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Application-specific fast-recovery diodes

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Abstract
The number of fast recovery applications in high power systems continues to grow leading to various dynamic constraints and hence different diode designs and behaviours. Along with conventional RC (“SCR-type”) and C(“GTO-type”) snubber conditions, snubber less conditions in both IGBT and IGCT applications are gaining ground at ever higher currents and voltages (presently 6 kV). Within these two groups, the further distinctions of “inductive” and “resistive” commutation di/dt must be made for an optimal diode design. Diodes capable of high reverse di/dt and dv/dt can today be realised thanks to controlled life-time profiling which will be described here with both measured and simulated results.

Keywords: Diodes, GTO-type, SCR-type, IGBT, IGCT

1. Introductions

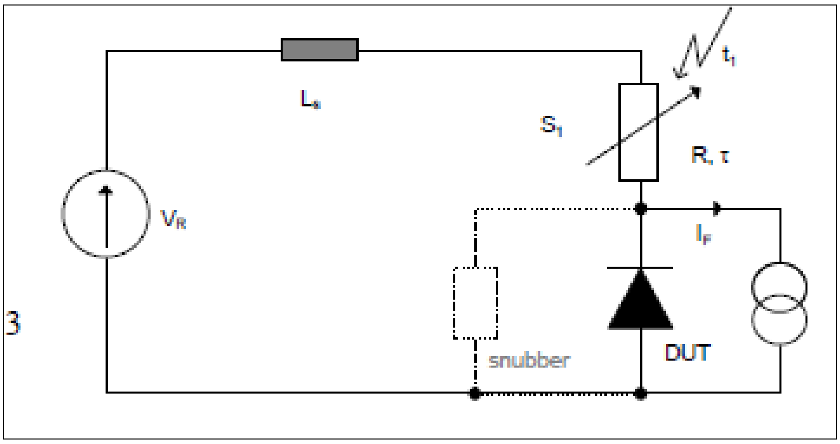
Fast recovery diodes are necessary in every modern power electronic circuit. Using modern switching devices, high current slopes di/dt occur, and it is essential that the diode answers with soft recovery behaviour. It took a comparatively long time until sufficient solutions for softrecovery were found. Diodes with control of the axial lifetime profile [1] or control of the p emitter efficiency are meanwhile established. In the 600V - 1700V voltage range they exhibit soft-recovery behaviour even under critical conditions such as high di/dt’s and low currents. Also trench structures in the p-anode for improving the recovery behaviour have been investigated [3]. However, for applications in the voltage range >3000V, the existing solutions are not sufficient.

Device simulation is a powerful tool for designing a soft recovery diode. But still not many papers have treated the reverse recovery behaviour in an analytical way, although, this is necessary for a complete understanding of simulation results and for evaluating the critical conditions. Moreover, if strong dynamical avalanche occurs, device simulations show formation of current filaments, and it becomes difficult to evaluate the results.

Therefore, this paper will try to give some useful approximations for the reverse recovery and dynamic ruggedness of fast power diodes. In a first part, the internal behaviour in the diode for both snappy and for soft recovery behaviour is presented qualitatively.

2. Resistive Commutation

In this mode of commutation, the turn-off di/dt is controlled by the active switch which is then “not perfect” in that is does not switch instantaneously but progressively over a (short) period of time. In practice the “switch” may be a transistor operating in the linear mode which allows di/dt control via base or gate.

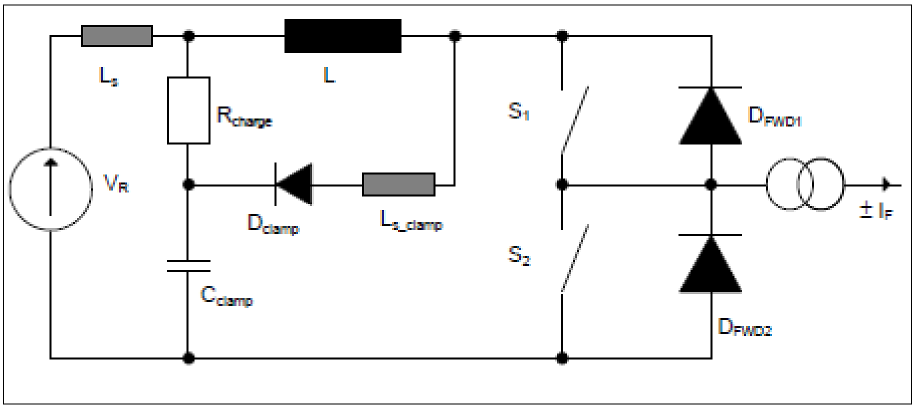


This is illustrated in Fig. 3 in which the active switch S_1 can be considered a time dependent resistance of constant t and initial value R. If the resultant circuit di/dt is determined by t rather than L then the circuit is said to impose “resistive” switching and L degenerates to the stray inductance L_s. This kind of circuit is encountered in McMurray or Undeland snubbers where the active switch is typically a GTO, or in FWD circuits where the active switch is an IGBT. Such circuits rarely use additional snubbers or clamps because if the inductance L_s is really negligible, the DUT voltage is ultimately clamped by the source voltage (V_R) and dv/dt is determined by the characteristics of the active switch. An additional snubber across the DUT would be an additional stress (and loss) for S_1.

3. Clamp Diodes

In Fig. 2, a clamp diode D_{clamp} is used to limit the peak voltage to a pre-determined maximum (in this case V_R obtained via D_{charge}). When the peak FWD voltage is reached this diode is called upon to conduct quickly (low forward recovery time, t_{fr}) and to stop a further increase of voltage. Depending on the value of C_{clamp}, clamp voltage will rise above V_R and D_{clamp} will block under a small voltage $DV=V_R$ - V_{clamp}. However, clamp diodes are not used only to clamp FWDs but also to clamp active switches such as IGBTs and IGCTs. Fig 4 shows an IGCT inverter phase-leg with clamp and FWDs in which a far more severe commutation mode may appear for D_{clamp}.

In the clamp circuit of Fig. 4, D_{clamp} limits voltage from the recovery of D_{FWD2} (S_1 conducting) and recovery of D_{FWD1} (S_2 conducting). Conversely, it clamps the turn-off of S_1 (D_{FWD2} conducting) and of S_2 (D_{FWD1} conducting). D_{clamp} also acts as a FWD for the di/dt snubber L but should S_1 or S_2 (complementary diodes conducting) be fired while D_{clamp} is still in conduction, the turn-off circuit of D_{clamp} degenerates to that of Fig. 3 where only clamp stray inductance L_{s_clamp} and the turn-on speed of S_1/S_2 determine the diode’s recovery di/dt. Thus the constraints of clamp diodes tend to be the same as those of snubber diodes.



4. Snubbers and Commutation Modes

Snubber circuits are commonly used on main switches and FWDs (less so on clamp and snubber diodes) to reduce turn-off/recovery losses and/or enhance Safe Operating Area (SOA). They do so essentially by controlling reapplied dv/dt which in turn strongly affects the recovery behaviour of diodes as will be shown later. The types of possible snubbers which will be described here, in combination with the types of applications seen above, determine both diode technology and design to be adopted.

The various snubbers and commutation types are summarised in Fig 5 below. The main configurations of Fig. 5 will be discussed later with reference to measurements and simulations since the former represent most of the dynamic diode constraints found in high power applications. It will be seen that no single diode technology covers all the possible applications but firstly the available technologies and their impact on performance will be reviewed to allow a better understanding of the measured and simulated results.

5. Reverse Recovery Time of Diode

A diode when functioning in its forward bias condition has its depletion region shrinked to almost nothing. That is, the external supply voltage applied will be used by the device to overcome the barrier potential which gets imposed on it due to the presence of immobile charge carriers in its depletion region. Now, imagine that one reverse biases this voltage by inverting the polarities connected to the terminals of the diode. Ideally, the act of doing so should bring the diode from its ON state to OFF state immediately. That is, the diode which is conducting current in its forward direction is expected to stop conducting instantly.

However, practically, this cannot be experienced as the flow of majority charge carriers through the diode does not cease right at the moment of reversing the bias. They will, in fact, take a finite amount of time before stopping and this time is known as reverse recovery time of the diode.

During this reverse recovery time of the diode, one can see that there will be fairly large amount of current flowing through the diode, but in the opposite direction (I_{rr} in Figure 1). However its magnitude reduces and gets saturated to a value of reverse saturation current, once the time-line crosses reverse recovery time (t_{rr}) of the diode. Graphically one can describe the reverse recovery time of the diode as the total time which starts from the instant at which the reverse current starts to flow through the diode to the time instant at which it reaches to zero (or any other pre-defined low level, say 25% of I_{rr} in the figure) while decaying (t_d), on reaching its negative maxima (t_p).

The ratio of these two time factors (*viz.*, t_p and t_d) is known as the softness factor. In the case of a normal diode, the time is taken by the current to decay (t_d) will be smaller in comparison to the time taken by the current to reach its negative peak (t_p). On the other hand, for a soft recovery diode, the situation will be the reverse. That is, here, t_d will be larger in comparison to t_p. We can see that the softness factor gives a measure of semiconductor losses incurred during switching. Greater is this ratio; greater will be the switching loss. From this, one can conclude that when we use soft-recovery diodes, the losses experienced by the semiconductor switching are more than those encountered when we use normal diodes.

This phenomenon of reverse recovery is basically parasitic effect experienced in the case of diodes and is seen to be dependent on the doping level of silicon and its geometry. Also, even the junction temperature, the rate at which the forward current falls and the value of the forward current just before the reverse biased gets applied are also seen to affect its value. Greater is the reverse recovery time; slower will be the diode and vice-versa. Thus the diodes with lesser reverse recovery time are preferred, especially when the requirement is of high switching speed. Moreover, during this time interval, there will be a significant amount of current-flow back towards the supply which provides power to the diode. Hence the reverse recovery time of the diode is an important design factor which we should consider while designing the power supplies.

6. Conclusion

A new generation of high power diodes is now becoming available to complement recent advances in snubber less switches. Three powerful tools have been combined to achieve soft-recovery, high SOA and optimal application-oriented designs: combined electron and proton lifetime profiling, Silvaco simulation and application-oriented Production Testing. Much of the laborious experimentation has been eliminated from power diode design allowing the concurrent engineering of both devices and equipment thus permitting new generations of equipment to be designed with drastically reduced components count with consequently enhanced reliability and reduced cost.

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