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A Study on Radiation Effects on PWM-IC Controller of DC/DC Power Buck Converter

Young Hwan Lho[1] and Surender Reddy Salkuti[2]

[1] Department of Railroad Electricity System,
Woosong University, Daejeon, Korea
yhlho@wsu.ac.kr, [2]salkuti.surenderreddy@gmail.com

Abstract. The DC/DC switching power converters are commonly used to generate a regulated DC output voltage with high efficiency. The DC/DC converter is composed of a pulse width modulation-integrated circuit (PWM-IC) controller, a metal-oxide semiconductor field effect transistor (MOSFET), an inductor, and a capacitor, etc. The PWM is applied to control and regulate the total output voltage. Radiation has the major influence on the changes in the electrical characteristics of PWM-IC. In PWM operation, the missing pulses and the changes in pulse width are studied by the simulation program with an integrated circuit emphasis (SPICE), Total Ionizing Dose (TID) and Single Event Latch-up (SEL) tests are accomplished and analyzed.

Keywords: DC/DC buck converter, PWM-IC, radiation effects, TID, SEL

1 Introduction

The DC/DC switching power converter [1] shown in Fig. 1 produces DC output voltage from different input sources. The switching power converter uses energy storage elements such as capacitors or inductors to transfer energy from the input to the output at periodic intervals. The ideal DC/DC converter exhibits 100% efficiency, but in practice the efficiency is 70 to 95%. The total input power is dissipated at both metal-oxide semiconductor field effect transistor (MOSFET) and pulse width modulation-integrated circuit (PWM-IC). The power [2] consumed in PWM-IC is computed as follows.

$$P_{pwm} = (I_c + f \times Q_g)V_{in} \tag{1}$$

where I_c is the current of 14 mA flowing in the PWM-IC of SG1525A voltage mode, f is the frequency with a value of 85 Khz, and Q_g is the gate charge with a value of 120 nC for turning-on the MOSFET. The output power is obtained by,

$$P_L = \frac{V_{out}^2}{R_L} \tag{2}$$

The output voltage of an ideal buck converter [1] is given by,

$$V_{out} = DV_{in} \tag{3}$$

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where the duty cycle D is dynamically adjusted by the feedback circuit to keep a stable DC output voltage. Note that D is between 0 and 1, and an output voltage decreases for the buck converter.

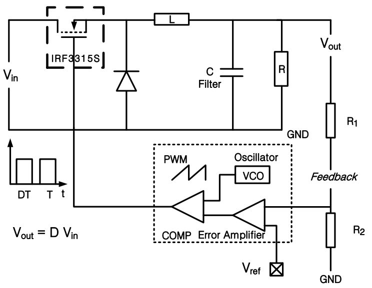

Fig.1. Block diagram of DC/DC Buck Converter.

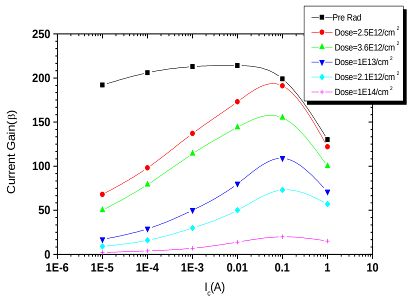

Fig. 2. Current gain (β) vs. collector current (I_c) for different neutron dose

For radiation environments, the current gains of β shown in Fig. 2 at a transistor decrease as neutron dose increases. Commercial devices often have a channel stopper or guard band to provide isolation between the adjacent devices. However, the threshold voltage of power MOSFET of this region is usually not sufficient to prevent the inversion in a radiation environment, and the guard band must be doped heavily enough to prevent the inversion after irradiation.

A simple method for estimating the threshold voltage shift [3] due to the ionizing irradiation of a low dose rate was proposed recently for MOSFET. Briefly, this method estimates the threshold voltage (V_T) shift by the oxide charge trapping at the gate oxide immediately after irradiation.

This paper presents the effects of various kinds of radiations in space environments that can cause the damage of electronic components. It is shown that the reference voltage and the threshold voltage in the electrical characteristics of PWM-IC are varied by the radiation effects in Total Ionizing Dose (TID) test at the low energy γ rays using ^{60}Co at Korea Atomic Energy Research Institute (KAERI) and Single Event Latch-up (SEL) test [4] by using the 4 heavy ions at Texas A&M University Cyclotron Facility, USA.

2 Radiation Effects of PWM-IC

The most common of PWM-IC is to generate periodic waveforms with adjustable duty cycles. PWM-IC also provides optimized features for DC/DC converter as a switching regulator. The PWM-IC block diagram has an additional transistor and two resistors in the left side, which are designed in this paper, to the existing PWM-IC [5] for operating the DC/DC converter. The electrical characteristics of UC2846 PWM-IC have various parameters, the crucial two parameters for operating DC/DC converter are given in Table 1.

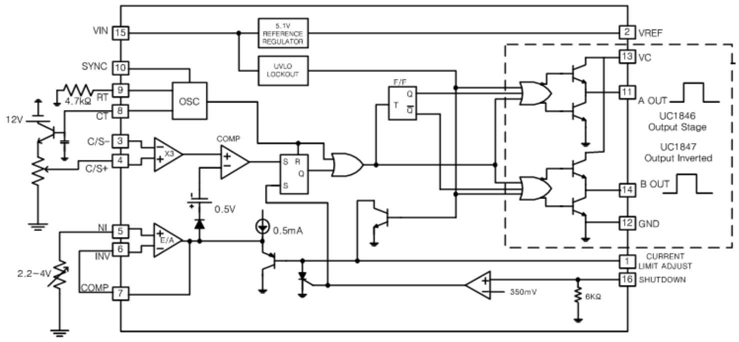

Fig. 3. A PWM IC block diagram with a bipolar transistor.

Table 1. Electrical characteristics of PWM-IC.

PARAMETER	TEST CONDITIONS	UC2846			UNIT
		MIN	TYP	MAX	
Reference Section					
Output Voltage (V_{ref})	TJ = 25℃, I_O = 1mA	5.00	5.10	5.20	V
Shutdown Terminal Section					
Threshold Voltage (V_{th})	-	250	350	400	mV

2.1 Simulation of PWM-IC

The simplified circuit [6] for the simulation of pulse missing transients is designed by using SPICE [7], as shown in Fig. 2. The PWM controller works at a constant input voltage of 10 V and output voltage of 1 V, using a switching frequency of 30 Khz, $D = 0.2$, $V_{th} = 4.0786$ V, $R = 0.2\ \Omega$, $R_F = 10\ \Omega$, and $C_F = 47$ pF. The output current is 5 A. In steady state, the oscillated signal is being connected to the 'AND' gate, then the output is set to the input of R/S flip flop. When MOSFET turns ON, and the inductor is activated due to the voltage, then the currents increase as time goes on. As for the input of comparator, the voltage of 1 V is connected to the input '-' terminal with the voltage reference error, and the output of comparator makes R/S flip flop set. When the voltage of greater than 1 V is applied to the input '+' terminal of comparator, the output of comparator goes to 'high' state, which makes the R/S flip flop be reset and the MOSFET be turned OFF. Then, the inductor current flowing across the diode is in the freewheeling in the loop. The inductor current decays with time constant of 10,000 seconds by $R_L = 10\ \Omega$, and $L = 1$ mH.

When both the input of 's' at R/S flip flop and the output of comparator for the feedback voltage keeping greater than 1 V are 'ON' state, the output of R/S flip flop turns to 'Inhibit' state. In order to prevent all 'High' from 'Q' and 'QB', the 's' terminal of R/S flip flop is set to 0, which is the output of 'AND' gate generated by reversing the output signal of comparator. Delay time is used to prevent 'reset' signal from initiating the output of comparator before the output of 'AND' gate fails to low state. The inductor currents are shown in Fig. 3 through the simulation decay with time constants of about 0.25 ms for 5 missing pulses and about 0.5 ms for 10 missing ones. The more missing pulses lead to the slower decay. When the threshold voltage below 3.0 V produced by V_g is applied to MOSFET, it becomes sensitive to less noise and disturbance than normal, and it easily turns on. It is difficulty in obtaining a steady state constant current since the fluctuation of the output increases.

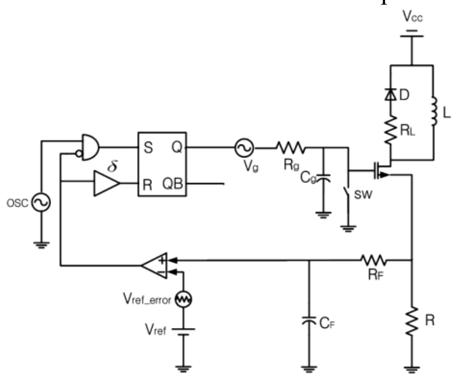

Fig. 2. A simplified PWM-IC block diagram for simulation.

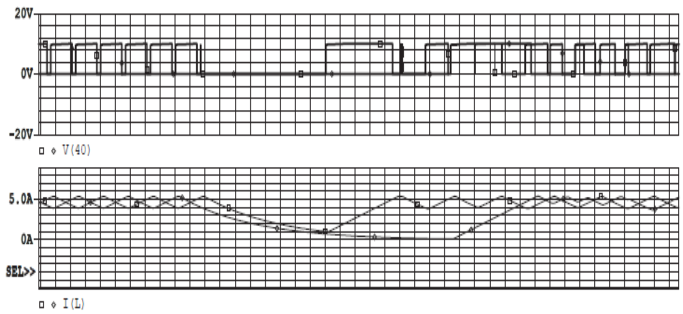

Fig. 3. The gate voltage of MOSFET and the inductor current

for missing pulses ($R = 0.2\ \Omega, V_{ref} = 1V, I_L = 5A$)

2.2 TID Test

A sample size of 6 pieces of PWM-IC [5] is used for each test. The output voltages shown in Fig. 4 of 6 PWM-IC's irradiated to the source using ^{60}Co are satisfied with the electrical specification up to 30 Krad with dose rate of 5 rad/sec, but the threshold voltages represented by Fig. 5, which are a higher value than the criterion, are not met with the specification. The test procedure is followed by MIL-STD-883 Method 1019.

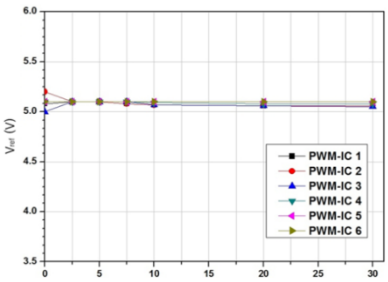

Fig. 4. Output voltage vs. dose

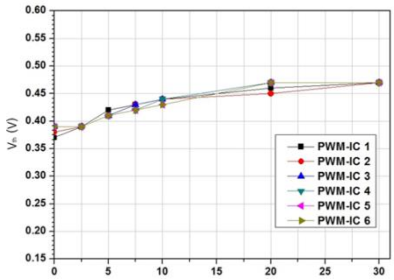

Fig. 5. Threshold voltages vs. dose

2.2 SEL Test

Single Event Effects (SEEs) [8] are caused by a single, energetic particle, and can take on many forms. SEE is classified into Single Event Upsets (SEUs), Single Event Latch-up (SEL), etc. SEUs are soft errors, and non-destructive. Several types of hard errors, potentially destructive, can appear. SEL leads to a high operating current, above the device electrical characteristics.

For the SEL test of PWM-IC, 4 kinds of heavy ions with 15 MeV/u energy at Texas A&M Univ. Cyclotron Facility are used. They are Kr (Initial LET (air) 26.6 (MeV/mg/cm$^{2)}$, LET at Bragg Peak 41.4), Xe (Initial LET 49.3, LET at Bragg Peak 63.4), Ho (Initial LET 66.7, LET at Bragg Peak 79.2) and Au (Initial LET 82.8, LET at Bragg Peak 93.5). The SEL to each heavy ion does not occur within the irradiated duration for reaching within 10% tolerance of normal output value, the corresponding fluence is computed. The evaluation of SEE is usually measured by means of cross section curve. Cross section is defined as the likelihood of the energetic particle interacting with the atoms of material. It reflects the area of the device sensitive to SEE. Linear energy transfer (LET) is a commonly used concept in the SEE evaluation. The cross section versus LET of PWM-IC is obtained as shown in Fig. 6. The equation between cross section and fluence is represented by,

$$\sigma(cm^2) = \frac{1}{fluence} \quad (ions/cm^2)$$

(4) The value of cross section is converged to below 1×10^{-8} (cm^2).

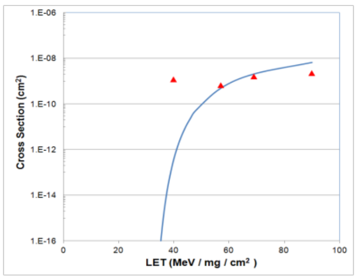

Fig. 6. Cross section vs. LET of PWM-IC（▲: transient capture, LET_{th} = 36 MeV/mg/cm^2)

3 Conclusions

The radiation effects of a designed PWM-IC module were simulated by SPICE, and the phenomena originated from missing pulses and the change of offset voltage at error amplifier is analyzed. The implementation of a macro model of PWM-IC should be considered to prevent the shift of threshold voltage the error voltage, and the missing pulses for obtaining the steady state current. In TID tests, the output voltages and the threshold voltages, two important characteristics of the electrical specifications for 6 PWM-ICs, are experimented for the radiation source using ^{60}Co with dose rate of 5 rad/sec up to total dose of 30 Krad. The output voltages are satisfied with the specifications, but the threshold voltages show a 10 % higher value than the criterion, which are not met with the specifications. It is estimated that SEL tests to get cross section versus LET by using 4 heavy ions at the Cyclotron Facility, which are not available in Korea, are successfully carried out, and the test procedure and method can be contributed to radiation hardening technology in Korean industry fields.

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