Power converter control for reducing EMI noise by temporally changing the PWM carrier frequency

A controller and method for reducing EMI noise by changing a frequency of a control (or carrier) signal in accordance with a waveform that periodically changes within a first frequency range from a frequency $f_{c1}$ to a frequency $f_{c2}$, where the frequency $f_{c1}$ is smaller than the frequency $f_{c2}$, and a second frequency range from a frequency $f_{c3}$ to a frequency $f_{c4}$, where the frequency $f_{c3}$ is smaller than the frequency $f_{c4}$. The frequencies $f_{c1}$ and $f_{c4}$ satisfy the inequalities $(n-1)f_{c4} \leq nf_{c2}$ and $nf_{c3} \leq (n+1)f_{c1}$ and/or satisfy an approximate expression $nf_{c4} = (n+1)f_{c1}$ where $n$ is an integer. The frequencies $f_{c2}$ and $f_{c3}$ satisfy the inequalities $nf_{c2} \leq fs-\Delta fs$ and $fs+\Delta fs \leq nf_{c3}$ where $fs \pm \Delta fs$ represents a predetermined frequency band.

![Diagram](image-url)
Description

[0001] The invention relates generally to power converter control and particularly, but not exclusively, to a control apparatus for power converters used for in-vehicle motors and a method of controlling such power converters. Aspects of the invention relate to an apparatus, to a controller, to a method and to a vehicle.

[0002] Stepping motor systems in which, in order to reduce electromagnetic interference (EMI) noise that is generated by controlling H-bridge field effect transistors (FETs), the frequency of a carrier signal (hereinafter referred to as a carrier frequency) used in pulse-width modulation (PWM) control is changed with time are known. In such systems, since the carrier frequency is changed sinusoidally with time, spectrum components having noise at high levels generated at an nth harmonic frequency of a predetermined carrier frequency are spread over an nth-order frequency range (for example, n·5 kHz to n·20 kHz) of a frequency range (for example, 5 kHz to 20 kHz) in which the carrier frequency is changed with time. Thus, the levels of the noise generated at the nth harmonic frequency can be reduced. Accordingly, interference with radio reception and other electronic apparatuses can be reduced. One example of such a system is shown in Japanese Unexamined Patent Application Publication No. 7-99795.

[0003] In systems such as that discussed in Japanese Unexamined Patent Application Publication No. 7-99795, if the frequency range of the carrier frequency that is changed with time is further increased, the levels of the noise generated at the nth harmonic frequency can be further reduced since spectrum components having noise at high levels generated at the nth harmonic frequency of the predetermined carrier frequency are spread over the nth-order frequency range. However, if the nth-order frequency range is too wide, the spectrum in which the levels of noise generated at the nth harmonic frequency of the predetermined carrier frequency are spread over the nth-order frequency range and the spectrum in which the levels of noise generated at the (n+1)th harmonic frequency are spread over the (n+1)th-order frequency range overlap each other. Thus, the level of noise generated in a predetermined frequency range is increased.

[0004] It is an aim of the invention to address this issue and improve upon known technology. Embodiments of the invention may be capable of reducing the level of noise generated in a wide frequency range and of further reducing the level of noise generated in a predetermined frequency range. Other aims and advantages of the invention will become apparent from the following description, claims and drawings.

[0005] Aspects of the invention therefore provide an apparatus, a method and a vehicle as claimed in the appended claims.

[0006] According to another aspect of the invention there is provided a controller for a power converter that converts input electric power into a desired form and outputs the converted electric power by controlling a power converter switch, the controller comprising a carrier signal generator operable to produce a carrier signal for controlling the power converter switch in accordance with a waveform that periodically changes within a first frequency range from a frequency fc1 to a frequency fc2, wherein the frequency fc1 is smaller than the frequency fc2, and within a second frequency range from a frequency fc3 to a frequency fc4, wherein the frequency fc3 is smaller than the frequency fc4, and a waveform generator operable to change a frequency of the waveform wherein the frequencies fc1 and fc4 satisfy at least one of: (A) an inequality (n-1)·fc4 ≤ n·fc2 and an inequality n·fc3 ≤ (n+1)·fc1 with respect to an integer n and (B) an approximate expression n·fc4 = (n+1)·fc1 with respect to the integer n; and wherein the frequencies fc2 and fc3 satisfy an inequality n·fc2 ≤ fs−Δfs and an inequality fs+Δfs ≤ n·fc3 wherein fs = Δfs represents a predetermined frequency band.

[0007] In an embodiment, the waveform generator is operable to receive a frequency of a channel to be received by a broadcast receiver device; and wherein the waveform generator is further operable to change the frequency of the waveform using the frequency of the channel as the frequency fs.

[0008] In an embodiment, the waveform generator is operable to generate the waveform by stepwisely changing a frequency value selected at random at each predetermined interval.

[0009] In an embodiment, the frequencies fc1, fc2, fc3, and fc4 are such that an equation (fc2-fc1): (fc4-fc3) = b: a is satisfied, wherein b: a represents a ratio of a period of time belonging to the second frequency range to a period of time belonging to the first frequency range.

[0010] In an embodiment, the waveform generator is operable to change the waveform in a triangular wave shape in a predetermined cycle within the first frequency range and within the second frequency range.

[0011] In an embodiment, the frequencies fc1, fc2, fc3, and fc4 are such that an equation (fc2-fc1): (fc4-fc3) = c: d is satisfied, wherein c: d represents a ratio of a number of triangular wave components of the waveform that shift within the first frequency range to a number of triangular wave components of the waveform that shift within the second frequency range.

[0012] In an embodiment, the waveform generator is operable to generate the waveform by stepwisely changing a frequency value selected at random at each predetermined interval.

[0013] In an embodiment, the frequencies fc1, fc2, fc3, and fc4 are such that an equation (fc2-fc1): (fc4-fc3) = b: a is satisfied, wherein b: a represents a ratio of a period of time belonging to the second frequency range to a period of time belonging to the first frequency range.

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The method may comprise changing the waveform in a triangular wave shape in a predetermined cycle within the first frequency range and within the second frequency range.

In an embodiment, the frequencies fc1, fc2, fc3, and fc4 are such that an equation \((fc2-fc1): (fc4-fc3) = c: d\) is satisfied, wherein \(c: d\) represents a ratio of a number of triangular wave components of the waveform that shift within the first frequency range to a number of triangular wave components of the waveform that shift within the second frequency range.

According to yet another aspect of the invention there is provided a controller for a power converter that converts input electric power into a desired form and outputs the converted electric power by controlling a power converter switch, the controller comprising means for temporally changing a frequency of a control signal for controlling the power converter switch in accordance with a waveform that periodically changes within a first frequency range from a frequency \(fc1\) to a frequency \(fc2\), wherein the frequency \(fc1\) is smaller than the frequency \(fc2\), and with within a second frequency range from a frequency \(fc3\) to a frequency \(fc4\), wherein the frequency \(fc3\) is smaller than the frequency \(fc4\), means for determining the frequencies \(fc1\) and \(fc4\) such that, with respect to an integer \(n\), at least one of: (A) an inequality \((n-1)·fc4 ≤ n·fc2\) and an inequality \(n·fc3 \leq (n+1)·fc1\) are satisfied, and (B) an approximate expression \(n·fc4 = (n+1)·fc1\) is satisfied, and means for determining the frequencies \(fc2\) and \(fc3\) that satisfy an inequality \(n·fc2 \leq fs·Δfs\) and an inequality \(fs+Δfs \leq n·fc3\) wherein \(fs·Δfs\) represents a predetermined frequency band.

According to a further aspect of the invention there is provide a control method for a power converter that converts input electric power into a desired form and outputs the converted electric power by controlling a power converter switch, the control method comprising changing a frequency of a control signal for controlling the power converter switch in accordance with a waveform that periodically changes within a first frequency range from a frequency \(fc1\) to a frequency \(fc2\), wherein the frequency \(fc1\) is smaller than the frequency \(fc2\), and within a second frequency range from a frequency \(fc3\) to a frequency \(fc4\), wherein the frequency \(fc3\) is smaller than the frequency \(fc4\) and determining the frequencies \(fc1\) and \(fc4\) such that at least one of: (A) an inequality \((n-1)·fc4 ≤ n·fc2\) and an inequality \(n·fc3 \leq (n+1)·fc1\) are satisfied, and (B) an approximate expression \(n·fc4 = (n+1)·fc1\) is satisfied with respect to the integer \(n\), and determining the frequencies \(fc2\) and \(fc3\) that satisfy an inequality \(n·fc2 \leq fs·Δfs\) and an inequality \(fs+Δfs \leq n·fc3\) wherein \(fs·Δfs\) represents a predetermined frequency band.

The method may comprise changing the waveform in a triangular wave shape in a predetermined cycle within each of the first frequency range and the second frequency range.

In an embodiment, the frequencies \(fc1\), \(fc2\), \(fc3\), and \(fc4\) satisfy an equation \((fc2-fc1): (fc4-fc3) = c: d\), wherein \(c: d\) represents a ratio of a number of triangular wave components of the waveform that shift within the first frequency range to a number of triangular wave components of the waveform that shift within the second frequency range.

The method may comprise generating the waveform by stepwisely changing a frequency value selected at random at each predetermined interval.

In an embodiment, the frequencies \(fc1\), \(fc2\), \(fc3\), and \(fc4\) satisfy an equation \((fc2-fc1): (fc4-fc3) = b: a\), wherein \(b: a\) represents a ratio of a period of time belonging to the second frequency range to a period of time belonging to the first frequency range.

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In an embodiment, the frequencies \(fc1\), \(fc2\), \(fc3\), and \(fc4\) satisfy an equation \((fc2-fc1): (fc4-fc3) = b: a\), wherein \(b: a\) represents a ratio of a period of time belonging to the second frequency range to a period of time belonging to the first frequency range.

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[0032] In an embodiment, the frequencies fc1, fc2, fc3 and fc4 satisfy an equation (fc2-fc1) = c: d, wherein c: d represents a ratio of a number of triangular wave components of the waveform that shift within the first frequency range to a number of triangular wave components of the waveform that shift within the second frequency range.

[0033] For example, embodiments of the invention may provide a controller for a power converter that converts input electric power into a desired form and outputs the converted electric power by controlling a power converter switch. According to one example of a controller taught herein, the controller comprises a carrier signal generator operable to produce a carrier signal for controlling the power converter switch in accordance with a waveform that periodically changes within a first frequency range from a frequency fc1 to a frequency fc2, wherein the frequency fc1 is smaller than the frequency fc2, and within a second frequency range from a frequency fc3 to a frequency fc4, wherein the frequency fc3 is smaller than the frequency fc4. The controller in this example also includes a waveform generator operable to change a frequency of the waveform wherein the frequencies fc1 and fc4 satisfy at least one of: (A) an inequality n·fc2 ≤ fs and an inequality fs+Δfs ≤ n·fc3 wherein fs±Δfs represents a predetermined frequency band. 

[0034] In another example, a controller for a power converter that converts input electric power into a desired form and outputs the converted electric power by controlling a built-in switch. The controller comprises a switching frequency changing system for temporally changing a frequency of a control signal for controlling the switch. The switching frequency changing system changes the frequency of the control signal in accordance with a waveform that periodically changes within a first frequency range from a first frequency fc1 to a second frequency fc2, where the first frequency fc1 is smaller than the second frequency fc2, and a second frequency range from a third frequency fc3 to a fourth frequency fc4, where the third frequency fc3 is smaller than the fourth frequency fc4. This method also includes a waveform generator operable to change a frequency of the waveform wherein the frequencies fc1 and fc4 satisfy at least one of: (A) an inequality (n+1)·fc1 ≤ fs-Δfs and an inequality fs+Δfs ≤ n·fc3 wherein fs±Δfs represents a predetermined frequency band. 

[0035] In an embodiment of the invention, a control method for a power converter that converts input electric power into a desired form and outputs the converted electric power by controlling a built-in switch may comprise the steps of: changing the frequency of a control signal for controlling the switch in accordance with a waveform that periodically changes within a first frequency range from a first frequency fc1 to a second frequency fc2, where the frequency fc1 is smaller than the frequency fc2, and within a second frequency range from a frequency fc3 to a frequency fc4, wherein the frequency fc3 is smaller than the frequency fc4, and means for determining the frequencies fc1 and fc4 such that, with respect to an integer n, at least one of: (A) an inequality (n+1)·fc1 ≤ fs-Δfs and an inequality fs+Δfs ≤ n·fc3 wherein fs±Δfs represents a predetermined frequency band.

[0036] In another example of a controller taught herein, the controller comprises means for temporally changing a frequency of a control signal for controlling the power converter switch in accordance with a waveform that periodically changes within a first frequency range from a frequency fc1 to a frequency fc2, wherein the frequency fc1 is smaller than the frequency fc2, and within a second frequency range from a frequency fc3 to a frequency fc4, wherein the frequency fc3 is smaller than the frequency fc4, and means for determining the frequencies fc1 and fc4 such that, with respect to an integer n, at least one of: (A) an inequality (n+1)·fc1 ≤ fs-Δfs and an inequality fs+Δfs ≤ n·fc3 wherein fs±Δfs represents a predetermined frequency band.

[0037] In an embodiment a control method changing a frequency of a control signal for controlling the power converter switch in accordance with a waveform that periodically changes within a first frequency range from a frequency fc1 to a frequency fc2, wherein the frequency fc1 is smaller than the frequency fc2, and within a second frequency range from a frequency fc3 to a frequency fc4, where the frequency fc3 is smaller than the frequency fc4. This method also includes determining the frequencies fc1 and fc4 such that at least one of: (A) an inequality (n+1)·fc1 ≤ fs-Δfs and an inequality fs+Δfs ≤ n·fc3 wherein fs±Δfs represents a predetermined frequency band.

[0038] Embodiments of the invention may be arranged to change a frequency of a control signal in accordance with a waveform that periodically changes within a first frequency range from a frequency fc1 to a frequency fc2, where the frequency fc1 is smaller than the frequency fc2, and a second frequency range from a frequency fc3 to a frequency fc4, where the frequency fc3 is smaller than the frequency fc4. They can also determine the frequencies fc1 and fc4 such that an inequality (n+1)·fc1 ≤ fs-Δfs and an inequality fs+Δfs ≤ n·fc3 are satisfied with respect to an integer n and the frequencies fc2 and fc3 that satisfy an inequality n·fc2 ≤ fs-Δfs and an inequality fs+Δfs ≤ n·fc3 when a predetermined
frequency band is represented by $f_s \pm \Delta f_s$. Accordingly, the level of noise generated in a wide frequency range can be reduced, and the level of noise generated in a predetermined frequency range can be further reduced.

[0039] Within the scope of this application it is envisaged that the various aspects, embodiments, examples, features and alternatives set out in the preceding paragraphs, in the claims and/or in the following description may be taken individually or in any combination thereof.

[0040] The present invention will now be described, by way of example only, with reference to the accompanying drawings in which:

- FIG. 1 shows a configuration of an inverter system;
- FIG. 2A shows a temporal change of a carrier frequency in a first embodiment of the invention;
- FIG. 2B shows harmonic spectra in the first embodiment;
- FIG. 3A shows a temporal change of a carrier frequency in a second embodiment of the invention;
- FIG. 3B shows harmonic spectra in the second embodiment;
- FIG. 4 shows a configuration of an inverter system according to a third embodiment of the invention and a configuration of a receiver;
- FIG. 5A shows a temporal change of a carrier frequency in a fourth embodiment of the invention;
- FIG. 5B shows a harmonic spectrum in the fourth embodiment;
- FIG. 6A shows a temporal change of a carrier frequency in a fifth embodiment of the present invention; and
- FIG. 6B shows a harmonic spectrum in the fifth embodiment.

[0041] An inverter system includes an inverter, which is an example of a power converter used in an embodiment of the invention, that supplies sinusoidal alternating current (AC) power by performing PWM modulation on an output of a direct current (DC) power source will be described. Inverter systems according to first to fifth embodiments of the invention are described with reference to FIGS. 1 to 6.

[0042] Configuration and operation of an inverter system 1 is now described with reference to FIG. 1.

[0043] Referring to FIG. 1, the inverter system 1 includes, as main component parts, a PWM inverter 2, a three-phase brushless motor (hereinafter, referred to as a motor) 3, current sensors 4a, 4b, and 4c, a controller 13, a battery B and a capacitor C. The controller 13 includes a current command generator 5, proportional-integral-differential (PID) controllers 6a, 6b and 6c, comparators 8a, 8b and 8c and a carrier frequency changing unit 12. Although the controller 13 is shown as a microcomputer including a central processing unit (CPU), input and output ports (I/O), random access memory (RAM), keep alive memory (KAM), a common data bus and read only memory (ROM) as an electronic storage medium for executable programs and certain stored values as discussed hereinafter. The functions performed by the elements of the controller 13 described herein could be implemented in software as executables, or could be implemented in whole or in part by separate hardware in the form of one or more integrated circuits (IC).

[0044] The PWM inverter 2 includes six switching elements Tu+, Tu-, Tv+, Tv-, Tw+ and Tw-. Each of the switching elements Tu+, Tu-, Tv+, Tv-, Tw+ and Tw- selects the positive terminal or the negative terminal of a current power source including the battery B and the capacitor C under the control of the corresponding one of the comparators 8a, 8b and 8c and connects the selected terminal to a terminal of one of the U phase, V phase, and W phase of the motor 3 corresponding thereto. Each of the switching elements Tu+, Tu-, Tv+, Tv-, Tw+ and Tw- is formed of a semiconductor element, such as an insulated gate bipolar transistor (IGBT).

[0045] The current sensors 4a, 4b and 4c detect a U-phase current, a V-phase current and a W-phase current supplied from the PWM inverter 2 to the motor 3. The current command generator 5 generates sinusoidal current commands to convert the currents detected by the current sensors 4a, 4b and 4c into sinusoidal AC currents. The PID controllers 6a, 6b and 6c perform PID control on the currents detected by the current sensors 4a, 4b and 4c such that the currents detected by the current sensors 4a, 4b and 4c comply with the current commands generated by the current command generator 5.

[0046] The carrier frequency changing unit 12 includes a carrier signal generator 7 and a waveform generator 9. The waveform generator 9 generates a voltage waveform that is output for changing the frequency of a carrier signal (hereinafter, referred to as a carrier frequency). More specifically, the waveform generator 9 performs the functions of a first
oscillator, a second oscillator and an adder. The first oscillator outputs a triangular wave having a predetermined frequency. The second oscillator outputs a square wave having a frequency that is smaller than the frequency of the triangular wave. An output of the first oscillator and an output of the second oscillator have the same cycle, and the waveform of the output of the first oscillator and the waveform of the output of the second oscillator are symmetrical to each other in each half cycle. The adder generates a voltage waveform obtained by adding the triangular wave and the square wave and outputs the generated voltage waveform to the carrier signal generator 7.

A change of a carrier frequency fc in a first embodiment of the invention is described next. FIG. 2A shows a temporal change of a carrier frequency fc in the first embodiment. FIG. 2B shows harmonic spectra in the first embodiment.

As shown in FIG. 2A, in a first frequency range from a frequency fc1 to a frequency fc2, where the frequency fc1 is smaller than the frequency fc2, and a second frequency range from a frequency fc3 to a frequency fc4, where the frequency fc3 is smaller than the frequency fc4, the carrier frequency fc changes in a triangular wave shape. In addition, in a third frequency range from the frequency fc2 to the frequency fc3, where the frequency fc2 is smaller than the frequency fc3, the carrier frequency fc shifts almost vertically. In the case where the carrier frequency fc changes with time as shown in FIG. 2A, two consecutive triangular wave components are observed in each of the first frequency range from the frequency fc1 to the frequency fc2 and the second frequency range from the frequency fc3 to the frequency fc4. In this case, the frequency spectrum of nth harmonic components (n is an integer) of the carrier frequency fc are obtained as shown in FIG. 2B.

Referring now to FIG. 2B, the frequency spectrum of the nth harmonic components exhibits first noise level 21, which is substantially flat, in an nth-order frequency range from n·fc1 to n·fc2 and second noise level 22, which is substantially flat, in an nth-order frequency range from n·fc3 to n·fc4. In addition, the frequency spectrum exhibits third noise level 23, which is lower than the first noise level 21 and the second noise level 22, in an nth-order frequency range from n·fc2 to n·fc3. Thus, EMI noise in a predetermined frequency range, that is, the nth-order frequency range from n·fc2 to n·fc3, can be further reduced.

Similarly, the frequency spectrum of (n+1)th harmonic components exhibits first noise level 24, which is substantially flat, in an (n+1)th-order frequency range from (n+1)·fc1 to (n+1)·fc2 and second noise level 25, which is substantially flat, in an (n+1)th-order frequency range from (n+1)·fc3 to (n+1)·fc4. In addition, the frequency spectrum exhibits third noise level 26, which is lower than the first noise level 24 and the second noise level 25, in an (n+1)th-order frequency range from (n+1)·fc2 to (n+1)·fc3. Similarly, the frequency spectrum of (n+1)th harmonic components exhibits first noise level 27, which is substantially flat, in an (n+1)th-order frequency range from (n+1)·fc1 to (n+1)·fc2 and second noise level 28, which is substantially flat, in an (n+1)th-order frequency range from (n+1)·fc3 to (n+1)·fc4. In addition, the frequency spectrum exhibits third noise level 29, which is lower than the first noise level 27 and the second noise level 28, in an (n+1)th-order frequency range from (n+1)·fc2 to (n+1)·fc3.

Thus, in this embodiment, “fc1”, “fc2”, “fc3” and “fc4” are set such that inequalities (1.1) and (1.2) are satisfied:

\[(n-1)\cdot fc4 \leq n\cdot fc2; \quad \text{and} \quad (1.1)\]

\[n\cdot fc3 \leq (n+1)\cdot fc1. \quad (1.2)\]
When inequalities (1.1) and (1.2) are satisfied, in the frequency spectrum of the nth harmonic components of the carrier frequency fc, the frequency range having the third noise level 23, that is, the nth-order frequency range from n·fc2 to n·fc3, does not overlap the frequency range having the second noise level 28 of the adjacent frequency spectrum of the (n-1)th harmonic components, that is, the (n-1)th order frequency range from (n-1)·fc2 to (n-1)·fc3. Similarly, in the frequency spectrum of the nth harmonic components of the carrier frequency fc, the frequency range having the third noise level 23, that is, the nth-order frequency range from n·fc2 to n·fc3, does not overlap the frequency range having the first noise level 24 of the adjacent frequency spectrum of the (n+1)th harmonic components, that is, the (n+1)th-order frequency range from (n+1)·fc1 to (n+1)·fc2. Thus, in the nth-order frequency range from n·fc2 to n·fc3 of the frequency spectrum of the nth harmonic components of the carrier frequency fc, an increase in the level of noise caused by overlapping of the first noise level 24 and the second noise level 28 with the third noise level 23 can be suppressed.

When "n", "fc2" and "fc3" are set such that, for example, a range of radio broadcasting waves, which is a broadcasting frequency band fs±Δfs, is included in the nth-order frequency range from n·fc2 to n·fc3 of the frequency spectrum of the nth harmonic components, a problem caused by EMI noise due to a carrier frequency fc generated by the operation of the inverter system 1 when a user listens to a broadcast received by a radio receiver located in the vicinity of the inverter system 1 can be prevented. In addition, since the carrier frequency fc is temporally changed, concerning a frequency band other than the broadcasting frequency band fs±Δfs, spectrum components with high-level noise, which would be generated at an nth harmonic frequency of the carrier frequency fc if the carrier frequency fc is constant, can be spread over the nth-order frequency range from n·fc1 to n·fc4 in which the carrier frequency fc changes with time. Thus, compared with a case where the carrier frequency fc is constant, the level of noise can be much reduced.

In addition, since the frequency range having the first noise level 24 of the adjacent frequency spectrum of the (n+1)th harmonic components of the carrier frequency fc or the frequency range having the second noise level 28 of the frequency spectrum of the (n-1)th harmonic components does not overlap the broadcasting frequency band fs±Δfs, an increase in the level of noise generated in the broadcasting frequency band fs±Δfs can be suppressed. Thus, an interference with other receivers or apparatuses can be reduced.

Accordingly, by setting "fc1", "fc2", "fc3" and "fc4" such that inequalities (1.1) and (1.2) are satisfied while changing the carrier frequency fc with time, the level of noise generated in a wide frequency range can be reduced and the level of noise generated in a predetermined frequency range, that is, the nth frequency range from n·fc2 to n·fc3, can be further reduced.

An inverter system according to a second embodiment is described next with reference to FIGS. 3A and 3B, paying particular attention to a difference between the inverter system according to the second embodiment and the inverter system 1 according to the first embodiment. The same component parts as in the first embodiment are referred to with the same reference numerals, and the descriptions of those same parts will be omitted. FIG. 3A shows a temporal change of a carrier frequency fc in the second embodiment. FIG. 3B shows harmonic spectra in the second embodiment. The configuration of the inverter system according to the second embodiment is the same as the configuration of the inverter system 1 according to the first embodiment. In addition, the waveform of the carrier frequency fc shown in FIG. 3A is the same as the waveform of the carrier frequency fc shown in FIG. 2A. Moreover, the frequency spectra of the carrier frequency fc shown in FIG. 3B closely resemble the frequency spectra of the carrier frequency fc shown in FIG. 2B. The inverter system according to the second embodiment is different from the inverter system 1 according to the first embodiment only in how the range in which the carrier frequency fc changes is determined.

More specifically, in the second embodiment "fc1" and "fc4" are determined such that approximate expression (2) is satisfied:

\[ n \cdot fc4 = (n+1) \cdot fc1. \]  

When "fc1" and "fc4" are determined as described above, the frequency spectrum of the nth harmonic components and the frequency spectrum of the (n+1)th harmonic components that are almost next to each other, that is, that are most close to each other but less likely to overlap each other, are formed. If approximate expression (2) is satisfied, the frequency spectrum of the nth harmonic components is less likely to overlap the frequency spectrum of the (n-1)th harmonic components. This has advantages in the following two points.

First, in the frequency spectrum of the nth harmonic components, the first noise level 24 of the frequency spectrum of the (n+1)th harmonic components and the second noise level 28 of the frequency spectrum of the (n-1)th harmonic components do not overlap the frequency range having the third noise level 23, that is, the nth-order frequency range from n·fc2 to n·fc3. Thus, in the nth-order frequency range from n·fc2 to n·fc3, an increase in the level of noise can be suppressed. Second, in terms of increasing a frequency range of a frequency spectrum of harmonic components of each order and reducing the level of noise by temporally changing the carrier frequency fc, it is effective to further
increase the frequency range of the frequency spectrum of the harmonic components. Thus, when \( fc1 \) and \( fc4 \) are determined such that approximate expression (2) is satisfied, a frequency range not included in a spectrum, that is, a frequency range located between frequency spectrums of harmonic components that are adjacent to each other, can be reduced as much as possible while suppressing overlapping of a frequency spectrum of harmonic components whose order is less than \( n \). Accordingly, a frequency range can be effectively used, and a reduction of the level of noise can be achieved in a wider frequency range.

[0062] In addition, as in the first embodiment, concerning the temporal change of the carrier frequency \( fc \), the carrier frequency \( fc \) is shifted from the frequency \( fc2 \) to the frequency \( fc3 \) substantially vertically. Thus, EMI noise generated in a predetermined frequency range, that is, the \( n \)-th-order frequency range from \( n \cdot fc2 \) to \( n \cdot fc3 \), can be further reduced.

[0063] As described above, since \( fc1 \), \( fc2 \), \( fc3 \) and \( fc4 \) are determined such that approximate expression (2) is satisfied while the carrier frequency \( fc \) is changed with time, the level of noise generated in a wide frequency range can be reduced. Also, the level of noise generated in a predetermined frequency range, that is, the \( n \)-th frequency range from \( n \cdot fc2 \) to \( n \cdot fc3 \), can be further reduced.

[0064] An inverter system according to a third embodiment is described next with reference to FIG. 4, paying particular attention to a difference between the inverter system according to the third embodiment and the inverter system 1 according to the first embodiment. The same component parts as in the first embodiment are referred to with the same reference numerals, and the descriptions of those same parts will be omitted. FIG. 4 shows a configuration of the inverter system 1 according to the third embodiment and a configuration of a receiver 10. In the third embodiment, the receiver 10 is disposed in the vicinity of the inverter system 1 according to the first embodiment. Thus, an advantage similar to that in the first embodiment can be achieved.

[0065] In the third embodiment, an amplitude modulation (AM) radio receiver is used as the receiver 10. The AM radio receiver 10 has a function to inform the waveform generator 9 of the carrier frequency changing unit 12 provided in the inverter system 1 of a channel frequency of a broadcasting station that is being received by the AM radio receiver 10. That is, the AM radio receiver 10 includes a channel frequency output unit 11. Thus, even when a broadcasting station to be received by the AM radio receiver 10 is changed, the range of a temporal change of the carrier frequency \( fc \) can be changed in accordance with the channel frequency. Thus, in a desired channel, a problem caused by EMI noise due to a carrier frequency \( fc \) generated by the inverter system 1 when the user listens to a broadcast received by the AM radio receiver 10 can be prevented.

[0066] An inverter system according to a fourth embodiment is described next with reference to FIGS. 5A and 5B, paying particular attention to a difference between the inverter system according to the fourth embodiment and the inverter system 1 according to the first embodiment. FIG. 5A shows a temporal change of a carrier frequency \( fc \) in the fourth embodiment. FIG. 5B shows a harmonic spectrum in the fourth embodiment. The configuration of the inverter system according to the fourth embodiment is the same as the configuration of the inverter system 1 according to the first embodiment. The inverter system according to the fourth embodiment is different from the inverter system 1 according to the first embodiment only in the temporal change, that is, the waveform of the carrier frequency \( fc \), as shown in FIG. 5A.

[0067] In the fourth embodiment, as shown in FIG. 5B, in the frequency spectrum of the \( n \)-th harmonic components, an \( n \)-th-order frequency range from \( n \cdot fc2 \) to \( n \cdot fc3 \) including the broadcasting frequency band \( fs \pm \Delta fs \) is located in a higher frequency portion, not at the center of the \( n \)-th-order frequency range from \( n \cdot fc1 \) to \( n \cdot fc4 \). As in the first embodiment, the frequency spectrum of the \( n \)-th harmonic components exhibits first noise level 41, which is substantially flat, in the \( n \)-th-order frequency range from \( n \cdot fc1 \) to \( n \cdot fc2 \) and second noise level 42, which is substantially flat, in the \( n \)-th-order frequency range from \( n \cdot fc3 \) to \( n \cdot fc4 \). In addition, the frequency spectrum exhibits third noise level 43, which is lower than the first noise level 41 and the second noise level 42, in the \( n \)-th-order frequency range from \( n \cdot fc2 \) to \( n \cdot fc3 \). In this case, periods \( T1 \) and \( T2 \) are determined such that equation (3) is satisfied:

\[
(fc2-fc1): (fc4-fc3) = T2: T1. \tag{3}
\]

[0068] In equation (3), \( T1 \) represents a period in which the carrier frequency \( fc \) changes in the first frequency range from the frequency \( fc1 \) to the frequency \( fc2 \), and \( T2 \) represents a period in which the carrier frequency \( fc \) changes in the second frequency range from the frequency \( fc3 \) to the frequency \( fc4 \). Referring to FIG. 5A, the carrier frequency \( fc \) changes in a triangular wave shape during the period \( T1 \) and the period \( T2 \). When triangular wave components in the period \( T1 \) have a cycle of \( Tm1 \) and triangular wave components in the period \( T2 \) have a cycle of \( Tm2 \), equation (4) is satisfied:
In addition, in accordance with equation (3) the ratio of the number of triangular wave components in the first frequency range from the frequency fc1 to the frequency fc2 to the number of triangular wave components in the second frequency range from the frequency fc3 to the frequency fc4 is represented by T1: T2. Thus, in the frequency spectrum of the nth harmonic components, the first noise level 41 is substantially equal to the second noise level 42. Accordingly, the level of noise in a frequency spectrum of harmonic components of each order can be reduced as much as possible.

In addition, as in the first embodiment, concerning the temporal change of the carrier frequency fc, since the carrier frequency fc is shifted in the third frequency range from the frequency fc2 to the frequency fc3 substantially vertically, EMI noise generated in a predetermined frequency range, that is, the nth-order frequency range from n·fc2 to n·fc3, can be further reduced. In addition, since "fc1", "fc2", "fc3" and "fc4" are determined such that inequalities (1.1) and (1.2) are satisfied, an increase in the level of noise caused by overlapping of the first and second noise levels with the third noise level 43 in the nth-order frequency range from n·fc2 to n·fc3 of the frequency spectrum of the nth harmonic components of the carrier frequency fc can be suppressed. Thus, the level of noise generated in a wide frequency range can be reduced, and the level of noise generated in a predetermined frequency range, that is, the nth-order frequency range from n·fc2 to n·fc3, can be further reduced.

An inverter system according to a fifth embodiment is described next with reference to FIGS. 6A and 6B. Paying particular attention to a difference between the inverter system according to the fifth embodiment and the inverter system according to the fourth embodiment. FIG. 6A shows a temporal change of a carrier frequency fc in the fifth embodiment. FIG. 6B shows a harmonic spectrum in the fifth embodiment. The configuration of the inverter system according to the fifth embodiment is the same as the configuration of the inverter system according to the fourth embodiment, that is, the inverter system 1 according to the first embodiment. The inverter system according to the fifth embodiment is different from the inverter system according to the fourth embodiment only in that, as shown in FIG. 6A, the temporal change, that is, the waveform of the carrier frequency fc has a shape in which a frequency value selected at random at each predetermined interval is changed stepwise, instead of a triangular wave shape.

In this case, the carrier frequency fc is determined so as to form uniform distribution in a unit time (T1+T2) in the first frequency range from the frequency fc1 to the frequency fc2 and the second frequency range from the frequency fc3 to the frequency fc4. For example, in FIG. 6A, the ratio of the bandwidth of the first frequency range from the frequency fc1 to the frequency fc2 to the bandwidth of the second frequency range from the frequency fc3 to the frequency fc4 is represented by 5:3. In the first frequency range from the frequency fc1 to the frequency fc2, five frequency values are provided in accordance with the above-mentioned frequency bandwidth ratio. One of the five frequency values is selected as the carrier frequency fc at random at each predetermined interval, and the carrier frequency fc is shifted stepwise to the selected frequency value. In this case, a frequency value that has already been selected is not selected again.

Similarly, in the second frequency range from the frequency fc3 to the frequency fc4, three frequency values are provided as the carrier frequency fc in accordance with the above-mentioned frequency bandwidth ratio. One of the three frequency values is selected as the carrier frequency fc at random at each predetermined interval, and the carrier frequency fc is shifted stepwise to the selected frequency value. In this case, similarly, a frequency value that has already been selected is not selected again. In this case, since the ratio of T1 to T2 is represented by 5:3, uniform distribution of the carrier frequency fc is achieved. Accordingly, as in the fourth embodiment, in the frequency spectrum of the nth harmonic components, the first noise level 41 can be substantially the same as the second noise level 42. Therefore, the level of noise in a frequency spectrum of harmonic components of each order can be reduced as much as possible.

In addition, as in the fourth embodiment, concerning the temporal change of the carrier frequency fc, since the carrier frequency fc is shifted in the third frequency range from the frequency fc2 to the frequency fc3 substantially vertically, EMI noise generated in a predetermined frequency range, that is, the nth-order frequency range from n·fc2 to n·fc3, can be further reduced. In addition, since "fc1", "fc2", "fc3" and "fc4" are determined such that inequalities (1.1) and (1.2) are satisfied, an increase in the level of noise caused by overlapping of the first and second noise levels with the third noise level 43 in the nth-order frequency range from n·fc2 to n·fc3 of the frequency spectrum of the nth harmonic components of the carrier frequency fc can be suppressed. Thus, the level of noise generated in a wide frequency range can be reduced, and the level of noise generated in a predetermined frequency range, that is, the nth-order frequency range from n·fc2 to n·fc3, can be further reduced.

Each of the embodiments is merely an example. The invention is not limited to any of the embodiments. Various changes and modifications can be made to the invention within the scope of the claims. For example, in each of the first to fifth embodiments, the invention is applied to an inverter system. However, the present invention can be applied to a controller of another type of power converter. For example, the invention is applicable to a case where a DC motor is
null
(b) an inequality \((n-1) \cdot fc4 \leq n \cdot fc2\) and an inequality \(n \cdot fc3 \leq (n+1) \cdot fc1\) with respect to an integer \(n\); and
(b) an approximate expression \(n \cdot fc4 \approx (n+1) \cdot fc1\) with respect to the integer \(n\);

wherein the frequencies \(fc2\) and \(fc3\) satisfy an inequality \(fc2 \leq fs - \Delta fs\) and an inequality \(fs + \Delta fs \leq n \cdot fc3\) wherein \(fs \pm \Delta fs\) represents a predetermined frequency band.

3. An apparatus as claimed in claim 2 wherein the waveform generator is operable to receive a frequency of a channel to be received by a broadcast receiver device and to change the frequency of the waveform using the frequency of the channel as the frequency \(fs\).

4. An apparatus as claimed in claim 2 or claim 3 wherein the waveform generator is operable to generate the waveform by stepwisely changing a frequency value selected at random at each predetermined interval.

5. An apparatus as claimed in any of claims 2 to 4 wherein the waveform generator is operable to change the waveform in a triangular wave shape in a predetermined cycle within the first frequency range and within the second frequency range.

6. A method for controlling a power converter arranged to convert input electric power into a desired form and output the converted electric power by controlling a power converter switch, the method comprising:

changing a frequency of a control signal for controlling the power converter switch in accordance with a waveform that periodically changes within a first frequency range from a frequency \(fc1\) to a frequency \(fc2\), wherein the frequency \(fc1\) is smaller than the frequency \(fc2\), and within a second frequency range from a frequency \(fc3\) to a frequency \(fc4\), wherein the frequency \(fc3\) is smaller than the frequency \(fc4\);

determining the frequencies \(fc1\) and \(fc4\) such that at least one of:

(a) an inequality \((n-1) \cdot fc4 \leq n \cdot fc2\) and an inequality \(n \cdot fc3 \leq (n+1) \cdot fc1\) are satisfied with respect to an integer \(n\), and

(b) an approximate expression \(n \cdot fc4 \approx (n+1) \cdot fc1\) is satisfied with respect to the integer \(n\); and

determining the frequencies \(fc2\) and \(fc3\) that satisfy an inequality \(fc2 \leq fs - \Delta fs\) and an inequality \(fs + \Delta fs \leq n \cdot fc3\) wherein \(fs \pm \Delta fs\) represents a predetermined frequency band.

7. A method as claimed in claim 6, comprising:

selecting a frequency of a broadcast channel to be received by a receiver disposed in the vicinity of the power converter as the frequency \(fs\); and

changing \(fc1\), \(fc2\), \(fc3\) and \(fc4\) when \(fs\) changes.

8. An apparatus or a method as claimed in any preceding claim wherein the frequencies \(fc1\), \(fc2\), \(fc3\), and \(fc4\) satisfy an equation \((fc2-fc1):(fc4-fc3) = b:a\), wherein \(b:a\) represents a ratio of a period of time belonging to the second frequency range to a period of time belonging to the first frequency range.

9. An apparatus or a method as claimed in any preceding claim wherein the frequencies \(fc1\), \(fc2\), \(fc3\), and \(fc4\) satisfy an equation \((fc2-fc1):(fc4-fc3) = c:d\), wherein \(c:d\) represents a ratio of a number of triangular wave components of the waveform that shift within the first frequency range to a number of triangular wave components of the waveform that shift within the second frequency range.

10. A vehicle having an apparatus or adapted to use a method as claimed in any preceding claim.
REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description