DC-DC CONVERTERS

1. DC-DC Converters

1.1. Purpose of Experiment

Observing the behaviors of the circuits of DC-DC voltage reducing converter (buck converter) and DC-DC voltage increasing converter (boost converter). In this experiment, the steady state behaviors of the voltage reducing and the voltage increasing converter circuits will be observed. The results of the variation in load on the circuit with the effect of pulse width on the output voltage and the effect of switching frequency on the converter's efficiency will be observed. If it is necessary, the switching characteristics of the MOSFET and the diode which are used as switching elements may be observed again on these circuits.

1.2. Theory

DC-DC converters are used commonly in industry. They are used for;

-sometimes directly and adjustable voltage power supply,

- providing any dc voltage level for any application,
- matching the impedances of two consecutive stages,

There are DC-DC converters which make switching at the frequencies of kHz and the levels of 1W-a few hundreds of watts in the market.

1.3. Steady State Analyze of The Voltage Reducting Converter

In the Figure 1, the circuit scheme of a typical single-transistor voltage reducing converter (buck converter) is shown.

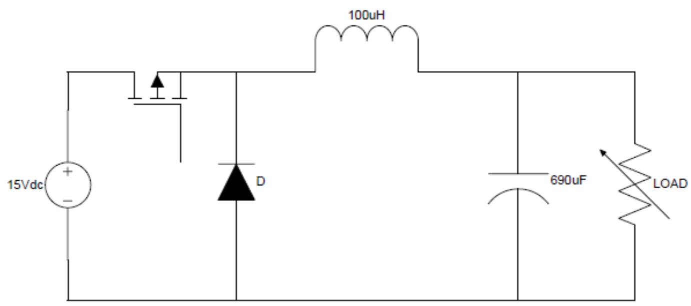


Figure1. Buck converter circuit

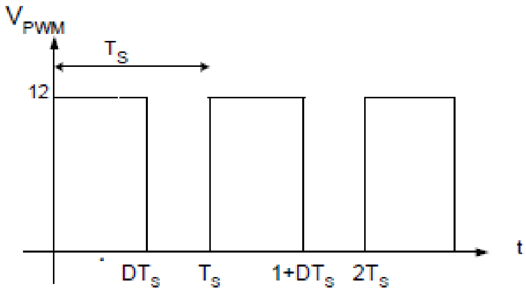
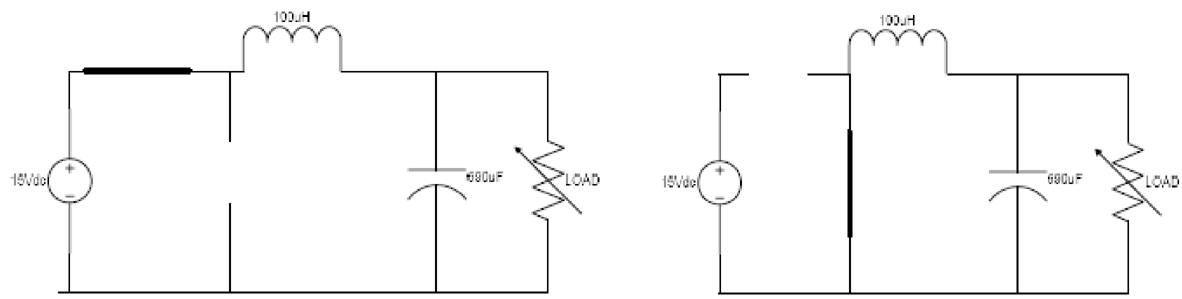


Figure 2. PWM waveform

As it seen, there are two switches in the circuit one of which is controlled (MOFSET) and one of which is uncontrolled (diode). A constant-frequency PWM signal which has an adjustable pulse width is being applied to the gate-source terminal of the MOSFET as it seen in the figure 1. During the DTs of this signal (namely, the duration while the pulse is applied) the transistor is conducting; during the remaining time which is shown with (1-D)Ts, the diode is conducting.

This state causes the circuit to work in two different modes and show a nonlinear structure. Now we can find the relation between the input and output voltages of the voltage reducing converter by observing these different two modes of the circuit.



(a) Mode 1 **(b)** Mode 2

Figure 3. Working modes of buck converter

In the figure 3a, the state of the converter, when the transistor is on and the diode is off, is shown. Because the transistor is on, it is shown as short circuit and because the diode is off, it is shown as open circuit.

As it seen in the figure, in mode 1, inductor is connected between directly output and input. In this case, in this mode, the voltage between the terminals of the inductor is equivalent to the difference between the input voltage and the output voltage.

$$V_L = V_g - V \tag{1}$$

If we look at the mode 2 state in the Figure 3b, we see that the transistor is off and the diode is on. In this case, we observe a reverse polarized voltage over the inductor which is equivalent to the output voltage.

$$V_L = -V \tag{2}$$

In this case, the wave form of the inductor will be as it shown in the Figure 4.

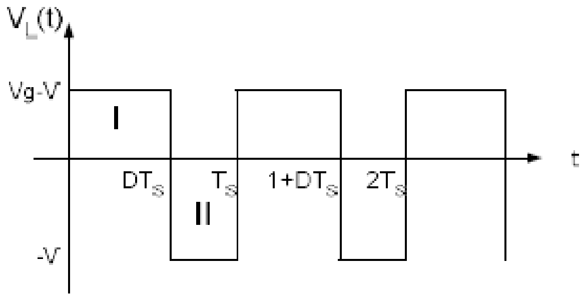


Figure 4. Variation of inductor voltage

Now, we know the voltage values of the coil at two modes. In this case, we can find a relation between input and output. At a steady state stable system, during one switching period, the net variation of the inductor current is zero. This is known as inductor volt-second balance. According to this, we can write the expression below.

$$V_L(t) = L\frac{di_L(t)}{dt}$$

$$[i_L(t)]_0^{T_s} = \frac{1}{L}\int_0^{T_s} V_L(t)dt \Rightarrow i_L(T_s) - i_L(0) = \frac{1}{L}\int_0^{T_s} V_L(t)dt \tag{3}$$

Here, Ts expresses one switching period and as we have said above, during one switching period, the current variation is zero. The left side of the last equation expresses the difference between the first and the last current values of a switching period, namely, the change of the current during one switching period. Consequently, it is zero and we obtain the equation below, which requires that the left side of this equation must be zero.

$$\frac{1}{L}\int_0^{T_s} V_L(t)dt = 0 \Rightarrow \int_0^{T_s} V_L(t)dt = 0 \tag{4}$$

This equation expresses clearly that the total area under the wave form of the inductor voltage which are shown as I and II in the Figure 4 is zero. According to this;

$$\int_0^{T_s} V_L(t)dt = (V_g - V)DT_s + (-V)(1-D)T_s = 0$$

$$V_gDT_s - VDT_s - VT_s + VDT_s = 0 \tag{5}$$

$$V = DV_g$$

As you see, we have found the relation between input and output voltages by using the principle of inductor volt-second balance. Here, D is the pulse width value (duty cycle) and varies between 0 and 1.

But, it is known that this result is obtained by making some assumptions and approximations. These assumptions accept the circuit as ideal. For example, in both modes, while writing the inductor voltage equation, we assume that the voltage drop over the transistor and the diode is zero, namely, we do not consider them. Also, as the transistor in mode 2 is off, the source at the input does not supply the circuit, namely, the output circuit flow its current, accordingly its energy, in itself. As the load does not take energy from the source in this mode, it takes its energy from the energy stored in capacitor and inductor. Therefore, there will be decreases in the currents and the voltages of these elements whose energy has decreased. Then, when the circuit comes back to mode 1 again, the source will be connected to the circuit and it will start transferring energy over transistor to load. Therefore, the energy of the capacitor and the inductor will increase and respectively their voltage and the currents will increase. Namely, when we write the equations of both modes, we assume the output voltage as a stable value V. However, the output voltage is a value shown as $V + v(t)$ and swinging between $V + \Delta V$ and $V - \Delta V$ because of the energy transfers of the capacitor that we have said shortly before. Therefore, by taking V value, we assume that the ΔV swing is quite low with respect to V average value and it can be ignored.

Lastly, another important parameter for us is the inductor current. Because as it is seen in the circuit, the continuity of the load current is provided by the inductor. The total current of the capacitor and the load gives us the inductor current. Since the coil is an element which transfers energy continuously to the circuit, there will be variations in its current. The levels of these swings can be calculated when the voltages to which the coil exposed in each mode.

$$V_L(t) = L\frac{di_L(t)}{dt} \Rightarrow \frac{V_L(t)}{L} = \frac{di_L(t)}{dt} \tag{6}$$

Here $di_L(t)/dt$ gives us the expression of the coil current's curve. Namely, while the coil in mode 1 increases during DT_s with the curve of $(V_g - V)/L$, in mode 2 it decreases with the curve of $-V/L$. This variation is shown in the figure 5.

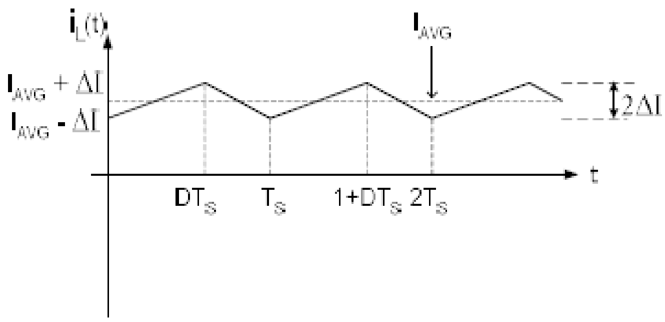


Figure 5. Variation of inductor current

1.4. Steady State Analyze of The Voltage Increasing Converter (STEP UP)

In the Figure 6, the circuit scheme of a typical single-transistor voltage increasing converter (boost converter) is shown. In this circuit, as it is in the voltage reducing converter circuit, there is a MOSFET and a diode as switches. The MOSFET is driven by a constant-frequency PWM signal again.

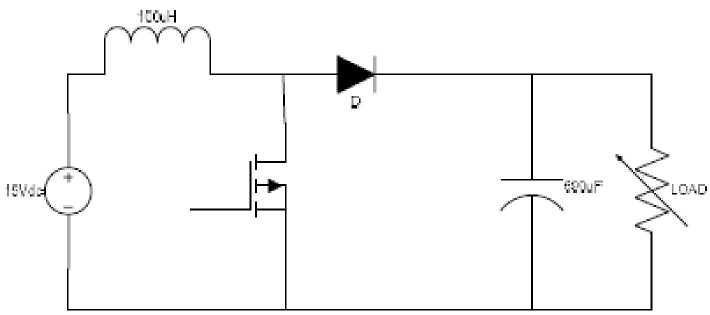
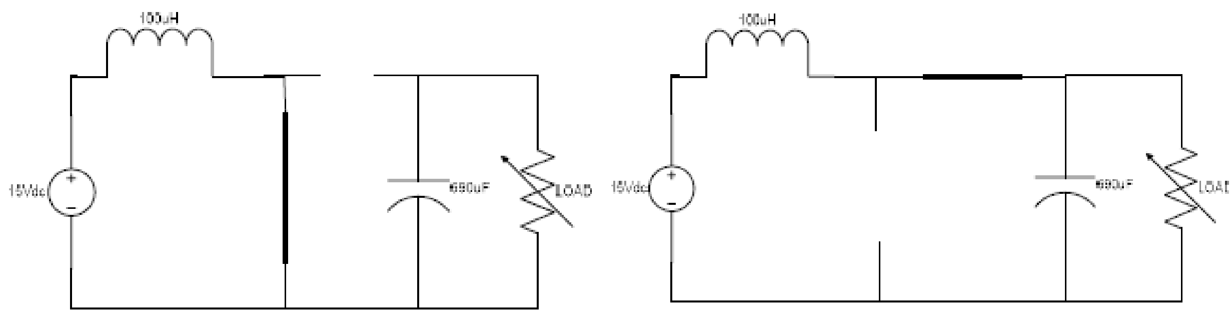


Figure 6. Boost converter circuit

This circuit is also composed of two modes according to the conduction of the diode and the transistor. These modes are shown in the Figure 7a-b.



(a) Mode 1 **(b)** Mode 2

Figure 7. Working modes of boost converter

As we did in the voltage reducing circuit, we mode 1 the circuit by considering the coil voltage and so we obtain the relation between the output and the input voltages. In mode 1, when the transistor is on and the diode is off, coil is directly connected to the ground through the transistor. Therefore, the input voltage over it can be seen as it is.

$$V_L = V_g \tag{7}$$

In mode 2, the transistor is off and the circuit is transferring energy to the output through the diode. In this case, the coil voltage is equivalent to the difference between input and output voltages.

$$V_L = V_g - V \tag{8}$$

With reference to this, the voltage between the terminals of the coil is shown in the Figure 8. We can find the expression of input-output voltage by applying the principle of inductor volt-second balance to the voltage increasing converter. As we explained in the previous part, for the principle of the volt-second balance,

$$\int_0^{T_s} V_L(t)dt = 0 \tag{9}$$

Must be provided. This is again the total area under the wave form of the inductor voltage.

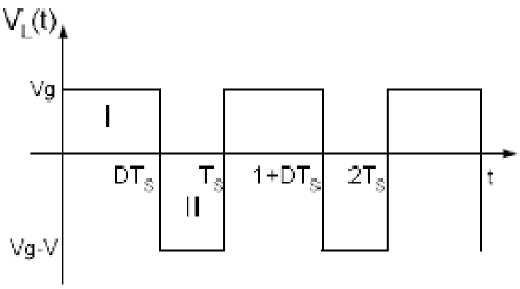


Figure 8. Variation of inductor current

$$\int_0^{T_s} V_L(t)dt = V_g DT_s + \left(V_g - V\right)(1-D)T_s = 0$$

$$V_g DT_s + V_g T_s - VT_s - V_g DT_s + VDT_s = 0 \tag{10}$$

$$V = \frac{V_g}{1-D}$$

Similarly, we can calculate the curve of the coil current with voltages. With reference to this, in mode 1, the coil current will increase with the curve of V_g/L and in mode 2, it will decrease with the curve of $\left(V_g - V\right)/L$This state is shown in the Figure 9.

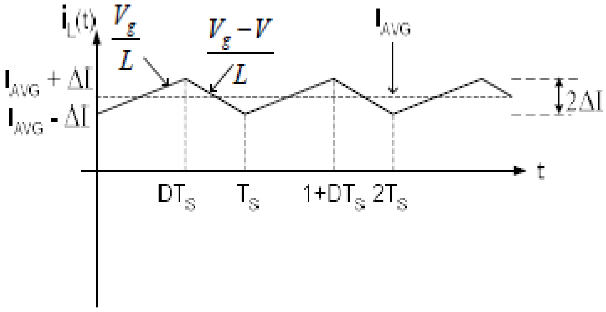


Figure 9. Variation of inductor current

2. The Conduct of Experiments

2.1. Buck Converter

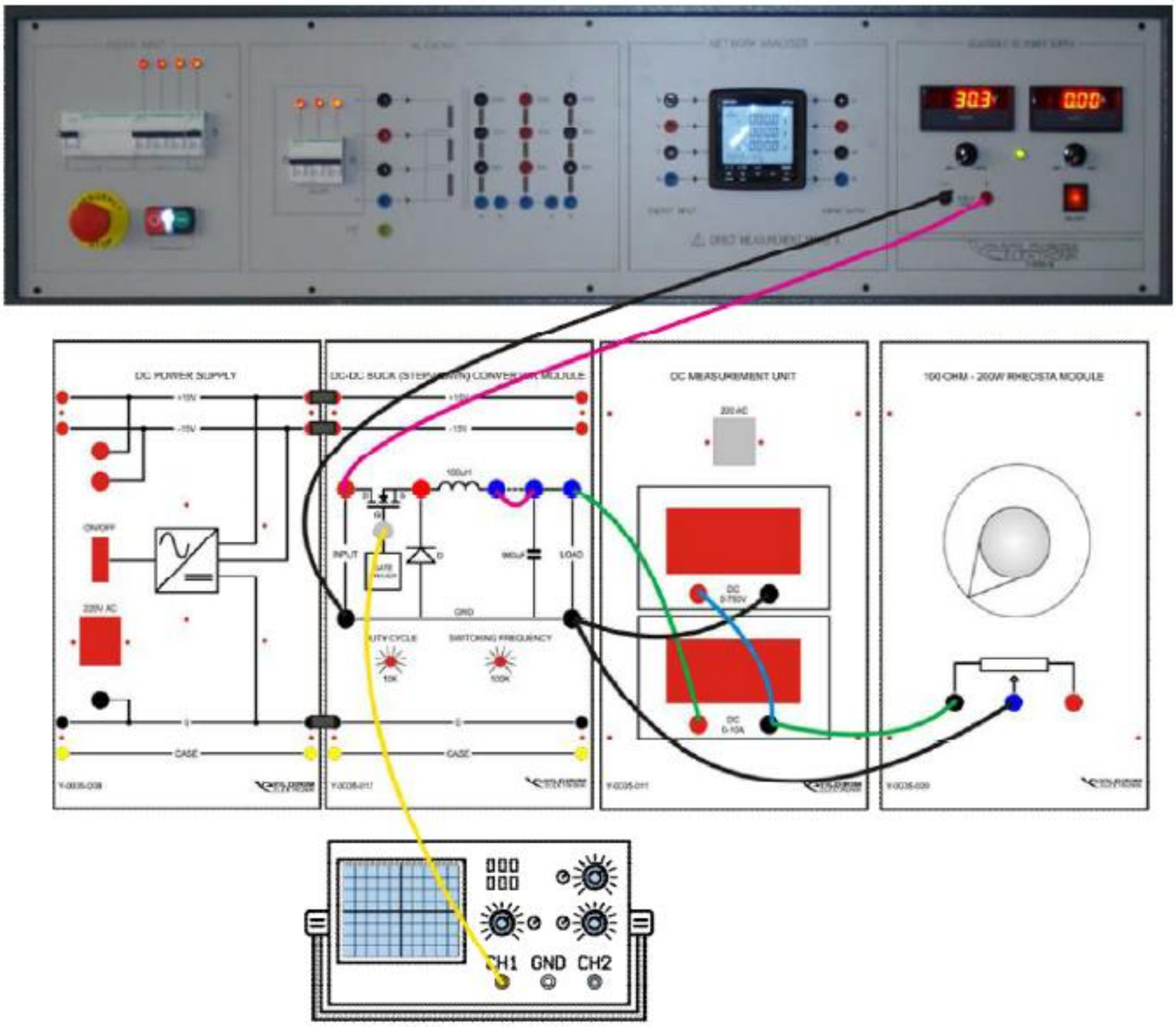


Figure 10. Wiring diagram for buck converter

2.1.1. Pulse Width Effect

1. Connect the circuit in the Figure 10. Adjust the rheostat, which you connect as the load, to 100 Ω. After controlling the connections, apply the energy to the circuit.
2. After connecting the load, by starting the power supply which you have connected to the input of the converter, adjust the input voltage to 15 V.
3. With the same way, adjust the switching frequency to 50 kHz by using "switching frequency" pot.
4. Calculate the average value of the output voltage in each step while changing the pulse width from 0.1 to 0.9 with 0.2 units changing in each step. For the values of $D = 0.1$ $D = 0.5$ and $D = 0.9$, by observing the fluctuation over the inductor current and the output voltage from the oscilloscope, sketch the waveforms.

2.1.2. Switching Frequency Effect

1. In addition to the circuit shown in Figure 10, before entering the coil output, that is, the ammeter, enter the current measuring end of the oscilloscope measuring unit and then connect the ammeter. So, we can observe the coil current on the oscilloscope. After checking the connections, energize the circuit.
2. Turn on the power supply you have connected to the input of the converter and set the input voltage to $15\ V$.
3. Adjust the pulse width to 0.5.
4. Look through the oscilloscope and set the switching frequency to $40\ kHz$, $60\ kHz$, $80\ kHz$ and $100\ kHz$ using the "switching frequency" pot. Draw the coil current waveform. Take the necessary measurements.

2.1.3. Load Effect

1. Adjust the rheostat that you will connect as a load to $10\ \Omega$ without making any changes in the previous connections. After checking the connections, energize the circuit.
2. Turn on the power supply you have connected to the input of the converter and set the input voltage to $15\ V$.
3. Adjust the switching frequency to $100\ kHz$ and the pulse width to 0.5.
4. In this case take the first measurements.
5. Then set the rheosta to $50\ \Omega$ and $100\ \Omega$ and take similar measurements.

2.2. Boost Converter

2.2.1. Pulse Effect

1. Connect the circuit in the Figure 11 Adjust the resistance of the rheostat, which you have connected as the load, to $100\ \Omega$ ohm. By controlling the connections, apply the energy to the circuit.
2. Adjust the input voltage to $5\ V$.
3. Look through the oscilloscope and set the switching frequency to $50\ kHz$, using the "switching frequency" pot.
4. Look through the oscilloscope and change the pulse width from 0.1 to 0.9 in 0.2 steps and take the necessary measurements at each step. For $D = 0.1$, $D = 0.5$ and $D = 0.9$ values, observe the square wave signal at the gate entrance on the oscilloscope and draw the waveforms.

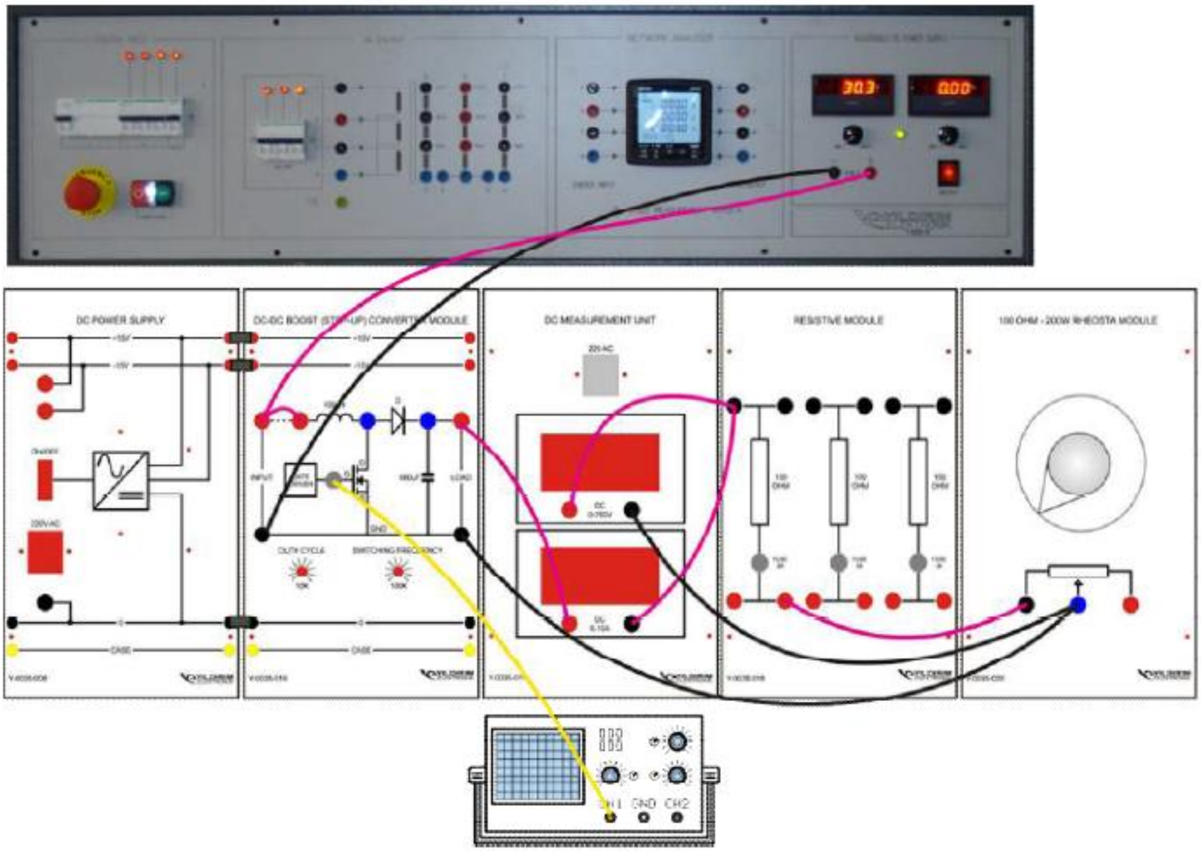


Figure11. Wiring diagram for boost converter

2.2.2. Switching Frequency Effect

1. In addition to the circuit shown in Figure 11, enter the coil input, that is, the current measuring end of the oscilloscope measuring unit after the positive terminal of the source, and then connect the coil. So, we can observe the coil current on the oscilloscope. After checking the connections, energize the circuit.
2. Turn on the power supply you have connected to the input of the converter and set the input voltage to $5\ V$.
3. Set the pulse width to 0.5.
4. Look through the oscilloscope and set the switching frequency to $40\ kHz$ using the "switching frequency" pot. Draw the coil current waveform. Take the necessary measurements.
5. Repeat the same operations for $60\ kHz$, $80\ kHz$ ve $100\ kHz$.

2.2.3. Load Effect

1. Adjust the rheostat that you will connect as a load to $10\ \Omega$ without making any changes in the previous connections. After checking the connections, energize the circuit.
2. Turn on the power supply you have connected to the input of the converter and set the input voltage to $5\ V$.

3. Set the pulse width to 0.5 and the switching frequency to $100\ kHz$
4. In this case, take the first measurements.
5. Then set the rheostat to $50\ \Omega$ and $100\ \Omega$ and take similar measurements.