Comparison of High-Frequency Application of Silicon Rectifiers, GaAs Rectifier, and ZVT Technology in a PFC Boost Converter

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Abstract-The use of silicon rectifiers in the continuous mode boost converter results in excessive reverse recovery currents. In order to overcome this problem, one solution is to use soft-switching techniques, such as the ZVT technology, while another solution is to use better rectifiers, namely, the recently developed GaAs rectifiers. In this paper, two PFC boost converters are built to compare the benefits derived from these two solutions and to compare the performances of silicon rectifiers and the GaAs rectifier.

I. INTRODUCTION

The recently introduced IEC 1000-3-2, IEC 1000-3-4 and IEEE 519 norms [1] and other international, national, or product-category standards require that the harmonic currents generated by line-connected equipment, including single-phase line rectifier circuits, stay below certain limits. In addition, increased noise requirements of sensitive electronics for communication, medical, and computing equipment are also affecting manufacturers.

Many high-power PFC circuits rely on the continuous mode boost converter to correct the power factor and reduce harmonic distortion of the line. However, when the boost switch turns on, the reverse recovery charge, which is stored in silicon rectifiers, creates a large current spike that increases losses in both the switch and the rectifier. As a result, their applications in higher power and higher frequency are limited. Also, the current spike is a source of broadband EMI that can be difficult to manage [2].

One possible way to solve these problems is based on improved circuit topologies. In the last decade, an array of zero-voltage-switching (ZVS) converter topologies [3] have been developed. Noticeable among them is the zero-voltage-transition (ZVT) [4] technology, which combines the merits of the resonant converter and PWM technology, while avoiding their respective drawbacks.

Another solution is based on the application of specific devices, such as the recently developed Gallium Arsenide (GaAs) rectifier [5]. Silicon, as a material, has inherent limitations due to its physical structure[6]. On the other hand, its reverse recovery time (trr) increases with junction temperature, which increases switching loss and, in many cases, causes thermal runway. With a larger bandgap, the GaAs rectifier achieves superior performance: less stored charge, shorter reverse recovery time, higher temperature stability and higher operating junction temperature. Its reverse recovery current is minimized, and the turn-on loss of power switches is reduced significantly.

The objective of this paper is to provide a comprehensive comparison of the performances of silicon rectifiers, the GaAs rectifier, and ZVT technology, and to quantify the benefits which can be derived from different solutions (one based on topology – ZVT, the other based on devices – the GaAs rectifier). In this paper, the experimental waveforms for silicon rectifiers and the GaAs rectifier under hard-switching conditions, and the results of the ZVT technology (with silicon rectifiers) are presented and analyzed.

II. TEST SET-UP

Two continuous mode boost converter power stages were built and used to test the performances of the GaAs rectifier, silicon rectifiers, and the benefits of ZVT soft-switching technology. The output of each boost converter is 400 V and the maximum output power is 2000 W. The power switch used is the Motorola MTW20N50E, whose voltage rating is 500 V and current rating is 20 A. The devices under test (DUT) are silicon rectifiers MUR860 and MURH860 and the GaAs rectifier MGR560. All these rectifiers are from Motorola. Their voltage ratings are 600 V. Table 1 shows the parameters of the different rectifiers. In addition, a fan is used in the test to cool devices.

Table 1. Parameters of different rectifiers [7]

	MUR860	MURH860	MGR560
Vrrm (V)	600	600	600
Vf (V) at Tj=25°C	1.5	2.8	2.75
If (A)	8	8	5
trr (nS) at Tj=25°C	60 (If=1 A, di/dt=50A/us)	35 (If=1A, di/dt=50A/us)	25 (Vr=400V, If=4A, di/dt=200A/uS)

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A. Hard-switching Test Circuit

The first converter is shown in Figure 1. This converter operates at 150 kHz in the hard-switching mode. Under this condition the different rectifiers (MUR860, MURH860 and GaAS MGR560) are compared.

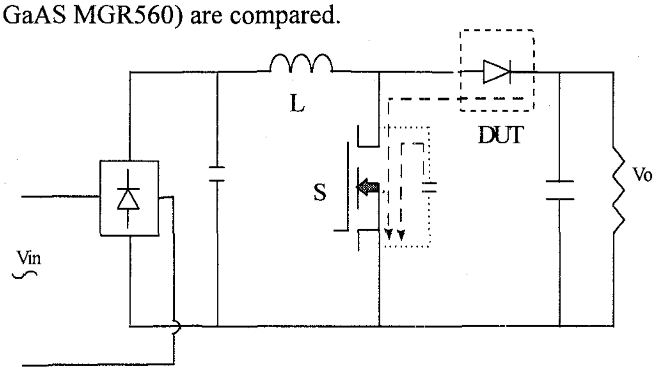

Fig .1 Hard -Switching PFC boost converter

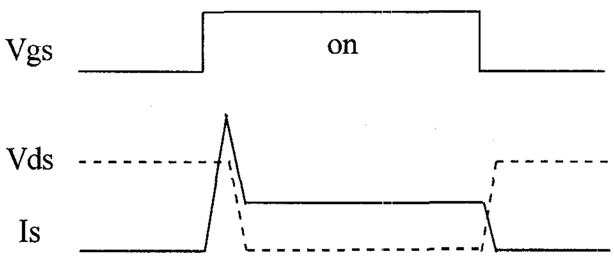

Fig. 2 Power Switch Switching waveforms
When the silicon rectifier is used as the output rectifier

Figure 2 shows that, when a silicon diode is tested, during the turn-on process, there is a large overlap between the switch current (Is) and voltage (Vds). It results in the high turn-on loss of the MOSFET. Several turn-on loss mechanisms can be identified: first, the loss caused by the reverse recovery current of the output rectifier; second, the loss associated with the discharge of the MOSFET output capacitance (Cds). When a GaAs rectifier is tested, the switch turn-on loss caused by reverse recovery current is reduced and the loss associated with the output capacitance of the switch is still the same. The EMI problem and device stress are alleviated.

During the turn-off process, the turn-off loss of the main switch is decided by its turn-off time, which includes turn-off delay time and fall time. High power rating MOSFETs have considerable turn-off loss due to their long turn-off time.

Therefore, in high power and high frequency applications, hard-switching of MOSFETs presents severe switching loss and thermal reliability problems. When a silicon rectifier is used as the output rectifier, there is high EMI noise and high device stresses. It is particularly attractive to employ soft-switching techniques to solve these problems.

B. Zero-Voltage-Transition Test Circuit

The ZVS techniques, including the ZVT scheme, were first introduced to solve the reverse recovery problem of the rectifiers and the capacitive turn-on loss [4].

Figure 3 shows the second converter, which operates at 150 kHz in the ZVT soft-switching mode. Rectifier MUR860 is used in this topology. The auxiliary switch used here is the IRF840 (600V, 4A). The resonant inductor Lr is 10 uH. The resonant capacitor is 1 nF.

Figure 4 shows the key operation waveforms of the ZVT circuit. The auxiliary switch S1 is turned on at t_0. From t0 to t1, the resonant inductor takes over the current from the output rectifier D. The ensuing resonance between Lr and Cr brings the voltage across the main switch S to zero. After t2, the surplus current beyond the main choke current flows through the body diode of the main switch and the main switch can be turned on under the zero-voltage conditions. From t3 to t4, the current in the resonant inductor is linearly transferred to the main switch.

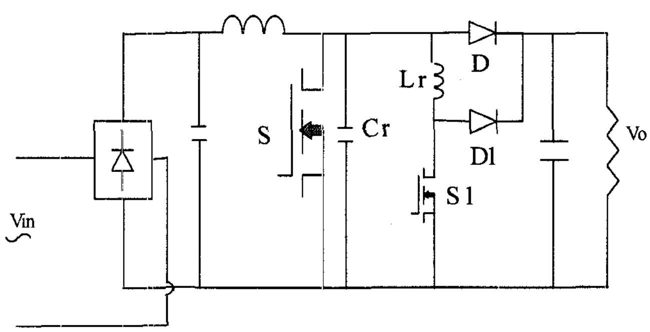

Fig. 3 The ZVT topology

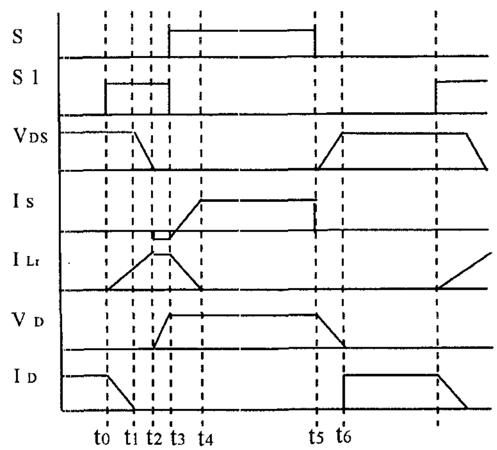

Fig. 4 Key waveforms in the ZVT Circuit

During turn-off, due to the additional resonant capacitor Cr, the voltage of the main switch cannot increase as quickly as that in the hard-switching mode. This can help to reduce the turn-off loss of the main switch.

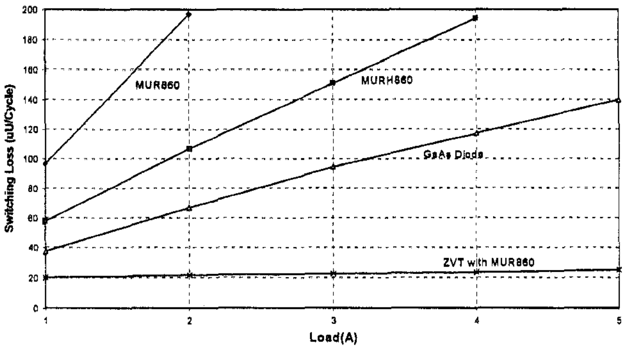

Fig. 5 Switching Loss of the Power switch (Vo=400V)

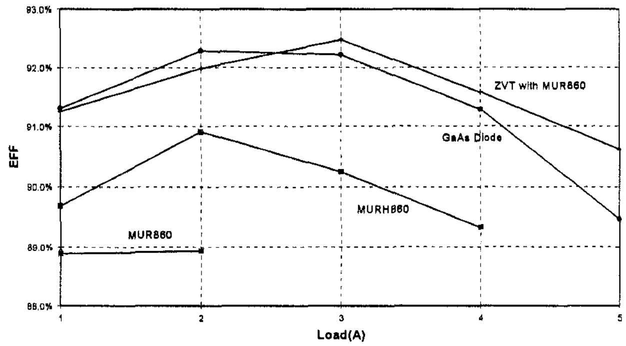

Fig 6. Efficiency Comparison (Vo=400V)

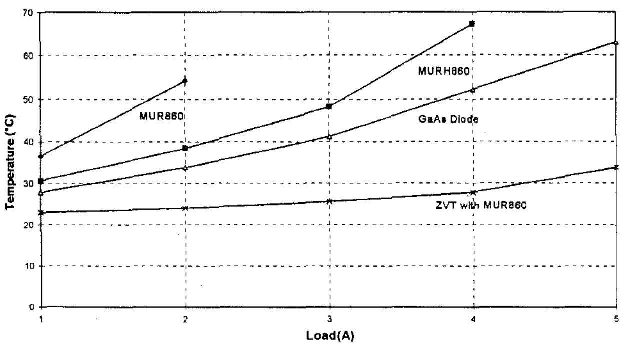

Fig.7 Temperature of the Power Switch (Vo=400 V)

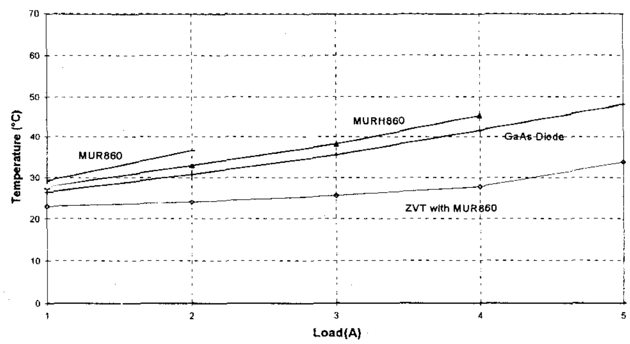

Fig 8. Temperature of Rectifiers (Vo=400 V)

In summary, the ZVT technique eliminates the MOSFET turn-on loss, solves the diode reverse recovery problem, lessens the EMI noise, reduces the device stress and alleviates the thermal problem. Moreover, it can also reduce the main switch turn-off loss.

III. Test Results Comparison

(1) Hard-Switching with the MUR860 Rectifier

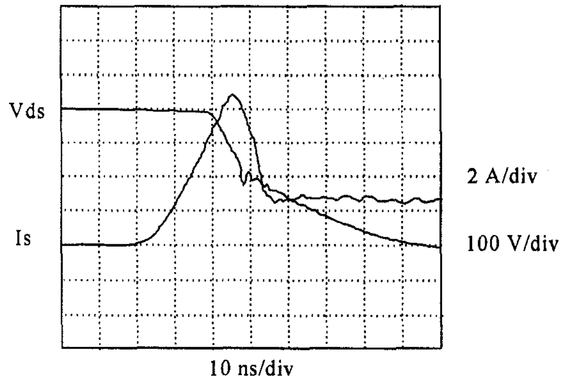

Fig. 9 Hard-switching with the MUR860 Power Switch Turn-On (Vo=400V, Io=2 A)

Figure 9 shows the power switch turn-on waveform when the MUR860 is used. With the MUR860, the power switch turn-on current shows the largest peak value (more than three times the load current). Also, the power stage has the lowest efficiency. The measured highest efficiency is 88.8% at Vo=400 V and Io=2 A. The power switch and rectifier in this converter have the highest case temperature compared with other topologies at the same power rating. When Vo=400 V and Io=2 A, the power switch temperature is 54.3°C, while the rectifier is 37.1 °C. In Figure 5, the power switch has the highest switching loss. Due to the high temperature of the rectifier and the power switch, the reverse recovery current caused by the output rectifier is increased, and the on-resistance of the main switch is also increased. As a result, the switching loss and conduction loss of the power switch are the largest.

The test results show that it is difficult to use the MUR860 in a 2-kW, 150-KHz hard-switching PFC Boost converter without the help of soft-switching techniques.

(2) Hard-Switching with the MURH860 Rectifier

Figure 10 shows the turn-on waveform of the power switch, when the MURH860 is used. The MURH860 is faster than the MUR860. Its reverse recovery time is only half that of the MUR860. Its reverse recovery current is much smaller than that of the MUR860. However, its forward voltage drop is two times that of the MUR860. Because of the smaller reverse recovery current, the turn-on loss of the power switch is lower than the loss occurring, when the MUR860 is used.

From Figure 5, it can be seen that, when the MURH860 is used as the output rectifier, the total switching loss of the power switch is only half that with the MUR860. As a result, the converter efficiency is 2% higher than when the MUR860 is used. From Figure 6, at Vo=400 V and Io=2 A, the power device case temperature is 15°C lower than with the MUR860 and the rectifier case temperature is 6°C lower. Due to lower the junction temperature, the reverse recovery time of the output rectifier and the loss in the power switch are reduced. The maximum efficiency of the converter is close to 91% at Vo=400 V and Io=2 A. However, it is still difficult to push the converter to operate at maximum power rating. The power switch case temperature is close to 70°C at Vo=400 V and Io=4 A, which means the converter needs additional circuitry to achieve a higher power rating.

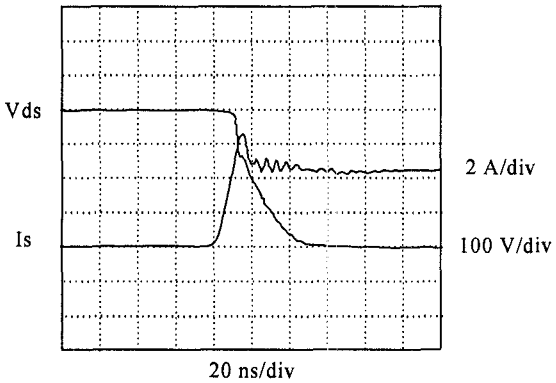

Fig.10 Hard-Switching with the MURH860 Power Switch Turn-On (Vo=400 V, Io=4 A)

(3) Hard-Switching with the GaAs Rectifier

Figure 11 shows the turn-on waveform of the power switch when the GaAs rectifier MGR560 is used. Due to its larger energy gap, gallium arsenide (GaAs) has insignificant minority carrier injection and stored charge, which minimizes the rectifier reverse recovery current and reverse recovery time. When the GaAs rectifier is used, the turn-on loss of the power switch is significantly reduced. Its turn-on loss is only one-fourth of the loss occurring when the MUR860 is used and half of that occurring when the MURH860 is used. From Figure 5, it can be seen that, when the GaAs rectifier is used, the power switch's switching loss is only one-third of that of the MUR860 and two-thirds that of the MURH860. This induces another 1-2% efficiency improvement. The highest efficiency is 92.3% at Vo=400V and Io=2A. The device temperature is the lowest compared with other hard-switching topologies. At Vo=400V and Io=5A, the power switch case temperature is 63°C and the rectifier case temperature is 42.6°C. When the MUR860 or MURH860 is used, the temperatures already are close to 70°C at a lower power rating. The GaAs rectifier allows converter operation up to the full output voltage and maximum output power. Figure. 11 shows the turn-on waveform of the power switch, when GaAs is used as an output rectifier. The current spike is very small and the rise of the current is soft. All these advantages are helpful in reducing the device stress and EMI filter size. Additionally, unlike the silicon rectifier, the GaAs rectifier performance is almost independent of temperature. Figure 12 shows the turn-off waveform of the power switch. The waveform is close to that when the MUR860 and MURH860 are used. The GaAs rectifier cannot help to reduce the power switch turn-off loss.

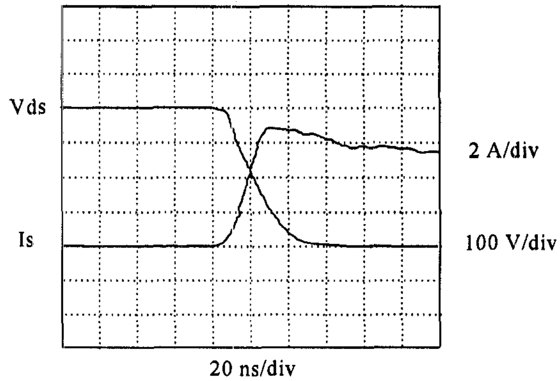

Fig. 11 Hard-switching with the MGR560 Power Switch Turn-On (Vo=400 V, Io=5 A)

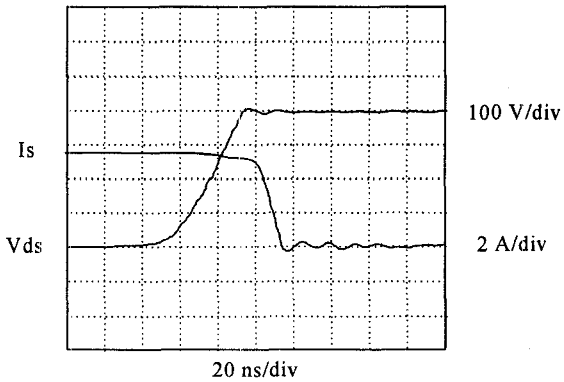

Fig. 12 Hard-switching with the MGR560 Power Switch Turn-off (Vo=400 V, Io=5 A)

(4) Zero-Voltage-Transition Soft-Switching

Numerous soft-switching techniques are subject to either high voltage stresses or current stresses. With some of them, such as ZVS-QRC and ZVS-PWM, their soft-switching condition is strongly dependent on load current and input voltage. For the ZVT technology, both switches are subjected to minimum voltage and current stresses compared to their PWM counterparts. Soft-switching operation can be easily maintained. Both the active and passive switches operate with zero-voltage switching. Also, the switching frequency is constant.

In practice, there is a parasitic capacitor in parallel with the auxiliary switch. Therefore, the auxiliary inductor resonates with this capacitor at turn-off. This resonance causes a considerable conduction loss in the auxiliary circuit. On the other hand, there is the reverse recovery current problem of the auxiliary diode. As a result, the turn-on loss of the auxiliary switch is high, and the ZVT efficiency is reduced significantly. In order to avoid the effect of the auxiliary switch parallel parasitic capacitance, the test uses the practical ZVT circuit shown in Fig. 13. A diode in series with the auxiliary inductor is used to keep the unique direction of the auxiliary current and prevent the resonance of the auxiliary inductor and the parasitic capacitor. At the same time, a saturable inductor is used in series with the auxiliary inductor to dampen the ringing caused by the parasitic capacitor of the series diode.

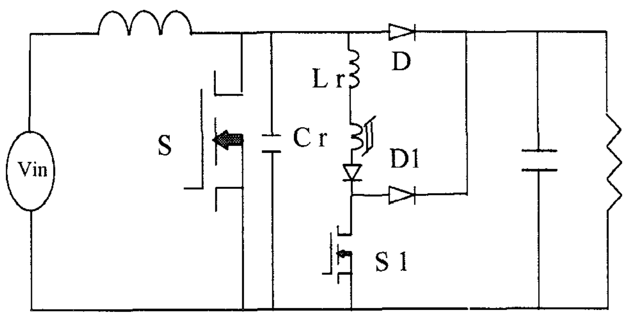

Fig. 13 The ZVT Circuit Used in Test

In this ZVT boost converter, the MUR860 is used as the output rectifier. Its purpose is to reduce conduction loss and cost. The resonant capacitor Cr in the ZVT can help to reduce the turn-off loss of the power switch. Here, a 1nF capacitor is selected. Since the average current is much smaller in the auxiliary circuit, a low power rated MOSFET can be used as the auxiliary switch. Here, an IRF840 (600V, 4A) is selected. For the same reason, the auxiliary diode can also use a lower power rated rectifier.

Figure 14 shows the turn-on waveform of the power switch. The reverse recovery current is eliminated. The EMI problem and device stress is significantly improved. Figure 15 shows the turn-off waveform of the power switch, the turn-off loss is only one-third of that in har-switching. From Figure 15, it can be seen that with ZVT, the total switching loss of the power switch is one-tenth of that when the MUR860 is used, one-fifth of the loss occurring when the MURH860 is used, and one-third of that occurring when the GaAs rectifier is used. The power switch case temperature is only 33°C at the full load, which is 30°C lower than that with the GaAs rectifier. The case temperature of the auxiliary power switch is also close to 33°C at the full load. Compared with hard-switching topologies, the case temperature of the MUR860 used in ZVT circuit is 15°C lower than that of the GaAs rectifier used in the hard-switching circuit at the full load, It is 10°C lower than that of the MUR860 used in the hard-switching circuit at Vo=400 V and Io=2 A. The maximum efficiency of the ZVT circuit is close to 92.5% at Vo=400 V and Io=3 A. Compared with the efficiency of the hard-switching circuit when the GaAs rectifier is used, the efficiency of the ZVT circuit is close to it at light load and 1 % higher at heavy load. All the test results show that ZVT can not only improve efficiency, but also solve thermal problems.

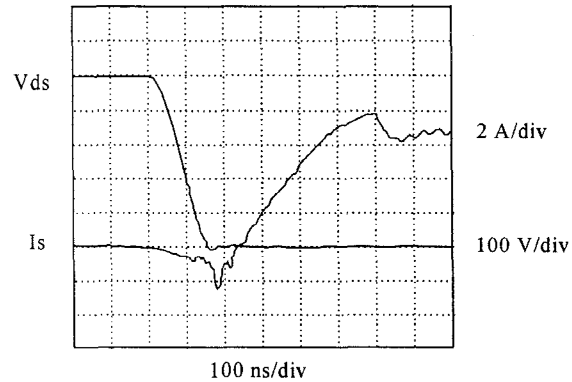

Fig.14 ZVT with the MUR860
Power Switch Turn-On (Vo=400 V, Io=5 A)

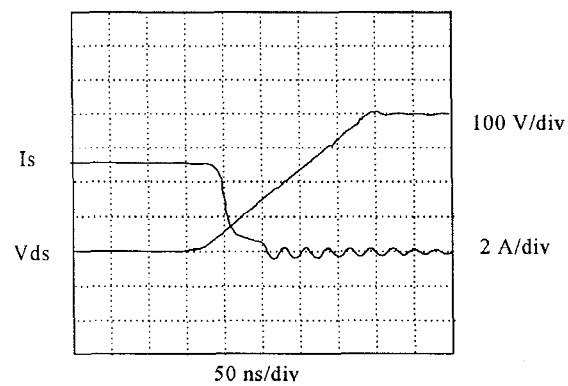

Fig. 15 ZVT with the MUR860
Power Switch Turn-Off (Vo=400V, Io=5 A)

(5) Gate Signal Waveform

The gate signal waveform is strongly affected by the rectifier reverse recovery current. Figures 16, 17, 18 and 19 show the gate signal waveform under four different conditions (hard-switching with the MUR860, MURH860 and GaAs MGR560 and ZVT with the MUR860). The gate resistor used here is 10 Ω. When the MUR860 and MURH860 are used, due to the large reverse recovery current, the noise in the gate drive is very noticeable. A larger gate resistor can help to dampen the noise. However, turn-on loss increases with the gate resistor. When the GaAs rectifier is used, the gate signal waveform is improved. When the ZVT circuit is used, the power switch gate signal shows the cleanest waveform. With the ZVT technique, the circuit operation will not be significantly affected by the circuit layout.

IV Conclusion

For hard-switching topologies, using the GaAs rectifier can significantly improve the efficiency and make the converter easy to control. But thermal problems still exist and the GaAs rectifier is expensive. The ZVT soft-switching technology not only improves efficiency (1% higher than that obtained with the GaAs rectifier at heavy load), but also solves the thermal problem. The price of the auxiliary network is less than that of the GaAs rectifier at this time.

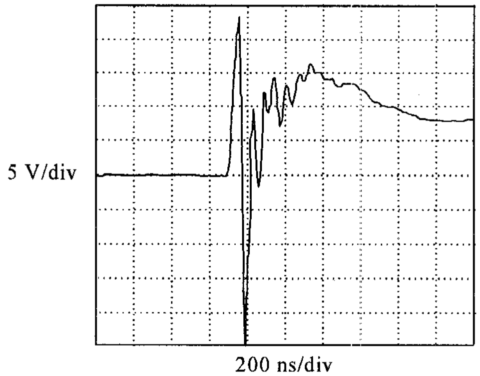

Fig. 16 Turn-On Gate Signal Waveform
Hard-switching with the MUR860 (Vo=400 V, Io=1 A)

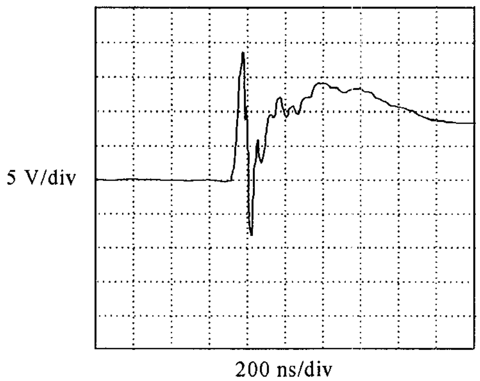

Fig. 17 Turn-On Gate Signal Waveform
Hard-switching with the MURH860 (Vo=400 V, Io=1 A)

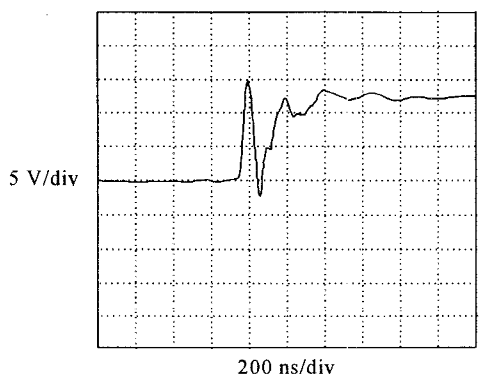

Fig. 16 Turn-On Gate Signal Waveform
Hard-switching with the MGR560 (Vo=400 V, Io=1 A)

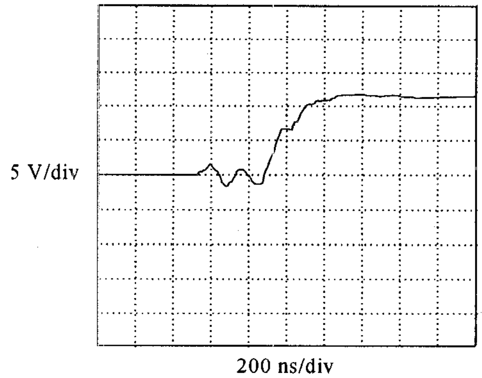

Fig. 19 Turn-On Gate Signal Waveform
ZVT with the MUR860 (Vo=400 V, Io=1 A)

Acknowledgment

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