Effects of Diode Recovery Characteristics on Electromagnetic Noise in PFCs

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Abstract— **This paper presents a comparison of different diodes used in Boost Power Factor Correctors (PFC) from the point of view of electromagnetic compatibility. Diodes produced by various manufacturers, all with the same nominal recovery time, have been characterized and tested on a PFC circuit. Whereas the conducted emissions do not depend on the used diode, the radiated emission are strongly influenced by the recovery behavior. In particular the snap factor is important for the noise level and the reverse capacitance determines the ringing frequency and hence the noise peak.**

I. Introduction

Power Factor Corrector (PFC) circuits are gaining a large dominance in electronic systems due to the line frequency harmonic emission limitations imposed by various bodies. Although a PFC in some cases can be implemented using passive components, the usual solution consists of a high frequency switch mode converter suitably controlled, typically a boost topology. Switching converters however generate high frequency noise, starting from the switching frequency up to hundreds of megahertz. This aspect must be considered by the designer in order to avoid unwanted radio frequency emissions both conducted and radiated.

In a DC to DC converter many factors (including the parasitic elements) are involved in the mechanism of noise production and coupling. In some cases the designer is well aware of this mechanisms, and he/she can consider them from the beginning of the design phase. In some case however the designer lacks the information required for a successful design, as in the case of recovery characteristics of diodes.

For instance, it is well known that in a continuous conduction mode converter the diode recovery time must be as short as possible in order to reduce the commutation losses, but less interest is placed on the recovery behavior in order to control the electromagnetic noise.

Diodes dynamic parameters are, beyond the recovery time t_{rr}, the recovery charge Q_{rr} that is mainly responsible for a part of commutation losses and the snap factor, that gives an indication about the behavior of recovery current and the current derivative during the turn-off phase.

In order to investigate the effects of diode recovery behavior on the electromagnetic noise generated by a PFC circuit, four commercially available diodes of different manufacturers have been chosen, that have similar typical characteristics. These samples have been measured on a test equipment to extract their recovery characteristics. Then these diodes have been mounted on the same circuit and the generated electromagnetic noise has been measured. As a further check of the characterization, the switch losses induced by the diode turn-off have been measured and related with the Q_{rr}.

II. Diode Choice and Characterization

Four different commonly available ultrafast diodes have been selected for this test. The choice has been based on information usually known by the designer and printed on data sheets, i.e. maximum reverse voltage 600 V, recovery time 30-40 ns, and maximum current 5-10 A: these values are typical for PFC circuits.

Characterization has been done using an experimental test equipment designed and produced at IR plant: the equivalent circuit is depicted in fig. 1.

Inductor L_S is charged closing S_1 to the desired forward current, then S_1 is switched off and current flows in D.U.T. Finally S_1 is switched on again controlling its $\frac{\mathrm{d}I}{\mathrm{d}t}$. Reverse voltage is imposed by generator V_R.

The used circuit allows one to perform measures in the following ranges:

- Forward current: $I_\mathrm{f} = 0.5 \div 2\,\mathrm{A}$
- Current slope: $\frac{\mathrm{d}I_\mathrm{f}}{dt} = 20 \div 160\,\mathrm{A}/\mu\mathrm{s}$
- Reverse voltage: V_R=30 V

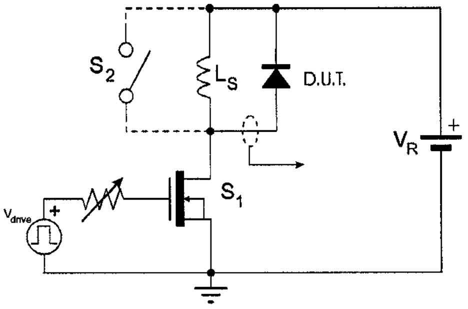

Figure 1 – Equivalent circuit for tester used in reverse recovery measurements

Waveforms have been sampled using an HP54510A digital sampling computer controlled scope offering a bandwidth of 250MHz.

Forward current has been set to 1 A, according to the standard value used in data sheets of different manufacturers[1]. For the same reason recovery current slope has been set to 100 A/μs.

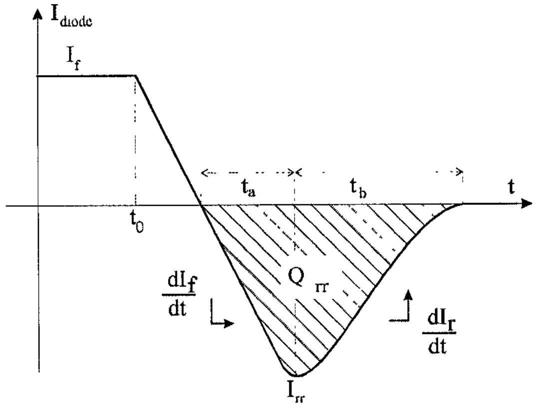

Figure 2 – Reverse recovery parameters

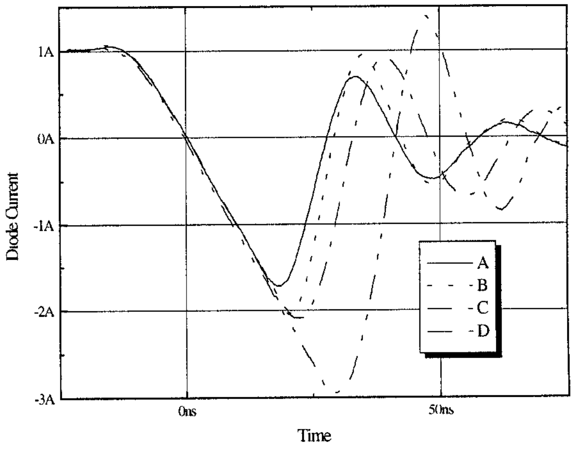

Figure 3 – Reverse recovery waveforms of characterized diodes

Measurement results are shown in fig. 3. Data extracted from these graphs are reported in table 1. Recovery time t_rr is measured from zero current levels, Q_rr has been obtained by numerical integration of current curve, and snap factor is defined as ratio between the times t_a and t_b, as indicated in fig 2. As it can be seen, diode B presents a steeper current recovery, and about the same recovery time as diode A. The difference is pointed out by the snap factor having a value of only .45. The higher the snap factor, the softer the diode recovery and less noise is generated. However the snap factor (or the detailed recovery characteristics) usually are not given by diode manufacturer.

The examined diodes have a die size indicated in table 2: this information is related to the reverse capacitance that influences the ringing frequency after

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[1] Authors are well aware that these conditions are unrealistic for a 10 A diode, but only recently diode manufacturers started to use realistic values for the diode recovery parameters.

Diode Type	A	B	C	D
t_{rr} (ns)	28.2	30.1	33.5	41.2
I_{RR} (A)	-1.72	-2.04	-2.09	-2.95
$\frac{dI_R}{dt}$ (A/μs)	220.2	310.4	269	360.7
Q_{RR} (nC)	-26.5	-31.9	-38.6	-68.5
Snap Factor	0.57	0.45	0.52	0.42

Table 1. Main diode switching parameters

the diode turn-off.

Diode Type	**A**	**B**	**C**	**D**
Die size (mils)	95×95	90×90	135×100	100×100
Current (A)	8	5	10	8
Technology	Mesa	Planar	Moat	Planar

Table 2. Die Size of tested diodes

III. PFC Circuit and Test Conditions

For the tests and measures of electromagnetic noise related to the diodes, a demo board produced by ST has been used. This board consists of a PFC circuit using a standard boost topology, capable of 200 W of output power at 400 V. The control strategy is average current mode and the boost is operated in fixed frequency, continuous conduction mode. This board has not been optimized for low EMI emission, so only relative values are significant.

Measurements of conducted and radiated emissions have been carried out according to the EN 55011 rules, but using a peak detector (instead of the required quasi-peak detector) in order to decrease the measurement time and measuring the electrical field from a distance of 3 m. Measurements have been carried out with the standard European main voltage (230 V_{eff}, 50 Hz), and about 180 W of delivered output power.

Time domain measurement of diode current and input voltage have also been done. In this case the measure has been synchronized to line voltage peak in order to observe the effects with the maximum input current. During the time domain test, the PFC was fed through the same LISN used for conducted emission tests. The PFC output loop, including output capacitor, output diode and MOS transistor presents an inductance in the order of 100 nH. This value has been estimated from the physical dimension of components and layout.

IV. EMI Measurement Results and Discussion

A. *Time domain analysis*

Time domain measurements have shown the different diodes behavior in a real circuit operation. Diode current and line voltage have been monitored during MOS turn-on and turn-off switching.

The MOS turn-off transition (i.e. diode turn-on) is not particularly influenced by the diode dynamic characteristics. This is due to the presence of an RCD snubber network connected between drain and source of MOS and used to control $\frac{dV_{DS}}{dt}$. The typical diode turn-on transition for this circuit can be seen in fig.4. The ringing frequency is mainly dominated by the time constants of RCD snubber and resulted to be the same for all four diodes tested, in a range between 20 and 25 MHz: so this ringing can have some effect on conducted emission band (150 kHz÷30 MHz).

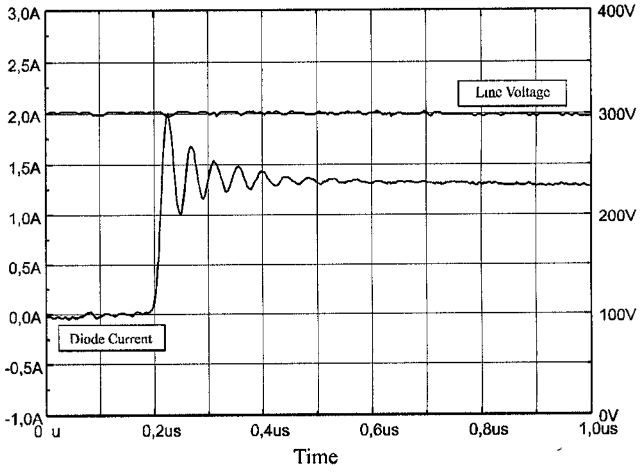

Figure 4 – Typical diode turn-on

The line voltage measured before the input rectifier bridge (fig.4) is only slightly affected by this transition.

Figures from 5 to 8 show different diodes behavior during MOS turn on transition (i.e. diode turn-off). Type A and type B have almost the same reverse recovery current (about -2 A), but, as it can be seen, frequency and amplitude of ringing are differ-

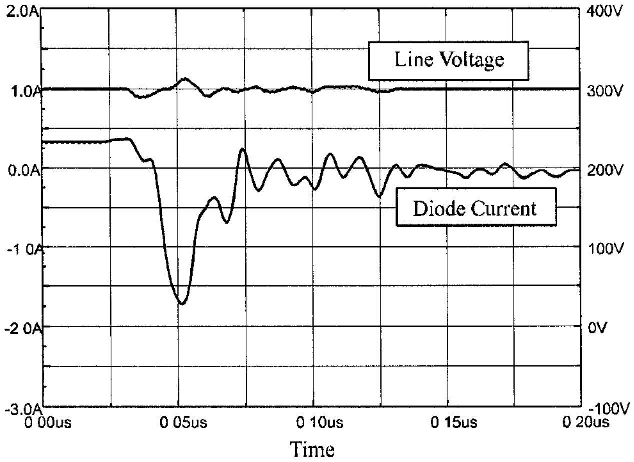

Figure 5 – Time domain waveforms for type A diode

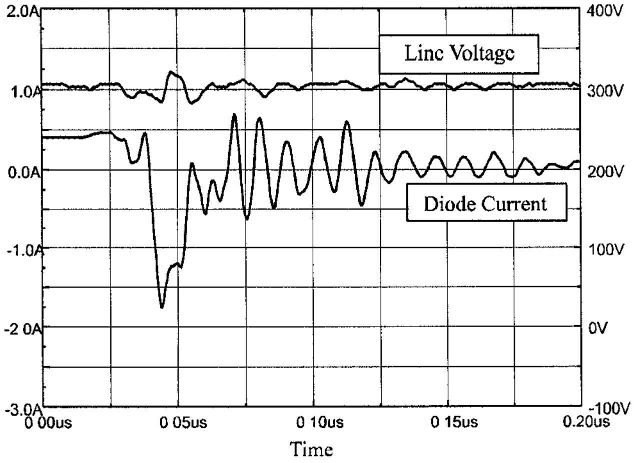

Figure 6 – Time domain waveforms for type B diode

ent. Moreover line voltage is affected by this transition.

Type C diode has a reverse peak current slightly larger than type B, but ringing amplitude is almost the same as type B. Type D, which has the lowest snap factor (and also the largest reverse recovery time) exhibits a large reverse recovery current and its ringing amplitude is about 6A (peak-to-peak). The ringing frequency can be related to the diode junction capacitance and to the connections parasitic inductance. Mean values of ringing frequency and amplitude are shown in tab. 3.

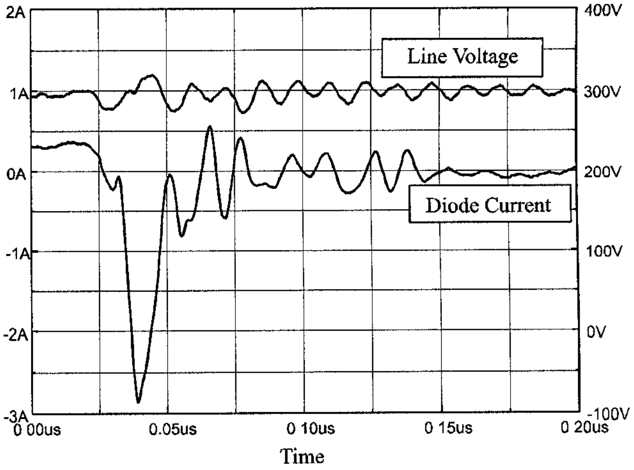

Figure 7 – Time domain waveforms for type C diode

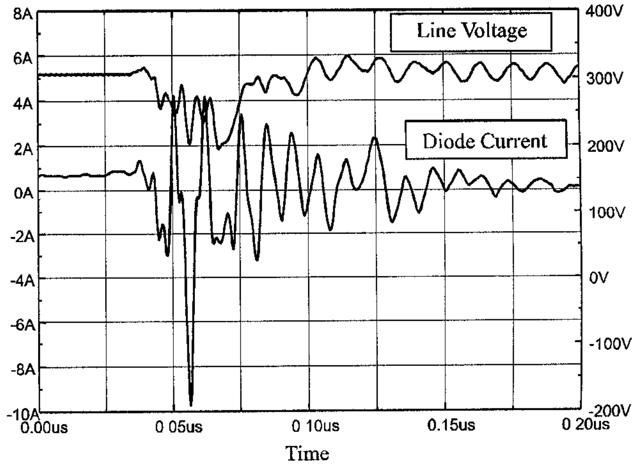

Figure 8 – time domain waveforms for type D diode

A better layout offering a smaller output loop inductance would push the ringing frequency towards higher values, where the EN55011 emission limits are higher. Moreover the inductance reduction would decrease the loop area where the ringing current flows thus reducing the magnetic dipole moment. However a designer must also consider that a higher ringing frequency has a better radiation from a loop antenna and currents can assume different values.

Figure 8 shows that diode turn-off transition has a strong influence on voltage line. It can be seen that

Diode type	A	B	C	D
Frequency (MHz)	88.6	100	76.9	71.4
Amplitude (A)	0.5	1.3	1.2	6

Table 3. Amplitudes and frequencies of diode turn-off ringing

in correspondence with reverse current spike there is a fast transient in the line voltage about 100 V deep.

B. Conducted emission comparison

As previously seen, the main differences are in frequency ranges well above 30 MHz. Conducted emission measurements confirms that considerable differences cannot be pointed out, because the snubber capacitance is dominating the resonance frequency and the oscillation amplitude is given by the switch turn-on time. The used board has no input filters for conducted radiation reduction. A PFC input filter design is different from a standard input filter for a DC to DC convertes, as shown in [6].

C. Radiated emission analysis

In the radiated emission range (30 MHz÷1 GHz) differences between diodes stand out. Radiated electric field measured in this range is depicted in fig. 9 and 10.

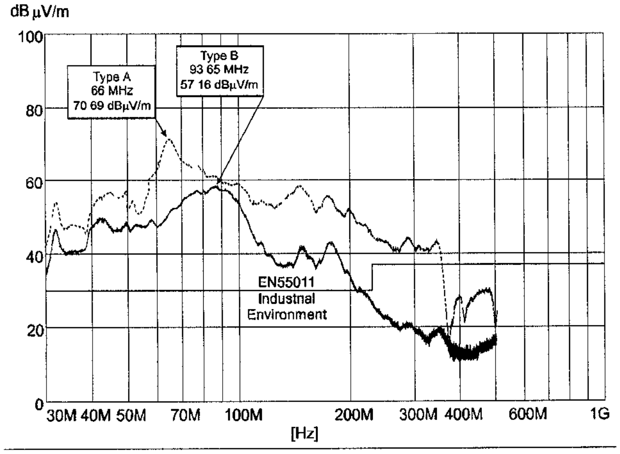

Figure 9 – Radiated emission comparison between type A and type C diodes

Diode B and C (fig.10) exhibit a similar frequency behavior: peak frequency is lower for type C which has a larger die size and therefore a larger capacitance.

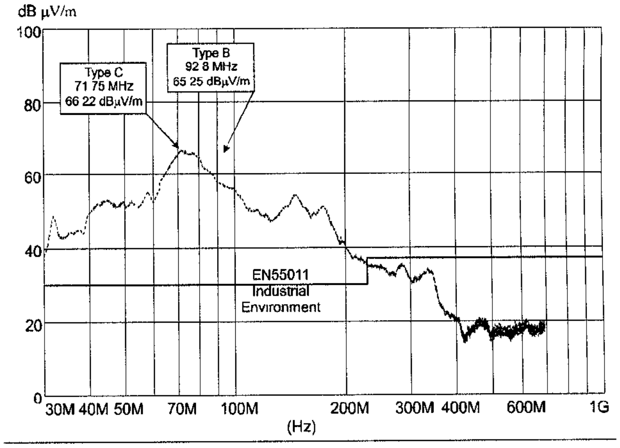

Figure 10 – Radiate emission comparison between type B and type C diodes

Type A exhibits lower emission: in some bands of the frequency spectrum differences with other diode types can reach values around 20 dB.

V. EFFICIENCY ISSUES

Reverse recovery time and charge have always had a considerable importance to reduce switching losses in DC to DC converters. In PFC Boost converter working in continuous current mode this importance is enhanced by the high output voltage.

A very rough model for the switch losses in a boost converter states that the lost power due to the recovery charge is:

$$P_{\mathrm{rr}} = V_{\mathrm{out}} \cdot Q_{\mathrm{rr}} \cdot f_{\mathrm{sw}} \qquad (1)$$

This fact is qualitatively shown in fig. 11, where the *total* (including conduction losses) MOS dissipated power versus Q_{rr} is shown. As one can see, dissipated power is related to the recovery charge, but changing from diode B to diode C the MOS dissipated power is approximately constant. This suggests that not only Q_{rr} is involved in dissipation phenomena. A partial explanation is that the charge recovered during t_{b} is released when the switch voltage is already decreasing from V_{out}, reducing thus the switch losses, but increasing by the same amount the diode losses. This phenomena however were impossible to observe because diodes have different areas, direct voltage drop V_F and thus different conduction losses.

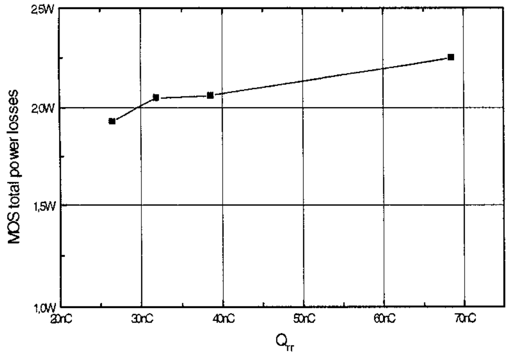

Figure 11 – MOS total power losses as a function of diode reverse recovery charge

Dissipated power has been measured by thermal comparison, using a temperature probe to measure the MOS heating during normal conditions, then a controlled and measured DC power was dissipated in the same MOS in order to obtain the same temperature increase.

VI. Conclusion

In this paper four commercial ultrafast diodes have been compared to point out the differences in noise generation when used in a PFC circuit. The importance of diode recovery characteristics on efficiency and generated noise has been shown. The snap factor, along with the recovery charge and recovery time, is of great importance for the noise generation. The main differences among the different diodes are at frequencies higher than 30 MHz, i.e. in the band of radiated noise, where the peak position of noise is mainly given by the diode reverse capacitance, hence by the die size, whereas the noise amplitude is given by the current slope during the second part of the recovery process, i.e. it depends on the snap factor which should be included in the data sheets as a merit figure.

In order to model the diode recovery, many macromodels for Spice and other simulators have been proposed. These models can be quite accurate but they cannot be directly used to determine the electromagnetic noise, because below 30 MHz, that is in conducted band, where a Spice-like simulator could be used provided that the circuit parasitic elements are known, there are no significant differences among various diodes. At higher frequency (in radiated band) the diode turn-off behavior is important and it strongly determines the generated noise, but standard circuit simulators are unable to cope with radiation problems.

The effects shown in this paper occur of course also in other topologies running in continuous conduction mode used in DC to DC converters. A PFC has been chosen because this particular circuit will have in the future a wide spread as input stage of electronic devices.

VII. References

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