NOVEL HIGH EFFICIENCY BASE DRIVE USING ZERO VOLTAGE SWITCHING CONVERTER

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ABSTRACT

A new small size and high efficiency base drive scheme is proposed using high frequency partial resonant converter with zero voltage switching(ZVS). By using this base drive, The performance of switching power transistor is enhanced to some extent because the transistor can be lightly saturated in accordance with the load condition owing to easy control capability of transistor base current.

I. Introduction

The power transistors have been found increasing popularity among power semiconductor devices in the industrial applications. The transistor switching speed is considerably faster than thyristor type devices because of excess minority carriers in the base can be removed by negative base current. Darlington transistors are more popular because of higher current gain, but the disadvantages are higher leakage current, higher conduction drop and reduced switching frequency.

The size and cost of transistors decrease along with the improvement of performance and reliability whereas those of base drive are seldom reduced. It is very important to achieve low cost, high efficiency and small size for the base drive. When high current flows through the transistors, small size high efficiency base drive is more important.

Conventional constant base drive circuit usually includes resistors in the base circuit as shown in Fig. 1. The resistor is used to limit the base current but the power is dissipated in the resistor directly proportional to the square of the base current. This type drive is to provide a constant base current without regard to load conditions. Therefore, storage time of power transistor is large at low collector currents if base current is high. A large storage time determines dead time of inverter leg. The required base current is to be rated continuously for full current any way, then efficiency is decreased at lower collector current.

Proportional base drive is a simple and effective method of achieving improve performance with high voltage switching transistor. During the ON time of the switching transistor, base drive is provided regeneratively from collector circuit through the drive transformer. But, drive transformer is bulky and heavy, and base drive is redesigned when power circuit is changed. Also, the proportional base drive has a limit to the maximum on-state period because of the transformer is magnetized at on-state

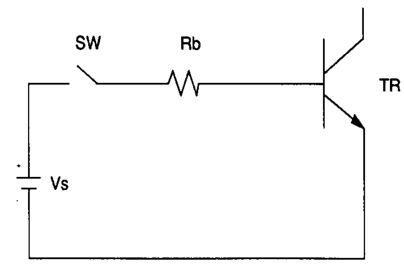

Fig. 1 Conventional constant base drive

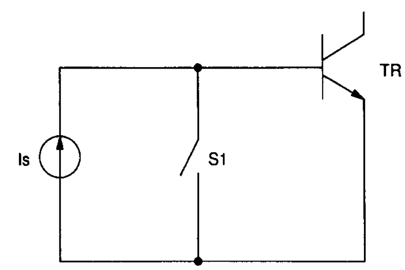

Fig. 2 Basic idea of the proposed base drive

The best way to achieve small size and high efficiency base drive is to get rid of the resistors in the base circuit omitting any feed-back path from the collector and has the capability of the proportional drive without any limitation to the maximum on-state period.

Hence, a new base drive using zero voltage switching converter is proposed in this paper. The proposed base drive is small size, light weight, high efficiency and no limitation to the maximum on-state time. As it is simple to control the current magnitude, it is implemented using a proportional drive with a suitable control law.

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II. Requirements for Effective Base Drive

The switching speed of power transistor can be increased by reducing turn-on time and turn-off time. The commonly used technique for effective base drive of a transistor are

1) Turn-on control,
2) Turn-off control,
3) Proportional base control,
4) Antisaturation control.

Turn-on control : Turn-on time can be reduced by allowing base current peaking during turn-on, resulting in low forced β at the beginning. After turn-on, β can be increased to a sufficiently high value to maintain the transistor in the quasi-saturation. The base current peaking can be achieved by overvoltage of base drive at turn-on instant.

Turn-off control : Turn-off time can be reduced by a negative base current which removes stored charge in the transistor allowing base current peaking during turn-off. This negative base current must be large enough to minimize storage time but not too large to cause tailing of the collector current, otherwise the reverse bias safe operating rating may be exceeded.

Proportional base control : This type of control has advantages over the constant drive circuit. If the collector current changes due to the variation of the conditions, the base drive current is changed proportional to the collector current.

Antisaturation control : If the transistor is driven into deep saturation, the storage time which is proportional to the base current increases and the switching speed is reduced. The storage time can be reduced by operating the transistor in light saturation rather than deep saturation. This can be accomplished by clamping the collector-emitter voltage to a predetermined level. The clamping action thus results in a reduced base current and almost eliminates the storage time. At the same time a fast turn-on is accomplished. However, due to the increment of the on-state voltage drop, the on-state power dissipation in the transistor is increased whereas the switching power loss is decreased.

Usually the basic ways to provide electrical isolation are by means of either fiber optics, optocouplers or transformers. The transformer used in the base drive is usually magnetized during the entire on-state period and demagnetized during turn off. This type of base drive generally include a third winding in series with the main device to provide base current proportional to the collector current. This kind of drive generally has a limitation to maximum on-state period. In addition if the current range of the transistor is high, the transformer size becomes excessively large and bulky. It is therefore not appropriate for high-current switches.

III. Basic Principle of the Proposed Base Drive

A transistor is a current-controlled device. This means that a current type base drive is more effective compared with voltage type. If the voltage type base drive is used, overvoltage required at switch-on for fast switching and to avoid tailing of the collector is quasi-saturation region. But current type base drive does not require the above mentioned conditions because sufficient base current at switch-on can be supplied. Therefore, a novel approach to the base drive of transistor is proposed as an optimal solution for high current applications. The basic principle of operation of proposed base drive is illustrated in Fig. 2. The current source I_s is used to supply the base current and the switch S_1 is used to control the switching of the power transistor.

The power transistor is in off state during the ON state of switch S_1. Conversely, the power transistor is in on state during the OFF state of switch S_1. During the off state of the transistor, the current I_s flows through switch S_1. There is no resistance included in this operation and thus loss is negligible.

Usually the power switching transistor operates in saturation during ON state for low conduction voltage drop. Since a large amount of internal charge is stored in this state, the base current need not be continuous. A converter with high frequency triangular current can be used to supply the ON state base current. When switching frequency of the converter is high enough, the magnetic material in transformer-coupled base drive circuit is a considerably small part of the total volume and mass of the base drive. Fig. 3 shows proposed base drive circuit using high frequency partial resonant half-bridge converter with zero voltage switching(ZVS) as for the current source I_s of Fig. 2.

The half-bridge circuit is to incorporate a simple mean of balancing the volt-second interval of each switch turned on without inserting air gap to the transformer or to use additional symmetry correction circuits. In the inverter or converter applications it is required for the base drive not to limit the maximum or minimum duration of the on and off state of the transistor. The proposed base drive places no limitation on the time duration for the on/off states of the power transistor.

IV. Operation of The Converter

Resonant capacitors C_1 and C_2 represent the output capacitances of the MOSFET switches, whereas D_1 and D_2 represent their body diodes as shown in Fig. 3. The voltage and current waveforms flowing through the switch and inductor L_r are shown in Fig. 4. As shown in this figure, the waveshape of the inductor current is determined according to three operation modes : powering, resonance and free-wheeling modes as shown in Fig. 4. The respective mode operations are as follows.

I) Powering Mode

The inductor current increases linearly from zero through switch Q_1. During this mode power is being transferred from source to load. If the capacitor voltage v_{c1} and inductor current i_{Lr} are assume to zero at time t_0, then the switch Q_1 is turned on under zero voltage condition. At proper time t_1, the switch Q_1 is turned off with zero voltage condition.

II) Resonant Mode

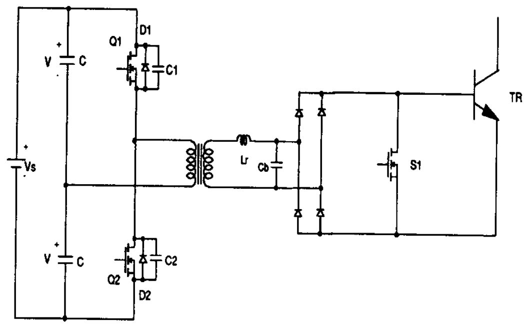

Fig. 3 The proposed base drive circuit

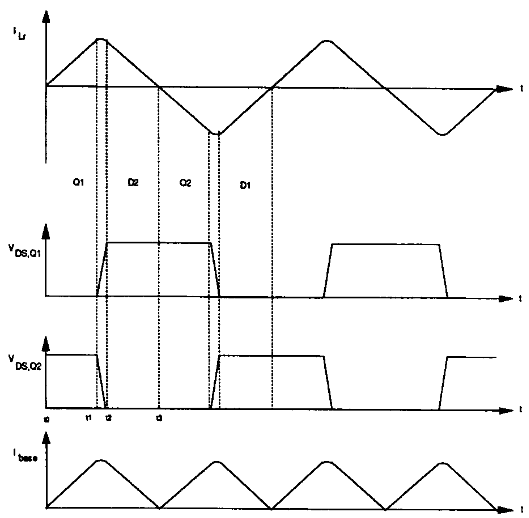

Fig. 4 Current and voltage waveforms

By turning off the switch Q_1 at the time t_1, the inductor current path is changed from switch Q_1 to capacitor c_1 and c_2. In this case the inductor current is partially resonant. At the same time, the capacitor voltage V_{c2} begins to decrease from supply voltage to zero with resonant manner and capacitor voltage V_{c1} begin to increase from zero as shown in Fig. 4. This mode ends when the capacitor voltage V_{c2} reaches zero. It is found that there is no sensing circuit for zero voltage switching.

III) Free-Wheeling Mode

As soon as the capacitor voltage V_{c2} reaches zero at time t_2, the diode D_2 begins to conduct and the inductor current freewheels through diode D_2 and inductor L_r. During this period, the inductor current decreases linearly and reaches zero at time t_3 as shown in Fig. 4.

During the total switching cycle the applied voltage to all of the switches Q_1, Q_2, D_1 and D_2 are limited to the supply voltage V_s as shown in Fig. 4.

All of the switches are turned on and off with zero voltage switching condition. This zero voltage switching provides low switching loss and low device loss. If the operation frequency of this converter are high enough, the inductor can be very small. In such a case, the resonant inductor L_r can be replaced by the leakage inductance of the transformer. Also, the VAR ratings of the capacitors of this converter are very small compared with those of the resonant converter. One of the most important things is the diode reverse recovery. This phenomenon limits the maximum switching frequency of the converter and results in substantial reduction of converter efficiency and reliability. This problem is eliminated by providing zero voltage switching for the rectifying diodes. To do so, a small capacitor c_b is added to the secondary side of the transformer in parallel with the diodes. The converter can operate at higher frequency as a result. By doing so, we obtained reduced size, weight and efficiency of the converter. The zero voltage switching condition provided automatically without voltage sensing improves the reliability of the converter.

V. Analysis of Converter Operation

The associated equations of the inductor current i_{Lr} and capacitor voltage V_{c2} in each mode are as follows :

Mode I ($t_0 \le t \le t_1$) :

$$i_{L_r} = \frac{V^* - V_b}{L_r} \cdot t \tag{1}$$

$$V_{c2} = V_s \tag{2}$$

$$\text{where } V_b = 0 \;\; ; \;\; on-state\ S_1 \tag{3-a}$$

$$V_b = V_{be} \;\; ; \;\; off-state\ S_1 \tag{3-b}$$

Mode II ($t_1 \le t \le t_2$) :

$$i_{L_r} = i_{L_r}(t_1) \cdot \cos\omega t + \frac{V^* - V_b}{z_r} \cdot \sin\omega t \tag{4}$$

$$V_{c2} = z_r i_{L_r}(t_1) \cdot \sin\omega t + (V^* - V_b)(1 - \cos\omega t) \tag{5}$$

$$\omega = \frac{1}{\sqrt{L_r \cdot C}} \tag{6}$$

$$z_r = \sqrt{\frac{L_r}{C}} \tag{7}$$

$$C = C_1^* + C_2^* \tag{8}$$

Mode III ($t_2 \le t \le t_3$) :

$$i_{L_r} = i_{L_r}(t_2) - \frac{V_b}{L_r} \cdot t \tag{9}$$

$$V_{c2} = 0 \tag{10}$$

In these equations, the '*' represents values reflected from the transformer secondary side. To satisfy the zero voltage switching condition of the switch Q_2, the capacitor voltage V_{c2} should be decreased to zero the second interval, $t_1 \le t \le t_2$. In this interval, there should be a minimum inductor current to provide zero voltage switching condition(see Eq. 4) which is given by

$$i_{L_r}(t_2) = \frac{2\sqrt{V^* V_b}}{z_r} \tag{11}$$

VI. Base Current Control

In case of using continuous base current, the required base current is larger than I_c/β. However, in this ZVS converter, the peak inductor current becomes twice the average load current if it is used for the dc/dc converter application, which may be regarded as a demerit because of the conduction loss of the MOSFET switches. However, in this base drive circuit, the triangular current can be utilized fully and it is considered to be rather advantageous.

If the base drive current is fixed and made large enough to handle the full load collector current, then the switching transistors are severely overdriven under lightly load conditions, resulting in long storage and fall times and more difficult to turn off. However if the base drive current is controlled according to the load conditions, the performance of the power switching transistor is able to be improved. In this base drive, current magnitude control of the converter can be achieved by varying the switching frequency. In a bounded frequency range, the output current becomes highest at lower bound and lowest at upper bound.

In general, the output current information of inverters or AC drives is easily sensed or estimated to process in the control circuit. By using this current information, proper amount of current can be supplied so that the switching transistor saturates lightly in accordance with the load current. This means that proportional base control can be achieved easily. This type of control has advantages over the constant drive circuit.

Another feature is easy extensibility to multi base drive because the secondary sides of drive can be simply added in parallel as shown in Fig. 5. Since it is simple to control the current magnitude, the proposed base drive is flexible.

VII. Experimental Results

In the experiment, the proposed base drive shown in Fig. 6 is used. In this figure, diodes D_{S1} - D_{S2} and capacitor C_s are used to provide negative base current at switch-off to remove stored charge in the transistor. This negative current must be large enough to minimize storage time. D_{R1} and D_{R2} are used Schottky diode which have relatively low forward voltage drop for efficiency improvement.

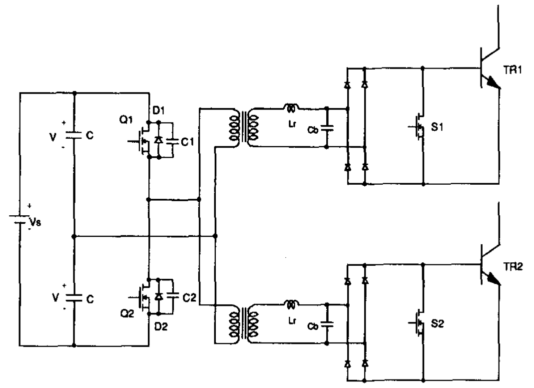

Fig. 5 Multiple base drive

The converter of the base drive is operated at about 500 kilohertz switching frequency and the power transistor is switched on and off at about 1 kilohertz in the experiment. The current waveforms flowing through the inductor L_r and the base current and the base-emitter voltage are shown in Fig. 7, 8 and 9. It is also seen that discontinuous base current has no effect on the collector current or the collector-emitter on state voltage. Fig. 10 shows the inductor current and base-emitter voltage waveforms. During the switch-off period of the power transistor, the inductor current is larger than on state. It shows that the base drive overcurrent at switch on is able to be supplied for fast switching. Also, the base-emitter voltage is nearly zero, which shows that the power loss at switch-off state is low if MOSFET switch S_1 has low on-state resistance. Fig. 11 shows base current waveform when a control is being done in accordance with the load current.

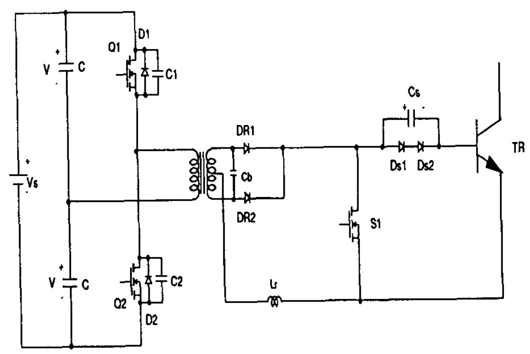

Fig. 6 Final experimental base drive circuit

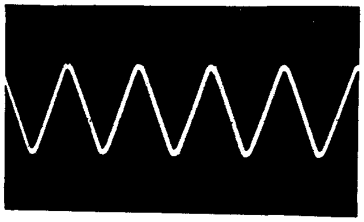

Fig. 7 The resonant inductor current waveform
5[A/div], 1[uS/div]

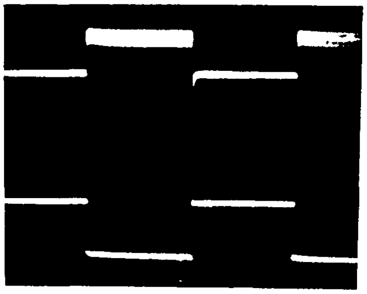

Fig. 8 The base current and collector voltage
5[A/div], 50[V/div], 0.2[mS/div]

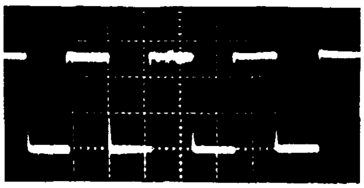

Fig. 9 The collector current waveform
10[A/div], 0.5[mS/div]

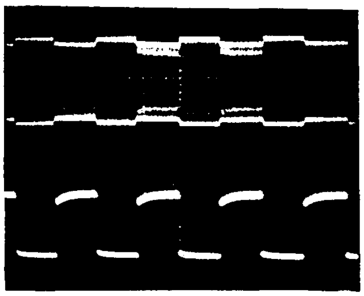

Fig. 10 The resonant inductor current
and base voltage waveform
5[A/div], 1[V/div], 0.5[mS/div]

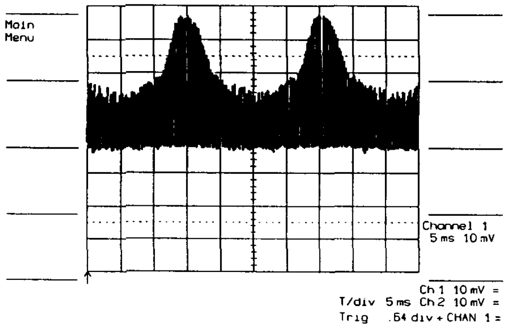

Fig. 11 Controlled base current proportional
to load current

VIII. Conclusion

New base drive scheme using ZVS converter is suggested in this paper. As the peak inductor current of the converter is twice as large as the average load current, the triangular shape current can be fully utilized due to the storage time of the switching transistor, and the required average current is somewhat low compared with the fixed base drive. Because the converter operates at very high frequency, the leakage inductance of the transformer can be utilized to control the output current.

The features of proposed base drive are summarized as follows :

(1) small size and light weight,
(2) high efficiency,
(3) easy to extend to multi-drive,
(4) inherent electrical isolation drive,
(5) flexible to load conditions in order to prevent power transistors from deep saturation,
(6) no limitation on the on/off period of the power transistor.

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