

Feb. 15, 1966

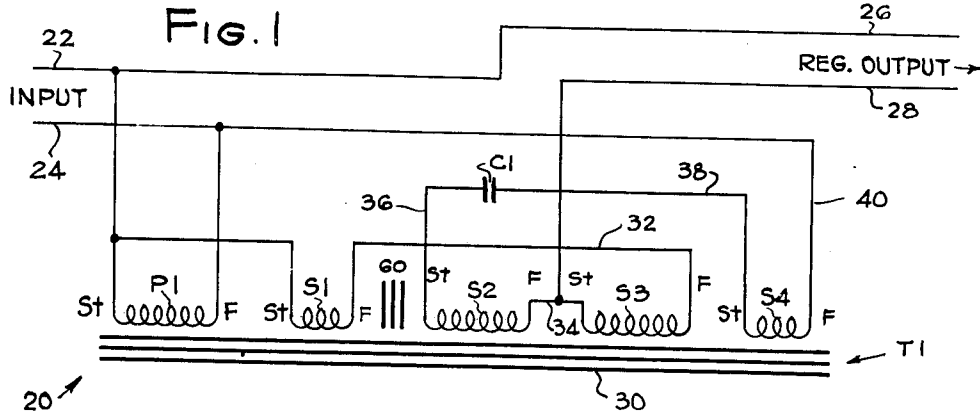
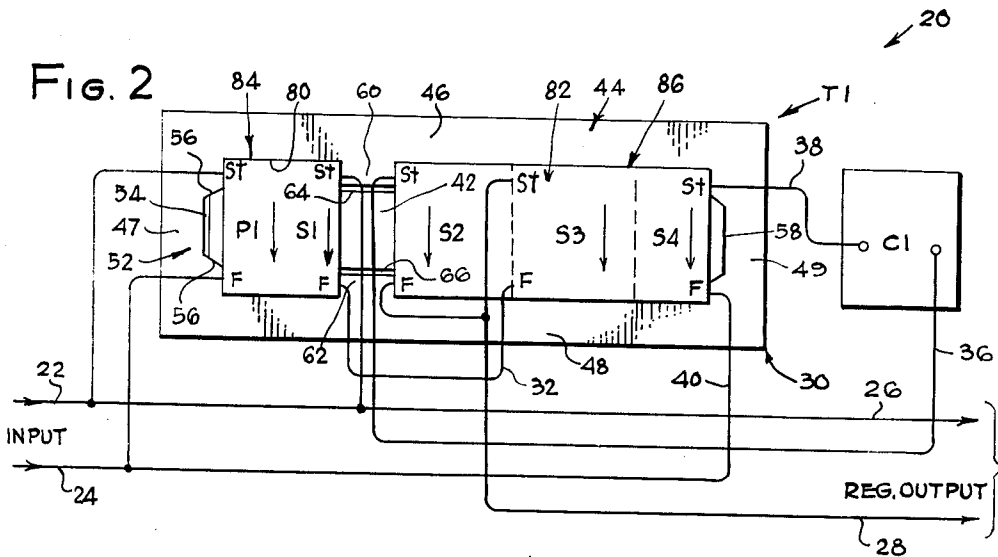
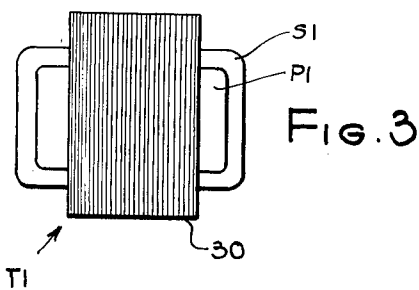
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3,235,789

VOLTAGE REGULATORS

Filed July 10, 1961

5 Sheets-Sheet 1



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VOLTAGE REGULATORS

5 Sheets-Sheet 2

FIG. 4

INPUT

22

24

26

REG. OUTPUT

28

40

38

36

34

32

S4

C1

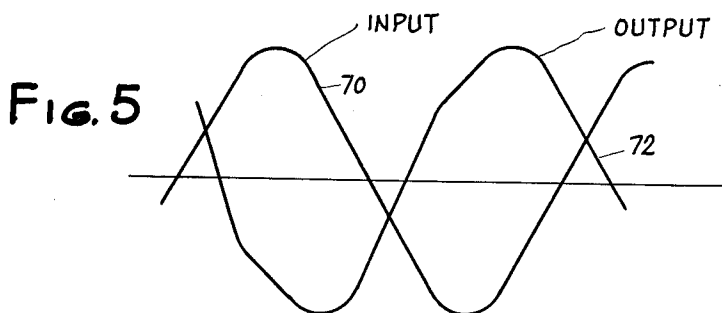
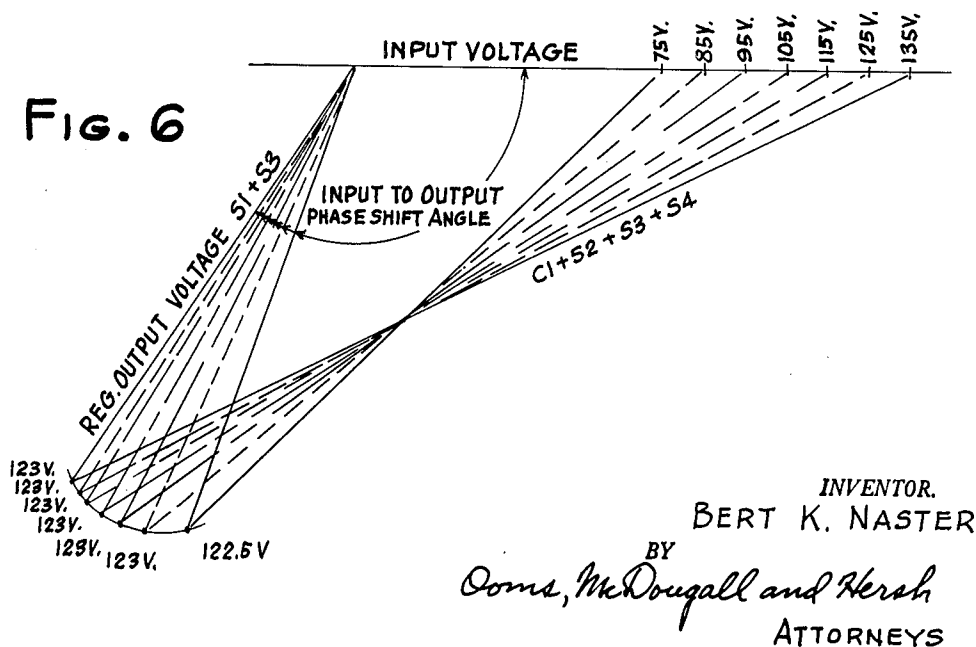
20 mf.

S2

S3

P1

S1



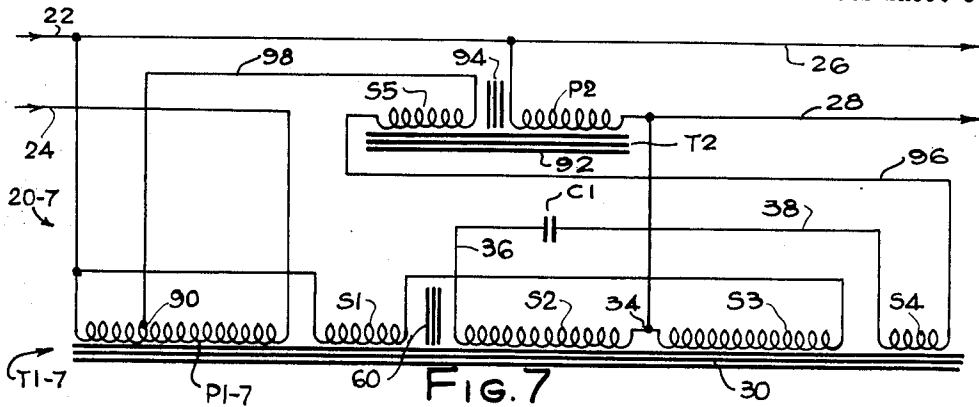
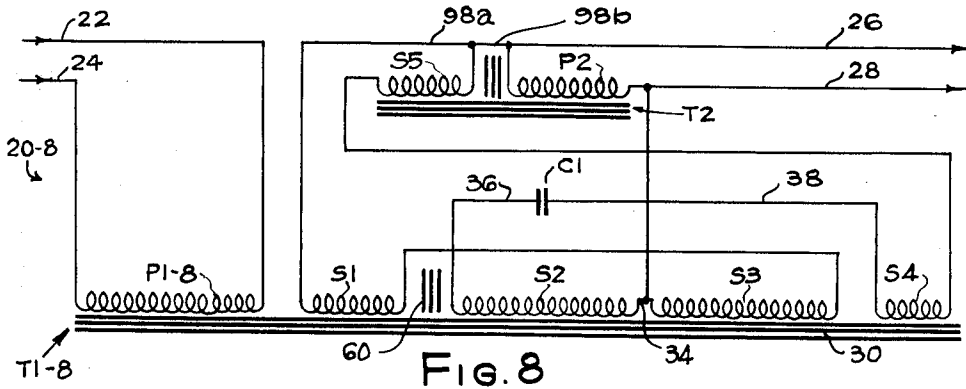
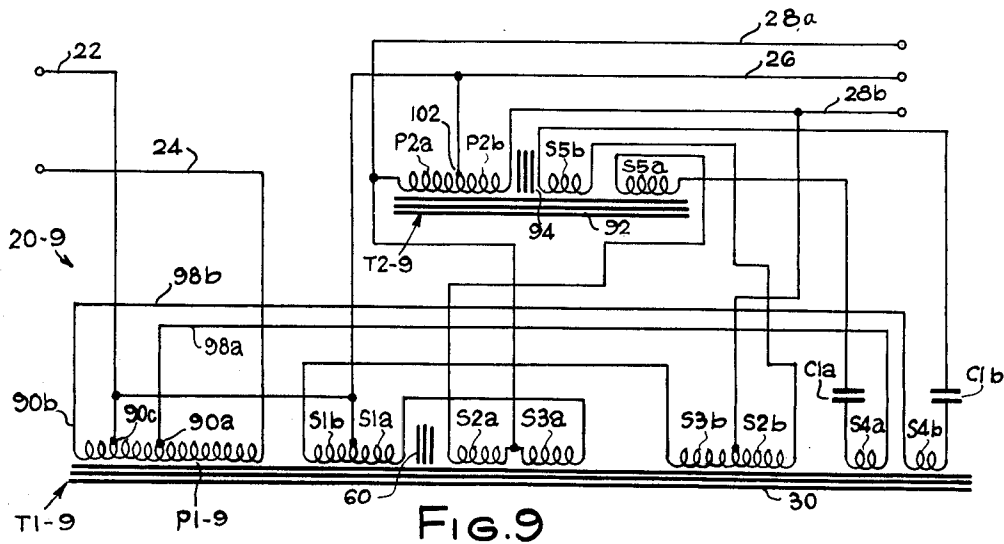
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5 Sheets-Sheet 3



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5 Sheets-Sheet 5

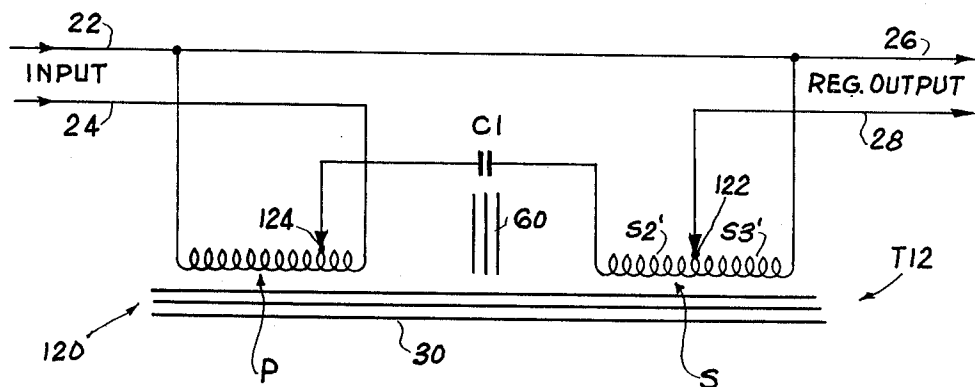


FIG. 12

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VOLTAGE REGULATORS

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23 Claims. (Cl. 323-45)

This is a continuation-in-part of application Serial No. 783,335, filed December 29, 1958, now abandoned.

This invention relates to voltage regulators of the type utilizing one or more electromagnetic transformers.

One object of the present invention is to provide a new and improved voltage regulator requiring only one transformer having a plurality of windings.

A further object is to provide a new and improved voltage regulator of the foregoing character which affords excellent voltage regulation, yet is small, light in weight, and low in cost.

Another object is to provide a new and improved voltage regulator in which power is supplied to the output circuit not only by the regulating transformer but also by a resonant circuit containing a condenser, the condenser current being a factor in the regulating action.

A further object is to provide a new and improved voltage regulator in which the regulating transformer is arranged so that some or all of the secondary windings of the transformer will have a high leakage reactance.

Another object is to provide a new and improved voltage regulator utilizing a single regulating transformer, plus a single auxiliary transformer to correct the output wave form so that it will be substantially a sine wave.

A further object is to provide a new and improved voltage regulator arranged to provide a balanced three wire output circuit having two line wires and a neutral wire, the voltages between the line wires and the neutral wire being half the voltage between the two line wires.

Another object is to provide a new and improved voltage regulator of the foregoing character which may be arranged for use as a distribution transformer, to step down a high input voltage to a relatively low voltage suitable for operation of household lamps and appliances.

Further objects and advantages of the present invention will appear from the following description, taken with the accompanying drawings, in which:

FIG. 1 is a schematic diagram showing a voltage regulator to be described as an illustrative embodiment of the present invention.

FIG. 2 is a diagrammatic elevational view showing not only the circuit of the regulator but also the layout of the windings and the laminated core of the regulating transformer.

FIG. 3 is an end view of the regulating transformer shown in FIG. 2.

FIG. 4 is a schematic circuit diagram of the regulator, the view being similar to FIG. 1 but rearranged to present certain aspects of the regulator with greater clarity.

FIG. 5 is a diagram showing oscillograms of the input and output voltages.

FIG. 6 is a vector diagram illustrating certain aspects of the operation of the regulator.

FIG. 7 is a schematic diagram showing a modified regulator adapted for use as a distribution step-down transformer, the regulator having a wave form correction transformer to provide a substantially sine wave output.

FIG. 8 is a schematic diagram of another modified regulator, similar to that of FIG. 7, but with the input circuit electrically isolated from the output circuit.

FIG. 9 is a schematic diagram of another modified regulator, similar to that of FIG. 7, but arranged to provide a balanced three wire output.

FIG. 10 shows another modified regulator, similar to

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that of FIG. 8, but adapted to provide a balanced three wire output.

FIG. 11 shows still another modified regulator, somewhat similar to that of FIG. 8 but again arranged to provide a balanced three wire output.

FIG. 12 illustrates a modified regulator similar to the regulator of FIGS. 1-6 but of simplified construction.

It will be seen that the regulator 20 of FIGS 1-4 employs a single regulating transformer T1 and a capacitor C1. The regulator 20 has input leads 22 and 24 which may be connected to a source of alternating current at any suitable voltage and frequency, such, for example, as 115 volts and 60 cycles. The regulator supplies a regulated output voltage across a pair of output leads 26 and 28. In this case, the output lead 26 is connected directly to the input lead 22.

While the construction of the transformer T1 may be varied to a considerable extent, the illustrated transformer has a single primary winding P1 and four secondary windings S1, S2, S3 and S4. All of the windings are mounted on a magnetic core or lamination 30.

All of the windings of the transformer T1 may be wound in the same direction. In FIGS. 1 and 2, the starting end of each winding is indicated by St, while the finishing end is indicated by F.

It will be seen that the starting and finishing ends of the primary P1 are connected to the input leads 22 and 24, respectively. The secondary windings S1 and S3 are connected in series across the output leads 26 and 28. However, the windings S1 and S3 are connected so that their induced voltages will buck each other. Thus, the starting end of S1 is connected to the output lead 26, and also to the input lead 22. A lead 32 is connected between the finishing end of S1 and the finishing end of S3. It will be seen that the starting end of S3 is connected to the output lead 28.

All of the secondary windings S1-S4 are employed to feed current through the condenser C1. Thus, S1, S3, S2, C1 and S4 are connected in series between the input leads 22 and 24. More specifically, a lead 34 extends between the starting end of S3 and the finishing end of S2. The starting end of S2 is connected to one side of the condenser C1 by a lead 36. The other side of the condenser C1 is connected to the starting end of S4 by a lead 38. A lead 40 extends between the finishing end of S4 and the input lead 24. It will be understood that the condenser C1 may be located elsewhere in the series circuit. Thus, it may be broken into either the lead 34 or the lead 40.

The physical layout of the transformer T1 is shown in FIGS. 2 and 3. The illustrated lamination 30 comprises a single, straight elongated leg 42 upon which all of the windings are mounted. To provide return paths for the magnetic flux, the core 30 includes a rectangular magnetic member 44 having four legs 46, 47, 48 and 49. It will be seen that the legs 46 and 48 are parallel to each other and are relatively elongated. The legs 47 and 49 are relatively short and are connected between the opposite ends of the legs 44 and 48. As shown, the central leg 42 extends between the end legs 47 and 49 and is parallel to the side legs 46 and 48.

In this case, the secondary winding S1 is closely coupled to the primary P1, while the secondaries S2, S3 and S4 are loosely coupled to the primary. Thus, the secondary S1 is immediately adjacent the primary P1. In fact, as shown in FIG. 3, it is wound over the primary P1. The secondaries S2, S3 and S4 are spaced from the primary P1, at successively increasing distances. As shown in FIG. 2, these secondaries are arranged end to end. The secondary S4 is on the opposite end of the central leg 42 from the primary P1. The arrows on the

windings in FIG. 2 indicate the winding directions, all of which may be the same.

The arrangement of the transformer T1 is such that the secondaries S2, S3 and S4 will have considerable leakage reactance. In part, this is due to the spacing between the primary P1 and the secondaries S2-S4. In addition, however, a joint 52 of relatively high reluctance is provided between the left-hand end of the central leg 42 and the end leg 47. The reluctance is provided by an air gap 54 between the end of the central leg 42 and the end leg 47. Of course, the air gap may be filled with nonmagnetic material. As shown, the left-hand end of the central leg 42 has tapered or beveled corners 56 which are in local engagement with the end leg 47. However, the area of engagement is small so as to maintain the high reluctance. It will be noted that the air gap 54 is at the end of the central leg 42 occupied by the primary P1. Accordingly, this air gap imparts leakage reactance to the secondaries S2, S3 and S4 and also, to some extent, to the primary P1

value of 20 microfarads. The following table gives the number of turns and wire size for each of the windings:

Winding	Number of Turns	Wire Gauge
P1-----	340	24
S1-----	67	20
S2-----	170	18
S3-----	255	18
S4-----	14	18

This regulator has sufficient capacity to operate a television receiver or other appliances. The voltage regulation of the output voltage is very good. Moreover, the input power factor is quite high. The output to input efficiency of the regulator is also very satisfactory. These facts are clearly shown by the following table, representing the results of a series of tests in which the input line voltage was varied from 95 to 135 volts:

Input Line Volts	Input Amp	Input Watts	Input Volt-Amp	Input Power Factor, percent	Output Volts	Output Amps	Output Watts	Output to Input Efficiency percent
95-----	2.05	188	194	97.0	111.0	1.43	153	81.4
100-----	2.29	223	229	97.4	123.5	1.52	182	81.5
105-----	2.32	228	243	94.0	124.0	1.51	184	80.6
110-----	2.34	231	254	91.0	124.0	1.51	184	79.6
115-----	2.34	233	269	96.5	124.0	1.51	184	78.9
120-----	2.33	235	280	84.0	124.0	1.51	184	78.4
125-----	2.32	238	290	82.0	123.5	1.52	184	77.4
130-----	2.31	241	300	80.4	123.0	1.53	184	76.3
135-----	2.30	244	310	78.8	123.0	1.54	185	76.0

and the secondary S1. A butt joint 58 is formed between the right-hand end of the central leg 42 and the end leg 49.

Additional leakage reactance is provided by magnetic shunts 60 and 62 which extend part way between the side legs 46 and 48 and the central leg 42. As shown, the shunts 60 and 62 take the form of projections on the side legs 46 and 48. Air gaps 64 and 66 are formed between the central leg 42 and the shunts 60 and 62. It will be seen that the shunts 60 and 62 are disposed between the primary P1 and the secondary S2. Thus, the shunts impart considerable leakage reactance to the secondaries S2, S3 and S4. Of course, the leakage is greater as to S3 and S4 than it is as to S2.

It will be noted that the secondaries S2 and S3 are connected so that their induced voltages are in phase with each other and with the input voltage across the input leads 22 and 24. The secondaries S1 and S4 are connected so as to buck the secondaries S2 and S3. Thus, the induced voltages in S1 and S4 are opposite in phase to those in S2 and S3. Of course, the condenser current passes through all of the secondaries S1-S4. In the operation of the regulator, a resonant or near resonant condition exists so that the condenser current is quite substantial. Thus, the condenser current causes voltage drops in the reactances of the secondaries S1-S4. With changing input line voltage, the saturation of the core 30 changes. This changes the leakage reactances of the windings and therefore changes the degree of resonance. All these factors are combined and balanced to provide a regulated output over a wide range of input voltage.

Of course, the regulator may be constructed in various sizes to handle various voltages and deliver various amounts of power. However, various details of a particular regulator will be of interest. This regulator was tested and was found to operate with a high degree of satisfaction with an output of about 185 watts at about 120 volts, and an input ranging from about 100 volts to 135 volts. This regulator employed a condenser having a

This regulator also has the advantage that the output voltage rises very little if the load is disconnected from the output. Thus, in one test, the output voltage with a load of 175 watts was 120 volts, while the output voltage with no load was only 121 volts.

Moreover, the condenser current is kept down to a reasonable level at no load. The primary current decreases substantially when the load is removed, so that the regulator does not overheat at no load. These facts are shown by the following table:

Line Volts	Primary Wire Current		Capacitor Current	
	Loaded, A.	No Load, A.	Loaded, A.	No Load, A.
90-----	.800	.330	1.60	2.70
100-----	.700	.240	1.95	2.85
110-----	.625	.200	2.20	3.00
120-----	.550	.185	2.40	3.10
130-----	.500	.200	2.60	3.30

FIG. 5 shows oscillograms 70 and 72 representing the wave forms of the input and output voltages, respectively. Of course, the input wave form is substantially a sine wave. The output wave form shows some harmonic content, due to the action of the condenser C1. Moreover, the phase of the output voltage is displaced from that of the input voltage.

FIG. 6 shows a series of vector diagrams illustrating certain aspects of the operation of the regulator. Each of these diagrams shows the input voltage, the output voltage, and the vector difference between the voltages. It has already been noted that the output voltage is the vector sum of the voltages across S1 and S3. The vector difference between output and input voltages is equal to the vector sum of the voltages across C1, S2 and S4. FIG. 6 shows successive vector diagrams for input voltages of 75, 85, 95, 105, 115, 125 and 135. It will be seen that the vector representing C1 plus S2 plus S4 increases substantially in length with increasing input voltage.

However, the phase of this vector changes considerably. This change in phase compensates for the change in magnitude, so that the magnitude of the output voltage remains substantially constant. Of course, the phase of the output voltage changes to a considerable extent.

It has already been indicated that the output of the regulator is taken across the secondaries S1 and S3. These windings are so phased that S1 bucks S3. In the illustrated regulator, S3 has nearly four times as many turns as S1. With a regulated output voltage of 118 volts, S3 may deliver 140 volts, while S1 is delivering 40 volts. The regulated output voltage is substantially greater than the simple difference (100 volts), because the voltages across S1 and S3 are somewhat less than 180 degrees out of phase. The relative phasing of the voltages across S1 and S3 changes with various values of input voltage to maintain the regulated output voltage at a substantially constant value. This phase shifting action is due to the condenser current and the inductive reactances of the secondary coils in the condenser circuit. S1 acts as a bucking winding at high input voltages and as an aiding winding at low input voltages. Thus, the action of S1 improves the regulation by pushing up the output voltage at low input voltages and by holding down the output voltage at high input voltages.

The bucking action of the secondary coils S1 and S4 is an important factor in limiting the condenser current at high values of input voltage. The secondary S1 is closely coupled to the primary P1, so that the bucking action of S1 is particularly pronounced. The loose coupling between the primary and S2, S3 and S4 also contributes to the stabilizing of the condenser current and the maintenance of a substantially constant output voltage. The provision of S4 makes it possible to reduce the value of C1 so that C1 will be physically smaller.

The arrangement of the secondary coils S1-S4 also provides output wave form correction, so as to minimize the departure of the output wave form from a sine wave. The bucking action of the coils S1 and S4 contributes to the improvement in wave form by limiting the condenser current at high values of input voltage. The inductive reactances of the secondary coils also improves the wave form. Still further correction of the wave form may be achieved by tapping down the lead 40 on the primary P1. This loosens the coupling between the input and the condenser circuit and also tends to improve the efficiency of the regulator.

The lamination or core 30 is of the "two window" type. Thus, the shunts 60 divide the opening in the rectangular core member 44 into two portions or windows 80 and 82. The primary P1 and the secondary S1 are disposed in the window 80. These windings may be wound in one operation as one coil unit 84. The secondaries S2, S3 and S4 are disposed in the second window 82. Here again, these coils may be wound in one operation as a second coil unit 86. Thus, the provision of only two windows simplifies the winding of the coils, so that only two basic coil units are needed.

The series circuit comprising the coils S1, S2, S3 and S4 and the condenser C1 is energized directly from the input leads 22 and 24. Accordingly, current flows in this series resonant circuit, even without the aid of the primary P1. Thus, in a real sense, the circuit comprising S1, S2, S3 and S4 constitutes a second primary circuit. Additional inductive excitation is provided by the primary P1. As already noted, the primary P1 is quite loosely coupled to S2, S3 and S4. While the excitation afforded by the primary furnishes a high degree of regulation in the output voltage, the primary handles only a portion of the power delivered to the output circuit. Thus, the primary losses and the transformer losses are minimized. This improves the efficiency of the regulator and reduces the heat generated therein. This factor also minimizes the amount of core material and wire that must be employed in the transformer. Accordingly, the size, weight and cost of the transformer are reduced. The direct cou-

pling of the secondary coils to the input also provides faster response time, so that the regulator quickly accommodates itself to abrupt changes in input voltage.

The regulator provides excellent voltage regulation under a variety of load conditions. Thus, various appliances having different power requirements may be operated by the regulator. Even at no load, the output voltage of the regulator rises only slightly from the full load value.

If the output of the regulator is accidentally short circuited, the regulator is thrown out of resonance, so that the output current does not increase excessively. This protects both the regulator and the appliance from damage. The power input to the regulator actually is reduced with a short-circuited output.

As already indicated, the regulator may be arranged to operate at any input voltage and frequency, and at any output voltage. S2 and S3 may constitute a single winding with a tap thereon. The output voltage may be varied by changing the position of the tap. In effect, the lead 34 constitutes a tap between S2 and S3. This tap may be moved to any desired point on these windings.

Two or more of these regulators may be connected in parallel to increase the load capacity. The total load capacity is equal to the sum of the individual load capacities of the regulators. The regulators are connected in parallel simply by connecting the corresponding input and output leads together. Of course, the leads must be properly phased. The regulators may also be connected in various two-phase, three-phase or polyphase arrangements.

FIG. 7 illustrates a somewhat modified regulator which will be designated 20-7. Except as indicated below, this regulator may be the same as FIGS. 1-3. Corresponding components of the regulators 20 and 20-7 have been given the same reference characters.

The regulator 20-7 differs from the regulator 20 in two principal respects. First, the regulator 20-7 is adapted to step-down a high input voltage to a relatively low output voltage. Thus, the regulator may be employed as a distribution transformer. The input voltage may be any suitable value, such as 2300, 13,000, or the like. The output may be the 120 volts, 230 volts, or any other suitable value. The regulator is adapted for use as a distribution transformer by providing a slightly modified regulating transformer T1-7. This transformer differs from the transformer T1 in that it has a high voltage primary winding P1-7. As before, the starting end of S1 is connected to the starting end of P1-7. However, the primary P1-7 has a tap 90 which is employed to excite the condenser circuit, so that only a portion of the input voltage is applied to the condenser circuit.

The second difference between the regulators 20-7 and 20 resides in the fact that the regulator 20-7 is provided with a second transformer T2 adapted to correct the wave form of the output voltage, so that the output wave form will be substantially a sine wave. The illustrated transformer T2 has a primary P2 and one secondary S5, both of which are wound on a magnetic core 92. It will be seen that the core 92 has a magnetic shunt 94 between the primary P2 and the secondary S5, so that the secondary will be loosely coupled to the primary. Thus, both the primary and the secondary have substantial leakage reactances.

In order to minimize harmonic current through the condenser C1, the secondary S5 is connected in series with the condenser circuit. In this case, the finishing end of S4 is connected to one end of S5 by a lead 96. The other end of S5 is connected to the primary tap 90 by a lead 98. It will be understood that S5 might be connected elsewhere in the series condenser circuit. The inductive reactance of S5 reduces the harmonic content of the condenser current, and thus improves the output wave form.

It will be seen that the primary P2 is connected direct-

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ly between the output leads 26 and 28. The harmonic content in the output voltage is thus fed back into the condenser circuit, by the electromagnetic transforming action between P2 and S5. The feed back is phased so as to be negative or out of phase. In this way, the harmonic content in the output voltage and the harmonic component of the condenser current cancel or buck each other. Thus, the provision of the transformer T2 results in an output wave form which is substantially sinusoidal. The sine wave output makes the regulator 20-7 particularly applicable as a distribution transformer.

FIG. 8 illustrates another modified regulator 20-8 which is similar in most respects to the regulator of FIG. 7. The principal difference between the regulators 20-8 and 20-7 resides in the fact that the regulator 20-8 has a slightly modified regulating transformer T1-8 with a primary winding P1-8 which is isolated or floating, with respect to the output leads 26 and 28. Thus, there is no electrical connection between the input leads 22 and 24 and the output leads 26 and 28. The input leads 22 and 24 are simply connected across the primary P1-8. This arrangement contributes an additional safety factor, in that the input circuit, which may be at a high voltage, is not electrically connected to the output circuit. Thus, the transformer may be arranged to step-down an extremely high voltage, such as 2300 or 13,000 volts, to a relatively low voltage, such as 115 or 230 volts.

In the regulator 20-8, the lead 98 is replaced with a lead 98a, to connect the right-hand end of the secondary S5 to the starting end of S1. A lead 98b runs from the lead 98a to the output lead 26. Thus, the leads 98a and 98b complete the output circuit and the condenser circuit. In this case, the condenser circuit is energized entirely by the voltages induced in the secondaries S2 and S3. The action of the bucking secondaries S1 and S4 is the same as previously described.

FIG. 9 illustrates a modified regulator 20-9, which is the same as the regulator 20-7, except for modifications to provide a balanced three-wire output. In general, the balanced output is obtained by providing an additional set of regulator components connected in the same manner as the original set. The output of the additional regulator components is connected additively in series with the output of the original components. The two outputs share one lead in common, to provide a center tap or neutral wire.

In the regulator 20-9, the output lead 26 is shared to provide the neutral wire. The output lead 28 is replaced with two leads 28a and 28b delivering voltages which are balanced with respect to the neutral lead 26.

The regulator 20-9 has a somewhat modified regulating transformer T1-9, which is provided with two sets of secondary windings. Each set comprises four secondaries, as before. The secondaries of the first set are designated S1a, S2a, S3a and S4a. Similarly, the secondaries of the second set are designated S1b, S2b, S3b and S4b. It will be seen that the starting end of S1a is connected to the finishing end of S1b, and also to the input lead 22, as in FIG. 7. In this case, two condensers C1a and C1b are provided. The regulator 20-9 has a somewhat modified correction transformer T2-9 having two primaries P2a and P2b and two secondaries S5a and S5b. It will be seen that the primary P2a is connected between the leads 28a and 26, while the primary P2b is connected between the leads 26 and 28b. As shown, the windings P2a and P2b may actually comprise a single center tapped winding, the neutral lead 26 being connected to the center tap 102. The neutral lead 26 is also connected to the input lead 22 and the starting end of S1a, as before.

The transformer T1-9 has a somewhat modified primary winding P1-9. In this case, the input lead 22 is connected to a tap 90c near the starting end of the primary P1-9. This tap 90c serves, in effect, as a center

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tap between the starting end 90b and another tap 90a, spaced up the winding P-9 from the tap 90c. The resonant circuits for the condensers C1a and C1b have return leads 98a and 98b which are connected to the coil taps or terminals 90a and 90b. With this arrangement, oppositely phased voltages, derived from the primary winding P1-9, are fed into the circuits for the condensers C1a and C1b.

The secondaries S1a, S3a, S2a, S4a and S5a and the condenser C1a are connected much the same as the corresponding components in FIG. 7. This is also true of the components S1b, S3b, S2b, S4b, S5b and C1b, except the polarities of all windings are reversed. Thus, the secondaries S1a and S3a are connected in a bucking series circuit between the leads 26 and 28a. Likewise, the secondaries S1b and S3b are connected in a bucking series circuit between the leads 26 and 28b.

All of the secondaries S1a, S3a, S2a, S5a, and S4a are connected in series with the condenser C1a between the primary terminals 90c and 90a. In this case, the condenser C1a is disposed in the series circuit between the windings S4a and S5a. The windings S1b through S5b are similarly connected in series with the condenser C1b across the primary terminals 90c and 90b.

It will be appreciated that the input lead 22 could be connected to the end lead 90b, but the illustrated arrangement has the advantage of permitting both the input lead 22 and the neutral output lead 26 to be grounded. With the illustrated arrangement, equal but oppositely phased voltages appear between the leads 28a and 28b and the neutral 26. The voltage between the leads 28a and 28b is twice the voltage between either lead and the neutral.

FIG. 10 illustrates another modified regulator 20-10 which is similar to the regulator 20-9 of FIG. 9, except that the primary arrangement is similar to that of the regulator 20-8 of FIG. 8. Thus, the regulator 20-10 employs a regulating transformer T1-10 with a primary P1-8 which is the same as described in connection with FIG. 8. The input leads 22 and 24 are connected across the primary P1-8, but are entirely isolated from the output leads 26, 28a and 28b. In this case, the neutral output lead 26 is connected directly to the ends of the secondaries S1a and S1b by a lead 106. A lead 108 runs between the output lead 26 and the ends of the secondaries S4a and S4b. It will be noted that the leads 106 and 108 connect the ends of the secondaries S1a and S1b to the ends of the secondaries S4a and S4b. Otherwise, the regulator circuit is the same as described in connection with FIG. 9.

It will be noted that the secondaries S1a and S1b of FIG. 10 may be formed as a single center tapped winding. This is also true of the secondaries S4a and S4b. The secondaries S2a and S3a may be wound as a single tapped coil. The same is true of the secondaries S2b and S3b.

FIG. 11 illustrates still another modified regulator 20-11 which also provides a balanced three-wire output across leads 26, 28a and 28b. The regulator 20-11 actually comprises two regulators of the type shown in FIG. 8. In FIG. 11, the regulators are designated 20-8a and 20-8b. In this case, the inputs of the regulators are connected in parallel, while the outputs are connected additively in series. The output lead 26 is shared by both regulators to form a neutral which may be grounded.

In all of the regulators, the fourth secondary S4 of the regulating transformer may be omitted in many cases. The leads that would run to these windings are then simply connected together. Omission of this winding tends to increase the capacitor current and voltage at high input voltages, but in some cases this can be tolerated.

FIG. 12 illustrates a simplified voltage regulator 120 which is somewhat similar to the regulator 20 of FIG. 1.

However, both S1 and S4 have been omitted. Moreover, S2 and S3 have been combined to form a single secondary S, having a tap 122, corresponding to the lead 34 between the secondaries S2 and S3 in FIG. 1. The portions of the secondary S corresponding to S2 and S3 have been designated as S2' and S3' in FIG. 12.

The regulator 120 has a primary winding P which corresponds to the primary P1 of FIG. 1, except that the primary P may have a tap 124. It will be seen that the input leads 22 and 24 are connected directly across the primary P. The output leads 26 and 28 are connected across the coil S3', constituting a portion of the secondary winding S. It will be understood that the output may be connected across all or any portion of the secondary S, depending upon the desired output voltage.

The resonant series circuit comprising the capacitor C1 and the secondary winding S may be connected directly across the input, but, in the arrangement of FIG. 12, this resonant circuit is connected to the tap 124 and thus is connected to only a portion of the primary winding P. Thus, a series circuit may be traced from the tap 124 through the capacitor C1 and the secondary winding S to the input lead 22. This series circuit is connected across the portion of the primary winding P between the tap 124 and the input lead 22.

It will be understood that the portion of the input voltage between the tap 124 and the lead 22 produces current through the series circuit comprising the capacitor C1 and the secondary winding S. Additional excitation is supplied to the secondary S by virtue of the inductive coupling between the primary winding P and the secondary S. Due to the spacing between the primary P and the secondary S, and also due to the provision of the magnetic shunt 60, the coupling between the primary P and the secondary S is quite loose. Thus, the secondary S has a high leakage reactance. The combined effect of the capacitive coupling and the loose inductive coupling produces the voltage regulating effect, so that very little change in the output voltage occurs, even when the input voltage across the leads 22 and 24 varies widely.

Only a portion of the energy is transmitted to the output circuit by the transformer T12, comprising the primary P and the secondary S. The remaining portion of the energy is transmitted by the capacitor C1. Thus, the transformer T12 may be made with a smaller amount of materials, both copper and iron, than would normally be the case. Moreover, the losses in the transformer are relatively low. Thus, the regulator is efficient in operation and low in cost.

The capacitor current through the secondary S is phased in such a manner that the magnetic flux produced by the capacitor current tends to oppose the flux produced by the primary winding. This action reduces the total magnetic flux in the iron core 30 so that a relatively small core may be employed.

If the output is accidentally short-circuited, this merely has the effect of short-circuiting S3', which is only a portion of the secondary S. Due to the high leakage reactance of S3', the short-circuited current through S3' is quite low. Moreover, the short-circuiting of S3' throws the series circuit, comprising the capacitor C1 and the secondary S, out of resonance so that the input current to the regulator does not increase appreciably and may actually decrease.

Although the winding S has generally been referred to as a secondary, it constitutes, in a real sense, a second primary, fed directly from the input by the condenser C. Current will flow through the series circuit, comprising C and S, independently of the induced excitation from the winding P.

By moving the tap 122, the output may be connected across all or any portion of the winding S. This will change the output voltage.

By moving the tap 124, the series resonant circuit, comprising C1 and S, may be connected across all or any

portion of the winding P. Tapping down this series circuit on the primary P loosens the coupling between the input and the series circuit and tends to improve the wave form of the output voltage, as well as improving the efficiency of the regulator. The regulator may provide either a voltage step-down or a voltage step-up, according to the positions of the taps 122 and 124, and the number of turns in the windings.

It will be evident that the regulators of the present invention provide excellent voltage regulation, yet are remarkably simple, small in size, light in weight and low in cost. The regulators operate with a high degree of efficiency. The regulated output voltage is maintained with a high degree of accuracy, despite wide variations in the input voltage and the load. The regulators may be arranged to deliver a substantially sinusoidal output.

Various other modifications, alternative constructions and equivalents may be employed without departing from the true spirit and scope of the invention, as exemplified in the foregoing description, and defined in the following claims.

I claim:

1. In a voltage regulator, the combination comprising a transformer having a magnetic core, a primary winding and first, second, third and fourth secondary windings on said core, said first secondary winding being adjacent and closely coupled to said primary winding, said second, third and fourth secondary windings being spaced along said core successively farther from said primary winding, said core having a magnetic shunt disposed between said primary winding and said second, third, and fourth secondary windings to afford loose coupling between said primary winding and such secondary windings while imparting high leakage reactance to such secondary windings, first and second input leads connected across said primary winding, first and second output leads, an output circuit connecting said first and third secondary windings in series across said output leads, said first secondary winding being phased to buck said third secondary winding, a resonating condenser, a condenser circuit connecting all of said secondary windings in series with said condenser, said second and third secondary windings being phased to aid each other, said first and fourth secondary windings being phased to buck said second and third secondary windings in said condenser circuit.

2. The combination of claim 1, with a second transformer having a secondary winding connected in series with said condenser circuit to reduce harmonic current therein, said second transformer having a second magnetic core, said secondary winding of said second transformer being mounted on said core, a secondary primary winding mounted on said core and connected across said output leads to feed back harmonics from said output leads to said condenser circuit and thereby effect mutual cancellation of the harmonic content in the output voltage and the condenser current, said second core having a magnetic shunt disposed between said second primary winding and said secondary winding of said second transformer.

3. The combination of claim 1, with a second similar regulator having input leads connected in parallel with the input leads of the first regulator, said second regulator having one output lead shared in common with said first regulator, and an additional output lead to provide a balanced three-wire output, said second regulator having its output circuit connected additively in series with the output circuit of the first regulator.

4. In a voltage regulator, the combination comprising a regulator transformer having a magnetic core, a primary winding and four secondary windings mounted on said core, said core having magnetic shunt means imparting inductive reactance to at least some of said secondary windings, first and second input leads connected across said primary winding, first and second output leads, an output circuit connecting two of said secondary windings in series across said output leads, one of the secondary

windings in said output circuit being phased to buck the other, a condenser, and a condenser circuit connecting all of said secondary windings in series with said condenser to provide circulating current in said condenser circuit, two of the secondary windings in said condenser circuit being phased to buck the other two secondary windings.

5. The combination of claim 4, with a second transformer comprising a magnetic core having a second primary winding and an additional secondary winding thereon, said additional secondary winding being connected in series with said condenser circuit, said second primary winding being connected across said output leads to effect mutual cancellation of the harmonic content in the output voltage and the condenser current.

6. The combination of claim 4, with a second similar regulator having its input leads connected in parallel with the input leads of the first regulator, and the output leads of the second regulator connected additively in series with the output leads of the first regulator, one output lead thereby being shared by both regulators to provide a balanced three-wire output.

7. The combination of claim 4, in which said primary winding is provided with a tap, and in which said condenser circuit includes the portion of said primary winding between said tap and one end thereof.

8. The combination of claim 4, in which said input leads are connected in series with said condenser circuit.

9. The combination of claim 4, with four additional secondary windings on said core, each of said additional windings corresponding to one of said first mentioned four windings, an additional condenser, an additional pair of output leads, and means connecting said additional secondary windings with said additional condenser and said additional output leads in the same manner as said first mentioned secondary windings, condenser and output leads, said additional output leads being connected additively in series with said first mentioned output leads to provide a balanced three-wire output.

10. In a voltage regulator, the combination comprising a transformer having a magnetic core, a primary winding and a plurality of secondary windings mounted on said core, at least one of said secondary windings being loosely coupled to said primary winding to impart inductive reactance to such secondary windings, an circuit connected to said primary winding, a pair of output leads, an output circuit connecting two of said secondary windings in series across said output leads, said secondary windings in said output circuit being phased to buck each other, a condenser, and a condenser circuit connecting all of said secondary windings in series with said condenser, at least one of the secondary windings in said condenser circuit being phased to buck the other windings.

11. The combination of claim 10, in which said condenser circuit includes at least a portion of said primary winding.

12. The combination of claim 10, in which said input circuit is connected in series with said condenser circuit.

13. The combination of claim 10, with a second transformer including a second magnetic core having a second primary winding and an additional secondary winding thereon, said additional secondary winding being connected in said condenser circuit, said second primary winding behind connected to said output circuit to effect mutual cancellation of harmonics in said output circuit and said condenser circuit.

14. The combination of claim 10, with additional similar regulator components having output leads connected additively in series with the output leads of the first regulator to provide a balanced three-wire output.

15. In a voltage regulator, the combination comprising a transformer having a magnetic core, a primary

winding and four secondary windings mounted on said core, said core having magnetic shunt means imparting inductive reactance to at least some of said secondary windings, first and second input leads connected across said primary winding, first and second output leads, an output circuit connecting two of said secondary windings in series across said output leads, one of said secondary windings in said output circuit being phased to buck the other, a condenser, and a condenser circuit connecting at least a portion of said primary winding and all of said secondary windings in series with said condenser to provide circulating current in said condenser circuit, two of said secondary windings in said condenser circuit being phased to buck the other two secondary windings.

16. In a voltage regulator, the combination comprising a transformer having a magnetic core, a first winding on a first portion of said core, a second winding on a second portion of said core and loosely coupled to said first winding, input means for producing a voltage across said first winding, a capacitor, a closed circuit connecting said capacitor and said second winding in series with at least a portion of said first winding to form a closed loop, and an output circuit connected to at least a portion of said second winding.

17. The combination of claim 16, in which said input means comprise an input circuit connected across at least a portion of said first winding.

18. The combination of claim 16 in which said input means comprise an input winding on said first portion of said magnetic core and closely coupled to said first winding.

19. The combination of claim 16, including a magnetic shunt between said first and second windings to loosen the coupling therebetween.

20. In a voltage regulator, the combination comprising a transformer having a magnetic core, a primary winding on said core, a pair of input terminals connected across said primary winding, a secondary winding on said core and loosely coupled to said primary winding, a capacitor, a circuit connecting said capacitor and said secondary winding in series across said primary winding to form a closed loop therewith, said primary and secondary windings being additively phased around said loop, and a pair of output terminals connected across at least a portion of said secondary winding.

21. In a voltage regulator, the combination comprising a transformer having a magnetic core, a first winding on a first portion of said core, a second winding on a second portion of said core and loosely coupled to said first winding, input means for producing a voltage across said first winding, a capacitor, and a closed circuit connecting said capacitor and said second winding in series with at least a portion of said first winding to form a closed loop.

22. In a voltage regulator, the combination comprising a transformer having a magnetic core, a first winding on a first portion of said core, a second winding on a second portion of said core and loosely coupled to said first winding, input means for producing a voltage across said first winding, a capacitor, a closed circuit connecting said capacitor and said second winding in series with at least a portion of said first winding to form a closed loop, and means for deriving an output voltage from said second winding.

23. In a voltage regulator, the combination comprising a transformer having a magnetic core, a first winding on a first portion of said core, a second winding on a second portion of said core and loosely coupled to said first winding, input means for producing a voltage across said first winding, a capacitor, a closed circuit connecting said capacitor and said second winding in series with at least a portion of said first winding to

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form a closed loop, and output means for deriving an output voltage from said transformer.

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