SGS-THOMSON MICROELECTRONICS

APPLICATION NOTE

USE OF INTERNAL MOSFET DIODE IN BRIDGE-LEGS FOR HIGH FREQUENCY APPLICATIONS

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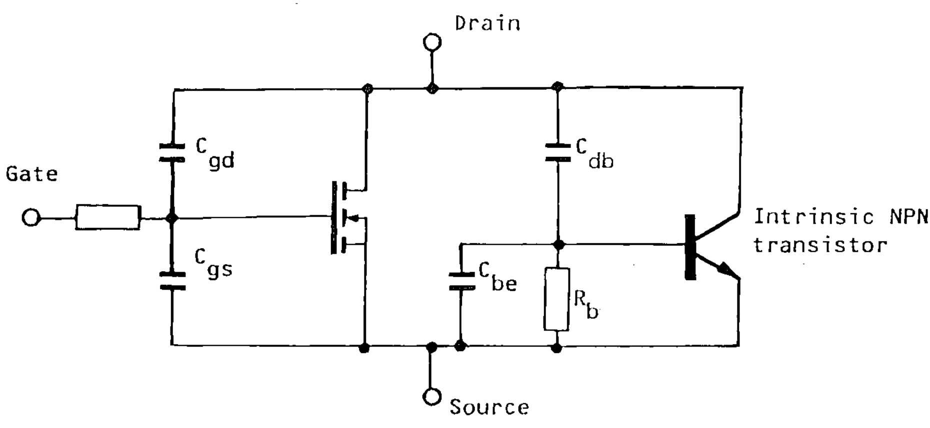
ABSTRACT

Reverse recovery of the intrinsic MOSFET diodes is investigated for the classical MOSFET and the MOSFET with minority carrier lifetime control. Turn-on losses in bridge-legs using intrinsic MOSFET diodes limit the switching frequency particularly in the case of the classical MOSFET. Adapted bridge-leg configurations are presented which enable the use of the intrinsic MOSFET diodes for the free wheeling function in inductive load switching without any appreciable reverse recovery current and MOSFET turn-on switching losses !

INTRODUCTION

The MOS field effect transistor (MOSFET) contains an intrinsic PN diode within the structure which can conduct a current from source to drain. The PN junction diode is in fact part of a parasitic NPN bipolar transistor as shown in figure 1. Free-wheeling diodes in bridge-legs are necessary when switching inductive loads. The intrinsic diode can be used to fulfil this free-wheeling function. However, the intrinsic diode of the classical MOSFET has a long reverse recovery time and "snap-off" characteristic which can cause large dV/dt. The snap-off can result in the device failing in one of two ways. Firstly, due to internal capacitances, C_{db} and C_{be}, a base current may be established which turns-on the intrinsic bipolar transistor (see figure 1)[1]. Secondly, the dV/dt may be such that the drain to source voltage of the MOSFET exceeds the blocking voltage thus causing avalanche breakdown. This paper investigates various means of limiting the maximum reverse recovery current of the intrinsic diode to ensure reliable operation. A comparison is made between the novel solutions presented permitting the use of internal diode, and conventional solutions for using MOSFETs in bridge-legs, such as lifetime controlled MOSFETs and series blocking diodes.

Figure 1 : Equivalent Circuit for a MOS Field Effect Transistor (MOSFET).



METHODS OF LIMITING REVERSE RECOVERY CURRENT

Limiting the reverse recovery current of the intrinsic diode can be achieved by stopping current from passing through the blocked MOSFET by means of a series blocking diode or limiting the rate of change of current in the intrinsic diode. The snap-off characteristics of the internal diode can be limited by having small RC snubbers across the drain to source of MOSFETS in bridge-leg configuration. Solutions which limit the rate of change of current in the intrinsic diode are discussed below.

BRIDGE-LEG DESIGNS UTILIZING MOSFET INTRINSIC DIODES

a) SOLUTION WITH UNCOUPLED UNSATURABLE INDUCTORS

In the circuit shown in figure 2, if T1 is blocked and T2 is conducting, the load current flows through T2. As T2 turns-off the current transfers to the freewheeling diode D2, as the rate of change of current into the intrinsic MOSFET diode of T1 is limited by inductors L1 and L2. The zener voltage across Z2 causes the current to transfer from the external freewheeling diode D2 to the intrinsic MOSFET diode in T1 until D2 no longer conducts (as shown in figure 3). When T2 is turned-on subsequently the current transfers from the intrinsic diode of T1 to T2. The reverse recovery of the intrinsic diode is, however, limited by inductances L1 and L2. This can be seen clearly in figure 4. The bridge-leg can be designed (by dimensioning L1, L2 and V_Z) such that the external freewheeling and zener or transil diodes only conduct for a small fraction of the freewheeling period. Consequently, they do not have to be mounted on a heatsink. The disadvantage of using the zener is that the MOSFETs must now be rated for at least the high voltage DC rail, HVDC, plus the zener voltage.

Figure 2 : Bridge-leg with Uncoupled Unsaturable Inductors.

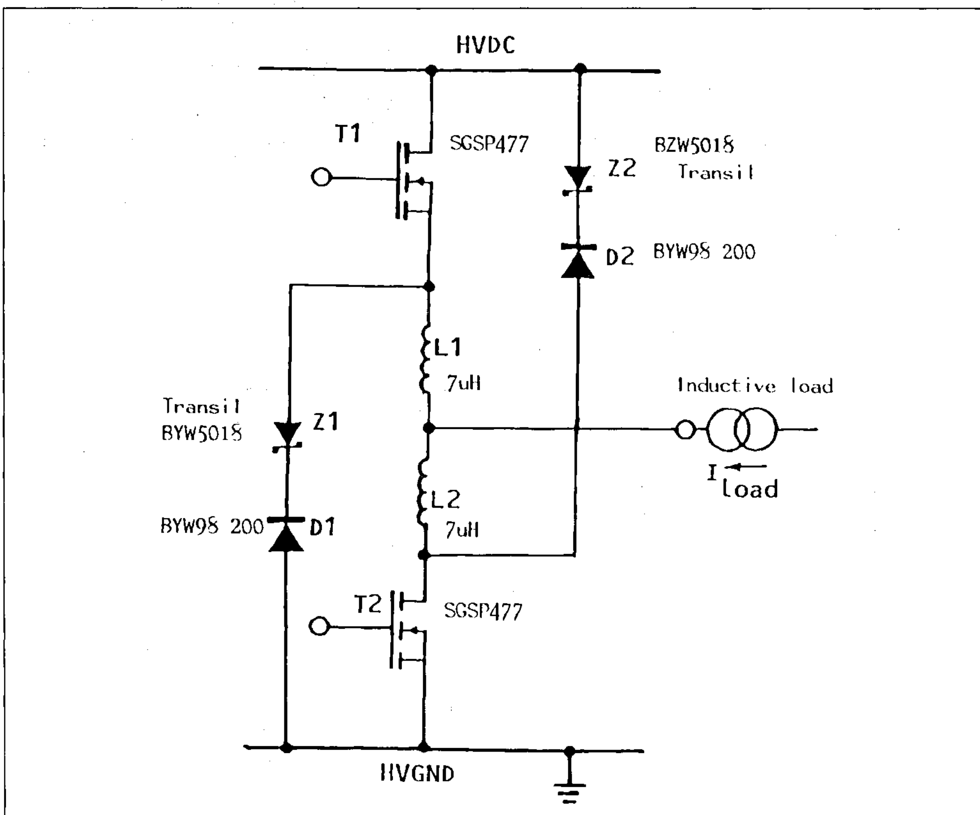
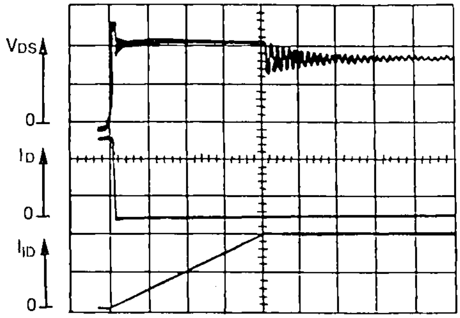


Figure 3 : Transfer of Current to Intrinsic Diode.

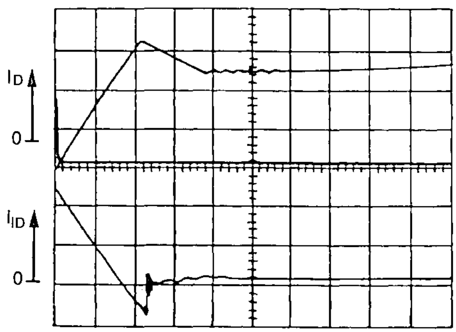


Time scale : 2µs/DIV
V_{DS} : 50V/DIV
I_D : 10A/DIV

Intrinsic
Diode : 10A/DIV
Current (I_{ID})

MOSFET : SGSP477

Figure 4 : Turn-off of the Intrinsic Diode.



Time scale : 1µs/DIV
V_{DS} : 50V/DIV
I_D : 10A/DIV

Intrinsic
Diode : 10A/DIV
Current (I_{ID})

MOSFET : SGSP477

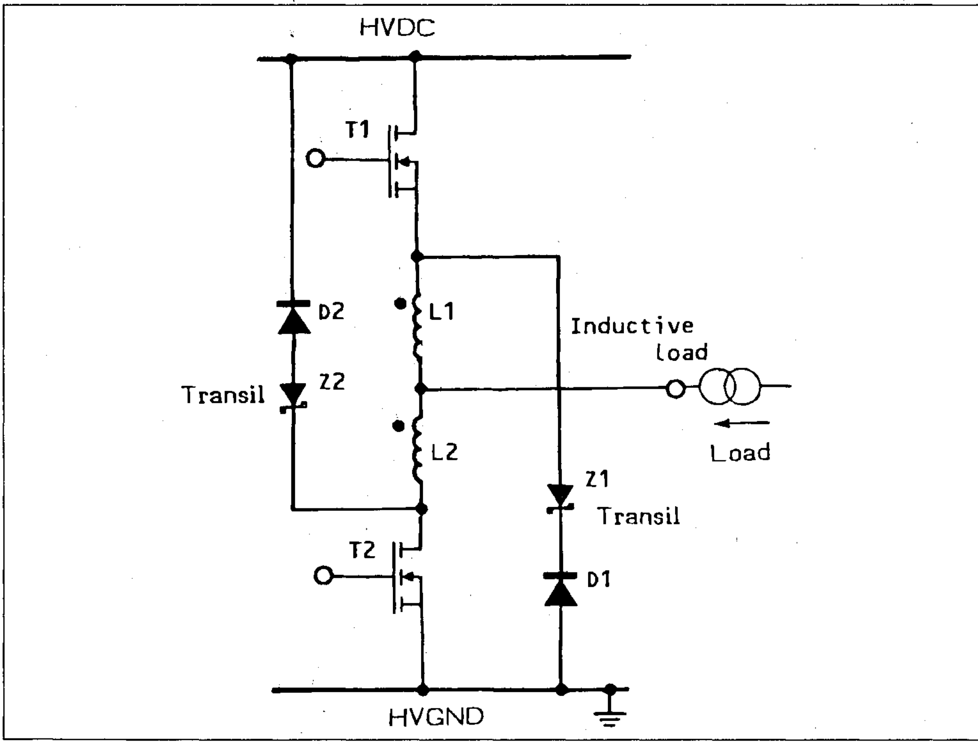
Another advantage of inductances L1 and L2 in the circuit is that they limit the build up of current during fault conditions such as simultaneous conduction of the two devices.

L1 and L2 must be chosen such that their inductances are big enough to prevent intrinsic diode reverse recovery problems hence reduce losses. They must be small enough to allow current to transfer from the freewheeling diodes D2 and D1 to the intrinsic MOSFET diodes in T1 and T2 such that the average current passing through the external diode and zener or transil is low.

b) SOLUTION WITH MUTUALLY COUPLED INDUCTORS

Inductors L1 and L2 can be mutually coupled as shown in figure 5. Coupling L1 and L2 doubles the inductance between transistors T1 and T2 (SGSP477), thus reducing the reverse recovery problem of the intrinsic diode as the rate of change of current is reduced. Coupling, therefore, saves the cost of one core and less windings are necessary to provide the same degree of protection as in the case of uncoupled inductors. The voltage and current waveforms of the MOSFETs and their intrinsic diodes for this solution are similar to that obtained with solution (a).

Figure 5 : Bridge-leg with Mutual Inductors.



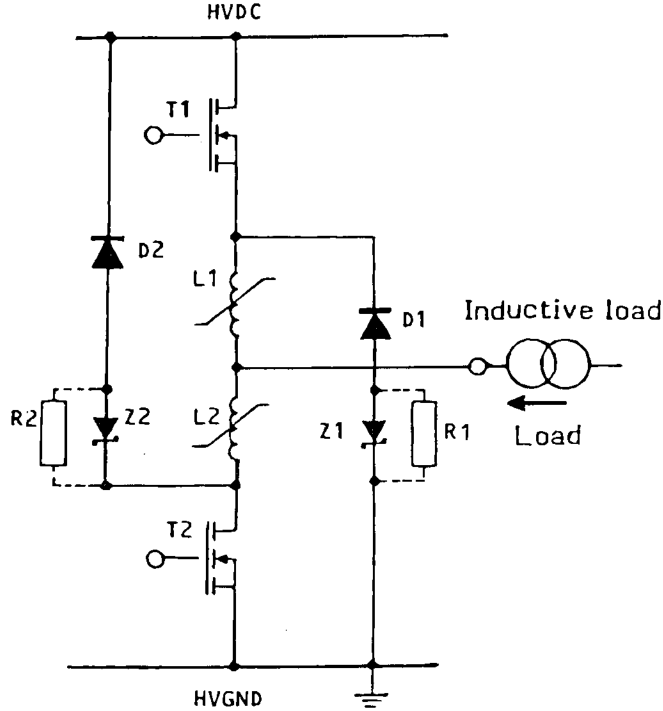
C) SOLUTION WITH SATURABLE INDUCTORS

Saturable inductors such as toroids with a few turns can be used in the bridge configuration shown in figure 6. Saturable inductors are better suited than non-saturable inductors in so much as they can be used to limit the reverse recovery of the intrinsic diode to an almost negligible level. The saturable inductor is designed to saturate after the intrinsic diode has reverse recovered. Before saturation the inductor presents a high impedance and only a low magnetising current flows.

In figure 6, it is assumed that T1 and T2 are blocked and the intrinsic diode of T1 is conducting. If T2 is now turned-on, the current in the intrinsic diode decreases rapidly since inductor L1 is saturated until this current reverses resulting in negative volts-seconds across the inductor which thus desaturates. The inductor thus presents a high impedance while the current through it is equal to or less than the magnetising current. The intrinsic MOSFET diode begins to reverse recover as the current through it becomes negative. The inductor is designed not to saturate for a period of at least 1μs, thus enabling the reverse recovery of the intrinsic diode without excessive reverse recovery current. There is a certain degree of minority carrier recombination while the inductor is unsaturated which also reduces the maximum reverse recovery current, I_{RM}. The reverse recovery of the intrinsic diode can be seen in figure 7.

While T2 is conducting the load current inductor L2 is saturated. When T2 turns-off the MOSFET current transfers to diode D2. The free-wheeling current path through the intrinsic diode of T1 has a high impedance due to L1 being unsaturated. Consequently the build-up of current through the intrinsic diode of T1 is slow until this current reaches a value equal to the magnetising current, I_{mag}, of inductor L1 which then saturates. This effect can be clearly seen in figure 8.

Figure 6 : Bridge-leg with Saturable Inductors.



The turn-on of the MOSFET in the solution with saturable inductors (shown in figure 6) is illustrated in figure 9. It can be seen that the MOSFET losses are negligible, since the saturable inductor in series with the MOSFET that turns-on, limits the rate of rise of current while it is unsaturated. Figure 9 also illustrates that the reverse recovery of the intrinsic diode of the free wheeling MOSFET is also limited..

In the bridge-leg with saturable inductors (figure 6), if transils (Z1 and Z2) and resistors (R1 and R2) are removed, the external free-wheeling diodes have to be of high current rating as they conduct all the load current until the saturation of L1 and L2. Subsequently the external diode shares part of the free-wheeling current with the intrinsic diode. It is advantageous to reduce the current through the external free-wheel diodes D1 and D2 as rapidly as possible for the following reasons :

1. If D1 and D2 conduct for a small fraction of the maximum free-wheeling duty cycle, then their power rating is substantially reduced.
2. If the free wheeling current through the external diode D1 or D2 is reduced rapidly, the inductor in series (L1 or L2) is no longer saturated. At the consecutive turn-on of T1, L1 presents a high impedance thus performing a turn-on snubber function. Transistor turn-on losses are thus minimised particularly for inductive loads.
3. Output short-circuit protection is also enhanced if the inductors are unsaturated prior to transistor turn-on.

The current through the external free-wheeling diodes can be reduced rapidly by increasing the rate of release of inductor stored energy by transils (Z1 and Z2) and/or resistors (R1 and R2) as shown in figure 6.

Figure 7 : Reverse Recovery of Intrinsic Diode using Saturable Inductors in the Configuration of Figure 6.

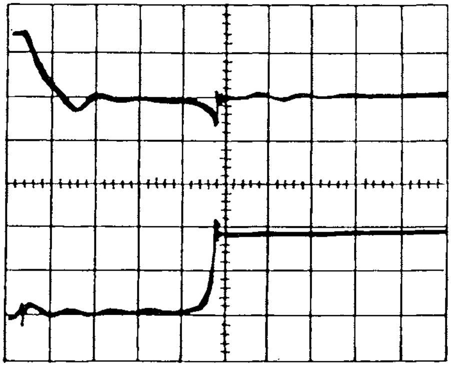


Figure 8 : Transfer of Current to Intrinsic Diode using Saturable Inductors in the Configuration of Figure 6.

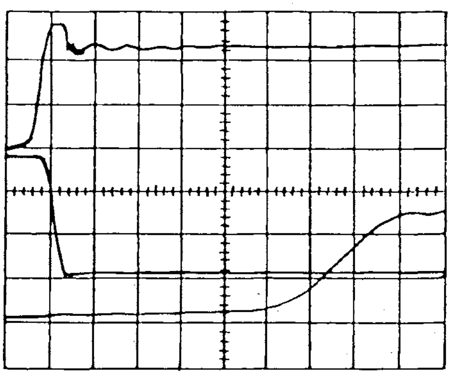


Figure 9 : Turn-on of the MOSFET in the Configuration with Saturable Inductors.
(The turn-on snubber and the intrinsic diode reverse recovery actions are illustrated).

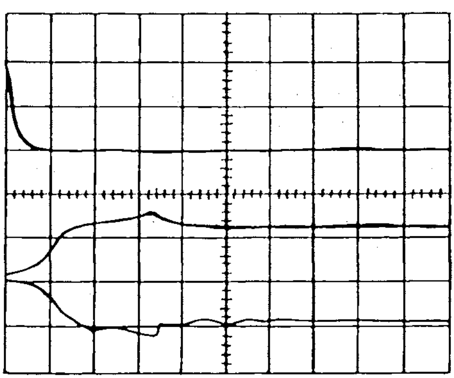


Table 1 : Advantages and Disadvantages of Solutions for limiting Reverse Recovery Current in the Intrinsic MOSFET Diode.

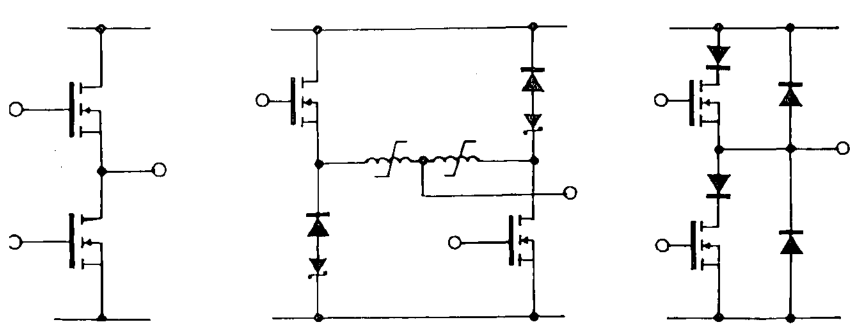
Sol.	Type of Protection Used	Advantages	Disadvantages
a)	Unsaturable Inductors	– Reduction of turn-on losses. – Controlled dI/dt at turn-on. – Controlled reverse recovery of intrinsic diode.	– In order to use low current rated freewheeling diodes, transil diodes have to be used . increasing the voltage rating of the MOSFETs in the circuit.
b)	Unsaturable Mutual Inductances	– Smaller and less expensive than two inductors since only one coupled inductor. – As above.	– As above.
c)	Saturable Inductors	– Negligible turn-on losses. – Negligible intrinsic MOSFET diode reverse recovery losses. – Controlled dI/dt turn-on.	– As above.

COMPARISON OF USE OF INTRINSIC MOSFET DIODE WITH ALTERNATIVE SOLUTION

Figure 10 illustrates three bridge-leg configurations that can be used with MOSFETs when switching inductive loads. Figure 10a) illustrates a bridge-leg which uses the intrinsic diode of a classical MOSFET having a reverse recovery in the order of a microsecond. The same configuration can be used with a lifetime controlled MOSFET which has an intrinsic diode having a reverse recovery time around 250ns. An asymmetrical bridge-leg illustrated in figure 10b), is similar to the above mentioned solutions permitting the use of the intrinsic diode. The configuration illustrated in figure 10c) has series "blocking" diodes which prevent conduction of the intrinsic MOSFET diodes and thus avoid reverse recovery problems associated with the slow intrinsic diodes. In this configuration fast recovery epitaxial diodes are used as external free wheeling diodes.

Tests were performed using 500V, 0.6 ohm at 25°C classical MOSFETs (BUZ353) and lifetime controlled MOSFETs in the bridge-leg illustrated in figure 10a). Experimentally obtained losses within the diode and the MOSFET at turn-on are presented in figure 11. The solution enabling the use of the intrinsic diode without reverse recovery problems (figure 10b) has practically no losses due to reverse recovery of the intrinsic diode.

Figure 10 : Bridge-leg Configurations.



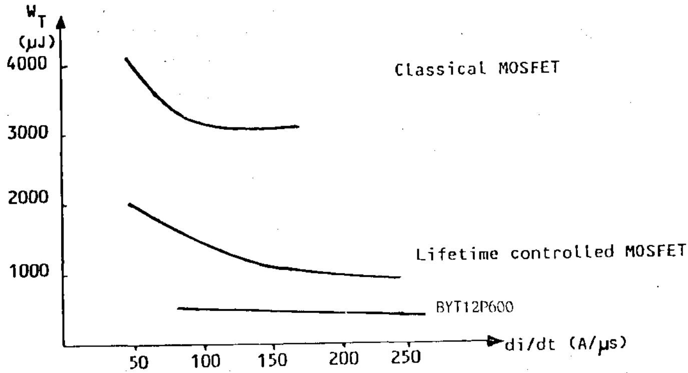
a) Bridge-leg using intrinsic MOSFET diode

b) Asymmetrical bridge-leg providing di/dt protection, turn-on snubber and limited reverse recovery problems

c) Bridge-leg with series blocking diodes and fast freewheeling diodes

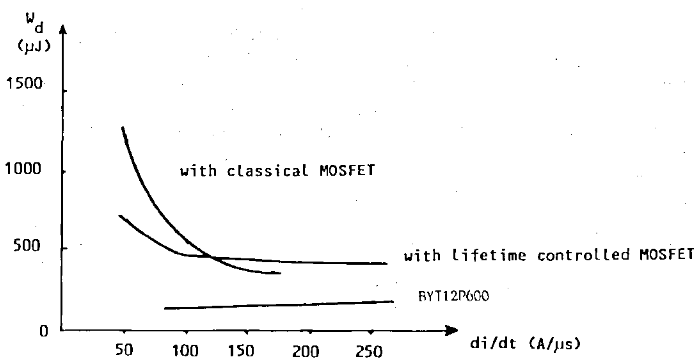
Figure 11 : Turn-on Losses in a Bridge-leg.

Turn-on Losses in the MOSFET



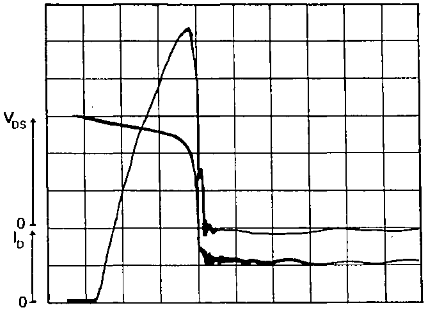
a) Turn-on losses in the MOSFET when switching 10A inductive load current on $400V_{DC}$ rail as a function of the rate of change of MOSFET drain current (dI_D/dt)

Reverse Recovery Losses in the Diode



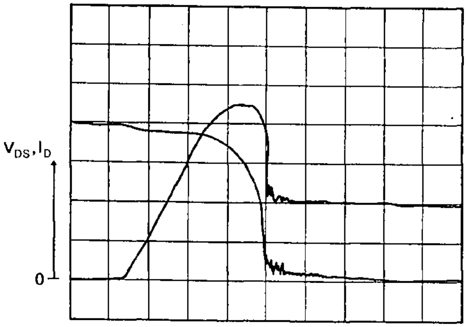
b) Reverse recovery losses in the freewheeling diode when switching 10A inductive load current on $400V_{DC}$ rail as a function of the rate of change of freewheeling diode current (dI_{FD}/dt) during diode turn-off.

Figure 12 : Turn-on Ilustrations of the MOSFET Drain to Source Voltage (V_{DS}) and Current (I_D) at Turn-on of the Transistor Limited to 100A/µs.



a) Classical MOSFET
(500V, 0.6 ohm)
BUZ353
Diode losses = 540µJ
MOSFET losses = 3200µJ

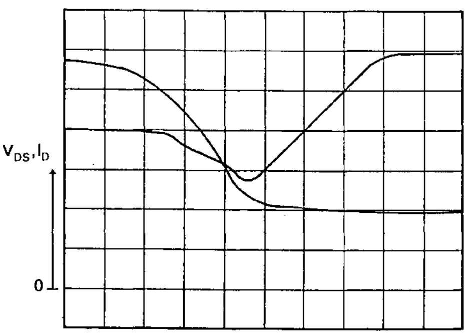
V_{DS} MOSFET drain to source voltage
100V/DIV
I_D Drain current
5A/DIV
Time 200ns/DIV



b) Lifetime controlled MOSFET
(500V, 0.6 ohm)

Diode losses = 460µJ
MOSFET losses = 1600µJ

V_{DS} 100V/DIV
I_D 5A/DIV
Time 100ns/DIV



c) External fast diode
BYT12P-600

Diode losses = 130µJ
MOSFET losses = 560µJ

V_{DS} 100V/DIV
I_D 5A/DIV
Time 50ns/DIV

It can be seen that due to the slow intrinsic diode of the classical MOSFET, turn-on losses are twice that with a lifetime controlled MOSFET. With external fast freewheeling diodes losses are only 20% of the losses in the classical MOSFET.

CONCLUSION

Reverse recovery of the intrinsic MOSFET diode has been investigated. Losses caused by slow intrinsic diode recovery for the classical MOSFET have been compared with losses using lifetime controlled MOSFETs in a bridge-leg and losses using fast external freewheeling diodes. It has been shown that turn-on losses in a bridge-leg using classical MOSFETs are five times greater than losses in bridge-legs with fast external freewheeling diodes and two times greater than losses in bridge-legs using lifetime controlled MOSFETs.

By using different types of inductors (such as saturable inductors) in bridge-legs it has been shown that negligible turn-on losses can be achieved as reverse recovery of the intrinsic MOSFET diode can be limited. Practical results confirm that by using saturable inductors astutely in bridge-legs, it is possible to use the intrinsic diode of the classical MOSFET in high frequency inductive load switching applications with negligible turn-on losses.

REFERENCES

1 SGS

"Power MOS Devices", 1st Edition, October 1985.

2 J.T. DAVIES - P. WALKER - K.I. NUTTALL

"Optimisation of VDMOS power transistors for minimum on-state resistance", IEE Proceeding, vol. 134, PT.1, No. 3, June 1987.