Fast, faster, fastest!

Optimized diodes for switching applications

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Abstract

Great efforts have been made to improve power switches – MOSFETs and IGBTs – to decrease forward voltage drop and as well as to decrease turn-off energy. In switching inductive loads, the turn-on losses depend strongly of the behavior of the companion free-wheeling diode and now form the major part of over-all power losses. New developments like series connected diodes in a single package can greatly improve a given design. This paper shows how to choose the optimum diode using the specific example of a PFC circuit.

INTRODUCTION

In hard switching applications with an inductive load, the free-wheeling diode causes high losses during the turn-on transition of the power switch. Power factor correction in non resonant mode is a typical example for such hard inductive switching. A very common topology is the boost configuration (Fig. 1), using a MOSFET as the usual power switch at higher frequencies.

Fig. 1:
Boost converter, e. g. for Power Factor Correction

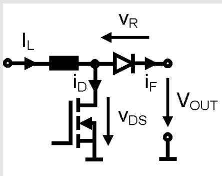


Fig. 2 shows idealized current and voltage waveforms during the diode's turn-off and MOSFET's turn-on. These waveforms are also valid in inverter designs, where the diode and the power switch are parts of a phase leg. So the results obtained with this example can also be used for designing drive inverters, switched mode power supplies, line inverters and other similar applications.

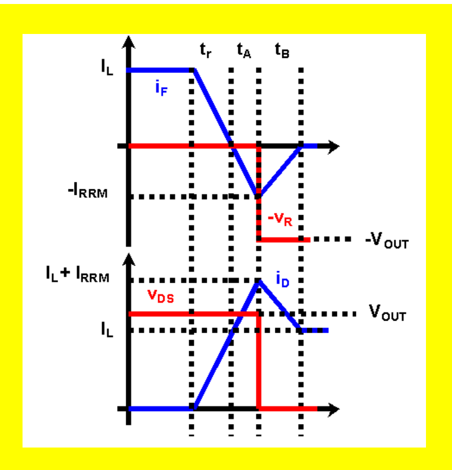


Fig. 2:
Idealized current and voltage waveforms; current commutates from diode to switch

A known method to achieve better performance for rectifiers for a given blocking voltage is to connect lower voltage diodes in series [1]. For equal voltage sharing, it is sometimes necessary to connect RC snubber networks in parallel to each single diode, thereby making this solution rarely used. A newly developed housing makes it possible to connect two or more diodes in series within one single package. Matching and testing the dice for voltage sharing allows the user to design in these diodes without any additional snubber circuits. It now depends on the application and its switching frequency if single die or series connected diode is the better choice.

CALCULATING POWER LOSSES AND JUNCTION TEMPERATURE

A rectifier carrying a forward current needs a non-negligible time to change from the on-state to the blocking state. Until the reverse recovery charge Q_{rr} has not been removed from the P-N junction, the diode behaves like a short circuit – causing high current flowing not only through it self, but also through the power switch that is turning off the diode. As can be seen from Fig. 2, the maximum reverse recovery current I_{RRM} of the diode is added to the load current I_L, so drain current of the MOSFET reaches the maximum $I_{RRM} + I_L$. As the voltage drop for a short is zero, the switch carries not only high current but also sees the full output voltage V_{out}, resulting in enormous instantaneous power dissipation and thus turn-on energy loss. Energy times frequency gives total power-loss, increasing junction-temperature of the semiconductor which in the end sets the limit for the switching frequency f_{sw}. But to reduce weight, volume and costs of passive components like inductors and capacitors (and which designer of a power supply does not want to this), it is necessary to go for higher switching frequencies f_{sw}. So over-all losses of the switch have to be reduced and the key for this is a better free-wheeling diode. At high switching frequencies, turn-off time and reverse recovery current should be as low as possible to save energy while the power switch turns on.

An estimation of switching energies can easily be derived from the curves in Fig. 2 by the use of following formulas [2]:

$$E_{off}(\text{diode}) = 0.5 \bullet I_{RRM} \bullet V_{out} \bullet t_B \qquad (1)$$

$$E_{on}(\text{MOSFET}) = 0.5 \bullet (I_{RRM} + I_L) \bullet V_{out} \bullet (t_r + t_A) \qquad (2)$$

It is obvious that turn-on losses of the switch will be higher than turn-off losses of the rectifier in this example.

To compare different diode types, it is also necessary to calculate their on-state and blocking losses. The first are obtained using the linear model of the output curve (Fig. 3):

$$P_{on} = V_{T0} \bullet I_{F(AV)} + r_T \bullet I_{F(RMS)}^{\ 2} \qquad (3)$$

$$P_{off} = I_R \bullet V_R \bullet D \quad \text{(Note: D = duty cycle)} \qquad (4)$$

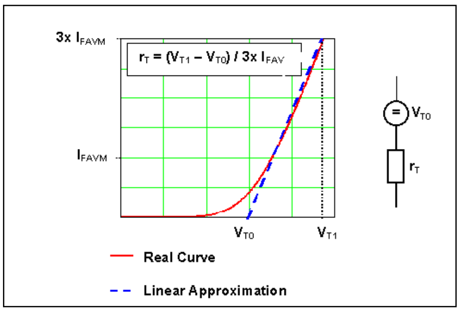


Fig. 3:
Linear model for the forward voltage drop of the output curve: deriving of V_{T0} and r_T

Dynamic losses are calculated by multiplying switching energy with switching frequency, so total diode losses become:

$$P_{tot}(\text{diode}) = P_{on} + E_{off}(\text{diode}) \bullet f_{sw} + P_{off} \qquad (5)$$

To get junction temperature of the diode, power loss has to be multiplied by the thermal resistance from junction (J) to case (C):

$$T_J = P_{tot}(\text{diode}) \bullet R_{th(JC)} + T_C \qquad (6)$$

A good compromise between improved reliability and optimized chip size (= optimized costs) is achieved with T_J around 125°C to 150°C. Therefore the values for the parameters in formulas (1) to (4) must be interpolated for the operating junction temperature T_J from the values given in the data sheet.

If all power losses affected by the free-wheeling diode are to derived, the following formula should be used:

$$P_{tot}(\text{diode affected}) = P_{on} + [E_{off}(\text{diode}) + E_{on}(\text{MOSFET})] \cdot f_{sw} + P_{off} \quad (7)$$

Having derived all necessary formulas, it is now possible to draw some conclusions:

1. Diode selection depends strongly upon switching frequency. For lower frequency applications, forward voltage drop plays the major role in the diode's power loss. At higher frequencies, the switching losses become more and more important. Losses in the commutating switch will rise with frequency and dynamic behavior of the diode.
2. To maintain low junction temperatures for increased reliability and lifetime, either power loss or thermal resistance must be decreased (or even both).

DIFFERENT APPROACHES FOR DIODE OPTIMIZATION

In addition to the well-known IXYS FREDs (named DSEI... for single diodes and DSEK... for common cathode configuration), a new diode series has been developed called HiPerFRED™ (respectively DSEP... and DSEC...). Blocking currents have been reduced at high temperatures while dynamic parameters, like I_{RRM} and t_{rr} (= $t_A + t_B$), were improved. Forward voltage drop decreases with increased T_J, giving lower static losses when the device is running at its working temperature.

Combining these diodes with the latest package development of IXYS, called ISOPLUS247™, it is possible to achieve acceptable junction temperatures even at high switching frequencies. ISOPLUS247™ is an isolated, discrete housing in which the standard copper lead frame has been replaced by Direct-Copper-Bonded alumina, the same isolation material used in IXYS' high power modules. This package also meets the JEDEC standard TO-247 outline and is an UL recognized package. This ceramic isolation has an unbeatable low thermal resistance junction to heatsink while providing 2500 V_{RMS} isolation voltage from leads to backside.

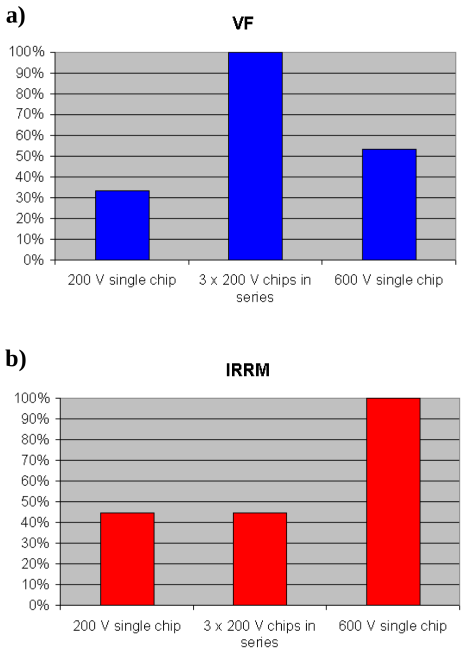
ISOPLUS247™ also allows an interesting method for decreased dynamic parameters: series connection of diodes. Because the DCB-substrate can be patterned like a printed circuit board, it is easy to connect two or more chips in series in a single package. Fig. 4 shows the impact of series connection on V_F and I_{RRM}. The higher the blocking voltage for the same chip size, the higher are also dynamic parameters and forward voltage drop. Connecting three 200 V devices in series results in a 600 V blocking diode. The resulting voltage drop is increased by a factor of 3 but when compared to an actual 600 V diode, the value is only doubled (a). However, the big advantage is that the reverse recovery current is as low as of a single 200 V chip, in this case only half the value of the 600 V device (b).

In table 1 there are three examples of diodes shown representing the above technologies [3,4].

Table 1: 600 V-diodes suitable for PFC and similar applications

Type	V_{RRM} [V]	I_{FAV} [A]	Total chip size	Package	Remarks
DSEP 8-06A	600	10	33%	TO-220	single chip
DSEP 9-06CR	600	9	83%	ISOPLUS247™	3 chips in series, isolated
DSEP 30-06B	600	30	100%	TO-247	single chip, high speed
Competition	600	8	-	TO-220	2 chips in series, isolated

All are rated at a blocking voltage of 600 V and are suited for the application described below. The DSEP 8-06A is a single chip diode with normal switching speed (suffix "A"). DSEP 9-06CR is a series connection of three 200 V diodes in one package which exhibits very low dynamic parameters. Suffix "C" corresponds to the Lightspeed™ IGBT series of IXYS, while "R" stands for the ISOPLUS247™ package. DSEP 30-06B finally is again a single chip device with improved switching speed (suffix "B"). A competitive, series-connected diode is listed last.



4: Effect of series connection on
a) forward voltage drop
b) reverse recovery current

HOW TO CHOOSE THE OPTIMUM DIODE

A single phase PFC circuit which is fed from an input voltage of 230 V AC and draws a current of 7 A (RMS) gives a nominal input power of 1.6 kW. To simplify calculation the current is assumed to be rectangular with constant duty cycle of D=0.5 and constant amplitude of I_{peak}=10 A (RMS of rectangular waveform equals $I_{peak} \cdot \sqrt{D}$, thus giving the value mentioned above).

Static losses of the investigated diodes were calculated from formulas (3) and (4), dynamic losses of diode and turn-on losses of the switch

Table 2: Static and dynamic parameters of the tested diodes

Type	V_F [V]	I_{RM} [A]	t_A [ns]	t_B [ns]
	I_F=10 A T_J=150°C	**I_F=10 A, V_R=400 V di/dt=300 A/µs, T_J=150°C**		
DSEP 8-06A	1.24	15	37	43
DSEP 9-06CR	3.09	10	28	11
DSEP 30-06B	0.99	19	47	20
Competition	2.17	14	34	2

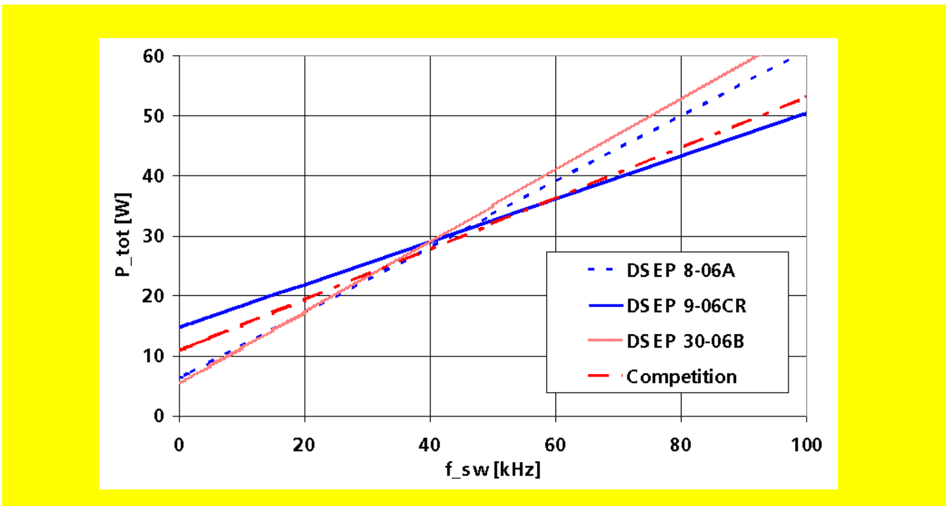


Fig. 5:
Diode affected power losses vs. switching frequency using Table 2 data

from (1) and (2). Parameters needed for the calculations can all be found from the datasheets: V_{T0} and r_T were derived from the curve forward current vs. voltage drop as shown in Fig. 2. I_{RRM} and t_{rr} were read out directly from their curves. For rough approximations, $t_A = t_B = t_{rr}/2$.

This method of getting the necessary parameters is useful for a first approximation of power losses. Having choosen suitable devices, it is recommended to measure dynamic losses within the application to prove the theoretical assumptions.

Results in Table 2 have been measured using the circuit shown in Fig. 1 under equal conditions so that now a direct comparison of the different types is possible.

With the measured values and the above calculations, the optimum diode for a given design can be found. Fig. 5 shows the total diode affected power losses vs. switching frequency according to equation (7) and using the values of Table 2. It can be seen that above 50 kHz, the series connected diodes lead to lowest power losses. At 100 kHz the DSEP 9-06CR produces only 80% of the losses of the single chip diodes. So if total efficiency of the circuit is to be increased, one should use the series connected diodes.

In Fig. 6, the maximum allowed case temperature vs. switching frequency is shown calculated by formula (6), again using the values in Table 2. Junction temperature was set at 150°C, which is still well below the maximum value of 175°C for IXYS HiPerFRED™ diodes. Now the diode with largest chip size (DSEP 30-06B) requires lowest cooling effort and therefore it should be used if ambient temperatures are high or cooling is a problem. The series connected diode DSEP 9-06CR starts to outperform the smaller DSEP 8-06A single chip type above 80 kHz. Because in this diagram only diode losses appear, the cross-over point is higher than in Fig. 5; so turn-on losses of the power switch play a major rule in total diode affected losses!

Within the frequency range from 50 to 100 kHz (which is typical for most PFC applications), one has to make a decision depending upon the design goal. If the type of switch is already fixed and efficiency and cooling is no problem, the DSEP 8-06A would be best choice because it is least expensive. If the switching device has not been chosen yet, maybe a smaller part can be taken when using the series connected diodes because of reduced turn-on losses of the switch. In this case, overall costs may be lower compared to a solution with single chip diode and larger transistor. Above 100 kHz or if high system efficiency is required, there is no alternative to the series connected diodes. It may also be possible to discard active snubber networks that 'discharge' the diode junction before the main switch turns on so that there is no superimposed reverse recovery current in the main switch's drain current. Replacing the conventional rectifier with the series connected diodes with their very low reverse recovery current provides a similar effect without additional circuitry.

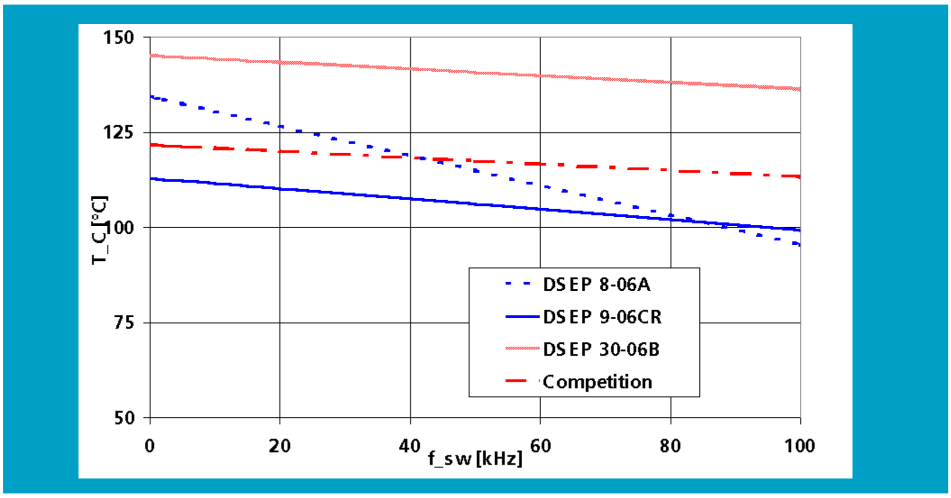


Fig. 6:
Maximum allowed case temperature vs. switching frequency using Table 2 data; T_J=150°C

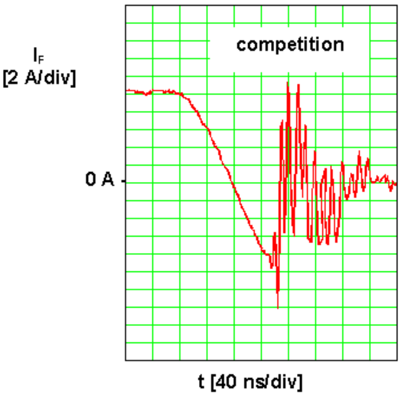


Fig. 7:
Turn-off behavior of competitive type; I_F=10 A, -di_F/dt=300 A/µs, V_R=400 V, T_J=150°C

The competitive diode type requires less cooling effort than the IXYS series diode DSEP 9-06CR. This is due to its very short second portion of recovery time t_B, what leads according to formula (1) to low diode losses. The price which has to be paid for this is a very snappy turn-off behavior which might cause EMC problems as can be seen in Fig. 7.

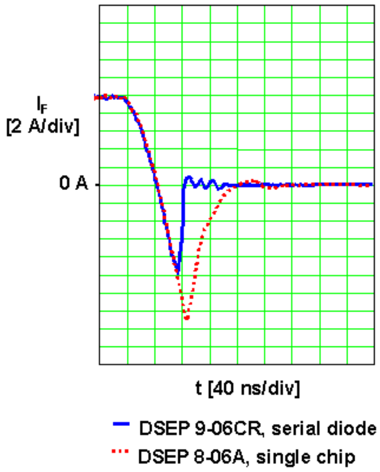


Fig. 8:
Comparison of series connected diode to single chip type; I_F=10 A, -di_F/dt=300 A/µs, V_R=400 V, T_J=150°C

The DSEP 9-06CR is slightly slower but much softer, oscillations are negligible. Fig. 8 shows clearly its much better reverse recovery behaviour compared to the single chip diode DSEP 8-06A.

When connecting devices in series, it is normally necessary to ensure voltage sharing. This can be achieved by connecting RC-networks in parallel to each single part – R for static, C for dynamic voltage sharing. For the above introduced, single package, series connected diode, there is no more the need for external networks. Chips built into one housing were matched so that parameter differences are kept low. 100% testing of both static and dynamic voltage sharing gives additional safety so devices can replace single chip parts without any restriction or the need for additional parts.

SUMMARY

It has been shown that, depending on switching frequency, there are optimized solutions. In the low frequency range, the single chip diodes are best because of their low static losses. In the medium frequency range, the user has to choose a suitable diode according to his main goal. If low cost is required, a single chip part is maybe the first choice but one should determine if the better performing series connected diode allows a smaller switch leading to lower overall costs. High ambient temperature or poor cooling ability leads to a large chip device with good heat transfer characteristic. High efficiency of the total system is achieved when using series connected diodes with low dynamic parameters. For this reason they are also unbeatable in the high and very high frequency range. The method described enables a designer to choose a perfect rectifier for his application.

[1] B. Rivet: The Advantages of a 300 V Fast Recovery Epitaxial Diode (FRED) Power Conversion, June 1997 Proceedings

[2] IXYS Technical Information 33: Fast Recovery Epitaxial Diodes

[3] IXYS Semiconductor Databook 2000, CD-ROM

[4] http://www.ixys.com