Teaching low voltage electronics: the case of the rectifier circuit

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Abstract— **This paper highlights some deficiencies of the classical model of the basic rectifier circuit and presents an alternative analytical model for very low voltage operation. The goal is to introduce the model in a course and lab on Electronics Fundamentals.**

I. Introduction

The analysis techniques of nonlinear circuits in introductory textbooks are not appropriate when the available voltages are not larger than a few hundred milivolts. The classical constant-voltage-drop model of the diode, for example, which assumes that the voltage drop in a forward biased diode is, for example, 600 mV, is obviously useless for very low voltage circuits.

A good example of the weakness of the conventional constant-voltage-drop model is the analysis of the diode rectifier of Fig. 1. The formula for the peak value of the diode current presented in some textbooks [1-2] is recalled below for convenience

$$I_P = 2\pi\sqrt{\frac{2V_P}{\Delta V}}I_L \tag{1}$$

where ΔV is the ripple voltage, Vp is the input peak voltage, and I_L is the load current.

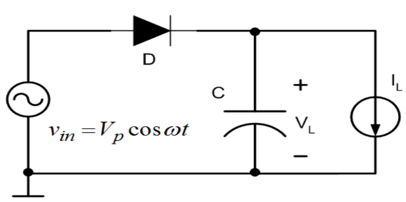

Fig. 1 Half-wave rectifier circuit with a dc current load.

For the limit case of very low ripple ($\Delta V \to 0$), the maximum diode current $I_P \to \infty$ (eq. 1), which is obviously a non physical result, consequence of the constant-voltage-drop model which gives no maximum for the diode current.

Fig. 2 illustrates the steady-state operation of the half-wave rectifier of Fig. 1 for an input peak voltage V_p of 4.5 V for three different (increasing) values of the filtering capacitor and constant load current.

In Fig. 2a the ripple voltage is large (1 V) and the diode behaves as expected in the classical analysis, *i.e.* the peak diode current occurs at the point in which the diode turns on.

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The ripple in Fig. 2b is reduced five times with respect of that in Fig. 2a but we observe only a moderate increase in the peak diode current. The phase difference $\Delta\phi$ between the peaks of input voltage and diode current is reduced when compared to Fig. 2a. Finally, in Fig. 2c, the load voltage is nearly constant and, as a consequence, the peak diode current occurs simultaneously with the peak input voltage, as expected. The maximum diode current has approximately the same value as in case (b). As we can conclude from Fig. 3b-c, for low ripple voltage, the diode peak current is independent of the ripple voltage, in contradiction with Eq. (1).

A rectifier circuit operating with a low ripple voltage was analyzed in a recent paper [3] using the Shockley (exponential) model of the diode and the alternative formula below for the peak diode current was obtained

$$I_P = \sqrt{\frac{2\pi V_P}{n\phi_t}}I_L \tag{2}$$

where n is the slope factor of the diode and ϕ_t is the thermal voltage. By applying Eq. 2 to our example, we obtain I_P=100µA, which is, in good agreement with the simulation results.

II. Half-wave rectifier physical model

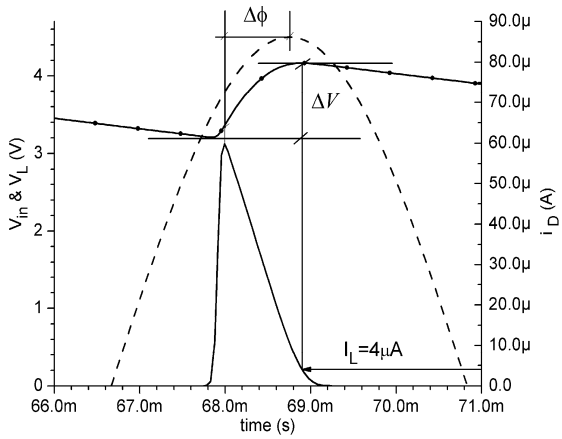
We assume that the value of the load capacitance is such that the output voltage variation is a small fraction of the thermal voltage ϕ_t and that the diode in Fig. 1 is characterized through the Shockley (exponential) model:

$$I_D = I_S\left[\exp\left(\frac{V_D}{n\phi_t}\right)-1\right] \tag{3}$$

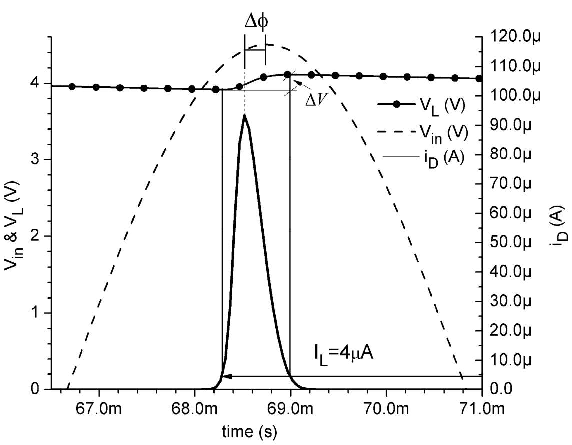
where the diode voltage is $V_D = V_{in} - V_L$.

Under steady state, the average value of the diode current over a complete cycle of the input signal equals the load current. Equation (2) for the peak current follows from the approximation of the diode current waveform by a normal function [3]. The dc output voltage is the peak value of the input voltage minus the diode voltage drop for the peak diode current.

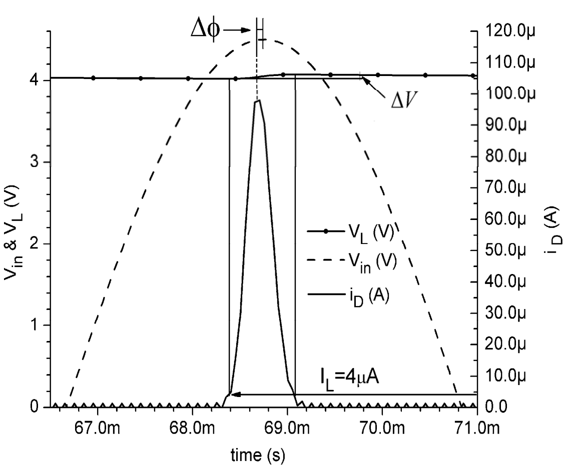
$$V_L = V_P - n\phi_t \ln\left[\left(I_P + I_S\right)/I_S\right] \tag{4}$$



(a)



(b)



(c)

Fig.2. Input and output voltage and diode current of the rectifier of Fig. 1 for, V_P = 4.5 V, f=120Hz and I_L=4μA. The diode parameters are I_S = 4.5 nA and $n\phi_t$ =48.5 mV. (a) C=30 nF, (b) C=150 nF, (c) C=600 nF.

III. Experiment

In order to check the validity of the model, undergrad students have simulated and measured the steady state and transient performance of the half-wave rectifier. For the measurements we have employed off-the-shelf 1N4148 diodes and 470nF capacitors. Figure 3 shows the dependence of the dc output voltage of the half-wave rectifier on the load current, for several values of the magnitude of the sinusoidal wave input. The solid lines represent Eqs. (2) and (4), which, as would be expected, fit very well both the simulated and experimental results.

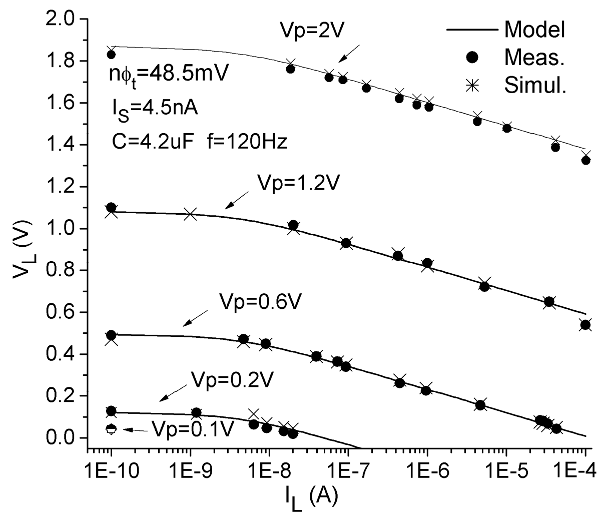


Fig.3 – Output voltage of the half-wave rectifier versus load current

IV. Conclusions

We presented an analytical model of the one-stage rectifier circuit based on the diode Shockley equation valid even for very low voltage operation. Experiments were carried out by undergrad students and we expect to include the experiments in next semester lab of Electronics Fundamentals.

V. Acknowledgment

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References

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