

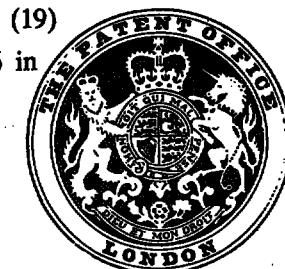
PATENT SPECIFICATION

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(54) DC TO AC INVERTER CIRCUIT

(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:-

This invention relates to DC to AC inverters and, more particularly, to a highly efficient circuit which advantageously develops a sinusoidal waveform having a low harmonic content from rectangular or square wave components.

As discussed in our copending Application No. 1542803 (11239/77), inverters serve the purpose of providing AC power requirements when only DC is available. Inverters are well known and are usually considered to be off-the-shelf items when efficiency, weight and harmonic levels are not a consideration. However, when such considerations become important, one must carefully evaluate the particular inverter.

When evaluating inverters, consideration is generally given to the total harmonic noise level rejection, the efficiency of the inverter and its total weight. An evaluation of these considerations is most critical where the environment of the inverter is adverse. For example, in aircraft, balloon or space use, it becomes important to obtain an inverter capable of providing power with a low harmonic content so that the noise resulting from the presence of the harmonics will not interfere with other airborne components and systems. Furthermore, good efficiency is a requirement because of the limited DC power available. Finally, the weight associated with the inverter is an important consideration for obvious reasons.

It is difficult to obtain a highly efficient, low harmonic, lightweight inverter, and usually the improvement of one characteristic is accomplished at the expense of one or both of the other two. As shown in Patent Specification No. 1542803 a sine wave can be approximated by generating a rectangular wave and then combining it with a stepped waveform while advantageously eliminating the first to eleventh harmonics. The system disclosed in Specification No. 1542803 is desirable because it is light in weight and at the same time it has the capability of minimizing the harmonics.

The present invention provides another inverter which eliminates the first to eleventh harmonics, is even lighter in weight than the inverter disclosed in Specification No. 1542803, and is driven by a fundamental rectangular component at a frequency equal to the output frequency.

The invention provides a DC to AC inverter circuit comprising means for generating first, second and third fundamental rectangular waveforms at the same frequency wherein each of the first, second and third rectangular waveforms is out of phase with the other two by 120°; means for generating notching rectangular waveforms for each of the first, second and third fundamental waveforms; means for combining the notching rectangular waveforms for each of the first, second and third fundamental waveforms to provide a single rectangular triplex waveform having a frequency equal to three times the fundamental frequency; and means for combining the first fundamental rectangular waveform, the notching rectangular waveform for the first fundamental waveform and the single triplex waveform to provide an output which approximates a sinusoidal waveform in phase with the first fundamental waveform. The first, second and third fundamental rectangular waveforms each have a frequency

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cy equal to the desired output frequency of the approximately sinusoidal AC output. An auxiliary inverter circuit may be used to generate the two distinct waveforms to be summed with the main rectangular waveform. The two distinct waveforms generated by the auxiliary circuit comprise individual "notching" pulses and a square triplex wave having a frequency equal to three times that of the fundamental main rectangular wave. When the triplex wave, the notching wave and the main rectangular wave are summed, the resulting waveform approximates a sinusoidal waveform which by selection of the relative amplitudes of the component waves being summed may be virtually free of the first to eleventh harmonics.

An inverter having such a circuit may be made lightweight while maintaining high efficiency. The output may be single phase or three phase.

Advantageously the circuit of the invention has a main inverter circuit portion which switches the major part of power at the same frequency as the desired synthesized sinusoidal output.

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 a three-phase inverter circuit according to the invention;

Figure 2 is a schematic diagram of the main DC source, the main inverter circuit, and the main inverter switching circuit;

Figure 3(a) shows the secondary DC source, the auxiliary inverter switching circuit and the auxiliary inverter circuit;

Figure 3(b) depicts the switching sequence of the switches in the auxiliary inverter circuit;

Figure 4(a) depicts the fundamental rectangular waveform (phase A) as developed by the main inverter circuit;

Figure 4(b) is the fundamental rectangular waveform developed by the main inverter circuit 120° out of phase (phase B) from the wave form shown in Figure 4(a);

Figure 4(c) is the fundamental rectangular waveform developed by the main inverter circuit 120° out of phase (phase C) from the waveform shown in Figure 4(b);

Figure 4(d) illustrates the three notching waveform outputs of the auxiliary inverter circuit for the three phases of the fundamental wave of Figures 4(a)-4(c);

Figure 4(e) illustrates an inversion of the notching output of the auxiliary circuit for the waveform (phase A) of Figure 4(a);

Figure 4(f) depicts the triplex waveform resulting from combining the three phases of notching waveforms;

Figure 4(g) is a graphical representation of the sinusoidal output (phase A) having a frequency equal to the fundamental rectan-

gular wave of Figure 4(a);

Figure 5 is a schematic diagram of the entire inverter system;

Figure 6(a) is a schematic diagram of another auxiliary inverter circuit;

Figure 6(b) depicts the switching sequence of the circuit in Figure 6(a); and

Figure 7 illustrates the waveforms from the circuit in Figure 6(a).

Referring to Figure 1, one embodiment of the three-phase DC to AC inverter circuit includes a main inverter circuit 10 supplied by a main DC source 9 and coupled to provide summed waveform 27. The main inverter circuit 10 is switched by main inverter switching circuit 12 which controls the frequency of the three-phase output on line 20 of the main inverter circuit. A clock circuit 14 provides timing control to the main inverter switching circuit 12 for synchronizing it with the operation of auxiliary inverter switching circuit 16. Auxiliary inverter switching circuit 16 is supplied by an auxiliary DC source 17 which may be derived from the main DC source 9. Auxiliary inverter switching circuit 16 switches DC from the source 17 to the auxiliary inverter circuit 18. The auxiliary inverter circuit 18 develops two outputs on lines 22 and 24. Line 22 carries the "notching" waveform signal for each of three phases. The notching waveform is a series of four pulses for every period of the main waveform. The position of the four pulses is discussed below. Typically, however, each pulse width is 30° of the main frequency. Line 24 provides the triplex signal (Figure 4(f)) for all three phases. The triplex signal is appropriately combined with the notch waveform on line 22 and the main waveform on line 20 to provide the desired synthesized sinusoidal three-phase waveform 27 (Figure 4 (g)) for phase A. The triplex waveform has a frequency of three times the fundamental frequency and is constructed by combining the notching waveforms of the three phases as they are generated by the auxiliary inverter circuit 18. The waveforms on lines 20, 22 and 24 are combined for the production of all three phases of the synthesized sinusoidal three-phase waveform. Filter 28 is a simple passive filter for smoothing the synthesized waveform.

Referring to Figure 2, a schematic diagram is provided for main DC source 9, main inverter circuit 10 and main inverter switching circuit 12. Source 9, as illustrated, includes batteries V₁ and V₂ connected in series with a centre lead connected between them to provide a three-phase circuit ground, or neutral. Battery V₁ provides a positive voltage with respect to circuit ground whereas battery V₂ provides a negative voltage with respect to circuit ground. Although batteries V₁ and V₂ are shown for

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convenience, the source 9 could alternatively if desired provide direct current by the use of a rectified AC source, for example. The characteristics of V_1 and V_2 are essentially the same, and the voltage of the two batteries depends upon the desired peak value of the sinusoidal AC output. The voltage of V_1 and V_2 is approximately 83% of the peak value of the filtered synthesized waveform. The main inverter switching circuit 12 has six switches in three pairs: S1-S2, S3-S4 and S5-S6. These switches may be SCR's, heavy duty power transistors, or any other type of switching mechanism capable of switching the power from batteries V_1 and V_2 . Each pair of switches provides a rectangular waveform of the fundamental frequency in a 120° phase relationship with the other two phases. Figures 4(a) to 4(c) best depict the waveforms produced by the three pairs of switches. The clock circuit 14 provides the necessary timing pulses to a ring counter or other similar device (not shown) to effect the appropriate switching action of the switching circuit 12 for generating the three fundamental waves. The main inverter circuit 10, as shown in Figure 2, provides the fundamental waveforms at the selected fundamental frequency between the switch pairs for phase A, phase B and phase C. The circuit neutral from the junction of the two batteries V_1 and V_2 provides a line-to-neutral voltage for all three phases.

Referring to Figure 3(a), the auxiliary DC source 17, shown as a battery V_s for convenience, is connected to the auxiliary inverter circuit 16 which in turn is coupled to auxiliary inverter circuit 18. The voltage established by the battery V_s may be less than that of V_1 or V_2 , but is determined by the selected transformer ratio as discussed below.

Switches S7 to S14, which comprise the auxiliary inverter switching circuit 16, provide the necessary switching for the auxiliary inverter circuit 18. The switches may be transistors, SCR's or any other suitable switching mechanisms and are required to provide four pulses per period for each of phase A, phase B and phase C on lines 30, 32 and 34, respectively. Switches S7 to S14 are timed by the clock circuit 14 and are switched in a manner depicted in Figure 3(b). Figure 4(d) shows the notching pulse waveforms for the three phases A, B and C as they appear on lines 30, 32 and 34, respectively. Line 36 and its associated switches S13 and S14 complete the switching for the three phases at each of the transformers 38, 40 and 42 to produce the notching pulse waveforms of Figure 4(d) as is apparent from considering Figure 3(a) in combination with Figure 3(b). During the time between the pulses, the appropriate switch

pair connects both sides of the coil to the same side of the voltage source to assure a zero voltage drop across it. During the period of time that a particular coil is energized, the switching sequence is such, as is apparent from Figure 3(a) and Figure 3(b), that one side of the coil is connected to the positive side of the voltage source and the other side of the coil connected to the negative side. Thus, the total voltage across the coil is that of the battery V_s . Coil windings 50, 52 and 54 provide notching pulses for phases A, B and C, respectively, as shown in Figure 4(e) for phase A, by selectively switching opposite ends of the coil 38 to the positive and negative side of the battery V_s in the manner described above. The notching voltages on the line 22 from the auxiliary inverter switch circuit 18 are available from the coil windings 44, 46 and 48 of transformers 38, 40 and 42, respectively. As illustrated in Figure 4(d), the notching pulses for phase A are inverted when compared to the pulses provided by winding 44. The inversion of the pulses is achieved by the appropriate winding configuration of the auxiliary transformers as indicated by the dot notation of Figure 3(a).

Transformers 38, 40 and 42 also have another winding, 50, 52 and 54 respectively, and they are connected in series to provide the triplex waveform shown in Figure 4(f). Specifically, winding 50 provides pulses similar to that developed by winding 44, and when each of the pulses for phases A, B and C are developed by windings 50, 52 and 54, the triplex waveform, such as that shown in Figure 4(f), is available on line 24. The triplex waveform obtained on line 24 originates from the switching of switches S7 to S14. This can best be seen in Figure 4(f), which shows the various notching waveforms of phases A, B and C, and how they combine to form the triplex waveform ultimately available on line 24. The triplex waveform available on line 24, as shown in Figure 4(f), differs 180° in phase from that shown in Figure 4(d). The phase is changed by the appropriate winding configuration of the transformer as shown by the dot notation in Figure 3(a).

The windings of transformers 38, 40 and 42 are critical because, as discussed in Specification No. 1542803, the amplitudes of the various components affect the harmonic content of the desired sinusoidal output. Figure 4(a), Figure 4(e) and Figure 4(f) depict the individual components of the synthesized sinusoidal wave for phase A, which is shown in Figure 4(g). The relative amplitudes of the individual components shown are selected to cancel the first to eleventh harmonics. That is to say, if the desired sinusoidal output has an amplitude of K volts, a notching waveform having a

value of .443 times K will eliminate the fifth and seventh harmonics of the main line-to-neutral if the main fundamental waveform has an amplitude of .827 times K. Similarly, the triplex wave will cancel the third harmonic and multiples thereof in the line-to-neutral voltage if the amplitude is selected at .128 times the constant K. Thus, it is important that the separate winding of each transformer be wound in the following proportions as typified by transformer 38: 1.0 (winding 39) : 0.128 (winding 50) : 0.443 (winding 44)

Figure 5 is a schematic circuit diagram of the entire inverter circuit, and the reference numbers used in Figure 5 correspond to their respective components in Figures 1 to 4. Several features illustrated in Figure 5 have not heretofore been described. For example, the switch S1 is shown as comprising a main inverter switch having a SCR 58 (controlled by the clock 14 of Figure 1) and diode 80. The SCR 58 is switched as described previously with reference to Figure 3(b). The diode 80 is connected across the SCR and provides a path for regeneration current back to the main DC supply 9. Other similarly placed diodes throughout the switches S1 through S14 provide a similar function. Also, it should be noted that auxiliary switches S7 through S14 are shown as transistors. The base of each transformer is coupled to the clock 14.

Other auxiliary inverter circuit configurations and switching circuits may be used to combine a notching waveform, a triplex, and a fundamental to produce a three-phase synthesized sinusoidal wave. For example, other systems may be developed for a further reduction of transformer weight. Figure 6(a) is a schematic of an embodiment which illustrates such an alternative.

As shown in Figure 6(a), a winding 66 of a transformer 60 is connected to the line which provides the main fundamental waveform (phase A) from the main inverter circuit 10. Accordingly, the fundamental wave, as shown in Figure 4(a), is impressed across the winding 66. Similarly, the main fundamental waveforms for phase B and phase C are impressed across windings 70 and 74 of transformers 62 and 64, respectively. The fundamental wave adds to or subtracts from the notching voltages which are developed across windings 59, 61 and 63, and which are created by the appropriate switching sequence of switches S15 to S20. The switching sequence of switches S15 to S20 is shown in Figure 6(b). By the appropriate tap selection of transformers 60, 62 and 64, a wide range of voltage ratios of V_A to V_B is available wherein V_A is the voltage across transformer windings 59, 61 and 63, and V_B is the voltage across windings 68, 72 and 78. Minimum transfor-

mer weight may be achieved while minimizing the first to eleventh harmonics if the tap is placed such that V_A equals $4V_B$. This result is obtained because the switching sequence of switches S15 to S20 permits V_A to exist for a period of four times the length of V_B .

The transformers 60, 62 and 64 provide two functions. Winding 59 provides the addition of notching waveforms for each phase, as discussed above, while winding 68 provides the triplex wave resulting from summing the notching waveforms of all three phases. It should be noted that windings 68, 72 and 78 of transformers 60, 62 and 64 are connected in series in a manner similar to that discussed earlier to effect the triplex waveform.

The resulting waveform for phase A developed by the inverter having an auxiliary circuit of the type shown in Figure 6(a) is depicted in Figure 7. The resultant waveform is applied through a filter (not shown) to provide a smooth sinusoidal shape. To maintain the low level of harmonics, the voltages which comprise the sine wave having the amplitude of K volts are: fundamental wave equals 0.74 times K; V_A equals .084 times K; V_B equals .34 times K; and the triplex equals .126 times K.

WHAT WE CLAIM IS:

1. A DC to AC inverter circuit comprising:

means for generating first, second and third fundamental rectangular waveforms at the same frequency wherein each of the first, second and third rectangular waveforms is out of phase with the other two by 120° ;

means for generating notching rectangular waveforms for each of the first, second and third fundamental waveforms;

means for combining the notching rectangular waveforms for each of the first, second and third fundamental waveforms to provide a single rectangular triplex waveform having a frequency equal to three times the fundamental frequency; and

means for combining the first fundamental rectangular waveform, the notching rectangular waveform for the first fundamental waveform and the single triplex waveform to provide an output which approximates a sinusoidal waveform in phase with the first fundamental waveform.

2. An inverter circuit according to claim 1, further comprising means for combining the second fundamental rectangular waveform, the notching rectangular waveform for the second fundamental waveform and the single triplex waveform to provide an output which approximates a sinusoidal waveform in phase with the second fundamental waveform.

3. An inverter circuit according to claim

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value of .443 times K will eliminate the fifth and seventh harmonics of the main line-to-neutral if the main fundamental waveform has an amplitude of .827 times K. Similarly, the triplex wave will cancel the third harmonic and multiples thereof in the line-to-neutral voltage if the amplitude is selected at .128 times the constant K. Thus, it is important that the separate winding of each transformer be wound in the following proportions as typified by transformer 38: 1.0 (winding 39) : 0.128 (winding 50) : 0.443 (winding 44)

Figure 5 is a schematic circuit diagram of the entire inverter circuit, and the reference numbers used in Figure 5 correspond to their respective components in Figures 1 to 4. Several features illustrated in Figure 5 have not heretofore been described. For example, the switch S1 is shown as comprising a main inverter switch having a SCR 58 (controlled by the clock 14 of Figure 1) and diode 80. The SCR 58 is switched as described previously with reference to Figure 3(b). The diode 80 is connected across the SCR and provides a path for regeneration current back to the main DC supply 9. Other similarly placed diodes throughout the switches S1 through S14 provide a similar function. Also, it should be noted that auxiliary switches S7 through S14 are shown as transistors. The base of each transformer is coupled to the clock 14.

Other auxiliary inverter circuit configurations and switching circuits may be used to combine a notching waveform, a triplex, and a fundamental to produce a three-phase synthesized sinusoidal wave. For example, other systems may be developed for a further reduction of transformer weight. Figure 6(a) is a schematic of an embodiment which illustrates such an alternative.

As shown in Figure 6(a), a winding 66 of a transformer 60 is connected to the line which provides the main fundamental waveform (phase A) from the main inverter circuit 10. Accordingly, the fundamental wave, as shown in Figure 4(a), is impressed across the winding 66. Similarly, the main fundamental waveforms for phase B and phase C are impressed across windings 70 and 74 of transformers 62 and 64, respectively. The fundamental wave adds to or subtracts from the notching voltages which are developed across windings 59, 61 and 63, and which are created by the appropriate switching sequence of switches S15 to S20. The switching sequence of switches S15 to S20 is shown in Figure 6(b). By the appropriate tap selection of transformers 60, 62 and 64, a wide range of voltage ratios of V_A to V_B is available wherein V_A is the voltage across transformer windings 59, 61 and 63, and V_B is the voltage across windings 68, 72 and 78. Minimum transfor-

mer weight may be achieved while minimizing the first to eleventh harmonics if the tap is placed such that V_A equals $4V_B$. This result is obtained because the switching sequence of switches S15 to S20 permits V_A to exist for a period of four times the length of V_B .

The transformers 60, 62 and 64 provide two functions. Winding 59 provides the addition of notching waveforms for each phase, as discussed above, while winding 68 provides the triplex wave resulting from summing the notching waveforms of all three phases. It should be noted that windings 68, 72 and 78 of transformers 60, 62 and 64 are connected in series in a manner similar to that discussed earlier to effect the triplex waveform.

The resulting waveform for phase A developed by the inverter having an auxiliary circuit of the type shown in Figure 6(a) is depicted in Figure 7. The resultant waveform is applied through a filter (not shown) to provide a smooth sinusoidal shape. To maintain the low level of harmonics, the voltages which comprise the sine wave having the amplitude of K volts are: fundamental wave equals 0.74 times K; V_A equals .084 times K; V_B equals .34 times K; and the triplex equals .126 times K.

WHAT WE CLAIM IS:

1. A DC to AC inverter circuit comprising:

means for generating first, second and third fundamental rectangular waveforms at the same frequency wherein each of the first, second and third rectangular waveforms is out of phase with the other two by 120°;

means for generating notching rectangular waveforms for each of the first, second and third fundamental waveforms;

means for combining the notching rectangular waveforms for each of the first, second and third fundamental waveforms to provide a single rectangular triplex waveform having a frequency equal to three times the fundamental frequency; and

means for combining the first fundamental rectangular waveform, the notching rectangular waveform for the first fundamental waveform and the single triplex waveform to provide an output which approximates a sinusoidal waveform in phase with the first fundamental waveform.

2. An inverter circuit according to claim 1, further comprising means for combining the second fundamental rectangular waveform, the notching rectangular waveform for the second fundamental waveform and the single triplex waveform to provide an output which approximates a sinusoidal waveform in phase with the second fundamental waveform.

3. An inverter circuit according to claim

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2, further comprising means for combining the third fundamental rectangular waveform, the notching rectangular waveform for the third fundamental waveform and the single triplex waveform to provide an output which approximates a sinusoidal waveform in phase with the third fundamental waveform.

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4. An inverter circuit according to any preceding claim, wherein the means for combining the notching rectangular waveforms for each of the first, second and third fundamental waveforms is effective to combine four pulses of the notching waveforms for every period of the single triplex waveform.

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5. An inverter circuit according to any preceding claim, wherein the means for generating the notching rectangular waveforms for each of the first, second and third fundamental waveforms is effective to provide notching pulses intermittently for 30° durations of the fundamental waveforms.

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6. An inverter circuit according to any preceding claim, having means for filtering the approximately sinusoidal output or outputs.

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7. An inverter circuit according to claim 6, wherein each of the first, second and third fundamental rectangular waveforms has an amplitude of .827 times the amplitude K of the filtered sinusoidal output, each of the notching rectangular waveforms has an amplitude of .443 times K and the single triplex waveform has an amplitude of .128 times K.

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8. An inverter circuit according to any preceding claim, wherein the means for generating the notching rectangular waveforms for each of the first, second and third fundamental waveforms provide the notching rectangular waveforms each at a frequency less than that of the single triplex waveform.

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9. An inverter circuit according to claim 6 wherein each of the first, second and third fundamental rectangular waveforms has an amplitude of .74 times the amplitude K of the filtered sinusoidal output, each of the notching rectangular waveforms has a maximum positive amplitude of .084 times K and a maximum negative amplitude of .34 times K, and the single triplex waveform has an amplitude of .126 times K.

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10. A DC to AC inverter circuit for generating an output approximating a sinusoidal waveform, substantially as particularly described herein with reference to Figures 1 to 5 of the drawings.

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11. A DC to AC inverter circuit for generating an output approximating a sinusoidal waveform, substantially as particularly described herein with reference to Figures 1 to 5 as modified by Figures 6a, 6b, and 7 of the drawings.

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