SOFT SWITCHING AND LOSS ANALYSIS OF A HALF-BRIDGE DC-DC CONVERTER WITH IGBT-MOSFET PARALLEL SWITCHES

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ABSTRACT - Due to high power ratings and low conduction loss, the IGBT has become more attractive in high power applications. However, its slower characteristics than those of MOSFET cause severe switching losses and switching frequency limitation.

This paper proposes the IGBT's soft switching concept with the help of MOSFET, where each of the IGBT and MOSFET plays its role during on-periods and switching instants. Also, the switching losses are analyzed by using the linearized modeling and the operations of a converter are investigated to confirm the soft switching of IGBTs.

1. INTRODUCTION

High performance and reliability are required to the converter for communication facilities, where IGBTs are more attractive than MOSFETs due to the lower conduction voltage drop and higher power ratings. However, IGBT's relatively slow characteristics cause severe switching losses, especially turn-off loss, a decrease in efficiency and a limitation of switching frequency.

One of methods to make use of the high power ratings of IGBT at a higher switching frequency is to use capacitor added in parallel with the IGBT.[1] But the capacitor is charged with the saturation voltage generated at turn-on and the internal inductance and external capacitance consists of a oscillation circuit. As a result, the switching losses are increased. Especially, such drawbacks become more severe in high frequency operation for its zero voltage switching.

Recently, ZVT PWM method has been reported, which greatly reduce the voltage and current stress of active and passive switches.[2] But, since its method need auxiliary switches and passive devices correspondent to a number of main power switches, the overall circuit become more complex and expensive.

To overcome these difficulties, it was proposed a method using IGBT-MOSFET parallel switch coupled IGBT and MOSFET in parallel.[3],[4] This method is known to achieve the soft switching of IGBT with the aid of the fast MOSFET, where the IGBT is the main power switch and its soft switching can be realized by parallelled MOSFET. Using parallel switch, the soft switching of IGBT is achieved at turn-off process and not at turn-on process. The reason is that the turn-on time of IGBT is not much greater than that of MOSFET.

In this paper, an advanced method to achieve the soft switching of IGBT even at turn-on process is proposed in 48V, 50A half-bridge DC-DC converter using IGBT-MOSFET parallel switches, which converter is for communication facilities. Also, the switching loss and conduction loss are analyzed by using the linearized model. To verify the proposed method, the operation of the converter are investigated by simulations and experiments.

2. CONSTRUCTION OF CONVERTER

There are two possible ways for DC power supplies to obtain a constant DC output voltage. One is the one-stage scheme that is generally suitable for cheap and low power converters. The other is the two-stage scheme that can be dealt with various control methods and is suitable for high power converters.

In the two-stage scheme as shown in Fig. 1, AC-DC converter is generally a boost PFC circuit and DC-DC converter is a half-bridge or full-bridge converter. Although the full-bridge converter has the advantage in power ratings, the half-bridge converter is also suitable in a few kW grade and has another merit in a number of switching devices.

In this study, under the condition of 400V DC input and 48V DC output, a half-bridge circuit is employed as the DC-DC converter shown in Fig. 2.

In the half-bridge circuit, the main power switches are IGBTs(Q_{11}, Q_{12}), and parallel MOSFETs(Q_{21}, Q_{22}) are relatively small auxiliary switches. As a secondary circuit, it is selected the center tap type full-wave rectifier that has an advantage over the low-voltage output characteristics and efficiency.

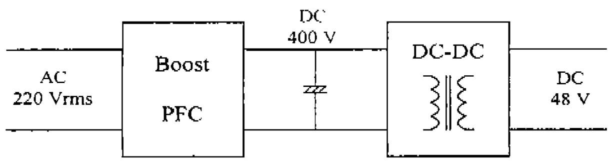


Fig. 1 Scheme of two-stage DC power supply.

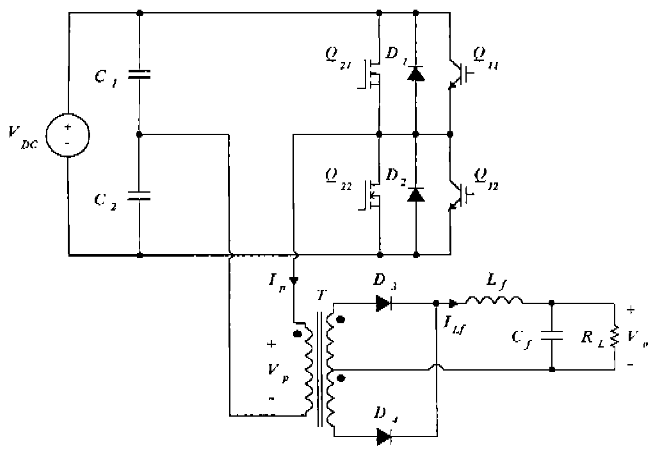


Fig. 2 Half-bridge DC-DC converter using IGBT-MOSFET parallel switches.

3. ANALYSIS OF LOSSES AND OPERATION

3.1 Losses in parallel switch

In this paper, IGBT-MOSFET parallel switches as shown in Fig. 3(a) are used for the soft switching of IGBT and the reduction of switching losses.

For the soft switching of IGBT, it is important the timing that gate signals are applied to parallel switches. Turn-on signals should be applied to MOSFET in advance of IGBT and turn-off signals to IGBT in advance of MOSFET as shown in Fig. 3(b). Since IGBT is turned on after MOSFET is turned on and turned off before MOSFET is turned off, the IGBT is switched under zero voltage condition. Although MOSFET is hard switched, the switching loss of MOSFET is much smaller than that of IGBT and then the efficiency of the converter can be improved.

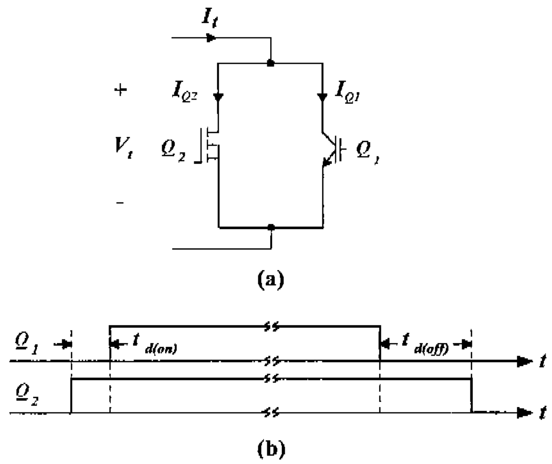


Fig. 3 (a) Parallel switch and (b) gate signals.

To analyze the switching loss and conduction loss in switching element, the waveforms of the voltage and current can be linearized.[5] Fig. 4 shows the voltage and current waveforms in case that only the IGBTs are used as switching elements. Fig. 5 shows the current waveform of IGBT part and the voltage and current waveforms of parallel switch in case that IGBT-MOSFET parallel switch is used. From Figs. 4 and 5, equations to analyze the losses of a switch can be derived. The symbols used in Fig. 4 are defined as follows:

V_t : Voltage across the switch during off-period
V_{oni}, V_{onm} : Conduction voltage drops of IGBT and MOSFET
V_{on} : Conduction voltage drop of parallel switch
I_t : Current flowing through switch during on-period
t_{rii}, t_{rim} : Current rise times of IGBT and MOSFET
t_{fvi}, t_{fvm} : Voltage fall times of IGBT and MOSFET
t_{rvi}, t_{rvm} : Voltage rise times of IGBT and MOSFET
t_{fii}, t_{fim} : Current fall times of IGBT and MOSFET
$t_{i(on)}$, $t_{m(on)}$: Turn-on times of IGBT and MOSFET
$t_{i(off)}$, $t_{m(off)}$: Turn-off times of IGBT and MOSFET
t_{on} : Conduction time of IGBT per switching period
f_s : Switching frequency($=1/T_s$).

Firstly, we derive the equations describing the switching loss and conduction loss for the cases of Figs. 4 and 5. And then, the reduced losses are analyzed by comparing these resultant equations.

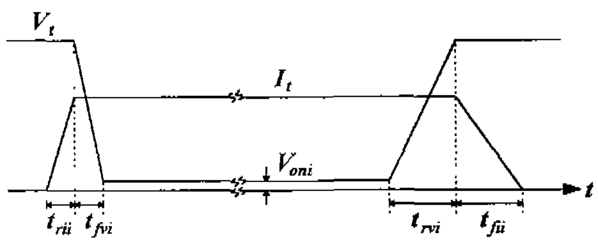


Fig. 4 Linearized waveforms of the voltage and current in case that only the IGBT is used as switching elements.

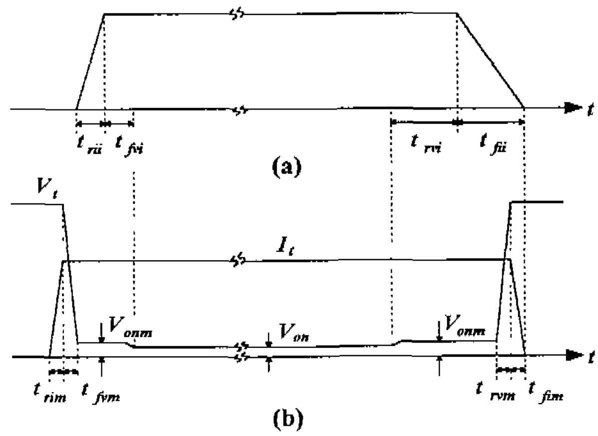


Fig. 5 Linearized waveforms of (a) the current in IGBT part and (b) the voltage and current in parallel switch.

From Fig. 4, it can be derived the turn-on loss for the case that only the IGBT is used as switching element. As $t_{i(on)}=t_{rii}+t_{fvi}$, the turn-on loss is expressed as

$$P_{i(on)} = V_t I_t t_{i(on)} f_s/2, \tag{1}$$

As $t_{m(on)}=t_{rim}+t_{fvm}$, the turn-on loss in parallel switch during the time of $t_{m(on)}+t_{i(on)}$ is

$$P_{p(on)} = V_t I_t t_{m(on)} f_s/2 + V_{onm} I_t t_{i(on)} f_s. \tag{2}$$

Thus, the reduced turn-on loss is obtained as

$$P_{s(turn-on)} = I_t f_s\{ (V_t/2)(t_{i(on)} - t_{m(on)}) - V_{onm} t_{i(on)}\}. \tag{3}$$

In the same way, the turn-off loss can be derived for the case that only the IGBT is used. As $t_{i(off)}=t_{rvi}+t_{fii}$, the turn-off loss is expressed as

$$P_{i(off)} = V_t I_t t_{i(off)} f_s/2, \tag{4}$$

As $t_{m(off)}=t_{rvm}+t_{fim}$, the turn-off loss in parallel switch during the time of $t_{i(off)}$ is

$$P_{p(off)} = V_t I_t t_{m(off)} f_s/2 + V_{onm} I_t (t_{i(off)} - t_{m(off)}) f_s. \tag{5}$$

Hence, the reduced turn-off loss is obtained as

$$P_{s(turn-off)} = (V_t/2 - V_{onm}) I_t f_s (t_{i(off)} - t_{m(off)}). \tag{6}$$

The conduction loss is also reduced when the parallel switch is used. Because MOSFET is connected in parallel with IGBT, the on-state resistance of parallel switch is smaller than that of IGBT. The reduced conduction loss is

$$\begin{aligned} P_{s(conduction)} &= P_{i(conduction)} - P_{p(conduction)} \\ &= \{ V_{oni} t_{on} - V_{on} (t_{on} - t_{m(on)})\} I_t f_s. \end{aligned} \tag{7}$$

With the above equations, the total reduced loss P_s per in one parallel switch is represented as

$$\begin{aligned} P_s = I_t f_s [& (V_t/2)\{ (t_{i(on)} - t_{m(on)}) + (t_{i(off)} - t_{m(off)})\} \\ & - V_{onm} (t_{i(on)} + t_{i(off)} - t_{m(off)}) \\ & + \{ V_{oni} t_{on} - V_{on} (t_{on} - t_{m(on)})\}]. \end{aligned} \tag{8}$$

3.2 Operation analysis of the converter

In IGBT-MOSFET parallel switch, the parallel switch is switched by the function of MOSFET and most current during the conduction period flows through IGBT due to the relatively low conduction voltage drop. If only the IGBTs are used for a converter shown in Fig. 2, there are four modes of operation. But the operation of the proposed circuit is divided into eight modes because of the differences of gate signals between IGBT and MOSFET. Fig. 6 shows the waveforms of converter, and the operation of each mode are described as follows.

Mode I (t_0 - t_1) : At t_0, Q_{21} is turned on in advance of Q_{11} as much as $t_{d(on)}$. At this time, the parallel switch is turned on by MOSFET with fast switching characteristics and thus the turn-on loss is reduced. After $t_{d(on)}$, the parallelled IGBT can be turned on without the stress of voltage since MOSFET Q_{21} is fully turned on.

In this mode, the power is transferred to the load, and the inductor current I_{Lf} begins to increase with the slope of $(n \cdot V_{DC}/2 - Vo)/L_f$. Here, n is the ratio of the number of turns of isolation transformer.[Fig. 7(a)]

Mode II(t_1 - t_4) : At t_1, Q_{11} is turned on. And during the turn-on time (t_1 - t_2) of IGBT Q_{11}, the input current of Q_{21} begins to be transferred to IGBT Q_{11} due to the lower conduction voltage drop.

At t_2, since Q_{11} is fully conducted, most input current flow through IGBT. Therefore, the continuous current ratings of MOSFET may be lower than that of IGBT. The operation of secondary circuit is the same as that of Mode I.

At t_3, IGBT Q_{11} is turned off in advance of MOSFET Q_{21} and most input current are rapidly transferred to Q_{21}. For the zero voltage switching of IGBT, parallel MOSFET Q_{21} is keeps being conducted during $t_{d(off)}$[Fig. 7(b)]

Mode III(t_4 - t_5) : MOSFET Q_{21} is also turned off at t_4. During the turn-off time (t_4 - t_5) of MOSFET, the parallel switch is rapidly turned off with the aid of MOSFET. Thus, the turn-off loss of parallel switch can be reduced. Here, the ZVS of IGBT is realized since the MOSFET is being conducted until the IGBT is fully turned off.

The operation of secondary circuit is equal to those of Modes I and II.[Fig. 7(c)]

Mode IV(t_5 - t_6) : At t_5, MOSFET Q_{21} is fully turned off. When the load is purely resistive, there is

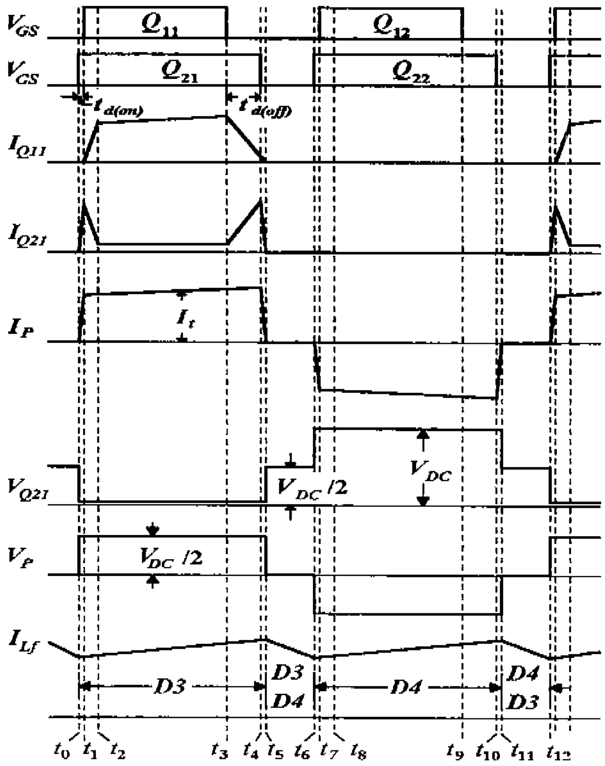
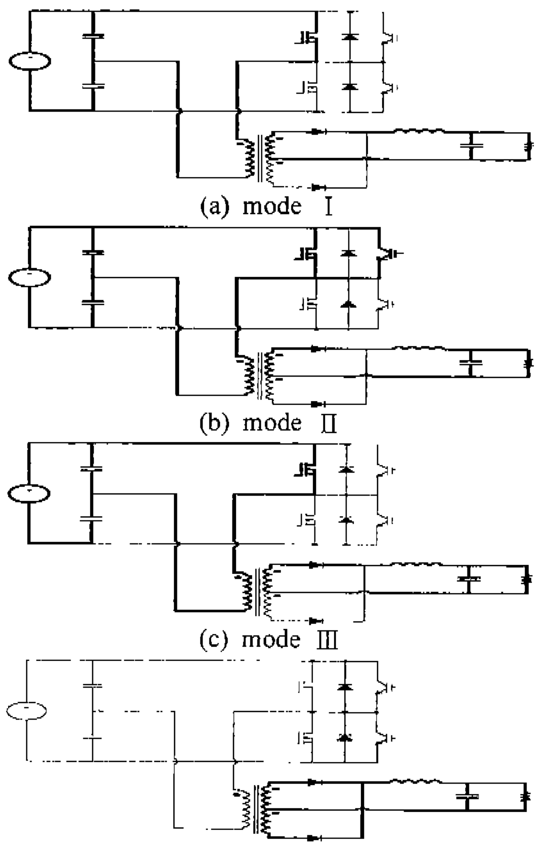


Fig. 6 Operation waveforms.



(a) mode I

(b) mode II

(c) mode III

(d) mode IV

Fig. 7 Operation in each mode.

current in the primary circuit and the current of the secondary circuit is free-wheeling through D_3 and D_4.[Fig. 7(d)]

Mode V ~ VIII is symmetrical to Mode I ~ IV at the other half switching cycle, where Q_{12} and Q_{22} are switched instead of Q_{11} and Q_{21}, and the role of D_4 is contrary to that of D_3.

4. AN EXAMPLE OF LOSS ANALYSIS

For the loss analysis, we calculate all the losses in half bridge DC-DC converter as an example. IGBT IRGBC30S and MOSFET IRF840 are selected and the data needed in calculation are as the followings.

V_t = 200[V]	I_t = 15.79[A]
$t_{i(on)}$ = 35[nsec]	$t_{i(off)}$ = 1500[nsec]
$t_{m(on)}$ = 21[nsec]	$t_{m(off)}$ = 20[nsec]
t_{on} = 16[μsec]	f_s = 25[kHz]
V_{oni} = 1.75[V]	V_{onm} = 12.63[V]
V_{on} = 1.54[V].	

Turn-on losses are determined from eqs. (1) and (2).

$$P_{i(on)} = 1.38[W]$$
$$P_{p(on)} = 1.00[W]$$

Hence, the reduced turn-on loss is obtained as follows:

$$P_{s(turn-on)} = 0.38[W].$$

Also, turn-off losses are determined from eqs. (4) and (5).

$$P_{i(off)} = 59.21[W]$$
$$P_{p(off)} = 8.17[W].$$

Therefore, the reduced turn-off loss is

$$P_{s(turn-off)} = 51.04[W].$$

Since the conduction losses are

$$P_{i(conduction)} = 11.06[W]$$
$$P_{p(conduction)} = 9.72[W],$$

the reduced loss during the conduction period is obtained as

$$P_{s(conduction)} = 1.34[W].$$

Because two switches are used in a half bridge converter, total losses are

$$P_i = 2\times(P_{i(on)} + P_{i(off)} + P_{i(conduction)}) = 143.30[W],$$

$$P_p = 2\times(P_{p(on)} + P_{p(off)} + P_{p(conduction)}) = 37.78[W].$$

Therefore, the reduced total loss by using parallel switches is obtained as follows:

$$P_{ps} = P_i - P_p = 105.52[W].$$

The reduced loss, 105.52W, is correspondent to 4.4% of the converter output. With the above results, the loss reduction ratio by using parallel switches can be obtained as

$$Loss\ reduction\ ratio(\%) = \frac{P_{ps}}{P_i} \times 100 = 73.64[\%].$$

5. SIMULATIONS AND EXPERIMENTS

To confirm the operation of parallel switches and the soft switching of IGBTs, the converter shown in Fig. 2 is tested. Test conditions are as follows:

Input voltage	:	DC 400[V]
Switching frequency	:	25[kHz]
Output voltage	:	DC 48[V]
Average output current	:	50[A]
IGBT	:	IRGBC30S
MOSFET	:	IRF840.

Figs. 8 and 9 are the simulated waveforms and experimental results of the converter. As shown in Figs. 8 and 9, IGBTs are switched under zero voltage condition and the IGBT and MOSFET play its main roles during on-periods and switching instants, respectively.

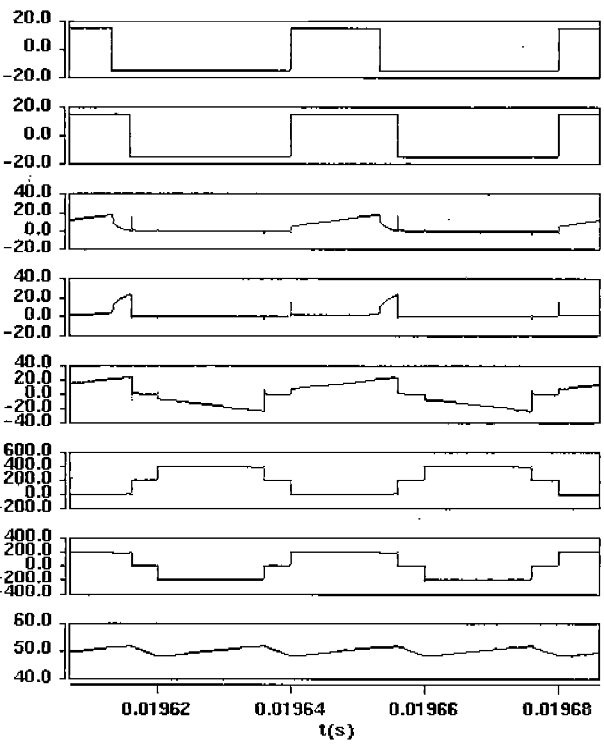


Fig. 8 Waveforms of converter. (From top, V_{GE11}, V_{GS21}, I_{Q11}, I_{Q21}, I_p, V_{Q21}, V_P, and I_{Lf}).

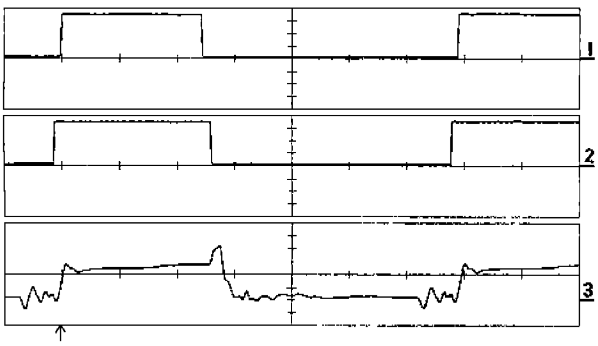


Fig. 9 Gate signals and current.
(From top, V_{GE11}, V_{GS21}, and I_{Q21}).

6. CONCLUSIONS

In this paper, to take the advantage of IGBT's high power ratings even at a high switching frequency, an advanced soft switching concept of IGBT is proposed, that can be realized with the aid of parallelled MOSFET. Loss equations are derived by using the linearized model and applied to a half bridge DC-DC converter as an example. Also, to verify the soft switching of IGBTs, the operation of the converter are investigated by simulations and experiments.

The advantages by using the parallel switches are summarized as follows:

(1) Switching characteristics is improved with the aid of MOSFET which has inherently the fast switching characteristics. And the soft switching of IGBT is achieved since IGBT is turned on and off while parallelled MOSFET is on-state.

(2) During conduction period, the voltage drop of parallel switches is lower than that of either IGBT or MOSFET.

(3) Efficiency is improved about 4.4% by taking the advantages of the IGBT and MOSFET.

(4) Due to the improved switching characteristics, the high power ratings of IGBT can be actively used even at high frequency. Here, the continuous current ratings of MOSFET may be relatively lower than that of IGBT.

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