STATIC INDUCTION REGULATOR EMPLOYING TRANSFORMERS
WITH EVEN-HARMONIC FEEDBACK

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Fig. 4

Fig. 6

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STATIC INDUCTION REGULATOR EMPLOYING TRANSFORMERS WITH EVEN-HARMONIC FEEDBACK

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ABSTRACT OF THE DISCLOSURE

The static induction regulator of the type which employs two transformers with their primaries connected in series to an A.C. power source, their secondaries connected in series in opposition so that under normal conditions the secondary voltages are equal and opposite, and control windings on the transformers such that when control currents are applied to the control windings the secondary voltage from one transformer (e.g. the "boost" transformer) increases the secondary voltage from the other transformer (e.g. the "bucking" transformer) decreases, has each transformer constructed with two flux paths, and with windings which are connected to a rectifier to provide even harmonic feedback. The second harmonic feedback windings can be combined with either the control windings or the primary windings. In the latter case the primary windings are divided.

This invention relates to apparatus for static magnetic control of A.C. power. It is of particular application to A.C. voltage stabilising and regulating systems of high power handling capacity. Since the performance and characteristics of the device are very similar to those of the induction regulator it will hereinafter be called a Static Induction Regulator.

Apparatus in accordance with the invention is an improvement over other known magnetic systems in that a bucking or boosting voltage is introduced in series with the line, and the magnitude and phase of this voltage may be controlled to either add to or subtract from the supply voltage. Further, this voltage is derived from a source having good load regulation characteristics, and is capable of providing a fast response.

The following advantages also result:
(1) Very high electrical efficiency.
(2) Good input power factor.
(3) Efficient utilisation of materials with consequent low weight and small size.
(4) Low distortion.
(5) Fast response time and low control power requirements.
(6) Better performance for transient line voltages than equipment using series connected magnetic regulating elements.

An object of this invention is to provide a static induction regulator in which two transformers have their primaries connected in series across an A.C. power supply line and their secondaries connected in series with each other and the line, the outputs from the two secondaries opposing one another, each transformer having two separate or divided flux paths, even harmonic feedback windings on each transformer so connected that even-order harmonic components are induced in them, said last-mentioned windings being shunted by rectifying elements, control windings on each transformer, and means for applying control currents to the control windings in such sense that as the secondary winding voltage from one transformer increases the secondary winding voltage from the other transformer decreases.

For the purposes of this description each transformer with its associated feedback and control winding will be termed a "controlled saturable transformer" and the system as a whole will comprise two of these for a single phase supply.

Each controlled saturable transformer has inherent constant voltage characteristics, and the voltage at which they "saturate" may be varied by a control circuit provided in association with each primary. A condition may be set up by the application of a particular control current to each primary, such that the sum of the individual primary saturation voltage is equal to, or is slightly lower than the line voltage. As a result of the constant voltage characteristics of each primary the voltage across each will be approximately equal and this balanced condition will be only slightly affected by the load. Under these circumstances the common secondary winding will have practically no voltage induced in it, and the load voltage will be equal to the line voltage less a slight regulation drop.

Now if the control current to the bucking primary is increased, whilst that to the boosting primary is decreased the voltage distribution across the primaries will no longer be equal, the higher voltage appearing across the boosting primary. Under these conditions the resultant voltage induced in the common secondary will boost the line voltage. Maximum boost will be obtained when the control current to the bucking primary is a maximum whilst that to the boosting primary has been reduced to zero. Reversal of the control condition will result in a load voltage lower than that of the incoming line. Odd order harmonic components will be present across whichever primary is controlled into saturation, but since this primary contributes a proportionately lower voltage to the total secondary waveform of the output voltage is not seriously distorted.

The control current may be D.C., A.C., double frequency A.C., half wave rectified A.C., or a combination of these. Control may be achieved by variation of amplitude, or phase shift, or alternatively by modification of the feedback rectifier characteristics. In general, control by half wave elements leads to a simple and economical system.

The physical arrangement of windings and cores may take one of a large number of mechanical forms, and is readily adaptable to standard core forms used for transformer manufacture.

Reference will now be made to the accompanying drawings in which

FIGURE 1 is a diagrammatic showing of a form which the two controlled saturable transformers may take,

FIGURE 2 is a section through a core and winding assembly showing a physical form which the arrangement of FIGURE 1 may take,

FIGURE 3 is a circuit diagram of an arrangement in which the controlled saturable transformers of FIGURE 1 are connected as a static induction regulator according to the invention, and in which means are provided to control a voltage across a load,

FIGURE 4 is a circuit diagram of a static induction regulator using the controlled saturable transformers of FIGURE 1 which is generally more suited to a voltage stabiliser,

FIGURE 5 shows a diagram of a single-phase line-voltage stabiliser using the static induction regulator of FIGURE 4,
FIGURE 6 shows an alternative arrangement of windings on the cores of the controlled saturable transformers, and FIGURE 7 shows a modification of FIGURE 6.

FIGURE 1 shows diagrammatically the preferred form which the two controlled saturable transformers I, II may take, and the manner in which the windings are inter-connected, while FIGURE 2 is a section through a core and winding assembly showing a physical form which the assembly of FIGURE 1 may take. Each transformer I, II has a divided or separate pair of flux paths 6A, 6B and 11A, 11B, respectively. The main or primary windings 3A, 3B, 5C, 5D and 8A, 8B, 8C, 8D respectively of the two transformers are each wound in four sections to provide two parallel current paths, namely 3A, 3B and 3C, 3D for transformer I and 8A, 8B and 8C, 8D for transformer II. Rectifiers 7 and 12 are connected between points on the two primaries respectively of equal potential with respect to fundamental frequencies and odd order harmonics. Thus rectifier 7 is connected between the junctions of 3A, 3B and the junction of 3C, 3D. When so connected the two primary windings also operate as even harmonic feedback windings.

Each core pair 6A, 6B and 11A, 11B carries a secondary winding 4A, 4B and 9A, 9B. The two primaries are connected in series, phased as shown, and are connected to terminals 13, 14. Each core pair is also provided with a control winding 5A, 5B and 10A, 10B respectively which windings connect to terminals 15, 16 and 17, 18 respectively. Control currents are supplied to the control windings 5A, 5B and 10A, 10B so as to provide a controllable and non-symmetrical and unidirectional component of magnetic flux in the individual core pairs. Under these conditions each transformer primary will exhibit "constant voltage" characteristics. The electrical operating principles of each controlled saturable transformer which lead to their constant voltage characteristic are described in United States Patent No. 3,253,212. When connected in series across a source of alternating voltage the voltage distribution between primaries will be a function of the flux components producing even order harmonics in the individual core pairs.

FIGURE 3 is a circuit of an arrangement using the controlled saturable transformers of FIGURE 1 which accepts a fixed input voltage at the terminals 1, 2 and provides a voltage across a load which is controllable over a range. The two secondaries 4, 9, which are each shown as a single winding in this drawing, are connected in series with each other and with the line 1, 2 and load 13, 14. The primaries are phased such that one provides a secondary voltage in phase with the supply, a "boosting voltage," and the other provides a secondary voltage 90° out of phase with the supply voltage, a "bucking voltage." The vector sum of the individual primary saturation voltages is set to be approximately equal to the supply voltage by passing the same control current through each control winding 5A, 5B, 10A, 10B and increasing this current until the A.C. primary magnetising current is just over the knee of the saturation curve. In the circuit of FIGURE 3 this current is provided by the battery 23. Since each primary has been controlled to a same extent the open circuit output voltage will be equal to the input voltage. Further for changes of load the output voltage regulation will be low, since the voltage across either primary cannot rise without drawing a heavy magnetising current.

To provide for either a boost or buck condition the control currents are unbalanced by displacing the moving arm 25 of the potentiometer 24. The rectifiers 19, 20 and resistors 21, 22 are included to limit loading of the even-harmonic components present across the control windings by the low control source impedance.

In FIGURE 3 the control current has been shown for purposes of illustration as a direct current. However, since the primary "saturation voltages" are dependent on both control current and line frequency, it is desirable that the control current be made frequency dependent if the equipment is required to operate over a range of frequencies. For example, the control current could be supplied from a constant voltage transformer or through a series connected capacitor.

FIGURE 4 illustrates a connection of a static induction regulator generally more suited to a voltage stabiliser where the output voltage is to remain constant for variations of input voltage and load. The two transformers I, II are again the two transformers of FIGURE 1 but are shown diagrammatically as in the case of FIGURE 3. The windings are connected in the same manner as in FIGURE 1 but, as was also done in the case of FIGURE 3, the secondaries 4, 9 have each been shown as a single winding whereas in fact each consists of the two windings 4A, 4B and 9A, 9B respectively, as shown in FIGURE 1. Also as in the case of FIGURE 3 the secondaries 4, 9 are connected so as to oppose each other, one secondary winding providing a "BOOST" voltage and the other a "BUCKING" voltage. The only difference between the arrangement of the transformers in FIGURES 3 and 4 is that in FIGURE 4 the secondary windings 4, 9 are connected ahead of the primary windings with respect to the input line, whereas in FIGURE 3 the primary windings appear directly across the input line. Control terminals 15, 16 and 17, 18 of FIGURE 4 may be connected to the similarly numbered control terminals of FIGURE 3, but an alternative automatic control arrangement is shown in FIGURE 5 where transistors are used as control elements.

In this arrangement the voltage across whichever primary is heavily controlled is substantially in quadrature with the output voltage. Further it may be readily arranged that this phase angle is constant for various loadings, and that consequently the phase relationship of the A.C. component of an unsmoothed D.C. control current may also be constant. Another advantage of this connection is that the total primary voltage is constant.

FIGURE 5 shows a diagram of the static induction regulator applied to a single-phase line-voltage stabiliser. The two controlled saturable transformers have been shown diagrammatically, the primaries being numbered 3 and 8 respectively, and the secondary windings being combined in a single winding, numbered "4" and "9," by appropriate phasing of primary and control windings. The physical construction of such an induction regulator is illustrated by FIGURE 2. The control windings 5, 10 are supplied from a full-wave rectifier 29, 30 and the currents are varied differentially by control of the transistors 26, 27. The primary of the transformer 31 is connected to the output voltage through a phase-shifting capacitor 32 chosen to give optimum phasing of the control currents (approx. 90° lead). A second transformer 33, with its primary sensing the output voltage, is connected to a voltage-sensitive bridge 34 which in turn supplies an error signal to the differential amplifier 35. The resistor 28 is chosen to make the total primary saturation voltage slightly higher than the output voltage. Where the output voltage is required to have an extremely pure waveform harmonic filters may be controlled to the main windings of the induction regulator.

One alternative arrangement of windings on the controlled saturable transformers is shown in FIGURE 6 where primaries 3, 8 and secondaries 4, 9 are wound on the centre legs of shell type laminations. Windings 5A, 5B and 10A, 10B are wound on the two divided windings 6A, 6B and 11A, 11B, respectively, and are phased to cancel voltages of fundamental frequency and odd order harmonies. They are shunted by rectifying elements 7, 12 and operate simultaneously as feedback and control windings. It will be seen that the arrangement of the two transformers has primary terminals 1, 2, secondary terminals 13, 14, and control terminals 15, 16 and 17, 18, all of which corresponds to the similarly numbered terminals of
FIGURE 1. The arrangement of FIGURE 6 can replace the arrangement of FIGURE 1 in the circuits of FIGURES 3, 4 and 5 directly by connecting the terminals 1, 2, 13, 14, 15, 16, 17 and 18 of the arrangement of FIGURE 6 to the same numbered terminals in FIGURES 3, 4 and 5, after removing the transformers of FIGURE 1 from the circuit.

If desired separate control and even-harmonic feedback windings may be used. In all the arrangements described the relationships of the primary and secondary windings can be reversed.

Whilst, in the interests of simplicity, the operating principles have been described for a single phase unit, similar considerations will apply for polyphase operation, and the invention is equally applicable to polyphase as to single phase operation.

FIGURE 7 shows a variant of the circuit arrangement of FIGURE 6 in which the two transformers each have ever-harmonic feedback windings 42A, 42B and 43A, 43B respectively which are separate from the control windings 40A, 40B and 41A, 41B respectively. The control windings 40A, 40B connect to terminals 15, 16, as did the windings 5A, 5B of FIGURE 6 and the control windings 41A, 41B connect to terminals 17, 18 as did also the windings 2A and 10B of FIGURE 6. The primary and secondary windings 3, 8 and 4, 9 respectively of FIGURE 7 are positioned and connected similarly to those of FIGURE 6, and are similarly numbered. It is thought that the operation of the embodiment of FIGURE 7 will be obvious from the above description and that of FIGURES 6 and 3.

It will be seen that the control terminals 15, 16, 17, 18 have been connected to a manual current control comprising battery 23, potentiometer 24, resistors 21 and 22, and rectifier 19, 20 which is the same control as is used in FIGURE 3, and whose operation will be evident from the description of that figure.

What I claim is:

1. A static induction regulator comprising input terminals to the regulator, output terminals to the regulator, two transformers, a three legged core for each transformer consisting of a central limb and two outer limbs, a primary winding for each transformer on the central limb thereof, series connections between the primary windings, a secondary winding for each transformer on the central limb thereof, series connections between the secondary windings and the input and output terminals such that the secondary voltages oppose each other, a control winding for each transformer having portions on each outer limb, a rectifier connected across each control winding whereby it functions as a second harmonic feedback winding, means for applying currents through said control windings such that the two secondary voltages are equal and opposite, and means for varying the currents through the control windings such that as one secondary winding voltage increases the other secondary winding voltage decreases.

2. A static induction regulator comprising input terminals, output terminals, two transformers, an iron core for each transformer having a central leg and two outer limbs, a primary winding on the central leg of each transformer, series connections of the primary windings to the input terminals, a secondary winding on the central leg of each transformer, series connections of the secondary windings between the input and output terminals so that the secondary voltages oppose each other, a pair of even-harmonic feedback windings, one on each outer limb of the core for the first transformer, connected in opposition with respect to voltages of fundamental frequency induced in them, a rectifier connected in shunt with the even-harmonic feedback windings, a second pair of even-harmonic feedback windings, one on each outer limb of the core for the second transformer, connected in opposition with respect to voltages of fundamental frequency induced in them, a second rectifier connected in shunt with the said second pair of similar windings, means for applying control currents to the said two pairs of similar windings that as the secondary voltage of the first transformer increases the secondary voltage of the second transformer decreases.

3. A static induction regulator comprising input terminals, output terminals, two transformers, an iron core for each transformer having a central leg and two outer limbs, a primary winding on the central leg of each transformer, series connections of the primary windings to the output terminals, a secondary winding on the central leg of each transformer, series connections of the secondary windings between the input and output terminals so that the secondary voltages oppose each other, a pair of even-harmonic feedback windings, one on each outer limb of the core for the first transformer, connected in opposition with respect to voltages of fundamental frequency induced in them, a rectifier connected in shunt with the even-harmonic feedback windings, a second pair of even-harmonic feedback windings, one on each outer limb of the core for the second transformer, connected in opposition with respect to voltages of fundamental frequency induced in them, a second rectifier connected in shunt with the said second pair of similar windings, means for applying control currents to the said two pairs of similar windings that as the secondary voltage of the first transformer increases the secondary voltage of the second transformer decreases.

4. A static induction regulator comprising input terminals, output terminals, two transformers, an iron core for each transformer having a central leg and two outer limbs, a primary winding on the central leg of each transformer, series connections of the primary windings to the input terminals, a secondary winding on the central leg of each transformer, series connections of the secondary windings between the input and output terminals so that the secondary voltages oppose each other, two similar windings, one on each outer limb of the core of the first transformer, connected in opposition with respect to voltages of fundamental frequency induced in them, a rectifier connected in shunt with the said two similar windings, a second pair of similar windings, one on each outer limb of the core of the second transformer, connected in opposition with respect to voltages of fundamental frequency induced in them, a second rectifier connected in shunt with the said second pair of similar windings, means for applying control currents to the said two pairs of similar windings that as the two secondary voltages are equal and opposite, and means for varying the control currents so that as one secondary voltage increases the other secondary voltage decreases.

5. A static induction regulator comprising input terminals, output terminals, two transformers, an iron core for each transformer having a central leg and two outer limbs, a primary winding on the central leg of each transformer, series connections of the primary windings to the output terminals, a secondary winding on the central leg of each transformer, series connections of the secondary windings between the input and output terminals so that the secondary voltages oppose each other, two similar windings, one on each outer limb of the core of the first transformer, connected in opposition with respect to voltages of fundamental frequency induced in them, a rectifier connected in shunt with the said two similar windings, a second pair of similar windings, one on each outer limb of the core of the second transformer, connected in opposition with respect to voltages of fundamental frequency induced in them, a second rectifier connected in shunt with the said second pair of similar windings, means for applying control currents to the said two pairs of similar windings...
such that the two secondary voltages are equal and opposite, and means for varying the control currents so that as one secondary voltage increases the other secondary voltage decreases.

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