

PATENT SPECIFICATION

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(54) DC TO AC INVERTER

(71) We, SUNDSTRAND CORPORATION, a corporation organised and existing under the laws of the State of Delaware, United States of America, of 4751 Harrison Avenue, Rockford, Illinois 61101, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed to be particularly described in and by the following Statement:—

The invention relates to DC to AC inverters and provides such an inverter in which a multiple step approximation to a sinusoidal wave is developed by summing in phase rectangular waves of different frequency.

Inverters are used in a wide variety of applications where only DC power is available, but AC power is needed. Inverters are also used in situations where AC power is available, such as aboard an aircraft, but is unregulated with respect to frequency. In such situations, the available AC power from generators or the like is converted to DC power, regulated with respect to amplitude, and then reconverted to AC power by an inverter which establishes a fixed frequency therefor. In most of these applications it is desired to minimize the number of harmonics in the AC output signal, and in airplane applications in particular it is most important that the weight of electromagnetic components of the inverter be minimized.

The invention provides a DC to AC inverter, comprising means for generating an alternating stepped waveform having a magnitude which varies incrementally during each half cycle and which has a first value at the beginning and end segments of each half cycle thereof and a second value greater than said first value during a segment intermediate the beginning and end segments, means for developing a

rectangular wave in phase with and having a frequency greater than that of the alternating stepped waveform; and means for summing the alternating stepped waveform and the rectangular wave to form a composite waveform which approximates a sinusoidal waveform and has three steps in each quarter cycle thereof. The invention also provides a DC to AC inverter with a three-phase output, comprising means for generating first, second and third alternating stepped waveforms phase displaced with respect to each other by 120° and each having a magnitude that varies incrementally during each half cycle, the magnitude of each waveform having a first value at the beginning and end segments of each half cycle thereof and a second value greater than said first value during the segment intermediate said beginning and end segments; means for developing a rectangular wave in phase with, and having a frequency greater than that of, each of the first, second and third waveforms and means for summing the rectangular wave with each of the first, second and third waveforms to form three composite waveforms, each of said composite waveforms approximating a sinusoidal waveform and having three incremental steps of different magnitude in each quarter cycle thereof.

It is possible to design an inverter according to the invention which has an output with a low harmonic content.

The invention is hereinafter particularly described by way of example only with reference to the drawings of which:

Figure 1 is a simplified block diagram of an inverter according to the invention;

Figure 2 is a schematic circuit diagram partially in block diagram form, of a single phase inverter according to the invention;

Figure 3a is an illustration of two waveforms developed in the main inverter sche-

atically illustrated in Figures 1 and 2;

Figure 3b is an illustration of the switching sequence of the inverter switches of Figure 2 for development of the waveform of Figure 3a;

Figure 3c is a schematic illustration of the waveform produced by the rectangular wave source of Figures 1 and 2;

Figure 3d is a schematic illustration of the composite waveform, and the sinusoidal waveform which it approximates, that is achieved by summing the stepped waveform of Figure 3a with the rectangular waveform of Figure 3c;

Figure 4 is a schematic circuit diagram of a three-phase inverter according to the invention; and

Figure 5 is a schematic illustration of the pulses developed across the various coils of the inverter of Figure 4 and of a rectangular wave which is obtained by summing these pulses.

Referring to Figure 1, one embodiment of the DC to AC inverter circuit of this invention is seen to include a main inverter 10, a rectangular waveform source 12 and a summation circuit 14. Referring also to Fig. 3a, the main inverter 10 produces a stepped waveform VM with alternating positive and negative half cycles with respect to a neutral or ground reference potential. The magnitude of stepped waveform VM varies incrementally during each half cycle, having a first value VM1 at beginning and end segments 16 of each half cycle and a second value VM2 greater than the first value VM1 during a segment 18 of each half cycle intermediate the beginning and end segments 16. Referring to Fig. 3c, a rectangular waveform source 12 produces a rectangular wave VT in phase with the stepped waveform VM and having a frequency three times greater than that of the alternating waveform VM. The rectangular waveform VT has alternating positive and negative portions with respect to ground reference potential, each portion having a duration less than that of the intermediate segment of the alternating stepped waveform, and is added to the alternating waveform VM by summation circuit 14 to form a composite waveform VO, schematically illustrated in Fig. 3d. The composite waveform VO comprises an approximation of a sinusoidal waveform S shown in broken line in Fig. 3d with three incremental steps for each quarter cycle. The three steps have relative magnitudes in the ratio of 262:716:978.

The harmonic content of the composite output signal VO can be controlled through selection of the magnitude VM1 of the beginning and end segments 16 of the alternating waveform VM relative to the

magnitude VM2 of the intermediate section 18 and also by selecting the duration of the beginning and end segments. In the illustrative waveform of Fig. 3a, the duration of the beginning and end segments 16 is 30° and the magnitude of VM1 is approximately .452 VM2 which is a value that substantially eliminates the 5th and 7th harmonics in the output voltage VO. The rectangular waveform VT likewise affects the harmonic content of the output voltage VO. If the rectangular waveform VT is a square wave with a peak magnitude approximately equal to .150 of VM2 as illustrated in Fig. 3c, the third harmonic and its multiples are cancelled. All of the odd harmonics up to the 11th are thus eliminated in the composite output waveform VO. The 11th harmonic is relatively small and, accordingly, easily filtered.

One particular form of the main inverter 10 and the summation circuit 14 is shown in Fig. 2. It should, however, be appreciated that other techniques for developing the alternating waveform VM may be employed while still obtaining the benefits derived from synthesizing the composite output waveform VO in the manner described. As seen in Fig. 2, the main inverter 10 includes a coil 20 with an intermediate tap 22 offset from center and a center tapped or tripolar voltage source 24 schematically illustrated by two DC batteries 26 and 28 connected in series with a junction or center tap 30 therebetween connected to ground. Battery 26 provides a DC voltage +V at a voltage line 32 positive with respect to ground, and battery 28 provides a negative voltage -V on a negative voltage line 32 negative with respect to ground. The composite output waveform VO is developed between ground and intermediate tap 22.

The alternating waveform VM is developed by selectively switching the opposite ends of coil 20 to the positive and negative voltage lines 32 and 34. The end of coil 20 closest to intermediate tap 22 is switched to the positive voltage line 32 through control of a silicon-controlled rectifier (SCR) 35 and switched to the negative voltage line 34 through control of an SCR 36. The other end of coil 20 is switched to the positive voltage line 32 through control of an SCR 38 and connectable to the negative voltage line 34 through control of an SCR 40. Four diodes, 42, 44, 46 and 48, respectively connected in parallel with SCR's 35, 36, 38 and 40, provide paths for regenerative current back to the DC power supplies or batteries 26 and 28, and may also be employed to conduct commutating pulses across the SCR's associated therewith.

A conventional switching control circuit 50 is connected to the gates of each of the SCR's 35, 36, 38 and 40 to apply trigger and commutating pulses thereto to turn the SCR's on and off in the sequence illustrated in Fig. 3b. As can be seen, during the positive half cycle, SCR 35 is conducting and SCR 36 is nonconducting to apply the positive battery voltage +V to the left side of coil 20, and during negative half cycles, SCR 35 is nonconducting and SCR 36 is conducting to apply the negative battery voltage -V to the left side of coil 20. The right side of coil 20 is selectively switched to the positive and negative battery voltage line during each half cycle to obtain the different output voltages during the different segments thereof. During the beginning and end segments, the appropriate one of SCR's 38 and 40 is turned on to connect the right side of the coil to the voltage line of polarity opposite to that which is connected to the left side of the coil so that the magnitude of voltage applied across the coil is equal to +2V, the sum of the two battery voltages. The voltage signal applied across the coils during the end segments is illustrated by pulses 41 shown in broken line in Fig. 3a. During the intermediate segments 18, SCR's 38 and 40 are selectively switched on to connect the right side of coil 20 to the same voltage line as the left side of the coil so that a zero voltage is applied across coil 20. The voltage at tap 22 relative to ground during the intermediate segments 18 is therefore equal to the magnitude V of the batteries 26 and 28.

For a single phase inverter, the rectangular waveform source 12 may take the form of any number of well-known conventional rectangular wave generators. Maintenance of the proper phase and frequency relationships between the rectangular waveform VT and the alternating waveform VM may be easily achieved by employing a common source of clock signals for both the rectangular wave source and the switching control circuit 50. Summation of the rectangular wave VT with the stepped alternating waveform VM is achieved by applying it between the battery junction 30 and the grounded output terminal.

Referring to Fig. 4, a three-phase embodiment of the inverter is shown wherein three composite output signals VO1, VO2 and VO3, are produced, identical to the composite output waveform VO illustrated in Fig. 3d but which are phase displaced with respect to one another by 120°. The three composite output signals VO1-VO3 are respectively developed by three inverter stages, 54, 56 and 58. Each of these stages is identical

to, and functions in the same manner as, the single pulse inverter 10 illustrated in Fig. 2.

Accordingly, the circuit elements of each phase have been given the same reference numeral as the corresponding element of the inverter 10 followed by the suffix -1, -2 and -3, respectively designating the stage association with the first, second and third phases. All phases are powered by batteries 26 and 28 and are connected in parallel between the positive voltage line 32 and the negative voltage line 34. The gates of the SCR's of each phase are connected to a conventional switching control circuit (connection not shown) which causes the SCR's of each phase to turn on and turn off in the exact same sequence as SCR's 35, 36, 38 and 40 illustrated in Fig. 3b.

Unlike the single phase inverter shown in Fig. 2 which requires a separate rectangular wave source 12, the three-phase inverter of Fig. 4 develops an appropriate rectangular wave VT by summing together the voltage pulses developed across the coils 20-1 through 20-3 during the beginning and end segments 16 of the output waveforms thereof. The voltages applied across coils 20-1, 20-2 and 20-3 and the relative phase relationships between these pulses is illustrated in the top three waveforms of Fig. 5. These pulses applied across coils 20-1 through 20-3 respectively induce voltage pulses of proportional magnitude in the coils 52-1 through 52-3 inductively coupled therewith. The coils 52-1 through 52-3 are connected in series with one another between the center tap 30 and a neutral output terminal 60 common to all three phases which is connected to ground reference potential. This series connection causes the voltage pulses induced in windings 52-1 through 52-3 to be summed together to form the rectangular waveform VT, which in this instance, as seen in the last waveform of Fig. 5, is a square wave at three times the frequency of the three individual pulses from which it is made. The series connection of coils 20-1 through 20-3 and coils 52-1 through 52-3, of course, also results in this rectangular wave being summed at the neutral terminal 60 of all three phases to form the three composite output waveforms VO1, VO2 and VO3.

WHAT WE CLAIM IS:

1. A DC to AC inverter, comprising means for generating an alternating stepped waveform having a magnitude which varies incrementally during each half cycle and which has a first value at the beginning and end segments of each half cycle thereof and a second value greater than said first value during a segment intermediate



A conventional switching control circuit 50 is connected to the gates of each of the SCR's 35, 36, 38 and 40 to apply trigger and commutating pulses thereto to turn the SCR's on and off in the sequence illustrated in Fig. 3b. As can be seen, during the positive half cycle, SCR 35 is conducting and SCR 36 is nonconducting to apply the positive battery voltage +V to the left side of coil 20, and during negative half cycles, SCR 35 is nonconducting and SCR 36 is conducting to apply the negative battery voltage -V to the left side of coil 20. The right side of coil 20 is selectively switched to the positive and negative battery voltage line during each half cycle to obtain the different output voltages during the different segments thereof. During the beginning and end segments, the appropriate one of SCR's 38 and 40 is turned on to connect the right side of the coil to the voltage line of polarity opposite to that which is connected to the left side of the coil so that the magnitude of voltage applied across the coil is equal to +2V, the sum of the two battery voltages. The voltage signal applied across the coils during the end segments is illustrated by pulses 41 shown in broken line in Fig. 3a. During the intermediate segments 18, SCR's 38 and 40 are selectively switched on to connect the right side of coil 20 to the same voltage line as the left side of the coil so that a zero voltage is applied across coil 20. The voltage at tap 22 relative to ground during the intermediate segments 18 is therefore equal to the magnitude V of the batteries 26 and 28.

For a single phase inverter, the rectangular waveform source 12 may take the form of any number of well-known conventional rectangular wave generators. Maintenance of the proper phase and frequency relationships between the rectangular waveform VT and the alternating waveform VM may be easily achieved by employing a common source of clock signals for both the rectangular wave source and the switching control circuit 50. Summation of the rectangular wave VT with the stepped alternating waveform VM is achieved by applying it between the battery junction 30 and the grounded output terminal.

Referring to Fig. 4, a three-phase embodiment of the inverter is shown wherein three composite output signals VO1, VO2 and VO3, are produced, identical to the composite output waveform VO illustrated in Fig. 3d but which are phase displaced with respect to one another by 120°. The three composite output signals VO1-VO3 are respectively developed by three inverter stages, 54, 56 and 58. Each of these stages is identical

to, and functions in the same manner as, the single pulse inverter 10 illustrated in Fig. 2.

Accordingly, the circuit elements of each phase have been given the same reference numeral as the corresponding element of the inverter 10 followed by the suffix -1, -2 and -3, respectively designating the stage association with the first, second and third phases. All phases are powered by batteries 26 and 28 and are connected in parallel between the positive voltage line 32 and the negative voltage line 34. The gates of the SCR's of each phase are connected to a conventional switching control circuit (connection not shown) which causes the SCR's of each phase to turn on and turn off in the exact same sequence as SCR's 35, 36, 38 and 40 illustrated in Fig. 3b.

Unlike the single phase inverter shown in Fig. 2 which requires a separate rectangular wave source 12, the three-phase inverter of Fig. 4 develops an appropriate rectangular wave VT by summing together the voltage pulses developed across the coils 20-1 through 20-3 during the beginning and end segments 16 of the output waveforms thereof. The voltages applied across coils 20-1, 20-2 and 20-3 and the relative phase relationships between these pulses is illustrated in the top three waveforms of Fig. 5. These pulses applied across coils 20-1 through 20-3 respectively induce voltage pulses of proportional magnitude in the coils 52-1 through 52-3 inductively coupled therewith. The coils 52-1 through 52-3 are connected in series with one another between the center tap 30 and a neutral output terminal 60 common to all three phases which is connected to ground reference potential. This series connection causes the voltage pulses induced in windings 52-1 through 52-3 to be summed together to form the rectangular waveform VT, which in this instance, as seen in the last waveform of Fig. 5, is a square wave at three times the frequency of the three individual pulses from which it is made. The series connection of coils 20-1 through 20-3 and coils 52-1 through 52-3, of course, also results in this rectangular wave being summed at the neutral terminal 60 of all three phases to form the three composite output waveforms VO1, VO2 and VO3.

WHAT WE CLAIM IS:

1. A DC to AC inverter, comprising means for generating an alternating stepped waveform having a magnitude which varies incrementally during each half cycle and which has a first value at the beginning and end segments of each half cycle thereof and a second value greater than said first value during a segment intermediate



the beginning and end segments; means for developing a rectangular wave in phase with and having a frequency greater than that of the alternating stepped waveform; 5 and means for summing the alternating stepped waveform and the rectangular wave to form a composite waveform which approximates a sinusoidal waveform and has three steps in each quarter cycle 10 thereof.

2. An inverter according to claim 1, wherein the means for generating the alternating stepped waveform comprises a source of DC voltage providing both positive and negative voltages with respect to 15 a neutral reference potential, a coil with an intermediate tap offset from its centre, and means for selectively switching the positive and negative voltages to opposite sides of the coil to generate the alternating stepped waveform at the intermediate tap, the composite waveform being developed 20 between the intermediate tap and the reference potential.

3. An inverter according to claim 2, in which the switching means includes a first switch connected to one side of the coil for applying the positive voltage thereto, a second switch connected to the one side of 30 the coil for applying the negative voltage thereto, a third switch connected to an opposite side of the coil for applying the positive voltage thereto, a fourth switch connected to the opposite side of the coil for applying the negative voltage thereto, and switch controlling means for causing the first and fourth switches to assume 35 conductive states during the beginning and end segments of each positive half cycle, the first and third switches to assume conductive states during the intermediate segments of each positive half cycle, the second and third switches to assume conductive states during the beginning and 40 end segments of each negative half cycle, and the second and fourth switches to assume conductive states during the intermediate segments of each negative half cycle.

4. An inverter according to any preceding claim, in which the rectangular wave has alternating positive and negative portions with respect to a neutral reference potential, each portion having a duration 55 less than that of the intermediate segment of the alternating stepped waveform.

5. An inverter according to any preceding claim, in which the rectangular wave has a frequency three times that of the 60 alternating stepped waveform.

6. An inverter according to any preceding claim, in which the rectangular wave is a square wave.

7. An inverter according to any preceding claim, in which the alternating stepped

waveform, the rectangular wave and the composite waveform vary above and below a reference potential during alternating half cycles.

8. An inverter according to any preceding claim, in which each of the beginning and end segments of each half cycle of the alternating stepped waveform has a duration of 30°.

9. An inverter according to any preceding claim, wherein the three steps of the composite output waveform have relative magnitudes in the ratio of 262:716:978. 75

10. An inverter according to any preceding claim, including means for generating second and third alternating stepped waveforms substantially identical to the first-mentioned alternating stepped waveform and out of phase therewith by 120° and 240° respectively, and in which the 85 summing means comprises means for summing said rectangular wave with both the second and the third alternating waveforms to form second and third composite waveforms each substantially identical to the 90 first-mentioned composite waveform but out of phase therewith by 120° and 240° respectively, providing a three-phase output.

11. An inverter according to claim 10, 95 in which each of the alternating stepped waveform generating means comprises a coil, and means for switching a source of DC voltage across the coil during the beginning and end segments of each half cycle 100 of the alternating waveform thereof; and the means for developing a rectangular wave comprises means inductively coupled with each of the coils for developing pulses at the beginning and end segments of each 105 of the first, second and third alternating waveforms, and means for adding all of the pulses together to form the rectangular wave.

12. An inverter according to claim 11, 110 in which each of the coils has a tap at which the one alternating waveform associated therewith is produced.

13. An inverter according to claim 11 or claim 12, in which the first, second and 115 third composite waveforms are developed between respective output terminals associated with the individual waveform generating means and another terminal common to all the waveform generating 120 means; the source of DC voltage has a reference terminal at which a reference potential is provided, a positive terminal at which a voltage positive with respect to the reference voltage is provided and a 125 negative terminal at which a voltage negative with respect to the reference voltage is provided; and the inductively coupled means comprise a circuit having three windings connected in series with one an- 130

other between the reference terminal and the common terminal, and inductively coupled with the coils of the first, second and third alternating waveform generating means respectively.

14. An inverter according to claim 13, in which each output terminal associated with an individual waveform generating means is connected with an intermediate tap of the coil of that waveform generating means, and each waveform generating means further includes a first electronic switch connected between one end of the coil and the positive terminal, a second electronic switch connected between the one end of the coil and the negative terminal, a third electronic switch connected with the other end of the coil and the positive terminal and a fourth electronic switch connected between the other end of the coil and the negative terminal, and switch controlling means effective during each positive half cycle of each coil to cause the associated first and fourth electronic switches to assume conductive states during the beginning and end segments thereof and the associated first and third electronic switches to assume conductive states during the intermediate segment thereof, and effective during each negative half cycle of each coil to cause the associated second and third electronic switches to assume conductive states during the beginning and end segments thereof, and the associated second and fourth electronic switches to assume conductive states during the intermediate segment thereof.

15. An inverter according to any of claims 10 to 14, wherein the rectangular wave is a square wave with a frequency three times that of the alternating stepped waveforms; the three steps in each quarter

cycle of each of the three resulting composite waveforms have relative magnitudes in the ratio of 262:716:978; and the beginning and end segments of each of the alternating stepped waveforms have durations of 30°.

16. A DC to AC inverter with a three-phase output, comprising means for generating first, second and third alternating stepped waveforms phase displaced with respect to each other by 120° and each having a magnitude that varies incrementally during each half cycle, the magnitude of each waveform having a first value at the beginning and end segments of each half cycle thereof and a second value greater than said first value during the segment intermediate said beginning and end segments; means for developing a rectangular wave in phase with, and having a frequency greater than that of, each of the first, second and third waveforms, and means for summing the rectangular wave with each of the first, second and third waveforms to form three composite waveforms, each of said composite waveforms approximating a sinusoidal waveform and having three incremental steps of different magnitude in each quarter cycle thereof.

17. A DC to AC inverter substantially as particularly described herein with reference to Figures 1 to 3 of the drawings.

18. A DC to AC inverter with a 3-phase output, substantially as particularly described herein with reference to Figures 4 and 5 of the drawings.

SERJEANTS,
Chartered Patent Agents,
25 The Crescent,
Leicester.

