A New Macro-Model for Power Diodes Reverse Recovery

ALI DASTFAN
Department of Electrical & Robotic Engineering
Shahrood University of Technology
Shahrood, Iran

Abstract: - The power diode is one of the most important elements of the power electronics circuits, because of its role in different converters. The objective of this paper is to find a model for power diode reverse recovery, which can be used in circuit simulation. A simple macro-model for reverse recovery in power diode, that is the most important dynamic effect for power circuit, is developed. Then in order to verify the accuracy of the model, PSPICE simulation and benchmark test results of a power diode in a DC/DC boost converter are given. The simulation and experimental results demonstrates the accuracy of the proposed power diode models. Finally, calculation of the diode power losses due to the diode reverse recovery is given and is compared with simulation and experimental results.

Key-Words: -Macro model, power diode model, power losses, PSPICE simulation, test result

1 Introduction

The power diode is one of the most important, because of its role in power electronics circuits, and in the some ways the least understood power device. Till today, various power diode models have been proposed [1-9], however, due to the different requirements and simulators, there is no unique model for the power diodes. That means a power diode model may work on one particular simulator but suffer from some difficulty on other simulator.

In general the power diode models can be classified as either macro-models [1]-[4] or detailed physical models [6], [8], [9]. The macro-models are composed of electrical equivalent circuits which are not directly related to internal physical processes in the device. Physical models include equations for drift and diffusion of electrons and holes. They usually contain many mathematical equations and parameters, and are complicated to incorporate into circuit simulators.

In the first section of this paper a simple macro-model for reverse recovery in power diode is developed to simulate the behaviour of the power diodes during reverse recovery transient. Then in order to verify the diode model, operation of power diode in the boost converter is investigated by PSPICE simulation and experiment. The calculation of the diode power losses due to the diode reverse recovery is also presented. The predicted value of the losses for different switching frequencies is compared with the power losses found by experiments.

2 Diode Model for Reverse Recovery Transient

The reverse recovery phenomenon in diode occurs when a forward biased diode is turned off rapidly. The excess charges stored in its junction during forward conduction, takes some time to be removed. During this time, the diode remains conducting and a reverse current flows through it. After most of the stored charge has been removed, deplition layer in diode begins to accumulate a reverse voltage and the diode current eventually falls to almost zero.

Figure 1 shows diode current and voltage waveforms during turn-off and definitions related to that. Where:

t_{rr}= Reverse recovery time
I_{rm}= Maximum reverse current

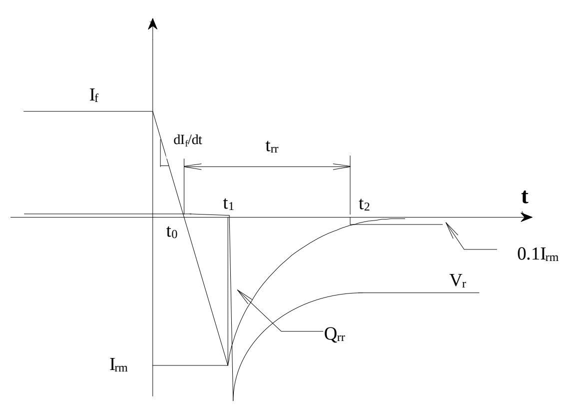

Figure 1: Diode reverse recovery current and voltage waveforms

Q_{rr}= Reverse recovery charge
dI_f/dt= Slope of the diode forward current

This transient can be divided into two sections. The first section, 0< t< t1, starts when current is decreasing from i_f. Prior to this time (at t=0$^-$), the diode stored charge can be represented by:

$$Q(t)\big|_{t=0} = i_f \tau_f \quad (1)$$

Where τ_f is the forward minority carrier lifetime. The diode current during first section can be found by using the following equation:

$$i_d(t) = \frac{Q(t)}{\tau_f} + \frac{dQ(t)}{dt} \quad (2)$$

At the end of section one (at $t=t_1$), the diode reverse current reach its maximum value, I_{rm}. This time can be found by assuming that the total stored charge during section 2 (t_1< t< t_2) is directly proportional to the reverse current [7].

$$Q(t)\big|_{t=t_1} = I_{rm}\tau_r \quad (3)$$

Where τ_r is the reverse biased minority carrier lifetime. During section 2 the diode current falls exponentially and can be represented as:

$$i_d(t) = -I_{rm} e^{\frac{-(t-t_1)}{\tau}} \quad (4)$$

When τ is the time constant of the circuit. Figure 2 is a proposed simple macro-model for power diode reverse recovery and consists of an ideal diode, two resistances, an inductance, and a voltage controlled current source. In this circuit, after diode turned off, for $0<t<t_0$ the ideal diode conducts and the series inductance of the external circuit determines the diode current and its slope(di_f/dt). As diode current linearly decreases, ($t_0<t<t_1$), the constant voltage across inductance ($L\frac{dI_F}{dt}$) commands a constant reverse current through the controlled current source until current reaches I_{rm}. The ideal diode then becomes blocked since its current has decreased to zero and it can be regarded as an open switch. The paralleled RL at $t_1<t<t_2$, imposes an exponential current with a time constant equal to L/R as given in (4) where τ=L/R. Therefore, this model only depends on two parameters: L/R and K (the coefficient of the voltage controlled current source).

Some power diode manufacturers may provide one or two diode parameters, such as I_{rm}, t_{rr}, and Q_{rr}, for specified I_f and dI_f/dt conditions. The other parameters can be found as explained by Flinders et al [2]. Q_{rr} and dI_f/dt have been used in this simulation, and L/R and K can be related to these parameters. From Equation (4) time constant L/R can be found as follow:

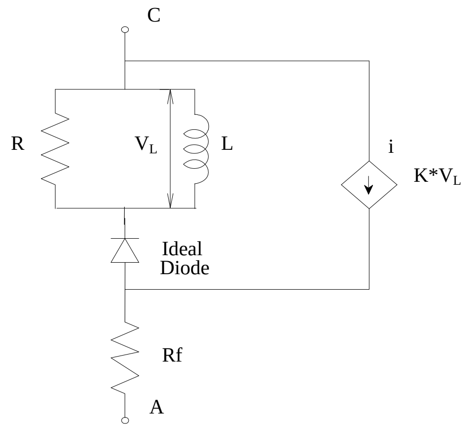

Figure 2: Proposed Model for the diode reverse recovery

$$t = t_1 \Rightarrow i(t) = -I_{rm}$$
$$t = t_2 \Rightarrow i(t) = -0.1 I_{rm}$$

Therefore, by solving Equation (4), time constant is equal to:

$$\frac{L}{R} = \frac{1}{\ln 10}\left(t_{rr} - \frac{I_{rm}}{dI_f/dt}\right) \quad (5)$$

For power diodes with soft recovery, Equation (5) can be simplified, because the Reverse Snap-off Factor (RSF) in these diodes is close to one [2], [7]. That means:

$$RSF = \frac{Q_2}{Q_1} = \frac{t_1 - t_0}{t_2 - t_1} \approx 1$$

Therefore, I_{rm} and t_{rr} can be related to Q_{rr} and dI_f/dt as follow:

$$I_{rm} = \sqrt{Q_{rr}\frac{dI_f}{dt}} \qquad t_{rr} = 2\times\sqrt{\frac{Q_{rr}}{dI_f/dt}} \quad (6)$$

Therefore in that case time constant is equal to:

$$\frac{L}{R} = \frac{1}{\ln 10}\left(2\times\sqrt{\frac{Q_{rr}}{dI_f/dt}} - \frac{\sqrt{Q_{rr}\frac{dI_f}{dt}}}{dI_f/dt}\right) = \frac{1}{\ln 10}\sqrt{\frac{Q_{rr}}{dI_f/dt}} \quad (7)$$

A degree of freedom exists between L and R, so the inductance set to a small value that makes V_L negligible compared to forward voltage across diode (e.g., 10pH). Therefore, for K>>1, this inductance acts as a probe measuring dI_f/dt for the controlled current source. R can be calculated from L and time constant, that has been calculated from (7), as follow:

$$R = \frac{L}{\tau} = 10^{-11}\times \ln 10\sqrt{\frac{dI_f/dt}{Q_{rr}}} \quad (8)$$

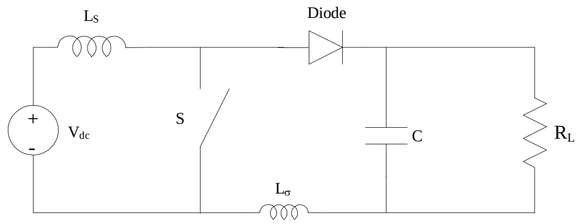

Figure 3: DC boost converter

At $t=t_1^-$ voltage across L is LdI_f/dt, therefore K can be found at this time which reverse current has maximum value:

$$KL\frac{dI_f}{dt} = I_{rm} \Rightarrow$$
$$K = \frac{I_{rm}}{LdI_f/dt} = \frac{1}{L}\sqrt{\frac{Q_{rr}}{dI_f/dt}} = 10^{11}\sqrt{\frac{Q_{rr}}{dI_f/dt}} \quad (9)$$

3 Simulation and Experiment Results

To validate the proposed model, simulation and experimental test have been carried out. Figure 3 shows the circuit used to study diode reverse recovery. The power diode is BYX25, which is 1000 V, 20 A with maximum forward voltage of 1.8 V. The reverse recovery time, t_{rr}, and Q_{rr} are given by the manufacturer.

Computer Simulation for the DC/DC boost converter circuit was conducted for the switching frequency of 10 kHz using PSPICE. Circuit component values that have been used are:

L_s= 8.2mH, C= 10mF, R_L= 25Ω, L_σ=1μH

Figure 4 shows the simulation results of the current and voltage waveforms of the power diode D_1 during the reverse recovery transient. Figure 5 shows the experimental result when the forward current is around 3 A. From this graph it can be seen that total reverse recovery charge is approximately 38 μC, I_{rm} is about 25 A, dI_f/dt is about 30 A/μs when i_f is about 2.5 A.

Comparison of the simulation and experimental waveforms (Figures 4 & 5) shows that the general characteristics are very similar. The only difference is between voltage waveforms. In simulation results the voltage across the diode falls to a value which is even greater than the blocking voltage and then gradually settles to its final value, but experimentally the diode voltage falls to value less than the blocking voltage and recovers back to it. This might be due to not having a realistic IGBT model in the simulation. The current and voltage waveforms of the IGBT found by experiment during turn-on process and when the current is 2.5 A is shown in Figures 6. It will be shown in the next subsection that this difference has little effect on the calculation of power losses.

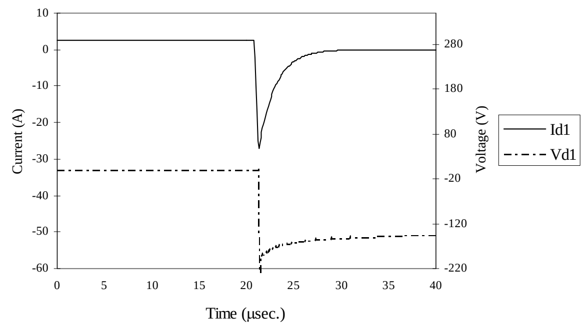

Figure 4: Simulation result: Diode current and voltage waveforms

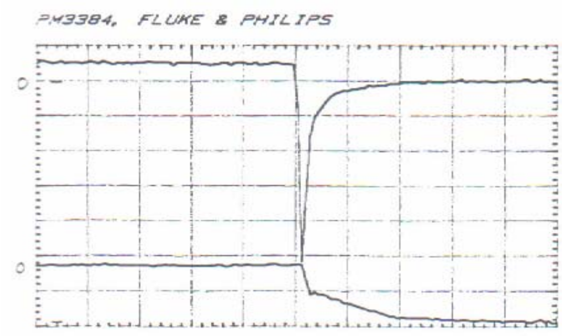

Figure 5: Experimental result: diode current and voltage waveforms during diode turn-off transient (5 A/div 100 V/div & 5 μsec/div)

4 Diode Power Losses

One of the objectives of this paper is to find power losses due to diode reverse recovery in the circuit with different switching frequencies. Using the basic definition of average power in Figure 1 and for one cycle is:

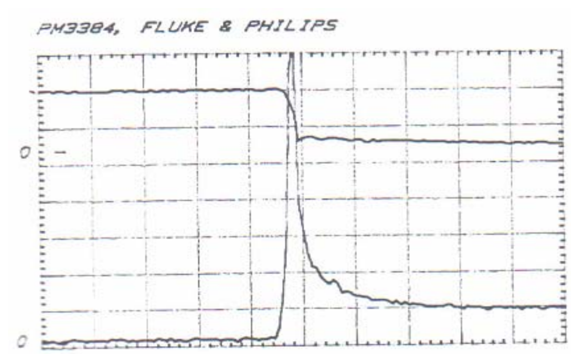

Figure 6: Experimental result: IGBT current and voltage waveforms during switch turn-on transient (2.5 A/div 100 V/div & 2.5 μsec/div)

$$p_{losse} = \frac{1}{T}\int_0^T v_d(t) i_d(t) dt = f_s \int_{t_1}^{t_2} v_d(t) i_d(t) dt \quad (10)$$

Where $i_d(t)$ is given in (1), and $v_d(t)$ is equal to:

$$v_d(t) = -V_r - L_\sigma \frac{di}{dt} = -(V_r + L_\sigma \frac{I_{rm}}{\tau} e^{\frac{-(t-t_1)}{\tau}}) \quad (11)$$

So power losses are equal to:

$$p_{losse} = f_s \int_{t_1}^{t_2} (V_r + L_\sigma \frac{I_{rm}}{\tau} e^{\frac{-(t-t_1)}{\tau}}) I_{rm} e^{\frac{-(t-t_1)}{\tau}} dt \quad (12)$$

$$\int_{t_1}^{t_2} e^{\frac{-(t-t_1)}{\tau}} dt = -\tau(0.1-1) = 0.9\tau$$

$$\int_{t_1}^{t_2} e^{\frac{-2(t-t_1)}{\tau}} dt = -\frac{\tau}{2}(0.01-1) \approx \frac{\tau}{2}.$$

After solving this integration,

$$\begin{aligned} p_{losse} &= f_s(1.1 V_r I_{rm} \tau + \frac{1}{2} L_\sigma I_{rm}^2) \\ &= f_s Q_{rr} (\frac{1.1}{\ln 10} V_r + \frac{1}{2} L_\sigma \frac{dI_F}{dt}) \end{aligned} \quad (13)$$

By using diode parameters and its current, the diode power losses due to reverse recovery can be estimated.

4.1 Estimation of Diode Power Losses

The estimated diode power losses due to reverse recovery in circuit shown in Figure 3 for different switching frequencies by using Equation (13) are given in Table 1. The power losses have also been estimated by simulation for different switching frequencies, which are given in Table 1. This has been calculated by multiplying diodes currents by their voltages to obtain the instantaneous power, and then finding its average for duration of one power cycle.

The measurement of diode power losses by experiment has been done by measurement of currents and voltages in one switching cycle and then calculating the losses as done in the simulation. Unlike estimation by equation (13) and by simulation, which just include power diode losses due to reverse recovery phenomena, the power losses

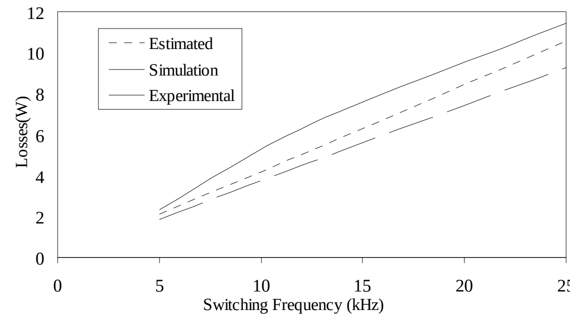

Figure 7: Diode power losses

found by experiment include all power losses in the power diode shown in Figure 3. The total power losses found by experiments for switching frequencies up to 25 kHz for this circuit are also given in Table 1.

Figure 7 shows these power losses for different switching frequencies. The simulation results are less than the estimated results and this may be due to not using a good model for the IGBTs in the simulation.

5 Conclusion

In this paper, a simple model of power diode for reverse recovery transient has been presented and implemented in PSPICE simulator. A major feature of this model is its simplicity and simulation speed compares to other subcircuit models. The model has been verified by comparing experimental and simulation results for power diode used in DC boost converter. Power losses have been predicted for different switching frequencies and compared with simulation and experimental results. The power diode model proposed here provides good performance in accuracy and simulation speed.

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Table 1: Diode power losses for different switching frequencies

	Diode power losses (W)		
Switching Frequency (kHz)	Estimated by (13)	Simulations results	Experimental results
5	2.11	1.85	2.33
12.5	5.25	4.68	6.56
25	10.55	9.27	11.43

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