

CIRCUIT AND METHOD FOR IMPROVING
SHORT-CIRCUIT CAPABILITY OF IGBTs ✓

BACKGROUND OF THE INVENTION

1. Field of the Invention:

5 The present invention relates to short-circuit protection circuits and, more specifically, to a circuit for protecting high efficiency IGBTs in a motor controller circuit.

2. Description of the Related Art:

10 A common requirement of IGBT inverters for motor control is that the IGBTs must be able to withstand short-circuits for periods that are in the range of 5 to 10 μ s.

15 The capability of an IGBT to withstand short-circuit for a given period of time is essentially determined by the gain under short-circuit.

20 At present, two basic types of IGBTs are generally available, namely "short-circuit" types which are designed primarily for motor control applications, and "high-efficiency" types, which are designed for applications where short-circuit capability is not needed, such as switching power supplies. An inherent trade-off exists between these two types of devices. Short-circuit IGBTs (typically designed to withstand
25 short-circuits for up to 10 μ s) are inherently less efficient than high-efficiency IGBTs, but the latter have more limited short-circuit capability.

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As illustrated by the plots shown in Fig. 1, Gen 4 high-efficiency IGBTs manufactured by the assignee of the present application, International Rectifier Corporation, have about twice the short-circuit current of short-circuit rated types. The greater short-circuit current of the high-efficiency type restricts its short-circuit withstand time to less than a half of that of the short-circuit rated type.

It would be desirable for semiconductor manufacturers such as the present assignee to eliminate the manufacture of short-circuit rated components, in favor of high efficiency types only.

The potential advantages would be:

1. Simplified manufacturing logistics, inventory control, etc., through the manufacture of one basic high-efficiency type of IGBT, instead of two different types; and

2. Better system solutions for applications that require short-circuit capability, with greater design flexibility and improved system performance.

SUMMARY OF THE INVENTION

The present invention achieves the above-described objectives and advantages by providing a circuit and method for improving the short-circuit capability of high-efficiency IGBTs in a strikingly simple off-chip solution which is essentially transparent to the user.

More specifically, the present invention, in its various embodiments, comprises the addition of an external common emitter resistor to a high gain high

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efficiency type of IGBT to increase the short-circuit capability of the IGBT.

Other features and advantages of the present invention will become apparent from the following
5 description of the invention which refers to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows the short circuit characteristics of high-efficiency IGBTs vs. short-circuit rated IGBTs.

10 Figs. 2A and 2B shows the effect of adding a common-emitter resistance on the short circuit current of high-efficiency IGBTs in accordance with the present invention.

15 Fig. 3 demonstrates the 20 μ s short-circuit withstand time of a 1200V size 7 Gen 3 IGBT provided with a 20 mohm common emitter resistance.

20 Fig. 4A shows the use of an existing current sensing shunt in the common lower bus circuit to provide common emitter resistance for limiting short-circuit current; Fig. 4B shows the use of existing individual vector control lower legs shunts to provide common emitter resistance for limiting short-circuit current.

Fig. 5 shows the use of a low voltage HEXFET to protect a high voltage, high-efficiency IGBT.

25 Fig. 6 shows that ground fault current flows through the input line impedance, and therefore has a slow rate of rise and limited amplitude.

30 Fig. 7 shows an upper fault detector design for slow response to a line-to-line short circuit, and rapid response to a short circuit resulting from an inadvertent

external connection of an ac output terminal to the negative bus terminal.

5 Fig. 8 shows a circuit for avoiding a short circuit resulting from an inadvertent external connection of an ac output terminal to the negative bus terminal by detecting a pre-existing short circuit and inhibiting the gate driver.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

10 A comparison of Figs. 2A and 2B shows the addition of an external common emitter resistor R to the high gain high efficiency type of IGBT, in accordance with the present invention. More specifically, the addition of resistor R as shown in Fig. 2B reduces the effective gain under short-circuit, by virtue of the
15 voltage $I_{sc} \times R$, which subtracts directly from the net gate-emitter voltage.

The oscillograms shown in Fig. 3 demonstrate an example in which a 20 m Ω common emitter resistor, for a size 7 1200V IGBT, permits a short-circuit time of 20 μ s
20 at 850V, as compared with a short circuit withstand time of about 5 μ s without the resistor.

Advantageously, under normal operating conditions, the voltage developed across R is small, and the modifying effect on the normal operating gate-emitter
25 voltage is almost negligible, as evidenced by the following calculated estimates.

1. Circuit of Fig. 2B with 600 V, Size 4, Gen 4 High-Efficiency IGBT, provided with 33 m Ω common emitter resistor R:

Normal operating output current (3 hp) = 12A rms
 Normal operating current in R = 8.4A rms
 Normal operating loss in R = $8.4^2 \times 0.033$
 = 2.3 W.

5 Estimated losses in IGBT at 12A output:

<u>Frequency</u>	<u>Loss</u>	<u>Percent Losses in R</u>
4kHz	13.5W	17.6
8kHz	15.4W	14.9
12kHz	17.8W	12.9

10 2. Circuit of Fig. 2B with 1200 V, Size 4,
 Gen 4 High-Efficiency IGBT, provided with 66 mΩ common
 emitter resistor R:

Normal operating output current = 6A rms
 Normal operating current in R = 4.2A rms
 15 Normal operating loss in R = $4.2^2 \times 0.066$
 = 1.15W.

Estimated losses in IGBT at 6A output:

<u>Frequency</u>	<u>Loss</u>	<u>Percent Losses in R</u>
4kHz	11.3W	10.6
20 8kHz	18.1W	6.6
12kHz	24.8W	4.8

The above calculations show that the projected losses in the common emitter resistor at full load, for a 600V rated high efficiency IGBT, are between 13 and 17.5% of the IGBT losses, for a common emitter resistor that provides 10 μ s short-circuit time. This estimated added loss in the resistor actually is about the same as the estimated added loss for a 10 μ s short-circuit rated 600V IGBT, over that of a high efficiency type.

The estimated full load losses in the common emitter resistor that provides 10 μ s short-circuit capability for a 1200V rated high efficiency IGBT are between 5 and 11% of the IGBT losses. Significantly, these added losses are about 30% less than the loss which would be added if a 10 μ s short-circuit rated 1200V IGBT were used instead of a high-efficiency type with a common emitter resistor.

Although the use of a common emitter resistor in accordance with the present invention probably does not afford any significant reduction of overall losses, versus the losses of short-circuit rated types, when viewed at the component level, the invention does in fact offer reduced losses at the system level, as well as other application advantages, in addition to the manufacturing advantages discussed above. The application advantages are as follows:

1. Short-circuit time can be tailored to the specific value required for a particular application without changing the IGBT design, simply by selecting the value of the common emitter resistance. The lower the required short circuit time, the lower the resistance value and the lower the added losses.

2. The added losses in the common emitter resistor are dissipated externally to the IGBT die. The IGBT remains a high efficiency type with minimum losses, allowing more output for a given IGBT die size than can be obtained from short-circuit rated IGBTs; i.e., given that power has to be dissipated, it is better to dissipate power in a resistor than in the IGBT,

3. In a three-phase inverter for motor control, a common emitter resistor for only three of the six IGBTs can endow the entire inverter with the necessary short-circuit capability (e.g. $10\mu\text{s}$), as discussed in further detail below. Moreover, a single common emitter resistor can serve all three IGBTs in the lower section of a three phase inverter circuit. The total loss contribution of the common emitter resistor or resistors reduces the incremental losses of the total inverter to about 7.5% versus 15% total incremental losses for six short-circuit rated IGBTs. It should be recognized, however, that it would be possible to use three short-circuit-rated IGBTs and three high efficiency types, and no common emitter resistors, to achieve a circuit with about the same overall losses. However, such a circuit would require two different types of IGBTs and would therefore not achieve the stated objective of the invention to eliminate the need for short-circuit IGBTs.

4. If a resistive current measuring shunt is a part of the total powertrain, as will normally be the case for drives up to a few horsepower, the shunt resistor (or resistors) can serve the dual functions of common emitter resistance for short-circuit current

limiting, and current signal feedback. This is shown in Figs. 4A and 4B. The present invention therefore makes it feasible to substitute high efficiency IGBTs into existing powertrains that include a single lower shunt resistor (or individual "vector control" shunt resistors for the lower IGBTs), obtain 10 μ s short-circuit capability, and reduce the total inverter losses by about 15% for the same output current.

Various embodiments of the common emitter resistor circuit of the present invention are as follows:

1. The preferred method and circuit is to use existing current sensing shunt (or shunts) if such shunts are already present in the powertrain.

2. An alternative embodiment is to use bonding wires with the desired resistance.

3. A further embodiment is to mount external thick film resistors on the substrate of a powertrain circuit board.

4. A still further embodiment is to use connectors from a power level circuit board to a separate driver board having the desired resistance.

5. Another embodiment is to add the desired resistance in a separate driver board.

To obtain lower incremental losses during normal operation and/or increased short-circuit time, a non-linear common emitter resistor with a low resistance value at normal operating current and a higher value at short-circuit current is preferred in yet another possible embodiment of the present invention. Such a nonlinear resistor can be realized by:

1. A polysilicon resistor with a positive temperature coefficient. The increased temperature caused by the short-circuit current would give higher common emitter resistance when needed, increasing the short-circuit withstand time. The increased resistance at higher operating temperature would also give greater limiting of short-circuit current when the fault occurs at initial high operating temperature.

2. A device having a resistance which increases with current, such as a power MOSFET, e.g. a 20V HEXFET manufactured by the present assignee, International Rectifier Corporation. Fig. 5 shows the circuit configuration in which a 20V HEXFET (e.g. a Gen 5 size 1 HEXFET) provides the common emitter resistance for a high efficiency IGBT (e.g. a Gen 4 600V Size 4 high efficiency IGBT). The short-circuit current of the IGBT is limited to that of the HEXFET. Thus, in the example of Fig. 5, the high efficiency IGBT is endowed with a short-circuit time of about 15 μ s. Since the area of the HEXFET die is about 15% of that of the IGBT, the added HEXFET does not add significant cost. Note that, in the configuration shown in Fig. 5, it is possible to apply drive pulses only to the IGBT or only to the HEXFET, with only a fixed 15V applied to the gate of the other device.

As stated previously, a single common emitter resistor, or individual resistors for the bottom IGBTs only of a three-phase inverter, can be used to protect all six IGBTs against line-to-line output short-circuit. This is because line-to-line short-circuit current flows through a lower and an upper IGBT in series. Line-to-line short-circuit protection of the upper IGBT is thus

provided by the current limiting action of the lower IGBT.

5 The use of common emitter resistors for just the upper side IGBTs also provides complete inverter protection against line to line short circuits. However, where a resistive shunt, or shunts, are already present in the bottom side of the circuit, it is simpler and more economical to utilize such existing components as the common emitter resistance.

10 It should be recognized that, under certain types of faults, it is possible for fault current to flow just through the upper side IGBTs, in which case the lower side IGBTs are powerless to limit the current in the upper side. Two types of fault that can give rise to short-circuit current in the top IGBTs only are as follows:

 Type 1 fault - Ground fault at the output of the inverter.

20 Type 2 fault - Inadvertent external connection of a short-circuit from an ac output terminal to the negative bus terminal, N.

25 Both of these types of faults can be handled without resort to common emitter resistors for the upper side IGBTs. Specifically, Type 1 faults can almost always be withstood naturally by high efficiency IGBTs for a period of 10 μ s or more without any additional means of protection. As shown in Fig. 6, since the path for ground fault current is through the input supply impedance, the rate of rise and prospective amplitude of ground fault current is severely limited by the impedance of the ac input line. The relatively low amplitude

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ground fault current will not damage high efficiency IGBTs within a 10 μ s shut-down period.

5 Type 2 faults are more severe, because fault current flows from the low impedance bus capacitor via the upper side IGBT to the negative bus terminal N. The need for common emitter resistors for the upper side IGBTs for this type of fault can be avoided by:

10 a) Preventing user access to the negative bus terminal N. The reason for providing external access to the negative bus N is to provide a connection point for an optional external brake circuit. Powertrains that have an internal brake transistor therefore do not require an externally accessible N terminal. The possibility still exists that a user might miswire an
15 inverter ac terminal to the brake terminal, but now the brake IGBT, with its own common emitter resistor, will provide short circuit protection for the upper side IGBT.

20 b) Designing the upper bus current detector to discriminate between line-to-line faults and Type 2 faults, the latter having a much higher short-circuit current because of the higher effective gain of the upper side IGBTs, which do not have common emitter resistors. For example, the upper bus may be provided with a resistor/opto circuit which is designed to discriminate
25 between the line-to-line and the Type 2, higher current, faults. The resistor/opto detection circuit is designed to respond more slowly than the lower fault detection circuit to line-to-line fault, allowing the latter to control the shut-down time for line-to-line fault.

30 The upper detection circuit is preferably designed to respond as rapidly as possible to the higher

amplitude Type 2 faults, so that it shuts down the inverter and protects the upper IGBTs as quickly as possible, e.g. within 1 or 2 μ s.

5 A conceptual schematic of the upper fault detector is shown in Fig. 7. For line-to-line short-circuit, the voltage developed across R_s is insufficient for Zener diode Z (or some other type of threshold diode) to conduct. Capacitor C charges through resistor R1. The time constant $R1C$ is such that the opto does not
10 deliver an output during the trip time set by the lower detection circuit (not shown). It should be noted that Zener diodes may not be available with a sufficiently low threshold, in which case Zener diode Z can be replaced by two or three diodes in series, or possibly an LED, which
15 has about a 2V threshold.

For a high amplitude Type 2 fault, the voltage developed across R_s is sufficient for Z to conduct. Capacitor C now charges rapidly via R2, which has a much lower resistance value than R1. The opto-isolator
20 delivers a trip pulse within 1 or 2 μ s, protecting the upper IGBTs. A trip time of 1 or 2 μ s for Type 2 faults only should be completely noise-free, thus avoiding "nuisance trip" problems with very fast shut-down time for this type of fault.

25 For normal levels of fault current, the top trip circuit actually has more filtering and more noise immunity than the bottom one. A fast trip can only be initiated by abnormally high current in the upper shunt, which itself can only be caused by a bona fide Type 2
30 fault.

c) Adding a circuit that detects a low impedance between any ac output terminal to the negative bus terminal N, to prevent the occurrence of Type 2 faults as a result of miswiring between terminals prior to powering-up the inverter. If a low impedance is detected from either U, V or W to N during the power-up period, while the IGBT gates are still inhibited, inhibition of the driver (and hence the driver signal to the IGBT gates) at the end of power-up sequence is maintained, thereby preventing initiation of a type 2 fault. A conceptual implementation is shown in Fig. 8.

The present invention, in the various embodiments set forth above, offers a way of focusing manufacturing of high efficiency IGBTs only, with all the ramifications relative to cost savings thereby entailed.

Although the present invention has been described in relation to particular embodiments thereof, many other variations and modifications and other uses will become apparent to those skilled in the art. It is preferred, therefore, that the present invention be limited not by the specific disclosure herein, but only by the appended claims.

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WHAT IS CLAIMED IS:

5 1. A circuit for protecting a high efficiency IGBT in a motor controller circuit, wherein a common emitter resistor is provided in series with said high efficiency IGBT to increase the short-circuit capability of the IGBT.

5 2. The circuit as recited in claim 1, wherein said motor controller circuit comprises a three-phase inverter for motor control with six high efficiency IGBTs, and wherein individual ones of said common emitter resistor are provided in series with three of said six IGBTs.

3. The circuit as recited in claim 1, wherein said common emitter resistor comprises a single shunt resistor provided on a low side rail of said three-phase inverter motor controller circuit, and wherein said common emitter resistor serves the dual functions of providing a common emitter resistance for short-circuit current limiting and, in addition providing a resistive current measuring shunt for current signal feedback.

4. The circuit as recited in claim 1, wherein said common emitter resistor comprises bonding wires having the desired resistance.



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5. The circuit as recited in claim 1, wherein the circuit includes a connector from a powertrain circuit board to a separate driver board, and wherein said common emitter resistor: (i) is disposed on the separate driver board; (ii) includes a thick film resistor disposed on the powertrain circuit board; or (iii) includes the connector having a desired resistance.

6. The circuit as recited in claim 1, wherein said common emitter resistor comprises a non-linear resistor having a low resistance value at normal operating current and a higher value at short-circuit current.

7. The circuit as recited in claim 6, wherein said non-linear resistor comprises a power MOSFET transistor.

8. The circuit as recited in claim 1, wherein said three-phase inverter motor controller circuit is provided with high efficiency IGBTs on both a high side and low side of said circuit, and wherein said circuit further comprises a current detector for detecting a Type 2 fault on said high side.

9. The circuit as recited in claim 8, wherein said current detector for detecting a Type 2 fault comprises a resistor/opto-isolator circuit including a threshold diode which permits a capacitor to be relatively rapidly charged through a resistor of a relatively low value in the presence of a Type 2 fault,



and relatively slowly charged through a resistor with a relatively high value in the absence of a Type 2 fault.

5 10. The circuit as recited in claim 2, wherein said individual ones of said common emitter resistor comprise vector control shunt resistors for the three of said six IGBTs on the low side of said three-phase inverter, the motor controller circuit further comprising a current detector comprising a plurality of comparators for detecting a low impedance between any ac output terminal of said three-phase inverter circuit and a low side bus rail.

