Experiment # 6

Step-Up (Boost) and Step-Down/Up (Buck-Boost) Converters

Objectives

- Understanding the PWM technique used to control a Step-up and Step-down/Step-up converters
- Understanding the principle of operation of a Step-up and Step-down/Step-up converters
- Measuring and interpreting various parameters of the Step-up and Step-down/Step-up converters and validating the relationship between output and input parameters

Components and Accessories

1	735 65	Rectifier B6 3X400V, 10A
1	735 09	Load, Power Electronics
1	735 18	Fuse, Three-Fold, Super fast
1	735 095	Capacitor, 2 X 1000 µF / 385 V
1	735 341	Control Unit PWM; PFM
1	734 02	Setpoint Potentiometer
1	735 342	Field-effect transistor MOSFET
1	735 346	IGBT
1	735 02	Diode
1	537 34	Rheostat 100 Ohm
1	537 35	Rheostat 330 Ohm
1	726 80	Transformer 45/90, 3N
1	726 86	Stabilized power supply ± 15V/3A
2	501 02	BNC cable, 1 m
2	727 10	RMS Meter
1	524 013S	Sensor-CASSY 2 – Starter
2	500 59	Safety bridging plugs, black, set of 10
1	500 851	Safety connecting leads, 32 A, set of 32
1	500 852	Safety connecting leads, yellow/green, set of 10
2	500 59	Safety bridging plugs, black, set of 10

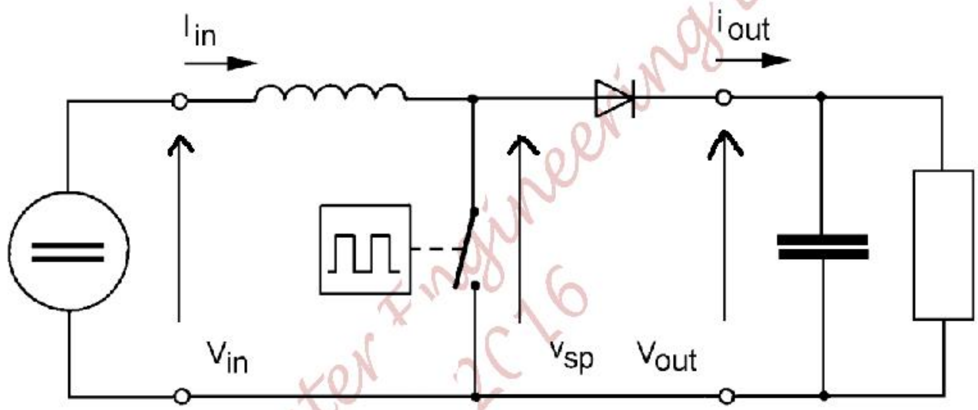
Theory

- **Step-Up (Boost) Converter**

As its name implies, the step-up converter transfers DC power from a source of a low direct voltage to a load requiring a higher direct voltage. This load can be ohmic, whose voltage is based on the operating data of the DC chopper. The circuit is examined with an ohmic load in Pulse Width Modulation (PWM).

In this experiment, the recommend maximum frequency for the MOSFET is 10kHz for ohmic load, and for the IGBT the recommended maximum frequency is 5kHz.

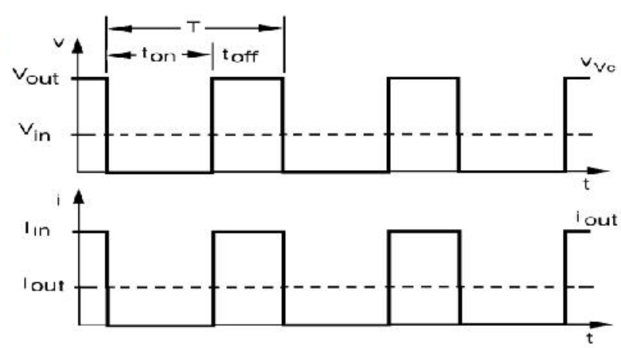
Step-Up Converter Circuit Layout



The significant variables are represented in the waveforms of the Figure next. The following applies:

1st section, t_{on}: $v_{Vc} = 0$; $i_{out} = 0$

2nd section, t_{off}: v_{Vc} = Vout; $i_{out} = I_{in}$



The direct input voltage V_{in} = the direct component of the curve V_c (t), as a pure alternating voltage drops across the reactor.

$$V_{in} = (V_{out} \cdot t_{off}) / T = V_{out} \cdot (T - t_{on}) / T$$

$$\mathbf{V_{out} = V_{in} \cdot T / (T - t_{on})}$$

⇨ $$\mathbf{V_{out} = V_{in} / (1 - k)}$$

Where k is the duty cycle; $k = t_{on} / T$

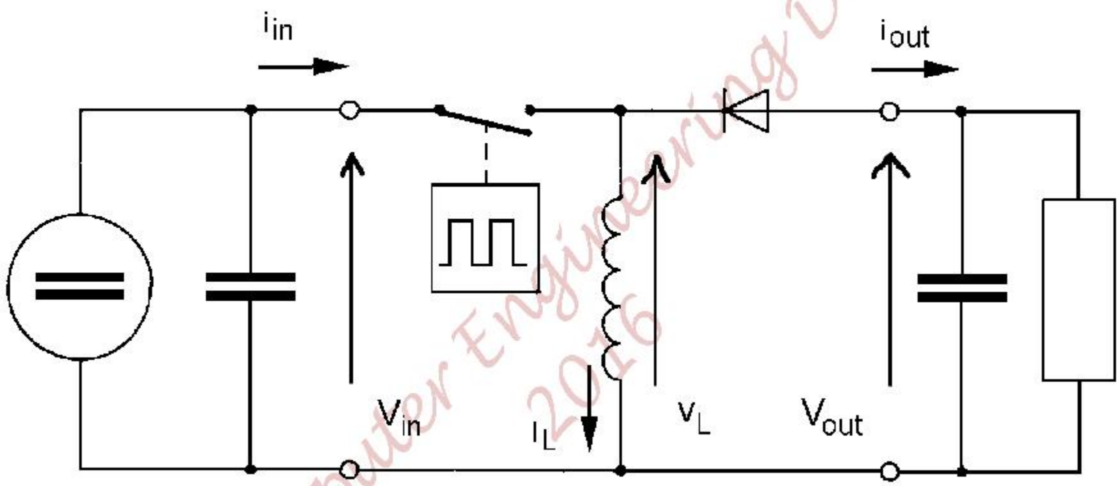
Correspondingly, the mean value of the output current I_{out} = the direct component of the curve $i_{out}(t)$:

$$I_{out} = (I_{in} \cdot t_{off}) / T = I_{in} \cdot (T - t_{on}) / T$$

$$\Rightarrow \mathbf{I_{out} = I_{in} \cdot (1 - k)}$$

- **Step-down/Step-up (Inverting) Converter**

Circuit Layout of the Step-down/Step-up



The significant variables are represented in the figure next. The following applies:

1st section, t_{on}: $v_L = V_{in}$; $i_{in} = I_L$; $i_{out} = 0$

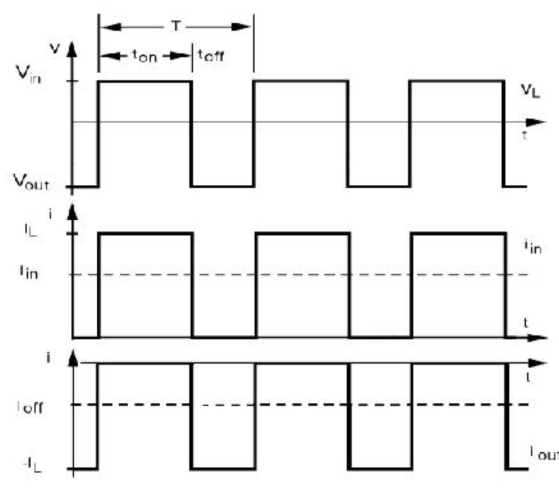
2nd section, t_{off}: $v_L = V_{out}$; $i_{in} = 0$; $i_{out} = -I_L$

The direct component of the voltage across the reactor $v_L(t) = 0$: Consequently,

$$V_{in} \cdot t_{on} + V_{out} \cdot t_{off} = 0$$

$$\Rightarrow V_{out} = - V_{in} \cdot t_{on} / (T - t_{on})$$

$$\Rightarrow \mathbf{V_{out} = - V_{in} \cdot k / (1 - k)}$$



Correspondingly, the mean value of the input current I_{in} = the direct component of the curve $i_{in}(t)$

$$I_{in} = (I_L \cdot t_{on}) / T \quad \Rightarrow \quad I_L = I_{in} \cdot T / t_{on}$$

And the mean value of the output current I_{out} = the direct component of the curve $i_{out}(t)$

$$I_{out} = (- I_L \cdot t_{off}) / T$$

$$\Rightarrow \quad I_L = - I_{out} \cdot T / (T - t_{on})$$

In short:

$$I_L = I_{in} \cdot T / t_{on} = -I_{out} \cdot T / (T - t_{on})$$

$$\Rightarrow \quad \mathbf{I_{out} = - I_{in} \cdot (1 - k) / k}$$

Experimental Procedure

- *Do not turn on any part of the equipment without a prior notice from the supervisor!*
- *Before changing the Cassy probes of any part of experiment, always turn off the Transformer Supply Voltage Cat. No 726 80, and insert a jumper between the INH port of the Control Unit and the 0V!*

6.1 Connection of the Controller

1) To setup the Controller for the converter, connect the following equipment as shown in Figure 6.1; DC Power Supply, Setpoint Potentiometer, and Control Unit PWM/PFM/ZPR. Refer to Appendix B for more details about the Control Unit.

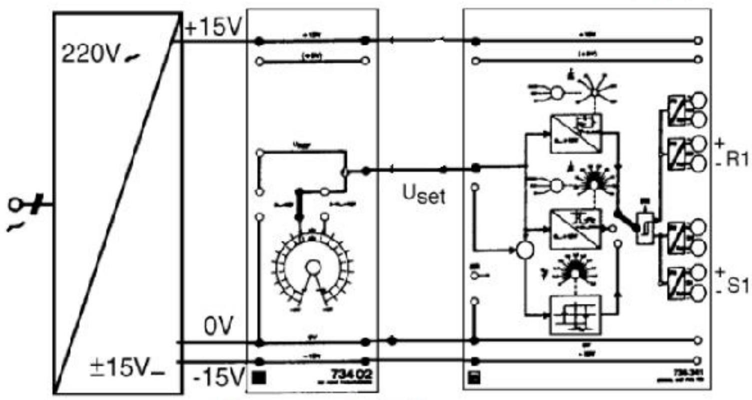


Figure 6.1 Configuration of the control equipment for a DC-DC chopper

- The Power Supply provides the +/- 15V needed for controller!
- The potentiometer provides a voltage between **0 to 10V** to vary the duty cycle from 0 to 1, respectively. The switch **'S' must be set to internal**!

2) The Setpoint Potentiometer is adjusted at 5V.
3) Set the frequency of the Control Unit PWM/PFM to 10kHz; the switching frequency of the MOSFET is 10kHz!

6.2 Step-up (Boost) Converter with PWM and Ohmic Load

Notes:

- The equivalent power circuit of the Step-up (Boost) converter is shown in Figure 6.2. It implements a power MOSFET as a switch.

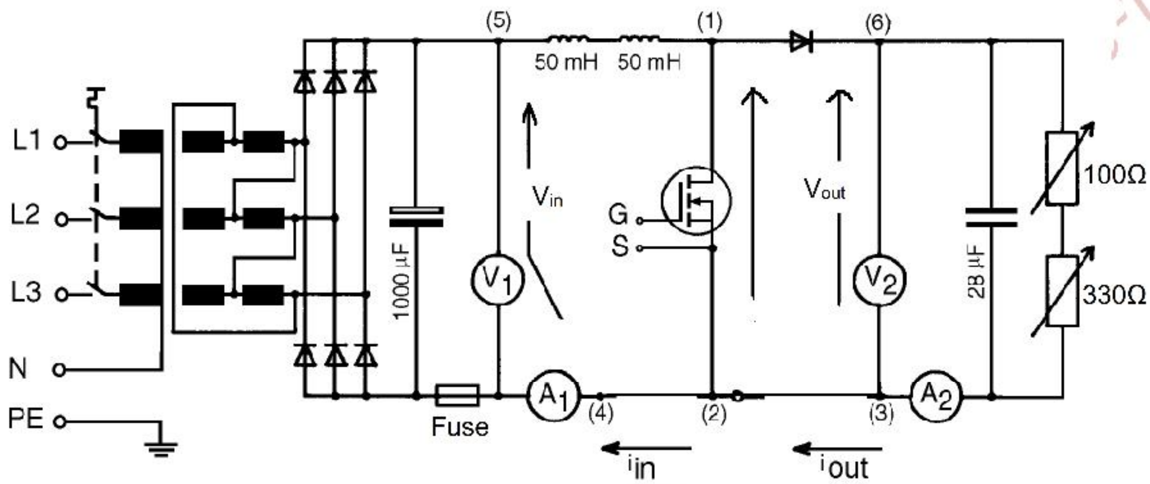


Figure 6.2 The equivalent power circuit of a Step-up (Boost) converter implementing a MOSFET

- The transformer is wired such that its output voltage is as small as possible. Thus, for each limb, only one phase winding with the phase voltage V_{Φ} = 45V is used; the phases are delta-connected, so that the line-to-line voltage $V_{LL} = V_{\Phi}$ = 45V.
- A fuse (Fuse, Three-Fold, Super Fast Cat. No. 735 18) is connected at the lower side of the input to the Boost; between the Rectifier capacitor and the Boost, as shown in the equivalent power circuit of Figure 6.2.
- The converter inductance consists of two inductors in series; 2X50mH in series i.e. 100mH.
- The filter capacitance at the output consists of 4μF//8μF//16μF; i.e. 28μF.
- The load is resistive type and consists of two rheostats set, initially, to their maximum values, 100Ω and 330Ω; i.e. 430Ω.
- The MOSFET receives the control pulse S_1 from the Control Unit for controlling;

  S_1+ to the Gate terminal (G), and S_1- to the Source terminal (S)

Operation of the Step-up Converter with PWM and Ohmic Load

1) Connect the actual equipment in a Step-up converter as shown in Figure 6.3. Use "Rectifier B6 3X400V, 10A (Cat. No. 735 65)" instead of 3 single legs! The load is a resistive type and consists of two rheostats set, initially, to their maximum values, 100Ω and 330Ω; i.e. 430Ω.

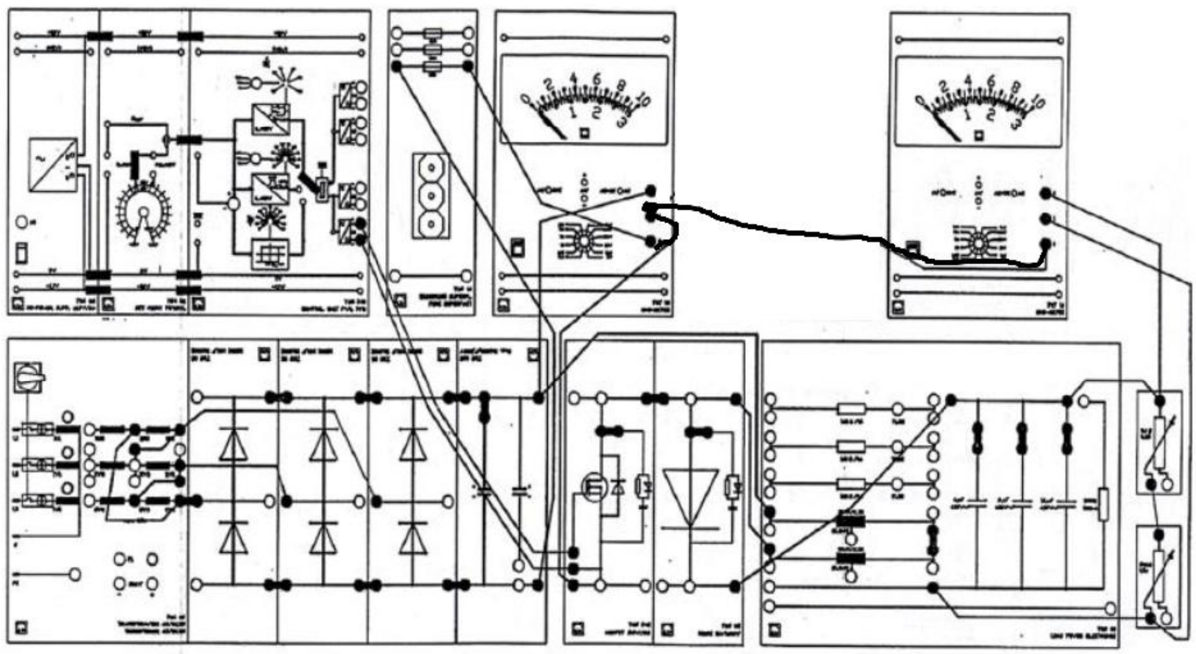


Figure 6.3 Configuration of the equipment as a Step-up converter implementing a MOSFET

2) Do not forget to connect the plugs for the RC circuit of the MOSFET and the diode.
3) Make the necessary connections of the Cassy probes to plot the MOSFET current and the instantaneous voltage across it.
4) Set the **Measured** time of "Cassy Lab software" to 200μs. It is the time interval of the waveform to display. The **Interval** (sampling time) is set to1μs. The latter affects the resolution of the waveform to display. Refer to **Appendix A** for Cassy setup help!
5) Ensure that the frequency (f) is set to 10,000Hz. The switching frequency can be adjusted (slowly) coarsely with the rotary switch (4) and finely with the potentiometer (5) of the PWM Control Unit; refer to the description of the PWM Control Unit in Appendix B. **Make your changes slowly!**
6) Adjust, slowly, the Setpoint Potentiometer ($\mathbf{V_{set}}$) to 7V (of the full range [0…10V]), which is equivalent to a duty cycle (k) of 70%.
7) Before turning on the 15V Power Supply, **the INH port of the Control Unit should be plugged in to 0V via a jumper!**

Ask

8) Turn on the 15V Power Supply
9) Turn on the Transformer Supply Voltage Cat. No. 726 80
10) Unplug the INH port of the Control Unit; let it open!

Note: If the Boost does not start when unplugging the INH jumper, turn off the Transformer Supply Voltage, insert the INH jumper to 0V, and repeat steps 9) and 10)!

11) Using CASSY Lab software, plot the voltage across the MOSFET and its current, then take a screen (snap) shot. Refer to **Appendix A** for Cassy setup help!
12) Notice and describe the current and voltage waveforms, measure t_{on} and calculate the duty cycle; $k = t_{on}/T$. Comment!
13) Adjust the Setpoint Potentiometer as in Table 6.1, and for each value of Setpoint voltage measure the respective parameters. Always adjust the load resistance to maintain the output current (I_{out}) at **0.6A**.

Table 6.1: The effect of duty cycle on the Step-up converter characteristics at I_{out}=0.6A

Setpoint Potentiometer (V_{set}) [V]	8	7	6	5	4	3	2	1.5
The average input voltage of the Boost [V]								
The average output voltage of the Boost [V]								
The average input current of the Boost [A]								
t_{on} [µs]								
Calculated duty cycle; $k = t_{on}/T$								
Calculated (theoretical) average output voltage of the Boost [V]								
Calculated (theoretical) average input current of the Boost [A]								

14) Turn off the Transformer Supply Voltage Cat. No 726 80
15) **Plug in the INH port of the Control Unit to 0V via a jumper**!
16) Adjust the load resistance to maximum value immediately after completing the table measurements.
17) Turn off the 15V Power Supply
18) Plot each parameter of Table 6.1 versus duty cycle on the same figure!
19) Compare the practical and theoretical values, and comment on results!
20) What do you notice about the input voltage? Explain why?!

6.3 Step-down/Step-up (Buck-Boost) Converter with PWM and Ohmic Load

Notes:

- The equivalent power circuit of the Step-down/Step-up (Buck-Boost) converter is shown in Figure 6.4. It implements an IGBT as a switch.

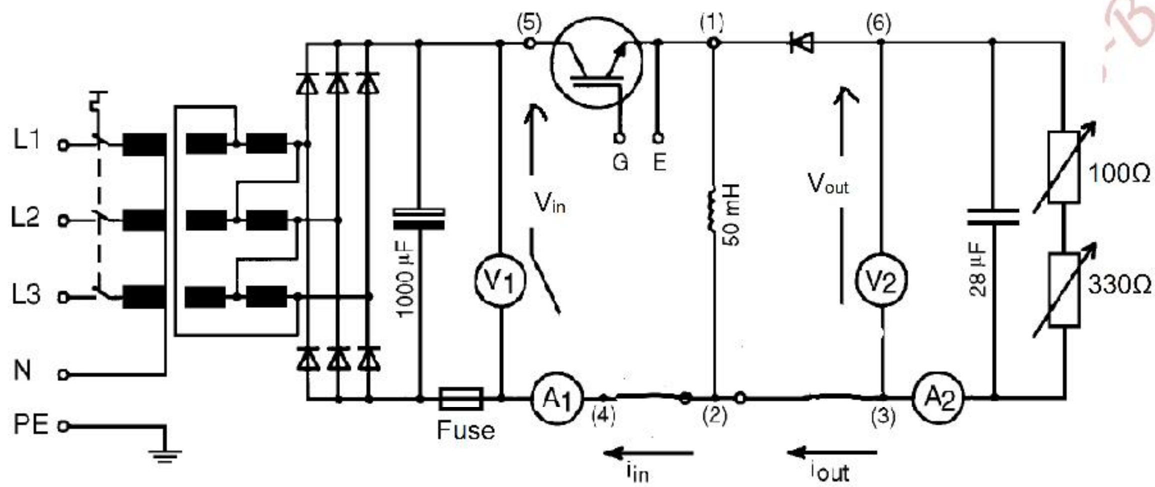


Figure 6.4 The equivalent power circuit of a Step-down/Step-up (Buck-Boost) converter implementing an IGBT

- Also here, the transformer is wired such that its output voltage is as small as possible. Thus, for each limb, only one phase winding with the phase voltage V_{Φ} = 45V is used; the phases are delta-connected, so that the line-to-line voltage $V_{LL} = V_{\Phi}$ = 45V.
- A fuse (Fuse, Three-Fold, Super Fast Cat. No. 735 18) is connected at the lower side of the input to the Buck-Boost; between the Rectifier capacitor and the Buck-Boost, as shown in the equivalent power circuit of Figure 6.4.
- The converter inductance is of 50mH.
- The filter capacitance at the output consists of 4μF//8μF//16μF; i.e. 28μF.
- The load is resistive type and consists of two rheostats set, initially, to their maximum values, 100Ω and 330Ω; i.e. 430Ω.
- The IGBT receives the control pulse S_1 from the Control Unit for controlling;
  S_1+ to the Gate terminal (G), and S_1- to the Emitter terminal (E)

Operation of the Step-down/Step-up Converter with PWM and Ohmic Load

1) Connect the actual equipment in a Step-down/Step-up converter as shown in Figure 6.5. Use "Rectifier B6 3X400V, 10A (Cat. No. 735 65)" instead of 3 single legs! The load is a resistive type and consists of two rheostats set, initially, to their maximum values, 100Ω and 330Ω; i.e. 430Ω.

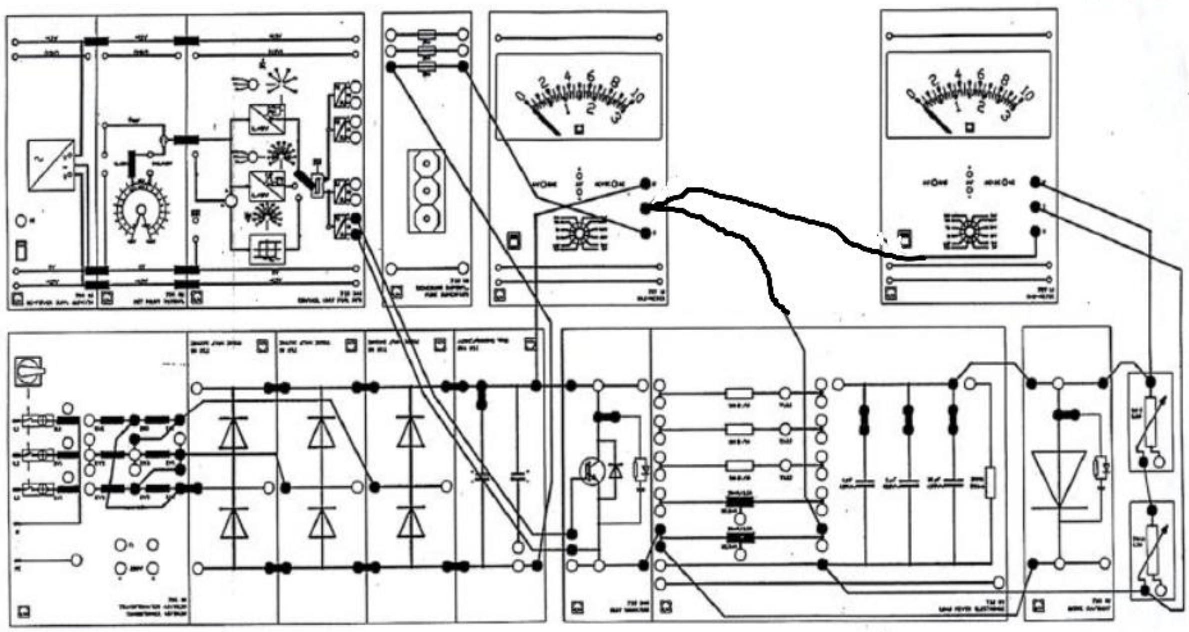


Figure 6.5 Configuration of the equipment as a Step-down/Step-up converter implementing an IGBT

2) Do not forget to connect the plugs for the RC circuit of the IGBT and the diode.
3) Make the necessary connections of the Cassy probes to plot the IGBT current and the instantaneous voltage across it.
4) Set the **Measured** time of "Cassy Lab software" to **400µ**s. It is the time interval of the waveform to display. The **Interval** (sampling time) is set to1µs. The latter affects the resolution of the waveform to display. Refer to **Appendix A** for Cassy setup help!
5) Ensure that the frequency (f) is set to **5,000Hz**. The switching frequency can be adjusted (slowly) coarsely with the rotary switch (4) and finely with the potentiometer (5) of the PWM Control Unit; refer to the description of the PWM Control Unit in Appendix B. **Make your changes slowly!**
6) Adjust, slowly, the Setpoint Potentiometer (**V_{set}**) to 7V (of the full range [0…10V]), which is equivalent to a duty cycle (k) of 70%.
7) Before turning on the 15V Power Supply, **the INH port of the Control Unit should be plugged in to 0V via a jumper!**

Ask

8) Turn on the 15V Power Supply
9) Turn on the Transformer Supply Voltage Cat. No. 726 80
10) Unplug the INH port of the Control Unit; let it open!

Note: If the Buck-Boost does not start when unplugging the INH jumper, turn off the Transformer Supply Voltage, insert the INH jumper to 0V, and repeat steps 9) and 10)!

11) Using CASSY Lab software, plot the voltage across the IGBT and its current, then take a screen (snap) shot. Refer to **Appendix A** for Cassy setup help!
12) Notice and describe the current and voltage waveforms, measure t_{on} and calculate the duty cycle; $k = t_{on}/T$. Comment!
13) Adjust the Setpoint Potentiometer as in Table 6.2, and for each value of Setpoint voltage measure the respective parameters. Always adjust (decrease) the load resistance to maintain the average input current (I_{in}) at **1A** (start decreasing the 430Ω first).

Table 6.2: The Effect of duty cycle on the Step-down/Step-up converter characteristics at I_{in} = 1A

Setpoint Potentiometer (V_{set}) [V]	7	6.5	6	5.5	5	4.5	4	3.5	3
The Buck-Boost average input voltage [V]									
The Buck-Boost average output voltage [V]									
The Buck-Boost average output current [A]									
t_{on} [µs]									
Calculated duty cycle; $k = t_{on}/T$									
Calculated (theoretical) average output voltage of the Buck-Boost [V]									
Calculated (theoretical) average output current of the Buck-Boost [A]									

14) Turn off the Transformer Supply Voltage Cat. No 726 80
15) **Plug in the INH port of the Control Unit to 0V via a jumper**!
16) Adjust the load resistance to maximum value immediately after completing the table measurements.
17) Turn off the 15V Power Supply
18) Plot each parameter of Table 6.2 versus duty cycle on the same figure!
19) Compare the practical and theoretical values, and comment on results!
20) What do you notice about the input voltage? Explain why?!