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Kim et al.

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[54] **CIRCULATING CURRENT FREE TYPE HIGH FREQUENCY SOFT SWITCHING PULSEWIDTH MODULATED FULL BRIDGE DC/DC CONVERTER**

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[*] Notice: This patent issued on a continued prosecution application filed under 37 CFR 1.53(d), and is subject to the twenty year patent term provisions of 35 U.S.C. 154(a)(2).

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[22] Filed: **Nov. 27, 1996**

[30] **Foreign Application Priority Data**

Dec. 2, 1995 [KR] Rep. of Korea 95-46168

[51] **Int. Cl.**^{6} **H02M 3/335**; H02M 3/24; H02M 7/5387

[52] **U.S. Cl.** **363/17**; 363/98; 363/132

[58] **Field of Search** 363/17, 98, 132

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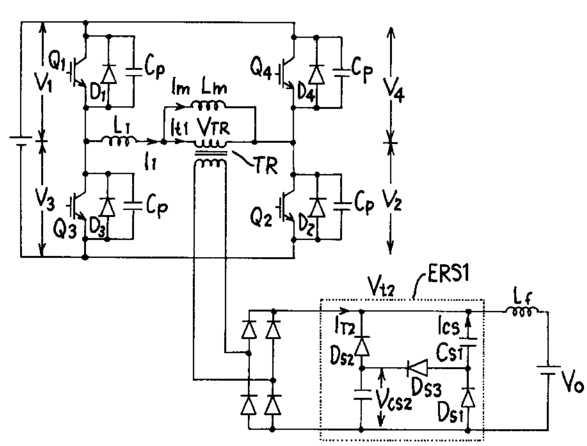
Assistant Examiner—Bao Q. Vu
Attorney, Agent, or Firm—Flynn, Thiel, Boutell & Tanis, P.C.

[57] **ABSTRACT**

An improved soft switching topology of a full bridge PWM DC/DC converter is described. The new topology employs an energy recovery snubber to minimize a circulating current flowing through the transformer and switching devices. By using an energy recovery snubber instead of adding a tapped inductor and a saturable reactor to reduce RMS current stress, the converter achieves nearly zero current switching for the right leg of the full bridge circuit due to the minimized circulating current, and achieves zero voltage switching for the left leg of the full bridge circuit due to the reflected output current during the interval of left leg transition. The converter achieves soft switching for secondary side rectifier and freewheeling diode because at the turn-on time of the primary switching device, the energy recovery snubber provides a low impedance path.

8 Claims, 12 Drawing Sheets



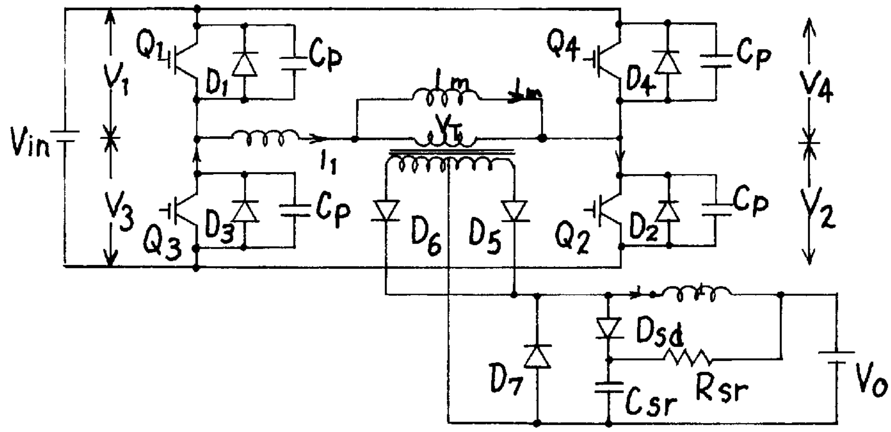


FIG. 1 PRIOR ART

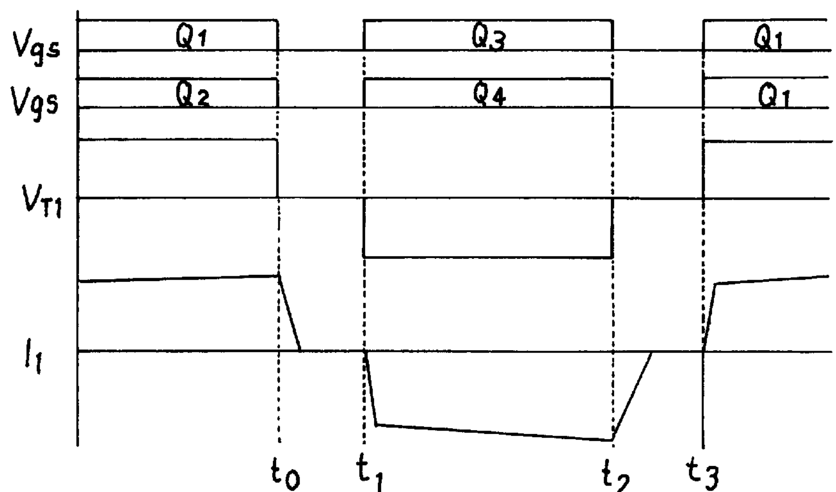


FIG. 2 PRIOR ART

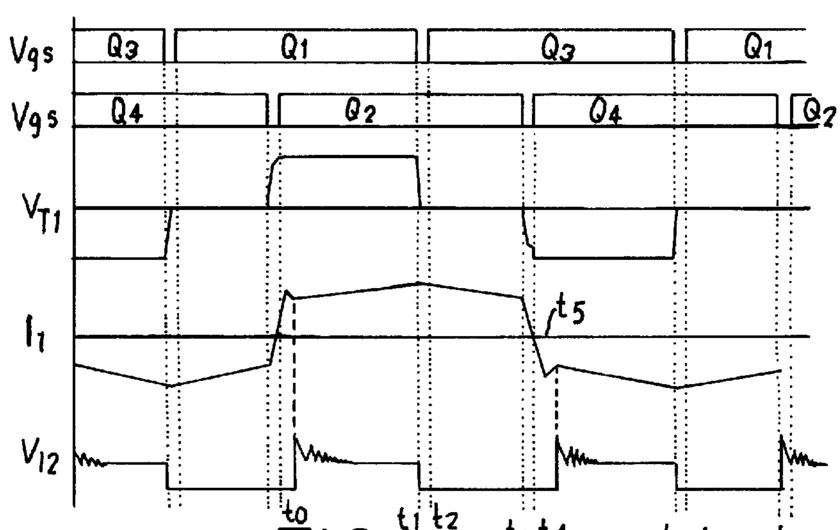
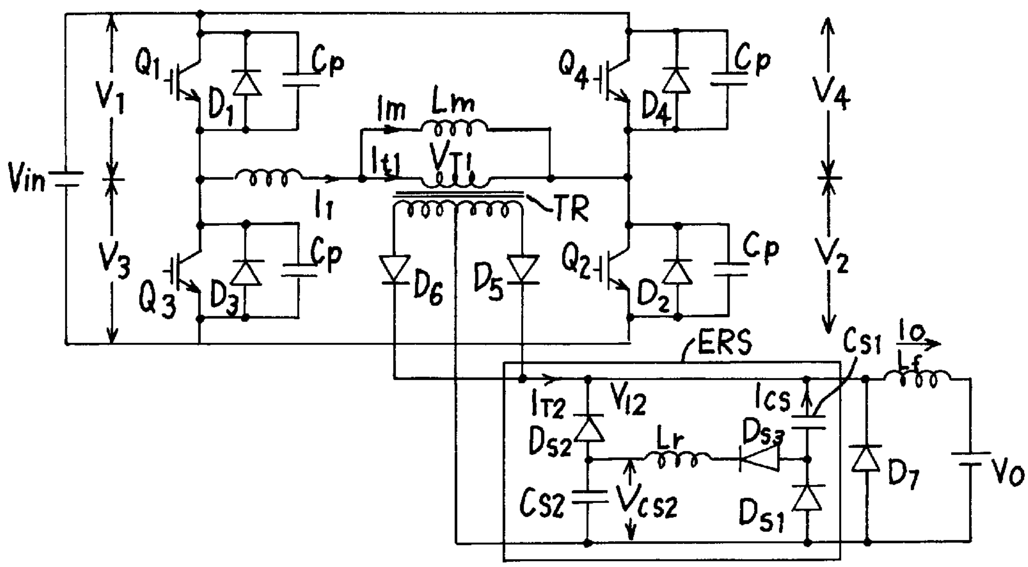


FIG. 3 PRIOR ART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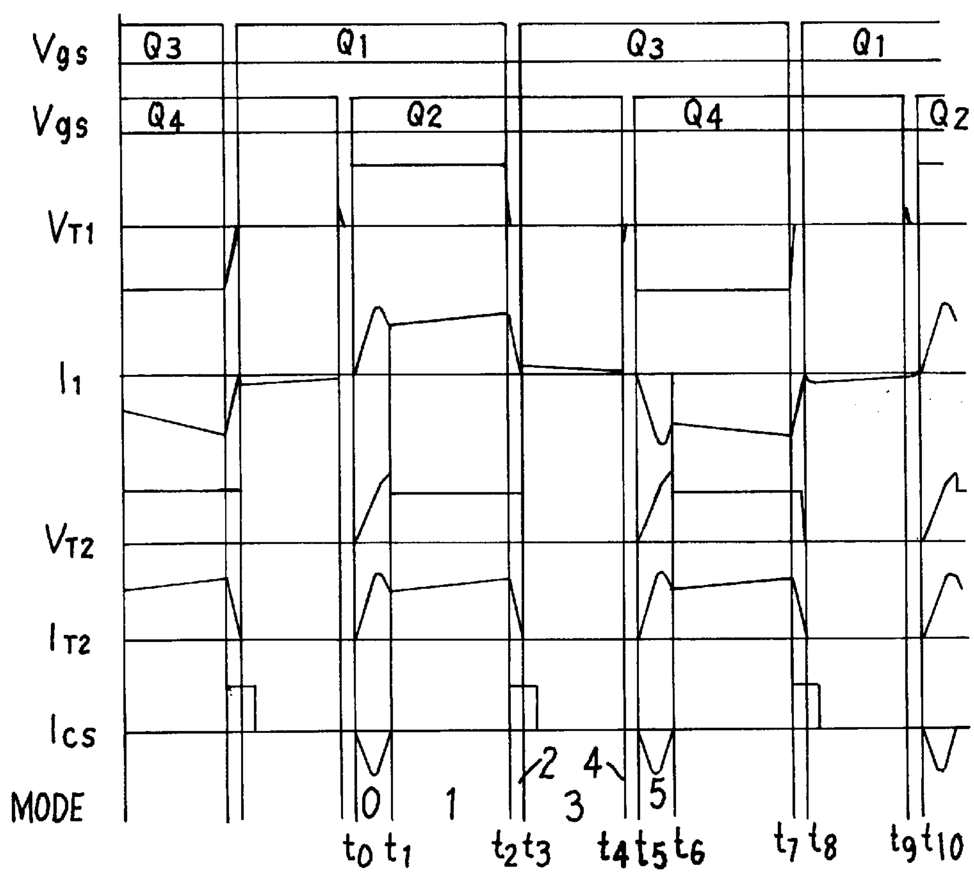
V3
V4
V2
Q1
Q3
Q4
Q2
D1
D3
D4
D2
Cp
Cp
Cp
Cp
Im
Lm
It1
VT1
I1
TR
D6
D5
ERS
IT2
V12
Ds2
Lr
Ds3
Ics
Cs1
Io
Lf
CS2
Vcs2
Ds1
D7
Vo

FIG. 4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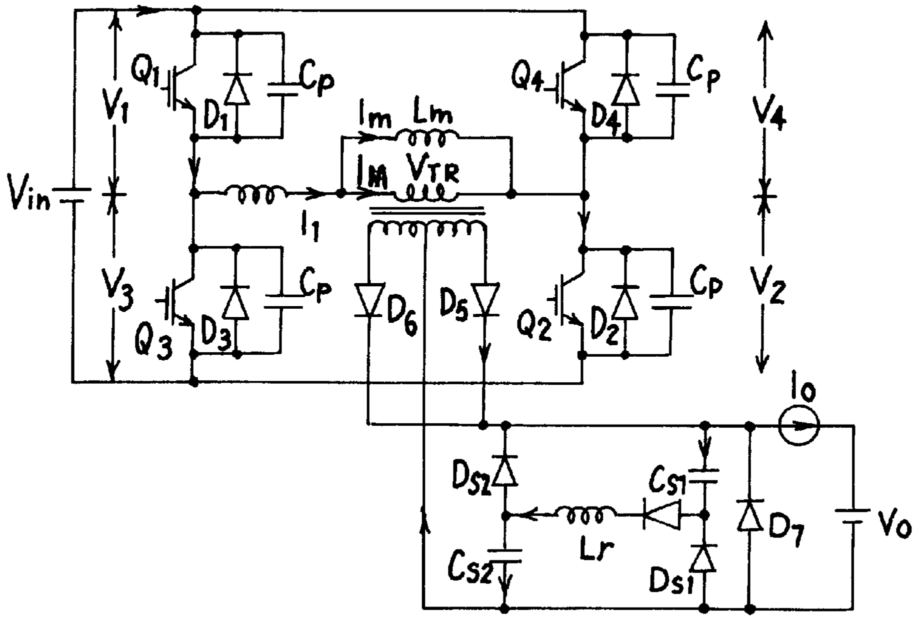
Vgs
VT1
I1
VT2
IT2
Ics
MODE
Q3
Q1
Q3
Q1
Q4
Q2
Q4
Q2
0
1
2
3
4
5
t0 t1
t2 t3
t4 t5 t6
t7 t8
t9 t10

FIG. 5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Im
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V4
D4
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VTR
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I1
V3
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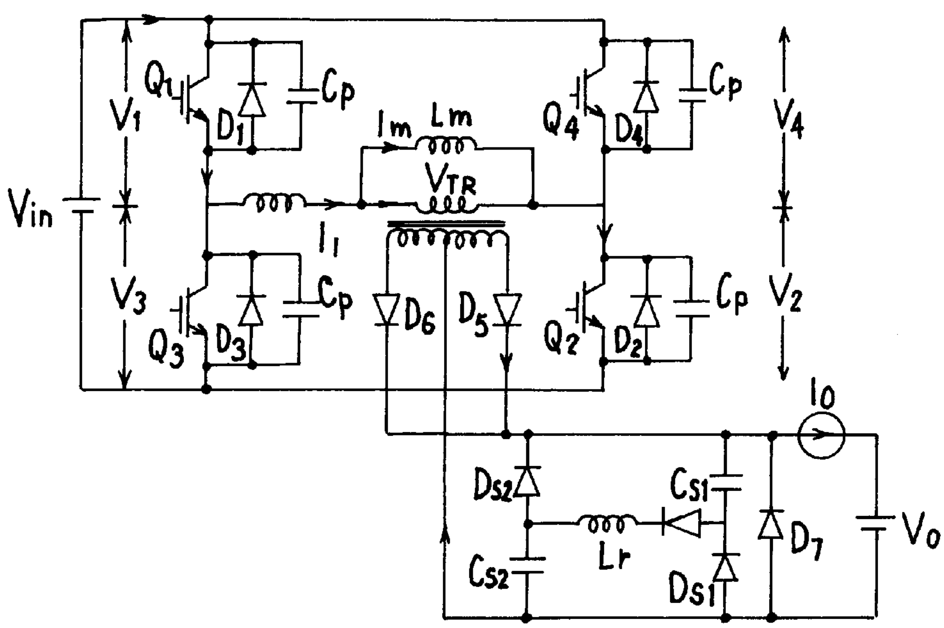
D6
D5
Q2
Cp
V2
Q3
D3
D2
Io
DS2
CS1
D7
Vo
Lr
CS2
DS1

FIG. 6A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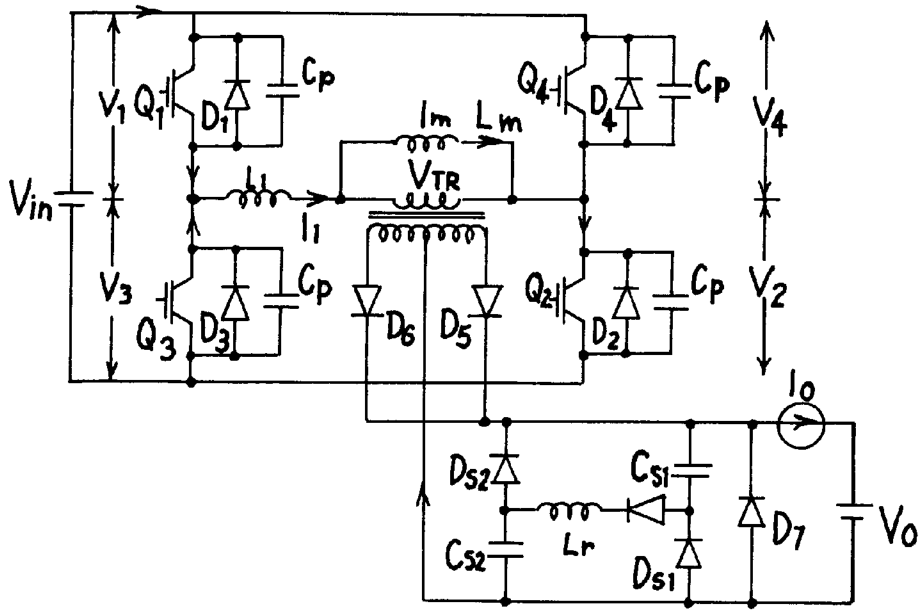
D1
Im
Lm
Q4
Cp
V4
D4
VTR
Vin
I1
V3
Cp
D6
D5
Q2
D2
Cp
V2
Q3
D3
Io
DS2
CS1
D7
Vo
Lr
CS2
DS1

FIG. 6B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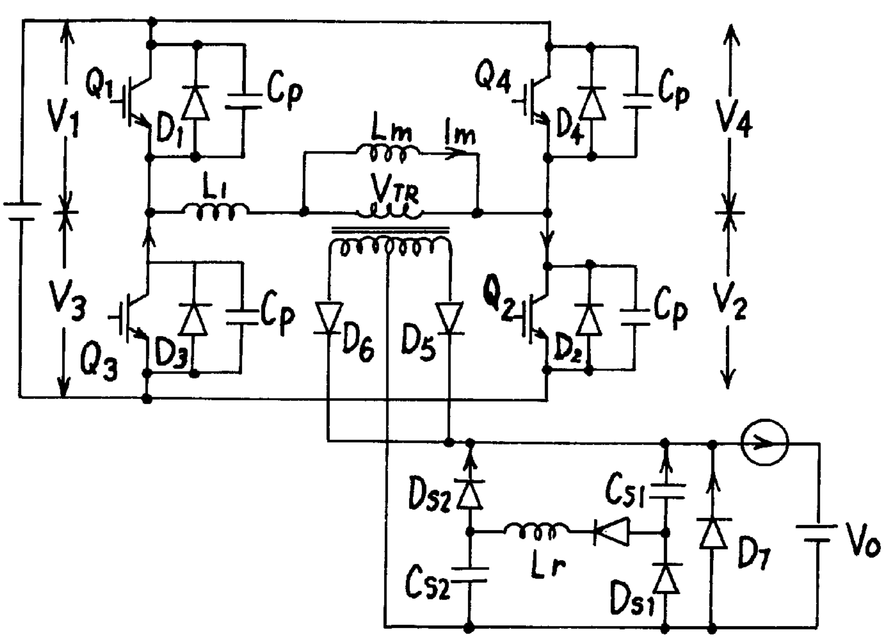
D1
Cp
Im
Lm
Q4
D4
Cp
V4
Vin
L1
I1
VTR
V3
Q3
D3
Cp
D6
D5
Q2
D2
Cp
V2
Io
Ds2
Cs1
Cs2
Lr
Ds1
D7
Vo

FIG. 6C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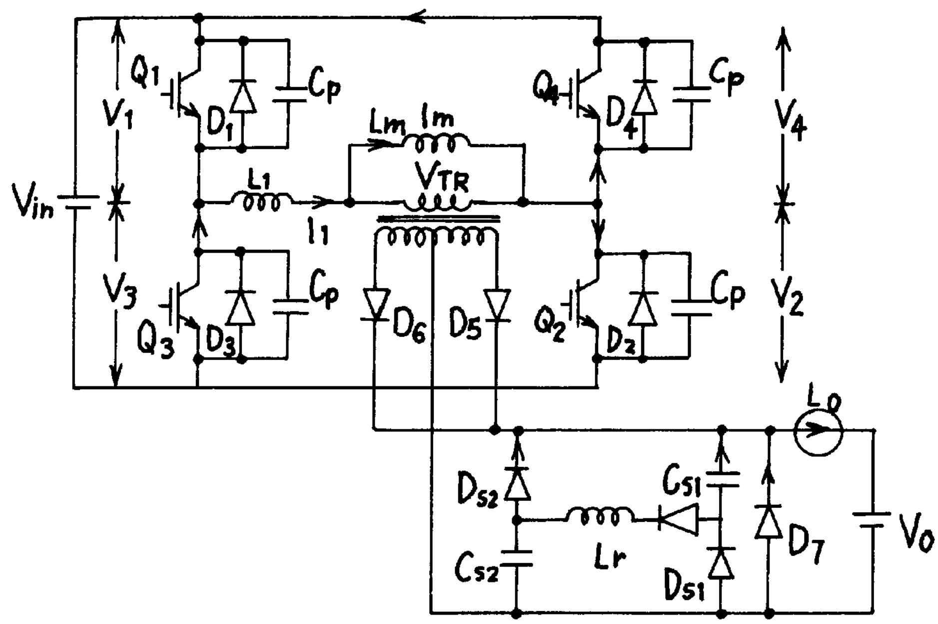
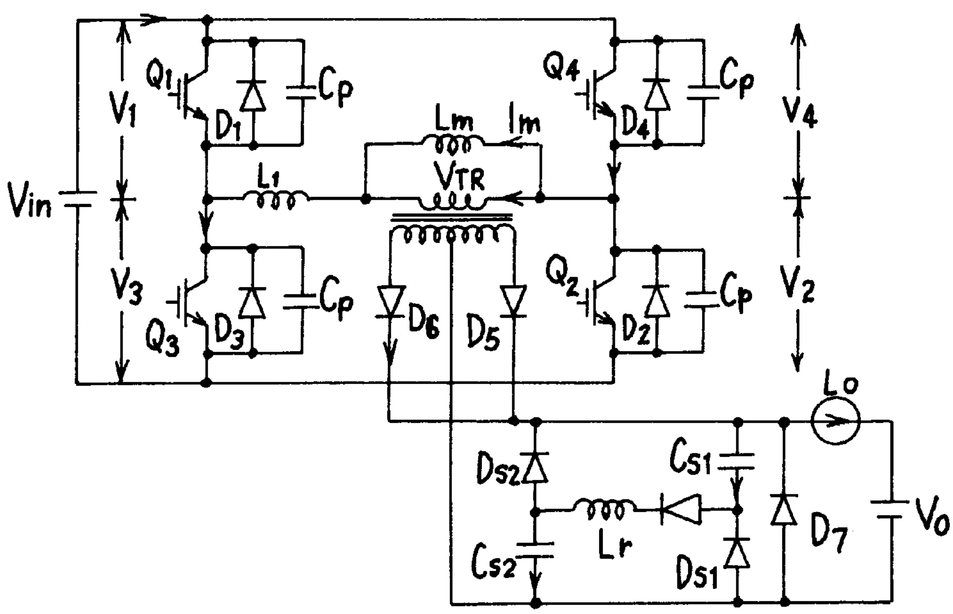
V1
D1
Cp
Lm
Im
Q4
D4
Cp
V4
L1
VTR
V3
Q3
D3
Cp
D6
D5
Q2
D2
Cp
V2
Ds2
Cs1
Cs2
Lr
Ds1
D7
Vo

FIG. 6D



Q1
D1
Cp
V1
Vin
V3
Q3
D3
L1
I1
Lm
Im
VTR
D6
D5
Q4
D4
Q2
D2
V4
V2
Lo
Ds2
Cs2
Lr
Cs1
Ds1
D7
Vo

FIG. 6E



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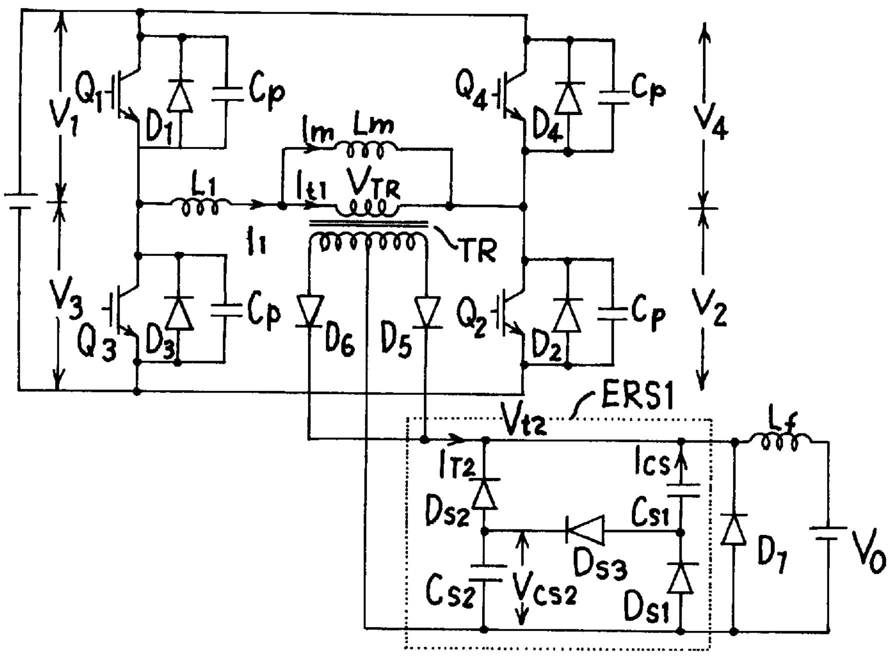
Cp
V1
Vin
V3
Q3
D3
L1
Lm
Im
VTR
D6
D5
Q4
D4
Q2
D2
V4
V2
Lo
Ds2
Cs2
Lr
Cs1
Ds1
D7
Vo

FIG. 6F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V1
D1
Im Lm
Q4
D4
Cp
V4
L1
It1 VTR
I1
TR
V3
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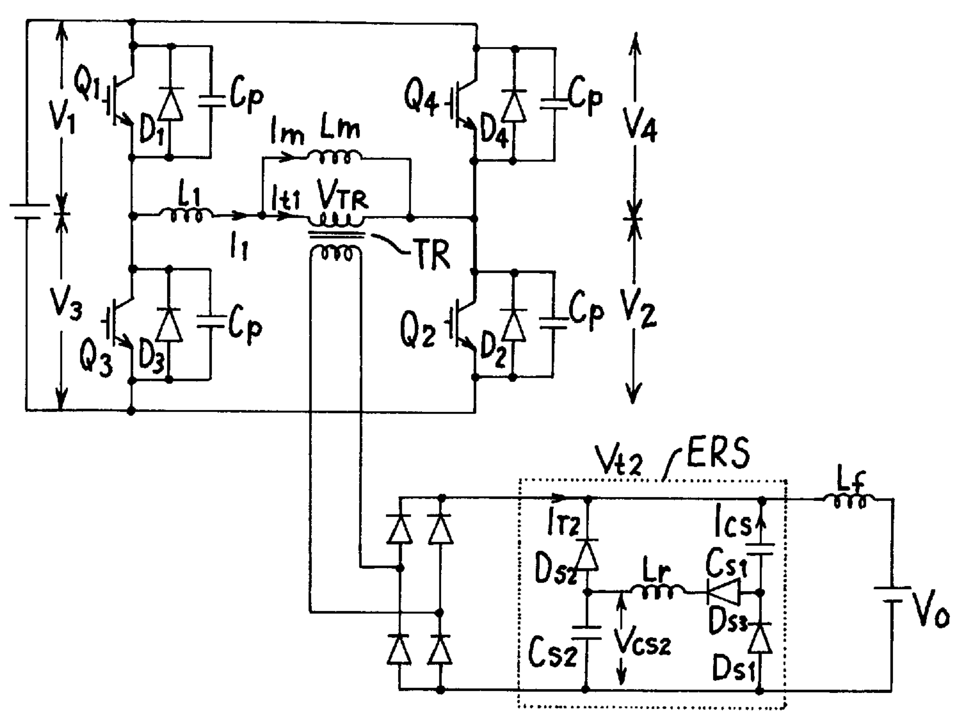
D3
Cp
D6
D5
Q2
D2
Cp
V2
ERS1
Vt2
Lf
IT2
Ics
DS2
CS1
DS3
CS2
VCS2
DS1
D7
V0

FIG. 7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V1
D1
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Q4
D4
Cp
V4
L1
It1 VTR
I1
TR
V3
Q3
D3
Cp
Q2
D2
Cp
V2
Vt2
ERS
Lf
IT2
Ics
DS2
Lr
CS1
DS3
CS2
VCS2
DS1
V0

FIG. 8

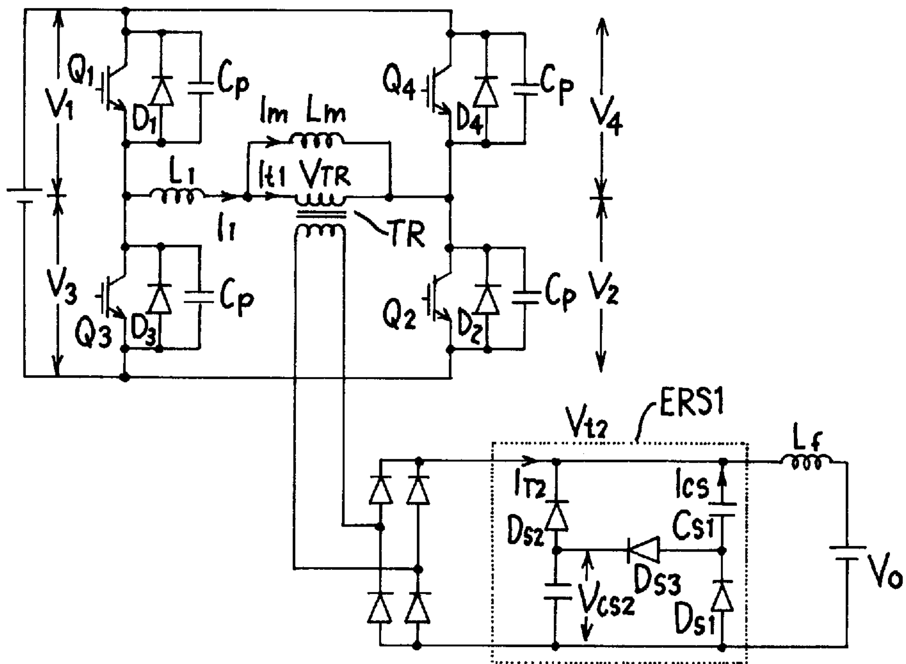
Q1
D1
Cp
V1
Im Lm
It1 VTR
L1
I1
TR
Q4
D4
Cp
V4
V3
Q3
D3
Cp
Q2
D2
Cp
V2
Vt2
ERS1
Lf
IT2
Ics
Cs1
Ds2
Ds3
Vcs2
Ds1
Vo

FIG. 9

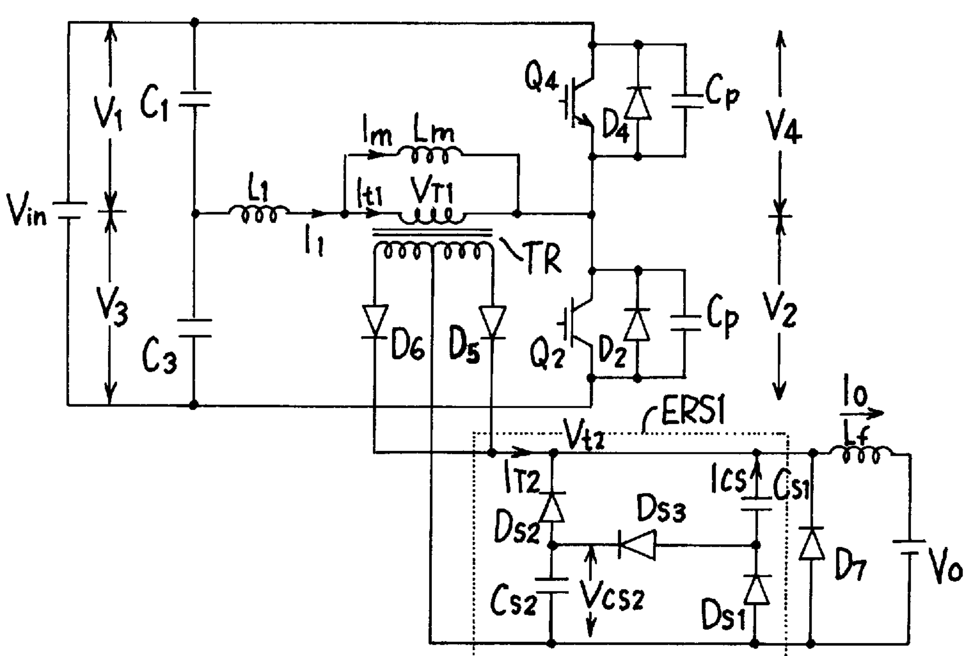
V1
C1
Vin
V3
C3
Im Lm
L1
It1 VT1
I1
TR
D6
D5
Q4
D4
Cp
V4
Q2
D2
Cp
V2
Io
Lf
ERS1
Vt2
IT2
Ics
Cs1
Ds2
Ds3
Cs2
Vcs2
Ds1
D7
Vo

FIG. 10

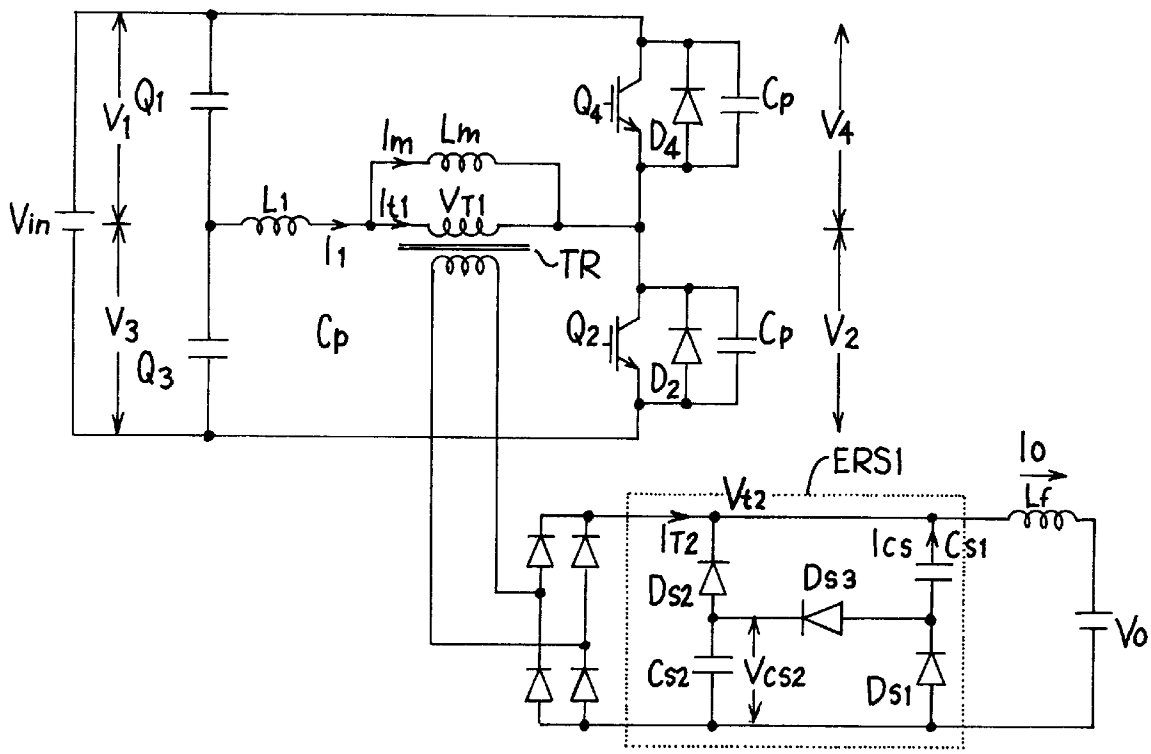
Vin
V1
Q1
V3
Q3
L1
I1
Cp
Im
Lm
It1
VT1
TR
Q4
D4
Cp
V4
Q2
D2
Cp
V2
ERS1
Vt2
IT2
Ds2
Ds3
Cs2
Vcs2
Ics
Cs1
Ds1
Io
Lf
Vo

FIG. 11

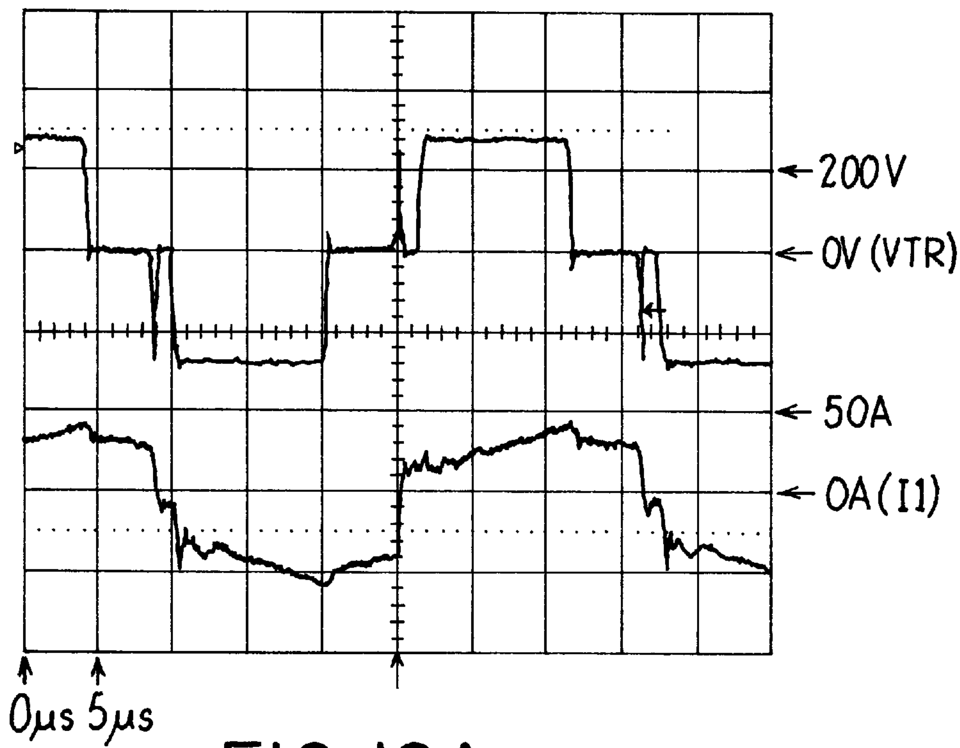

FIG. 12A PRIOR ART

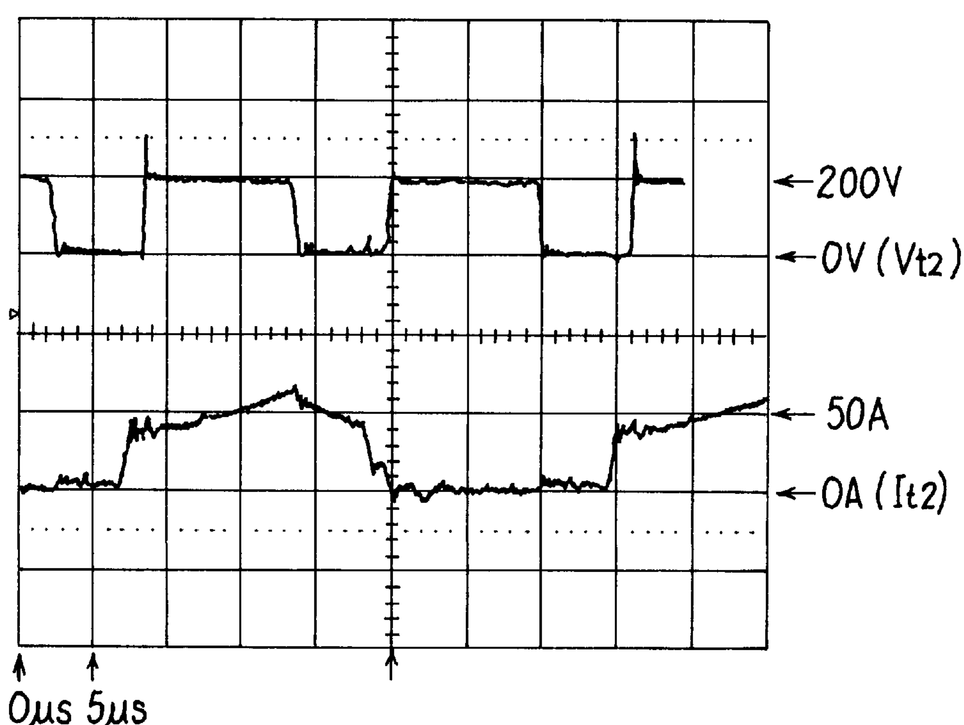

FIG. 12B PRIOR ART

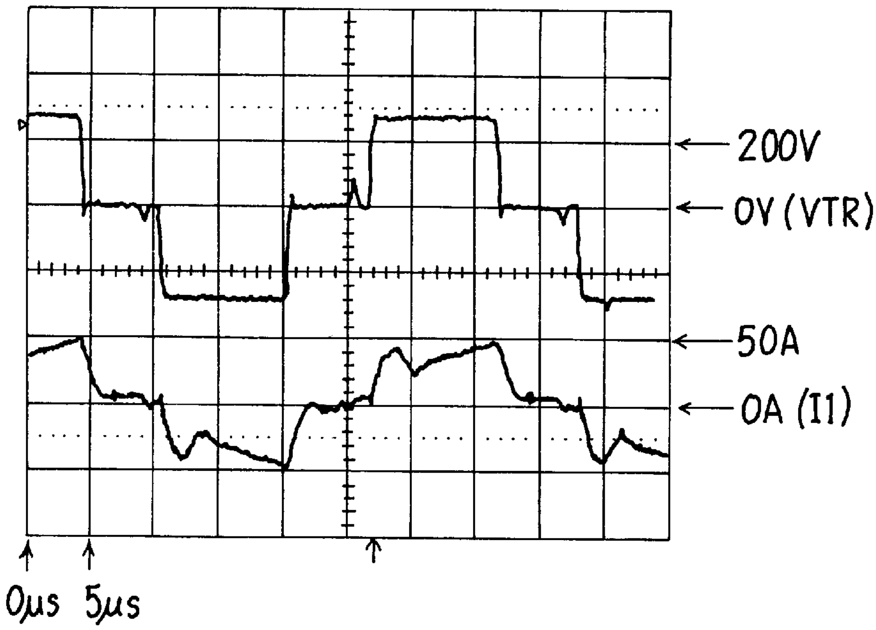

FIG. 13A

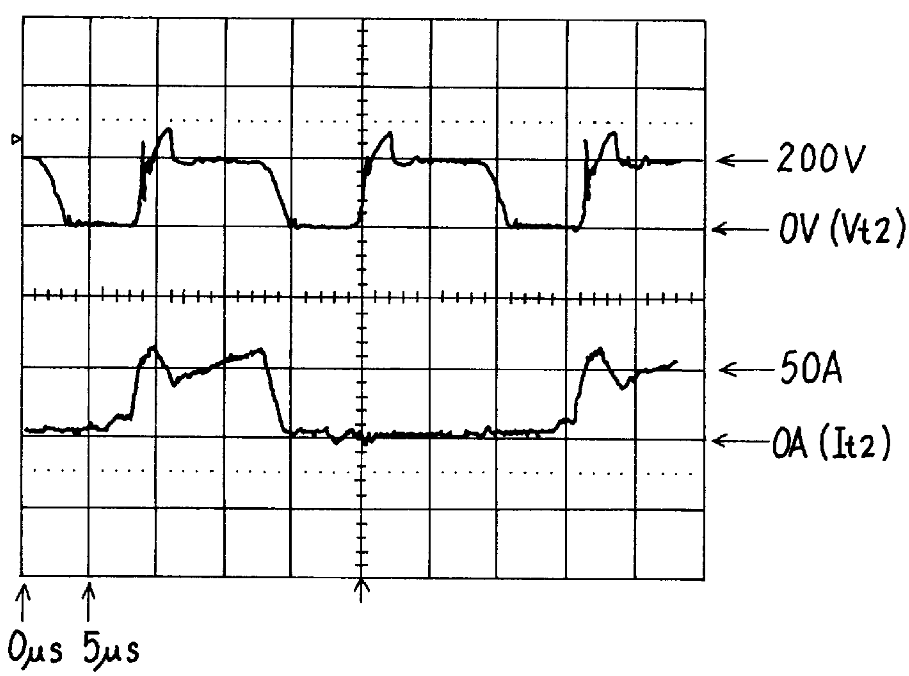

FIG. 13B

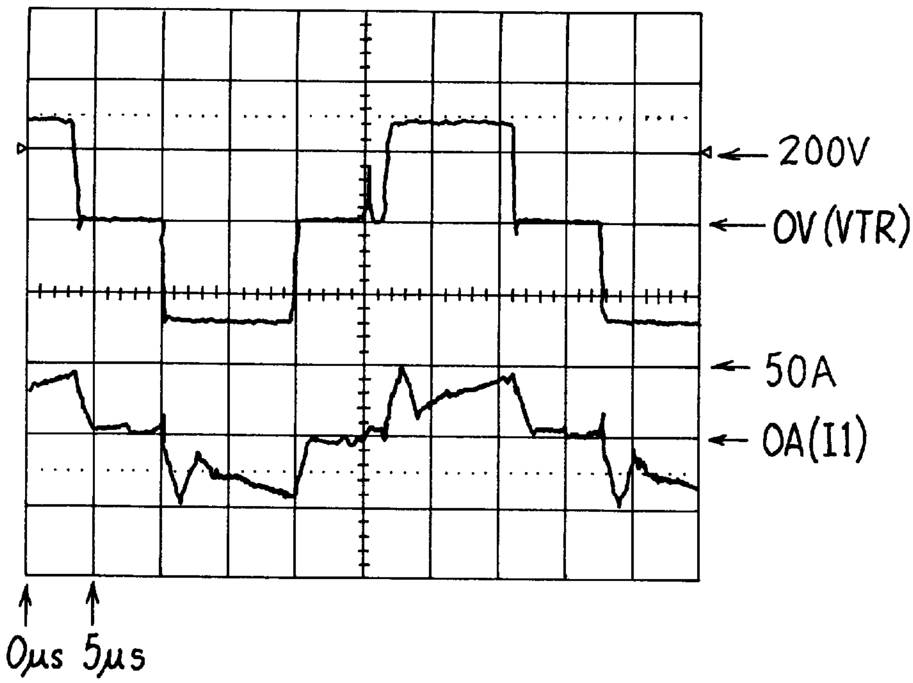

FIG. 14A

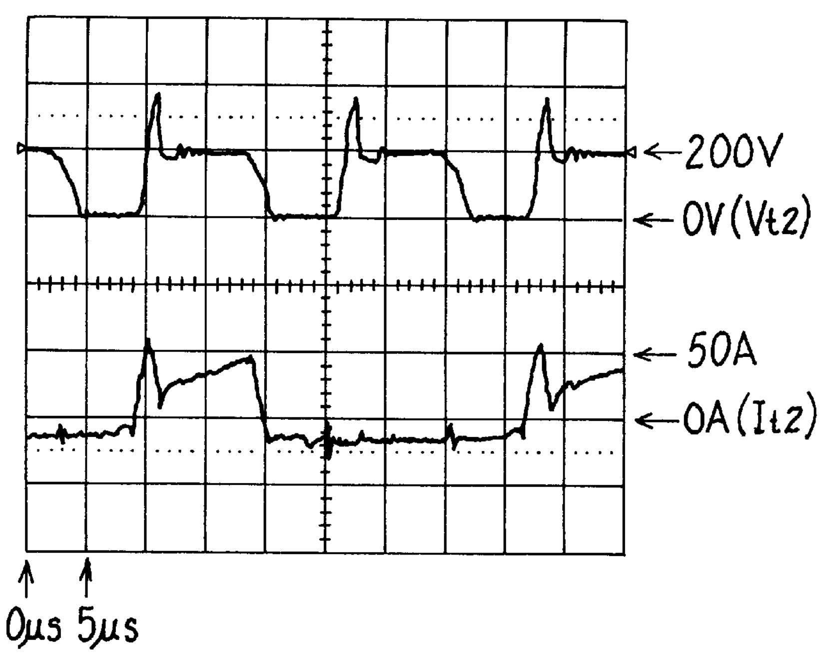

FIG. 14B

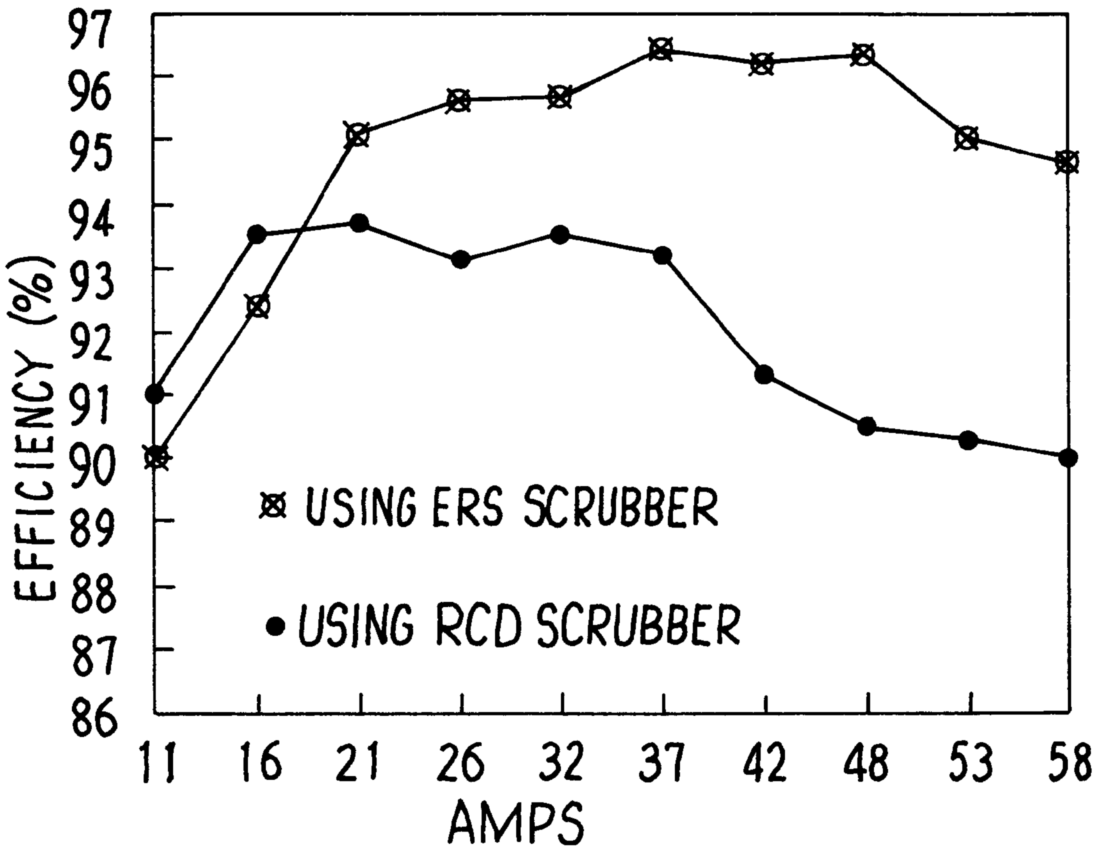
97
96
95
94
93
92
91
90
89
88
87
86
EFFICIENCY (%)
USING ERS SCRUBBER
USING RCD SCRUBBER
11
16
21
26
32
37
42
48
53
58
AMPS

FIG. 15

CIRCULATING CURRENT FREE TYPE HIGH FREQUENCY SOFT SWITCHING PULSEWIDTH MODULATED FULL BRIDGE DC/DC CONVERTER

FIELD OF THE INVENTION

This invention relates to a high frequency soft switching phase-shifted full bridge DC/DC converter free from a circulating current flowing through the transformer and switching devices. The DC/DC converter would be applied to the main unit of the power supply in a battery charger of a telecommunication system, etc.

BACKGROUND OF THE INVENTION

Recently, many new techniques for high-frequency conversion have been proposed to reduce the voltage and current stress to the component, and the switching losses in the traditional pulsewidth-modulated (PWM) converter. Among them, the phase-shifted full-bridge (FB) zero-voltage-switched PWM techniques (Dhaval B. Dalal, "A 500 KHz Multi-Output Converter with Zero Voltage Switching", APEC, 1990) are deemed most desirable for many applications because this topology permits all switching devices to operate under zero-voltage-switching (ZVS) by using circuit parasitic characteristics such as transformer leakage inductance and power device junction capacitance.

The conventional high frequency phase-shifted full bridge DC/DC converter has a disadvantage that the circulating current flows through transformer and switching devices during the freewheeling interval. The RMS current stress and conduction losses of transformer and switching devices are increased by this circulating current.

This invention solves these problems by attaching an energy recovery snubber (ERS or ERS**1**) to the secondary side of the transformer in the DC/DC converter. The energy recovery snubber (ERS or ERS1) of this invention has three fast recovery diodes Ds_1, Ds_2 and DS_3, two resonant capacitors Cs_1 and Cs_2, and a small resonant inductor Lr which can be ignored because the transformer leakage inductance L_l is used instead of inserting the resonant inductor Lr.

FIG. **1** shows a prior art full bridge DC/DC converter schematic circuit and relevant wave-forms thereof are shown in FIG. **2** and FIG. **3**. The circuit includes parasitic elements such as body diodes D_1, D_2, D_3 and D_4, junction capacitance Cp across each switching device, leakage inductance L_l, and magnetizing inductance Lm of the transformer. In the case of regular PWM control, shown in FIG. **2**, until the time at t_0, the energy is delivered from the source to the load through switches Q_1 and Q_2. When the switches Q_1 and Q_2 are turned off, the load current I_0 flows through rectifiers D_5 and D_6 during the freewheeling interval t_0–t_1 or t_2–t_3. Then, the transformer primary current ($I_1(t)$) becomes zero.

The main problem with this operating sequence is that when all four switches are turned off (t_o, t_2), the energy stored in the leakage inductance of the power transformer causes severe ringing with the junction capacitances of the switching devices.

To minimize the parasitic ringing as shown in FIG. **3**, the gate signals for switches Q_2 and Q_4 are delayed (phase-shifted) with respect to those of Q_1 and Q_3, so that during the time interval t_2–t_3 and t_7–t_8 when the secondary voltage is zero, one of the primary switches is always left on. This provides a low-impedance path for the current of the transformer leakage inductance L_l to circulate, thus solving the problem of the parasitic ringing associated with the conventional PWM control hard-switching FB converter (FIGS. **1** and **2**).

However, when switch Q_1 is turned off at time t_1 (switch Q_3 at time t_6), the primary current I_1, which is the sum of the reflected output current nI_o and the transformer primary magnetizing current Im, circulates through Q_2 and D_3 during freewheeling mode t_1–t_3 and decrease with a slope of the following equation (1):

$$\frac{dI_1(t)}{dt} = \frac{-V_o}{L_1 + n^2 L_f} \quad (1)$$

wherein n is a turns ratio of the transformer given as n=Ns/Np.

Due to this circulating current, RMS current stress, conduction losses of the transformer and switching devices are increased. The overall efficiency is also reduced.

SUMMARY OF THE INVENTION

The present invention is based on the object of providing a full bridge PWM DC/DC converter which minimizes the commutating and circulating current flowing through the transformer and switching devices. By applying an energy recovery snubber (ERS or ERS1), the converter achieves nearly zero current switching for the right legs Q_2 and Q_4 of the converter and obtains zero voltage switching for the left legs Q_1 and Q_3 of the converter.

Further, the converter achieves soft switching for the secondary side rectifiers $D_{5\ 1}$, D_6 and D_7. A circuit analysis and experiment according to the invention are performed to verify the topology by implementing a 7kw (12 VDC, 58 A), 30 kHz Insulated Gate Bipolar Transistor (IGBT) based experimental circuit.

This invention solves the above described problems—RMS current stress and conduction losses and so on associated with the conventional high frequency DC/DC converter. A high frequency, soft switching Full Bridge DC/DC converter free from a circulating current includes an energy recovery snubber attached to the secondary side of the transformer.

The energy recovery snubber (ERS or ERS1) of the present invention recovers the switching losses of the transformer secondary side to the load. It has three fast recovery diodes Ds_1, Ds_2, and Ds_3, two capacitors Cs_1 and Cs_2, and a small resonant inductor Lr. The small resonant inducter Lr may be ignored or removed because the transformer leakage inductance L_l may be used instead of inserting the small resonant inducer Lr in to the circuit.

The energy stored in the snubber capacitors Cs_1, Cs_2 during conduction mode begins discharging when the transformer secondary voltage in the freewheeling intervals becomes zero. Due to the discharging of the snubber capacitors Cs_1 and Cs_2, the output rectifiers D_5 and D_6 are reverse biased and the secondary windings of the transformer are open. Both primary and secondary currents in the transformer become zero.

Only a low magnetizing current Im circulates through D_3 and Q_2 during the freewheeling interval. Thus, the RMS current for the transformer and switches is considerably reduced during the freewheeling interval. The overall efficiency can be increased by the resultant lowered conduction losses. Additionally, the converter achieves nearly zero current switching for the right legs Q_2 and Q_4 due to the minimized circulating current during a right leg transition interval, and achieves zero-voltage-switching ZVS for the left legs Q_1 and Q_3 due to the reflected output current (nI_o=It_1, n=Ns/Np) during a left leg transition interval.

The converter achieves soft switching for secondary side rectifiers D_5 and D_6 and freewheeling diode D_7 because at the turn-on time of switches Q_1, Q_2, and Q_3, Q_4, the energy recovery snubber provides a low impedance path, for example the path of transformer→snubber capacitor Cs_1→snubber diode Ds_3→a small resonant inductor Lr (which can be ignored)→snubber capacitor Cs_2.

BRIEF DESCRIPTION OF THE DRAWINGS

The circulating current free type, high frequency, soft switching PWM Full Bridge DC/DC converter according to the present invention will be described in detail below with reference to embodiments shown in the accompanying drawings, in which:

FIG. **1** shows a schematic circuit of a prior art full bridge DC/DC converter;

FIG. **2** shows the wave forms of the hard-switching full bridge converter with regular PWM of FIG. **1**;

FIG. **3** shows the wave forms of phase-shifted FB DC/DC converter according to FIG. **1**;

FIG. **4** shows a circuit of a high frequency, soft switching phase-shifted full bridge DC/DC converter with energy recovery snubber (center-tapped transformer) having a circulating current free type, according to the present invention;

FIG. **5** shows the principal operation wave forms of the FIG. **4** circuit;

FIGS. **6**(*a*), **6**(*b*), **6**(*c*), **6**(*d*), **6**(*e*), **6**(*f*) show circuit configurations for the six operating modes of FIG. **4**, with FIG. **6**(*a*) showing Mode 0: Q_1 Q_2 conducting and Cs_1, Cs_2 charging; FIG. **6**(*b*) showing Mode 1: Q_1 Q_2 conducting (powering mode); FIG. **6**(*c*) showing Mode 2: the left leg transition; FIG. **6**(*d*) showing Mode 3: the freewheeling mode with Cs_1, Cs_2 discharging; FIG. **6**(*e*) showing Mode 4: the right leg transition; FIG. **6**(*f*) showing Mode 5: Q_4, Q_3 conducting and Cs_1, CS_2 charging;

FIG. **7** shows a circuit of a phase-shifted full-bridge DC/DC converter with energy recovery snubber (ERS1) according to the present invention (center-tapped transformer without a snubber inductor);

FIG. **8** shows a circuit of a phase-shifted full bridge DC/DC converter with energy recovery snubber (ERS) according to the present invention (single-tapped transformer with the snubber inductor);

FIG. **9** shows a circuit of a phase-shifted full-bridge DC/DC converter with energy recovery snubber (ERS1) according to the present invention (single-tapped transformer without a snubber inductor);

FIG. **10** shows a circuit of a half-bridge DC/DC converter with energy recovery snubber (ERS1) according to the present invention (center-tapped transformer without a snubber inductor);

FIG. **11** shows a circuit of a half-bridge DC/DC converter with energy recovery snubber (ERS1) according to the present invention (single-tapped transformer) without a snubber inductor;

FIGS. **12**(*a*) and **12** (*b*) show wave forms of the conventional phase-shift ZVS FB DC/DC converter with RCD snubber ERS in FIGS. **1** and **3** wherein FIG. **12**(*a*) depicts the voltage and current waveforms present on the primary side of the transformer and FIG. **12**(*b*) depicts the voltage and current waveforms present on the secondary side of the transformer.

FIGS. **13**(*a*) and **13**(*b*) show wave forms of the phase-shifted FB DC/DC converter with energy recovery snubber (ERS) in FIGS. **4** and **5** wherein FIG. **13**(*a*) depicts the voltage and current waveforms present on the primary side of the transformer and FIG. **13**(*b*) depicts the voltage and current waveforms present on the secondary side of the transformer;

FIGS. **14**(*a*) and **14**(*b*) show wave forms of the soft switching FB DC/DC converter with energy recovery snubber (ERS) (without a resonant inductor) in FIG. **7** wherein FIG. **14**(*a*) depicts the voltage and current waveforms present on the primary side of the transformer and FIG. **14**(*b*) depicts the voltage and current waveforms present on the secondary side of the transformer;

FIG. **15** shows the efficiency by comparing the invented DC/DC converter with the conventional ZVS DC/DC converter wherein the Vin applied to each converter is 280 VDC and Vout is 120 VDC.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

This invention will be now described with reference to the accompanying drawings. FIGS. **4** and **5** show a circulating current free type high frequency, soft switching, phase-shifted full bridge DC/DC converter that applies an energy recovery snubber (ERS) to minimize circulating current and their principal wave forms. A detailed circuit configuration of the power stage follows. Four switches Q_1–Q_4 form the full bridge with the power transformer.

The secondary side of high frequency transformer is center-tapped (or single-tapped) with output rectifiers. output inductor L_f and output capacitor C_o are used to smooth output current I_o and output voltage V_o. The energy recovery snubber has three fast recover diodes Ds_1, Ds_2 and Ds3, two resonant capacitor Cs_1 and Cs_2, and a small resonant inductor Lr. The small resonant inductor Lr can be ignored because the transformer leakage inductance L_l is used instead of inserting the small resonant inductor Lr. The energy recovery snubber is inserted between the transformer secondary side rectifier D_5 and D_6 and the output inductor Lf to reduce the circulating current.

By using the energy recovery snubber instead of adding a tapped inductor and a saturable reactor to reduce RMS current stress such as described in references(S. Hamada, Y. Maruyama, M. Nakaoka, "Saturable Reactor Assisted Soft-Switching Technique in PWM DC-DC Converters", PESC, 1992; and S. Hamada, M. Michihira, M. Nakaoka, "Using A Tapped Inductor for Reducing Conduction Losses in a Soft Switching PWM DC-DC Converter", EPE, 1993), the converter can reduce the circulating current flowing during freewheeling intervals t_3–t_4 and t_8–t_9.

As shown in FIG. **5**, the energy stored in the snubber capacitors Cs_2 and Cs_1 during conduction mode (t_o–t_2, t_5–t_7) starts discharging when the transformer secondary voltage in the freewheeling intervals becomes zero. Due to the discharging of the snubber capacitor Cs_1 and Cs_2, the rectifiers D_5 and D_6 are reverse-biased and the secondary windings of the transformer are opened. Therefore, both primary and secondary currents of the transformer become zero. Only a low magnetizing current Im circulates through D_3 and Q_2 during freewheeling interval in mode 3, shown in FIG. **6**.

Thus, the RMS current through the transformer and switches is considerably reduced in the freewheeling intervals t_3–t_4 and t_8–t_9. Hence, the converter achieves nearly zero current switching for the right legs Q_2 and Q_4 due to the minimized circulating current during the interval of right leg transition t_4–t_5, and achieves zero voltage switching for the left legs Q_1 and Q_3 due to the reflected output current

($nI_o=It_1$, n=Ns/Np) during the interval of left leg transitions t_2–t_3. Also, the converter achieves soft switching for secondary side rectifiers D_5 and D_6 and freewheeling diode D_7 because at the turn-on time of switches Q_1, Q_2 and Q_3, Q_4, the energy recovery snubber provides a low impedance path such as: transformer→snubber capacitor Cs_1→snubber diode Ds_3→a small resonant inductor Lr (which can be ignored in this application)→snubber capacitor Cs_2.

A snubber adopted in this invention recovers the switching losses to the load. As the diode Ds_2 is reverse-biased with zero initial conditions for the passive elements, the circuit operation of the invented circulating current free type, soft switching Full Bridge DC/DC converter is described as follows.

Mode 0: The reflected primary current (It_1/n) begins to flow to Cs_1, Lr (Lr can be ignored in this application) and Cs_2 providing a low impedance path through the transformer and rectifiers D_5 and D_6 when the switches Q_1, and Q_2 are conducting during time (t_o–t_1). During the charging process, if the voltage across Cs_2 becomes higher than Vt2 before the current reversing, Ds_2 starts conducting and constitutes a new resonant circuit through Lr and Cs_1. However, since Ds_3 is still reverse-biased, snubber capacitor Cs_1 and Cs_2 are charged up to the transformer secondary voltage Vt_2 evenly and stay charged until mode 2.

$$V_{cs2}(t) = \frac{V_{t2}}{2}\left[1-\cos\left[\sqrt{\frac{C_{s1}+C_{s2}}{(n^2L_f+L_r)(C_{s1}\cdot C_{s2})}}\,\right]\cdot t\right] \tag{2}$$

Also, the converter is transferring input power to the secondary side through transformer, D_6, D_5 and L_f.

Mode 1: After the snubber capacitors Cs_1 and Cs_2 are charged up to Vt_2 at time t_1, the converter transfers only input power to the load. If it is assumed that the output voltage V_o is a constant voltage source during this mode (energy transferring mode), the transformer primary current is increased with the slope of equation (3).

$$I_1(t) = \frac{V_{in} - \frac{V_o}{n}}{L_l + L_f/n^2} \tag{3}$$

wherein L_l is leakage inductance and L_f/n^2 is reflected output filter inductor.

Mode 2: Just before the time t_2, the switches Q_1 and Q_2, and rectifiers D_5 and D_6 are conducting. When the switch Q_1 is turned-off at the time t_2, energy stored in the snubber capacitors Cs_1 and Cs_2 begins discharging, and a circulating current which is the sum of the reflected output current nI_o and a low magnetizing current Im charges the junction capacitance C_p of Q_1 and discharges the junction capacitance C_p of Q_3 during the time interval t_2–t_3.

$$V_1(t) \approx \left(\frac{nI_o + I_m}{2C_p}\right)t \tag{4}$$

After the junction capacitance voltage $V_1(t)$ of Q_1 reaches input voltage Vin, body diode D_3 conducts prior to turn-on of the switch Q_3. Therefore, the switches Q_1 and Q_3 easily achieve zero voltage switching due to the reflected output current nI_o during the interval of the left leg transition t_2–t_3.

Mode 3: Due to the discharging of the snubber capacitors, Cs_1 and Cs_2, the rectifiers D_5 and D_6 are reverse-biased and the secondary windings of the transformer are opened. Therefore, both primary and secondary currents of the transformer become zero. Only a low magnetizing current Im circulates through D_3 and Q_2. The current I_o in output inductor L_f freewheels first through Cs_1, Cs_2 and L_f, and then freewheels through freewheeling diode D_7 and output inductor L_f after snubber capacitors Cs_1 and Cs_2 are completely discharged. Thus, the RMS current for the transformer and switches is considerably reduced in the freewheeling interval t_3–t_4.

Mode 4: When switch Q_2 is turned-off with nearly ZCS and ZVS at the end of freewheeling period t_4, the right leg transition starts and only a low magnetizing current Im flowing through the primary transformer transfers little energy to capacitors C_p of the switching devices Q_2 and Q_4. The stray capacitance voltage $V_2(t)$ of Q_2 increases with a slope of equation (5).

$$V_2(t) \approx \left(\frac{I_m}{2C_p}\right) \tag{5}$$

Mode 5: Switch Q_4 is also turned-on with ZCS at time t_5. Like Mode 0, the reflected primary current It_1/n begins to flow to Cs_1, Lr (again Lr can be ignored) and Cs_2 provide a low impedance path through transformer and rectifiers D_5 and D_6 and the input power is transferred to the load.

A circulating current free type, high frequency, soft switching DC/DC converter, according to the invention, has as its main circuit the phase-shifted full bridge DC/DC converter consisting of main switching devices Q_1, Q_2, Q_3 and Q_4, center-tapped (or single-tapped as shown FIG. **8**) transformer, rectifiers D_5 and D_6, freewheeling diode D_7, output filter L_f and C_o, and energy recovery snubber ERS. This circulating free type full bridge DC/DC converter has conduction losses from the switching devices, copper loss in the high frequency transformer, and reverse recovery loss of rectifiers D_5 and D_6 along with freewheeling diode D_7, which should be reduced. The energy recovery snubber attached between the transformer secondary side rectifiers D_5 and D_6 and output inductor L_f consists of three fast recovery diodes Ds_1, Ds_2 and Ds_3, two capacitors Cs_1 and Cs_2 and a small resonant inductor Lr (which can be ignored because the transformer leakage inductance L_l is useable instead of inserting a small resonant inductor Lr as shown FIG. **7**).

The energy stored in the snubber capacitor Cs_1 and Cs_2 during conduction intervals t_o–t_2 and t_5–t_7 starts discharging when the transformer secondary voltage during freewheeling intervals t_3–t_4 and t_8–t_9 becomes zero. Due to the discharging of the snubber capacitors Cs_1 and Cs_2, the output rectifiers D_5 and D_6 are reverse-biased and the secondary windings of the transformer are opened. Both primary and secondary currents of the transformer become zero. Only a low magnetizing current Im circulates through D_3 and Q_2 during freewheeling interval t_3–t_4 or D_1 and Q_4 in freewheeling interval t_8–t_9.

The RMS current through the transformer and switches is considerably reduced in the freewheeling intervals t_3–t_4 and t_8–t_9. Therefore, conduction loss of the switching devices and copper loss of the high frequency transformer are reduced. Also, the converter achieves nearly zero current switching for the right leg Q_2 and Q_4 due to the minimized circulating current during the interval of right leg transition, and achieves zero voltage switching for the left legs Q_1 and Q_3 due to the reflected output current ($nI_o=It_1$, n=Ns/Np) during the interval of left leg transition.

The converter achieves soft switching and reduces a reverse recovery loss for secondary side rectifiers D_5 and D_6

along with freewheeling diode D_7 because at the turn-on time of switches Q_1, Q_2 and Q_3, Q_4, the energy recovery snubber ERS provides a low impedance path such as transformer→snubber capacitor Cs_1→snubber diode Ds_3→a small resonant inductor Lr (which can be ignored)→snubber capacitor Cs_2.

The circulating current free type, high frequency, phase-shifted full bridge (or half bridge) DC/DC converter according to the invention is able to apply the energy recovery snubber ERS1 as shown in FIG. **7**, FIG. **9**, FIG. **10** and FIG. **11** in which a small resonant inductor Lr is not included. Due to use of the energy recovery snubber ERS1, the invented converter reduces the conduction losses in the primary side because output rectifiers D_5 and D_6 are reverse-biased and the secondary windings of the transformer TR are opened by blocking the voltage of the snubber capacitors Cs_1 and Cs_2 during the discharging mode thereof. Also, the converter with energy recovery snubber ERS1 does not generate the severe parasitic ringing or create diode reverse recovery loss in the secondary side because the energy recovery snubber ERS1 provides a low impedance path such as transformer→snubber capacitor Cs_1→snubber diode Ds_3→snubber capacitor Cs_2 during the conduction mode. However, the converter has a minor drawback wherein the secondary side voltage Vt_2 is slightly increased as shown in the experimental wave-forms of FIG. **14**.

The circulating current free type, high frequency, phase-shifted full bridge DC/DC converter of the invention has 6 operating modes in order to achieve soft switching and the reduced conduction loss, and has operational wave-forms corresponding with the above modes as shown FIG. **5** and FIG. **6**.

The circulating current free type, high frequency, soft switching, phase-shifted full bridge DC/DC converter of this invention is able to use not only center-tapped transformer (FIG. **4**, FIG. **7** and FIG. **10**) but also single-tapped transformer (FIG. **8**, FIG. **9** and FIG. **11**).

The half bridge DC/DC converter, as shown in FIG. **10** and FIG. **11**, is connect the energy recovery snubber ERS1 between the transformer secondary side rectifiers D_5 and D_6 and output inductor L_f to achieve soft switching and to reduce reverse recovery losses for main switching devices Q_1 and Q_2 secondary side rectifiers D_5 and D_6 and freewheeling diode D_7.

According to the present invention, experimental results are shown as in the followings: A 7Kw (120VDC, 58A), 30kHz IGBT based experimental circuit has been implemented to demonstrate the operation. The parameters of the circuit are as follows:

Q_1–Q_4: IGBT (2MBI120L060, 600V, 200A)

D_1–D_4: Body diodes of IGBT

C_p: 14 nF (stray capacitance of IGBT)

Lm: 286 uH (magnetizing inductance of transformer)

L_l: 3.5 uH (leakage inductance of transformer)

n: Transformer turn ratio (n=Ns/Np=6/8=0.75)

Cs_1, Cs_2: 0.2 uF (snubber capacitor)

Lr: 3 uH (snubber inductor)

Ds_1–Ds_3: snubber diode

D_5, D_6, D_7: Rectifier, freewheeling diode

L_f: 500 uH (output inductor)

δt: 1.3 us (dead time).

FIG. **12**, FIG. **13** and FIG. **14** show the voltage and current wave-form of the primary and secondary side of transformer in the converter with a RCD snubber (FIG. **1** and FIG. **3**) and the converter with an energy recovery snubber (FIG. **4**, **5** and FIG. **7**), respectively. Comparing FIG. **12** with FIG. **13** and FIG. **14**, it can be seen that by using an energy recovery snubber ERS or ERS1, the circulating current I_1, decreases nearly to zero and only a low magnetizing current Im is flowing during the freewheeling interval. Also, due to the reduced circulating current, soft switching is achieved without peak voltage and severe ringing from a light load to a full load.

FIG. **15** shows the measured efficiency of the proposed soft switching DC/DC converter in comparison with the conventional ZVS DC/DC converter. The efficiency of the invented converter with an energy recovery snubber shows especially a low efficiency characteristics in a light load state (below 16 A) even though the circulating current is reduced during the freewheeling interval. The reduced efficiency characteristics in the light load state is due to the charging current flowing through the snubber capacitors. However, when the load current is increased above **16**A, the efficiency of the invented converter with an energy recovery snubber shows some improvement (2% –4%) over the conventional ZVS DC/DC converter due to reduced circulating current and application of the non-dissipated snubber.

The converter according to the present invention can minimize the commutating and circulating current flowing from the transformer and switching devices. By applying an energy recovery snubber, the converter achieves nearly zero current switching for the right legs Q_2 and Q_4 and achieves zero voltage switching for the left legs Q_1 and Q_3.

Further, the converter achieves soft switching for the secondary side rectification diodes D_7, D_5 and D_6. A circuit analysis and experiment are performed to verify the proposed topology by implementing a 7 kW(120 VDC,58 A), 30 kHz IGBT based experimental circuit.

What I claim is:

1. A DC/DC converter comprising:

a DC/DC converter circuit including:

first and second switching transistors that are series-connected together across terminals for receiving an input voltage;

third and fourth switching transistors that are series-connected to each other and that are connected in parallel across said first and second switching transistors;

a transformer through which a circulating current flows having a primary winding that is connected between a junction of said first and second switching transistors and a junction of said third and fourth switching transistors and a secondary winding, said secondary winding having a center tap;

first and second rectifying diodes, each said rectifying diode having an anode attached to a separate end of said secondary winding;

a freewheeling diode having a cathode connected to cathodes of said rectifying diodes, and an anode connected to said center tap of said secondary winding;

an output filter connected at one end to a cathode of said freewheeling diode; and

an energy recovery snubber connected between said rectifying diodes and said output filter, said energy recovery snubber including:

a first snubber diode and a first snubber capacitor that are series connected together and that are connected across said freewheeling diode wherein an anode of said first snubber diode is connected to an anode of said freewheeling diode, and one end of said first snubber capacitor is connected to said cathode of said freewheeling diode;

a second snubber diode and a second snubber capacitor that are series connected together and that are connected across said freewheeling diode wherein a cathode of said second snubber diode is connected to said cathode of said freewheeling diode, and one end of said second snubber capacitor is connected to said anode of said freewheeling diode;

a third snubber diode connected in a forward biased orientation between a junction of said first snubber diode and said first snubber capacitor and a junction of said second snubber diode and said second snubber capacitor, so that said snubber capacitors are charged during conduction modes and discharged during freewheeling modes, said first and second rectifying diodes being reverse biased when said capacitors are discharged so that said secondary winding is opened so that, in the freewheeling mode, the circulating current flow through said secondary winding falls to zero so as to cause a reduction in current flow through said primary winding, said energy recovery snubber being free from a snubber inductor.

2. The DC/DC converter of claim **1**, wherein the first and second snubber capacitors have a value of 0.2 μ f.

3. A half-bridge DC/DC converter comprising:

a DC/DC converter circuit including:

first and second bridge capacitors that are series-connected together across terminals for receiving an input voltage;

first and second switching transistors that are series-connected to each other and that are connected in parallel across said first and second bridge capacitors;

a transformer through which a circulating current flows having a primary winding that is connected between a junction of said first and second bridge capacitors and a junction of said first and second switching transistors and a secondary winding, said secondary winding having a single tap;

first and second rectifying diodes, said first and second rectifying diodes having anodes attached to a separate end of said secondary winding and cathodes connected to each other;

third and fourth rectifying diodes, said third and fourth rectifying diodes having cathodes attached to separate ends of said secondary winding, and anodes connected to each other;

an output filter connected at one end to said cathodes of said first and second rectifying diodes and at another end to said anodes of said third and fourth rectifying diodes; and

an energy recovery snubber connected between said rectifying diodes and said output filter, said energy recovery snubber including:

a first snubber diode and a first snubber capacitor that are series connected together across said output filter wherein an anode of said first snubber diode is connected to said anodes of said third and fourth rectifying diodes, and one end of said first snubber capacitor is connected to the cathodes of said first and second rectifying diodes;

a second snubber diode and a second snubber capacitor that are series connected together and that are connected across said output filter wherein a cathode of said second snubber diode is connected to said cathodes of said first and second rectifying diodes, and one end of said second snubber capacitor is connected to said anodes of said third and fourth rectifying diodes; and

a third snubber diode connected in a forward biased orientation between a junction of said first snubber diode and said first snubber capacitor and a junction of said second snubber diode and said second snubber capacitor, said energy recovery snubber being free from a snubber inductor and free from a freewheeling diode.

4. The DC/DC converter of claim **3**, wherein said transformer has a turn ratio of 0.75.

5. The DC/DC converter of claim **3**, wherein said first and second snubber capacitors have a value 0.2 μ f.

6. A half-bridge DC/DC converter comprising:

a DC/DC converter circuit including:

first and second bridge capacitors that are series-connected together across terminals for receiving an input voltage;

first and second switching transistors that are series-connected to each other and that are connected in parallel across said first and second bridge capacitors;

a transformer through which a circulating current flows having a primary winding that is connected between a junction of said first and second switching transistors and a secondary winding, said secondary winding having a center tap;

first and second rectifying diodes, each said rectifying diode having an anode attached to a separate end of said secondary winding;

a freewheeling diode having a cathode connected to cathodes of said rectifying diodes, and an anode connected to said center tap of said secondary winding;

an output filter connected at one end to a cathode of said freewheeling diode; and

an energy recovery snubber connected between said rectifying diodes and said output filter, said energy recovery snubber including:

a first snubber diode and a first snubber capacitor that are series connected together and that are connected across said freewheeling diode wherein an anode of said first snubber diode is connected to an anode of said freewheeling diode, and one end of said first snubber capacitor is connected to said cathode of said freewheeling diode;

a second snubber diode and a second snubber capacitor that are series connected together and that are connected across said freewheeling diode wherein a cathode of said second snubber diode is connected to said cathode of said freewheeling diode, and one end of said second snubber capacitor is connected to said anode of said freewheeling diode;

a third snubber diode connected in a forward biased orientation between a junction of said first snubber diode and said first snubber capacitor and a junction of said second snubber diode and said second snubber capacitor, so that said snubber capacitors are charged during conduction modes and discharged during freewheeling modes, said first and second rectifying diodes being reverse biased when said capacitors are discharged so that said secondary winding is opened so that, in the freewheeling mode, the circulating current flow through said secondary winding falls to zero so as to cause a reduction in current flow through said primary winding, said energy recovery snubber being free from a snubber inductor.

7. The DC/DC converter of claim **6**, wherein the transformer has a turn ratio of 0.75.

8. The DC/DC converter of claim **6**, wherein the first and second snubber capacitors have a value 0.2 μ f.

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