SGS-THOMSON MICROELECTRONICS

APPLICATION NOTE

ANALYSIS AND OPTIMISATION OF HIGH FREQUENCY POWER RECTIFICATION

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How can the performance of power electronics be improved ? Today, in many cases, it is the job of the designer. The fast rectifier switching behaviour depends on the operating conditions. The analysis and the optimisation of these conditions can be an important source of improvement in performance.

1. SWITCH-OFF OF FAST RECOVERY RECTIFIERS

It is possible to define theoretically two types of switch-off[1].

1.1. FREE-WHEEL MODE (figures 1 & 2)

When the rectifier switches-off it is always in parallel with a voltage source. In this case the assumption is that the parasitic inductances are negligible. This type of behaviour can be met in the majority or rectifier applications such as free-wheel rectifiers in step-down and step-up converters, full wave rectifiers, etc... (figure 2). Generally, a rectifier in free-wheel mode is always in parallel with a voltage source when it turns-off.

1.2. RECTIFIER MODE (figures 1 & 3)

An inductance defines the dI_F/dt (decreasing slope of the rectifier current) and when the rectifier switches-off it is always in series with this inductance. This type of behaviour can be met in some applications such as rectifiers in flyback converters and many functions in thyristor circuits, (figure 3). Generally speaking a rectifier in the rectifier mode is always in series with an inductance L and this inductance L defines the dI_F/dt. The fundamental difference between these two modes is that in the rectifier mode there is a stored energy $1/2LI_{RM}^2$ due to the series inductance. After the turn-off this energy is dissipated in the rectifier and/or in the associated circuits.

1.3. TURN-OFF LOSSES

Free-wheel mode

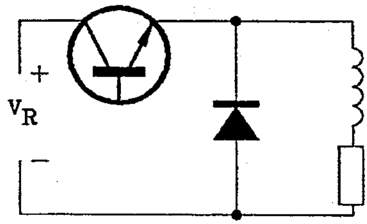
W_{OFF} is the energy dissipated in the rectifier during turn-off.

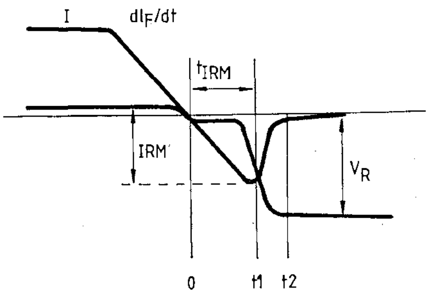
$$WFR = \int_{t_1}^{t_2} VIdt$$ (refer to figure 1)

Low voltage (< 200V) fast rectifiers have a high internal capacity and the minority carriers have a very short life time. High voltage fast rectifier have a thicker N silicon layer and the minority carriers have longer life time and consequently different behaviour during the turn-off condition blocking state. (Higher I_{RM} and t_{IRM} - more damping).

Figure 1 : Fast Rectifier : the two turn-off modes.

a) Free-wheel Mode.





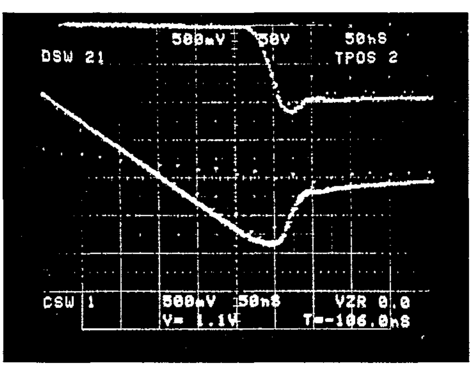
d_{IF}/dt FIXED BY THE TRANSISTOR (or by the external circuit)

LOW LOSSES IN THE RECTIFIER

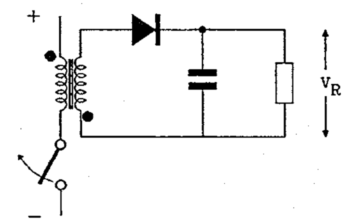
$W_{OFF} = K \cdot V_R \cdot I_{RM} \cdot T_{IRM}$

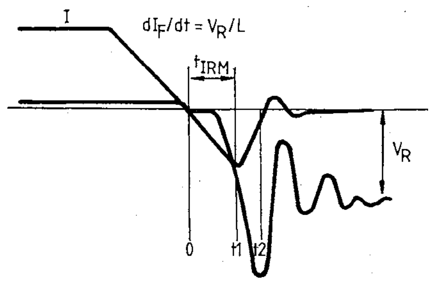
$(0.15 < K < 0.35)$

NO OSCILLATIONS AND OVERVOLTAGE



b) Rectifier Mode.





d_{IF}/dt FIXED BY THE INDUCTANCE

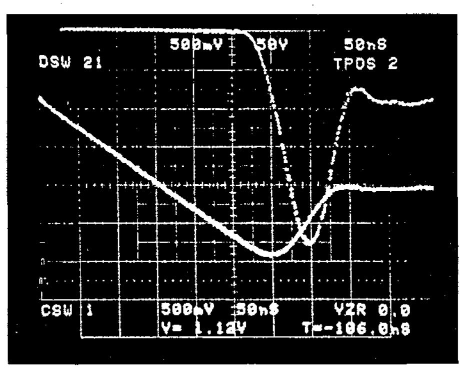
$dI_F/dt = V_R/L$

HIGH LOSSES IN THE RECTIFIER

$W_{OFF} = K \cdot V_R \cdot I_{RM} \cdot T_{IRM} + 1/2\ L_J{}^2{}_{RM}$

When a snubber is used some of the energy is dissipated in the snubber.

ALWAYS OVERVOLTAGE AND OSCILLATIONS IN SOME CONDITIONS



5A/div. 50V/div. 0.05μs/div.

BYT30 – 1000 – $I_F = 3A$ – $dI_F/dt = -75A/\mu s$ – $V_R = 100V$ – $T_{CASE} = 25°C$

According to the experimental results the turn-off energy loss $(W)_{FR}$ in the free-wheel mode can be written :

$$(W)_{FR} = K \times V_R \times I_{RM} \times t_{IRM} \quad (1)$$

$K^{(1)}$ is a constant that depends on the thickness of the N type silicon layer.

Max Voltage Rating (V)	200	400	800	1000	1200
K	0.12	0.14	0.22	0.28	0.35

Rectifier mode

Losses in this mode, $(W)_{REC}$, are the sum of the stored energy $1/2\ L\ I_{RM}^2$ and the recovery energy $(W)_{FR}$:

$$(W)_{REC} = (W)_{FR} + 1/2\ L\ I_{RM}^2 \quad (2)$$

In some cases, oscillations can occur. This depends on the damping due to the current tail effect after switch-off. When oscillations occur energy is dissipated during the oscillations partly in the rectifier and partly in the circuit. When snubbers are used a significant part of the energy is dissipated in the snubber.

2. PRACTICAL SWITCH-OFF BEHAVIOUR

The two cases, free-wheel mode and rectifier mode are simplified cases that are easy to simulate in a laboratory characterisation. In practical equipment there is always a possible overlap between the two theoretical modes, because :

1. No circuit is without parasitic inductances.
2. The rise time (or the fall time) of the switch is not infinitely fast when compared with the rate of change of current, dI_F/dt.

Experimental results show that in all cases the following formula can be used :

$$(W)_{OFF} = (W)_{FR} + 1/2\ L_S\ I_{RM}^2 \quad (3)$$

Where L_S = series inductance

This important relationship is a useful tool for the designer, giving him the main parameters that influence the turn-off energy.

N.B. : The following relationship (4) is only true for the pure rectifier mode.

$$(W)_{OFF} = Q_R \times V_R \quad (4)$$

Where Q_R = recovered charge

(1) K is experimental - Defined for SGS-THOMSON Microelectronics fast rectifiers.

Figure 2 : Rectifiers in Free Wheel Mode.

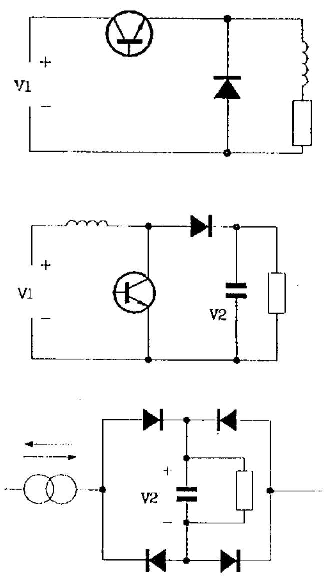


Figure 3 : Rectifiers in Rectifier Mode.

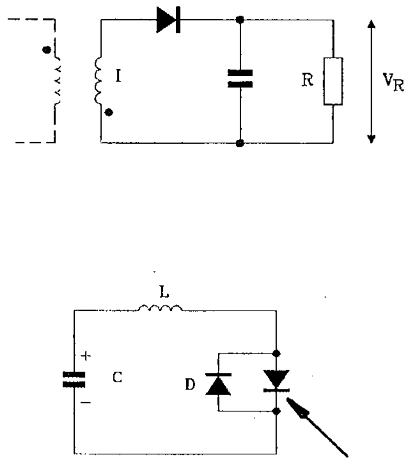
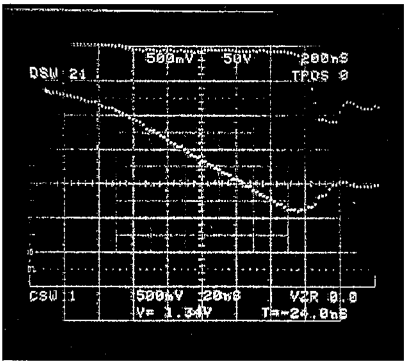
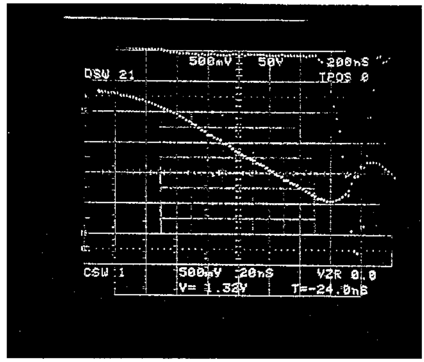


Figure 4 : Switch-off Behaviour of the Ultrafast BYT12-400V Rectifier (current rating 12A - voltage rating 400V).
Conditions : I_F = 13A dI_F/dt = – 150A/µs V_R = 100V T_{case} = 25°C.
In the case of rectifier mode : L = 0,6µH.
The turn-off lost energy calculated by the current and voltage is :
$(W)_{FR}$ = 3µJ free-wheel mode.
$(W)_{REC}$ = 10µJ rectifier mode.
The storage energy in the inductance is : $1/2\ L\ I_{RM}^2 = 7.5µJ$.

a) Free wheel mode.



b) Rectifier mode.



The use of this equation for a lot of practical circuits can be considered as a first approximation. It leads to over estimated losses, if the rectifier does not operate in pure "rectifier mode".

3. CHARACTERISTICS OF FAST RECTIFIERS

The characteristics of fast rectifiers are the result of a trade off between :

- Speed (I_{RM})
- Max voltage rating (V_{RRM})
- Forward voltage drop (V_F).

Example : 12A fast rectifiers.

V_{RRM}		200	400	800	1000
Type		BYW81	BYT12-400	BYT12-800	BYT12-1000
T_j = 100°C	I_{RM}(A)	1.8	3.7	6	7.8
dI_F/dt = – 50A/µs					
	t_{IRM}(µs)	0.05	0.075	0.160	0.200
V_F	(V)	0.66 + 0.0071	11 + 0.021	1.3 + 0.031	1.3 + 0.031

Operating conditions

I_{RM} increases with dI_F/dt (figure 5).

I_{RM} increases with T_j (figure 6).

The important points that emerge are :

1. High voltage fast rectifiers are not so fast as low voltage fast rectifiers, (comparing devices of equal current rating).
2. T_j and dI_F/dt have a strong influence on the reverse recovery current.

4. EXAMPLES

4.1. FLYBACK CONVERTER (figure 7)

The behaviour is as a pure rectifier ; the rectifier is driven by a current source, the inductor, L.

For a frequency less than 100kHz the switching losses are small in comparison to the conduction losses, because dI_F/dt defined by V_o/L is always small, (see table figure 7).

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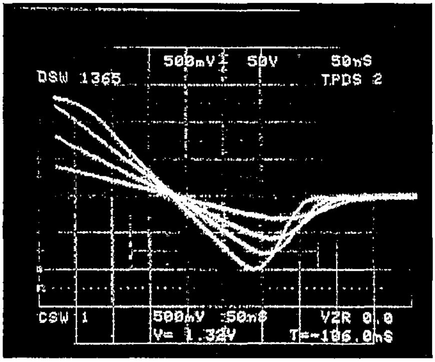
Figure 5 : Switch-off Behaviour of the Fast Rectifier BYT12P 1000 (current rating 12A voltage rating 1000V). Influence of the dI_F/dt.



5A/div, 50ns/div, Tj = 25°C

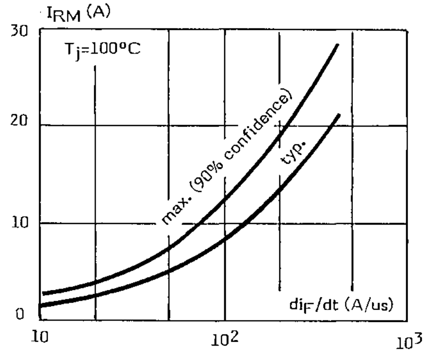
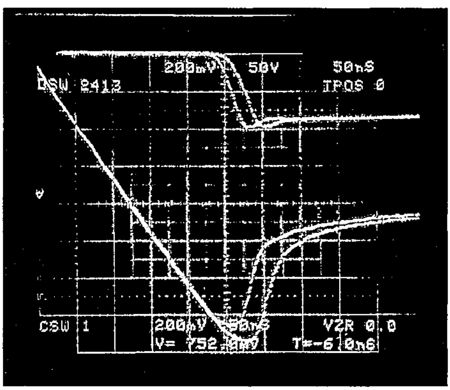
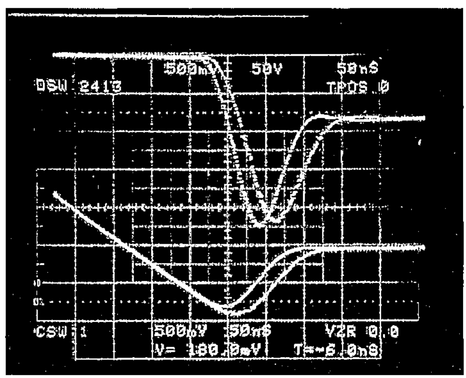


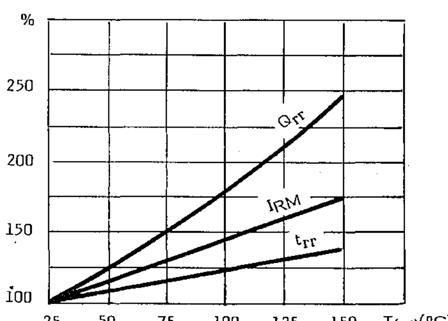
Figure 6 : Switch-off Behaviour of the Fast Rectifier BYT12 1000 Influence of T_j. One Curve T_j = 25°, one curve T_j = 60°.



100V/C, 2A/div, 50ns/div
Free-wheel mode



100V/C, 2A/div, 50ns/div
Rectifier mode



How can the designer reduce the losses ?

1. The ratio I peak/I_{AVG}, is very unfavourable in this type of circuit. It is essential when the peak voltage is less than 200V that the "high efficiency ultra fast" family which have very low conduction losses are used. When the peak voltage is greater than 200V one solution is to use a rectifier with higher current rating.

Example :

In the same circuit at 12A with :

- BYT12-800 : conduction losses = 7.6W, a 12A rectifier.
- BYT30-800 : conduction losses = 6W, a 30A rectifier

2. Reduce the junction temperature. If Tj is decreased from 100 to 75°C the switching losses are reduced by 20%.

4.2. SMALL CURRENT RECTIFIER (figure 8)

A transformer with a leakage inductance measured on the secondary side L_S = 1µH supplies a fast diode D. The average output current is 0.8A and the output voltage is 48V.

The designer wants to use the popular diode BA157. This is not possible because the total power dissipation is 1.15W at 40kHz. At this frequency he can only use a popular 2A current rated diode (for 0.8A rectified current) and at 200kHz there is no solution with popular diodes (see table in figure 8).

How can the designer reduce the losses ?

1. Choose a diode in the "high efficiency family". For example he can use the BYW100 for 40kHz to 200kHz, (see table figure 8).
2. Reduce the leakage inductance : with a leakage inductance L_S = 0.1µH, BY218 at 200kHz (1.24W, ΔTj = 93°C).

4.3. FULL WAVE OUTPUT RECTIFIER

There are two different full wave rectifying circuits.

4.3.1. VOLTAGE SOURCE - CURRENT OUTPUT

Current and voltage behaviour are indicated in figure 9. The inductance L_S is the leakage inductance of the insulation transformer.

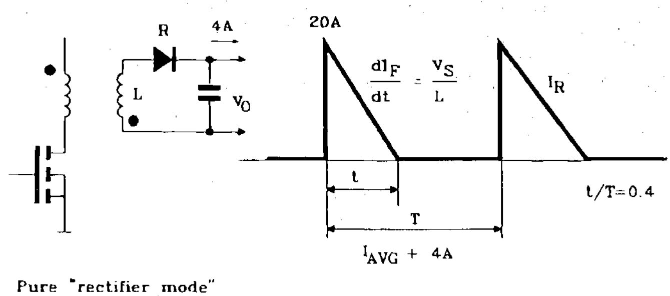
The 4 rectifiers operate in an intermediate mode between "free wheel" and "rectifier", because there are some 1/2 L_S I_{RM}^2 losses.

4.3.2. CURRENT SOURCE - VOLTAGE OUTPUT (figure 10).

In this circuit, each rectifier operates in "free wheel" mode. The series inductance does not introduce additional losses. (This assummes there is no parasitic inductance between the rectifiers and the capacitor C).

How can the designer reduce the losses ?

Figure 7 : Flyback Rectifier Output Average Current 4A.
Below 100kHz the switching losses are negligible, in comparison with the conduction losses.
The reason is limited dI_F/dt, consequently limited I_{RM}.



V_O (V)	12	48	100
Rectifier	BYW81-100 "High Efficiency"	BYT12-400	BYT12-800
Conduction Losses (W)	3.2	6	7.6
Switching Losses a 50kHz (W)	0.006	0.05	0.81
Switching Losses a 200kHz (W)	0.05	0.5	5.5

Figure 8 : The Popular Diodes BA157 – BY218 are not Fast Enough for High Frequency Rectifying. The BYW100 is well adapted.

DIODE	BA157 Popular	BY218 Popular	BYW100-200 High Efficiency
I_{RM} a 100°C dI/dt = – 20A/µs (A) t_{IRM} a 100°C dI/dt = – 20A/µs (A) $(W)_{FR}$ (µJ) 1/2 L_S I^2_{RM} (µJ)	2.8 0.14 2.08 3.9	2.8 0.14 2.08 3.9	0.75 0.05 0.01 0.28
Conduction Losses (W) Switching Losses a 40kHz (W) Switching Losses a 200kHz (W)	0.944 0.2 1.3	0.744 0.2 1.3	0.592 0.012 0.06
Total Diode Losses a 40kHz (W) Δ Tj a 40kHz (°C)	1.15 115°	0.44 71°	0.6 60°
Total Diode Losses a 200kHz (W) Δ Tj a 200kHz (°C)	1.97 197°	1.77 132°	0.65 65°

a) Voltage source - current output
Reduce the transformer leakage inductance. Table of figure 11 shows that in the case of the 400V 10A 200kHz bridge circuit the suppression of the inductance L_S can save 4 x 16.5W = 66W.
Replace in the same circuit the high voltage fast rectifier BYT12-600 by 3 "high efficiency" BYW81-200 in series (see figure 12 - table). The total losses decrease from 186W to 58W. This result is very important as it shows it is more efficient to use several "high efficiency" ultra fast rectifiers instead of a single high voltage one for high frequency operation.

b) Both
Use of sinusoidal current (resonant converter) instead of rectangular waveforms. Figure 11 shows that for the same conditions (400V - 10A - 200kHz) the switching losses with a sinusoidal current are only 4 x 7.5 = 30W (4 x 22 = 88W with rectangular wave forms).

4.4. STEP UP CONVERTER

The rectifier operates in free wheel mode. The main losses in this case occur in the transistor during the turn-on (similar to the step down converter). Figure 13 shows that with 600V output at 40kHz, if the rectifier switching losses are reasonable, the transistor turn-on losses are too high.

How can the designer reduce these turn-on losses ? (fig. 13).

a) Decrease the rectifier junction temperature by more efficient cooling.
If the BYT12-800 junction temperature decreases from 100 to 70°C, the transistor turn-on losses decrease from 39.5W to 33W.

b) To replace one BYT12-800 by 4 high efficiency BYW81-200 in series. The total balance is a reduction in losses from 39.5 to 16.6W in the transistor with same losses in the rectifier.

IN SUMMARY

Two major actions reduce switching losses caused by fast recovery rectifiers :

1. APPROPRIATE CHOICE OF COMPONENT

- The fastest rectifier compatible with the peak voltage in the application.

- If the peak voltage V_R exceeds 400V the designer must analyse carefully the switching losses :
  - These losses are proportional to $I^2_{RM} \times V_R$.

A 800V fast rectifier has an I_{RM} approximately two times higher than a 400V fast rectifier (same current rating).

Figure 9 : Voltage Source, Output Current Full Bridge Circuit.

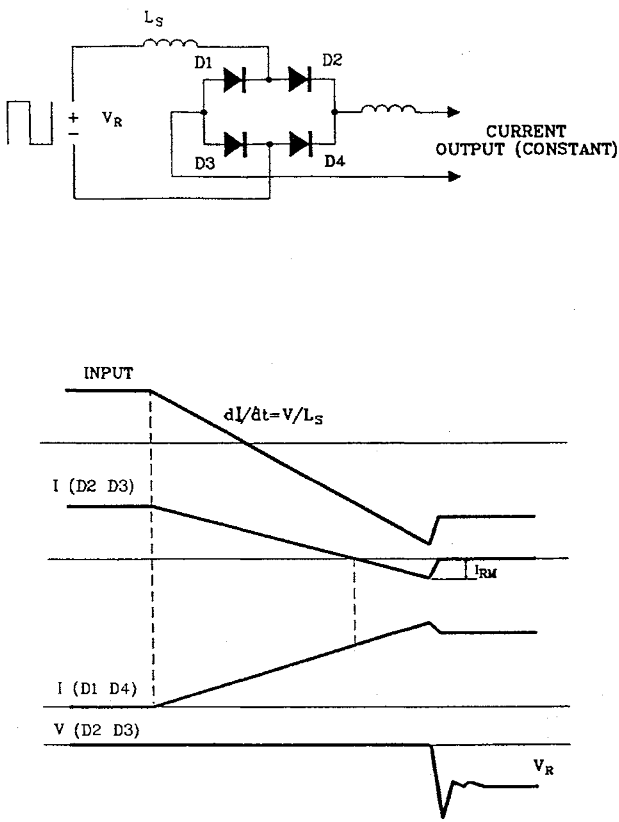


Figure 10 : Current Source, Output Voltage Full Bridge Circuit.

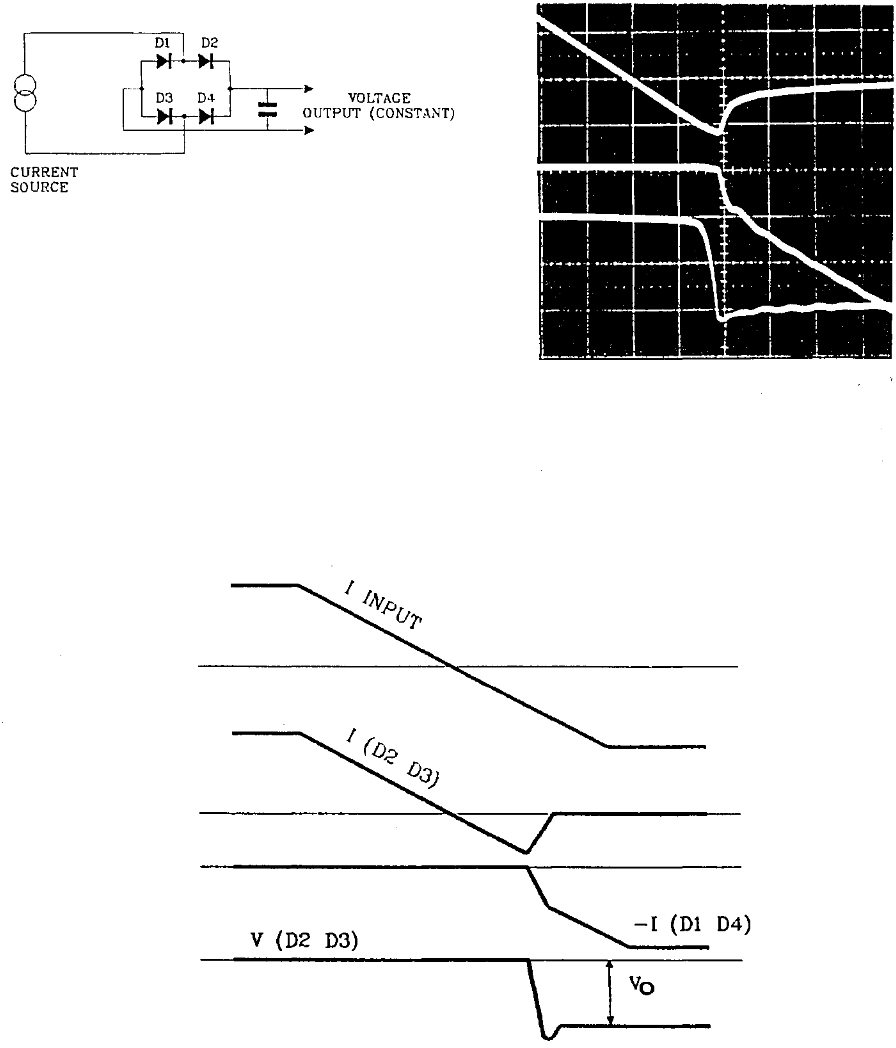
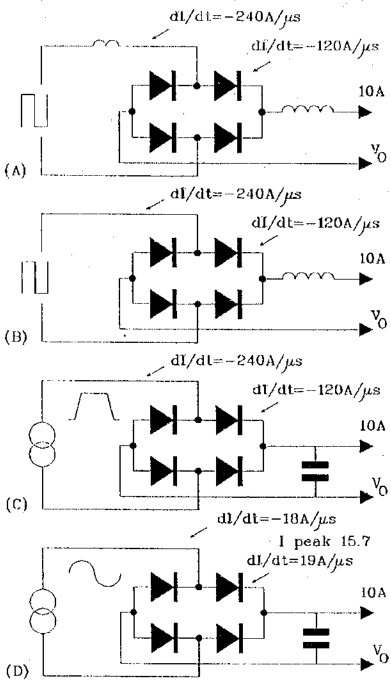


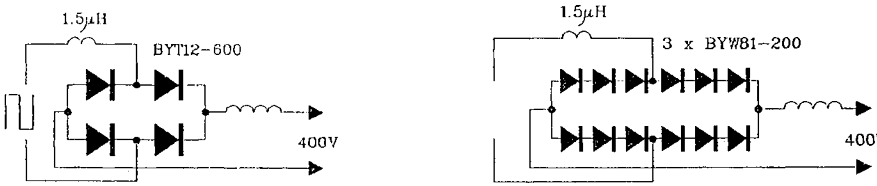
Figure 11 : Switching Losses (per leg) in a full Wave 200kHz Bridge Circuit. Output 10A.
In case of voltage source, current output, the (leakage) inductance L_S introduces $L_S I^2_{RM}$ losses.
In case D, the losses are smaller (6 x 4 = 24W instead of 22 x 4 = 88W) because dI/dt is smaller, consequently I_{RM} is smaller.

L_S = 0.5µH (48V)
1µH (200V)
1.5µH (400V)



V_O	48	200	400
Rectifier	BYW81-100	BYT12-300	BYT12-600
200kHz			
(A)	0.76W	5.6W	38.5W
(B)	0.16W	2W	22W
(C)	0.16W	2W	22W
(D)	0.04W	0.6W	6W

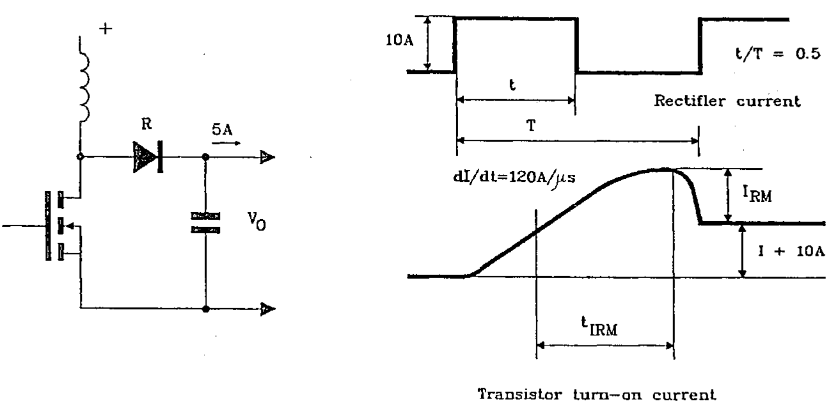
Figure 12 : Switching Losses (per leg) in the Full Wave 400V 200kHz Bridge Circuit with two Different "rectifiers".
Replacing the high voltage BYT12 – 600 rectifier by 3 "high efficiency" ultra fast BYW81 – 200 in series reduces the total losses dramatically. This is why the I_{RM} from BYW81 is very low and the voltage drop of this high efficiency rectifier is very low.



Rectifier	BYT12-600	3xBYW81-200
Conduction Losses (W)	8	11
Switching Losses (W)	38.5	3.5
Total Losses per Leg (W)	46.5	14.5

F = 200kHz
V_0 = 400V
I_{AVG} = 10A
dI_F/dt = – 120A/μs
t/T = 0.5

Figure 13 : In the Step-up (or step down) Converter the Majority of Losses Occur in the Transistor, Specially when a High Voltage Rectifier is used.
In some case replacing a high voltage rectifier by several faster rectifiers in series (and consequently with a lower voltage rating) can minimize the total losses despite the increase of the rectifier conduction losses.



$$(W)_{ON} = \frac{V_R}{2} \left[\frac{I}{dI/dt} + (I + I_{RM})\, t_{IRM} \right]$$

Figure 13 (continued).

V_0	48	300	600	600
Rectifier	BYW81-100	BYT12-400	BYT12-800	4 x BYT81-200
(d_I/dt = 120A/µs) I_{RM} (A) (T_j = 100°) t_{IRM} (µs)	3.8 0.04	6 0.06	10.5 0.12	3.8
Rectifier Conduction Losses (W)	3.65	6.5	8	14.6
Rectifier Switching Losses a 40kHz (W)	0.04	0.6	6.7	0.5
Total Rectifier Losses a 40kHz (W)	3.7	7.1	14.7	15.1
Transistor Turn-on Losses a 40kHz (W)	1.32	1	0.7	39.5

The rectifier voltage drop increases with the rating voltage.
Example : BYW81 "high efficiency" 200V rating V_F = 0.85V (max).
BYT12-600 600V rating V_F = 1.8 (max).

IMPORTANT CONSEQUENCES :

If the switching frequency is greater than 40kHz in many cases it will be more efficient to replace one high voltage (600 - 800 - 1000V) rectifier by a series of ultrafast rectifiers (200V or 400V). Despite the increase of conduction losses, a dramatic reduction of switching losses results in a decrease in the total losses.

2. OPTIMAL OPERATING CONDITIONS

2.1. In many cases parasitic inductance gives additional losses. A reduction of those parasitic inductances L_S decreases not only the voltage spikes but also the switching losses.

2.2. Junction temperature plays an important rôle. The switching losses are approximately proportional to Tj. Improving the rectifier cooling is very important for all high frequency rectifiers.

2.3. For full wave rectifying circuits, with an isolation transformer the switching losses are always lower in case of :

Current source → rectifying → voltage source

than :

Voltage source → rectifying → current source

because the impedance due to the transformer leakage inductance is integrated in the current source, and does not play any part in the additional losses.

2.4. The use of the resonant circuit with sinusoidal current waveforms results in a significant reduction in the switching losses due to the limited dI_F/dt or to the smaller V_R re-applied voltage.

CONCLUSION

Reducing the switching losses in high frequency converters is team work.

The manufacturer has improved the fast recovery rectifier characteristics. The designer has now some tools to analyse, with a greater accuracy, the rectifier behaviour and choose the optimal solution in order to minimize the losses.

REFERENCE

|1| "Switching behaviour of fast diodes in the converter circuits" - p.63 to 78 in the hand book SGS-THOMSON Microelectronics "Transistors & Diodes in Power Processing".