

July 21, 1959

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2,896,147

REFERENCE VOLTAGE DEVICE

Filed March 12, 1956

2 Sheets-Sheet 1

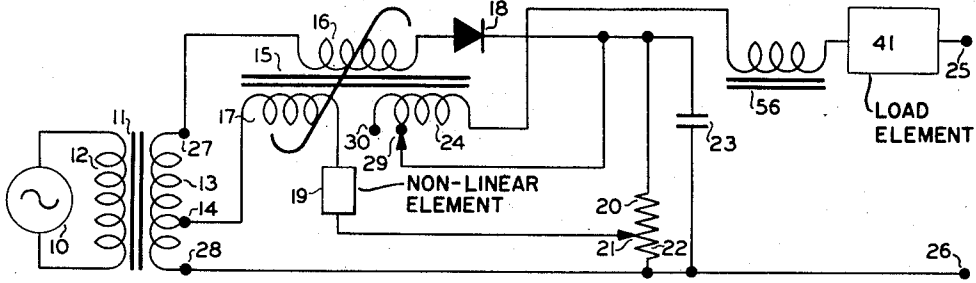


FIG. 1

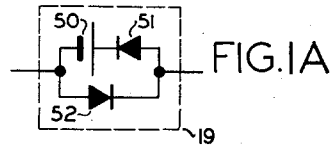


FIG. 1A

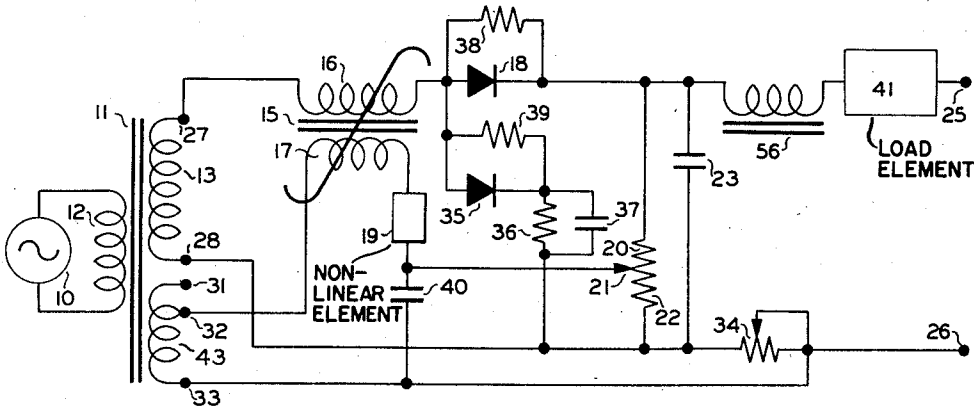


FIG. 2

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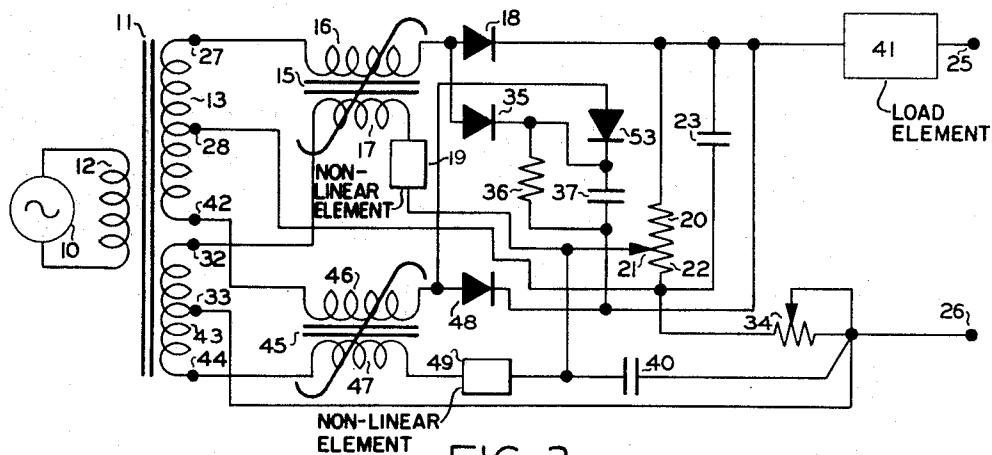
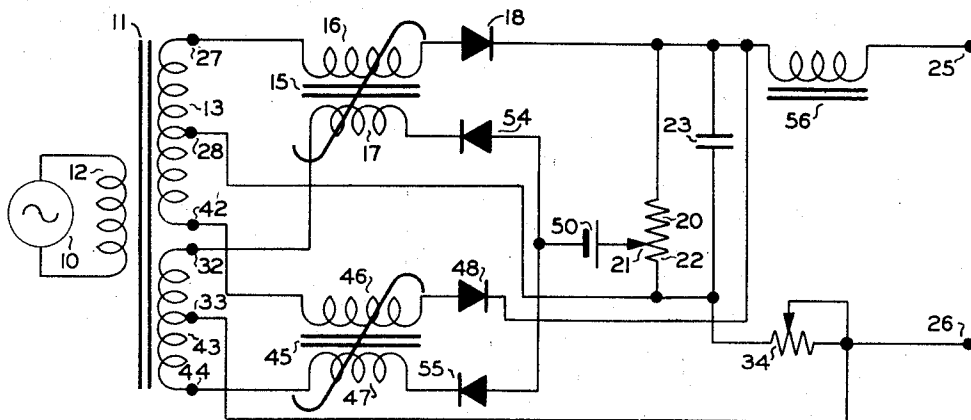
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REFERENCE VOLTAGE DEVICE

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16 Claims. (Cl. 321—25)

This invention relates to reference voltage devices and regulated power supplies, and in particular to such devices in which a saturable magnetic core is combined with a non-linear device characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage. A specific non-linear device having this property is a semi-conductor element of the class known as Zener diodes which are rectifying elements that pass very little reverse current until their critical voltage is exceeded, and thereafter have a substantially constant voltage region.

Many types of electronic and magnetic devices, especially voltage regulating devices, utilize a reference voltage potential as a basis for comparison with a quantity to be regulated. Reference voltage devices of several types have, therefore, been developed, employing either saturable magnetic elements, electronic discharge devices, batteries or Zener diodes for establishing the reference base. Such prior devices have generally been characterized by one or more of the following limitations:

- (1) Dependence on the frequency of the energizing source
- (2) The use of expendable or short lived compounds
- (3) Extremely small load capacity
- (4) Lack of adjustability, the voltage either being set by the basic design of the device or by the availability of reference elements having the required voltage rating
- (5) Dependence upon ambient temperature
- (6) The need for frequent readjustment to compensate for aging of components

The purpose of this invention is to provide a highly accurate yet small and relatively inexpensive device having none of the limitations mentioned above.

It is an object of this invention to provide a highly accurate reference voltage device employing static, long life components.

Another object of this invention is to provide a reference voltage device capable of delivering or absorbing substantial amounts of load current without loss of accuracy.

A further object of this invention is to provide a reference voltage device which is independent of the energizing frequency and voltage, and independent of the ambient temperature.

A further object of this invention is to combine a saturable magnetic core with a non-linear element characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage, to obtain a standard voltage considerably higher than the critical voltage of the non-linear element and having power capabilities much greater than those of the non-linear element.

An additional object of this invention is to utilize a battery in a reference voltage device or regulated power supply which will deliver substantial amounts of power without drawing any power from the battery.

A still further object of this invention is to provide in

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a reference voltage device an internal negative resistance characteristic so that the addition of a load resistance in the output of the device will not impair the accuracy of the reference voltage.

- 5 Other objects and a fuller understanding of this invention may be had by referring to the following description and claims, taken in conjunction with the accompanying drawings, in which:

Figure 1 is a schematic diagram of a circuit embodying features of my invention;

Figure 1A is a diagram of an equivalent combination which can be substituted for one of the elements of Figure 1;

Figure 2 is a schematic diagram showing additional features of my invention, including means for producing an internal negative resistance in the reference voltage device, and means for neutralizing the effect of temperature variations;

Figure 3 is a schematic diagram of a full wave circuit embodying features of my invention, and having increased load carrying ability, and

Figure 4 is a schematic diagram of a modification of Figure 3, using a single voltage standardizing element in place of the two elements shown in Figure 3.

With reference to Figure 1 of the drawings, the reference voltage device shown comprises a saturable reactor having a core 15, preferably of gapless construction and made of rectangular loop core material. The gate winding 16 on the reactor is connected in series with the rectifying element 18 and a voltage divider having two portions 20 and 22, one on each side of the slider 21. These elements are energized from secondary winding 13 of transformer 11 whose primary winding 12 is energized from the alternating current source 10. The reset winding 17 on core 15 is connected in series with non-linear element 19 to tap 21 on the voltage divider and energized from tap 14 of transformer winding 13. The non-linear element 19 is characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage. A specific non-linear device having this property is a semi-conductor element of the class known as Zener diodes which are rectifying elements that pass very little reverse current until their critical voltage is exceeded, and thereafter have a substantially constant voltage region.

Filter capacitor 23 is connected across the voltage divider 20, 22, to smooth the half-wave rectified voltage supplied from rectifying element 18. The load terminals 25 and 26 are energized from across capacitor 23 through a compounding winding 24 on core 15. Taps 29 and 30 are provided for adjusting the turns in the compounding winding. Filter inductance 56 and load element 41 are connected in series with output terminal 25.

In use, my reference voltage device of Figure 1 maintains a standardized reference voltage across output terminals 25 and 26, and these terminals are connected to an external circuit having a voltage with which the standard reference voltage is to be compared.

Load element 41 may be the saturating winding of a transducer, the field winding of a generator, the armature of a motor, or similar device having a regulating function in the equipment controlled by the reference voltage device. The controlled equipment, of which load element 41 is a part, may be anything the condition of which can be represented by a unidirectional voltage in the external circuit to which the load terminals 25 and 26 may be connected, so the unidirectional voltage from the controlled equipment can be balanced against the standardized reference voltage of my device. Any change detected in the external voltage across terminals 25 and 26 produces a flow of current through the load element 41. The current through element 41 is normally used

to restore the controlled equipment to normal, in which case the external voltage across terminals 25 and 26 returns to normal. The standardized reference voltage of my device is obtained as follows:

When the voltage of source 10 is first applied to the circuit, capacitor 23 is discharged, and the core 15 is saturated by repeated application of voltage in the gating direction through rectifier 18 in the absence of reset voltage applied to either winding 16 or winding 17, the reset voltages being blocked by the elements 18 and 19 respectively. The gate current through winding 16 and rectifier element 18 charges capacitor 23 until during a negative half cycle the biasing voltage developed across resistor 22 combined with the voltage from taps 14 to 28 of winding 13 exceeds the critical voltage of non-linear element 19, causing it to pass appreciable current through reset winding 17. Current through the element 19 and reset winding 17 resets the core 15 during the negative half cycles and prevents any further increase in the voltage across the resistors 20, 22 and capacitor 23.

For purposes of explanation, I will designate the number of turns in the winding 13 between taps 14 and 28 by the character N_1 , the turns between taps 27 and 28 by N_2 , the turns of the reset winding 17 by N_3 , the turns on the gate winding 16 by N_4 , the resistance of the resistor 22 as R_1 , and the sum of the resistances of 20 and 22 as R_2 .

Again for purposes of explanation, suppose that $N_1/N_2=N_3/N_4=R_1/R_2$, and suppose that the non-linear element 19 is a Zener diode polarized to pass current easily in the same direction as rectifier 18. Under this condition, there are effectively two half-wave rectifying devices operating in a modified parallel arrangement with all of the voltages in the lower voltage circuit energized from tap 14 being the same fraction of the corresponding voltages in the higher voltage circuit energized from tap 27, the ratio between the voltages being N_1/N_2 . Neglecting the resistances of the windings and the forward resistance of rectifier element 18, the voltage dividing resistors 20, 22 would then be completely energized through the high voltage circuit, and there would be no forward current flowing through the Zener diode 19, as the potential at tap 21 would always be equal to that impressed on the element 19 through winding 17.

During the negative half cycles, when terminal 27 is negative with respect to terminal 28, current through winding 16 is blocked by the reverse resistance of the rectifying element 18, and current through the reset winding 17 is blocked by the reverse resistance of the Zener diode 19. However, if the voltage impressed on the Zener diode during the reverse half cycle exceeds its critical voltage, reset current will flow through the reset winding 17 during negative half cycles. The amount of reset current which flows during this interval will determine how much forward current will be passed through the gate winding 16 during the next positive half cycle. As previously mentioned, if there is no reset current, the gate winding 16 will offer practically no opposition to the flow of forward current during positive half cycles. To achieve these results to the fullest extent, the material used in the core 15 should preferably have a rectangular magnetization characteristic, so that it retains a high percentage of the saturation flux which is produced during the gating or conducting half cycle, retaining it during the blocking half cycle unless reset current is applied to one of the windings. For best results, the leakage current passed by the rectifier element 18 should also be considerably smaller than the current required to reset the flux in core 15.

The action of the non-linear element or Zener diode 19 in the circuit can be explained by the use of the equivalent circuit shown in Figure 1A, consisting of a battery 50 having a voltage equal to the Zener or critical voltage of the element, a blocking rectifier 51 assumed to have ideal rectifying properties, and a forward con-

ducting rectifier 52 also assumed to have ideal rectifying properties. When a positive voltage is applied to the left hand side of the combination shown in Figure 1A, the rectifier element 52 conducts the current directly, equivalent to forward conduction in the Zener diode. When the positive voltage is applied to the right hand side of the circuit of Figure 1A, it is opposed by the potential of the battery 50, although the battery 50 can deliver no current itself because of the blocking action of rectifier element 51. As long as the positive voltage applied to the right hand side of the circuit of Figure 1A is less than the voltage of battery 50, there is no current flow through the circuit. However, as soon as the applied voltage exceeds the voltage of battery 50, current will pass through the combination in very much the same manner as it passes through a Zener diode when the potential is raised above its critical voltage.

It should also be pointed out, that although this description of my invention refers to the use of Zener diodes for establishing the reference voltage, other devices such as that shown in Figure 1A can be used in the practice of my invention. When using a substitute combination such as shown in Figure 1A, the rectifying element 52 may be omitted, as the forward conduction of the element 19 is not ordinarily used in the operation of my invention. Other non-linear resistance devices having less sharply defined critical voltages can also be used in the practice of my invention, at least partial compensation for the higher incremental resistance of such devices being obtainable by increasing the turns N in winding 13 between taps 14 and 28.

Upon reaching the critical voltage of the non-linear element 19, further increases in the voltage across the capacitor 23 are accompanied by very large increases in the reset current passed by the element 19 and consequent reduction in the gate current passed through winding 16. Increasing the voltage of source 10, therefore, does not increase the voltage across the capacitor 23 appreciably. However, using the turn ratios and resistance ratio set forth above, the voltage across capacitor 23 does rise slightly with increasing voltage from source 10, the rise being largely attributable to the effective resistance in the reset circuit, represented by the incremental resistance of the element 19, the resistance of winding 17, and of resistor 22. In order to compensate for the effect of resistance in this circuit I increase the number of turns N_1 so that the ratio N_1/N_2 is greater than N_3/N_4 , so that any increase in the voltage of source 10 produces more than a corresponding increase in the reset current passed by the element 19. By suitable choice of circuit constants, the voltage across capacitor 23 can be held constant within very close limits with considerable variation in the voltage of source 10.

Some equipment controlled from reference voltage devices has in itself a sensitivity to line voltage which requires that the reference voltage be reduced as the line voltage is increased. When this is required, the turns N_1 can be increased still further to provide a reduction in the voltage across capacitor 23 with increase of the voltage of source 10. This characteristic also permits the use of various types of non-linear element 19 other than the Zener diode mentioned, such as elements having less sharply defined critical voltages as previously mentioned.

Most prior reference voltage devices are characterized by a very high internal impedance, so that any change in the load current drawn from them produces a considerable change in the reference voltage. In order to make effective use of such prior devices, it has been necessary to use a high gain amplifier in conjunction with the reference voltage device and to perform the needed controlling functions with the output of the amplifier. Such a system has several disadvantages, chief among them being the possibility of phase shift and oscillation resulting from the time delay of the intermediate amplifier, as well as the added expense of the amplifier and pos-

sible loss of accuracy through drift in the D.-C. amplifier required.

One of the features of my invention, therefore, is the provision of a reference voltage device having a negative internal resistance of any required magnitude, capable of compensating not only for the losses within the reference voltage device itself but also in a load element which may be connected between the reference voltage device and the voltage representing the quantity being controlled. One method for obtaining this internal negative resistance property is shown in Figure 1 in which the compounding winding 24 on core 15 changes the magnetization of core 15 with changes in load current. Winding 24 is connected in series with the output terminal 25 so that current which flows from output terminal 25 through the load device 41 also flows through the compounding winding 24. Taps 29 and 30 are provided on this winding for adjusting the amount of negative resistance. The inductance element 56 is connected in series with winding 24 in order to assure a high reflected A.-C. impedance into the windings 16 and 17 on core 15 regardless of the load condition in the circuit which includes winding 24.

Load current flowing through load element 41 out through output terminals 25 and 26 will pass through winding 24. As this is a continuous current flowing during the entire cycle, it will be flowing during the reset period when current is flowing through the non-linear element 19 and the reset winding 17. The effect of load current will then be to reduce the effective reset current and increase the voltage appearing across capacitor 23. This increase in voltage can be made just sufficient to compensate for the voltage drop through windings 24 and 16 and through load element 41 so that the voltage across terminals 25 and 26 is substantially unchanged by the change of current through the load element 41. If the current is in the opposite direction, so that the reference voltage device is absorbing current rather than delivering it, the current through winding 24 adds to the reset current and reduces the voltage across resistor 20.

The arrangement shown in Figure 2 has several added features, including a different arrangement for obtaining the negative resistance characteristic. In Figure 2, resistances 34, 36, 38 and 39 have been added, as well as winding 43, rectifier 35 and capacitors 37 and 40. In particular, capacitor 40 added to Figure 2 has the effect of reducing the resistance in the reset circuit, particularly the resistance reflected by the voltage divider 20 into the reset circuit. During the portion of the cycle when the diode 19 is passing reset current through reset winding 17, this current can be supplied by capacitor 40 instead of from the tap 21 on resistor 20. As a result, less compensation for internal resistance need be applied in the form of increasing turns N_1 . Turns N_1 in Figure 2 appear on winding 43, an isolated winding having terminals 31, 32, and 33, 31 and 32 being taps for adjustment. The reduction of the effective resistance in the reset circuit also improves the effectiveness of the non-linear element 19 in compensating for changes in other parts of the circuit, such as changes in the leakage resistance of rectifier 18.

Another arrangement for minimizing the effective changes in the linkage resistance of rectifier element 18 is by the addition of the resistor 38, which can be a swamping resistor passing current considerably greater than the leakage current of element 18, or it can be a positive temperature coefficient resistor which will pass less current at higher temperatures when the element 18 normally will pass more current. When the leakage currents of elements 18 and 35 are so low as to be negligible in their effect on the output voltage of the reference voltage device, the resistors 38 and 39 can be omitted. The temperature coefficient of the non-linear element 19 may be extremely small, particularly when it is a silicon

Zener diode having a critical voltage in the neighborhood of 6 volts.

In devices using such silicon diodes directly for voltage reference, it is usually necessary either to use several units in series to reach the required voltage, or to use higher voltage diodes having less favorable temperature characteristics. By my invention both of these disadvantages are overcome and the output voltage of the reference voltage device can be many times greater than the critical voltage of the non-linear element without loss of accuracy.

Another feature of the circuit of Figure 2 is the addition of the resistor 34 in the load circuit so that its voltage is subtracted from the bias voltage applied to the non-linear element 19 from resistor 22. The voltage across resistor 34 is normally small compared to the load voltage, but it may be appreciable as compared with the bias voltage.

Since the voltage in the reset circuit, which is the bias voltage across resistor 22 minus the voltage across resistor 34, is maintained substantially constant by changes in the reset current through the non-linear element 19, the voltage across capacitor 23 will rise with increasing load current. The rise is linear and represents a negative resistance characteristic with respect to load current from terminals 25 and 26. Normally this negative resistance is cancelled by the resistance of elements 59 and 41 so that the internal resistance of the reference voltage device as measured at terminals 25 and 26 is substantially zero.

The use of the resistor 34 as shown in Figure 2 provides a linear negative resistance characteristic in my reference voltage device, and over a wide range of load current and input voltage and frequency, the output voltage across terminals 25 and 26 is very accurately regulated. This is true even when the voltage across the load device 41 becomes a considerable fraction of the voltage across output terminals 25 and 26.

In normal operation, the magnetic core 15 operates near its positive saturation point, being saturated in a positive direction by the gate current through windings 16 and rectifier element 18 during each positive half cycle, and being reset to the required point lower on the magnetization curve during each negative or reset cycle by the current through the reset winding 17. The amount of reset current passed during the negative or reset half cycle determines how much of the positive or gating half cycle will be blocked by the gate winding 16 before the core saturates and allows current to flow through rectifier element 18. In some cases however, a transient condition may be impressed upon load terminals 25 and 26, producing a large amount of reset current or several consecutive cycles of normal reset current flowing without forward or gating current being passed through winding 16. If this happens, the core 15 reaches negative saturation and with the voltage across capacitor 23 being maintained near its normal value by the measured voltage normally connected across terminals 25 and 26, the voltage from winding 13 will not exceed the voltage across capacitor 23 by a sufficiently large amount or for a sufficiently long time to cause the core 15 to saturate in the positive direction and allow forward current to flow through winding 16 and rectifier 18. Meanwhile, during each negative half cycle, a small amount of reset current will be passed through winding 17, so that an abnormal condition can be established in which the voltage across terminals 25 and 26 may drop several percent below the normal voltage before gating occurs and the circuit resumes normal operation.

To prevent this abnormal condition from occurring, the rectifier element 35 with load resistor 36 and capacitor 37 has been added to Figure 2. The resistor 39 shunting rectifier element 35 is similar in function to resistor 38 across rectifier element 18 and can be omitted when the leakage of rectifier element 35 is sufficiently

low as previously mentioned. The effect of this circuit comprising rectifier element 35, load resistor 36, and capacitor 37 acting as a load through the gate winding 16 and energized from winding 13, but independent of capacitor 23 and voltage divider 20, is to pass a small amount of gating current during every positive half cycle regardless of the voltage across capacitor 23. With the addition of these elements, the abnormal condition previously described can be eliminated, and regardless of the transient conditions imposed on the reference voltage device it resumes its normal operation as soon as the transient is overcome.

The current passed by the rectifier element 35 and resistor 36 need only be great enough to magnetize the core 15 in the positive direction, but the capacitor 37 is added in parallel with load resistor 36 to admit the maximum amount of current during the gating portion of the cycle. Capacitor 37 can be omitted if the resistance of element 36 is reduced sufficiently.

In Figure 3, a full wave rectifier circuit is used in place of the half-wave circuit used in Figures 1 and 2. This requires the addition of more turns to windings 13 and 43 and the addition of tap 42 to winding 13 and tap 44 to winding 43 to provide for the full wave rectification. A second saturable core reactor is added, with core 45, gate winding 46, and reset winding 47. A second non-linear element 49 is connected in series with the reset winding 47. A second auxiliary gating diode 53 is also connected in series with winding 46 and is connected to the same load resistance 36 and capacitor 37 as the first auxiliary gating diode 35.

Operation of each half of the circuit of Figure 3 is very much like that of Figure 2, the functions being divided into those which occur during the gating or positive half cycle and those during the reset or negative half cycle. In Figure 3, the elements associated with core 45 are in the reset half cycle while those associated with core 15 are in the gating half cycle, and while those associated with core 45 are in the gating half cycle, those associated with core 15 are in the reset half cycle. Full wave operation improves the load carrying ability of the circuit, as the capacitor 23 has less time to discharge when load current is drawn from the circuit of Figure 3 than when load current is drawn from the circuit of Figure 2.

In Figure 4, a battery 50 is used together with rectifiers 54 and 55 as the non-linear element, serving for both sides of the full wave circuit. This is in contrast with the arrangement of Figure 3, in which individual non-linear elements 19 and 49 are used, one for each side of the full wave circuit. However, it will be apparent that a single non-linear element could be used in Figure 4 in place of the battery 50 which is shown. Likewise, the battery 50 could be used in any of the other circuits as a substitute for one of the non-linear elements, by combining with it a diode 51 as shown in Figure 1A. Furthermore, a small voltage-regulated direct current power supply could be substituted for the battery 50 in each case.

In Figure 4 the blocking function is carried out by two rectifying elements, or diodes, 54 and 55, the diode 54 being connected in series with winding 17, diode 55 being connected in series with winding 47. These diodes prevent the battery 50 from delivering current into the circuit, but permit the reset current to flow through windings 17 and 47 when the voltage in the reset circuit exceeds the voltage of battery 50. The current which flows through the battery 50 is always in a direction opposite to the battery polarity so it will charge the battery if it is a storage battery or prevent its deterioration if it is a primary battery.

If the battery 50 in Figure 4 is replaced by a Zener diode or other non-linear element such as used in the other figures, the rectifiers 54 and 55 will still be required in order to block current through windings 17 and 47

during the gating portion of the cycle while admitting it during the reset portion of the cycle.

The load element 41 has been omitted from Figure 4 in order to point out that the reference voltage device of my invention can also be used as a regulated power supply in itself. It will be apparent that the circuits shown in Figures 1, 2 and 3 are likewise capable of operation as power supplies with the omission of the load element 41 from these figures.

It will also be apparent that the various features shown in the figures are for the most part interchangeable between the several figures and that many equivalent items can be used in place of the specific devices described therein.

Although this invention has been described in its preferred form with a certain degree of particularity, it is understood that the present disclosure of the preferred form has been made only by way of example and that numerous changes in the details of construction and the combination and arrangement of parts may be resorted to without departing from the spirit and the scope of the invention as hereinafter claimed.

What is claimed is:

1. In combination, a saturable magnetic core having first and second windings, a rectifying element, first and second resistance elements, a capacitor, a pair of direct current output terminals, an alternating current input transformer having first and second windings thereon, a non-linear device characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage, a first circuit comprising said first winding on the input transformer, said first winding on the saturable magnetic core, said rectifying element, and said first and second resistance elements in series, a second circuit comprising said second winding on the saturable magnetic core, said non-linear device and said second resistance element connected in series, circuit means for connecting said capacitor substantially in parallel with the series combination of said first and second resistance elements, and means for supplying said direct current output terminals with voltage from across said capacitor, said saturable magnetic core being magnetized by current through said rectifying element during conducting half cycles, and being demagnetized by current through said non-linear device during non-conducting half cycles of said rectifying device, whereby the voltage across said direct current output terminals is regulated by the critical voltage of said non-linear device.

2. In combination, a saturable magnetic core having first and second windings thereon, an input transformer having first and second windings thereon, a first circuit including the first winding of said transformer, the first winding on said saturable magnetic core, a rectifying element, and first and second resistance elements in series, a second circuit comprising said second winding on the input transformer, said second winding on the saturable magnetic core, a non-linear device characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage, and said second resistance element connected in series, a capacitor connected across the series combination of said first and second resistance elements, and a direct current output circuit energized with voltage from across said capacitor.

3. In combination, an alternating current input transformer having first and second windings, a saturable magnetic core having first and second windings, a rectifying element connected in series with said first winding on the saturable magnetic core and energized from said first transformer winding, a capacitor adapted to be charged by current through said rectifying element, first and second resistance elements connected in series across said capacitor, a non-linear device characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage, said non-linear

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device being connected in a closed circuit including said second transformer winding, said second winding on the saturable magnetic core and said second resistor, a third winding on said saturable magnetic core, a pair of direct current load terminals, and a load circuit extending from said capacitor to said direct current load terminals through said third winding.

4. In combination, saturable magnetic core means, rectifying means, and non-linear means characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage, first alternating current circuit means for magnetizing said saturable magnetic core means during the portion of the alternating current cycle when said rectifying means is conductive, second alternating current circuit means for demagnetizing said saturable magnetic core means with current passed through said non-linear means during the portion of the alternating current cycle when said rectifying means is non-conductive, and direct current circuit means energized through said rectifying means, the output voltage supplied by said direct current circuit means being controlled by the demagnetization of the saturable magnetic core means by said current through the non-linear means.

5. In combination, saturable magnetic core means, rectifying means and non-linear means characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage, first alternating current circuit means for magnetizing said saturable magnetic core means during the portion of the alternating current cycle when said rectifying means is conductive, second alternating current circuit means for demagnetizing said saturable magnetic core means with current passed through said non-linear means during the portion of the alternating current cycle when said rectifying means is non-conductive, means for applying a portion of said output voltage as a bias to said non-linear means, and means for reducing said bias with increasing output current in the direct current circuit means.

6. In combination, saturable magnetic core means characterized by a substantially rectangular magnetization characteristic, and having gate winding means and reset winding means thereon, semiconductor means characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage, rectifying means, direct current load circuit means, means for energizing said direct current load circuit means through said gate winding means and said rectifying means during conducting half cycles of said rectifying means, and means for energizing said reset winding means from said alternating current source through a portion of the load circuit means and through said semiconductor means during non-conducting half cycles of said rectifying means, whereby the voltage in said direct current load circuit means is regulated by reset current through said semiconductor means.

7. In combination, saturable magnetic core means characterized by a substantially rectangular magnetization characteristic, and having gate winding means and reset winding means thereon, semiconductor means characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage, rectifying means, direct current load circuit means, means for energizing said direct current load circuit means through said gate winding means and said rectifying means during conducting half cycles of said rectifying means, and means for energizing said reset winding means from said alternating current source through a portion of the load circuit means and through said semiconductor means during non-conducting half cycles of said rectifying means, means for reducing the current through said reset winding means with increases in load current in said load circuit means, load means in said load circuit means, said load means being effective in controlling a quantity characterized by a unidirectional voltage, and means for

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balancing said unidirectional voltage against the voltage in said load circuit means.

8. In combination with a device having its function controlled by unidirectional current through a controlling element and having its condition indicated by a unidirectional voltage, reference voltage means having direct current output terminals for connection across said unidirectional voltage, said reference voltage device comprising saturable magnetic core means with first and second winding means thereon, non-linear means which for applied voltages greater than a critical voltage is characterized by a substantially constant voltage region, rectifying means, first, second and third resistance means, means for energizing said first and second resistance means in series from a source of alternating current through said rectifying means and said first winding means, means for energizing said second winding means from said source of alternating current through said second and third resistance means and said non-linear means, and means for energizing said output terminals with voltage from across said first and second resistance means through said third resistance means and said controlling element.

9. In combination with a device having its function controlled by unidirectional current through a controlling element and having its condition indicated by a unidirectional voltage, reference voltage means having direct current output terminals for connection across said unidirectional voltage, said reference voltage device comprising saturable magnetic core means with first and second winding means thereon, non-linear means which for applied voltages greater than a critical voltage is characterized by a substantially constant voltage region, rectifying means, first, second and third resistance means, capacitive means, means for energizing said first and second resistance means in series from a source of alternating current through said rectifying means and said first winding means, means for charging said capacitive means from said source through said rectifying means and said first winding means, means for energizing said second winding means from said source of alternating current through said second and third resistance means and said non-linear means, and means for energizing said output terminals with voltage from across said first and second resistance means through said third resistance means and said controlling element.

10. In combination with a voltage regulating device having direct current load terminals energized from alternating current input terminals through first rectifying means and saturable reactor means, and having means for varying the saturation of said reactor means in response to changes in voltage across said load terminals, the combination of second rectifying means and auxiliary load means energized from said input terminals through said reactor means for controlling the saturation of said reactor means during periods of abnormal voltage across said load terminals.

11. In a voltage regulating device having direct current load terminals energized from alternating current input terminals through first rectifying means and having saturable magnetic core means, the combination of first means for magnetizing said core means during conducting periods of said first rectifying means with current flow through said first rectifying means, means responsive to the voltage across said load terminals for demagnetizing said core means during non-conducting periods of said first rectifying means, and second means including second rectifying means for magnetizing said core means during conducting periods of said first rectifying means, whereby said core means is magnetized in spite of abnormal voltages across said load terminals.

12. In combination, saturable magnetic core means, first and second rectifying means, and non-linear means characterized by substantial increases in current for slight increases in voltage above a predetermined critical volt-

age, direct current output circuit means, first alternating current circuit means for magnetizing said core means and energizing said output circuit means through said first rectifying means during its conducting periods, second alternating current circuit means for demagnetizing said saturable magnetic core means with current passed through said non-linear means during non-conducting periods of said first rectifying means and third alternating current circuit means for magnetizing said core means with current through said second rectifying means during its conducting periods, said second rectifying means being polarized the same as said first rectifying means.

13. In combination, saturable magnetic core means, first and second rectifying means, and non-linear means characterized by substantial increases in current for slight increase in voltage above a predetermined critical voltage, direct current output circuit means, first alternating current circuit means for magnetizing said core means and energizing said output circuit means through said first rectifying means during its conducting periods, second alternating current circuit means for demagnetizing said saturable magnetic core means with current passed through said non-linear means during non-conducting periods of said first rectifying means, third alternating current circuit means for magnetizing said core means with current through said second rectifying means during its conducting period and means for applying a portion of the voltage from said direct current output circuit means as a bias to said non-linear means, and means for reducing said bias with increasing output current in the direct current circuit means.

14. In combination, a saturable magnetic core, gate winding means and reset winding means on said core, alternating current input terminals and direct current output terminals, first and second rectifiers, a capacitor, first, second, and third resistors, a non-linear device characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage, first circuit means for changing said capacitor from said input terminals through said first rectifier and said gate winding means, said first and second resistors being serially connected across said capacitor, second circuit means for energizing said reset winding means from said input terminals through said second resistor and said non-linear device, third circuit means for energizing said third resistor through the second rectifier and the gate winding means from the input terminals, said first and second rectifiers being polarized to conduct simultaneously, and fourth circuit means for supplying voltage from said capacitor to said output terminals.

15. In combination with a device having its function controlled by a unidirectional current through a control-

ling element and having its condition indicated by a unidirectional voltage, reference voltage means having direct current output terminals for connection to said unidirectional voltage, said reference voltage device comprising saturable magnetic core means with first and second winding means thereon, non-linear means characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage, first and second rectifying means, first, second, third, and fourth resistance means, first and second capacitor means, means for energizing said first and second resistance means in series from a source of alternating current through said rectifying means and said first winding means, means for charging said first capacitive means from said source through said first rectifying means and said first winding means, means for energizing said second winding means from said source through said second and third resistance means and said non-linear means, means for energizing said second capacitive means and said fourth resistance means in parallel from said source through said first winding means and said second rectifying means, and means for energizing said output terminals with voltage from across said first and second resistance means through said third resistance means and said controlling element.

16. In a regulating device in which the flow of energy between an alternating current input circuit and a direct current load circuit is controlled by the degree of saturation of a magnetic core, the combination of first rectifying means for conducting load current between said input circuit and said load circuit, means for magnetizing said core with current through said first rectifying means during its conducting periods, non-linear means characterized by substantial increases in current for slight increases in voltage above a predetermined critical voltage, means for demagnetizing said core during non-conducting periods of said first rectifying means with current through said non-linear means, and supplemental means including second rectifying means for magnetizing said core during conducting periods of said first rectifying means, said supplemental means being effective in magnetizing said core when the flow of current through said first rectifying means is prevented by the condition of said load circuit.

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