The Design, Application and Production-Testing of High-Power Fast Recovery Diodes

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Abstract

Fast recovery diodes, though an integral part of inverter design, traditionally take a "back seat" both at the device and equipment design levels where attention tends to focus on the controlled switch. (IGBT, IGCT or GTO). As a result, Snubber, Clamp and above all Free-Wheel Diodes (FWD) remain the *Achilles Heel* of optimal equipment design. In recognition of this fact, together with the growing trend to eliminate voltage snubbers on diodes, semiconductor manufactures are developing new generations of diodes with profiled carrier life-times having enhanced Safe Operating Areas (SOA) and controlled (soft) recovery at very high di/dt and dv/dt levels. The growing concern for SOA (*ratings*) and not just recovery charge or losses (*characteristics*) imposes new constraints on production test equipment to ensure the cost-effective delivery of robust and reliable components. In contrast to turn-off devices (transistors and GTOs), thyristors and diodes have traditionally been production-tested for their characteristics only and classified accordingly. New generations of high-performance fast diodes must now also be tested for their dynamic ratings in production. In this paper, the design and application of rugged devices is summarised and new production test equipment capable of reproducing a wide range of SOA test-conditions is described.

1. Introduction

The types of commutation to which fast diodes may be subjected fall into 5 basic categories [1]. The first principal division comes from the means of di/dt generation which is typically a voltage source and inductance ("inductive switching") but may alternatively be a voltage source and a time-dependant resistor e.g. a slow-switching transistor ("resistive" switching). Further sub-groups arise from the presence/absence of snubbers and clamps. The five principal categories are shown in Fig. 2 along with the corresponding stylised recovery waveforms.
Since all bipolar diodes are minority carrier devices, they are all subject to reverse-recovery current whose amplitude depends principally on the rate of current decrease (negative di/dt) imposed by the external circuit. Thus the diode current becomes momentarily negative reaching a peak value of I_{RR} before returning to zero during the recovery phase - ideally without abrupt current changes which would generate voltage spikes in the equipment. Fig. 1 depicts such a monotonic recovery in an unclamped (voltage overshoot) inductive configuration: the "controlled" recovery, free of abrupt changes ("snap"), is a primary design goal for all diodes. The simultaneous presence of current and voltage during recovery generates power with the maximum allowable value determining the SOA - a high value being a secondary design goal. However, the "softer" the diode (slow return to zero of reverse current, the higher the losses so a compromise must be determined between a low "snap-factor", $s = t_b/t_a$ and high SOA (low losses). As long as this snap factor is controlled and measurable it may be part of the device specification; beyond the device's specified range of application it may be abrupt, result in wild oscillations and the device is said to "snap-off" - but with an Unspecified" snap-factor".

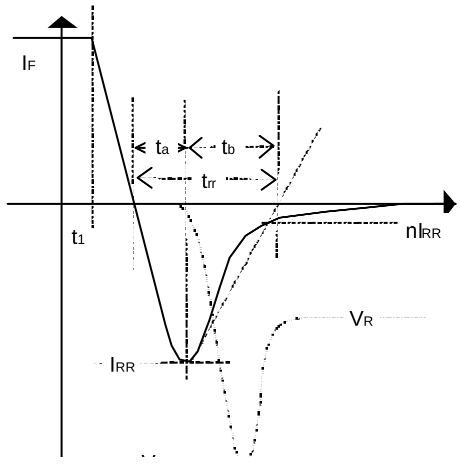


Fig. 1 Soft Recovery and basic parameter definitions

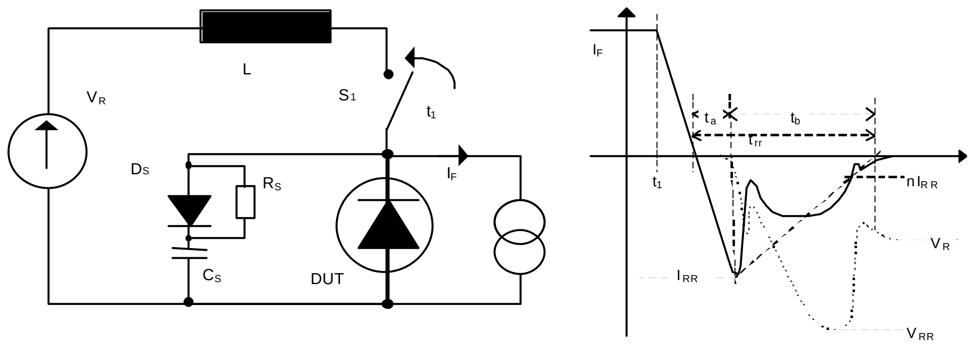


Fig. 2a) RCD-snubber for FWD, inductive switching

Category I

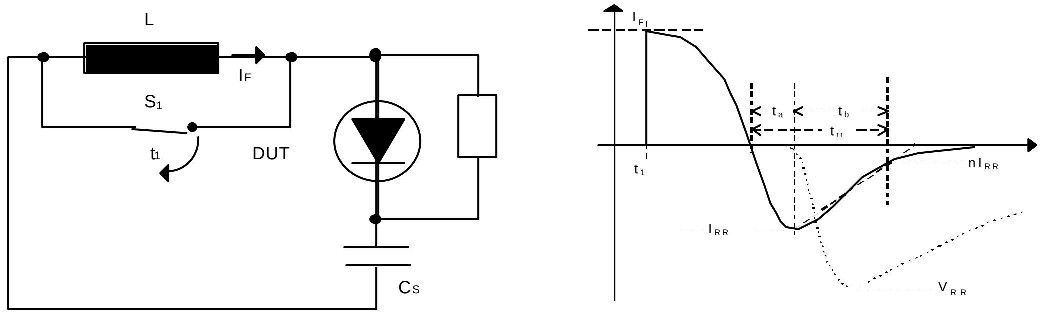


Fig. 2b) R-snubber for RCD, snubber-diode, inductive switching

Category II

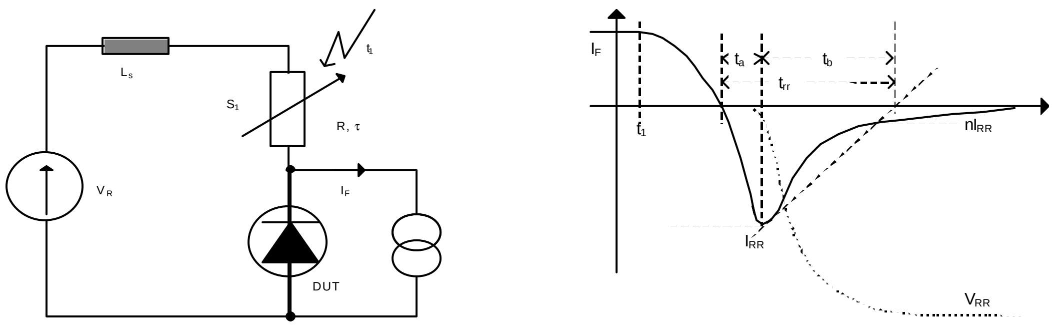


Fig. 2c) Snubberless Undeland/ McMurray snubber-diode, resistive switching

Category III

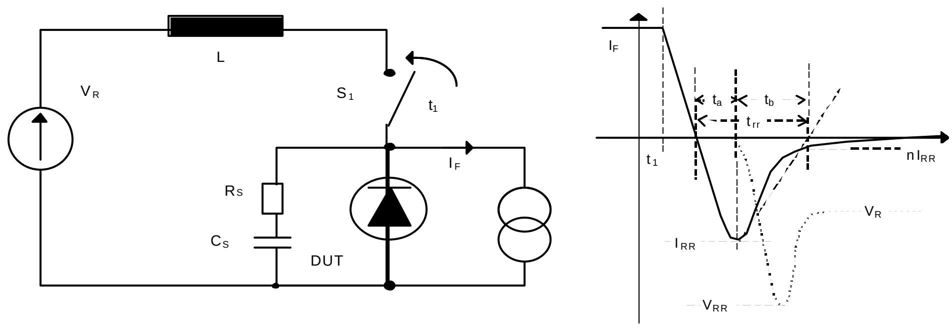


Fig. 2d) RC-snubber, inductive switching

Category IV

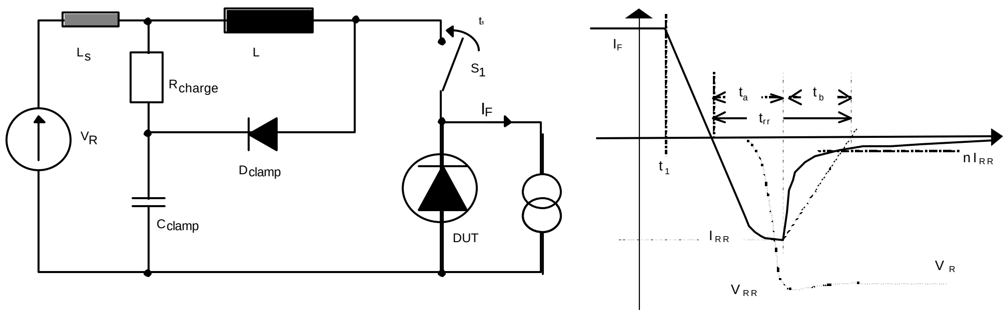


Fig. 2e) Snubberless, clamped inductive switching

Category V

1.1 Brief Description of the Application Categories

Beyond the concept of “resistive” and “inductive” switching mentioned above, further distinctions can be made depending on the associated snubbers and clamps (if any).

1.1.1 RCD-snubber for GTO-FWD, inductive switching per Fig. 2a

This is a standard *GTO free-wheel diode* application in Voltage-Source inverters (VSIs) in which the diode is fitted with a snubber designed for the GTO. This condition adequately represents the commutation of FWDs in McMurray and Undeland/Marquardt circuits.

1.1.2 R-snubber for RCD-snubber-diode, inductive switching per Fig. 2b

This is the test condition for a *snubber* diode used in the above referenced circuit. Diode commutation occurs sometime after switch turn-off and the equivalent circuit is valid from the instant that the snubber capacitor has reached DC-link voltage and the FWD starts to conduct transferring the energy of L to C_s The diode finally recovers under a voltage $\Delta V = I_F \sqrt{L / C_s}$ and with R_s as its own snubber.

1.1.3 Snubberless, unclamped resistive switching per Fig. 2c

Here the commutation di/dt is given by the characteristics of the active switch (thyristor or transistor). There is little or no energy storage and by the time the switch has fully closed the diode is, in effect, clamped to the source voltage. This is the case of snubberless snubber-diodes in McMurray or Undeland circuits but also of IGBT FWDs. In these circuits the di/dt is generally not linear but rather “accelerating” (as shown in Fig. 2c) where the switch is a *thyristor* or “flattening” where the switch is a *transistor* with collector-derived base-drive (IGBTs, Darlingtons).

1.1.4 RC-snubber, unclamped inductive switching per Fig. 2d.

In this figure we see the return of the ubiquitous RC-snubber as formerly used in SCR inverters. Its purpose is simply to enhance SOA or control dv/dt and may be used in unclamped circuits such as those of Current-Source Inverters (CSIs). If C_s is set very large it replaces Fig. 2c except that the current is then trapezoidal rather than co-sinusoidal.

1.1.5 Snubberless, clamped inductive switching per Fig. 2e

This is the general case of snubberless switches where di/dt control is inductive as opposed to resistive. Under these conditions the DUT is required to sustain peak reverse recovery current until its cathode voltage reaches DC-link level allowing the clamp diode to conduct.

1.1.6 Clamp Diodes

Clamp diodes such as D_{clamp} in Fig. 5e can be considered as the DUT of Fig. 2c as they may be subject to the same turn-off requirements either occasionally or repetitively (re-firing of S_1 while D_{clamp} still conducting) and have also the same low forward recovery voltage requirements at similar turn-on di/dts.

The following general observations, relevant to diode design, can be made with reference to the application categories:

- I is a *low* dv/dt condition, II to V are *high* dv/dt conditions.
- I and IV have *high* V_{RR} to V_R ratios as opposed to II, III and V which have low ratios.
- II and V require both high SOA and soft recovery (no snubber).
- The peak repetitive voltage of a diode (V_{RRM}) is not directly related to its DC rating (V_{DC}). This is the continuous DC level which may be applied under ambient cosmic radiation for an (acceptably) low failure rate not to be exceeded [2]. Typically FWDs and NPC diodes in VSIs have a *high* DC rating whereas snubber or clamp diodes have lower DC ratings and CSI commutation diodes have no DC ratings.

2. Life-Time and Emitter Engineering

It is beyond the scope of this paper to compare the relative merits of these two approaches for controlling the reverse recovery characteristics of diodes though ample literature is available describing these methods [3-11]. Suffice it to say that after extensive simulation and development, ABB Semiconductors has chosen *life-time engineering* to control the recovery phase for the five application categories of Fig. 2. This is realised by three techniques consisting of *uniform lifetime control* using *electron-irradiation*, *profiled lifetime control* using *proton-irradiation* and *combined lifetime control* using both irradiations. [1, 11].
As will be shown under “Measurements” most of the five application techniques require their specific technology. To briefly illustrate one of the significant differences between uniform and profiled lifetime control it is sufficient to compare categories I and III of Fig. 2. Category I is a typical GTO FWD application with low dv/dt (500 - 1000 V/ µs). Under these conditions, high reapplied voltage appears with a significant delay and it is desirable to ensure that minimal charge be extracted once the voltage is high thus implying that *maximal* charge be extracted previously, at low voltage. This is achieved by allowing a high reverse recovery current where the voltage is still close to zero whilst still ensuring that the charge diminishes progressively, as the voltage builds up, without an abrupt snap. In Category II by comparison, the dv/dt can be much higher (5 kV/ µs - no snubber). The voltage rising quickly, a large instantaneous current could not be tolerated for SOA reasons and in this design, I_{RR} must be kept low. Reapplied dv/dt is largely determined by the diode itself and if this is not to rise at 10 or 20 kV/ µs, the recovery current must reduce progressively. Profiled lifetime control allows this progressive recovery albeit at the cost of increased dynamic losses. Measurement results will be presented later.

Table 1 shows the diode types currently available or in development at ABB Semiconductors each allocated to its possible category. The greyed area shows the range of devices from which results are summarised later - the full range being beyond the scope of this discussion.

Table 1		Application Category				
Wa-ferÆ (mm)	**V_{RRM} (V)**	**I (RCD/FWD)**	**II (R/snubber)**	**III (Undeland snubber)**	**IV (RC/CSI)**	**V (snubberless FWD)**
	2500	5SDF 05D2505	5SDF 05D2501	5SDF 05D2501	5SDF 05D2501	/
38	4500	/	5SDF 03D4501	5SDF 03D4501	5SDF 03D4501	5SDF 04D4502
	6000	/	5SDF 02D6004	5SDF 02D6004	5SDF 02D6004	5SDF 03D6004
	2500	5SDF 11F2501	/	/	/	/
51	4500	5SDF 07F4501	/	/	/	5SDF 08F4502
	6000	/	/	/	5SDF 06F6004	5SDF 06F6004
	2500	/	/	/	/	/
68	4500	5SDF 14H4505	5SDF 07H4501	5SDF 07H4501	5SDF 10H4502	5SDF 10H4502
	6000	5SDF 10H6004	/	/	5SDF 08H6005	5SDF 08H6005
	2500	/	/	/	/	/
91	4.5	/	/	/	5SDF 16L4502	5SDF 16L4502
	6.0	/	/	/	*wafer*	*wafer*

Since the critical design parameters for fast diodes are snap behaviour and SOA, Production Testing must allow for both these parameters to be assessed at final outgoing inspection in the same way that an IGBT is tested for turn-off capability. To this end, advanced test gear has been developed and commissioned [13] capable of covering the above defined application categories. The specified range of conditions is shown in Table 2 and Fig. 3 shows the Test equipment built by LEM S.A. of Geneva.

Table 2

Diode Tester Ranges (Dynamic Sections)								
Reverse Recovery Section								
Application Category	**V_R (V)**	**V_{RR} (V)**	**I_F (A)**	**di/dt (A/ms)**	**t_{rr} (ms)**	**C_s (mF)**	**R_s (W)**	**I_{RR} (A)**
I	4500 3000 1500	6000 4500 2500	500 - 6000 500 - 6000 500 - 3000	100 - 600 100 - 600 100 - 600	<15 <12 <10	1 - 6 1 - 6 1 - 6	4.7 4.7 4.7	2000 1500 1000
II	4500 3000 1500	3000 2000 1500	500 - 6000 500 - 6000 500 - 4000	500 - 1000 500 - 1000 500 - 1000	<10 <8 <6	∞	3.3 - 10	300 - 2000 300 - 2000 300 - 2000
III	4500 3500 2000	4500 3500 2000	10 - 500 10 - 500 10 - 500	300 - 3000 300 - 3000 300 - 3000	<10 <8 <6	0	∞	300 - 2000 300 - 2000 300 - 2000
IV	2000 1000	3000 2000	500 - 4000 500 - 4000	50 - 300 50 - 300	<15 <12	0.1 - 1 0.1 - 1	4.7 - 22 4.7 - 22	100 - 1000 50 - 800
V	4500 3000 1500	5000 3500 2000	200 - 3000 300 - 3500 300 - 4000	50 - 1500 100 - 2000 100 - 2000	<6 <6 <5	0	0	100 - 2000 100 - 2000 100 - 2000
Forward Recovery Section								
Application Category		**V_{FR} (V)**	**I_{FR} (A)**	**di_{FR}/dt (A/ms)**	**t_{FR} (ms)**	**E_{ON} (Ws)**		
I - V		5 - 1000	300 - 6000	300 - 3000	0.1 - 10	0.1 - 20		

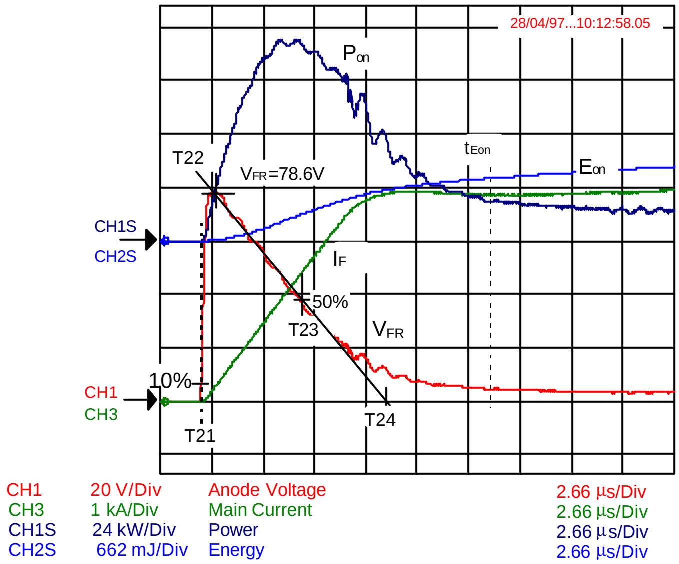
Fig. 3 Static and Dynamic Diode Tester up to 6 kV and 6 kA per Table 2

3 Test Results

3.1 Forward Recovery

A typical printout of the test equipment is shown in Fig. 4 to illustrate the turn-on waveforms of a diode. This test may be relevant to any diode type or application but the resulting turn-on is primarily a function of silicon geometry and junction temperature and is thus not highly process dependant. Such measurements are therefore effected at the evaluation stage and are not generally part of Production Test for Statistical Process Control. This particular waveform shows snubber diode type 5SDF 03D4501 tested at 500 A/µs producing a V_{FR} of 79 V, a peak power of 89 kW and a turn-on energy pulse of 860 mWs up to t_{EON} defined as $1.5{*}t_{FR}$ where t_{FR}, the forward recovery time, is defined as T24 - T21 and is 9.9 µs in Fig. 4.

Fig. 4



Forward Recovery Test Result from DD6060 Diode Tester on diode type 5SDF 03D4501

3.2 Category I

Fig. 5 shows two diode designs tested as GTO FWDs under the same conditions whereby 5a shows a true FWD with uniform life-time and 5b shows an Undeland snubber diode (profiled life-time) "misused" as an FWD.

Fig. 5 RCD-snubbered FWD test condition on 68 mm/4.5 kV diodes

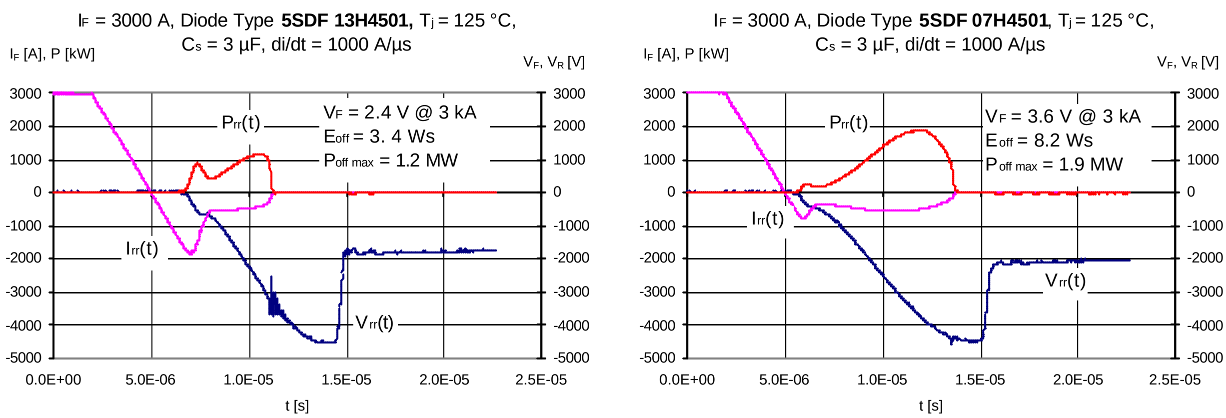


Fig. 5a Uniform life-time FWD, 2.8 kV DC rating

Fig 5b Profiled life-time snubber diode, 2.2 kV DC rating

Though I_{RR} of 5b is only 40% that of 5a, its turn-off loss is 2.4 times greater and its peak power dissipation (SOA driver) is 64% higher. Furthermore, the device of 5b has a 50% higher on-state voltage. Under the severe conditions of Fig. 5a (1000 A/µs, V_{RR} = 4.5 kV) the on-set of snap-off can be seen to initiate an oscillation in the voltage waveform. From this comparison it is clear that the 5SDF 13H4501 is far better suited for the low static and dynamic losses required of a FWD despite the appealingly low I_{RR} of the profiled life-time diode of Fig. 5b.

3.3 Category II

Category II shows the R-snubbered inductive commutation of a snubber diode at 1000 A/µs from 3000 A. The Category V diode of Fig. 6b (designed as a snubberless FWD) shows the *on-set* of snap at this condition whereas the lower resistivity diode of Fig. 6a recovers smoothly. Both devices have profiled lifetime but different resistivities are needed for the different dc ratings of their intended applications making them non-interchangeable at high SOAs. This type of circuit is used in some GTO snubbers but is of growing importance in series-connected GCTs as used in STATCOMs (static compensators). In the Production Test depicted here Category II is actually tested using the Category IV circuit with C_s set to be infinitely large (> 6 µF!). The opening switch of Fig. 2b is replaced by the closing switch of Fig. 2d with V_R (= ΔV) set equal to $I_F \bullet \sqrt{L / C_S}$. The forward current waveform is then trapezoidal instead of the co-sinusoidal decay of Fig. 2b - which has no measurable consequence on the recovery.

Fig. 6 R-snubbered Snubber Diode test with 68 mm/4.5 kV profiled life-time devices of different resistivities

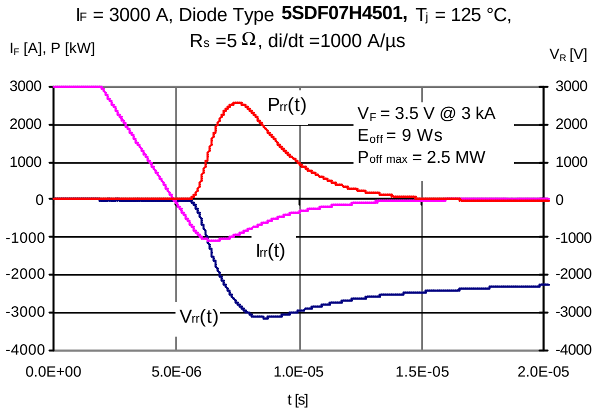


Fig. 6a Snubber diode showing no snap at 1000 A/µs

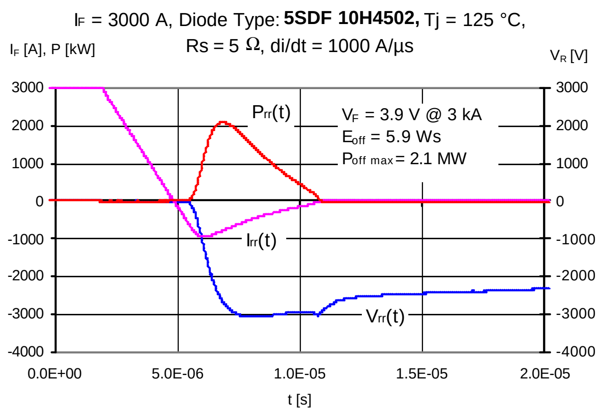


Fig. 6b FWD showing *on-set* of snap at 1000 A/µs

3.4 Category III

In Fig. 7a and 7b resistive switching at both high and low forward currents is demonstrated using a 68 mm snubber diode with profiled lifetime. A salient feature of diodes in Undeland or McMurray snubber circuits is the need to operate at low forward current without snapping off despite high di/dt and dv/dt. These diodes are subject to dc-link voltage only during the commutation periods and as such, have lower DC rating requirements which allows a further degree of freedom in the dynamic response design. The 4.5 kV diode of Figs. 7 a & b has a dc-link rating of 2200 V. In Category III switching, di/dt is determined by the active switch (usually a GTO). The speed at which it switches depends on the type of switch, its temperature, its anode voltage, diode forward current (I_F) and, most importantly, its gate current. In the test equipment of Fig. 3 configured for Fig. 2c, this function is provided by a 6 kV GTO-type device with a gate unit whose output is variable over the range $I_{GM} \approx$ 50 to 1500 A with $di_G/dt \approx$ 50 to 2000 A/µs. The large range of gate currents allows resistive switching from about 300 to 3000 A/µs. The stray inductance L_s of Fig. 2c is a fixed 300 nH and for a gate current of 1500 A and forward current I_F of ≈ 3 kA, S_1 becomes a “perfect switch” no longer determining the di/dt which is then solely dependant on V_R and L_S. At this stage, Fig. 2c “degenerates” to “Category VI” (unsnubbered, unclamped, inductive) not considered here for lack of practical applications at present. Nevertheless, the equipment has experimentally investigated this condition with di/dts of up to 7 kA/µs. Fig. 7 however represents a standard GTO snubber diode tested with a typical di/dt of 800 A/µs (measured at zero-current cross-over).

Fig. 7 Two critical test conditions for Undeland Snubber Diodes: a) SOA and b) snap-off

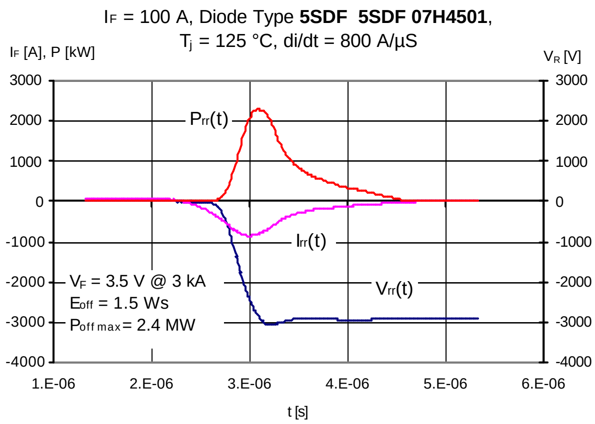


Fig. 7a Undeland snubber diode at “max.” I_F showing soft recovery

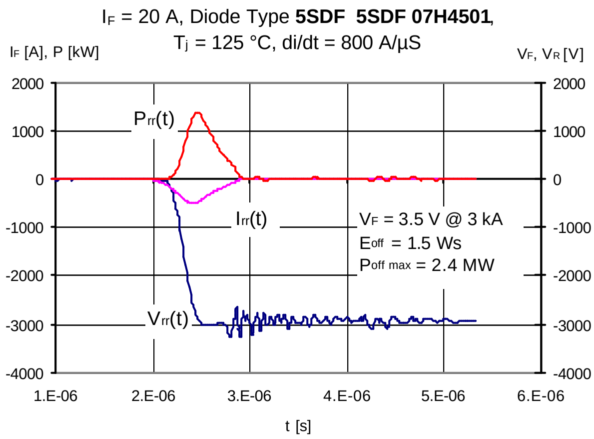
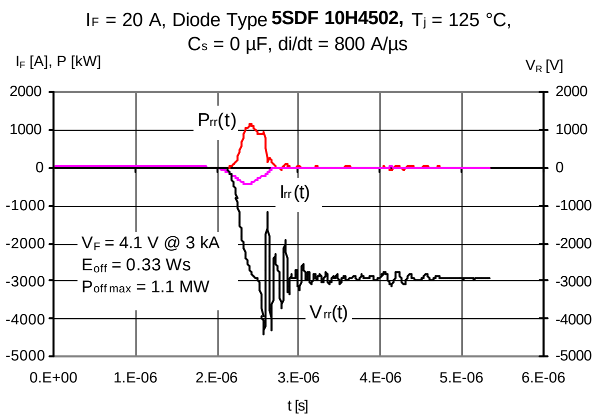


Fig. 7b Undeland snubber diode at “critical min” I_F showing on-set of snap-off



There is a non-zero current density at which snap is most likely to occur and for the diode type tested here this figure is around 500 mA/cm^2. The other operating limit of interest is the SOA which must be tested at the maximum application current - hence the two conditions. Repeating the low I_F test with another 68 mm/4.5 kV device optimised for Category V produces the waveforms of Fig. 7c rendering it unsuitable for Category III applications despite its profiled life-time. This is because the Category V diode is designed for 2.8 kV dc-link (free-wheel application) and not for the lower dc-rating allowable for a snubber diode (2.2 kV dc in this case).
The snap with a uniform lifetime diode (e.g. 5SDF 13H4501) is even worse than that of Fig. 7c (not shown here).

Fig. 7c Poor response of a Category V diode tested as an Undeland snubber (Category III)

3.5 Category IV

Fig. 8 compares profiled lifetime devices of different dc-link ratings fitted with high impedance RC snubbers. Again, the lower resistivity device offers better recovery and would be suitable for low dc-link applications such as series connected IGCT systems with device redundancy or current-source inverters (no dc-link). A uniform life-time device (5SDF 13H4501) failed under the above conditions at a mere 1500 V dc link after a peak power or 4 MW and after dissipating only 4.3 Ws by the instant of failure (not shown).

Fig. 8 Comparison of 68 mm, 4.5 kV_{DRM} profiled life-time diodes in inductive RC-snubbered application

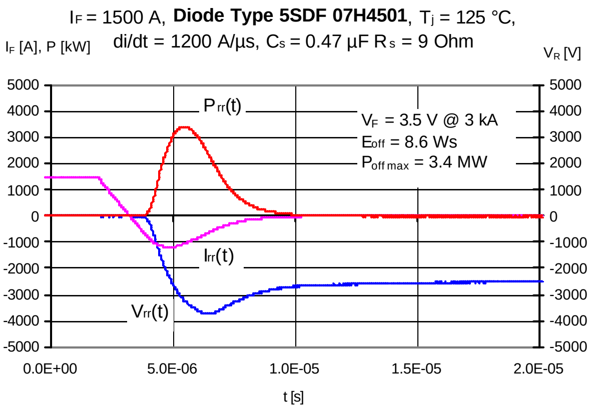


Fig. 8a Low resistivity (2.2 kV_{DC}), soft recovery

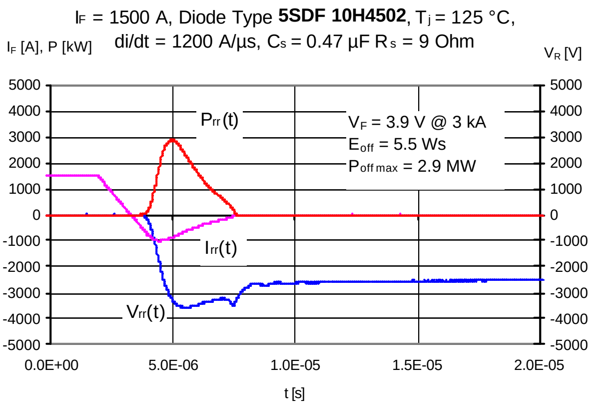


Fig. 8b High resistivity (2.8 kV_{DC}) at on-set of snap

3.6 Category V

Fig. 9 compares the snubberless, clamped (inductive) turn-off of two 68 mm 4.5 kV/2.8 kV dc FWDs designed for this application (9a) with one designed for RCD snubbered operation (9b). The device in 9a (profiled lifetime) limits the peak power to 3.8 MW and the recovery current decays smoothly after I_{RR} despite the severe turn-off condition (1 kA/µs). In Fig. 9b however, and despite the reduced di/dt of 500 A/µs, the peak recovery power reaches 5 MW (≈160 kW/cm^2) and the device fails 300 ns later when the peak voltage reaches 4.9 kV as the recovery current falls to 1250 A and then suddenly snaps to zero at 8 kA/µs (deduced by expanding Fig. 9b - not shown). At this speed, 125 nH of stray clamp inductance suffice to generate the additional 1000 V spike which fails the device. Clearly, much as the low on-state voltage is a desirable feature for all FWD applications, this diode design will not work where the reapplied dv/dt is not controlled by a low impedance snubber (Category I).

Fig. 9 Comparison of 68 mm, 4.5 kV_{DRM}/2.8 kV_{DC} diodes in clamped unsnubbered FWD application

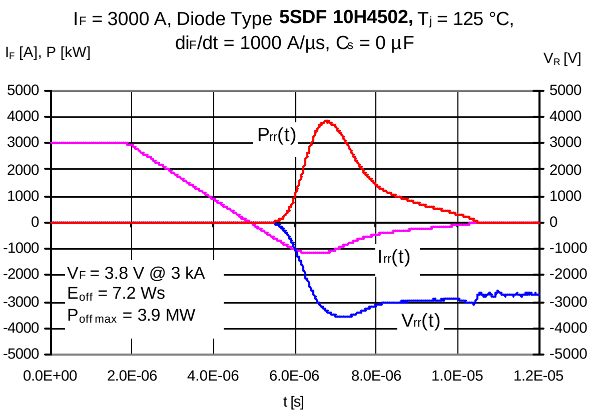


Fig. 9a Profiled life-time FWD at 1000 A/µs

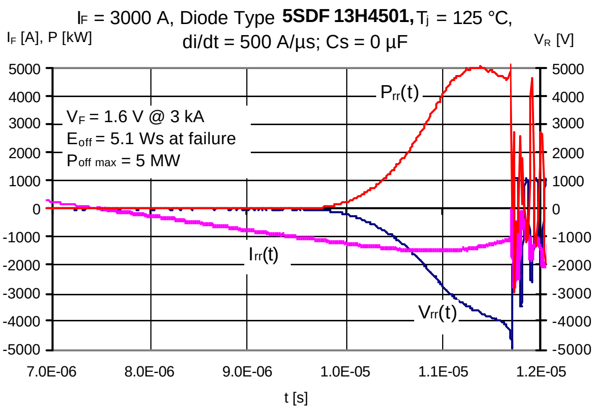


Fig. 9b Uniform life-time FWD at 500 A/µs

3 Simulations

A powerful tool in the design of semiconductors is the simulation of the physical processes prior to diffusing any samples. Certain devices, such as IGCTs, lend themselves particularly well to this approach, but the actual recovery process of a force-commutated p-n junction has long been a delicate matter. Recent progress has however been reported [1] allowing the concurrent engineering of active switches, diodes and circuits. An example of simulation is shown in Fig. 10

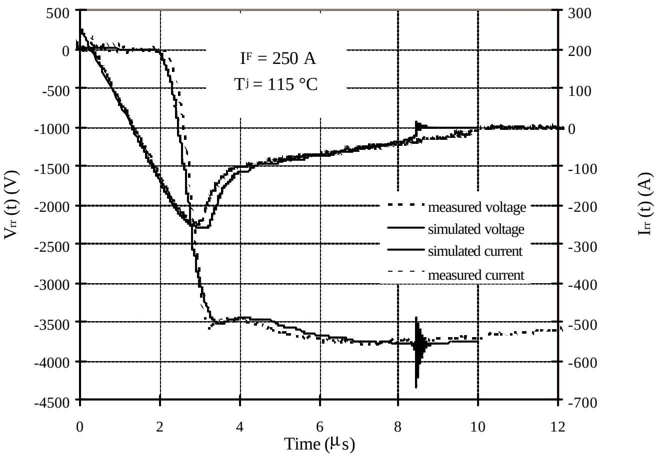


Fig. 10
Measured and simulated recovery of snubberless clamped inductive switching of 6 kV diode type 5SDF 03D6004. (Cat. V diode in Cat. V application)

Simulation software:
Atlas by Silvaco, CA., USA

Test equipment:
DS5060/DD6060 by LEM S.A., Geneva, CH

4 Safe Operating Area

In most of the preceding measurements, devices were taken to destruction. Discounting instances where failure was clearly due to snap-off (as in Fig. 9b for instance), the destruction limits lay between 150 and over 250 kW/cm^2. The further dependence of SOA on commutation category, reapplied voltage and energy-dissipated-per-pulse could not be quantified at this stage but will be the object of further investigation. The “first order” value of 150 kW/cm^2 however covers most of today’s identified applications and higher values are allowable where the exact application condition is tested for in production (100% test).

5 Conclusions

A new generation of high power diodes is now becoming available to complement recent advances in snubberless switches. Four tools have been combined to achieve soft-recovery, high SOA and optimal application-oriented designs:

1) *electron and proton irradiation life-time profiling* for application-specific recovery control
2) *Silvaco simulation* for accurate performance prediction and concurrent engineering
3) *application-oriented Production Testing* for guaranteed performance and reliability
4) *commutation mode categorisation* for improved user-supplier communications (specifications).

Much of the laborious experimentation has been eliminated from power diode design and selection thus shortening *time-to-market* through concurrent engineering of devices *and* equipment.
As predicted with the introduction of the snubberless IGCT at PCIM ‘96 [14]: the fast *snubberless* diode is today a commercially available reality permitting new generations of inverters to be designed with drastically reduced component-count and consequently enhanced reliability and reduced cost.

5 Acknowledgements

The authors wish to thank LEM S.A. for the design and construction of the advanced diode tester on which all results presented here were obtained.

6 References

[1] N. Galster, M. Frecker, E. Carroll, J. Vobecky, P. Hazdra," Application-Specific Fast-Recovery Diode: Design and Performance", PCIM, Tokyo, April 1998

[2] H-R. Zeller, "Cosmic Ray Induced Breakdown in High Voltage Semiconductor Devices, Microscopic Model and Phemomenological Lifetime Prediction", Proceedings of the 6th International Symposium on Power Semiconductor Devices & IC's, Davos 1994.

[3] A. Porst, F. Auerbach, H. Brunner, G. Deboy, F. Hille, "Improvement of the Characteristics using Emitter-Controlled Principles (EMCON-Diode), Proc. ISPSD, Weimar 1997, pp. 213 - 216.

[4] Heinrich Schlangenotto, Josef Sefarin, Friedhelm Sawitzki, Helmut Maeder, "Improved Recovery of Fast Power Diodes with Self-Adjusting p Emitter Efficiency", IEEE Electron Device Letters, Vol. 10, No. 7, July 1989, pp. 322 - 324.

[5] Manoj Mehrota and B. J. Baliga, "Comparison of High Voltage Power Rectifier Structures", Proc. ISPSD, 1993, pp. 199 - 204.

[6] H. Schlangenotto, M. Fullmann, "A Hybrid FAST Recovery Diode with strongly Improved Reverse Recovery", 5th EPE Conference, Brighton, U.K. 1993, pp. 185 - 190.

[7] Vobecký, P. Hazdra, N. Galster, E. Carroll, "Free-Wheeling Diodes With Improved Reverse Recovery By Combined Electron And Proton Irradiation", PEMC '98 *To Be Published*.

[8] "Gate Turn-off Thyristors, Gate-Commutated Thyristors, Fast Recovery Diodes: Section 2, Product Design", N. Galster, S. Klaka, A. Weber, ABB Semiconductor Ltd,. Lenzburg, 1997.

[9] J. Lutz, "The Freewheeling Diode - No Longer the Weak Component", Power Conversion, June 1997 Proceedings.

[10] J. Vobecky, P. Hazdra, J. Homola, "Optimization of Power Diode Characteristics by Means of Ion Irradiation", IEEE Trans. Electron devices, Vol. 43, pp 2283 - 2289, 1996.

[11] P. Hazdra, J. Vobecky, "Application of High energy ion Beams for Local Lifetime Control in Silicon", Materials Science Forum, Vol. 248 - 249, pp. 225 - 228, 1997.

[12] A. Weber, N. Galster and E. Tsyplakov "A New Generation of Asymmetric and Reverse Conducting GTOs and their Snubber Diodes", PCIM Nürnberg, June 1997.

[13] LEM Diode Tester type DS5060/DD6060, LEM S.A., Geneva.

[14] H. Grüning, B. ∅degård, J. Rees, A. Weber, E. Carroll, S. Eicher, "High-Power Hard-Driven GTO Module for 4.5 kV/3 kA Snubberless Operation", PCIM Nürnberg, 1996.