# Simulation Bits: Adding the Reverse Recovery Feature to a Generic Diode

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*Abstract* – A simplified behavioral model of diode reverse recovery, which is based on the lumped charge control concept, is proposed and tested experimentally. The model can be implemented in discrete transition simulators that do not apply full physical models of devices and it does not require heavy computational resources. The parameters of the model can be easily extracted from a simple single measurement. The model is demonstrated in the PSIM platform and is verified experimentally for various turn-off conditions.

## I. Introduction

Power electronics simulators can be divided into two groups with respect to the numerical algorithm used by them. One class are the SPICE [Berkeley SPICE2] based simulators such as Orcad [1]. SPICE uses an adjustable step, Newton-Raphson algorithm to solve the matrix of nodal equations when the circuit contains nonlinearity such as physical models of switches and diodes. The second class includes the discrete-transition simulators such as PSIM [2] and others. The ideal device models used by the discrete transition simulators and the fact that they disregard the transition instances makes them much faster than the SPICE based simulator and eliminate, to a large extent, convergence problems. On the down side, since most discrete transition simulators do not apply full physical models of devices, they are incapable of showing parasitic processes. For example, diodes in PSIM are ideal and include only one parameter: the forward diode voltage drop. Consequently, simulation results are unrealistic (Fig. 1) when simulating some power electronics circuits such as snubbers that are affected by non ideal and parasitic properties.

Here we propose a simple and portable modeling strategy for simulating the diode reverse recovery process within discrete-transition simulators.

## II. Modeling procedure and parameters extraction

The modeling method adopted in this study is based on the lumped charge control concept [3]. This principle is described analytically by the following equations:

$$i_D(t) = \frac{q_e - q_m}{T_m} \tag{1}$$

$$0 = \frac{dq_m}{dt} + \frac{q_m}{\tau} - \frac{q_e - q_m}{T_m} \tag{2}$$

$$q_e = I_S\tau\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right] \tag{3}$$

where, $i_D(t)$ is the diode current, $q_e$ is the injected charge level at the junction, $q_m$ is the total forward bias injected charge, $T_m$ is the drift region transit time, $\tau$ is the life time, $I_S$ is the diode saturation current, $v_D$ is the diode junction voltage, $V_T$ is the thermal voltage and $n$ is the emission coefficient. To minimize computational overheads as much as possible, the model was further simplified in this study by disregarding the exponential dependency between the forward voltage $v_D$ and the charge $q_e$ of the power diode (3).

The proposed equivalent circuit model of Fig. 2 emulates the physical behavior during the turn-off period of a typical power diode by solving the equations of the simplified diode model. The first order differential equation (2) is emulated in the model by an *RC* network. The resistor–capacitor pair $R_\tau C_\tau$ of the model reflects a time constant $\tau$ during $0 < t < t_a$ (Fig. 1). The resistor–capacitor pair $R_{\tau\_rr}C_\tau$ reflects a time constant $\tau_{rr}$ during the recovery period $t > t_a$. E_id is a current controlled voltage source associated with the diode current and is equal to $\tau \cdot i_D(t)$. The voltage controlled current source G_qm expresses the response $q_m(t)/T_m$. The role of the switch Srr is to select the correct time constant and is controlled by the state of the ideal diode Dvf. The diode Dvf carries the sum of $i_D(t) + q_m(t)/T_m$. As long as Dvf conducts with $i_{Dfv}(t) > 0$, the switch Srr is 'off' and the time constant is $\tau$. According to reference [3], at time instant $t_a$ the diode current $i_D(t_a)$ and $q_m(t_a)/T_m$ have equal magnitudes with opposite sign. At this instant, Dvf stops conducting and the switch Srr turns on. From now on the current $i_D(t)$ will decay to zero with a time constant $\tau_{rr}$ as follows,

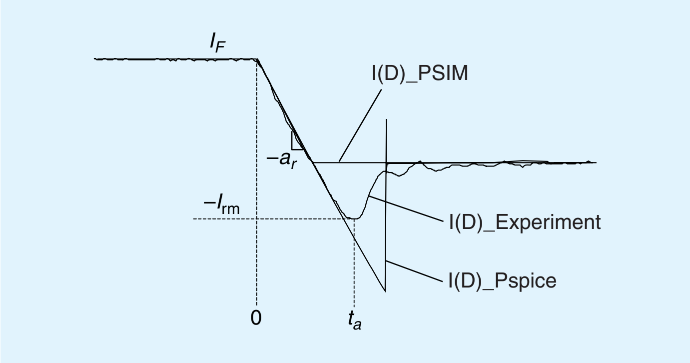


*Figure 1. Simulated and Experimental turn-off current waveforms of power diode (MUR8100E, ON-Semi) with stray inductance.*

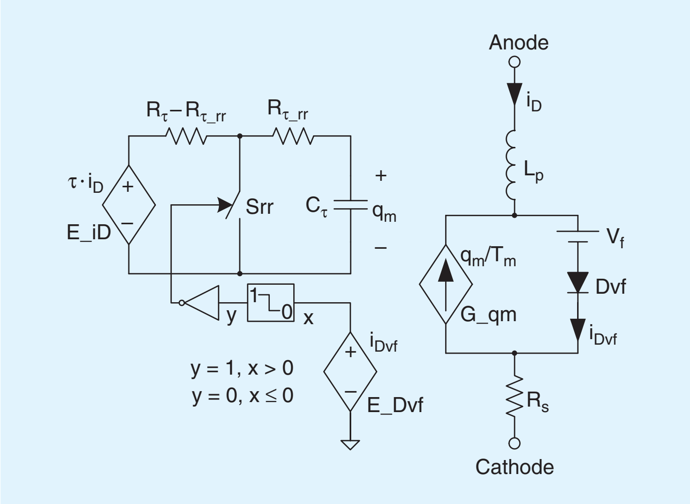


*Figure 2. Proposed diode model with reverse recovery. The $L_p$ inductor represents the parasitic lead inductance.*

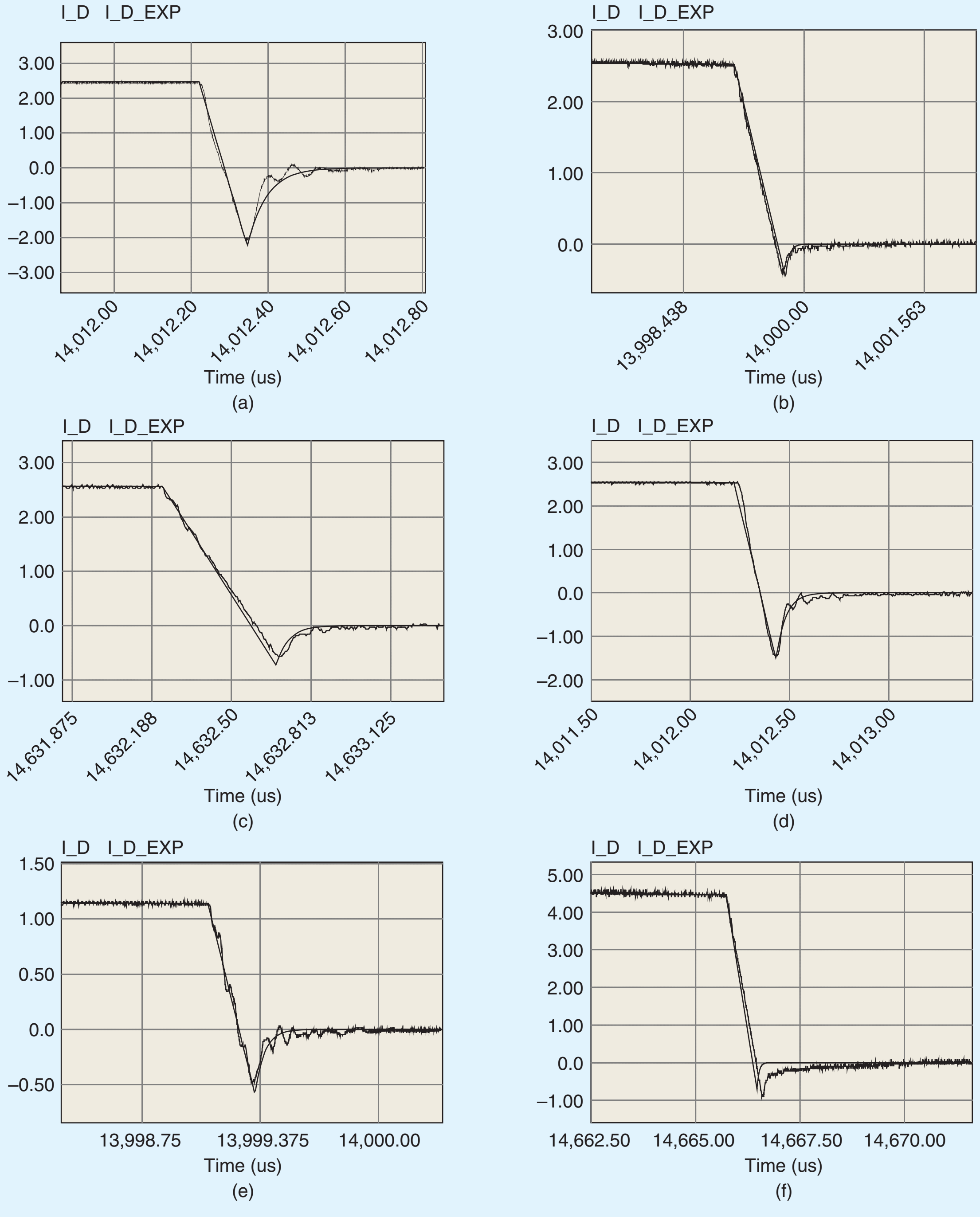


*Figure 3. Reverse recovery model validation (PSIM simulation): (a) Comparison to the measurement data, (b) $L_r = 10\mu H$, $I_F = 2.5A$, (c) $L_r = 6\mu H$, $I_F = 2.5A$, (d) $L_r = 1.3\mu H$, $I_F = 2.5A$, (e) $L_r = 6\mu H$, $I_F = 1.3A$, (f) $L_r = 6\mu H$, $I_F = 4.3A$.*

$$i_D(t) = -I_{rm}\exp\left(-\frac{t-t_a}{\tau_{rr}}\right) \qquad (4)$$

where $I_{\mathrm{rm}}$ is the peak reverse current (Fig. 1).

The model is calibrated by seven model parameters that need to be determined in the following order. The parameter $\tau_{\mathrm{rr}}$ can be obtained by fitting (4) against measurement data over $t>t_{\mathrm{a}}$. In [3], it is shown that the following relationships hold,

$$I_{rm} = a_r(\tau - \tau_{rr})\left[1 - \exp\left(-\frac{t_a}{\tau}\right)\right] \qquad (5)$$

$$\frac{1}{\tau_{rr}} = \frac{1}{\tau} + \frac{1}{T_m} \qquad (6)$$

where $a_{\mathrm{r}}$ is the current fall slope (Fig. 1).

By substituting the experiment parameters $I_{\mathrm{rm}}$, $a_{\mathrm{r}}$, $t_{\mathrm{a}}$, $\tau_{\mathrm{rr}}$ into (5) one can extract $\tau$. $T_{\mathrm{m}}$ is calculated from $\tau$ and $\tau_{\mathrm{rr}}$ using (6). Once the fundamental parameters are extracted, the calculation of the remaining five model parameters may proceed as follows: The contact resistance $R_{\mathrm{s}} = \Delta v_{\mathrm{D}}/\Delta i_{\mathrm{D}}$ (from diode forward static characteristic), $V_{\mathrm{f}}$ (from diode forward static characteristic), $C_\tau = C_{\mathrm{o}}$ (arbitrary number), $R_\tau = \tau/C_{\mathrm{o}}$ and $R_{\tau\_\mathrm{rr}} = \tau_{\mathrm{rr}}/C_{\mathrm{o}}$.

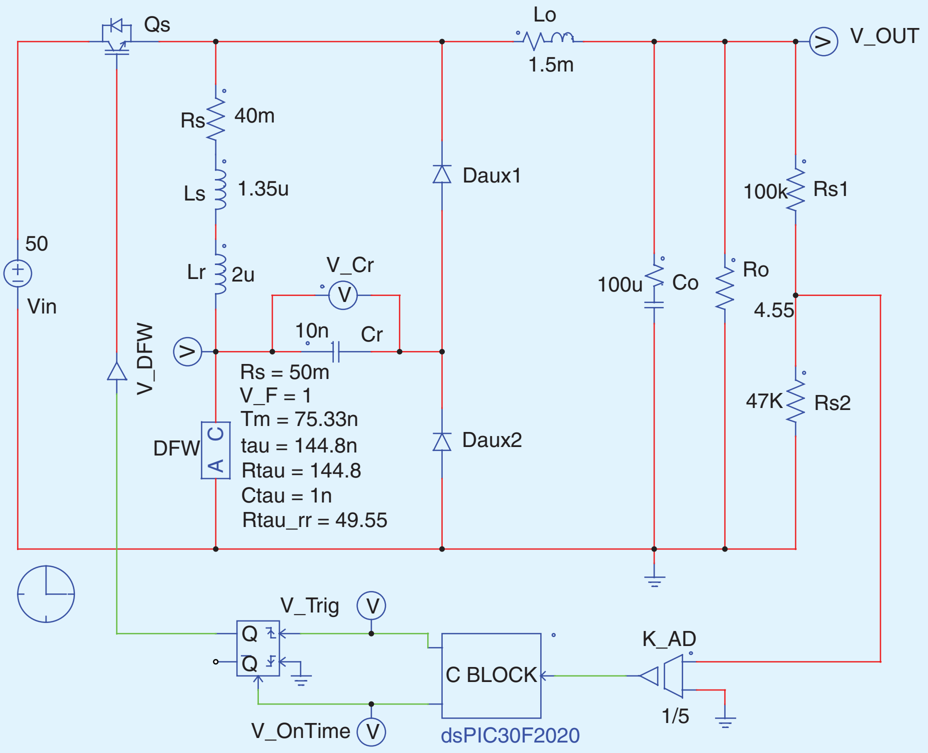


*Figure 4. Circuit diagram of simulation and experimental setup of dc-dc buck converter. $L_r$ and $L_s$ are the snubber inductor and stray inductance, respectively.*

## III. Model verification

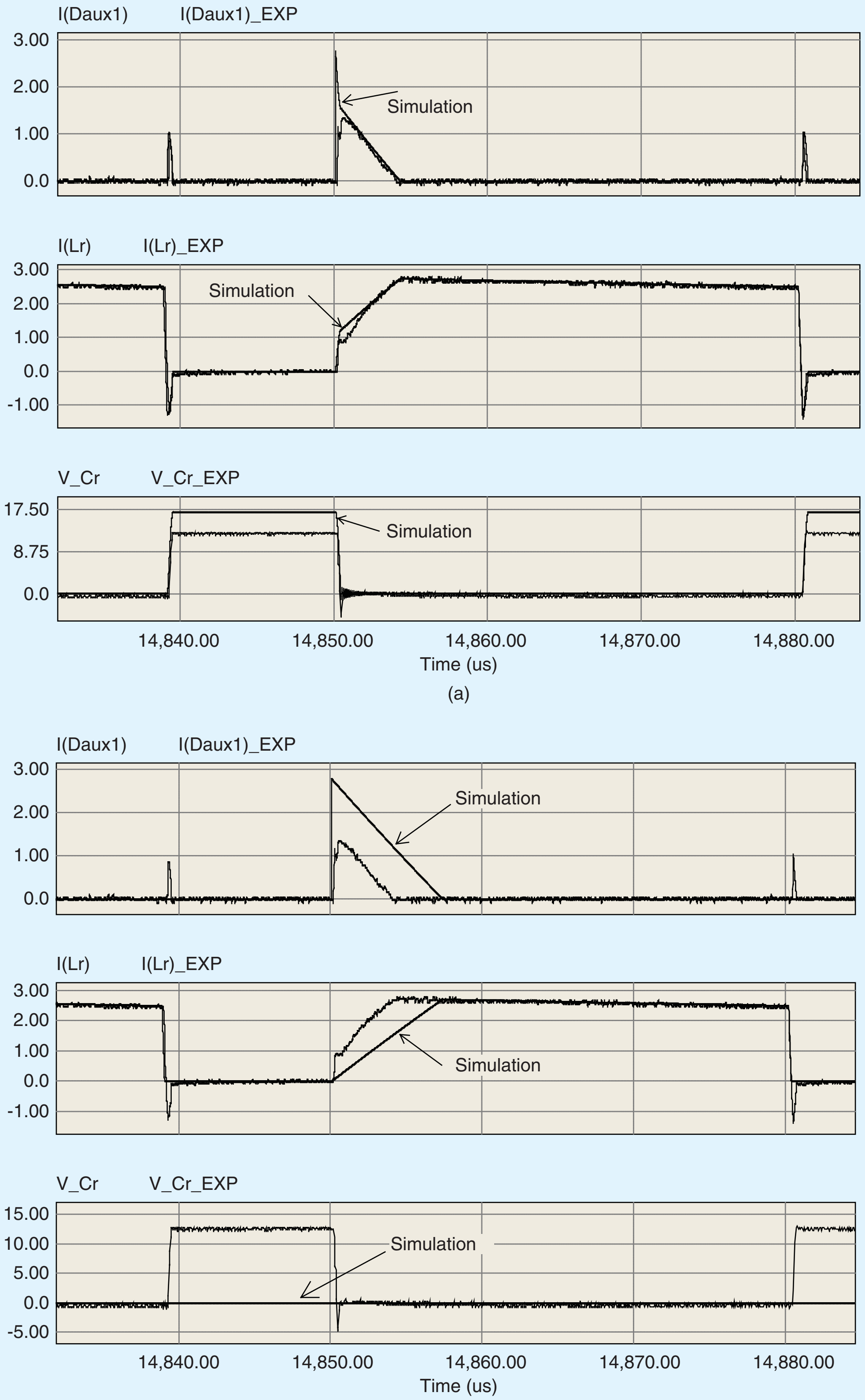
The diode tested in the experiments is a commercial fast recovery power diode MUR8100E, (ON-Semi.) with a nominal reverse recovery time of 75 nsec. Test measurements were carried out with an estimated reverse voltage of 50 V during the turn off period of the diode. The model parameters were calculated from a single measurement data of a typical turn off waveform in the presence of stray circuit inductance with the following experimental parameters: initial forward current $I_F = 2.5$ A, peak reverse current $I_{rm} =$ 2A, current fall slop $a_r = 4.5$ A/122 nsec and the length of the turn off period $t_a = 122$ nsec. The estimated stray inductance $L_s$ was found to be 1.35 $\mu$H. Applying the proposed extraction method, the extracted model parameters were found to be: $R_s = 50$ m$\Omega$, $V_f = 1$ V, $T_m = 75.33$ nsec, $\tau = 144.8$ nsec, $C_\tau = 1$ nF, $R_\tau = 144.8$ $\Omega$ and $R_{\tau\_rr} = 49.55$ $\Omega$ ($\tau_{rr}$ was estimated by fitting (4) against measurement data over $t > t_a$). The comparison between the experimental and simulated results of the proposed model for various turn off conditions is shown in Fig. 3. The figure shows a good fit of the simulation to the experimental data.

The model was also tested in a dc-dc buck converter that includes a passive lossless snubber network as shown in Fig. 4. A comprehensive analysis of this turn-on lossless snubber for dc-dc Boost converter was presented in [4]. In the experimental circuit: $V_{in} = 50$ V, $V_o = 12$ V, $P_o = 30$ W, $f_s = 24$ KHz, $L_r = 2$ $\mu$H, $C_r = 10$ nF, $D_{aux1}$ and $D_{aux2}$ were MUR415 (ON-Semi). The converter was digitally controlled by dsPIC30F2020, which in the simulation is represented by a C block (Fig. 4). The simulation was carried out under the following conditions: (1) auxiliary diodes $D_{aux1}$ and $D_{aux2}$ were ideal with constant forward voltage, (2) the reverse recovery of the freewheeling diode was implemented by the proposed model. Simulation results and the experimental verification waveforms are depicted in Fig. 5. The simulation model replicated very well the behavior of the experimental circuit (Fig. 5 (a)), except for some negligible differences stemming from stray capacitance and inductance and mismatch in forward voltage of the diodes between the simulation circuit and the experimental. As expected, large deviations are found between experiment and simulation when the original PSIM diode is used (Fig. 5 (b)).

## IV. Discussion and conclusion

The proposed diode reverse recovery model is suitable for very detailed study of device interactions with the rest of the circuit, e.g., snubber design. The experiment results were found to be in good agreement with the simulation waveforms (Fig. 3). The model gave good results for forward currents below 2.5 A and exhibited a reasonable accuracy for a forward current of $I_F = 4.3$ A (Fig. 3 (f)). The deviation can be explained by the fact that the parameters were fitted to give closest approximation to data in which the forward current was $I_F = 2.5$ A. In addition, a slow decay of the tail to zero was observed. This is probably because the single time constant of the model is incapable of simulating accurately the decay of higher order waveforms. The practical usefulness of the model over the standard ideal diode was demonstrated in a test bench dc-dc buck converter. The diode model was found to reproduce faithfully the experimental data (Fig. 5 (a)).

The strength of the model is in the ability to help designers to examine physical phenomena such as reverse recovery and its interaction with other circuit components and at the same time to explore control needs for stability, soft switching and others on one platform. The model can easily be incorporated in other discrete-transition power electronics simulators by following the proposed model construction procedure.



(a)

(b)

*Figure 5. Comparison between simulation (PSIM) and the experimental waveforms of the turn-on lossless snubber: (a) results when the proposed diode model is included, (b) results when the original PSIM diode is used.*

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## References

[1] Cadence Design Systems, Inc..
[2] *PSIM user manual*, Powersim Inc., Version 8.0, 2009.
[3] P. O. Lauritzen, and C. L. Ma, "A simple diode model with reverse recovery," *IEEE Trans. Power Electron.*, vol. 6, no. 2, pp. 188–191, Apr. 1991.
[4] H. Levy, I. Zafrany, G. Ivensky, and S. Ben-Yaakov, "Analysis and Evaluation of a Lossless Turn-On Snubber," in *Proc. IEEE Applied Power Electronics Conf.*, 1997, pp. 757–763.