(54) **LOW SWITCH COUNT DIRECT AC-TO-AC POWER CONVERTER**

DIREKTER AC-AC WANDLER MIT WENIGEN SCHALTERN

CONVERTISSEUR DE PUISSANCE ALTERNATIF-ALTERNATIF DIRECT AVEC PEU DE COMMUTATEURS

(73) Proprietor: **Eaton Corporation**
Cleveland, OH 44122 (US)

(72) Inventors:
• **FAMILIANT, Yakov, Lvovich**
Brown Deer, WI 53223 (US)

• **JANKOVIC, Zeljko, Radomir**
Milwaukee, WI 53211 (US)
• **LEQUESNE, Bruno, Patrice-Bernard**
Menomonee Falls, WI 53051 (US)
• **BHAVARAJU, Vijay**
Germantown, WI 53022 (US)

(74) Representative: **Schmidbauer, Andreas Konrad**
Wagner & Geyer Partnerschaft
Patent- und Rechtsanwälte
Gewürzmühlstrasse 5
80538 München (DE)

(56) References cited:
US-A- 5 949 672

Description

BACKGROUND OF THE INVENTION

5 **[0001]** The present invention relates generally to AC-to-AC converters and, more particularly, to AC-to-AC converters for motor drives and method of operation thereof that provides for variable frequency, variable voltage operation of the driven system, as particularly suited for the variable speed operation of electrical machines.
[0002] Electrical machines are often controlled by electronic drives (i.e., motor drives), especially to operate them at various speeds. Conventionally, such motor drives rectify the incoming AC voltage, smooth the DC voltage with a

10 capacitor, and then invert it with a six-IGBT inverter. This makes it possible to operate the machine at any speed, since the machine speed is proportional to the frequency generated by the inverter. Many sophisticated controls have been devised for such drives.
[0003] Not all machines and applications, however, can make use of such sophistication, and lower cost motor drives would be desirable. Aside from drives, however, the only option on the market, specifically for induction machines, is

15 the "soft starter", which typically employs silicon controlled rectifiers (SCRs) for reducing the inrush current to the motor but that offer limited control thereover (e.g., while SCRs can be turned on at will, they cannot be turned off in a dynamic and controllable fashion, as SCRs turn off naturally when the current reaches zero). Soft-starters that include IGBTs have been introduced more recently, but up until now such soft-starters have lacked the sophistication and controls necessary for controlling the machine and its load beyond the starting process. Furthermore, US 5 949 672 A relates to

20 a load control device to control current flow to an AC load, the load control device comprising:
a circuit including:

an input connectable to line terminals of an AC source so as to receive a supply voltage therefrom, the supply voltage having a supply frequency;
25 an output connectable to load terminals of the AC load;
supply lines connecting the input and output to transmit power from the AC source to the AC load, each supply line corresponding to a phase in the AC load;
a plurality of line-side switches connected between the line terminals and the load terminals;
the load control device further comprises:
30 a controller connected to the circuit.

[0004] It would therefore be desirable to provide a motor drive and method of operation thereof that provides many of the advantages of a sophisticated drive, but that is less complex and less expensive to manufacture.

35 BRIEF DESCRIPTION OF THE INVENTION

[0005] The present invention provides a system and method for variable speed operation of a load. A modulating function is applied to a line voltage such that a frequency, an average, and a phase of a voltage across the terminals of an AC load can be controlled to enable variable speed operation of the load. In accordance with the present invention,
40 an load control device and a method as set forth in claims 1 and 12 is provided. Further embodiments of the invention are claimed in the dependent claims
[0006] In accordance with one aspect of the invention, the load control device is to control current flow to an AC load and inter alia includes a circuit having an input connectable to line terminals of an AC source so as to receive a supply voltage therefrom having a supply frequency, an output connectable to load terminals of the AC load, supply lines
45 corresponding to phases in the AC load and connecting the input and output to transmit power from the AC source to the AC load, a plurality of line-side switches connected between the line terminals and the load terminals such that each supply line includes a line-side switch connected thereto, and a plurality of floating-neutral side switches connected to the load terminals at one end and together at a common connection at another end, such that each supply line includes a line-side switch connected thereto. The load control device also includes a controller connected to the circuit that is
50 programmed to control the circuit so as to cause each of the plurality of line-side switches and each of the plurality of floating-neutral side switches to switch between an On condition or an Off condition to selectively operate the circuit in an active mode and a free-wheeling mode, with a full phase voltage being provided to the load terminals during the active mode and a zero voltage being provided to the load terminals during the free-wheeling mode. In controlling the circuit, the controller is programmed to apply a modulating function to the circuit, so as to modulate the supply voltage
55 to control a frequency and an average of a load voltage present across the load terminals of the AC load, thereby enabling variable frequency operation of the AC load.
[0007] In accordance with another aspect of the invention, the method is for controlling operation of an AC load and includes the step of providing a supply voltage from an AC power source to an AC load, the supply voltage having a

supply frequency. The method also includes the step of providing a circuit in series between the AC power source and the AC load to condition the supply voltage, the circuit comprising a plurality of switches forming a group of line-side switches connected to supply lines between line terminals of the AC power source and load terminals of the AC load and a group of floating-neutral side switches connected to the supply lines at one end and together at a common connection at another end. The method further includes the step of selectively operating the circuit in an active mode and a free-wheeling mode so as to selectively provide a full phase voltage to the load terminals during the active mode and a zero voltage to the load terminals during the free-wheeling mode of operation. Operation of the circuit further includes controlling a duty cycle of the circuit so as to control an average voltage to be applied to the AC load, with the duty cycle comprising a ratio of a time of circuit operation in the active mode to a total time of circuit operation. The duty cycle of the circuit is controlled by applying a voltage modulating periodic function to the circuit, so as to modulate a frequency of a load voltage present across the load terminals of the AC load and enable variable speed operation of the AC load.

[0008] In accordance with yet another aspect of the invention, a motor drive to control transmission of voltage and current from an AC power source to an AC motor includes an input connectable to line terminals of an AC power source so as to receive a supply voltage therefrom having a supply frequency, an output connectable to motor terminals of an AC motor, a plurality of supply lines connecting line terminals of the AC power source to motor terminals of the AC motor such that each supply line corresponds to a phase in the AC motor, and a plurality of insulated gate bipolar transistors (IGBTs) selectively switchable between an On condition and an Off condition to control transmission of voltage and current from an AC power source to an AC motor, with the plurality of IGBTs further including a group of line-side IGBTs connected to the supply lines between the line terminals and the motor terminals such that each supply line includes a line-side IGBT connected thereto and a group of floating-neutral side IGBTs connected to the supply lines at one end and together at a common connection at another end, such that each supply line includes a floating-neutral side IGBT connected thereto. The motor drive also includes a processor programmed to apply a voltage modulating control algorithm to control switching of each of the group of line-side IGBTs and each of the group of floating-neutral side IGBTs between an On condition or an Off condition to selectively operate the circuit in an active mode and a free-wheeling mode, with a full phase voltage being provided to the motor terminals during the active mode and a zero voltage being provided to the motor terminals during the free-wheeling mode. In applying the voltage modulating control algorithm, the processor is further programmed to control a duty cycle of the motor drive so as to control an average motor voltage to be applied to the AC motor, with the duty cycle comprising a ratio of a time of motor drive operation in the active mode to a total time of motor drive operation and modulate a frequency of a motor voltage present across the motor terminals of the AC motor, so as to enable variable speed operation of the AC motor.

[0009] Various other features and advantages of the present invention will be made apparent from the following detailed description and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The drawings illustrate preferred embodiments presently contemplated for carrying out the invention.

[0011] In the drawings:

FIG. 1 is a schematic view of a 3-phase AC control system incorporating a load control device, such as a motor drive, for controlling voltage to the load in a controlled fashion, according to an embodiment of the invention.

FIG. 2 is a table illustrating a switching logic for switching IGBTs in the load control device in FIG. 1, according to an embodiment of the invention.

FIG. 3 is a diagram illustrating application of a modulating function over a period of time for switching IGBTs in the load control device in FIG. 1 to modulate a voltage waveform to the AC load, according to an embodiment of the invention.

FIG. 4 is a diagram illustrating load terminal voltage modulation, according to an embodiment of the invention.

FIGS. 5A-5C are diagrams illustrating pulse skipping voltage modulation for various conduction durations and or duty cycle constants, according to an embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0012] The embodiments of the invention set forth herein relate to a motor drive and method of operation thereof that provides for variable speed operation of a load, such as an AC induction motor. A motor drive is provided that includes

a plurality of switches (e.g., IGBTs) therein that control voltages and current to the AC motor, with a controller in the motor drive applying a modulating function to control operation of the switches in order to modulate a voltage provided to the motor and enable variable speed operation thereof. The approach uses a low number of switches to achieve this function.

[0013]   Referring to FIG. 1, an AC load is shown for use with embodiments of the invention. The AC load 10 may be an electrical machine, such as a permanent magnet machine, a synchronous machine, or an induction machine, where power is supplied to the rotor (not shown) thereof by means of electromagnetic induction, with the AC load 10 being operatively connected to a three-phase AC source 12a-12c through corresponding supply lines 14, 16 and 18, respectively, so as to receive power therefrom. Thus, for purposes of reference, supply line 14 corresponds to a Phase A, supply line 16 corresponds to a Phase B, and supply line 18 corresponds to a Phase C. As shown in FIG. 1, a load control device 20 is connected between AC source 12a-12c and AC load 10 that performs an AC-AC conversion of the AC waveform generated by AC source 12a-12c to another AC waveform for input to the AC load 10. In an exemplary embodiment of the invention, load control device 20 comprises a motor drive configured to operate an AC motor at various speeds (i.e. a variable speed drive (VSD)), and thus the load control device is hereafter referred to as a motor drive. Generally speaking, motor drive 20 uses a 3-phase AC supply voltage as input and provides a controlled AC voltage to a load.

[0014]   The basic structure of motor drive 20 is shown in FIG. 1 (i.e., circuitry 21 of the motor drive) as including a plurality of switches 22, 24, 26, 28, 30, 32 connected to supply lines 14, 16, 18, with each of the switches coupled in anti-parallel with a diode 34 so as to control the current flow and, in turn, the terminal voltages of the AC load 10. According to an exemplary embodiment of the invention, the switches are in the form of IGBTs, and thus the switches are hereafter referred to generally as IGBTs. However, it is noted that "IGBT" should be understood as any switch that can be turned on and off at will (at any frequency including high frequencies in the tens of kHz and beyond), IGBTs being currently a common technology in many induction motor drive applications. Other kinds of electronic switches, such as MOSFETs or MCTs (MOS-Controlled Thyristors) for instance, can be used depending on voltage level, power level, and other considerations.

[0015]   Also included in motor drive 20 are optional contactors 35 corresponding to each phase of the power supply, that provide for a bypassing of the IGBTs 22, 24, 26, 28, 30, 32, when bypassing of the motor drive is desired. According to an exemplary embodiment of the invention, an arrangement of six IGBTs 22, 24, 26, 28, 30, 32 is provided in the motor drive. Three IGBTs 22, 24, 26 are connected between the line terminals 36 of AC source 12a-12c and the load terminals 38 of AC load 10, and thus are herein referred to as "line-side IGBTs". Three other IGBTs 28, 30, 32 that are referred to herein as "floating-neutral side IGBTs" are connected to the load terminals 38 at one end and together at a common connection 40 at the other end. This common connection 40 forms what is referred to herein as a "floating neutral point," with the qualifier "floating" being used to distinguish this point from the machine neutral or source neutral, to which it is not connected. As shown in FIG. 1, six IGBTs are provided corresponding to the number of phases (i.e., three phases), with one "line-side IGBT" and one "floating-neutral side IGBT" per phase. It is recognized, however, that any number of phases can be envisioned and thus embodiments of the invention can be readily extended from a 3-phase example, with two IGBTs per phase in general, with special consideration for the case of a single-phase system which requires two "line-side IGBTs" (one each for the line and return) and similarly two "floating-neutral side IGBTs". Further, it is to be noted that "IGBT" should be understood as any switch that can be turned on and off at will (at any frequency, including high frequencies in the tens of kHz and beyond), IGBTs being currently a common technology in many induction motor drive applications. Other kinds of electronic switches, such as MOSFETs or MCTs (MOS-Controlled Thyristors) for instance, can be used depending on voltage level, power level, and other considerations.

[0016]   According to one embodiment of the invention, a means to sense the current in at least two of the load terminals 38 is included in motor drive 20, such as current sensors 42 positioned on two or more of supply lines 14, 16, 18. Additionally, according to one embodiment of the invention, capacitors 44 are positioned between the line terminals 36 and the line-side IGBTs 22, 24, 26 to provided buffering. While such capacitors 44 may be included in motor drive 20, it is recognized that the capacitors are small in size/capacity, as the controlling of the IGBTs 22, 24, 26, 28, 30, 32 according to a desired control scheme eliminates the need for larger capacitors and/or capacitors all together.

[0017]   Also included in motor drive 20 is a controller or processor 46 configured to control operation of IGBTs 22, 24, 26, 28, 30, 32 via the transmission of gate drive signals thereto. During start-up or stopping (i.e., braking) of AC load 10, controller 46 functions to cause the contactors 35 to open such that power from AC source 12a-12c passes through the IGBTs. Controller 46 functions to selectively cause each of IGBTs to operate in an On or Off condition, so as to control the current flow (and therefore the voltage) applied to the AC load 10. According to embodiments of the invention, controller 46 is configured and programmed to implement a switching pattern control scheme that provides for full control of the voltage and current provided to load terminals 38 on supply lines 14, 16, 18, while providing for the current in the machine inductances to never be interrupted.

[0018]   In implementing a switching control scheme or pattern for the IGBTs 22, 24, 26, 28, 30, 32, the controller 46 controls a switching of the IGBTs 22, 24, 26, 28, 30, 32 to the On and Off conditions based on a sensed direction of

current flow (positive or negative) on each of the supply lines 14, 16, 18. More specifically, in whichever one phase (or two phases) the current is positive, either the corresponding line side IGBT(s) 22, 24, 26, are turned on and all other IGBTs are turned off or, alternatively, the floating-neutral side IGBTs 28, 30, 32 in the other two (or one) phases are turned on and all other IGBTs are turned off. In controlling the IGBTs to operate in the On and Off states in such a manner via controller 46, current is caused to always flows through the AC load 10.

[0019] The switching logic described above is summarized in FIG. 2, in that the switching of IGBTs 22, 24, 26, 28, 30, 32 is primarily governed by the sign of the current of each phase at any given time. Referring to FIG. 2, and with continued referenced to FIG. 1, "positive" current should be understood as "greater than zero", or "greater than a small positive number," and similarly for "negative" current. This is for cleaner implementation in the presence of noise, and to avoid control confusion when the current signal is exactly zero. As a result of controller 46 implementing the switching logic illustrated in FIG. 2, the load terminals 38 will see either full phase voltage as provided by the source ($V_a=V_{an}$, $V_b=V_{bn}$, and $V_c=V_{cn}$) or zero voltage in all three phases ($V_a=V_b=V_c=0$). The first instance is referred to as an "active period" while the latter is referred to as a "free-wheeling period." The ratio of the active period over the sum of the active period and the free-wheeling period is referred to as the duty cycle, and is a key element in controlling the average voltage supplied to the AC load 10. The "active" mode/period refers to energy transfer from the source to the load (as in a motoring mode for a machine), or from the load to the source (as in a generating, regenerating, or braking mode for a motor or a generator), as opposed to the "free-wheeling" mode/period where any energy transfer is generally confined to the load (losses in the drive and wiring notwithstanding.

[0020] In summary, the switching logic and pattern for switching IGBTs 22, 24, 26, 28, 30, 32 implemented by controller 46 is governed by the sign of the currents on Phases A, B, and C. Within each current pattern, the voltage applied to the AC load 10 is either full line voltage (i.e., active period), or zero (i.e., free-wheeling period), as controlled by the duty cycle of the switching of the IGBTs 22, 24, 26, 28, 30, 32. The overall frequency at which the IGBTs 22, 24, 26, 28, 30, 32 are turned on and off is an additional degree of freedom which can be put to advantage to reduce harmonics among other things.

[0021] In general, with respect to controlling the voltage across the load terminals, it can be observed that at any point in time, the control of the IGBTs can result in either one of two states: the motor drive is On (i.e., active mode where the machine voltage is the line voltage), or Off (i.e., free-wheeling mode where the voltage across the load terminals is zero). Consequently, the only mechanism for controlling voltage consists of controlling when, and for how long, the line-side IGBTs are on - that is, the duty cycle of the drive. According to embodiments of the invention, for purposes of controlling a frequency of the voltage across the load terminals, the controller 46 is further programmed to implement a modulating function M(t) to switch the IGBTs On and Off at a higher switching frequency f_{sw} and to control the duty cycle, so as to modulate the supply line voltage across the load terminals 38 and enable variable speed operation of the AC load 10 by controlling the frequencies of the 3-phase voltage across the load terminals by choosing the correct modulating function.

[0022] According to embodiments of the invention, controller 46 modulates the line voltage V(t) by a modulating function M(t), such that the voltage $V_{mach}(t)$ across the load terminals is:

$$V_{mach}(t) = V(t)*M(t) \qquad [Eqn. 1].$$

[0023] M(t) is a higher-frequency (i.e., higher than the frequency of the supply voltage), periodic function with value of either 0 or 1, having a frequency f_{sw}, defining a period T_{sw}, as is illustrated in FIG. 3. Accordingly:

$$M(t) = 1 \text{ if } 0 < t < D(t) \text{ x } T_{sw}$$

and

$$M(t) = 0 \text{ if } D(t) \text{ x } T_{sw} < t < T_{sw},$$

where D(t) is a "duty cycle" function value between 0 and 1 Preferably, the switching frequency f_{sw} is a multiple of 6 times the supply frequency, e.g. a multiple of 360Hz if the supply frequency is 60 Hz. The choice of that switching frequency is a trade-off between switching losses and lower harmonics. It can be noted that an induction motor has a synchronous speed that depends on the number of poles and the fundamental frequency of the voltage applied to its terminals. At 60 Hz supply, a two pole machine has a synchronous speed of 1800 rpm. In order to run the machine at different synchronous speeds, the modulating function along with the switching frequency will result in a fundamental

frequency different from 60Hz or the line frequency. Further, and in order to achieve a drive speed different from synchronous speed (corrected by slip in the case of an induction machine), the function D(t) should be periodic of the period n/60, where n is an integer > 1. The number n corresponds to the desired drive speed (possibly corrected by slip).

[0024] Referring to FIG. 3, the average value $M_{ave}(t_i)$ of M(t) over a cycle T_{sw} starting at time t = t_i is:

$$M_{ave}(t_i) = D(t_i)$$

[0025] Therefore, on average over a short time span T_{sw}, the average machine voltage is:

$$V_{mach,ave}(t) = V(t)*M_{ave}(t) = V(t)*D(t) \qquad \text{[Eqn. 2]}.$$

[Eqn. 2] is equivalent to [Eqn. 1] above, and may be a more convenient expression, especially when D(t) is a continuous function of t.

[0026] With the proper selection of the duty cycle function D(t), one can select the frequency and voltage supplied to AC load 10. Typically, the pattern of D(t) over time can be used for frequency selection, while either or both the magnitude and the width of the pulses in the function D(t) will determine the magnitude of the drive output voltage.

[0027] According to an exemplary embodiment of the invention, for a 3-phase machine operating from a 60Hz grid, the modulating function M(t) is determinable in part from a duty cycle function D(t) that is a continuous function of t and is defined as:

$$D(t) = \frac{d}{2}\left[1 + \sin\left(2\pi\left(f_g - f_{out}\right)t + \phi\right)\right] \qquad \text{[Eqn. 3]},$$

where f_g = 60Hz, f_{out} corresponds to the desired drive speed (possibly corrected by slip), ϕ can provide a phase shift, and *d* ("duty-cycle constant") is a real number between 0 and 1.

[0028] With d being a number between 0 and 1, a factor of ½ is necessary so that $0 \le D(t) \le 1$. Therefore, if the line voltage is V(t) = $V\sin(2\pi f_g t)$, combining [Eqn. 2] and [Eqn. 3] leads to:

$$V_{mach,ave}(t) = \frac{d}{2}V\sin\left(2\pi f_g t\right) \cdot \left[1 + \sin\left(2\pi\left(f_g - f_{out}\right)t + \phi\right)\right] \quad \text{[Eqn. 4]}.$$

[0029] With some manipulation:

$$V_{mach,ave}(t) = \frac{d}{2}V\left[\frac{1}{2}\cos\left(2\pi f_{out}t + \phi\right) - \frac{1}{2}\cos\left(2\pi\left(2f_g - f_{out}\right)t + \phi\right) + \sin\left(2\pi f_g t\right)\right] \text{[Eqn. 5]}.$$

[0030] Therefore, the machine is excited with 3 rotating fields, one at frequency f_{out}, one at frequency f_g (normal synchronous speed), and one at frequency $(2f_g - f_{out})$. If $f_{out} < f_g$, then the machine can run at that corresponding lower speed (i.e., sub-synchronous speed). The machine can also run, in principle, at a "super-synchronous" speed corresponding to: $(2f_g-f_{out})$. The third rotating field, at frequency f_g, is at normal synchronous speed. As such, this third rotating field is of no immediate use since such rotating fields can be obtained by not modulating the line voltage.

[0031] For speeds near synchronous speed, the three rotating fields overlap. As a practical matter, therefore, operation of the motor drive (with modulation) at frequencies f_{out} close to f_g is difficult if not impossible. So with application of a modulation function as set forth in [Eqns. 3-5], the machine can run at any speed below and above synchronous speed. Speeds at or close to synchronous speed are achievable by not modulating the line voltage.

[0032] Further referring to [Eqn. 5], it is readily apparent that the magnitude of the output voltage is controlled by adjusting parameter *d* (i.e., the duty-cycle constant), and the phase ϕ can provide an additional control leverage by shifting the load voltage over time.

[0033] An example of machine voltage modulation resulting from application of the modulating function set forth in [Eqns. 3-5] by controller 46, is illustrated in FIG. 4. In FIG. 4, the top trace 50 shows the supply line voltage at 60Hz. The second trace 52 is the duty-cycle function D(t), in this case with a duty cycle magnitude d of 1, and a frequency f_{out}=15Hz (resulting in D(t) having a frequency of $(f_g - f_{out})$ = 45Hz). The bottom trace 54 is the resulting machine voltage,

while the trace 56 is an intermediary calculation.

[0034] According to another embodiment of the invention, for a 3-phase machine operating from a 60 Hz power grid, the modulating function M(t) is determinable in part from a duty cycle function D(t) that is defined as:

$$D(t) = d \qquad \text{if} \qquad 0 < t < \frac{\lambda}{60}$$

$$D(t) = d \qquad \text{if} \qquad \frac{1}{3}\frac{n}{60} < t < \frac{1}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = d \qquad \text{if} \qquad \frac{2}{3}\frac{n}{60} < t < \frac{2}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = 0 \qquad \text{otherwise, within the time bracket } 0 < t < \frac{n}{60} \qquad \text{[Eqn. 6],}$$

where d ("duty-cycle constant") is a real number between 0 and 1, and λ ("conduction duration") is a real number between 0 and 0.5. Additionally, all terms in [Eqn. 6] may be shifted by an angle ϕ, in order to control the phase of the load voltage.

[0035] The modulating function cycle described above is referred to as "pulse skipping," and corresponds to exciting the drive for part of one 60Hz cycle, then leaving it off for one or more "skipped" cycles. If (n-1) cycles are so skipped, the resulting main frequency of the machine voltage is 60Hz/n, and the machine can be driven up to, and stably at, the corresponding speed (minus slip in the case of an induction machine), with selected speeds being possible based on the ratio of 60/n, such as ¼ of the machine synchronous speed for example. This is illustrated in FIGS. 5A, 5B, and 5C, for the case where n=4 (15Hz), with three sub-cases being shown. In FIGS. 5A and 5B, the conduction period or duration λ, identified as 58, is maximum (λ=0.5), that is, conduction occurs over half of a 60Hz cycle, or 180°. In the first case (FIG. 5A), the duty-cycle constant d is 1, that is, the drive conducts all the time within the conduction period. In the second case (FIG. 5B), d is 0.5, that is, the voltage is chopped, and is on half of the time and off half of the time. In the second case, the switching frequency is 7x360Hz in this example. The third sub-case (FIG. 5C) is an example of a smaller conduction period 58 (λ=0.125, or 45° out of the 360° of each 60Hz cycle), for a duty cycle constant d = 1. If the conduction duration λ is less than 0.5, it is preferably centered in the middle of the possible conduction span. Further, it can be contemplated that there will be several conduction periods within one conduction span, adding up to 0.5, not all necessarily equal, and preferably but not necessarily symmetrically centered in the middle of the conduction span.

[0036] In implementing a pulse skipping modulation function by way of control 46, the motor drive can be turned on (1/n)[th] of the time, so that (n-1) cycles are skipped, resulting in a fundamental frequency at the load terminals of 60/n Hz. Conduction is therefore permissible during a fraction of the time. Aside from skipping (n-1) cycles, the drive also conducts, at the most, for only half of the 60Hz cycle. This is reflected by the coefficient λ, which is a number up to 0.5. Further still, within this conduction period, the voltage is chopped at a higher frequency at a constant duty cycle d. Accordingly, the number n determines the machine operating speed, and the coefficient λ and the constant duty cycle d determine the average voltage at the load terminals. For a given desired voltage, choosing λ =0.5 (maximum value), then adjusting d, is preferable in terms of reducing harmonics (at the expense of increasing switching losses). The chopping frequency is preferably a multiple of 6 times the supply frequency, e.g. a multiple of 360Hz if the supply frequency is 60 Hz, and is 7x360Hz in this example. The choice of that switching frequency is again a trade-off between switching losses and lower harmonics.

[0037] It is recognized that controller 46 can implement a modulating function as set forth above for a number of different applications/motor operations. For example, the controller can implement a modulating function for starting a motor, by sweeping the "desired operating speed" from zero to near synchronous speed. Upon reaching near synchronous speed, application of the modulating function can be stopped such that the motor can be switched to direct operation (as described with respect to the switching logic of the IGBTs shown in FIG. 2) or to a bypass mode in which the contactors 35 are closed to bypass the IGBTs.

[0038] As another example, the controller 46 can implement a modulating function for purposes of functioning as a regenerative drive. A conventional drive, when decelerating a load, will send energy back to the DC link. This energy can be stored in the DC link capacitor, but if the amount of energy is significant, the capacitor needs to be large. Alternatively, the energy can be wasted in a resistor bank. Finally, for regeneration to the grid, the diode bridge must be replaced by an active inverter. By contrast, the present invention makes it possible to operate at any speed, in either

motoring or generating mode, with only six IGBT switches, half as many as in a conventional, regenerative drive. In the case of an induction motor drive, regeneration is achieved by selecting an output frequency corresponding to a speed lower than the speed of the machine, so as to have a negative slip. For synchronous machines, regeneration is done by selecting an appropriate phase ϕ. In the latter case, and in a different respect, other values of phase ϕ will also allow field-weakening operation of the machine.

[0039] As still another example, the controller 46 can implement a modulating function for purposes of reversing a direction of operation of the AC motor. It is possible to modulate the line voltage in such a way as to effectively change the order of excitation of the 3 phases of the motor, from say phases A-B-C to phases A-C-B. This has the effect of making operation in the reverse direction possible. That is, with respect to the modulation function referenced in FIG. 5, for example, the choice of n = 2, 5, 8, 11, etc, leads to reverse-direction operation, while values of n = 4, 7, 10, etc, leads to operation in the same direction as with 60Hz. More generally:

$$n = i*p - 1 \qquad \text{for reverse direction operation,}$$

and

$$n = i*p + 1 \qquad \text{for standard direction operation,}$$

where *p* is the number of phases (generally *p*=3), and *i* is any integer larger or equal to 1.

[0040] Beneficially, the applying of a modulating function by the controller 46 for controlling the switching of the IGBTs 22, 24, 26, 28, 30, 32 provides for variable speed operation of the AC motor 10, while providing such capability in the form of a motor drive 20 that is less complex and less expensive to manufacture than traditional VSDs. Application of the modulating function also provides for: starting a motor by sweeping the desired operating speed from zero to near synchronous speed, operating the motor drive as a regenerative drive, and/or for reversing a direction of operation of the AC motor.

[0041] A technical contribution for the disclosed method and apparatus is that it provides for a computer implemented technique for modulating a line voltage by application of a modulating function, such that a frequency, an average, and a phase of a voltage across the motor terminals of an AC motor can be controlled to enable variable speed operation of the motor. The application of the modulating function controls switching of a plurality of IGBTs in the motor drive to control a duty cycle of the drive, so as to modulate the voltage.

[0042] While this invention was described in the particular case where the load 10 is an AC electric machine, induction, synchronous, permanent magnet, reluctance, brushless, or other, it will be recognized that it is, generally speaking, a control device and method of operation thereof for changing the frequency in an AC electric circuit, such that a load can be operated at a frequency other than that of the supply.

[0043] Therefore, according to one embodiment of the present invention, a load control device to control current flow to an AC load is provided that includes a circuit having an input connectable to line terminals of an AC source so as to receive a supply voltage therefrom having a supply frequency, an output connectable to load terminals of the AC load, supply lines corresponding to phases in the AC load and connecting the input and output to transmit power from the AC source to the AC load, a plurality of line-side switches connected between the line terminals and the load terminals such that each supply line includes a line-side switch connected thereto, and a plurality of floating-neutral side switches connected to the load terminals at one end and together at a common connection at another end, such that each supply line includes a line-side switch connected thereto. The load control device also includes a controller connected to the circuit that is programmed to control the circuit so as to cause each of the plurality of line-side switches and each of the plurality of floating-neutral side switches to switch between an On condition or an Off condition to selectively operate the circuit in an active mode and a free-wheeling mode, with a full phase voltage being provided to the load terminals during the active mode and a zero voltage being provided to the load terminals during the free-wheeling mode. In controlling the circuit, the controller is programmed to apply a modulating function to the circuit, so as to modulate the supply voltage to control a frequency and an average of a load voltage present across the load terminals of the AC load, thereby enabling variable frequency operation of the AC load.

[0044] According to another embodiment of present invention, a method for controlling operation of an AC load includes the step of providing a supply voltage from an AC power source to an AC load, the supply voltage having a supply frequency. The method also includes the step of providing a circuit in series between the AC power source and the AC load to condition the supply voltage, the circuit comprising a plurality of switches forming a group of line-side switches connected to supply lines between line terminals of the AC power source and load terminals of the AC load and a group of floating-neutral side switches connected to the supply lines at one end and together at a common connection at

another end. The method further includes the step of selectively operating the circuit in an active mode and a free-wheeling mode so as to selectively provide a full phase voltage to the load terminals during the active mode and a zero voltage to the load terminals during the free-wheeling mode of operation. Operation of the circuit further includes controlling a duty cycle of the circuit so as to control an average voltage to be applied to the AC load, with the duty cycle comprising a ratio of a time of circuit operation in the active mode to a total time of circuit operation. The duty cycle of the circuit is controlled by applying a voltage modulating periodic function to the circuit, so as to modulate a frequency of a load voltage present across the load terminals of the AC load and enable variable speed operation of the AC load.

[0045]   According to yet another embodiment of the present invention, a motor drive to control transmission of voltage and current from an AC power source to an AC motor includes an input connectable to line terminals of an AC power source so as to receive a supply voltage therefrom having a supply frequency, an output connectable to motor terminals of an AC motor, a plurality of supply lines connecting line terminals of the AC power source to motor terminals of the AC motor such that each supply line corresponds to a phase in the AC motor, and a plurality of insulated gate bipolar transistors (IGBTs) selectively switchable between an On condition and an Off condition to control transmission of voltage and current from an AC power source to an AC motor, with the plurality of IGBTs further including a group of line-side IGBTs connected to the supply lines between the line terminals and the motor terminals such that each supply line includes a line-side IGBT connected thereto and a group of floating-neutral side IGBTs connected to the supply lines at one end and together at a common connection at another end, such that each supply line includes a floating-neutral side IGBT connected thereto. The motor drive also includes a processor programmed to apply a voltage modulating control algorithm to control switching of each of the group of line-side IGBTs and each of the group of floating-neutral side IGBTs between an On condition or an Off condition to selectively operate the circuit in an active mode and a free-wheeling mode, with a full phase voltage being provided to the motor terminals during the active mode and a zero voltage being provided to the motor terminals during the free-wheeling mode. In applying the voltage modulating control algorithm, the processor is further programmed to control a duty cycle of the motor drive so as to control an average motor voltage to be applied to the AC motor, with the duty cycle comprising a ratio of a time of motor drive operation in the active mode to a total time of motor drive operation and modulate a frequency of a motor voltage present across the motor terminals of the AC motor, so as to enable variable speed operation of the AC motor.

Claims

1. A load control device (20) to control current flow to an AC load (10), the load control device (20) comprising:

    a circuit including:

        an input connectable to line terminals (36) of an AC source (12a, 12b, 12c) so as to receive a supply voltage therefrom, the supply voltage having a supply frequency;
        an output connectable to load terminals (38) of the AC load (10);
        supply lines (14, 16, 18) connecting the input and output to transmit power from the AC source (12a, 12b, 12c) to the AC load (10), each supply line (14, 16, 18) corresponding to a phase (A, B, C) in the AC load (10);
        a plurality of line-side switches (22, 24, 26) connected between the line terminals (36) and the load terminals (38), such that only one line-side switch (22, 24, 26) is provided for each phase (A, B, C) and its respective supply line (14, 16, 18); and
        a plurality of floating-neutral side switches (28, 30, 32) connected to the load terminals (38) at one end and together at a common connection at another end, such that only one floating-neutral side switch (28, 30, 32) is provided for each phase (A, B, C) and its respective supply line (14, 16, 18); and

    a controller (46) connected to the circuit and being programmed to control the circuit so as to cause each of the plurality of line-side switches (22, 24, 26) and each of the plurality of floating-neutral side switches (28, 30, 32) to switch between an On condition or an Off condition to selectively operate the circuit in an active mode and a free-wheeling mode, with a full phase voltage being provided to the load terminals (38) during the active mode and a zero voltage being provided to the load terminals (38) during the free-wheeling mode;
    wherein, in controlling the circuit, the controller (46) is programmed to apply a modulating function to the circuit, so as to modulate the supply voltage to control a frequency and an average of a load voltage present across the load terminals (38) of the AC load (10), thereby enabling variable frequency operation of the AC load (10).

2. The load control device (20) of claim 1 wherein, in applying the modulating function, the controller (46) is programmed to implement a duty cycle function that is a continuous function of time, the duty cycle function comprising a sine function.

3. The load control device (20) of claim 2 wherein, in applying the duty cycle function, the controller causes a voltage waveform to be generated across the load terminals (38) having a plurality of frequencies, so as to excite the AC load (10) with three rotating fields.

4. The load control device (20) of claim 3 wherein the plurality of frequencies of the voltage waveform comprises a first frequency that is equal to the supply frequency, a second frequency that is less than the supply frequency, and a third frequency that is greater than the supply frequency, and
wherein the voltage waveform comprising at least the first frequency, second frequency, and third frequency is described as:

$$V_{mach,ave}(t) = \frac{d}{2}V\left[\frac{1}{2}\cos(2\pi f_{out}t + \phi) - \frac{1}{2}\cos(2\pi(2f_g - f_{out})t + \phi) + \sin(2\pi f_g t)\right],$$

where d is a duty cycle constant, V is the supply voltage, f_g is the supply frequency, f_{out} is the desired load frequency, and ϕ is the desired phase of the load voltage.

5. The load control device (20) of claim 1 wherein, in applying the modulating function, the controller (46) is programmed to apply a pulse skipping modulating function where the circuit is operated in active mode for part of one supply frequency cycle and is operated in free-wheeling mode for one or more skipped supply frequency cycles.

6. The load control device of claim 5 wherein applying the pulse skipping modulating function results in a fundamental frequency at the load terminals (38) of:

$$f_{out} = \frac{f_g}{n},$$

where f_g is the supply voltage frequency and n is the number of cycles skipped plus one.

7. The load control device (20) of claim 5 wherein, in applying the pulse skipping modulating function, a duty cycle function defined as:

$$D(t) = d \quad \text{if} \quad 0 < t < \frac{\lambda}{60}$$

$$D(t) = d \quad \text{if} \quad \frac{1}{3}\frac{n}{60} < t < \frac{1}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = d \quad \text{if} \quad \frac{2}{3}\frac{n}{60} < t < \frac{2}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = 0 \quad \text{otherwise, within the time bracket } 0 < t < \frac{n}{60},$$

where d is a duty cycle constant comprising a real number between 0 and 1, λ is a conduction duration comprising a real number between 0 and 0.5, and n corresponds to the desired drive speed.

8. The load control device (20) of claim 7 wherein the controller (46) is programmed to control the conduction duration λ and the duty cycle constant d to achieve a desired average load voltage at the load terminals (38).

9. The load control device (20) of claim 8 wherein the conduction duration λ is equal to 0.5 and the controller (46) is programmed to control the duty cycle constant d to achieve a desired average load voltage at the load terminals (38).

10. The load control device (20) of claim 5 wherein, in applying the pulse skipping modulating function, the controller is programmed to cause the circuit to chop the supply voltage at a higher frequency than the frequency of the supply frequency and at a constant duty cycle during operation in the active mode.

11. The load control device (20) of claim 10 wherein the supply voltage chopping frequency is a multiple of 6 times the supply frequency.

12. A method for controlling operation of an AC load comprising:

          providing a supply voltage from an AC power source (12a, 12b, 12c) to an AC load (10), the supply voltage having a supply frequency;
          providing a circuit in series between the AC power source (12a, 12b, 12c) and the AC load (10) to condition the supply voltage, the circuit comprising a plurality of switches forming a group of line-side switches (22, 24, 26) connected to supply lines (14, 16, 18) between line terminals (36) of the AC power source (12a, 12b, 12c) and load terminals (38) of the AC load (10) and a group of floating-neutral side switches (28, 30, 32) connected to the supply lines (14, 16, 18) at one end and together at a common connection at another end, with only one line-side switch (22, 24, 26) and only one floating-neutral side switch (28, 30, 32) being provided per phase (A, B, C); and
          selectively operating the circuit in an active mode and a free-wheeling mode so as to selectively provide a full phase voltage to the load terminals (38) during the active mode and a zero voltage to the load terminals (38) during the free-wheeling mode of operation;
          wherein operating the circuit further comprises controlling a duty cycle of the circuit so as to control an average voltage to be applied to the AC load (10), with the duty cycle comprising a ratio of a time of circuit operation in the active mode to a total time of circuit operation; and
          wherein the duty cycle of the circuit is controlled by applying a voltage modulating periodic function to the circuit, so as to modulate a frequency of a load voltage present across the load terminals (38) of the AC load (10) and enable variable speed operation of the AC load (10).

13. The method of claim 12 further comprising causing a voltage waveform to be generated across the load terminals (38) having a plurality of frequencies, so as to excite the AC load (10) with a plurality of rotating fields, the plurality of frequencies of the voltage waveform comprising at least a first frequency that is equal to the supply frequency, a second frequency that is less than the supply frequency, and a third frequency that is greater than the supply frequency;
wherein the voltage waveform comprising at least the first frequency, second frequency, and third frequency is described as:

$$V_{mach,ave}(t) = \frac{d}{2}V\left[\frac{1}{2}\cos(2\pi f_{out}t + \phi) - \frac{1}{2}\cos\left(2\pi\left(2f_g - f_{out}\right)t + \phi\right) + \sin\left(2\pi f_g t\right)\right],$$

where d is a duty cycle constant, V is the supply voltage, f_g is the supply frequency, f_{out} is the desired load frequency, and ϕ is the desired phase of the load voltage.

14. The method of claim 12 wherein applying the voltage modulating periodic function comprises applying a pulse skipping modulating function where the circuit is operated in active mode for part of one supply voltage frequency cycle and is operated in free-wheeling mode for one or more skipped supply voltage frequency cycles.

15. The method of claim 12 wherein applying the pulse skipping modulating function further comprises defining a duty cycle function as:

$$D(t) = d \quad \text{if} \quad 0 < t < \frac{\lambda}{60}$$

$$D(t) = d \quad \text{if} \quad \frac{1}{3}\frac{n}{60} < t < \frac{1}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = d \quad \text{if} \quad \frac{2}{3}\frac{n}{60} < t < \frac{2}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = 0 \quad \text{otherwise, within the time bracket } 0 < t < \frac{n}{60} \; ,$$

where d is a duty cycle constant comprising a real number between 0 and 1, λ is a conduction duration comprising a real number between 0 and 0.5, and n corresponds to the desired drive speed, and wherein the conduction duration λ and the duty cycle constant d are controlled to achieve a desired average load voltage at the load terminals (38).

Patentansprüche

1. Laststeuervorrichtung (20) zum Steuern des Stromflusses zu einer Wechselstromlast (10), wobei die Laststeuer-vorrichtung (20) Folgendes aufweist:

    eine Schaltung, die Folgendes aufweist:

        einen Eingang, der mit Leitungsanschlüssen (36) einer Wechselstromquelle (12a, 12b, 12c) verbindbar ist, um eine Versorgungsspannung davon zu empfangen, wobei die Versorgungsspannung eine Versorgungs-frequenz aufweist;
        einen Ausgang, der mit den Lastanschlüssen (38) der Wechselstromlast (10) verbindbar ist;
        Versorgungsleitungen (14, 16, 18), die den Eingang und Ausgang verbinden, um Leistung von der Wech-selstromquelle (12a, 12b, 12c) an die Wechselstromlast (10) zu übertragen, wobei jede Versorgungsleitung (14, 16, 18) einer Phase (A, B, C) in der Wechselstromlast (10) entspricht;
        eine Vielzahl von leitungs- bzw. netzseitigen Schaltern (22, 24, 26), die zwischen den Leitungsanschlüssen (36) und den Lastanschlüssen (38) verbunden sind, so dass nur ein leitungsseitiger Schalter (22, 24, 26) für jede Phase (A, B, C) und ihre jeweilige Versorgungsleitung (14, 16, 18) vorgesehen ist; und
        eine Vielzahl von potentialfreiseitigen Schaltern (28, 30, 32), die an einem Ende mit den Lastanschlüssen (38) und zusammen an einer gemeinsamen Verbindung an einem anderen Ende verbunden sind, so dass für jede Phase (A, B, C) und ihre jeweilige Zuleitung (14, 16, 18) nur ein potentialfreiseitiger Schalter (28, 30, 32) vorgesehen ist; und

    eine Steuerung (46), die mit der Schaltung verbunden und programmiert ist, um die Schaltung so zu steuern, dass jeder der Vielzahl von leitungsseitigen Schaltern (22, 24, 26) und jeder der Vielzahl von potentialfreiseitigen Schaltern (28, 30, 32) zwischen einem An-Zustand oder einem Aus-Zustand zum selektiven Betreiben der Schaltung in einem aktiven Modus und einem Freilaufmodus umschaltet, wobei den Lastanschlüssen (38) während des aktiven Modus eine Vollphasenspannung und den Lastanschlüssen (38) während des Freilauf-modus eine Nullspannung zugeführt wird;
    wobei bei der Steuerung der Schaltung die Steuerung (46) programmiert ist, um eine Modulationsfunktion an die Schaltung anzulegen, um die Versorgungsspannung zu modulieren, um eine Frequenz und einen Mittelwert einer Lastspannung zu steuern, die über den Lastanschlüssen (38) der Wechselstromlast (10) vorhanden ist, wodurch ein Betrieb mit variabler Frequenz der Wechselstromlast (10) ermöglicht wird.

2. Laststeuervorrichtung (20) nach Anspruch 1, wobei die Steuerung (46) beim Anlegen der Modulationsfunktion pro-grammiert ist, um eine Tastverhältnisfunktion zu implementieren, die eine kontinuierliche Funktion der Zeit ist, wobei die Tastverhältnisfunktion eine Sinusfunktion aufweist.

3. Laststeuervorrichtung (20) nach Anspruch 2, wobei die Steuerung beim Anlegen der Tastverhältnisfunktion bewirkt, dass eine Spannungswellenform über den Lastanschlüssen (38) mit einer Vielzahl von Frequenzen erzeugt wird, um die Wechselstromlast (10) mit drei Drehstromfeldern zu erregen.

4. Laststeuervorrichtung (20) nach Anspruch 3, wobei die Vielzahl von Frequenzen der Spannungswellenform eine erste Frequenz, die gleich der Versorgungsfrequenz ist, eine zweite Frequenz, die kleiner als die Versorgungsfre-quenz ist, und eine dritte Frequenz, die größer als die Versorgungsfrequenz ist, aufweist, und wobei die Spannungswellenform, die wenigstens die erste Frequenz, die zweite Frequenz und die dritte Frequenz

aufweist, beschrieben wird als:

$$V_{mach,ave}(t) = \frac{d}{2}V\left[\frac{1}{2}\cos(2\pi f_{out}t + \phi) - \frac{1}{2}\cos\left(2\pi\left(2f_g - f_{out}\right)t + \phi\right) + \sin\left(2\pi f_g t\right)\right],$$

wobei d eine Tastverhältniskonstante ist, V die Versorgungsspannung ist, f_g die Versorgungsfrequenz ist, f_{out} die gewünschte Lastfrequenz ist und ϕ die gewünschte Phase der Lastspannung ist.

5. Laststeuervorrichtung (20) nach Anspruch 1, wobei die Steuerung (46) beim Anlegen der Modulationsfunktion programmiert ist, um eine Impulssprung-Modulationsfunktion anzuwenden, wobei die Schaltung für einen Teil eines Versorgungsfrequenzzyklus im aktiven Modus betrieben wird und für einen oder mehrere übersprungene Versorgungsfrequenzzyklen im Freilaufmodus betrieben wird.

6. Laststeuervorrichtung nach Anspruch 5, wobei das Anlegen der Impulssprung-Modulationsfunktion in einer Grundfrequenz resultiert an den Lastanschlüssen (38) von:

$$f_{out} = \frac{f_g}{n},$$

wobei f_g die Frequenz der Versorgungsspannung und n die Anzahl der übersprungenen Zyklen plus eins ist.

7. Laststeuervorrichtung (20) nach Anspruch 5, wobei beim Anlegen der Impulssprung-Modulationsfunktion eine Tastverhältnisfunktion definiert ist als:

$$D(t) = d \quad \text{if} \quad 0 < t < \frac{\lambda}{60}$$

$$D(t) = d \quad \text{if} \quad \frac{1}{3}\frac{n}{60} < t < \frac{1}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = d \quad \text{if} \quad \frac{2}{3}\frac{n}{60} < t < \frac{2}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = 0 \quad \text{ansonsten innerhalb der Zeitspanne} \quad 0 < t < \frac{n}{60} \quad ,$$

wobei d eine Tastverhältniskonstante mit einer reellen Zahl zwischen 0 und 1 ist, λ eine Leitungsdauer mit einer reellen Zahl zwischen 0 und 0,5 ist und n der gewünschten Ansteuergeschwindigkeit entspricht.

8. Laststeuervorrichtung (20) nach Anspruch 7, wobei die Steuerung (46) programmiert ist, um die Leitungsdauer λ und die Tastverhältniskonstante d zu steuern, um eine gewünschte durchschnittliche Lastspannung an den Lastanschlüssen (38) zu erreichen.

9. Laststeuervorrichtung (20) nach Anspruch 8, wobei die Leitungsdauer λ gleich 0,5 ist und die Steuerung (46) programmiert ist, um die Tastverhältniskonstante d zu steuern, um eine gewünschte durchschnittliche Lastspannung an den Lastanschlüssen (38) zu erreichen.

10. Laststeuervorrichtung (20) nach Anspruch 5, wobei die Steuerung beim Anlegen der Impulssprung-Modulationsfunktion programmiert ist, um zu bewirken, dass die Schaltung die Versorgungsspannung bei einer höheren Frequenz als der Frequenz der Versorgungsfrequenz und bei einer konstanten Tastverhältnis während des Betriebs im aktiven Modus begrenzt.

11. Laststeuervorrichtung (20) nach Anspruch 10, wobei die Begrenzungsfrequenz der Versorgungsspannung ein Vielfaches des 6-fachen der Versorgungsfrequenz ist.

12. Verfahren zum Steuern des Betriebs einer Wechselstromlast, das Folgendes aufweist:

Vorsehen einer Versorgungsspannung von einer Wechselstromquelle (12a, 12b, 12c) zu einer Wechselstromlast (10), wobei die Versorgungsspannung eine Versorgungsfrequenz aufweist;
Vorsehen einer Schaltung in Reihe zwischen der Wechselstromquelle (12a, 12b, 12c) und der Wechselstromlast (10) zum Konditionieren der Versorgungsspannung, wobei die Schaltung eine Vielzahl von Schaltern aufweist, die eine Gruppe von leitungsseitigen Schaltern (22, 24, 26) bildet, die mit Versorgungsleitungen (14, 16, 18) zwischen Leitungsanschlüssen (36) der Wechselstromquelle (12a, 12b, 12c) und Lastanschlüssen (38) der Wechselstromlast (10) verbunden sind, und einer Gruppe von potentialfreiseitigen Schaltern (28, 30, 32), die an einem Ende mit den Versorgungsleitungen (14, 16, 18) und zusammen an einem gemeinsamen Anschluss an einem anderen Ende verbunden sind, wobei pro Phase (A, B, C) nur ein leitungsseitiger Schalter (22, 24, 26) und nur ein potentialfreiseitiger Schalter (28, 30, 32) vorgesehen sind; und
selektives Betreiben der Schaltung in einem aktiven Modus und einem Freilaufmodus, um selektiv eine Vollphasenspannung an die Lastanschlüsse (38) während des aktiven Modus und eine Nullspannung an die Lastanschlüsse (38) während des Freilaufbetriebs vorzusehen;
wobei das Betreiben der Schaltung ferner das Steuern einer Tastverhältnis der Schaltung aufweist, um eine durchschnittliche Spannung zu steuern, die an die Wechselstromlast (10) anzulegen ist, wobei das Tastverhältnisverhältnis ein Verhältnis von einer Zeit des Schaltungsbetriebs im aktiven Modus zu einer Gesamtzeit des Schaltungsbetriebs aufweist; und
wobei die Tastverhältnis der Schaltung durch Anlegen einer spannungsmodulierenden periodischen Funktion an die Schaltung gesteuert wird, um eine Frequenz einer Lastspannung zu modulieren, die über den Lastanschlüssen (38) der Wechselstromlast (10) vorhanden ist, und einen Betrieb mit variabler Geschwindigkeit der Wechselstromlast (10) zu ermöglichen.

13. Verfahren nach Anspruch 12, das ferner das Erzeugen einer Spannungswellenform über den Lastanschlüssen (38) mit einer Vielzahl von Frequenzen aufweist, um die Wechselstromlast (10) mit einer Vielzahl von Drehstromfeldern anzuregen, wobei die Vielzahl von Frequenzen der Spannungswellenform wenigstens eine erste Frequenz aufweist, die gleich der Versorgungsfrequenz ist, eine zweite Frequenz, die kleiner als die Versorgungsfrequenz ist, und eine dritte Frequenz, die größer als die Versorgungsfrequenz ist;
wobei die Spannungswellenform, die wenigstens die erste Frequenz, die zweite Frequenz und die dritte Frequenz umfasst, beschrieben wird als:

$$V_{mach,ave}(t) = \frac{d}{2} V \left[\frac{1}{2} \cos\left(2\pi f_{out} t + \phi\right) - \frac{1}{2} \cos\left(2\pi \left(2 f_g - f_{out}\right) t + \phi\right) + \sin\left(2\pi f_g t\right) \right],$$

wobei d eine Tastverhältniskonstante ist, V die Versorgungsspannung ist, f_g die Versorgungsfrequenz ist, f_{out} die gewünschte Lastfrequenz ist und ϕ die gewünschte Phase der Lastspannung ist.

14. Verfahren nach Anspruch 12, wobei das Anlegen der spannungsmodulierenden periodischen Funktion das Anlegen einer Impulssprung-Modulationsfunktion aufweist, wobei die Schaltung im aktiven Modus für einen Teil eines Versorgungsspannungs-Frequenzzyklus betrieben wird und im Freilaufmodus für einen oder mehrere übersprungene Versorgungsspannungs-Frequenzzyklen betrieben wird.

15. Verfahren nach Anspruch 12, wobei das Anlegen der Impulssprung-Modulationsfunktion ferner das Definieren einer Tastverhältnisfunktion aufweist als:

$$D(t) = d \quad \text{if} \quad 0 < t < \frac{\lambda}{60}$$

$$D(t) = d \quad \text{if} \quad \frac{1}{3}\frac{n}{60} < t < \frac{1}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = d \quad \text{if} \quad \frac{2}{3}\frac{n}{60} < t < \frac{2}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = 0 \quad \text{ansonsten innerhalb der Zeitspanne} \quad 0 < t < \frac{n}{60} \quad ,$$

wobei d eine Tastverhältniskonstante ist, die eine reelle Zahl zwischen 0 und 1 aufweist, λ eine Leitungsdauer ist, die eine reelle Zahl zwischen 0 und 0,5 aufweist, und n der gewünschten Ansteuergeschwindigkeit entspricht, und wobei die Leitungsdauer λ und die Tastverhältniskonstante d gesteuert werden, um eine gewünschte durchschnittliche Lastspannung an den Lastanschlüssen (38) zu erreichen.

Revendications

1. Dispositif de contrôle de charge (20) pour contrôler le flux de courant vers une charge alternative (10), le dispositif de contrôle de charge (20) comprenant :

   un circuit comprenant :

   une entrée pouvant être connectée à des bornes de ligne (36) d'une source de courant alternative (12a, 12b, 12c) afin de recevoir une tension d'alimentation provenant de celle-ci, la tension d'alimentation ayant une fréquence d'alimentation ;
   une sortie pouvant être connectée à des bornes de charge (38) de la charge alternative (10) ;
   des lignes d'alimentation (14, 16, 18) connectant les entrée et sortie pour transmettre de l'énergie de la source de courant alternatif (12a, 12b, 12c) à la charge alternative (10), chaque ligne d'alimentation (14, 16, 18) correspondant à une phase (A, B, C) de la charge alternative (10) ;
   une pluralité de commutateurs côté ligne (22, 24, 26) connectés entre les bornes de ligne (36) et les bornes de charge (38), de sorte que chaque phase (A, B, C) et sa ligne d'alimentation correspondante (14, 16, 18) comprend un seul seuil commutateur côté ligne (22, 24, 26) ; et
   une pluralité de commutateurs côté neutre flottant (28, 30, 32) connectés aux bornes de charge (38) à une extrémité et ensemble à une connexion commune à une autre extrémité, de sorte que chaque phase (A, B, C) et sa ligne d'alimentation correspondante (14, 16, 18) comprend un seul commutateur côté neutre flottant (28, 30, 32) ; et
   un contrôleur (46) connecté au circuit et programmé pour commander le circuit de manière à amener chacun de la pluralité de commutateurs côté ligne (22, 24, 26) et chacun de la pluralité de commutateurs côté neutre flottant (28, 30, 32) à commuter entre une condition fermée et une condition ouverte pour faire fonctionner de manière sélective le circuit en mode actif et en mode de roue libre, une tension de phase complète étant fournie aux bornes de charge (38) pendant le mode actif et une tension nulle étant fournie aux bornes de charge (38) pendant le mode de roue libre ;

   dans lequel, lors du contrôle du circuit, le contrôleur (46) est programmé pour appliquer une fonction de modulation au circuit, de manière à moduler la tension d'alimentation afin de contrôler une fréquence et une moyenne d'une tension de charge présente aux bornes de charge (38) de la charge alternative (10), permettant ainsi un fonctionnement à fréquence variable de la charge alternative (10).

2. Dispositif de commande de charge (20) selon la revendication 1, dans lequel, dans l'application de la fonction de modulation, le contrôleur (46) est programmé pour mettre en oeuvre une fonction de rapport cyclique qui est une fonction continue dans le temps, la fonction de rapport cyclique comprenant une fonction sinusoïdale.

3. Dispositif de commande de charge (20) selon la revendication 2, dans lequel, dans l'application de la fonction de rapport cyclique, le contrôleur provoque la génération d'une forme d'onde de tension aux bornes de charge (38) ayant une pluralité de fréquences, de manière à exciter la charge alternative (10) avec trois champs tournants.

4. Dispositif de commande de charge (20) selon la revendication 3, dans lequel la pluralité de fréquences de la forme d'onde de tension comprend une première fréquence qui est égale à la fréquence d'alimentation, une deuxième fréquence qui est inférieure à la fréquence d'alimentation et une troisième fréquence qui est supérieure à la fréquence

d'alimentation, et

dans lequel la forme d'onde de tension, comprenant au moins la première fréquence, la deuxième fréquence et la troisième fréquence, est décrite comme suit :

$$V_{mach,ave}(t) = \frac{d}{2} V \left[\frac{1}{2} cos(2\pi f_{out} t + \phi) - \frac{1}{2} cos(2\pi (2f_g - f_{out})t + \phi) + sin(2\pi f_g t) \right] \ ,$$

où d est une constante de rapport cyclique, V est la tension d'alimentation, f_g est la fréquence d'alimentation, f_{out} est la fréquence de charge souhaitée et • est la phase souhaitée de la tension de charge.

5. Dispositif de commande de charge (20) selon la revendication 1, dans lequel, dans l'application de la fonction de modulation, le contrôleur (46) est programmé pour appliquer une fonction de modulation par saut d'impulsion, le circuit fonctionnant en mode actif pendant une partie d'un cycle de fréquence d'alimentation et en mode de roue libre pendant un ou plusieurs cycles de fréquence d'alimentation sautés.

6. Dispositif de commande de charge selon la revendication 5, dans lequel l'application de la fonction de modulation par saut d'impulsion donne une fréquence fondamentale aux bornes de charge (38) de :

$$f_{out} = \frac{f_g}{n} \ ,$$

où f_g est la fréquence de tension d'alimentation et n est le nombre de cycles sautés plus un.

7. Dispositif de commande de charge (20) selon la revendication 5, dans lequel, dans l'application de la fonction de modulation par saut d'impulsion, une fonction de rapport cyclique est définie comme suit :

$$D(t) = d \quad si \quad 0 < t < \frac{\lambda}{60}$$

$$D(t) = d \quad si \quad \frac{1}{3}\frac{n}{60} < t < \frac{1}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = d \quad si \quad \frac{2}{3}\frac{n}{60} < t < \frac{2}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = 0 \quad autrement, dans\ l'intervalle\ de\ temps \quad 0 < t < \frac{n}{60} \ ,$$

où d est une constante de rapport cyclique comprenant un nombre réel compris entre 0 et 1, • est une durée de conduction comprenant un nombre réel compris entre 0 et 0,5, et n correspond à la vitesse de commande souhaitée.

8. Dispositif de commande de charge (20) selon la revendication 7, dans lequel le contrôleur (46) est programmé pour commander la durée de conduction • et la constante de rapport cyclique d afin d'obtenir une tension de charge moyenne souhaitée aux bornes de charge (38).

9. Dispositif de commande de charge (20) selon la revendication 8, dans lequel la durée de conduction • est égale à 0,5 et le contrôleur (46) est programmé pour commander la constante de rapport cyclique d afin d'obtenir une tension de charge moyenne souhaitée aux bornes de charge (38).

10. Dispositif de commande de charge (20) selon la revendication 5, dans lequel, dans l'application de la fonction de modulation par saut d'impulsion, le contrôleur est programmé pour amener le circuit à découper la tension d'alimentation à une fréquence supérieure à la fréquence de la fréquence d'alimentation et à un rapport cyclique constant pendant le fonctionnement en mode actif.

11. Dispositif de commande de charge (20) selon la revendication 10, dans lequel la fréquence de découpage de la tension d'alimentation est un multiple de 6 fois la fréquence d'alimentation.

12. Procédé de commande du fonctionnement d'une charge alternative comprenant les étapes consistant à :

fournir une tension d'alimentation provenant d'une source d'alimentation en courant alternatif (12a, 12b, 12c) à une charge alternative (10), la tension d'alimentation ayant une fréquence d'alimentation ;
amener un circuit, en série entre la source d'alimentation en courant alternatif (12a, 12b, 12c) et la charge alternative (10), à conditionner la tension d'alimentation, le circuit comprenant une pluralité de commutateurs formant un groupe de commutateurs côté ligne (22, 24, 26), connectés à des lignes d'alimentation (14, 16, 18) entre des bornes de ligne (36) de la source d'alimentation en courant alternatif (12a, 12b, 12c) et des bornes de charge (38) de la charge alternative (10), et un groupe de commutateurs côté neutre flottant (28, 30, 32) connectés aux lignes d'alimentation (14, 16, 18) à une extrémité et ensemble à une connexion commune à une autre extrémité, un seul commutateur côté ligne (22, 24, 26) et un seul commutateur côté neutre flottant (28, 30, 32) étant prévus par phase (A, B, C) ; et
faire fonctionner sélectivement le circuit dans un mode actif et dans un mode de roue libre de manière à fournir sélectivement une tension de phase complète aux bornes de charge (38) pendant le mode actif et une tension nulle aux bornes de charge (38) pendant le mode de fonctionnement en roue libre ;
dans lequel le fonctionnement du circuit comprend en outre la commande d'un rapport cyclique du circuit de manière à commander une tension moyenne à appliquer à la charge alternative (10), le rapport cyclique comprenant un rapport d'un temps de fonctionnement du circuit en mode actif sur un temps total de fonctionnement du circuit ; et
dans lequel le rapport cyclique du circuit est commandé en appliquant une fonction périodique de modulation de tension au circuit, de manière à moduler une fréquence d'une tension de charge présente aux bornes de charge (38) de la charge alternative (10) et à permettre un fonctionnement à vitesse variable de la charge alternative (10).

13. Procédé selon la revendication 12, comprenant en outre le fait de provoquer la génération d'une forme d'onde de tension ayant une pluralité de fréquences aux bornes de charge (38), de manière à exciter la charge alternative (10) avec une pluralité de champs rotatifs, la pluralité de fréquences de la forme d'onde de tension comprenant au moins une première fréquence qui est égale à la fréquence d'alimentation, une deuxième fréquence qui est inférieure à la fréquence d'alimentation et une troisième fréquence qui est supérieure à la fréquence d'alimentation ;
dans lequel la forme d'onde de tension comprenant au moins la première fréquence, la deuxième fréquence et la troisième fréquence est décrite comme suit :

$$V_{mach,ave}(t) = \frac{d}{2}V\left[\frac{1}{2}cos(2\pi f_{out}t + \phi) - \frac{1}{2}cos\left(2\pi(2f_g - f_{out})t + \phi\right) + sin\left(2\pi f_g t\right)\right] ,$$

où d est une constante de rapport cyclique, V est la tension d'alimentation, f_g est la fréquence d'alimentation, f_{out} est la fréquence de charge souhaitée et • est la phase souhaitée de la tension de charge.

14. Procédé selon la revendication 12, dans lequel l'application de la fonction périodique de modulation de tension comprend l'application d'une fonction de modulation par saut d'impulsion, le circuit fonctionnant en mode actif pendant une partie d'un cycle de fréquence de tension d'alimentation et fonctionnant en mode de roue libre pendant un ou plusieurs cycles de fréquence de tension d'alimentation sautés.

15. Procédé selon la revendication 12, dans lequel l'application de la fonction de modulation par saut d'impulsion comprend en outre la définition d'une fonction de rapport cyclique comme suit :

$$D(t) = d \quad si \quad 0 < t < \frac{\lambda}{60}$$

$$D(t) = d \quad si \quad \frac{1}{3}\frac{n}{60} < t < \frac{1}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = d \quad si \quad \frac{2}{3}\frac{n}{60} < t < \frac{2}{3}\frac{n}{60} + \frac{\lambda}{60}$$

$$D(t) = 0 \quad autrement, dans\ l'intervalle\ de\ temps \quad 0 < t < \frac{n}{60},$$

où d est une constante de rapport cyclique comprenant un nombre réel compris entre 0 et 1, • est une durée de conduction comprenant un nombre réel compris entre 0 et 0,5, et n correspond à la vitesse de commande souhaitée, et dans lequel la durée de conduction • et la constante de rapport cyclique d sont commandées pour atteindre une tension de charge moyenne souhaitée aux bornes de charge (38).
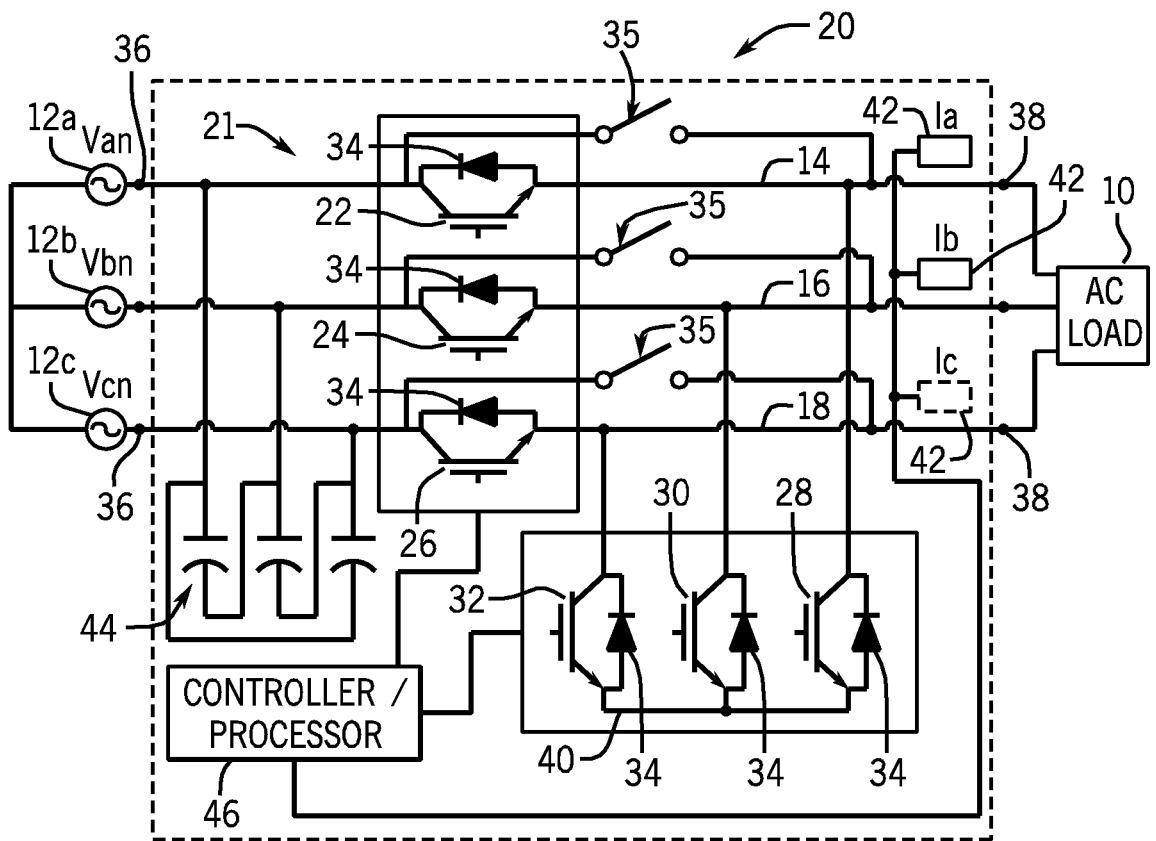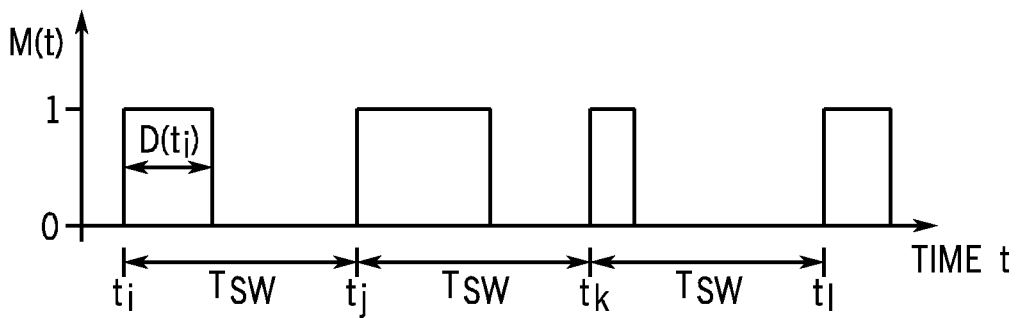
FIG. 1

FIG. 3

CASE	SUB-CASE	Ia	Ib	Ic	IGBT 22	IGBT 24	IGBT 26	IGBT 28	IGBT 30	IGBT 32	Va, Vb, Vc (V ACROSS MACHINE TERMINALS)
U	U1	POSITIVE +	NEGATIVE –	NEGATIVE –	ON	OFF	OFF	OFF	OFF	OFF	LINE VOLTAGE
	U2	POSITIVE +	NEGATIVE –	NEGATIVE –	OFF	OFF	OFF	OFF	ON	ON	0
V	V1	POSITIVE +	POSITIVE +	NEGATIVE –	ON	ON	OFF	OFF	OFF	OFF	LINE VOLTAGE
	V2	POSITIVE +	POSITIVE +	NEGATIVE –	OFF	OFF	OFF	OFF	OFF	ON	0
W	W1	NEGATIVE –	POSITIVE +	NEGATIVE –	OFF	ON	OFF	OFF	OFF	OFF	LINE VOLTAGE
	W2	NEGATIVE	POSITIVE +	NEGATIVE –	OFF	OFF	OFF	ON	OFF	ON	0
U'	U'1	NEGATIVE	POSITIVE +	POSITIVE +	OFF	ON	ON	OFF	OFF	OFF	LINE VOLTAGE
	U'2	NEGATIVE	POSITIVE +	POSITIVE +	OFF	OFF	ON	ON	OFF	OFF	0
V'	V'1	NEGATIVE	NEGATIVE –	POSITIVE +	OFF	OFF	ON	OFF	OFF	OFF	LINE VOLTAGE
	V'2	NEGATIVE	NEGATIVE –	POSITIVE +	OFF	OFF	OFF	ON	ON	OFF	0
W'	W'1	POSITIVE +	NEGATIVE –	POSITIVE +	ON	OFF	ON	OFF	OFF	OFF	LINE VOLTAGE
	W'2	POSITIVE +	NEGATIVE –	POSITIVE +	OFF	OFF	OFF	OFF	ON	OFF	0

FIG. 2

FIG. 4

60 Hz PERIOD   15 Hz PERIOD

Vmach

500

Vab

0

Vbc   58

-500

Vca

0   20   40   60   80   100
                T(ms)

CONDUCTION FOR 180° OF
60 Hz CYCLE (λ=.5)

FIG. 5A

Vab   60 Hz PERIOD   15 Hz PERIOD

Vmach

1K

0.5K

Vbc

0

Vca

-0.5K

-1K

0   20   40
        T(ms)

FIG. 5B   58   CONDUCTION FOR 180° OF
                60 Hz CYCLE (λ=.5)

Vab   Vbc   Vca

Vmach

500

0

-500

58

20   40   60   80
            T(ms)
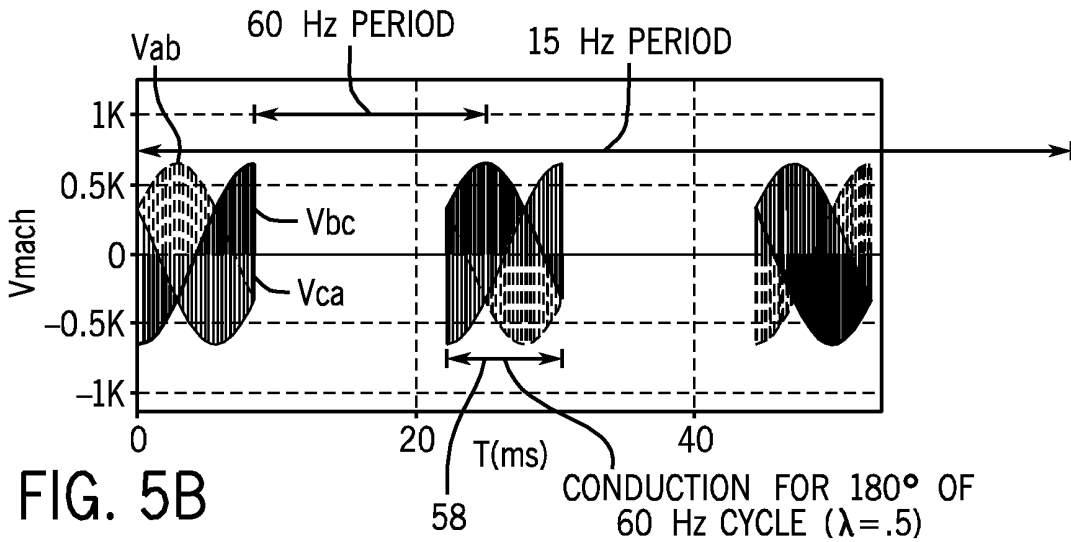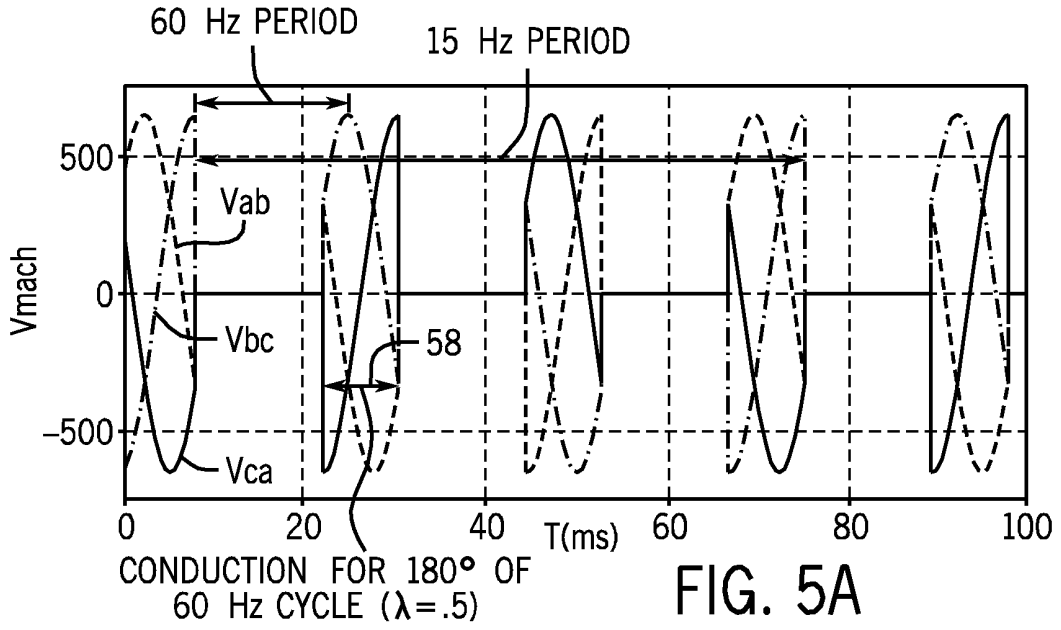
CONDUCTION FOR 45° OF   FIG. 5C
60 Hz CYCLE (λ=.125)
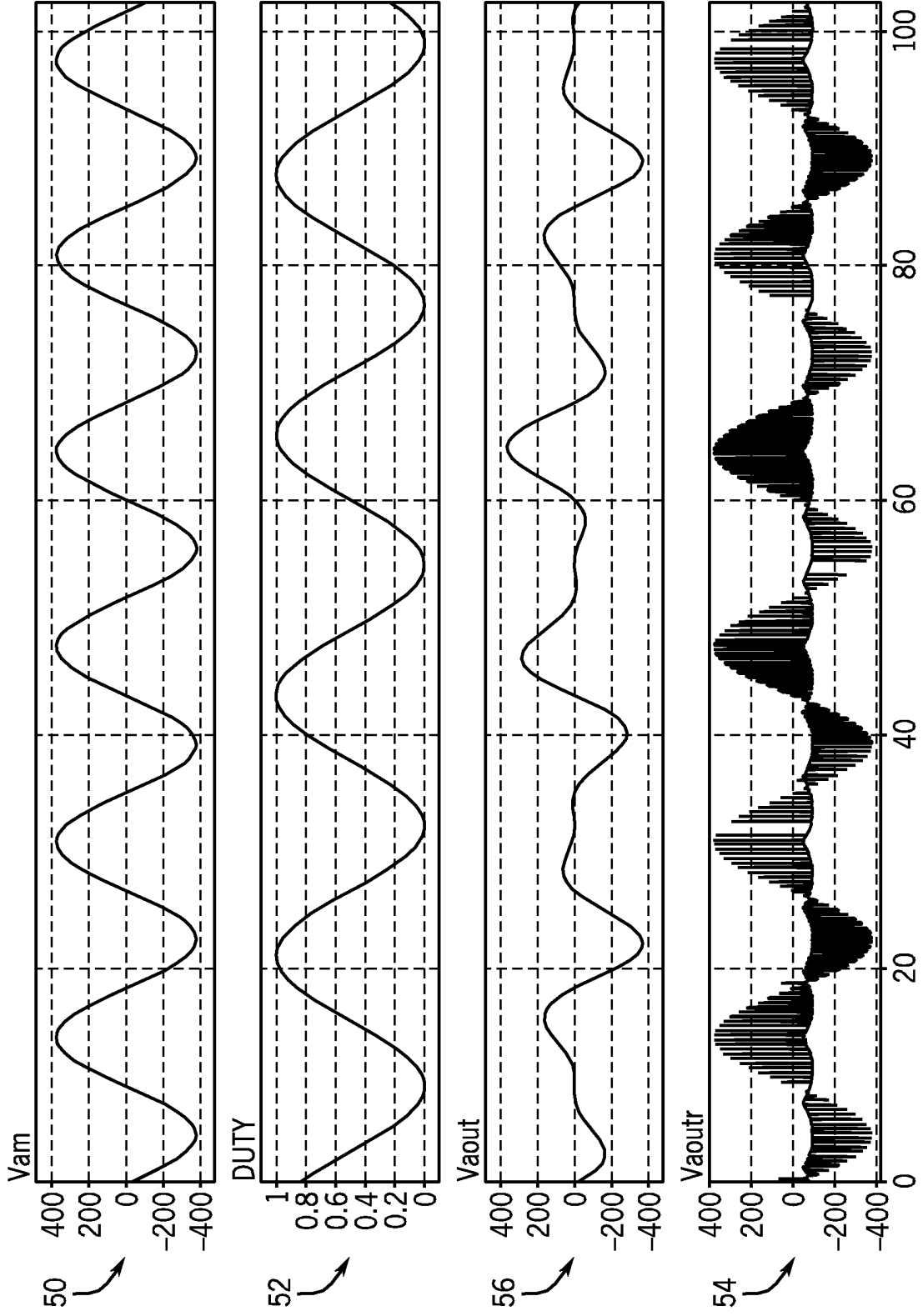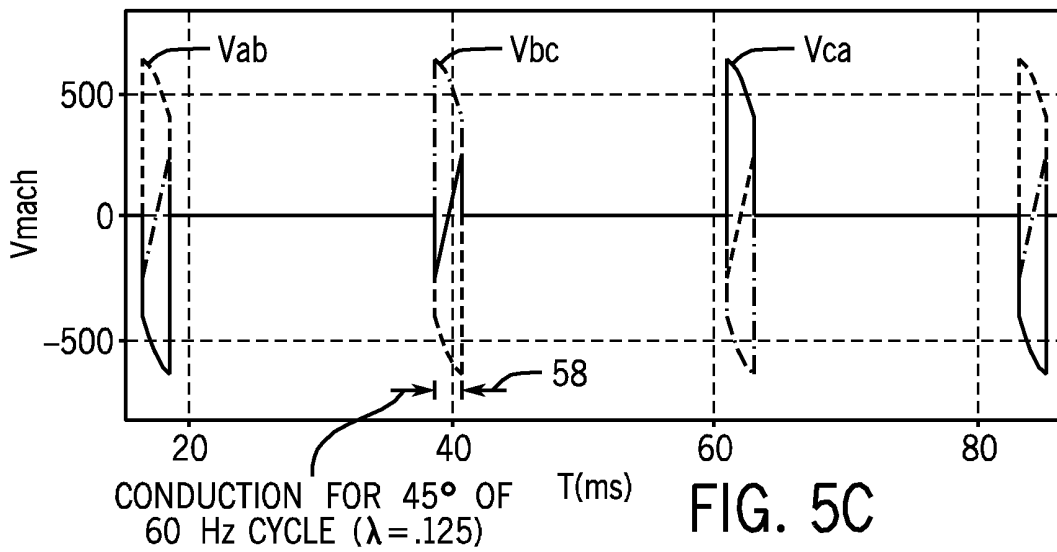
REFERENCES CITED IN THE DESCRIPTION

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