to minimize power consumption, but it also eliminates frequent cleaning of the iron's tip by slowing down the rate of oxidation. When it is necessary to use the iron again, the autotransformer is turned up to line voltage, and since the iron is already warm, it heats to proper operating temperature almost immediately. When additional heat is required, the Variac autotransformer can be used to supply a higher-than-normal voltage to the iron.

The Variac autotransformer and soldering iron combination can also be used to fasten explosive rivets. This type of rivet contains an explosive charge in its shank and is used in aircraft fabrication. Here, the autotransformer is used to adjust the heat necessary to explode the rivet.

Figure 3.18 shows the circuit for a hot-wire cutter. Here a Variac autotransformer is used to regulate the heat in a length of nichrome wire, that acts as the cutter. The device is especially useful for cutting foam-type plastics such as Styrofoam. The small diameter of the wire permits intricate work to be cut, which normally could not be done by sawing methods. A further refinement in the circuit is to include a step-down transformer in the secondary of the autotransformer (similar to Figure 2.8, a).

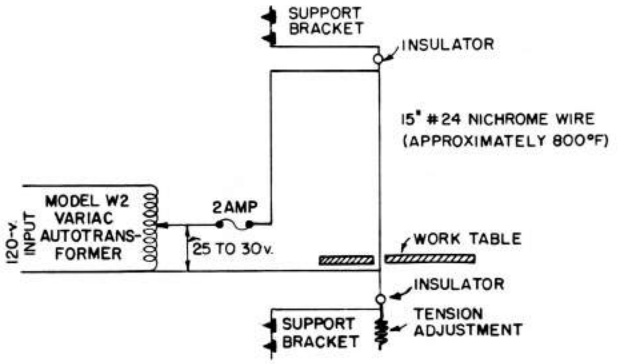


Figure 3.18.
Circuit for a hot-wire cutter.
Resistance of #24 Nichrome wire is
1.671 ohms per foot.

3.7 MOTOR SPEED CONTROL.

The control of motor speeds with the Variac autotransformer was mentioned briefly in the tabulation of types of loads in Section 1.7. Split-phase, capacitor, and shaded-pole ac motors can be successfully controlled only with fans and other loads where torque is proportional to speed. With constant loads, only a very limited speed range can be achieved.

Direct-current shunt- and compound-wound motors lend themselves well to speed control with a Variac autotransformer and rectifiers, when the field and armature windings are excited separately. Figure 2.25 shows the circuit that is used in the Variac Speed Controls, available as complete, packaged units. The field is excited at constant voltage, and the Variac autotransformer supplies an adjustable voltage to the armature. With this method of control, speed can be adjusted from rated value down to zero, at constant torque.

The same system can be used with universal and series-wound motors if an additional transformer, or a fixed tap on the Variac autotransformer, is provided to supply the low field voltage. As with the shunt motor, the field must be separately excited. This type of control enables shunt-motor operating characteristics to be obtained from an inexpensive universal motor.

General Radio Variac Speed Controls are available in ratings from 1/5 to 3/4 horsepower. Consult the current General Radio Catalog for details.

GENERAL RADIO COMPANY

WEST CONCORD, MASSACHUSETTS, USA

SALES ENGINEERING OFFICES

NEW YORK

Broad Avenue at Linden
Ridgefield, New Jersey

SYRACUSE

Pickard Building
East Molloy Road
Syracuse 11, New York

PHILADELPHIA

1150 York Road
Abington, Pennsylvania

WASHINGTON

Rockville Pike at Wall Lane
Rockville, Maryland

FLORIDA

113 East Colonial Drive
Orlando, Florida

CHICAGO

6605 West North Avenue
Oak Park, Illinois

DALLAS

2501-A West Mockingbird Lane
Dallas 35, Texas

SAN FRANCISCO

1186 Los Altos Avenue
Los Altos, California

LOS ANGELES

1000 North Seward Street
Los Angeles 38, California

CANADA

99 Floral Parkway
Toronto 15, Ontario

Distributors for Variac® AUTOTRANSFORMERS

Alabama: *Huntsville*
Electronic Wholesalers, Inc.
116 Washington St., S. E.

California: *Los Angeles*
Westates Electronics Corp.
6344 Arizona Circle

Colorado: *Denver*
Denver Electronic Supply Co.
2170 So. Grape St.

Florida, *Melbourne*
Electronic Wholesalers, Inc.
1301 Hibiscus Blvd.

Miami
Electronic Wholesalers, Inc.
9390 NW 27th Ave.

Maryland, *Baltimore*
Electronic Wholesalers, Inc.
3004 Wilkens Ave.

Massachusetts, *Boston*
Lafayette Radio Electronics Corp.
110 Federal St.

New Jersey, *Newark*
Lafayette Radio Electronics Corp.
24 Central Ave.

New York, *Jamaica*
Lafayette Radio Electronics Corp.
165-08 Liberty Ave.

North Carolina, *Winston-Salem*
Electronic Wholesalers, Inc.
938 Burke St.

Ohio, *Dayton*
Electrical Specialties Co.
3130 Valleywood Dr.

Pennsylvania, *Philadelphia*
Philadelphia Electronics, Inc.
1225 Vine Street

Norristown
Philadelphia Electronics, Inc.
624 W. Airy St.

Washington, (State)
Seattle, Tacoma, Bremerton,
Olympia, Centralia, Aberdeen

Washington, D.C.
Electronic Wholesalers, Inc.
2345 Sherman Ave., N. W.