Dec. 31, 1968 J. C. MAY 3,419,788

AUTOMATIC VOLTAGE REGULATOR

Filed Dec. 28, 1964 Sheet 1 of 3

Fig. 1

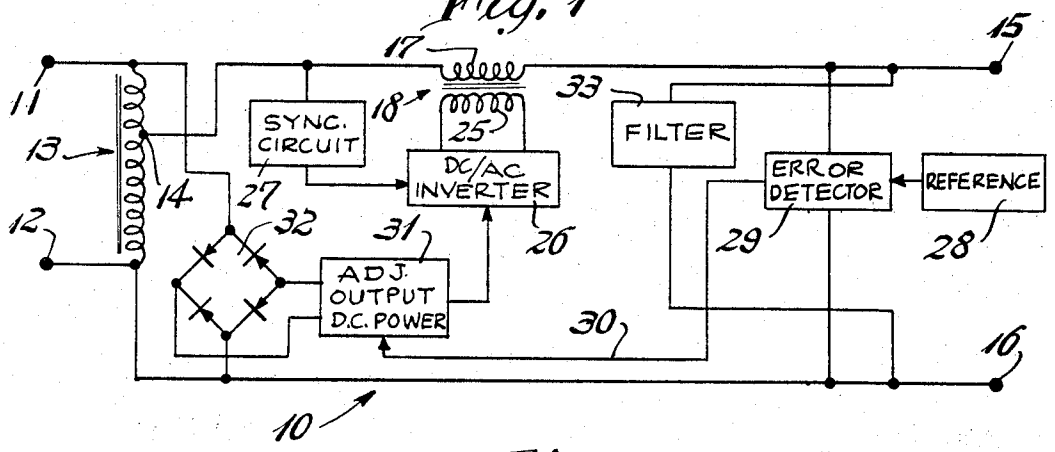


Fig. 2

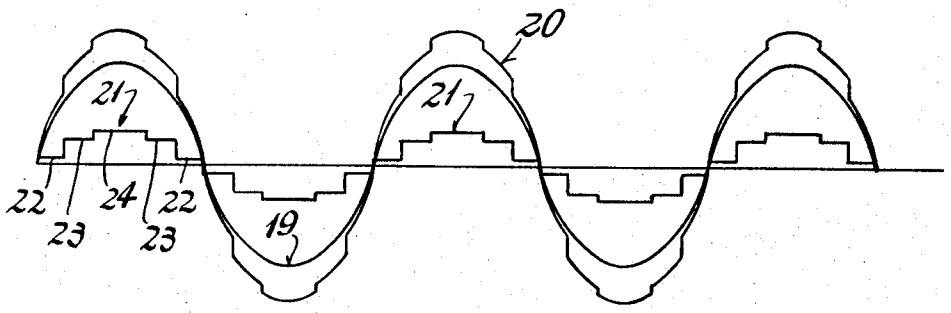
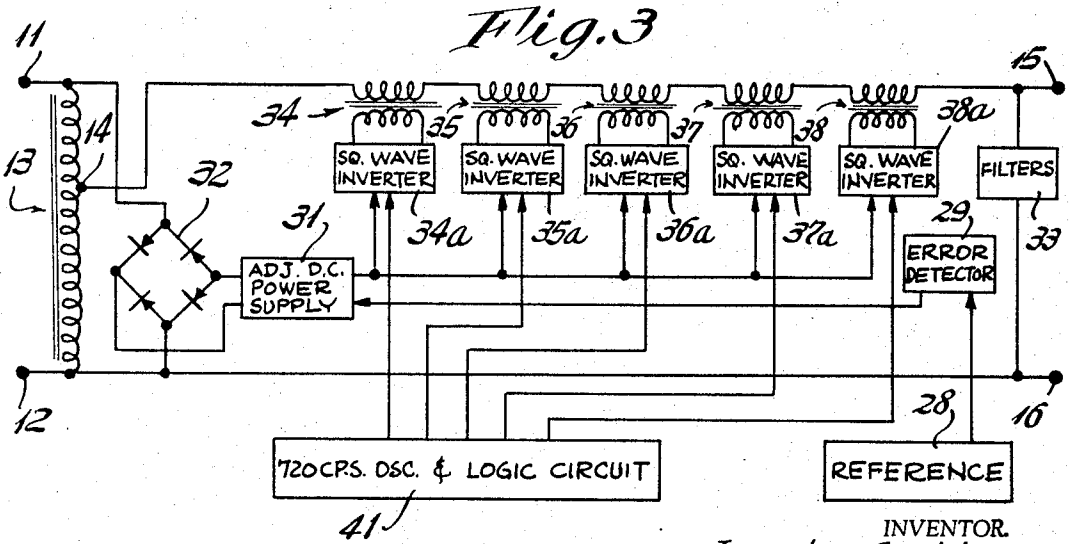


Fig. 3

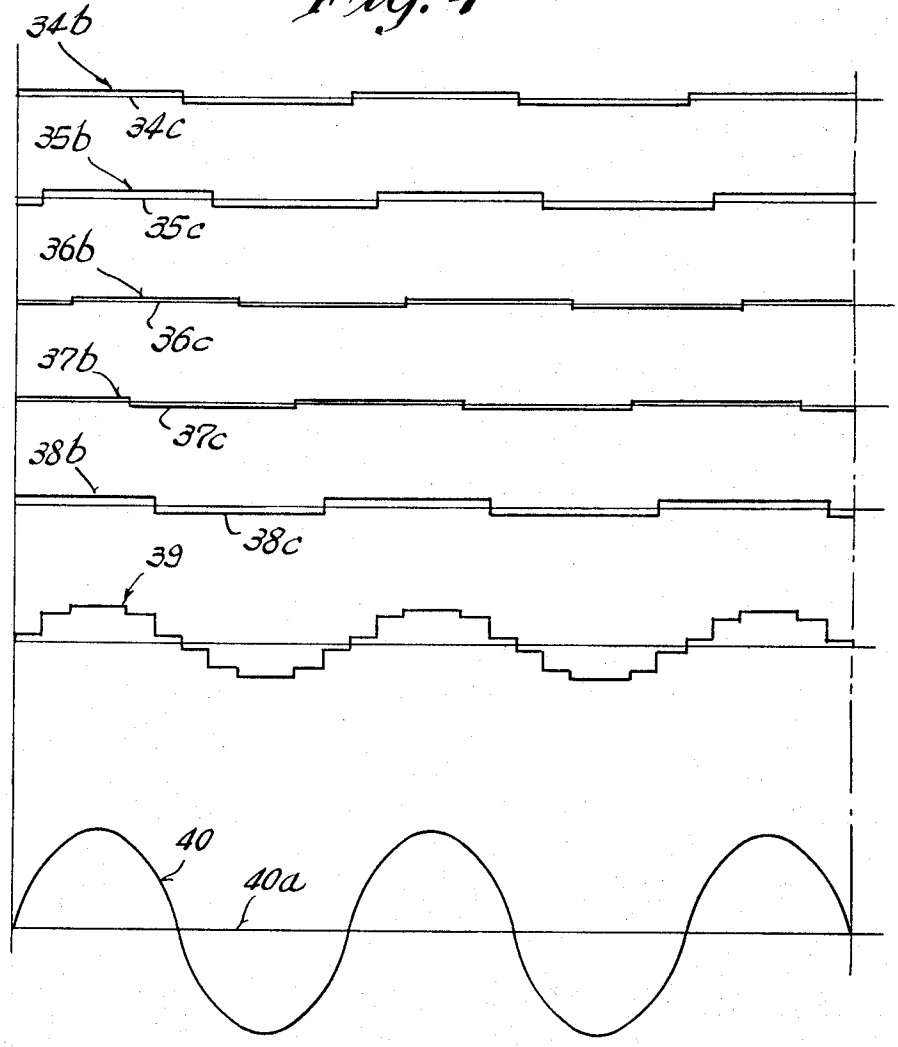


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Fig. 4



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Fig. 5

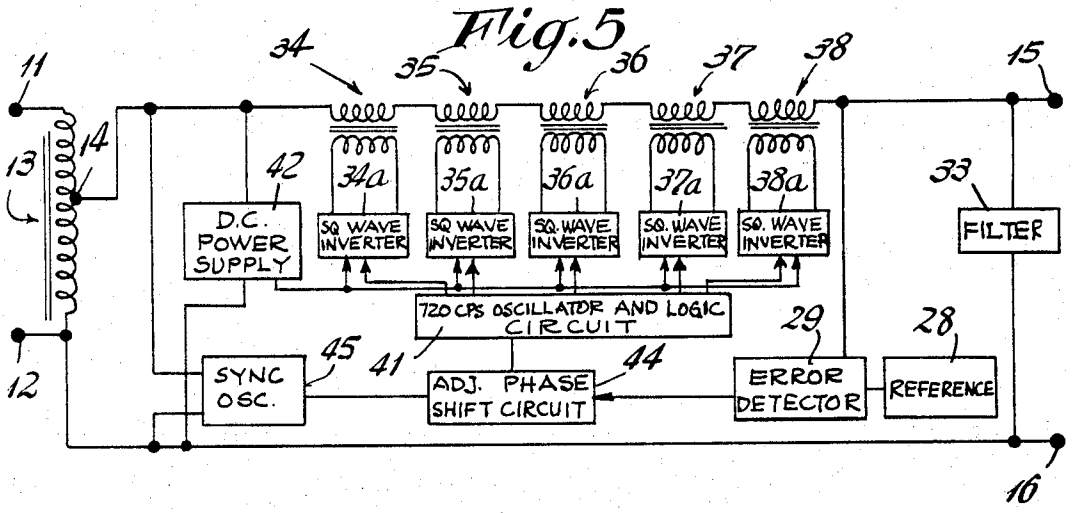


Fig. 6

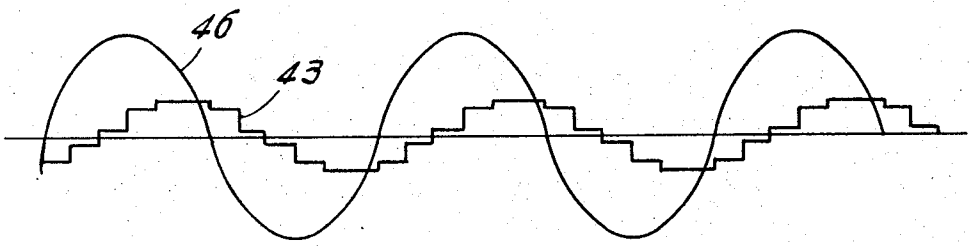
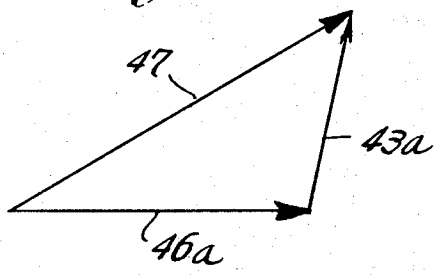


Fig. 7



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AUTOMATIC VOLTAGE REGULATOR

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ABSTRACT OF THE DISCLOSURE

An automatic voltage regulator for producing a substantially constant A.C. output voltage by initially providing an intermediate voltage and algebraically adding thereto an alternating voltage derived from a D.C. source and consisting of a stepped approximation of a sine wave whose value, either in amplitude or phase, is varied as required to maintain the desired value of output voltage.

The present invention relates to an alternating current automatic voltage regulator for maintaining the value of an output voltage substantially constant with changes in the input voltage and the power controlled by the regulator.

While it has heretofore been proposed to provide regulators which maintain a substantially constant output voltage, in many respects these regulators have not been found completely satisfactory. Many regulators have heretofore employed moving parts, such as slip rings, relays, etc. which inherently are objectionable by reason of mechanical wear or action. In addition, other regulators have employed devices such as inductive impedances which are also inherently somewhat slow acting and therefore decrease the time in which the output voltage may be corrected to its desired value with an abrupt change in the input voltage.

An object of the present invention is to provide an alternating current regulator which is quite rapid in correcting the output voltage to its desired value when a change in the input voltage occurs.

Another object of the present invention is to provide an automatic voltage regulator which provides an output of alternating voltage which is relatively low in distortion and which is quite efficient in operation.

A further object of the present invention is to provide an automatic voltage regulator which achieves the above objects but yet which presents a low internal impedance thereby enabling three phase alternating current to be regulated by a regulator for each phase thereof.

Still another object of the present invention is to provide an automatic voltage regulator which may include semiconductor devices but yet the devices are basically caused to function as on-off switches rather than as amplifying devices.

In carrying out the present invention the automatic voltage regulator includes a pair of input terminals connectible to a source of alternating current and a pair of output terminals at which the output voltage that is maintained substantially constant appears. The input voltage is initially altered to an intermediate value of alternating current and in the specific embodiment shown is preferably substantially the minimum value which the output voltage may have with the maximum input voltage. Added to the intermediate voltage is an alternating current which is derived from a source of direct current and is formed to approximate a sine wave similar to the sine wave of the input and intermediate voltages in order to have an output voltage that is substantially a sine wave. More specifically, the added voltage is a stepped approximation of a sine wave having a plurality of levels preferably at least three. Thus the output voltage consists of the intermediate voltage with which is combined the alternating current stepped voltage to produce the desired value of output voltage.

In order to maintain the value of the output voltage at that desired, the regulator includes an error detector which produces a signal that is indicative of the deviation of the output voltage from a known value with the known value being either the value of the output voltage desired or a different value of voltage bearing a relationship to the desired value of output voltage. The signal controls the value of the voltage of the stepped alternating current that is added to the intermediate voltage and in one embodiment of the invention the signal is employed to control the amplitude of the stepped alternating current and by adding the intermediate voltage and the stepped alternating current in phase with each other, the value of the output voltage may accordingly be changed by the change in the amplitude of the latter voltage. In another embodiment of the present invention the amplitude of the stepped alternating current is maintained constant but its phase is altered with respect to the phase of the intermediate voltage and accordingly the value of the output voltage is changed by changing the relationship of the phases between the two voltages.

Other features and advantages will hereinafter appear.

In the drawing:

FIGURE 1 is a block and schematic diagram of one embodiment of the automatic voltage regulator of the present invention.

FIG. 2 is a view of voltage wave forms which exist in the regulator.

FIG. 3 is a schematic and block diagram of a further embodiment of the present invention.

FIG. 4 is a plurality of voltage wave forms which appear in the regulator of FIG. 3.

FIG. 5 is a further embodiment of the regulator of the present invention.

FIG. 6 is a view of various voltage wave forms which occur in the regulator of FIG. 5.

FIG. 7 is a vector diagram of the phase relationship of the voltages in the regulator of FIG. 5.

Referring to FIG. 1, the automatic voltage regulator disclosed therein is generally indicated by the reference numeral **10** and includes a pair of input terminals **11** and **12** that are connectible to a source of alternating current, such as the usual 110 volt, 60 cycle having a sine wave form. The input terminals are connected across the winding of an autotransformer **13** having an intermediate tap **14**. The output voltage of the regulator appears at output terminals **15** and **16** with the terminal **16** being in effect connected to the input terminal **12** while the terminal **15** is connected to the tap **14** through a lead that includes a primary winding **17** of a transformer **18**.

It will be appreciated that with the structure set forth above that there is produced in the primary winding **17** an intermediate voltage which is less than the input voltage and as the former has a sine wave form, the latter also has a sine wave form and this wave form of the intermediate voltage is indicated in FIG. 2 by the reference numeral **19**. The output voltage wave form excepting minor percentages of harmonics and distortion, in FIG. 2, is indicated by the reference numeral **20** and consists of the intremediate voltage **19** combined with an alternating current that has the shape shown by the wave form **21**.

The wave form **21** is generally referred to as a stepped approximation of a sine wave with each half cycle including end portions **22** which have a value of .225 of the maximum value of the voltage of the wave form **21**; an intermediate portion **23** which may have a value of .770; and a top portion **24** which may have a value of about unity. Preferably, as shown, the maximum amplitude of the stepped wave form **21** is about one-fourth the maxi-

mum value of the output voltage wave form **20** in order to enable the regulator to have a relative wide range of values of output voltage from which one is chosen to be maintained constant with changes in the input voltage values also over a relatively large range.

As shown in FIG. 2, the output voltage wave form **20** results from the addition of the wave forms **19** and **21**. The value of the output voltage may thus be changed by changing the amplitude of the wave form **21**. In this embodiment both the wave forms **19** and **21** are in phase with each other. It is also noted that the portions **22** are each substantially 30°, the portions **23** each substantially 30° and the portion **24** substantially 60° of the 180° of each half cycle.

Referring to FIG. 1, the wave form **21**, as the stepped alternating current, is made to appear in the secondary winding **25** of the transformer **18** and is the output of a D.C. to A.C. inverter **26**. The inverter **26** preferably may include a plurality of transistors or other semiconductor devices which are switched on and off by a synchronous circuit **27** that not only maintains the stepped alternating current from the inverter **26** in synchronism with the intermediate voltage **19** but also serves to maintain for each half cycle the duration of the portions **22, 23** and **24**. For controlling the amplitude of the stepped alternating current, the regulator includes a reference source **28** that is connected to an error detector **29** with the latter being connected across the output terminals **15** and **16**. The error detector **29** produces a signal in a lead **30** to an adjustable output direct current power supply **31**. A source of direct current is derived from the input terminals by means of a full wave bridge **32**.

With the above structure, the reference source **28**, which may be adjustable to change the value of the output voltage desired to be maintained constant, produces an electrical value which is combined in the error detector with an electrical value related to the actual value of the output voltage to produce in the lead **30** a signal which is indicative of the difference between the output voltage value and the reference signal. The signal may be either a change in polarity or may be a greater or lesser value of current or voltage. The adjustable output D.C. power supply **31** increases its output power when the signal indicates that the output voltage is too low to thereby increase the amplitude of the stepped alternating current wave form **21** or decrease the amplitude thereof when the signal indicates that the value of the output voltage is greater than that desired.

It has been found that the use of a stepped alternating current only introduces a small percentage of distortion in the output voltage and the distortion is generally of the higher harmonics of the frequency of the sine wave. These higher harmonics may be effectively reduced by the use of a filter **33** connected across the output terminals tuned to the frqeuencies of the higher harmonics. It will thus be appreciated that with the present invention the percentage of the output current which consists of unwanted harmonics and is sometimes referred to as distortion is relatively small in comparison with other type regulators and accordingly enables the present regulator to operate quite efficiently.

In the regulator shown in FIG. 3 the same result is achieved as that shown in FIG. 2 in that the output voltage consists of an intermediate voltage which is combined with a stepped approximation of a sine wave. The regulator, as in the regulator shown in FIG. 1, includes many identical parts such as input terminals **11** and **12** connected to the same source of alternating current and to an autotransformer **13** having a tap **14** and output terminals **15** and **16**. In addition there is the full wave rectifying bridge **32** connected to the adjustable output D.C. power supply **31**, the reference source **28** and the error detector **29** together with the filter **33**. However, in place of the single transformer **18** there is provided in the connection between the tap **14** and the output **15** five transformers denoted **34, 35, 36, 37** and **38** each of which has a primary winding that is connected in series with the tap **14** and output terminal **15** and a secondary winding that is connected to the output of square wave inverters **34***a*–**38***a*.

Referring to FIG. 4, the voltage that is added to the intermediate voltage is the same as that shown in FIG. 2, i.e. is a stepped approximation of a sine wave, and its wave form is indicated in FIG. 4 by the reference numeral **39**. In order to achieve this wave form, however, the square wave inverter **34***a* produces the wave form **34***b* while the other square wave inverters **35***a*–**38***a* produce the wave forms **35***b*–**38***b* respectively. It will also be understood that with each wave form there is a line **34***c*–**38***c* which is the zero line for their respective wave form. Referring specifically to the wave form **34***b*, it is in phase with the intermediate voltage wave form **40** (having a zero line **40***a*) and has an amplitude which may be considered as being 1.00. The wave form **35***b* has an amplitude of 1.225 and is 30° advanced from the wave **34***b*. The wave form **36***b* has an amplitude of 0.500 and is 60° advanced while the wave form **37***b* has an amplitude of .500 and is 120° advanced and finally the wave form **38***b* has an amplitude of 1.225 and is 150° advanced from the zero position of the intermediate voltage wave form **40**.

It will thus be appreciated that at any angle of each half cycle if the five wave forms **34***b*–**38***b* are algebraically added together that they will produce the stepped approximation of the sine wave form **39** which is a wave form identical to the wave form **21** in FIG. 2. Moreover, while the relative proportions of amplitude of each of the waves have been given, it will be appreciated that by varying the amplitude of all by the same proportion that the amplitude of the wave form **39** may accordingly be varied.

For providing the switching of the square wave inverters **34***a*–**38***a* into conditions of positive and negative conduction to produce each of the half cycles of the wave forms **34***b*–**38***b*, the regulator in FIG. 3 includes an oscillator and logic circuit **41**. The oscillator circuit produces oscillations at a frequency of 720 cycles per second which is twelve times the 60 cycle alternating current to which the input terminals **11** and **12** may be connected in order to produce a pulse or other signal for every 30° of the 60 cycle input alternating current and thus enable control of the inverters at specific intervals after each zero crossing of the sine wave **40**. Naturally if the frequency of the source is other than 60 cycles, then the oscillator may have a different frequency. It will be understood that the inverters **34***a*–**38***a* preferably include semiconductor devices which are either switched on or off and thus may be more efficiently operated than if they were merely amplifying devices.

In the embodiment of the automatic voltage regulator of the present invention shown in FIG. 5, rather than having the amplitude of the stepped alternating current changed to provide the change in the value of the output voltage, herein the stepped alternating current may have a constant amplitude; however, its phase relation with the intermediate voltage is changed. Thus when the two voltages are added they are added vectorially thereby producing an output voltage which may have its value maintained at the desired value.

In the regulator in FIG. 5, there are again the input terminals **11** and **12** connected to a source of 60 cycle alternating current together with the autotransformer **13** having a tap **14**. Additionally there are provided output terminals **15** and **16**, filter **33**, reference source **28** and error detector **29**. As in the embodiment shown in FIG. 3, the stepped alternating current is added to the intermediate alternating voltage by a plurality of transformers **34, 35, 36, 37** and **38** having their primaries connected in series and their secondaries connected to square wave inverters **34***a*, **35***a*, **36***a*, **37***a* and **38***a*. Moreover, connected

to each of the square wave inverters **34***a*–**38***a* is a source of direct current, indicated by the reference numeral **42**. In order to enable the different waves **34***b*–**38***b* to be maintained in the same relationship with each other there is provided the oscillator and logic circuit **41**.

The initiation of each cycle of the circuit **41** to control the zero crossing of the stepped alternating current wave whose wave form is shown in FIG. 6 and indicated by the reference number **43**, is effected by an adjustable phase shifting circuit **44** connected to the error detector together with a synchronous oscillating circuit **45** connected to have the intermediate voltage impressed thereacross. The circuit **45** introduces into the phase shifting circuit **44**, the timing when the intermediate voltage (whose wave form is shown in FIG. 6 and indicated by the reference number **46**) begins each half cycle and the error detector serves to shift, with respect to the signal from the oscillator **45**, the signal to the circuit **41** to begin each half cycle. Thus the phase shifting circuit **44** merely serves as a delay circuit with the value of the signal from the error detector **29** changing the amount of the delay which may be from zero up to 180° for each half cycle. The zero delay adds the stepped alternating current in phase with the intermediate voltage while the 180° delay subtracts the stepped alternating current from the intermediate voltage. Other phase delays between not only the two extremes mentioned but also for 180° to 360° result in changing the sum of the two voltages to produce the output voltage having the desired value. The wave forms **43** and **46** in FIG. 6 are 60° apart or out of phase and they are combined by the transformers **34**–**38** in the manner shown vectorially in FIG. 7. Thus the voltage of the wave form **46** is indicated by the vector **46***a* while the voltage of the wave form **43** is indicated by the vector **43***a* and the resultant output voltage is indicated by the vector **47**. It will be thus understood that by changing the phase relationship between the wave forms **43***a* and **46***a*, the value of the output voltage may thus be changed even though there will also be a change between the phase of the output voltage and the phase of the input voltage except for the two conditions when the stepped wave **43** is exactly in phase or exactly out of phase with the intermediate voltage **46**. Moreover, by controlling the phase relationship, i.e. between zero and 180° and 180° and 360°, the output voltage may be made leading or lagging with respect to the phase of the input voltage.

It will accordingly be appreciated that there has been disclosed an automatic voltage regulator which regulates an alternating voltage applied to its input terminals to produce at its output terminals an alternating current which is maintained at a substantially constant value. The regulation is achieved by producing an intermediate alternating voltage and then combining with it another voltage which consists of a stepped approximation of a sine wave. By varying the amplitude or the phase of the stepped alternating current by sensing the actual value of the output voltage, the output voltage may thus be maintained at its desired value.

Variations and modifications may be made within the scope of the claims and portions of the improvements may be used without others.

I claim:

1. An automatic voltage regulator comprising input terminals connectible to a source of alternating current, output terminals at which an output voltage having a substantially constant value appears, means connected to the input terminals for producing an intermediate alternating voltage, a source of direct current, means connected to the direct current source for producing an alternating voltage having for each half cycle a plurality of different voltage levels forming a stepped wave that approximates a sine wave, means for combining the alternating voltage with the intermediate voltage to produce the output voltage, means for sensing the deviation of the output voltage from a known value and producing a signal indicative of the deviation and means receiving the signal and operative to control the value of the alternating voltage added to the intermediate voltage, with the sum of the alternating voltage and intermediate voltage constituting the output voltage having the desired value.

2. The invention as defined in claim **1** in which the means for controlling the value includes means for adjusting the value of the direct current to control the amplitude of the alternating voltage.

3. The invention as defined in claim **1** in which the means for controlling the value includes means for changing the phase relationship between the alternating voltage and the intermediate voltage.

4. An automatic voltage regulator comprising input terminals connectible to a source of alternating current, output terminals at which an output voltage having a substantially constant value appears, means connected to the input terminals for producing an intermediate alternating voltage having a value related to the input voltage, a source of direct current, means connected to the direct current source for producing an alternating voltage which is a stepped approximation of a sine wave and including a plurality of inverter means with each inverter means producing an alternating square wave with the phases of the square waves being different from each other, means for combining the alternating voltage with the intermediate voltage to produce the output voltage, said means including a plurality of transformers with each having a primary winding and a secondary winding, means connecting the primary windings in series with each other, means connecting each secondary winding to an inverter means, means for sensing the deviation of the output voltage from a known value and producing a signal indicative of the deviation and means receiving the signal and operative to control the value of the alternating voltage added to the intermediate voltage, with the sum of the alternating voltage and intermediate voltage constituting the output voltage having the desired value.

5. The invention as defined in claim **4** in which the relative voltage values of each of the square waves and the phase therebetween is such that when algebraically added together they produce the alternating voltage by a step approximation of a sine wave.

6. The invention as defined in claim **5** in which the means for controlling the value of the alternating voltage includes means for changing the amplitude of each square wave while maintaining the same relative voltage values therebetween.

7. The invention as defined in claim **5** in which the means for controlling the value of the alternating voltage includes means for shifting the phase of the alternating voltage with respect to the intermediate voltage while maintaining the same phase relationship between each of the square waves.

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