ABSTRACT: An autotransformer is connected to an unregulated voltage source, and serves as a supply transformer for a load. Interposed between this supply transformer and the load is the secondary winding of a regulating transformer, whose primary winding may be selectively coupled between various taps on the supply autotransformer winding. The primary winding of the regulating transformer is coupled to the desired points on the autotransformer winding by means of semiconductor switches, actuated when the system current waveform approaches zero.
VOLTAGE REGULATOR WITH ZERO CURRENT STATIC SWITCHING BETWEEN TAPS FOR A REGULATOR TRANSFORMER

BACKGROUND OF THE INVENTION

The present invention relates to voltage regulators, and, more particularly to apparatus wherein voltage regulation is achieved by means of bucking or boosting transformer windings which are energized through solid state switching devices such as SCR's.

Many attempts have been made in the past to satisfy the growing demand for rapid, economical means for regulating supply voltage within close limits. Chemical processes and industrial instrumentation, for example, require ever more closely regulated supply voltages for the exacting processes and components of modern technology.

One of the more popular methods for obtaining regulated voltages has been the provision of mechanical tap changers which connect a load circuit to a transformer tap having a desired voltage. Such mechanical switching arrangements are not only comparatively slow, but are prone to arcing and wear. Variable reactance devices which preclude the need for switching have been utilized, but introduce harmonic distortion of the resulting regulated voltage waveform.

With the advent of gated semiconductor devices such as SCR's, it has been found possible to overcome many of the above-mentioned deficiencies. The SCR switches rapidly compared to past mechanical devices, and can be switched synchronously, i.e., at the zero current point of a load current waveform. Several efforts have been made to devise voltage regulating circuits which take advantage of these characteristics. In one prior art circuit, disclosed in U.S. Pat. No. 3,195,038, a plurality of transformer secondary windings are provided, each of which may be shunted by a pair of inverse parallel SCR’s. Should the shunting SCR’s be rendered non-conductive, and other series connected SCR’s conductive, the transformer segment, and SCR’s coupled thereto, would be placed in series with the load circuit and an increment of voltage “buck” would be provided. Should voltage boost be desired, the series connected SCR’s are rendered nonconductive and the shunting SCR’s conductive so that only the shunting SCR’s then lie in series with the load circuit. In another mode, a “crisscross” arrangement of inverse parallel SCR switches is used to effect a reversal of polarity of a given winding segment to provide a “boosting” voltage increment.

It has been found, however, that for voltage loads such circuitry is not practical because of the forward voltage drops which exist across conducting SCR’s. By placing pairs of SCR’s in series and in shunt with the secondary winding segments, a number of SCR’s equal to the number of winding segments must always be in series with the load. At relatively low voltages the voltage drops across the SCR’s become a significant portion of the total load voltage, rendering the circuit relatively inefficient. The SCR voltage ratings are thus not fully exploited, while the surge current ratings thereof may be easily exceeded by small percentage changes in load current.

SUMMARY OF THE INVENTION

The present invention provides a new and improved circuit for obtaining bucking or boosting incremental voltages in a voltage regulating system without placing switching elements in series with a load circuit. The secondary winding of a regulating transformer is placed in series with the load circuit, and the primary winding connected, by means of SCR pairs, across various segments of an autotransformer, or equivalently, a supply transformer secondary winding. By using a step down regulating transformer, and applying high voltages to the primary winding through the SCR’s, the forward voltage drop across the SCR’s is only a small fraction of the total voltage applied to the primary winding circuit. The efficiency of the regulating circuit is thus practically unimpaired, and no significant switch impedance is inserted into the load circuit.

Further embodiments of the present invention provide additional switching elements for reversing the polarity of the primary winding of a buck-boost regulating transformer. Still other switches selectively connect one end of the primary winding of the regulating transformer to various points on the output winding of an autotransformer to various points on the primary winding being selectively coupled to various points on an auxiliary winding inductively coupled to the autotransformer. The auxiliary, or vernier, winding provides supplementary or vernier voltage increments to further adjust the voltage applied to the primary winding of the regulating transformer. Still further embodiments comprise multiple stages of regulating transformers, each of which is selectively coupled to various points on a supply autotransformer, and provide, in vernier fashion, a plurality of incremental voltages which extend over a broad range.

It is therefore an object of the present invention to provide a voltage regulator utilizing semiconductor switching elements which do not lie in series with a load circuit.

It is a further object of the present invention to provide a voltage regulation system which adds or subtracts incremental voltages to a load circuit without disturbing the continuity thereof.

It is a still further object of the present invention to provide a voltage regulation system having a regulating transformer in series with a load, wherein the transformer supplies various voltages to the load without the introduction of harmonic frequency disturbances in the load current.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention sought to be protected will be particularly pointed out and distinctly claimed in the claims appended hereto. However, it is believed that this invention will be more fully understood, and its several objects and advantages more fully appreciated, by referring to the following detailed description of preferred embodiments taken in conjunction with the accompanying drawings in which:

FIG. 1 is a schematic circuit diagram of a single stage voltage regulation system as taught by the present invention;

FIG. 2 is a circuit diagram of switching means suitable for use with the present invention;

FIG. 3 is a schematic circuit diagram of a further embodiment of the present invention wherein additional voltage increments are provided by means of a vernier transformer;

FIG. 4 is a schematic circuit diagram of a further embodiment of the present invention wherein the polarity of the regulating transformer may be reversed; and

FIG. 5 is a schematic diagram of a circuit utilizing plural regulating transformer stages.

DESCRIPTIONS OF THE PREFERRED EMBODIMENTS

Referring now to FIGURE 1, an autotransformer generally indicated at 12 is provided with taps A, B, C. Attached to tap B is one end of secondary winding 14 of a regulating transformer 16. The opposite end of the secondary winding is connected to a first end of a load indicated at 10. The second end of the load 10 is coupled to a point at a common potential with tap D of the autotransformer 12 which may be ground potential. A plurality of bilateral, normally nonconducting gated semiconductor switches S, through S, are provided, each switch being gated into the conducting mode upon reception of pulses provided by a control generally indicated at 20. The control is comprised of a group of trigger elements, each of which when energized providing a pulse to gate or trigger one of the above mentioned switches. These elements, designated S', through S', each gate that switch which has a corresponding number. Switch S, couples a first end of primary winding 18 of regulating transformer 16 to tap A of the autotransformer 12. Switch S, couples the ends of the primary winding 18 and switch S, couples the second end of the primary winding 18 to a point at the aforementioned common potential. Switch S, also connected to the second end of the
primary winding 18, couples the second end of primary 18 to tap C of the autotransformer 12, and switch S2 couples the first end of the primary winding 18 to tap C of the supply autotransformer 12. Zero current detector 40, as will be described hereinafter, derives a signal from current flowing in primary winding 18 which is indicative of the crossover, or zero, point of the current waveform and applies the signal to control 20. The operation of the inventive circuit will now be set forth. When the voltage supplied by tap B of autotransformer 12 is of the magnitude desired to be applied to load 10, it is not necessary that any voltage \( V_A \) exist across the ends of secondary winding 14. Under this condition, control 20 selectively energizes trigger element \( S_1 \), which actuates switch S2, short circuiting the primary winding 18 of the regulating transformer 16. If, however, the voltage applied to load 10 is of magnitude less than that desired, an additive voltage increment \( V_A \) must be supplied. The present circuit may provide additive voltages of three different magnitudes; a first, largest voltage wherein primary winding 18 is connected across the entire length of supply autotransformer 12 by coupling its opposite ends to taps A and D; a second, intermediate voltage wherein the primary winding 18 is connected between taps C and D; and a third, smallest voltage wherein the primary winding 18 is connected between taps A and C of the supply transformer. To accomplish these connections, preselected ones of switches S1 through S4 are energized by control 20. For example, if it is desired that incremental voltage \( V_A \) be the largest possible, in which event primary winding 18 must be connected between taps A and D of autotransformer 12, control 20 actuates gating units \( S_1 \) and \( S_3 \) which in turn energize switches S1 and S3, respectively. Since all other switches remain nonconductive, it will be seen that primary winding 18 now lies in shunt with the full length of the output winding of autotransformer 12, and experiences a voltage \( V_A \) across its ends. Similarly, to couple primary winding 18 between taps C and D switches S2 and S4 are energized by means of trigger elements \( S_2 \) and \( S_4 \) of control 20. Lastly, to afford the smallest incremental voltage afforded by the present circuit, the primary winding 18 is connected between taps A and C of autotransformer 12. This is accomplished by energizing switches S1 and S4 and means of trigger elements \( S_1 \) and \( S_4 \) of control 20.

FIG. 2 shows in greater detail a typical bilateral triggered semiconductor switch S2 such as is used in the circuit of FIG. 1, and associated triggering circuitry. As will be understood by those skilled in the art, SCR's 22 and 24 conduct current in opposite directions, SCR 22 conducting when a suitable triggering pulse is received at gate 22a, and SCR 24 conducting when such a pulse occurs at gate 24a. Triggering pulses are provided by trigger element \( S_2 \) of control 20 when may comprise a ring counter or other logic circuit which provides output pulses to trigger the bilateral switches in response to predetermined input signals. To insure that the switch will be triggered into conduction at a time when zero current is flowing in the circuit, a zero current detector generally indicated at 40, comprising a pair of diodes 42 and 44 connected in inverse parallel, and an isolation transformer 46 with a full wave rectifier connected thereto, are coupled to control 20. As will be understood by those skilled in the art, current traversing the diodes reverses direction a pulse is produced at the output of the isolation transformer. The pulse is applied to control 20 and causes the control to trigger the bilateral switches into conduction at a point in time when current in the system is zero. As a result, the switches are only energized at the crossover point of the alternating current waveform, and no harmonics are introduced into the load circuit due to the presence of the distorted current waveform. It will be seen that it is possible to utilize other triggered bilateral switches rather than inverse parallel SCR's as shown in the referred embodiment, the switching elements represented in the subject disclosures are thus intended to represent all such triggered bilateral devices as are suitable for use with the inventive circuit.

Referring now to FIG. 3, there is shown a further modification of the circuit depicted in FIG. 1. A first end of primary winding 18 is selectively coupled to a plurality of taps having different voltages by means of switches S2, S3, and S4 in the manner described with respect to the foregoing embodiment. In order to supply a plurality of voltage levels to which the second end of primary winding 18 may be selectively coupled, an additional, vernier transformer winding 30 is provided. Gated bilateral semiconductor switches S1, S2, and S3 selectivity couple the second end of winding 18 to taps located at a first or a second end of the vernier winding 30 or to a point intermediate their ends. Similarly, switches S3 and S4 are provided for coupling the first or second end of the vernier winding to line voltage or to ground by means of switches S3 and S4, respectively. As will be understood, the switches, such as S1, are energized by the triggering elements such as \( S'_a \) of control 20.

The second end of primary winding 18 may be placed at line voltage by coupling it to the first end of the vernier transformer by energizing switch S1, and coupling that end of the vernier transformer to tap \( B \) by energizing switches S2 and S3. Similarly, by energizing switches S3, S4, and S5, vernier winding 30 is interposed between the second end of primary winding 18 and transformer tap \( A \), at line voltage. A voltage equal to line voltage, less the voltage increment provided by the vernier transformer winding, then appears at the second end of primary winding 18.

It will now be seen that by energizing selected ones of switches S1 through S4, one end of primary winding 18 may be connected directly to points at either line or ground potential, or the voltage increment provided by all or one half of vernier winding 30 may be interposed between these points and the primary winding 18. By providing a relatively small voltage increment across vernier transformer winding 30, a plurality of vernier steps are thus provided which supplement the course voltage increments afforded through the use of switches S4 through S1, coupled to the first end of primary winding 18.

FIG. 4 shows a further embodiment of the subject invention wherein both additively and subtractive, or boost and buck, voltage increments may be combined with an unregulated voltage \( V_{BC} \) a step down regulating transformer indicated generally at 16 is provided having a secondary 14a placed in series with a load 10 and a voltage source such as transformer winding 112, having input voltage \( V_I \) impressed thereacross. Solid-state triggered bilateral switches S1, S3, and S4 are proved to selectively couple a first end of primary winding 18 of the regulating transformer 16 to points A, B, and C of transformer winding 112. Other switches S2 and S3 selectively couple the second end of the primary winding 18 to points A, B, and C. Should full boost voltage be desired, switches S2 and S4 are triggered by trigger elements \( S'_1 \) and \( S'_4 \) of control 20, providing voltage \( V_A \) across primary winding 18. A somewhat smaller boost voltage \( V_{BC} \) may be impressed across primary winding 18 by triggering switches S2 and S4, and a still smaller boost voltage \( V_{AB} \) may be applied to primary winding 18 by triggering switches S1 and S3. Corresponding bucking voltages are provided by reversing the polarity of primary winding 18 with respect to transformer winding 112, for instance, small bucking voltage \( V_{BA} \) is applied to winding 18 by triggering switches S3 and S4. A somewhat larger bucking voltage \( V_{BC} \) is obtained by triggering switches S2 and S4, while the largest bucking voltage available is obtained by triggering switches S1 and S3, which places primary winding 18 now within inverted polarity, across the entire length of transformer winding 112. A total of 6 voltage increments are thus made available by the disclosed circuit through the provision of only a single regulating transformer.

FIG. 5 shows a still further embodiment of the invention wherein a plurality of stages, each comprising boost-buck transformer and associated switching circuitry, is provided to supply additional voltage increments to a load circuit. A supply transformer winding 112 is provided to supply an initial
unregulated supply voltage $V_s$ to load 10. Connected in series with load 10 are secondary winding 14 and 114 of regulating transformers 16 and 116, respectively. Each transformer has a primary winding 18 and 118, respectively, which is coupled to the desired points by means of triggered bilateral switches $S_1$ through $S_6$ and $S_7$ through $S_{12}$ as described above. While it will be understood by those skilled in the art that the switching arrangement used for second regulating transformer 116 may be identical to that used for transformer 16, and electrically parallel thereto, for purposes of illustration a simpler circuit is provided whereby transformer 116 may provide a voltage having a single boost or buck value. For purposes of illustration, the buck or boost values afforded by transformer 16 may be considered to be $0 \pm 1$ percent, $\pm 2$ percent and $\pm 3$ percent while the boost-buck increments supplied by second stage regulating transformer 116 may be $\pm 7$ percent. A boosting voltage is afforded by transformer 116 when switches $S_7$ and $S_{12}$ are energized, placing voltages $V_s$ across winding 118. Similarly, a bucking voltage is provided by transformer 116 when voltage $V_s$ is reversed across primary winding 118 due to the energization of switches $S_1$ and $S_6$. Since voltage increments supplied by transformer 16 may be selectively added to, or subtracted from, those supplied by transformer 116, it will be seen that, in the embodiment described, voltage regulation from $-10$ percent to $+10$ percent, in 1 percent increments, is possible. As in the previous embodiments, a suitable control for triggering the bilateral solid state switches may be readily provided through the use of logic devices and an associated zero current detector.

While preferred embodiments of the invention have been described by way of illustration, many modifications will occur to those skilled in the art, and it is to be understood that it is intended in the appended claims to cover all such modifications as fall within the true spirit and scope of the invention.

What is claimed and desired to be secured by Letters Patent of the United States is:

1. A voltage regulator including an inductive winding divided into segments by a plurality of taps, said regulator further including:

   regulating transformer means having a secondary winding connected between a first tap on said inductive winding and a load, and having a primary winding having first and second ends and adapted to be selectively connected between pairs of said taps;

   a plurality of switch means coupled to said first end of said primary winding and a second plurality of switch means coupled to said second end of said primary winding of selectively coupling said primary winding of said regulating transformer between pairs of said taps;

   further switch means for coupling said first and said second end of said primary winding together and control means for operating predetermined ones of said switch means. 2. A voltage regulator as defined in claim 1, wherein each of said switch means comprises a gated, bilateral semiconductor switch.

3. A voltage regulator as defined in claim 1, wherein each of said switch means comprises a pair of SCR's connected in inverse parallel relationship.

4. A voltage regulator as defined in claim 1, further including means for supplying a signal to said control means when current in said primary winding approaches zero.

5. A voltage regulator as defined in claim 1, further including a second regulating transformer having a secondary winding adapted to be connected in series with said load and said secondary winding of said first regulating transformer, and having a primary winding having first and second ends;

   a plurality of switch means coupled to each end of said primary winding of said second regulating transformer for selectively coupling said primary winding between pairs of said taps; and control means for operating predetermined ones of said switch means.

6. A voltage regulator as defined in claim 5, wherein each of said switch means comprises a gated, bilateral semiconductor switch.

7. A voltage regulator as defined in claim 5, wherein each of said switch means comprises a pair of SCR's connected in inverse parallel relationship.

8. A voltage regulator as defined in claim 5, further including means for supplying a signal to said control means when current in said primary winding approaches zero.

9. A voltage regulator including an inductive winding for supplying an unregulated voltage to a load, said winding being divided into segments by first, second, and third taps, said regulator further comprising:

   regulating transformer means having a secondary winding connected between said load and said source of unregulated voltage, and further having a primary winding having first and second ends;

   first and second switch means for selectively coupling said first end of said primary winding to either said first or said second taps;

   third and fourth switch means for selectively coupling said second end of said primary winding to said second or said third taps;

   fifth switch means for coupling said first and said second end of said primary winding together; and

   control means for operating predetermined ones of said switch means.

10. A voltage regulator as defined in claim 9 wherein said switch means comprise gated bilateral semiconductor switch means. 11. A voltage regulator as defined in claim 9 wherein each of said switch means comprises a pair of SCR's connected in inverse parallel relationship.

12. A voltage regulator as defined in claim 9, further including means for supplying a signal to said control means when current in said primary winding approaches zero, for causing said control means to operate predetermined ones of said switch means at the zero current point.

13. A voltage regulator including a first inductive winding for supplying power to a load, said inductive winding having a plurality of taps thereon, said voltage regulator further comprising:

   a regulating transformer having a primary winding and a secondary winding, said secondary winding being connected in series between said load and one of said taps of said inductive winding;

   said switch means for selectively coupling a first end of said primary winding to selected ones of said plurality of taps on said first inductive winding;

   a vernier winding inductively coupled to said first inductive winding aid vernier winding having first and second ends, said vernier winding further having a plurality of taps thereon;

   switch means for selectively coupling said first or said second ends of said vernier winding to one of said taps, of said first inductive winding;

   switch means for coupling said second end of said primary winding to selected ones of said taps on said vernier winding;

   control means for operating predetermined ones of said switch means. 14. A voltage regulator as defined in claim 13 wherein said switch means comprise gated, bilateral semiconductor switches.

15. A voltage regulator as defined in claim 13, wherein each of said switch means comprises a pair of SCR's connected in inverse parallel relationship.

16. A voltage regulator as defined in claim 13, further including means for supplying a signal to said control means when current in said primary winding approaches zero, for causing said control means to operate predetermined ones of said switch means at the zero current point.
UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,621,374 Dated November 16, 1971

Inventor(s) Clarence J. Kettler

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 2, line 6 - after "autotransformer" insert -, the other end of the primary winding being selectively coupled -

Column 2, line 6 delete "the"

Column 2, line 7 delete entire line

Column 3, line 52 change "when" to - which -

Column 3, line 72 change "referred" to - preferred -

Column 3, line 73 change "he" to - the -

Column 4, line 48 change "proved" to - provided - (second occurrence)

Column 5, line 11 change "provided"/to - provide -

Column 5, line 15 change "boost-buck" to - buck-boost -

Column 5, line 25 Change "±10" to - +10 -

Column 5, line 47 change "of" (second occurrence) to - for -

Column 6, line 36 change "aid" to - said -

Column 6, line 50 change "aid" to - said -

Signed and sealed this 20th day of June 1972.

(Seal)
Attest:

EDWARD M. FLETCHER, JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents