Design of DC-DC Converter Kit for Undergraduate Laboratory Experiment

Mohd Ramzi Mat Hasan

Supervisor: Dr. Mohammad Nawawi Seroji

Faculty of Electrical Engineering, MARA University Of Technology

Abstract **-This project deals with the implementation of DC chopper trainer kit. A careful and detail design procedure of the chopper will be documented. Computer simulation will be used extensively to ascertain the workability of the design circuit. Finally, the trainer will be constructed and tested. The trainer can be used for undergraduate laboratory experiment purposes to help student get to know more about chopper by providing a selectable component layout for various of inductor, capacitor and resistor values. Eventually, student will be able to feel and see the concept of chopper. The duty ratio and frequency can be adjusted and rearranged. The value of active components can be compared to the result between the calculation and the simulation.**

I. INTRODUCTION

DC chopper is categorized into three. There are Buck Chopper, Boost Chopper and Buck-Boost Chopper. The main purpose of chopper is to amplify or to chop a DC signal to either reduce or amplify the voltage. Method of implementing chopper is using a component such as inductor, capacitor and resistive load. The process of converting a DC voltage from AC voltage is called converter. However the DC voltage still needs to be converted to desired DC voltage. Hence, the DC-DC converter is used. The idea of inventing the trainer kit module is, to prove and compare between theoretical calculation as well as simulation, to the actual device operations. By having a multiple selection of components, student can [illegible] level of voltage output they desired. There are few benefits that support this project to be implemented:-

1. Available trainer kit cost very expensive to buy.
   This project helps reducing cost to buy a trainer kit
2. Portable and ease to use.
   The design of the project will be based on the portability.
3. A PWM DC-DC converter, transistors are operated as switches. Therefore, the voltage is low when the current is high and the current is zero when the voltage is high, yielding low conduction loss and frequency [1].

II. THE PROPOSED METHODOLOGY

PWM Circuit Design

To get the higher frequency of switching, a proper design of PWM is important. Typical operation for buck, boost and buck-boost use at least 20 kHz. The basic concept of PWM is described in the figure 1 below.

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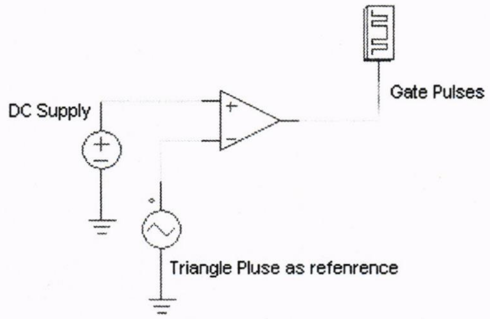

Figure 1.Concept of PWM signal

Referring to figure 1, when a triangle waveform intersects with solid DC line, a result of square wave or pulse is obtained. The waveform of the pulse is described in figure 2. Base on the waveform, the relationship between time and frequency is:

$$\delta = \frac{t_{on}}{t_{on}+t_{off}} \tag{1}$$

$$= \frac{t_{on}}{T} \tag{2}$$

Where:-

δ = duty cycle
t_{on} = on state condition
t_{off} = off state condition
T = total time in one cycle

Figure 2.Typical PWM signal with its T_on and T_off

The Circuit Design

With the increasing of technology there are a lot of choices that can be used as a PWM circuit. One of the Integrated Circuit (IC) will be used is SG3524. This device has all the capabilities to design a PWM. Figure 3 illustrate the functional block diagram of SG3524.

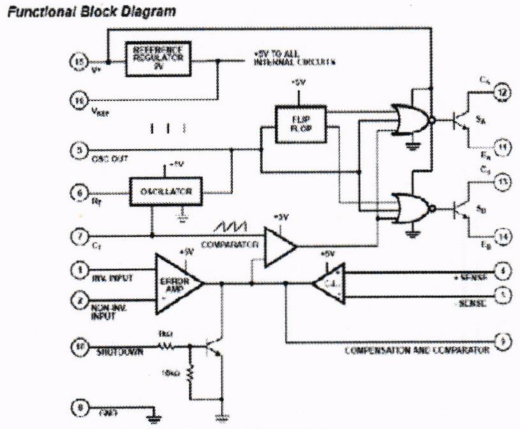

Figure 3.Block diagram for SG3524

The SG3524 is silicon monolithic integrated circuits designed to provide all the control circuitry to use in a broad range of switching regulator circuits. The circuit includes a zener voltage reference, transconductance, error amplifier, precision R-C oscillator, pulse-width modulator, pulse-steering flip-flop, dual alternating output switches, and current-limiting and shutdown circuitry. This device can be used for switching regulators of polarity, transformer-coupled dc-dc converter, transformer less voltage doublers, dc-ac power inverters, highly efficient variable power supplies, and polarity converter, as well as other power-control applications. The circuit that will be constructed must have the ability to vary the duty cycle. The relationship between its frequency adjustments can be described as:

$$f = \frac{1.18}{R_t C_t} \tag{3}$$

The duty ratio can be controlled by using 50kΩ variable resistor as shown in figure below:-

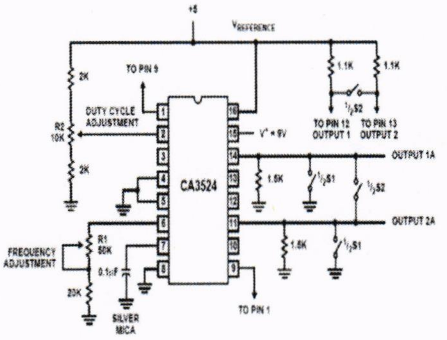

Figure 4.Duty cycle ratio adjustment

The device of PWM IC output signal is not enough to drive the MOSFET. The output voltage of PWM must exceed the operating value of VGS of the MOSFET. Therefore another MOSFET's driver is required to drive the MOSFET. The TC4227 is one of the devices that will be used.

The result of frequency and duty ratio is described table I below:-

TABLE I

MAXIMUM AND MINIMUM FREQUENCY AND DUTY CYCLE OF SG3524

Minimum frequency	$20kHz$
Maximum frequency	100kHz
Minimum duty cycle	7.8%
Maximum duty cycle	95%

III. PROJECT CIRCUIT DESIGN

From the equation 2, the frequency can be varied through the variable resistor and the connection shown in figure 5 below:

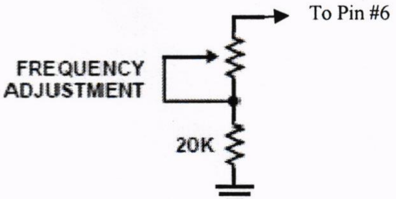

Figure 5.Adjustment for frequency

From equation [1], we have:

$$R_t = 2K\Omega + (0 - 50K\Omega)$$
$$C_t = 1000pF$$

$$f_{max} = \frac{1.18}{2E^3 \times 1000E^{-12}} \left\{ max\ value \right. \qquad (4)$$
$$= 590kHz$$

$$f_{min} = \frac{1.18}{52E^3 \times 1000E^{-12}} \left\{ min\ value \right. \qquad (5)$$
$$= 22.7kHz$$

When compare to experimental value, the results are almost the same as calculation, where the minimum frequency is 20 kHz and maximum frequency is 1000 kHz.

The circuit was constructed through the bread board and being tested at laboratory. Figure 6 below shows the block diagram of the circuit operation

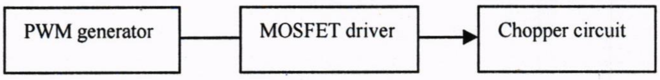

Figure 6.Block diagram of the project

IV. CALCULATION FOR BUCK CHOPPER DESIGN

To design Buck DC-DC converter, we need to calculate the required inductor. Then we have to determine the input capacitor, diode, and MOSFET characteristics. There are four steps to be considered when designing a buck converter.

a. Calculate required inductor value.
b. Calculate output capacitor
c. Diode selection
d. MOSFET.

Minimum Inductor value

Inductor is very important when we want to design a chopper. This component will determine whether we will get the continuous or discontinuous current operation. The circuit is said to be continuous and discontinuous is referred to the current in the inductor: in a discontinuous mode converter, the inductor current goes to zero at some time during the period, while continuous not. [2]
The value of output voltage was determined by the following derivation:

Assume:-

$$Vin = 12vdc$$
$$Vout = 6vdc$$
$$R_L = 1K\Omega$$
$$frequency = 200kHz$$
$$Duty\ cycle, \delta = 0.5$$

$$V_L = V_{in} - V_o \qquad (6)$$

$$\frac{d(I_L)}{dt} = \frac{V_{in}-V_o}{L} \qquad (7)$$

$$\int_{I_{L\_min}}^{I_{L\_max}} d(I_L) = \frac{V_{in}-V_o}{L} \int_0^{t_{on}} dt \qquad (8)$$

$$I_{L\_min} - I_{L\_max} = \frac{(V_{in}-V_o)}{L} \qquad (9)$$

$$V_L = -V_o \qquad (10)$$

$$\frac{d(I_L)}{dt} = \frac{-V_o}{L} \qquad (11)$$

$$\int_{I_{L\_max}}^{I_{l\_min}} d(I_L) = \frac{-V_o}{L} \int_0^{t_{off}} dt \qquad (12)$$

$$I_{L\_min} - I_{L\_max} = \frac{-V_o t_{off}}{L} \qquad (13)$$

$$I_{L\_max} - I_{L\_min} = \frac{V_o t_{off}}{L} \qquad (14)$$

$$\frac{(V_{in}-V_o)}{L} = \frac{V_o t_{off}}{L} \qquad (15)$$

$$V_o = \delta V_{in} \qquad (16)$$

To avoid a discontinuous operation a value of inductor is determined with this equation:

$$I_{dc} = \frac{I_{Lmax}+I_{Lmin}}{2} \quad (17)$$

$$I_{Lmax} + I_{Lmin} = 2I_{dc} \quad (18)$$

When discontinuous current operation, $I_{Lmin} = 0$ and the equation become:-

$$I_{Lmax} = 2I_{dc} \quad (19)$$

And,

$$I_{Lmax} = \frac{(V_{in}-V_o)t_{on}}{L} \quad (20)$$

Equating equation [15] and [16], resulting:

$$L_{critical} = \frac{(V_{in}-V_o)t_{on}}{2I_{dc}} \quad (21)$$

Buck discontinuous conduction mode analysis

If the output loads current is reduced below the critical current level, the inductor current will be zero for a portion of the switching cycle. This should be evident from the waveforms shown in Figure 8b since the peak to peak amplitude of the ripple current does not change with output load current. In a (non-synchronous) buck power stage, if the inductor current attempts to fall below zero, it just stops at zero and remains there until the beginning of the next switching cycle. This operating mode is called discontinuous conduction mode. A power stage operating in discontinuous conduction mode has three unique states during each switching cycle as opposed to two states for continuous conduction mode.

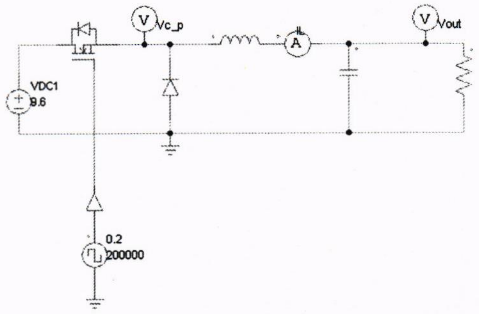

Figure 7.Vc_p is the voltage pulses during discontinuous mode

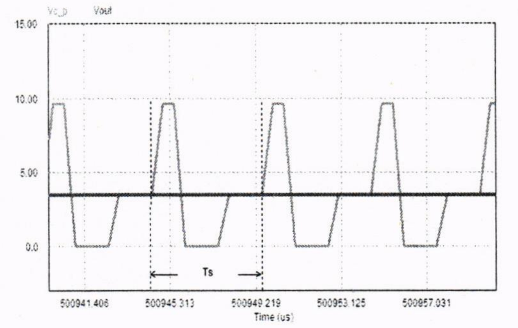

Figure 8a.The relationship between Ts and discontinuous waveform

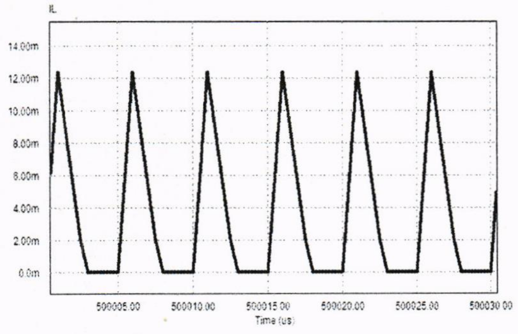

Figure 8b.The discontinuous current mode

The load current condition where the power stage is at the boundary between continuous and discontinuous mode is shown in Figure 8b. This is where the inductor current falls to zero and the next switching cycle begins immediately after the current reaches zero. Further reduction in output load current puts the power stage into discontinuous conduction mode. This condition is illustrated in Figure 8a. The discontinuous mode power stage frequency response is quite different from the continuous mode frequency response and is shown in the Buck Power Stage Modeling section. Also, the input to output relationship is quite different. The discontinuous conduction mode buck voltage conversion relationship is given by:

$$V_o = V_i \times \frac{2}{1+\sqrt{1+\frac{4K}{D^2}}} \quad (22)$$

Where K is defined as:

$$K = \frac{2\times L}{R\times T_s} \quad (23)$$

The above relationship shows one of the major differences between the two conduction modes. For discontinuous conduction mode, the voltage conversion relationship is a function of the input voltage, duty cycle, power stage inductance, the switching frequency and the output load resistance while for continuous conduction mode; the voltage conversion relationship is only dependent on the input voltage and duty cycle. It should be noted that the buck power stage is rarely operated in discontinuous conduction mode in normal situations, but discontinuous conduction mode will occur anytime the load current is below the critical level.

Output Capacitor

The voltage ripple across the output capacitor is the sum of ripple voltages due to the Effective Series resistance (ESR), the voltage sag due to the load Current that must be supplied by the capacitor as the inductor is discharged and the voltage ripple due to the capacitor's Effect Series Inductance". The ESL specification is usually not specified by the capacitor vendor. For this example, we will assume that the ESL value is zero. The capacitor ESR value was selected from a vendor's catalog of rated capacitors.

Diode

The diode's average current is equal to the load current times the portion of time the diode is conducting. The time the diode is on is: (1 – duty cycle). The maximum reverse voltage on the diode is V_in which is 12 volts in this example. The current and voltage ratings are low enough that a small diode can be used for this application. The forward voltage drop for the selected diode is about 0.7 volts. The estimated diode power dissipation is 0.47 watts.

MOSFET

In the battle between MOSFETs and IGBTs, either device can be shown to provide the advantage in the same circuit, depending on operating conditions. The best approach is to understand the relative performance of each device. MOSFET provides the longest battery life while meeting all peak-performance levels and usually at a lower cost. IGBT mostly selected due to its capability to handle high voltage across it. In this project, MOSFET was chosen because its capability of handling high frequency compared to IGBT that can only handled up to 10 kHz.

V. ANALYSIS RESULT

The results were obtained based on the calculation, simulation as well as actual. Table II and III shows the data being compared.

TABLE II
OUTPUT VOLTAGE FOR A CERTAIN INDUCTOR VALUE AND DISCONTINUOUS CURRENT MODE (DCM)

Inductor value = 0.5mH			
Duty Ratio	Output Voltage		
	Calculation	Simulation	Actual
0.2	4.2990	3.2923	3.4000
0.4	6.9575	5.5565	5.0000
0.6	8.5865	7.2000	6.2000
0.8	9.6000	9.6000	7.6000

TABLE III
OUTPUT VOLTAGE FOR A CERTAIN INDUCTOR VALUE AND CONTINUOUS CURRENT MODE (CCM)

Inductor value = 1.5mH			
Duty Ratio	Output Voltage		
	Calculation	Simulation	Actual
0.2	2.40000	2.39989	N/A
0.4	4.80000	4.80019	N/A
0.6	7.20000	7.20072	N/A
0.8	9.60000	9.59972	N/A

TABLE IV
OUTPUT VOLTAGE FOR A CERTAIN INDUCTOR VALUE AND CONTINUOUS CURRENT MODE (CCM)

Inductor value = 2.5mH			
Duty Ratio	Output Voltage		
	Calculation	Simulation	Actual
0.2	2.40000	2.4	N/A
0.4	4.80000	4.8	N/A
0.6	7.20000	7.2	N/A
0.8	9.60000	9.6	N/A

Table II vs. III and IV are both shown the different output voltage value. The value of actual for inductor value 0.5mH is slightly different from simulation due to hardware limitation and circuit design. At the same time the calculation for table II also show a little different from simulation. The calculation for DCM inductor value is using equation 22 and 23. On table III and IV, the calculation and simulation are almost equal.

The Results of laboratory experiment is shown in the figure (9-18) below.

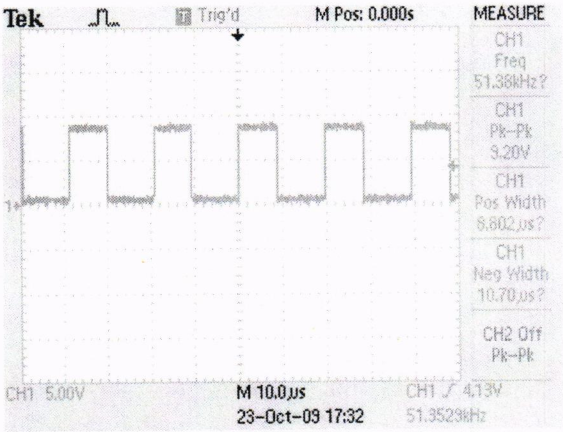

Figure 9.PWM without MOSFET driver and Low duty cycle

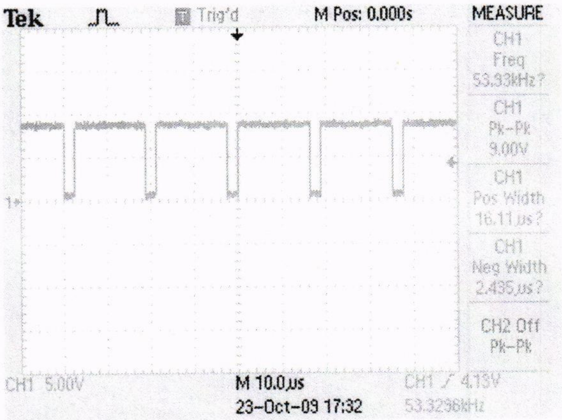

Figure 10.PWM without MOSFET driver and High duty cycle

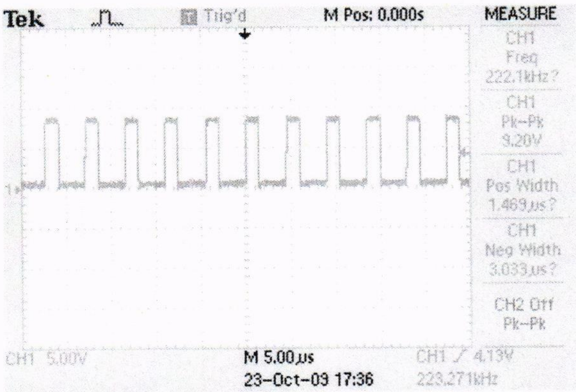

Figure 11.PWM with MOSFET driver and Low duty cycle

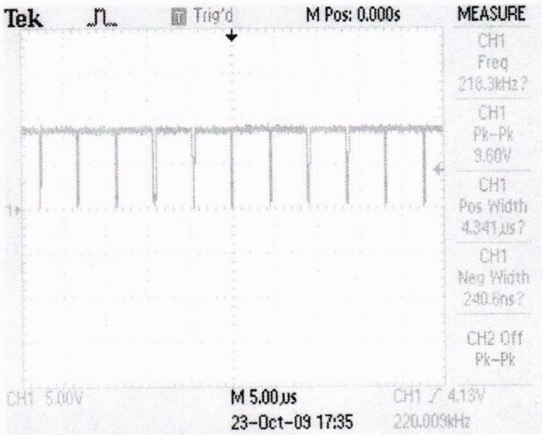

Figure 12.PWM with MOSFET driver and High duty cycle

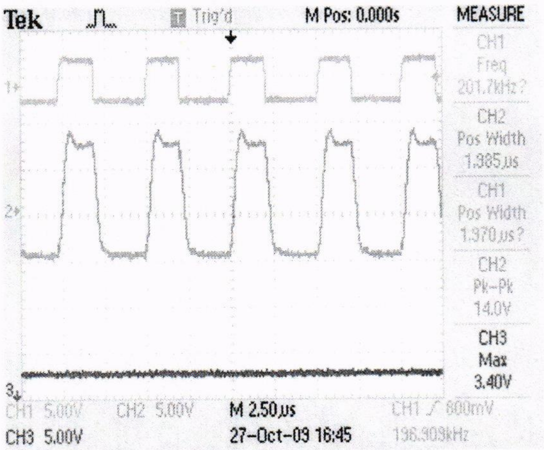

Figure 15.Buck Chopper with L=0.5mH and Duty cycle 0.2

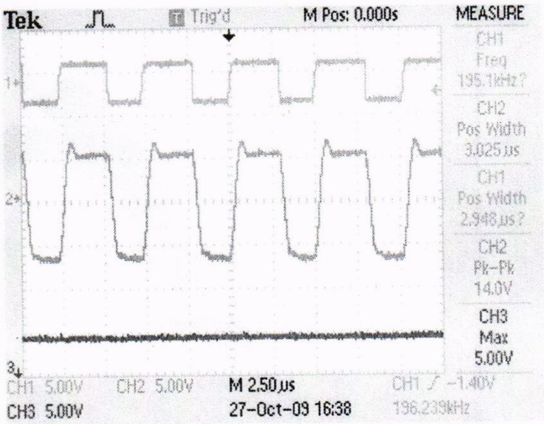

Figure 16.Buck Chopper with L=0.5mH and Duty cycle 0.4

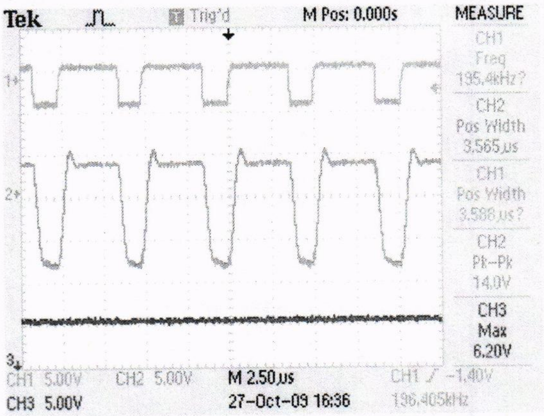

Figure 17.Buck Chopper with L=0.5mH and Duty cycle 0.6

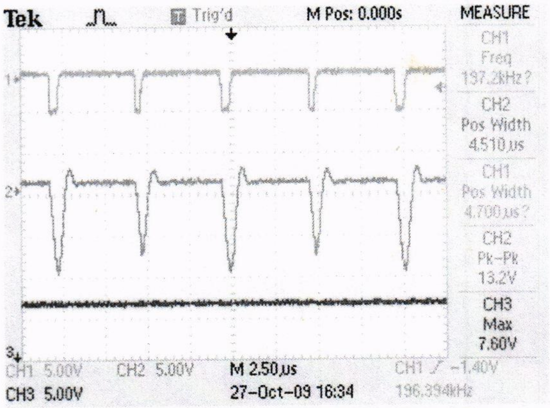

Figure 18.Buck Chopper with L=0.5mH and Duty cycle 0.8

VI. CONCLUSION

The results were obtained in laboratory are not same with simulation due to equipment boundary and the apparatus of component layout. The circuit is very sensitive to noise as the PWM signal has an error during the laboratory test. Therefore a proper construction of circuit design is essential to avoid noise and error. Both simulation and test are not using closed loop system, but use open loop system. The settling time for buck design can be shorter and will be finalize in later project progress. A complete hardware assembly will be constructed within a month based on the successful result obtained and will be presented during submission of project. Even though the results are not the same as simulation, the hardware of PWM is very successful to construct, hence achieving the target of laboratory kit design.

I. REFERENCES

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