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(71) Applicant: CENTER FOR INNOVATIVE TECHNOLOGY [US/US]; Suite 600, CIT Tower, 2214 Rock Hill Road, Herndon, VA 22070 (US).

(72) Inventors: LEE, Fred, C.; 2909 Stradford Lane, Blacksburg, VA 24061 (US). JIANG, Yimin; 214 Dogwood Drive, Plano, TX 75075 (US).

(74) Agent: REIF, Kevin, A.; Whitham, Curtis, Whitham & McGinn, Suite 900, 11800 Sunrise Valley Drive, Reston, VA 22091 (US).

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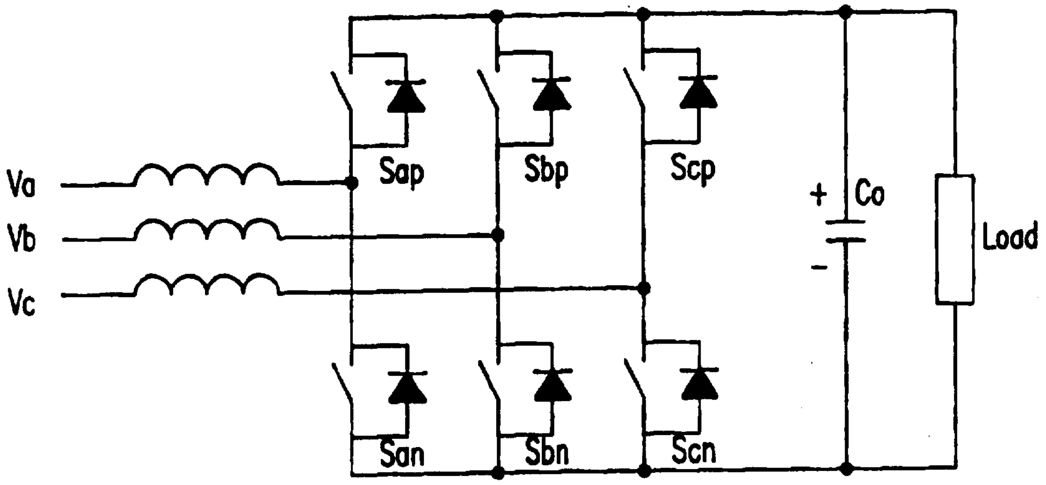

(57) Abstract

A boost rectifier is provided with an ultra high speed diode (D) in its direct current rail to reduce diode reverse recovery loss with or without implementing a soft switching technique. Full zero-voltage-transition (ZVT) as well as zero-current transition (ZCT) may also be achieved by adding a simple auxiliary network (Lr, Daux, Saux) across the DC rail which operates only during the short turn-on transients of the bridge switches (Sap-Scn). Similarly, a simple, inexpensive auxiliary circuit can be added to the DC rail of a conventional voltage source inverter shown to implement both ZVT and ZCT.

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NOVEL SOFT SWITCHED THREE-PHASE BOOST RECTIFIERS AND VOLTAGE SOURCE INVERTERS

DESCRIPTION

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention generally relates to soft switched three-phase converters and, more particularly, to three-phase rectifiers and inverters having improvements made to the DC rail side of the converter for improving performance, reliability and power factor correction (PFC).

Description of the Prior Art

Conventional diode and thyristor bridge rectifiers create strong harmonic currents which can pollute public utility networks. In an effort to protect utility quality, legislation has been proposed limiting rectifier harmonic output current. As such, companies that manufacture power electronics equipment are constantly looking for new power factor correction (PFC) techniques, and ways to integrate PFC into their products. Figures 1 and 2 are examples of prior art converters which offer PFC. Figure 1 is a three-phase boost rectifier ideal for high power applications which offers unity power factor with continuous input currents. Here, three a.c. phases, V_a, V_b, and V_c, are passed through a bridge switching network and over a smoothing capacitor C_o to supply a d.c. load. On the opposite end of the spectrum, Figure 2 shows a prior art three-phase voltage source inverter. Here, a d.c. voltage source V_{in} is transformed by a bridge switching network into three-phase a.c. currents, i_a, i_b, and i_c. This type of inverter is widely used in motor drives and Uninterrupted Power Supply (UPS) systems.

For both the rectifier in Figure 1 and the inverter in Figure 2, if no soft-switching technique is applied, the six bridge anti-parallel diodes will cause a severe reverse recovery problem due to a high DC rail voltage. For high power applications minority carrier switching devices, such as BJTs, IGBTs, GTOs are often used, which have severe turn-off current tail problem which further exacerbate switching losses and degrade the power factor. As a result, it is extremely difficult to operate such converters at a high switch frequencies (i.e. 20KHz or higher) without implementing soft-switching technique.

A lot of research has been spent on improving the prior art rectifier and inverter circuits, the major thrust being on pulse width modulation (PWM) strategies. Though many useful soft-switching PWM strategies have been developed, none are completely satisfactory. The most advanced available soft-switching techniques are the resonant DC link, the quasi-resonant DC link, and the space-vector based zero-voltage transition. The major drawback of the resonant DC link technique is that the resonant components appear in the main power path and the resonance increases the voltage or current stresses of the switches. The quasi resonant DC link technique requires more complicated control and produces more circulating energy causing high conduction losses. The space-vector based zero-voltage transition technique can only be implemented with high speed digital signal processor and requires many auxiliary components. Additionally, all these techniques are only about zero-voltage switching. Until now, a suitable zero-current switching technique has not been developed.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide to provide simpler and more effective soft-switching techniques for three-phase converters.

It is yet another object of the present invention to provide simple modifications to the DC rail of a boost rectifier which permits zero-voltage-transition (ZVT) and zero-current-transition (ZCT).

It is yet another object of the present invention to provide simple modifications to the DC rail of a voltage source inverter which permits zero-current-transition (ZCT) and zero-voltage-transition (ZVT).

These and other objects of the present invention are accomplished by adding relatively simple, inexpensive components to the DC rails of conventional converter circuits. For a boost rectifier, an ultra high speed diode, about an order of magnitude faster than the anti-parallel switching diodes, is inserted in the DC rail after the switching network. The reverse recovery current is thereby determined only by this diode and, consequently, much less reverse recovery loss is expected even with a hard switching technique. Zero-current-transition (ZCT) as well as Zero-voltage-transition (ZVT) may also be achieved by adding a simple auxiliary network across the DC rail which operates only during the short turn-on or turn-off transients of the bridge switches. Similarly, a simple, inexpensive auxiliary circuit is added to the DC rail of a conventional voltage source inverter shown in Figure 2 to implement either ZVT and ZCT.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, aspects and advantages will be better understood from the following detailed description of a preferred embodiment of the invention with reference to the drawings, in which:

Figure 1 is a prior art three-phase boost rectifier;

Figure 2 is a prior art three-phase voltage source inverter;

Figure 3 is an improved three phase boost rectifier according to the present invention for reducing diode reverse recovery loss;

Figure 4 is a three phase boost rectifier according to the present invention for achieving ZVT;

Figure 5 is a computer generated simulation of the operation of the ZVT rectifier shown in Figure 4;

Figure 6 is a ZCT three-phase boost rectifier according to the present invention;

Figure 7 is a computer generated simulation of the operation of the ZCT rectifier shown in Figure 6;

Figure 8 is a ZVT voltage source converter according to the present invention;

Figure 9 is a diagram of control waveforms for the ZVT voltage source converter shown in Figure 8 for $i_a<0$ and $i_b>i_c>0$;

Figure 10 is a computer simulation of a the ZVT voltage source inverter shown in Figure 8;

Figure 11 is a is a ZCT voltage source inverter according to the present invention;

Figure 12 is a diagram of control waveforms for the ZCT voltage source inverter shown in Figure 8 for $i_a<0$ and $i_c>i_b>0$;

Figure 13 is a computer generated simulation of the ZCT operation of the ZCT voltage source inverter shown in Figure 11;

Figure 14 is a bi-directional ZVT converter according to the present invention;

Figure 15 is a bi-directional ZCT converter according to the present invention.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT OF THE INVENTION

Referring now to the drawings, and more particularly to Figure 3, there is shown three-phase boost rectifier according to the present invention. The rectifier is similar to the rectifier shown in Figure 1 having a three-phase input, v_a, v_b, and v_c, and a bridge switching network comprised of six bridge switches, S_{ap}, S_{an}, S_{bp}, S_{bn}, S_{cp}, and S_{cn}, hereinafter collectively referred to as simply S. Each bridge switch S has an anti-parallel diode associated therewith. It is understood that these anti-parallel diodes may be either discrete components or the body diode in the case of an active switch such as a MOSFET. According to the invention, an ultra fast diode D is introduced in the d.c. rail prior to a smoothing capacitor C_o supplying a d.c. load. The introduction of the ultra-fast diode D alleviates diode reverse recovery experienced by the diodes in the switching bridge as well as facilitates soft-switching. In the prior art three-phase boost rectifier shown in Figure 1, at the moment the active switches S (one in each phase) are turned on, any previously conducting anti-parallel diodes will see a high output voltage as:

$$V_o \geq V_{line\ peak} \cdot \frac{3}{\Pi}$$

This high voltage creates a very high reverse recovery current spike in the much slower anti-parallel bridge diodes which in turn causes significant turn-on losses. The ultra fast diode D, which is chosen to be much faster (for example, ten times faster) than the bridge diodes, now determines the reverse recovery current. Consequently, a large reduction in turn-on loss, improved power factor, and a significant increase in the switching frequency is experienced even without implementing a soft-switching technique. However, it is noted that greater advantages can be realized if a soft switching technique is employed in addition. For example, zero-voltage-switching techniques can completely solve the diode reverse recovery problem and remove capacitive turn-on losses. Zero-current-switching techniques can eliminate the turn-off losses of IGBT, GTO, etc. Consequently, if soft-switching is also employed the switching frequency can be pushed much higher. This give rise to significant savings of filter inductor size and the circuit cost.

Referring now to Figure 4, using the DC rail diode D shown in Figure 3, it possible to implement zero-voltage-transition ZVT in by adding only one simple auxiliary network on the DC side. The proposed ZVT three-phase boost rectifier is shown in Figure 4, where the auxiliary network consists of resonant inductor L_r, auxiliary switch S_{aux}, and diode D_{aux}. The auxiliary network only operates during the short turn-on transients of the bridge switches. It is preferred that the bridge switches S are synchronized at their turn-on instants so that the auxiliary ZVT network only operates once per switching cycle. In operation, the auxiliary switch S_{aux} is turned on a short period before the turn-on of the bridge switches S. Therefore, a current builds up in inductor L_r. Once the current in L_r reaches the highest input phase current, resonance begins between L_r and bridge capacitances. This resonance will bring the bridge voltage down to zero thus achieving a ZVS condition for the bridge switches S. Figure 5 shows a computer generated simulation to verify the ZVT operation. The simulation shows one turn-on transient happens at $t=160\mu s$. Since, the switch voltage drops down to zero before its current starts to rise, no turn-on loss occurs.

Referring now to Figure 6, there is shown a ZCT three-phase boost rectifier having an auxiliary network which consists of resonant inductor L_r, resonant capacitor C_r, auxiliary switch S_{aux}, and auxiliary diode D_{aux}. The auxiliary network is similar to the network shown in Figure 4 with the addition of the resonant capacitor C_r. The ZCT network only operates during the short turn-off transients of the bridge switches S. Again, it is preferred that the bridge switches S are synchronized at their turn-off instants so that the auxiliary ZCT network only operates once per switching cycle. In operation, the auxiliary switch S_{aux} is turned on for a short period before the turn-off of the bridge switches S. A current builds up in L_r as a result of the resonance between L_r and C_r due to the initial voltage on C_r. Once the current in C_r reaches the highest input phase current, all three phase currents only flow through bridge diodes and no current is left in any bridge switch. Hence, a ZCT turn-off condition is achieved for the bridge switches S. Figure 7 shows a simulation of the ZCT operation for a turn-on transient at $t=160\mu s$. It is noted that there is no overlap between the switch voltage and the switch current indicating no turn-off losses.

All of the boost rectifier circuits of the present invention implement the novel DC rail diode D which has been found to naturally provide a six-step PWM operation which, in prior art circuits not having such a diode, requires a more complicated control circuitry. Briefly, six-step PWM refers to using six optimal bridge voltage vector combinations in a line cycle of 360°, one for each 60°. An optimal bridge voltage vector combination is the zero vector and the two bridge voltage vectors closest to the input voltage vector. Under six-step PWM, the boost inductors are only charged with the input voltage vector (zero-vector), which produces the minimum input current ripple as compared to other PWM schemes which allow the output voltage to participate in charging the boost inductor. Six-step PWM operation is inherent to the present invention because the DC rail diode D prevents the output voltage from participating in the boost inductor charging process. Consequently, undesired vectors are eliminated and the boost inductor current ripple is minimized automatically. In addition to above benefits from this DC rail diode D, another significant advantage is that it eliminates the possibility of shoot-through current from occurring even when both switches S on the same leg or phase of the switching bridge are conducting. Shoot through refers to the output capacitor in a conventional boost rectifier being shorted once both switches on the same leg are conducting. With the DC rail diode of the present invention, this shorting path is eliminated thus providing higher reliability than the conventional circuits.

Similar to the above discussed rectifiers, ZVT and ZCT can be also implemented in a voltage source inverter by adding an active switch on the DC rail side. Referring now to Figure 8, there is shown a soft switching ZVT voltage source inverter according to the present invention. Although a 20KHz inverter switching frequency, not necessarily requiring soft-switching, is fast enough for most motor drive systems to avoid the acoustic noise, soft-switching is still preferred. First, 20KHz is hard to attain for hard-switching high power circuits with currently available devices. Second, for uninterrupted power supply (UPS) systems there is always a demand to reduce the filter inductor size by increasing the switching frequency. Third, for bi-directional power flow applications, the off-line rectifier should be able to run as an inverter during regeneration (i.e. operate in reverse as an inverter).

In operation, the inverter shown in Figure 8 the bridge switches are turned on (i.e by applying gate drive control signals) while the DC rail switch S_R is off so that the switches are under zero voltage turn-on condition. Then, the DC rail switch S_R is turned on aided by the ZVT network composed of L_r, S_{aux}, and D_{aux}. An example of the operation is demonstrated in Figure 9 for the case of $i_a < 0$ and $i_c > i_b > 0$. In such case with synchronized turn-on scheme, the bridge switches S to be turned on at the beginning of each switching cycle should be S_{an}, S_{bp}, and S_{cp}. In fact, due to the existence of the DC rail switch, a very simple PWM scheme can be used which only operates one bridge switch and the DC rail switch S_R. This leaves S_{an} and S_{bp} on all the time and only switching S_{cp} and S_R to obtain the output current control. In this way, the DC rail voltage is kept at zero during the freewheeling state at the end of every switching cycle and thus provides the zero-voltage turn-on condition for S_{cp} at the beginning of the next switching cycle. In Figure 9, S_{cp} is gated earlier than S_R so that it is turned on under zero-voltage condition, which does not change the circuit freewheeling state. At t_0, the auxiliary switch S_{aux} is turned on to build a current in the resonant inductor L_r. The resonant inductor L_r resonates with capacitances across the bridge switches and the DC rail switch S_R to provide zero-voltage transition for the turn-on of S_R at t_1. Times t_2 and t_3 are determined by the current control loops. S_{cp} is turned on any time after S_{dc} is turned off. At t_5, another switching cycle starts. Simulation has been done to verify the ZVT operation. The results are given in Figure 10 which clearly show the zero-voltage turn-on of the bridge switches and the DC rail switch at $t = 160\mu s$.

Referring now to Figure 11, there is shown a zero-current-transition (ZCT) voltage source inverter. The operation principle is that the DC rail switch S is turned off first with the help of the ZCT network composed of L_r, C_r, D_{aux}, and S_{aux}. The drive signals of the bridge switches are removed after the turn-off of the DC rail switch S so that they are under zero voltage turn-off condition. Hence, no voltage applied on the switches after they are turned off. One example is shown in Figure 12 which is the same example case used above to explain the ZVT voltage-source-inverter. However, different from the ZVT voltage-source-inverter, the turn-off instants are synchronized. Only one bridge switch S_{cp} and the DC switch S are running under the given condition with S_{an} and S_{bp} on all the time. The control waveforms of Figure 12 show S_{aux} gated at t_0 to provide zero-current transition for the turn-off of S at t_1. After S is turned off, the DC link voltage drops down to zero, thus, S_{cp} can be turned off at t_2 without seeing voltage. t_3 and t_4 are determined by the current control loops. At t_5, another switching cycle starts. Simulation has been done to verify the ZCT operation. The results are given in Figure 13. It is noted that there is no overlap between the switch voltage and the switch current for bridge switches or the DC rail switch.

The introduction of the DC rail diode D imposes an undesirable limitation in that the power can flow only in one direction. However, there are many applications for which this is not an issue such as telecommunication systems and computer systems. Although the circuits embodied in Figures 8 and 11 do not provide soft-switching for the rectifier operation, if the anti-parallel diode of the DC rail switch S_R is an ultra fast diode it would serve to alleviate reverse recovery of the anti-parallel bridge diodes. Thus, the above proposed circuit could also be able to deal with bi-directional power flow to certain extent.

If soft-switching is necessary for bi-directional operation, the circuits shown in Figures 14 and 15 may be employed. Figure 14 shows a bi-directional ZVT converter which is a hybrid of the boost rectifier shown in Figures 4 and the voltage source inverter shown in Figure 8. It is noted that if the switch S' and switch S_{aux1} are kept open the circuit is identical to the boost rectifier of Figure 4. If, on the other hand, S_{aux2} is open, the circuit becomes functionally equivalent to the voltage source inverter of Figure 8.

Similarly, Figure 15 shows a bi-directional ZCT voltage source inverter which is a hybrid of the boost rectifier shown in Figures 6 and the voltage source inverter shown in Figure 11. If the switch S' and switch S_{aux1} are kept open the circuit is identical to the boost rectifier of Figure 4. If S_{aux2} is open, the circuit becomes functionally equivalent to the voltage source inverter of Figure 8. Hence, depending on the orientation of the switches S, S_{aux1}, and S_{aux2}, the circuits of Figures 14 and 15 can operate bi-directionally as either boost rectifiers or voltage source inverters.

While the invention has been described in terms of a single preferred embodiment, those skilled in the art will recognize that the invention can be practiced with modification within the spirit and scope of the appended claims.

CLAIMS

We claim:

1. A three-phase boost rectifier for converting a three-phase alternating current power supply to a direct current power supply, comprising:

a three-phase alternating current power input;

a switching bridge connected between said alternating power input and a direct current rail output, said switching bridge comprising a plurality of switches each having an anti-parallel diode associated therewith;

an ultra-fast recovery diode connecting said switching bridge and said direct current rail, said ultra-fast diode being faster than said anti-parallel diodes.

2. A three-phase boost rectifier as recited in claim 1, further comprising a auxiliary circuit connected across said switching bridge for achieving zero-voltage-transition, comprising:

a resonant inductor and an auxiliary diode connected in series across said ultra-fast diode; and

an auxiliary switch having a first pole connected between said resonant inductor and said auxiliary diode and a second pole connected to ground.

3. A three-phase boost rectifier as recited in claim 1, further comprising a auxiliary circuit connected across said switching bridge for achieving zero-current-transition, comprising:

a resonant capacitor, a resonant inductor and an auxiliary diode connected in series across said ultra-fast diode; and

an auxiliary switch having a first pole connected between said resonant inductor and said auxiliary diode and a second pole connected to ground.

4. A zero-voltage-transition voltage source inverter for converting a direct current power supply to a three-phase alternating current output, comprising:

a direct current power input;

a switching bridge connected between said direct current power input and said three-phase alternating current output; and

an auxiliary circuit connected between said direct current power input and said switching bridge, said auxiliary circuit comprising:

a rail switch connected to a direct current rail of said direct current power input;

an auxiliary switch connected in series with a resonant inductor across said rail switch; and

an auxiliary diode connected at a first end between said auxiliary switch connected and said resonant inductor and at a second end to ground.

5. A zero-current-transition voltage source inverter for converting a direct current power supply to a three-phase alternating current output, comprising:

a direct current power input;

a switching bridge connected between said direct current power input and said three-phase alternating current output; and

an auxiliary circuit connected between said direct current power input and said switching bridge, said auxiliary circuit comprising:

a rail switch connected to the direct current rail of said direct current power input;

an auxiliary switch connected in series with a resonant inductor and a resonant capacitor across said rail switch; and

an auxiliary diode connected at a first end between said auxiliary switch connected and said resonant inductor and at a second end to ground.

6. A bi-directional zero-voltage-transition (ZVT) converter, comprising:

a direct current power terminal;

a switching bridge connected between said direct current power terminal and a three-phase alternating current terminal;

a rail switch connected to the direct current rail of said direct current power terminal;

an ultra fast diode connected in parallel with said rail switch; and

an auxiliary circuit connected between said direct current power terminal and said switching bridge, said auxiliary circuit comprising:

a first auxiliary switch and anti-parallel diode connected in series with a resonant inductor across said rail switch; and

an second auxiliary switch and anti-parallel diode connected at a first end between said first auxiliary switch and said resonant inductor and at a second end to ground, whereby when said rail switch and said first auxiliary switch are open, said converter is a boost rectifier, and if said second auxiliary switch is open, said converter is a voltage source inverter.

7. A bi-directional zero-current-transition (ZCT) converter, comprising:

a direct current power terminal;

a switching bridge connected between said direct current power terminal and a three-phase alternating current terminal;

a rail switch connected to the direct current rail of said direct current power terminal;

an ultra fast diode connected in parallel with said rail switch; and

an auxiliary circuit connected between said direct current power terminal and said switching bridge, said auxiliary circuit comprising:

a first auxiliary switch and anti-parallel diode connected in series with a resonant inductor and a resonant capacitor across said rail switch; and

an second auxiliary switch and anti-parallel diode connected at a first end between said first auxiliary switch and said resonant inductor and at a second end to ground, whereby when said rail switch and said first auxiliary switch are open, said converter is a boost rectifier and if said second auxiliary switch is open, said converter is a voltage source inverter.

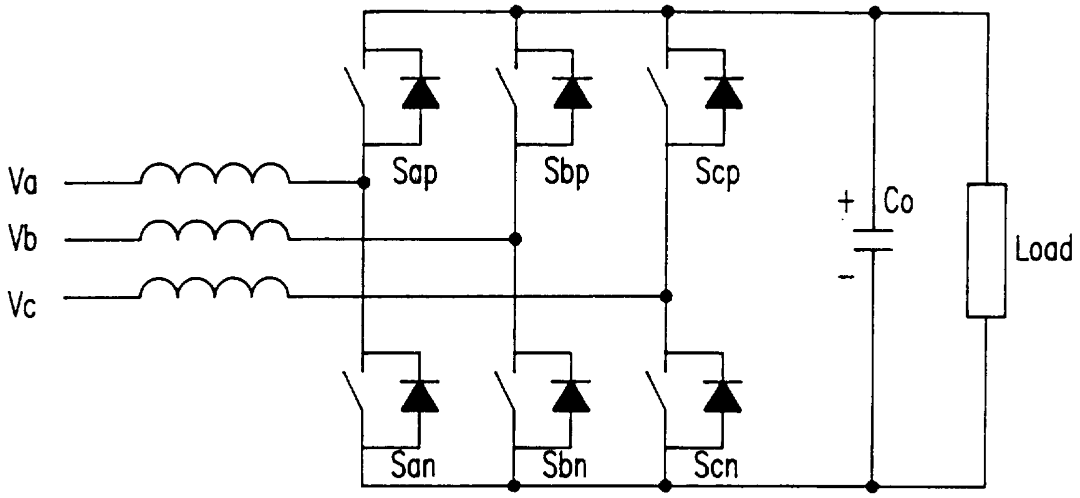

FIG.1
PRIOR ART

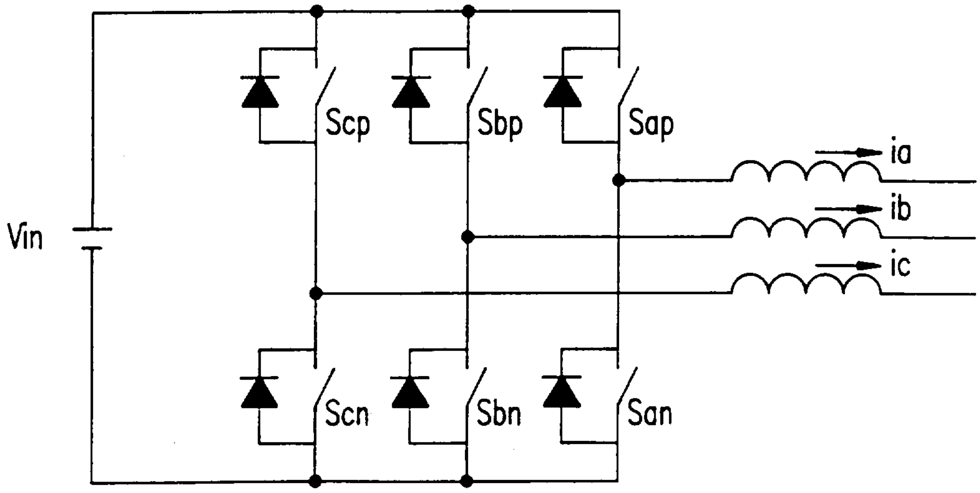

FIG.2
PRIOR ART

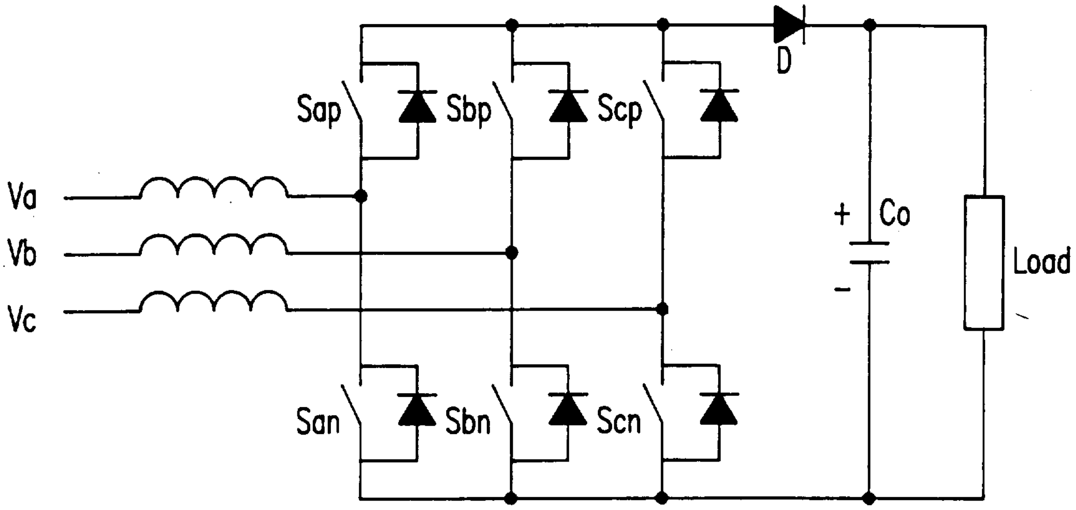
D
Sap
Sbp
Scp
Va
Vb
Vc
+
Co
-
Load
San
Sbn
Scn

FIG.3

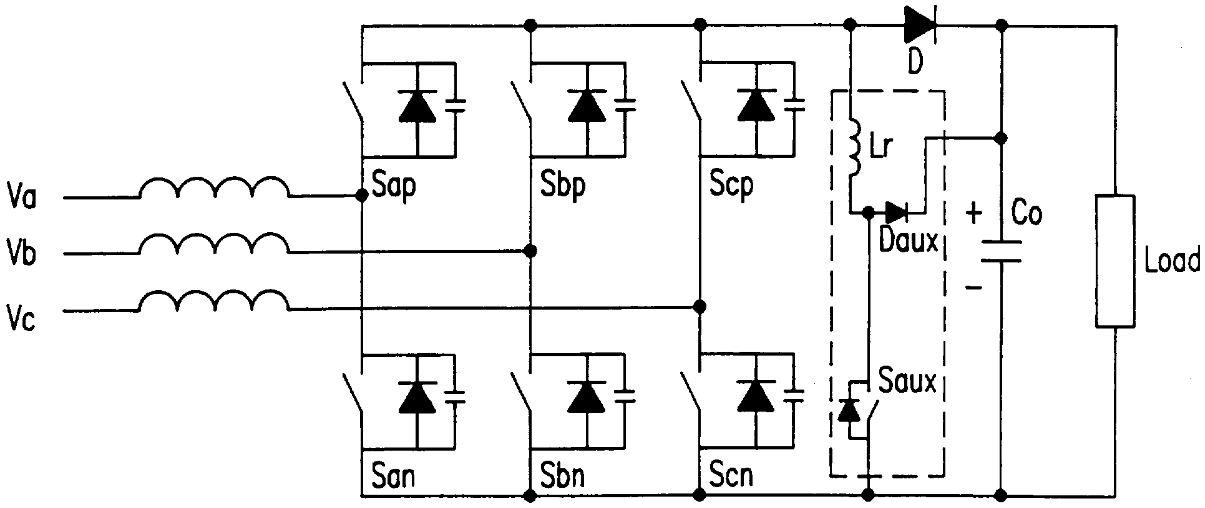
D
Lr
Sap
Sbp
Scp
Va
Vb
Vc
Daux
+
Co
-
Load
Saux
San
Sbn
Scn

FIG.4

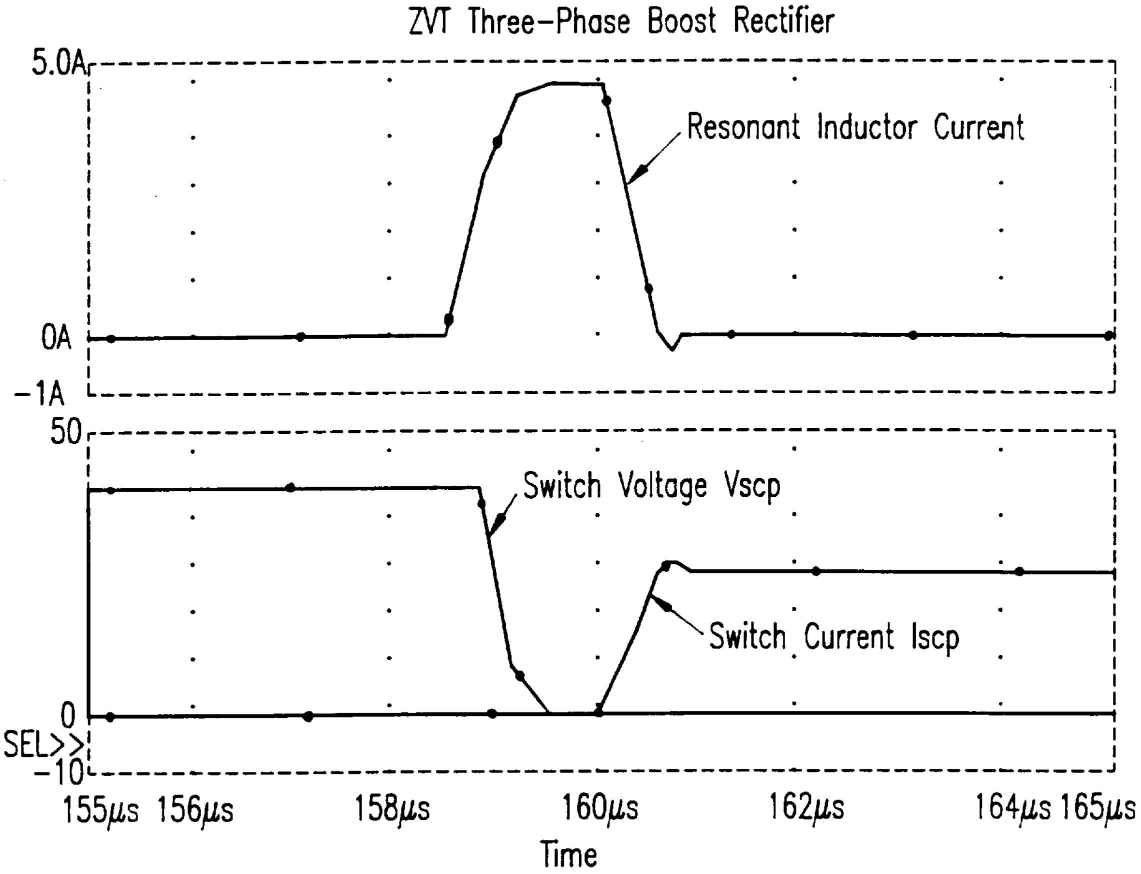
ZVT Three-Phase Boost Rectifier
5.0A
0A
-1A
Resonant Inductor Current
50
0
SEL>>
-10
Switch Voltage Vscp
Switch Current Iscp
155µs
156µs
158µs
160µs
162µs
164µs
165µs
Time

FIG.5

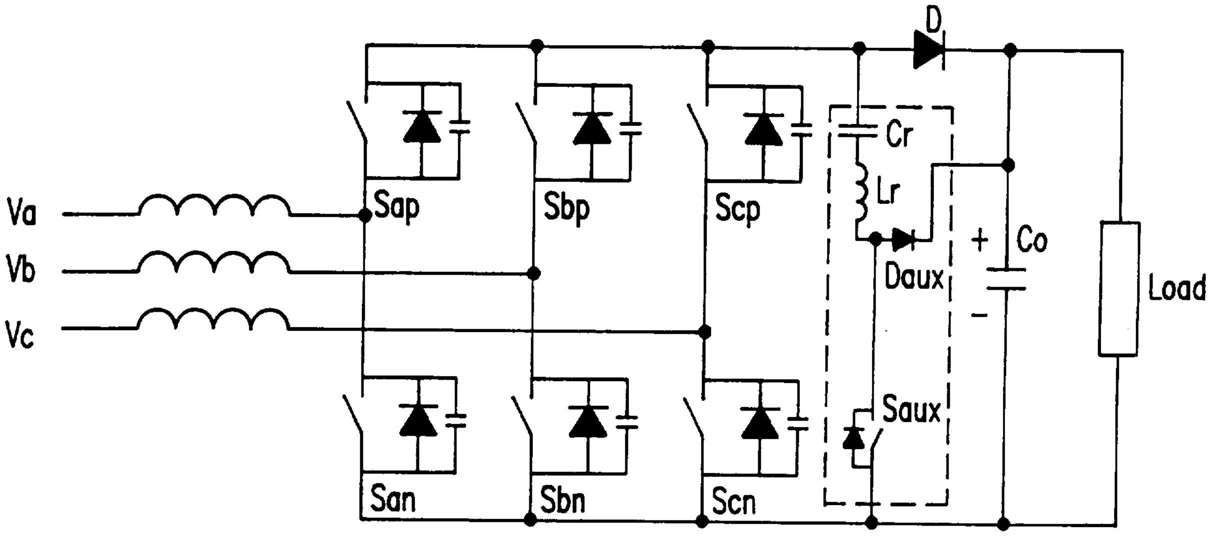
D
Cr
Lr
Daux
Saux
+
Co
-
Load
Va
Vb
Vc
Sap
Sbp
Scp
San
Sbn
Scn

FIG.6

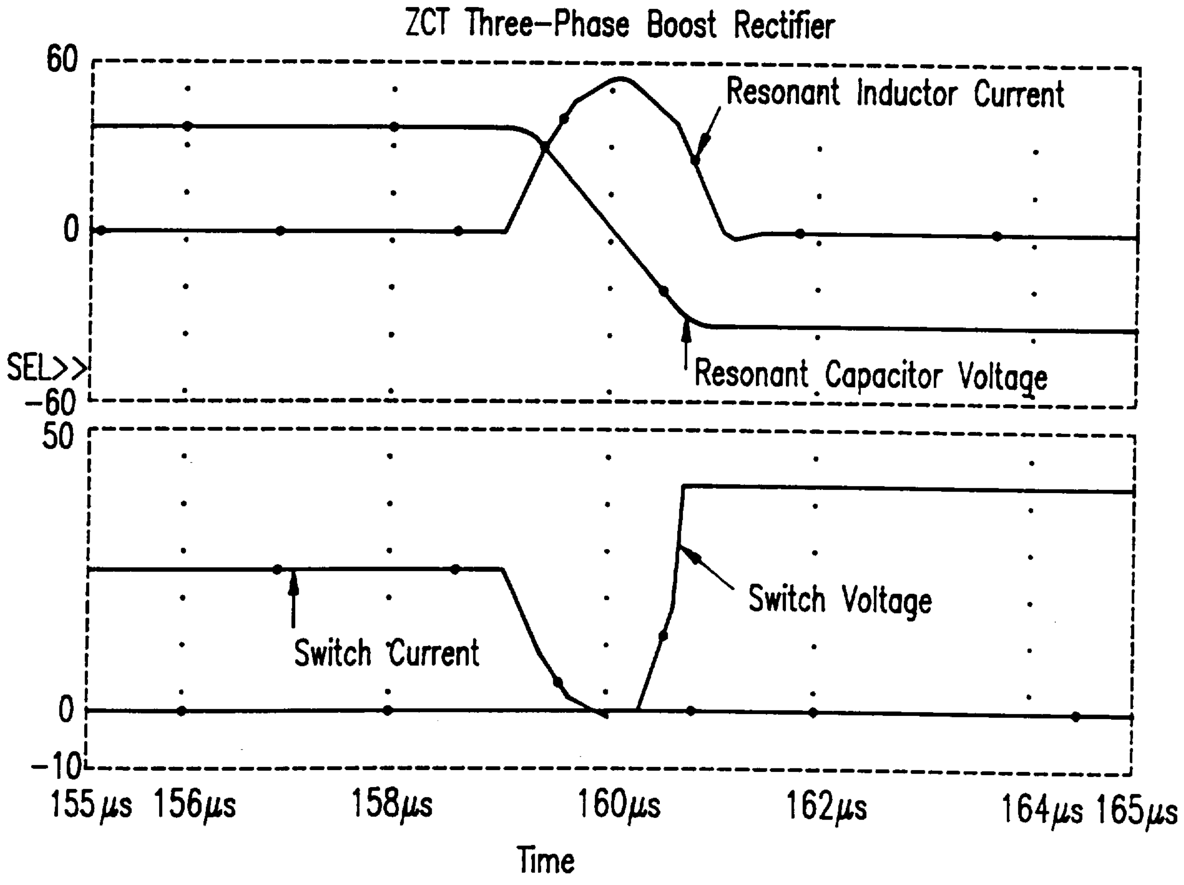
ZCT Three-Phase Boost Rectifier
60
0
SEL>>
-60
Resonant Inductor Current
Resonant Capacitor Voltage
50
0
-10
Switch Current
Switch Voltage
155μs
156μs
158μs
160μs
162μs
164μs
165μs
Time

FIG.7

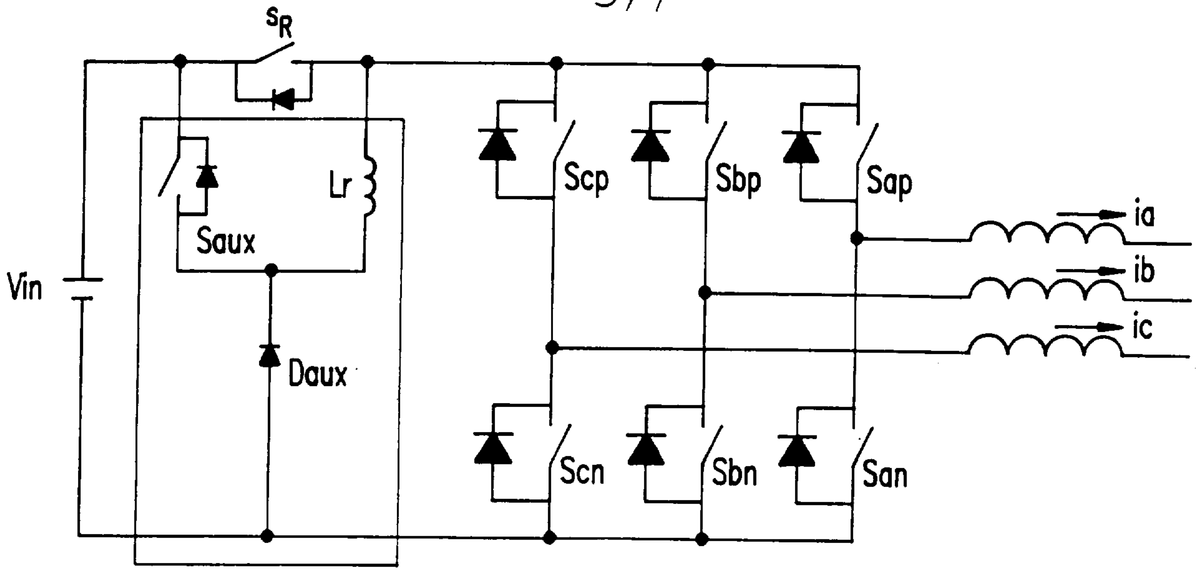

FIG.8

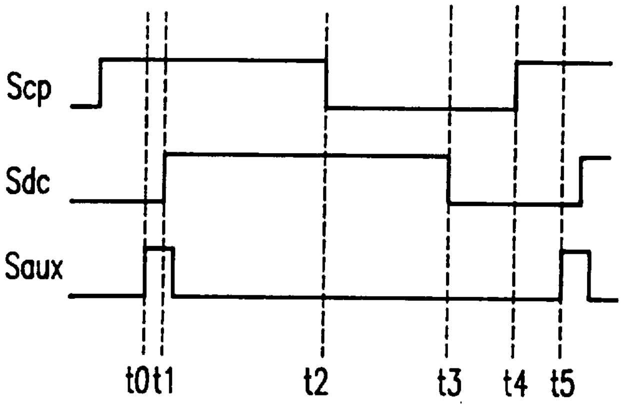

FIG.9

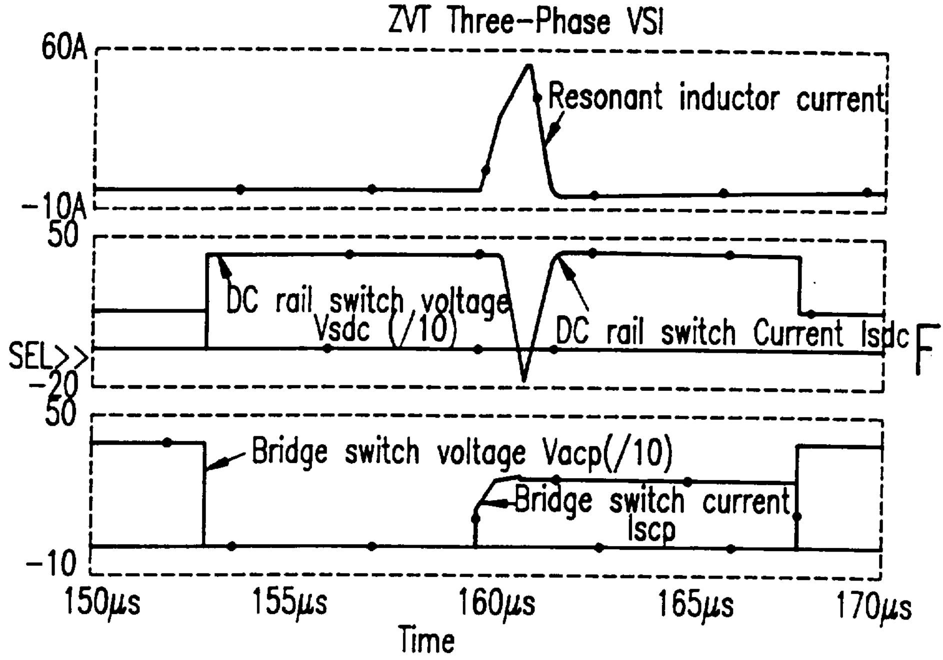

FIG.10

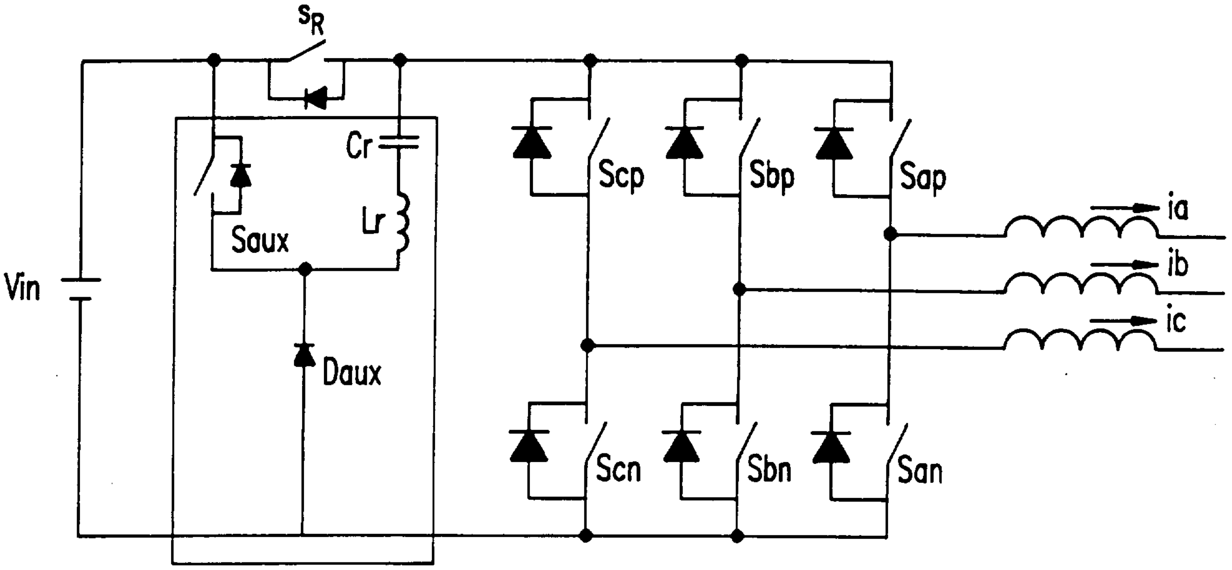

FIG.11

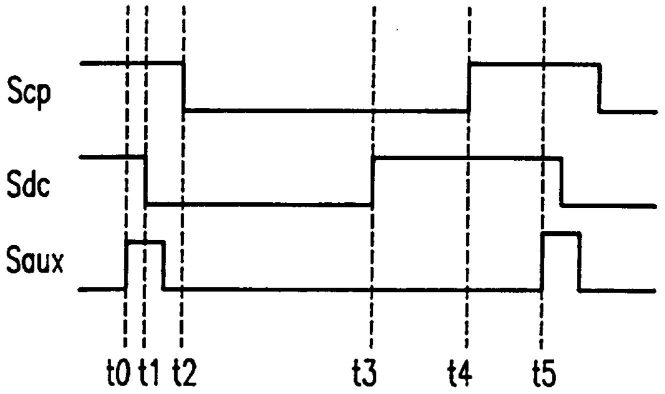

FIG.12

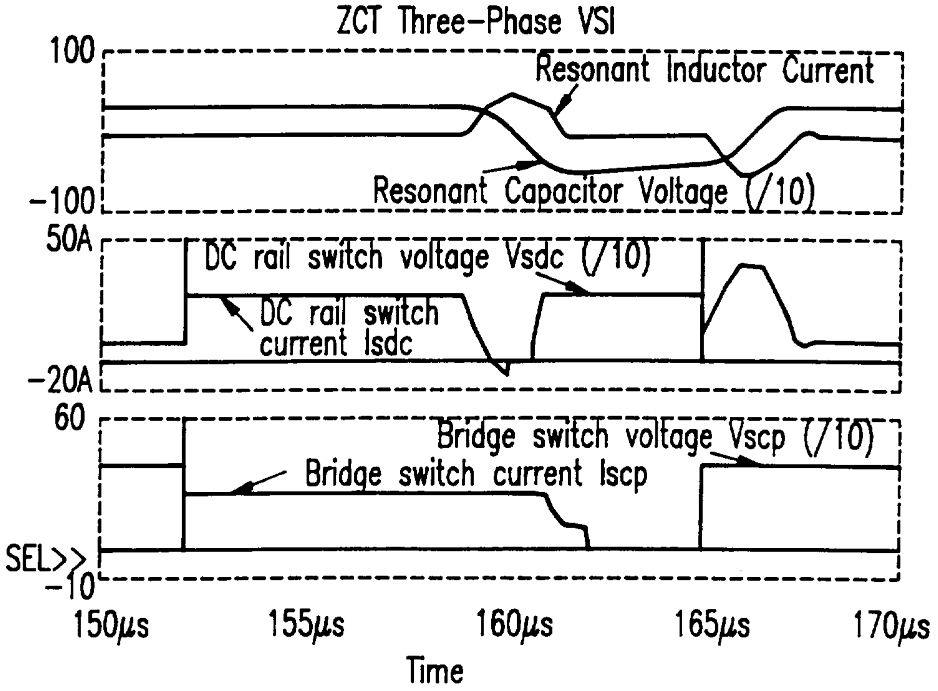

FIG.13

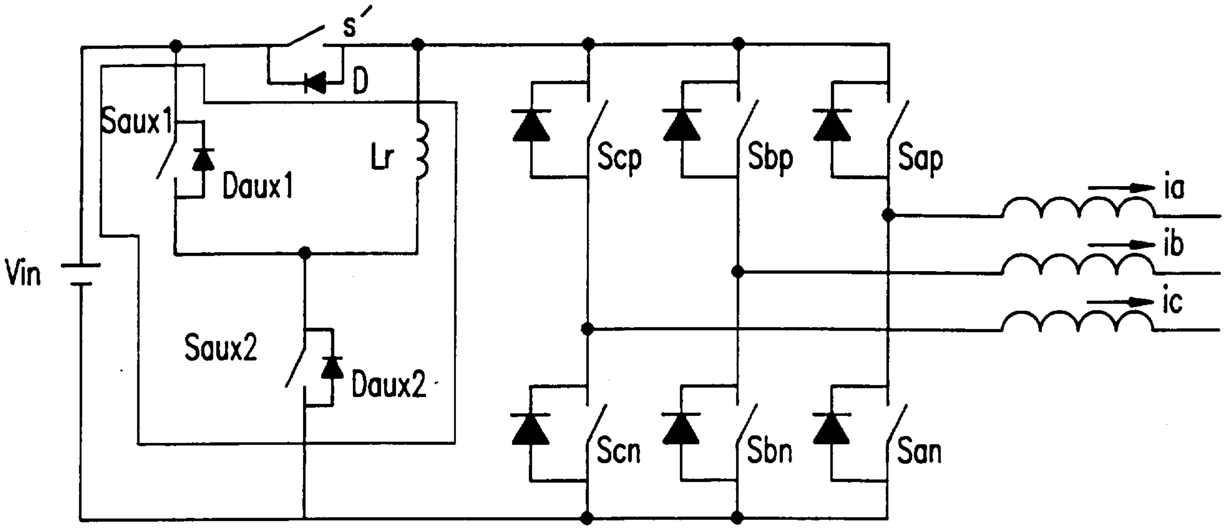
s´
D
Saux1
Daux1
Lr
Vin
Saux2
Daux2
Scp
Sbp
Sap
Scn
Sbn
San
ia
ib
ic

FIG.14

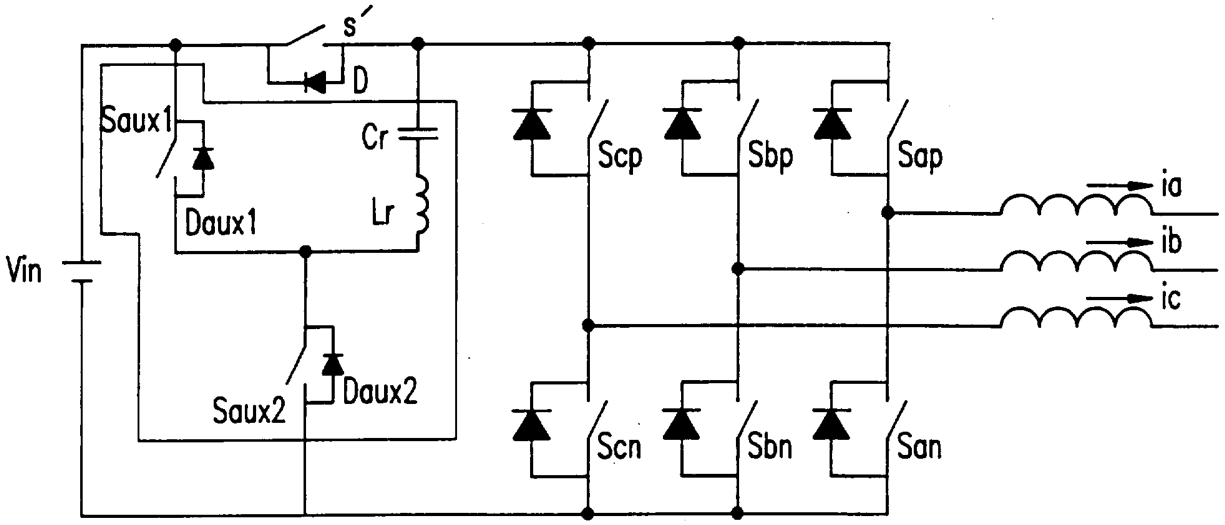
s´
D
Saux1
Cr
Daux1
Lr
Vin
Daux2
Saux2
Scp
Sbp
Sap
Scn
Sbn
San
ia
ib
ic

FIG.15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/01152

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :HO2M 7/217, 7/44, 7/5387
US CL : 363/17, 98, 127, 132
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 363/17, 98, 127, 132

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS: ((three or 3)(w)phase)(3w)rectifier

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 5,432,695 (VLATKOVIC ET AL) 11 July 1995, FIG.1A	1
A	US, A, 4,864,483 (DIVAN) 05 September 1989, FIG. 5	4, 5, 7 and 8
A	US,A, 5,255,175 (UCHINO) 19 October 1993, FIG. 1	1-3
A	US, A, 5,291,388 (HEINRICH) 01 March 1994, FIG. 2	4, 5, 7 and 8
A	US, A, 5,367,448 (CARROLL) 22 November 1994, FIG. 1C	1-3

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:
"A"	document defining the general state of the art which is not considered to be of particular relevance
"E"	earlier document published on or after the international filing date
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O"	document referring to an oral disclosure, use, exhibition or other means
"P"	document published prior to the international filing date but later than the priority date claimed
"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&"	document member of the same patent family

Date of the actual completion of the international search

09 APRIL 1996

Date of mailing of the international search report

02 MAY 1996

Name and mailing address of the ISA/US
Commissioner of Patents and Trademarks
Box PCT
Washington, D.C. 20231
Facsimile No. (703) 305-3230

Authorized officer
MATTHEW V. NGUYEN
Telephone No. (703) 308-1782