Experiment # 5
Step-Down (Buck) Converter

Objectives

- Understanding the PWM technique used to control a Step-down converter
- Measuring the turn-off time of a Thyristor
- Comparison between on-state characteristics of power electronic devices implemented in a Step-down converter
- Measuring and interpreting various parameters of the Step-down converter, 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	735 343	Thyristor with Turn-Off Circuit 230V/8A
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

- DC-DC choppers are considered to be ideal, i.e. the valves are ideal switches;

  On-state voltage = 0

  Off-state voltage = 0

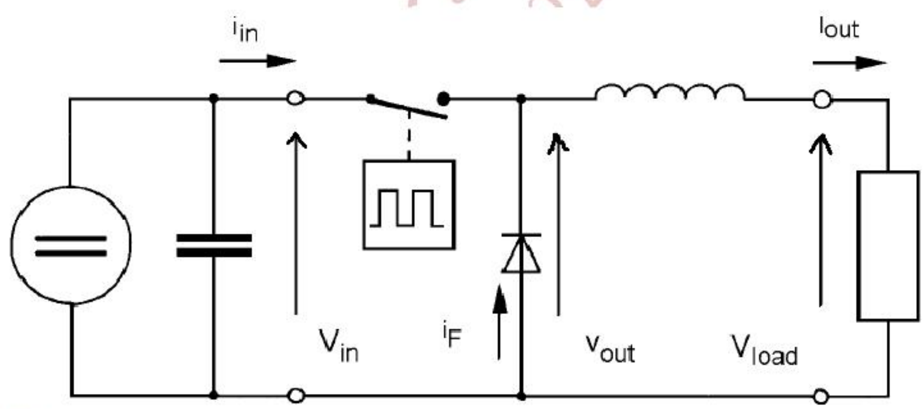
  Switching times = 0

  Switching losses = 0

- In the diagrams of this experiment, the controllable = turn-off valve is therefore represented as a periodically closing contact.
- t_{on} is the time during which the turn-off valve remains on (conducts), t_{off} is the time during which the turn-off valve remains off (blocks).
- Smoothing inductors are infinitely large, i.e. a constant current flows in them. Smoothing capacitors are infinitely large, i.e. a constant voltage lies across them, and they can conduct any undesired AC voltage component. Consequently, the chopping rate does not have any influence on the zero- frequency quantities of the DC-DC chopper.

Step-Down Converter Operation

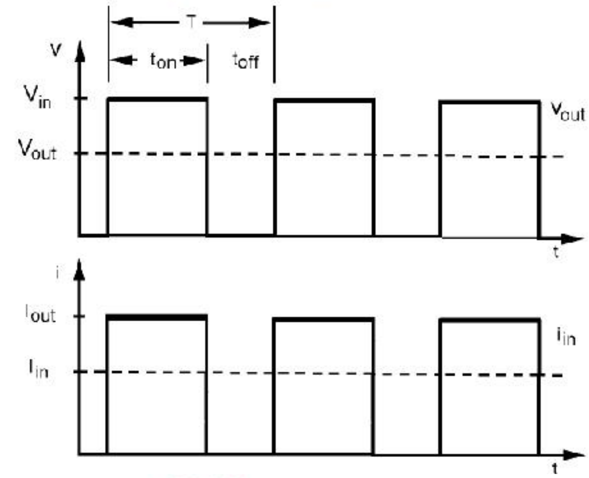
- The circuit layout of a Step-down (buck) converter is shown in the Figure below.



- Two operating modes exist:

During mode 1, the switch (valve) is closed $V_{out} = V_{in}$ and $i_{in} = I_{out}$

During mode 2, the switch (valve) is opened $V_{out} = 0$ and $i_{in} = 0$



- The switching waveforms are as shown in the Figure next.

- The average output voltage is the DC component of the waveform $V_{out}(t)$, as a pure alternating voltage drops across the reactor.

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

Correspondingly, the average value of the input current I_{in} = the DC of the waveform $i_{in}(t)$;

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

$k = t_{on} / T$ is the duty cycle; ranges from 0 to 1!

Commutation Circuit for an SCR

It applies, with the aid of auxiliary SCR, a reverse voltage across the Main SCR that has to be turned-off. The voltage across the Main SCR has to be reversed for a time longer than the turn-off time (t_q) of the Main SCR.

The **Hold-off time (t_C)** of the commutation capacitor is the time during which the commutation capacitor holds a reverse voltage across the Main SCR when the auxiliary SCR is turned on; it is the time that elapses before the voltage across the output falls from its maximum value to the input DC voltage level of the chopper.

Controllable Switches (Valves)

The DC-DC chopper implements three types of controllable switches; a Thyristor, MOSFET, and IGBT. The standard Thyristor exhibits an extremely non-linear on-state characteristic. Even at low on-state currents, a considerably high on-state voltage - a minimum voltage - is required, compared with the on-state voltage drop which continues to increase very slowly at higher currents.

The MOSFET exhibits an almost linear on-state V–I characteristic. Consequently, its on-state voltage at low currents is smaller than that of the Thyristor. Taking into account that these particular valves can be employed for currents of up to I = 8 ... 10A, **the (high-blocking capability) MOSFET has, by far, the poorest on-state characteristic.**

The IGBT, have a non-linear characteristic, similar to the Thyristors. In both cases, the collector-emitter saturation voltage V_{CEsat} is not strongly dependent on the current.

Apart from the MOSFET at high current levels, the tested IGBT has the highest on-state voltage of all the valves. However, its advantages lie mainly in its low control requirements.

The switching frequency of the Thyristor is less than 500Hz, of the IGBT is in the range 1kHz to 20kHz, and of the MOSFET is in the range 4kHz to 100kHz.

Ripple at the output of the Step-down Converter

Due to the switching operation of the DC-DC chopper, the output voltage vout is comprised of a desired component (a DC component) and a (non-sinusoidal) alternating (spurious) voltage component. The alternating voltage and current components of its variables are all non-sinusoidal.

With partial smoothing, the alternating output voltage Δv_{out} generates an alternating output current Δi_{out}, which is superimposed on the direct output current. The alternating input current generates an alternating input voltage Δv_{in}, which is superimposed on the direct input voltage V_{in}.

The ripple at the output depends on the inductor smoothing, the switching frequency and the duty cycle. Sufficient smoothing is, therefore, necessary in order to minimize the spurious component.

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!***

5.1 Connection of the Controller

1) To setup the Controller for the converter, connect the following equipment as shown in Figure 5.1; DC power supply, Setpoint Potentiometer, Control Unit PWM/PFM/ZPR, Thyristor with turn-off circuit, and RMS meter. Refer to Appendix B for more details about the Control Unit.

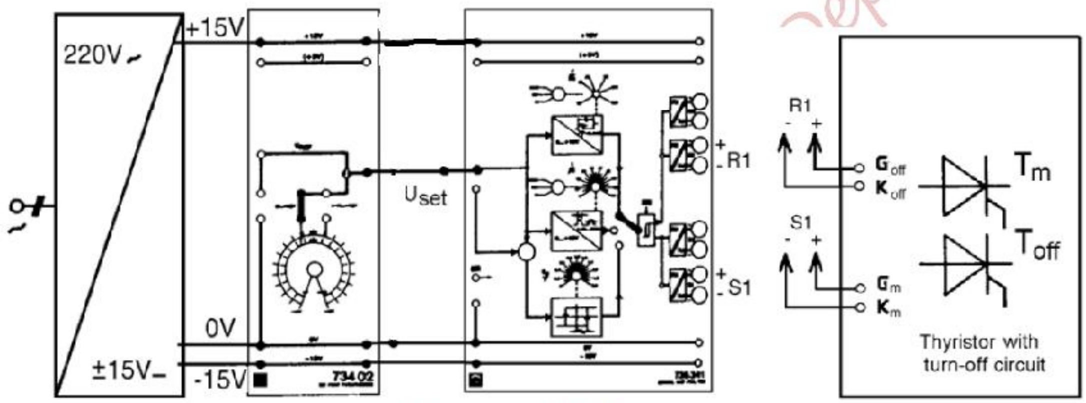


Figure 5.1 Configuration of the control equipment for a DC-DC Chopper

- 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) Set the frequency of the Control Unit PWM/ PFM to 200Hz, as the switching frequency of the Thyristor is well below 500Hz!

5.2 Step-down Converter Implementing an SCR with Commutation Circuit

Notes:

- The equivalent power circuit of the Step-down converter is shown in Figure 5.2. It implements an SCR and its turn-off commutation circuit.

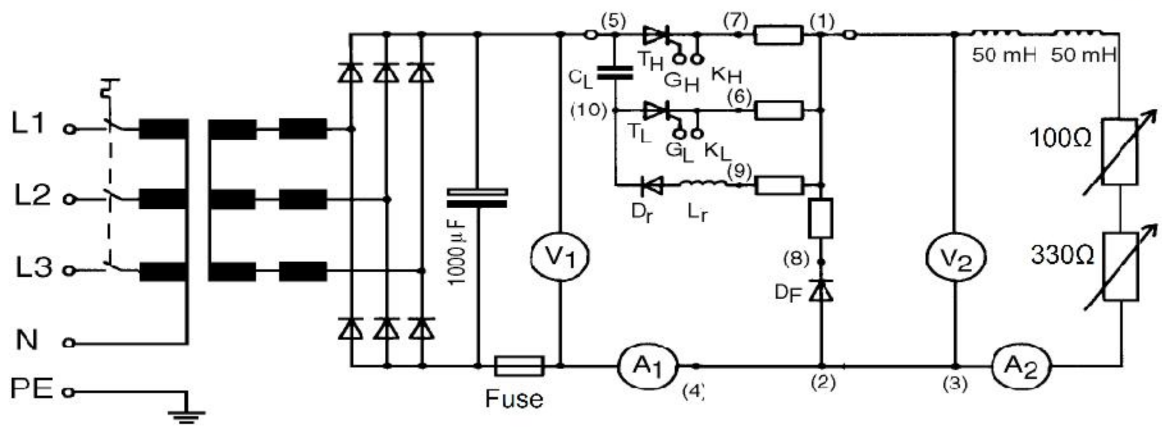


Figure 5.2 The equivalent power circuit of a Step-down Converter implementing an SCR

- A fuse (Fuse, three-fold, super fast Cat. No. 735 18) is connected at the lower side of the input to the chopper; between the rectifier capacitor and the chopper, as shown in the equivalent power circuit of Figure 5.2.
- The load is an RL type and consists of 2X50mH in series with and two rheostats set, initially, to their maximum values, 100Ω and 330Ω; i.e. 100mH in series with 430Ω.

I) Operation of Step-Down Converter (Chopper) with Resistive–Inductive Load

1) Connect the actual equipment in a Step-down converter as shown in Figure 5.3. Ignore the measurement meters; instead of an Ammeter insert a short circuit, and just open circuit the Voltmeter. Use "Rectifier B6 3X400V, 10A (Cat. No. 735 65)" instead of 3 single legs!
2) Make the necessary connections of the Cassy probes to plot the instantaneous voltage across the valve (SCR) and the current through it.
3) Set the **Measured** time of "Cassy Lab software" to 10ms. It is the time interval of the waveform to display. The **Interval** (sampling time) is set to10µs. The latter affects the resolution of the waveform to display. Refer to **Appendix A** for Cassy setup help!
4) Before turning on the 15V Power Supply, **the INH port of the Control Unit should be plugged in to 0V via a jumper!**

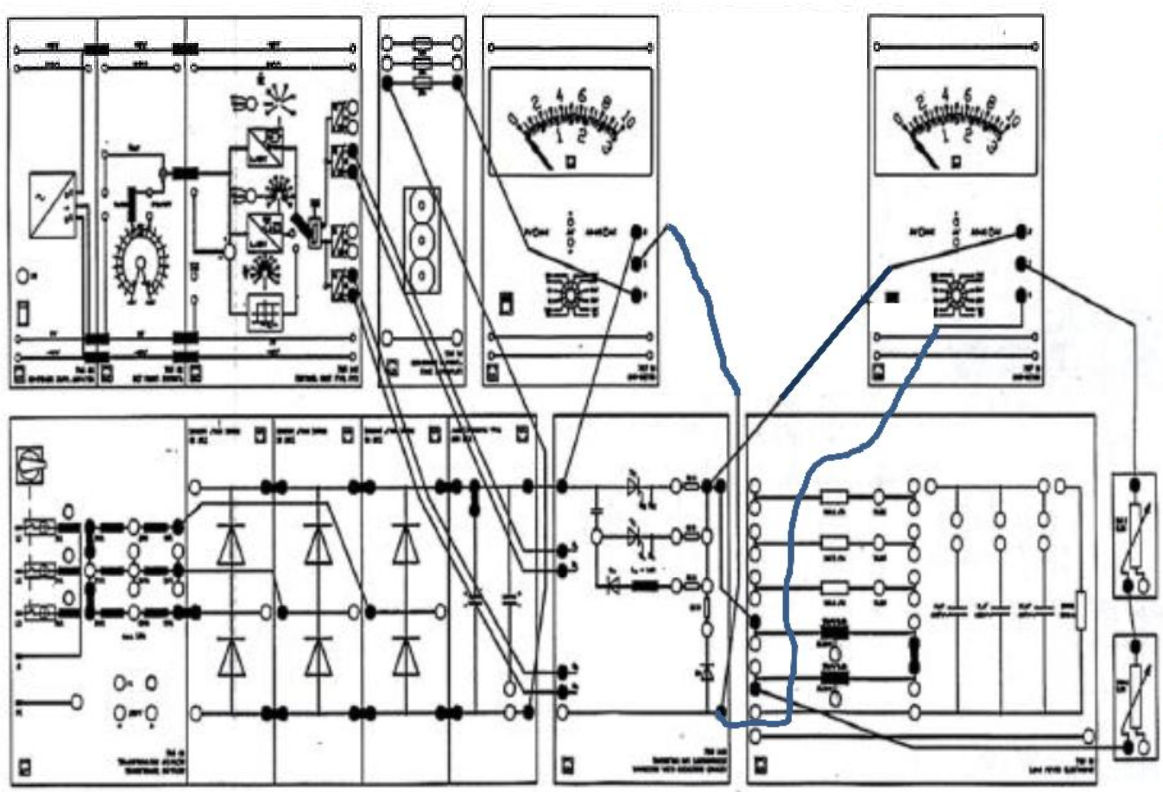


Figure 5.3 Configuration of the equipment for Step-down converter implementing an SCR

Ask

5) Turn on the 15V Power Supply and ensure that the frequency (f) is set to 200Hz. 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 the previous pages. **Make your changes slowly!**
6) Adjust, slowly, the Setpoint Potentiometer (**v_{set}**) to 3V (of the full range [0…10V]), which is equivalent to a duty cycle (k) of 30%. Measure the voltage of the potentiometer output using an RMS meter.
7) Turn on the Transformer Supply Voltage Cat. No. 726 80
8) Unplug the INH port of the Control Unit; let it open!

Note: If the chopper does not start when unplugging the INH jumper, turn off the Transformer Supply Voltage, insert the INH jumper to 0V, and repeat steps 7) and 8)!

9) Using CASSY Lab software, plot the voltage across the valve (SCR), and the current through it, then take a screen (snap) shot. Refer to **Appendix A** for Cassy setup help!
10) Notice and describe the current and voltage waveforms, and calculate the duty cycle; $k = t_{on}/T$

11) Adjust, slowly, the Setpoint Potentiometer to 7V, which is equivalent to a duty cycle of 70% (check that). Measure the potentiometer output voltage using the RMS meter.
12) Using CASSY Lab software, plot the voltage across the SCR (valve) and the current through the chopper valve, then take a screen (snap) shot, and calculate the duty cycle; $k = t_{on}/T$
13) Turn off the Transformer Supply Voltage Cat. No 726 80
14) **The INH port of the Control Unit should be plugged in to 0V via a jumper**!
15) Compare the waveforms you obtained for the two cases of setpoint voltages. Explain its effect!
16) Make the necessary connections of the Cassy probes to plot the instantaneous Gate-Cathode voltage of the Main Thyristor and its Gate current

Ask

17) Turn on the Transformer Supply Voltage Cat. No. 726 80
18) Unplug the INH port of the Control Unit; let it open!
19) Using CASSY Lab software plot the instantaneous Gate-Cathode voltage of the Main Thyristor and its Gate current, and then take a snap shot.
20) Measure the peak voltage and current, and comment on their shape and values
21) Turn off the Transformer Supply Voltage Cat. No. 726 80
22) Directly **plug in the INH port of the Control unit to 0V**.
23) Make necessary connections of the Cassy probes to plot the instantaneous voltage at the input of the chopper (across the 1000µF Capacitor), and the output voltage of the Step-down converter.
24) Adjust, slowly, the Setpoint Potentiometer to 1V, which is equivalent to a duty cycle of 10% (check that). Measure the potentiometer voltage using the RMS meter. The potentiometer must be turned in the counter clockwise direction!

Ask

25) Turn on the Transformer Supply Voltage Cat. No. 726 80
26) Unplug the INH port of the Control Unit; let it open!
27) Using CASSY Lab software plot and measure the average voltage at the output of the rectifier (across the 1000µF Capacitor), and plot and measure the average voltage at the output of the Step-down converter, then take a snap shot. Refer to **Appendix A** for Cassy setup help!!
28) Change the Setpoint Potentiometer, and take measurements to fill in Table 5.1

Table 5.1: The effect of the Setpoint Potentiometer on the duty cycle and on the average value of output voltage of the Step-down converter

Setpoint Potentiometer (V_{set}) [V]	1	2.5	4	6	7.5	9
t_{on} [ms]						
The chopper average input voltage [V]						
The chopper average output voltage [V]						

Calculated Duty Cycle; $k = t_{on}/T$						
Calculated (Theoretical) chopper average input voltage [V]						
Calculated (Theoretical) chopper average output voltage [V]						

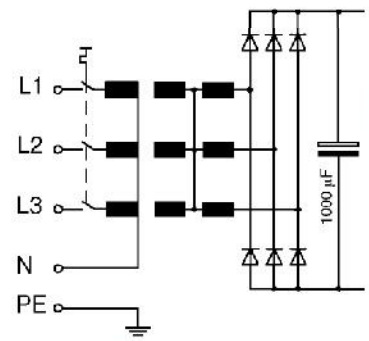
29) Turn off the Transformer Supply Voltage Cat. No 726 80
30) The **INH port of the Control Unit should be plugged in to 0V** via a jumper!
31) Compare the measured values with the theoretical values, explain!
32) On an excel sheet, plot the setpoint voltage versus t_{on}
33) On an excel sheet, plot the measured average output voltage versus duty cycle, k (= t_{on}/T), plot on the same figure the calculated output voltage versus k (= t_{on}/T)
34) Make necessary changes on the Cassy probes to plot the instantaneous output voltage and output current of the Step-down converter.
35) Adjust, slowly, the Setpoint Potentiometer to 4V, which is equivalent to a duty cycle of 40% (check that). Measure the voltage using the RMS meter.

Ask

36) Turn on the Transformer Supply Voltage Cat. No. 726 80
37) Unplug the INH port of the Control Unit; let it open!
38) Plot the output voltage and output current and measure their average values. Take a screen shot. Calculate the peak-to-peak ripple in the output current! Comment on the waveforms!
39) Turn off the Transformer Supply Voltage Cat. No. 726 80
40) Directly **plug in the INH port of the Control unit to 0V**.

II) Turn-Off time (t_q) of the Main Thyristor { Redo the test of this part; NOT optimised}

1) **Reconnect the input Transformers** such that the Transformer's secondary produces a phase-to-neutral voltage of **45V,** as shown in the next figure



2) Change the RL to be **two series-inductors** (100mH) **in series with two-parallel resistors** (100Ω in parallel with 330Ω). Initially, **set the resistors to their maximum values**.
3) Set the **Measured** time of "Cassy Lab software" to 3ms, which is the time interval of the waveform to be displayed. The **Interval** (sampling time) is set to10μs, which affects the resolution of the waveform to be displayed. Refer to **Appendix A** for Cassy setup help!
4) Scroll down the **Setting** window and tick the **Triggering** box; select the triggering voltage to be the output voltage probe at the rising edge of 250V level
5) Press on the **Invalid Cassy** icon on middle top of the screen, to start measuring.
6) Then press 'Yes' in the new pop up window

Ask

7) Turn on the Transformer Supply Voltage Cat. No. 726 80
8) Unplug the INH port of the Control Unit; let it open!
9) To freeze the waveforms, press on the **Measuring time icon** in the middle top of the screen
10) Zoom in the voltage waveform to measure the hold-off time (t_C) of the commutation capacitor, using the cursors
11) Plot the output voltage and current and measure the average value of current. Take a snap shot. Comment on Waveforms!
12) Fill in Table 5.2 by reducing the values of the parallel resistors simultaneously and slowly (make similar changes to the taps of both resistors). **Make measurement quickly, especially when the current exceeds 2.5A**

Table 5.2: The hold-off time (t_C) versus the output current (I_{out})

I_{out} [A]	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
t_C [μs]										

13) Turn off the Transformer Supply Voltage Cat. No. 726 80
14) Directly **plug in the INH port of the Control unit to 0V**. **Turn-off the 15V Power Supply**.
15) What is the turn-off time (t_q) of the Main Thyristor (when the commutation circuit fails to turn off the Main Thyristor)?

Note that, in this chopper, for proper operation, the minimum SCR on-time must be greater than the time needed for charging the commutation capacitor, which is 150μs!

5.3 Comparison Between Power Devices' On-State Characteristics

i) Thyristor in a Step-Down Converter

1) Modify the configuration of the Step-down converter equipment to match the equivalent circuit shown in Figure 5.4. Note that the Transformers' secondaries produce a phase-to-neutral voltage of **45V,** and the load is an RL type consisting of **two series-inductors** (50mH each) **in series with two-series resistors** (100Ω in series with 330Ω). Initially, **set the resistors to their maximum values**.

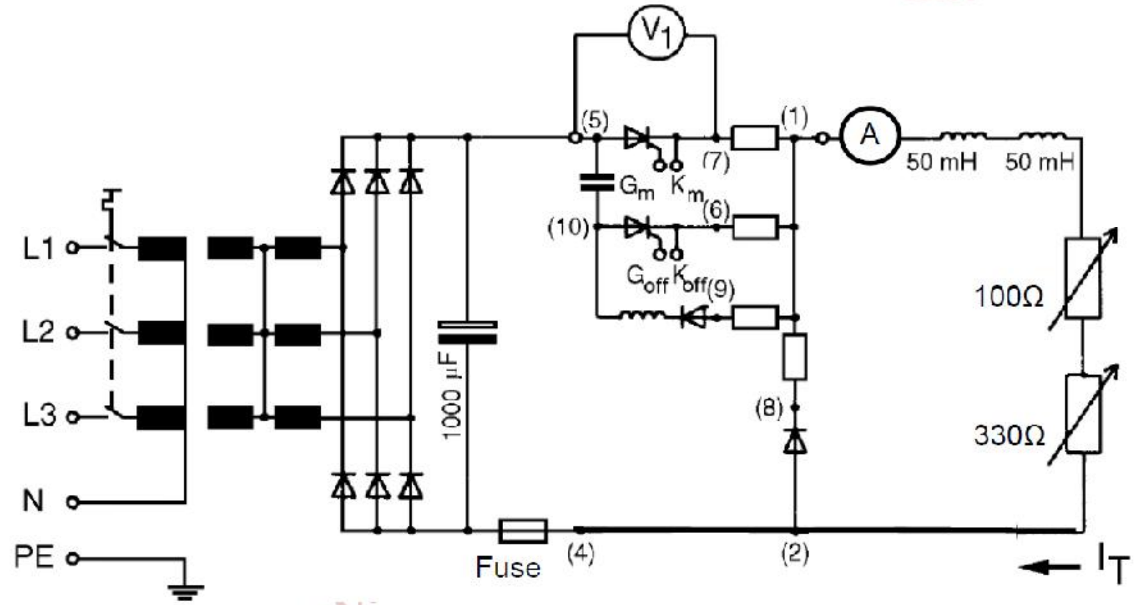


Figure 5.4 Modified Configuration of the equivalent circuit of a Step-down Converter implementing an SCR

2) Connect the current probe of an RMS meter (Cat. No. 727 10) to measure the load current (I_{out}), set the RMS meter to "AV" and ("AC+DC"), and the voltage probe is connected to measure the voltage ("AC+DC") across the main SCR (V_v).
3) Set the Setpoint Potentiometer to 10V, which is equivalent to a duty cycle of 100%
4) **Ensure that the INH port of the Control unit is plugged in to 0V!**
5) Turn on the 15V Power Supply
6) Turn on the Transformer Supply Voltage Cat. No. 726 80
7) Unplug the INH port of the Control Unit; let it open!
8) Reduce the load resistor to increase the load current in steps of 0.5A, and measure the SCR voltage to fill in Table 5.3, **starting by reducing the 330Ω first to zero, then start reducing the 100Ω resistor**. **Take readings quickly for currents greater than 1.5A!**

Table 5.3: The load current (I_{out}) versus the SCR voltage (V_v)

I_{out} [A]	0.5	1	1.5	2	2.5	3.0
V_v [V]						

9) Turn off the Transformer Supply Voltage Cat. No. 726 80

10) Directly **plug in the INH port of the Control unit to 0V**. **Turn-off the 15V Power Supply**!

ii) MOSFET and a Diode in a Step-Down Converter

1) Replace the Thyristor and the turn-off circuit (in the previous Figure; 5.4) with a MOSFET and Diode module having the same space requirement, as shown in the equivalent power circuit of Figure 5.5. Make sure that the diode polarity is correct. It must function as a free-wheeling diode and it must be ensured that it does not short-circuit the positive load voltage. With the MOSFET and diode, the RCD circuit must be connected by means of the bridging plug.

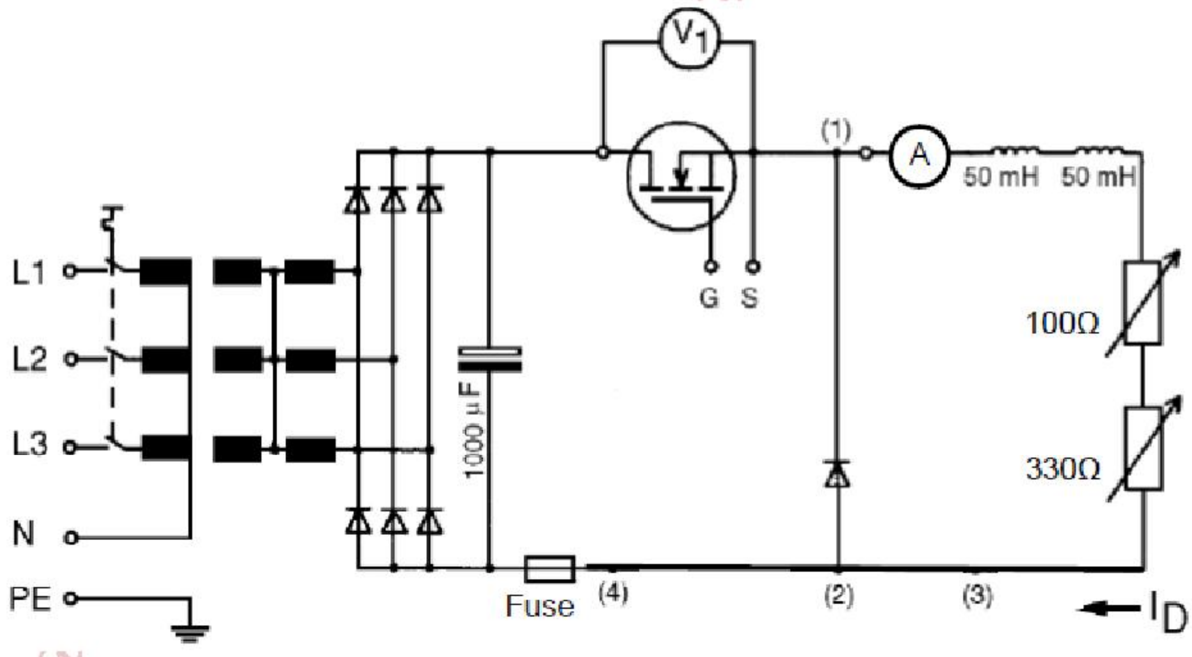


Figure 5.5 The equivalent power circuit of a Step-down converter implementing a MOSFET and a diode

2) The gate of the MOSFET (G) is connected to + S1 port of the Control Unit PWM, and the Source of the MOSFET (S) is connected to **-** S1 port of the Control Unit PWM.

3) The exact connection of control circuit, all power components and RMS meters are shown in Figure 5.6. **Use only one RMS (Cat. No. 727 10) to measure the voltage of the MOSFET and output current**.

4) The current probe of an RMS meter (Cat. No. 727 10) is connected to measure the load current (I_{out}), set the RMS meter to "AV" and ("AC+DC"), and the voltage probe is connected to measure the voltage ("AC+DC") across the MOSFET **(V_v).**
5) Note that, the Transformers' secondaries produce a phase-to-neutral voltage of **45V,** and the load is an RL type consisting of **two series-inductors** (50mH each) **in series with two-series resistors** (100Ω in series with 330Ω). Initially, **set the resistors to their maximum values**.
6) Set the Setpoint Potentiometer to 10V, which is equivalent to a duty cycle of 100%

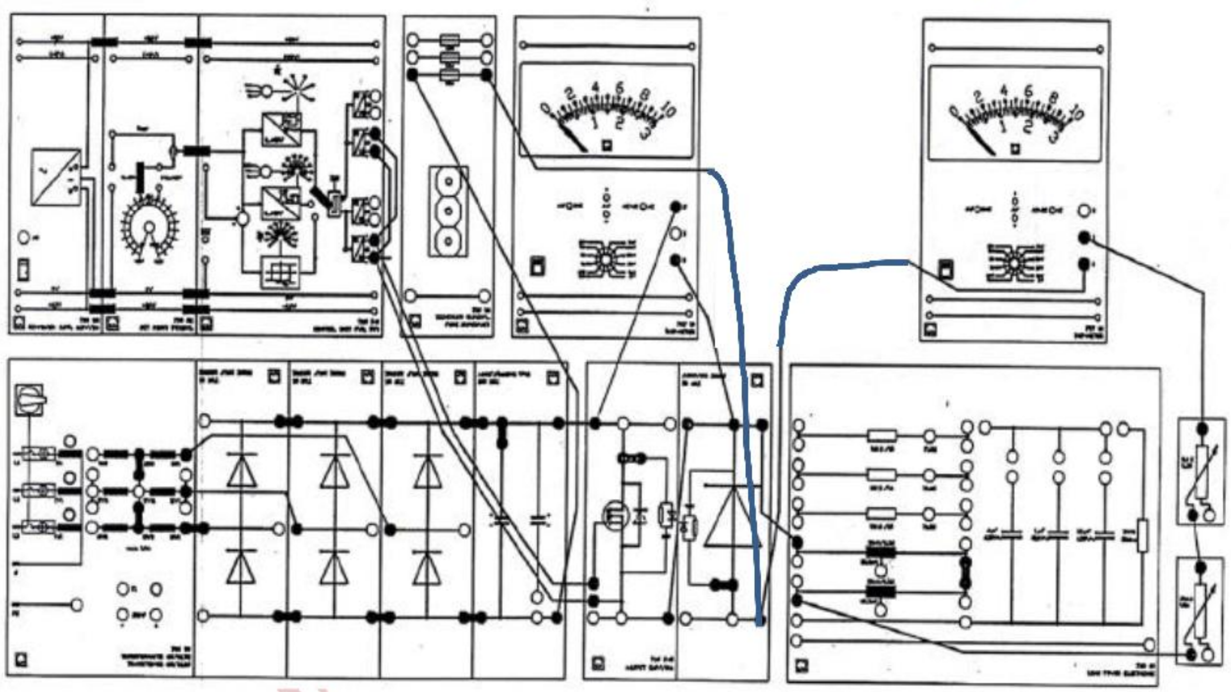


Figure 5.6 Configuration of the equipment as a Step-down converter implementing a MOSFET

Ask

7) Turn on the 15V Power Supply
8) Turn on the Transformer Supply Voltage Cat. No. 726 80
9) Unplug the INH port of the Control Unit; let it open!
10) Reduce the load resistor to increase the load current in steps of 0.5A, and measure the MOSFET on-state voltage to fill in Table 5.4, **starting by reducing the 330Ω first to zero, then start reducing the 100Ω resistor**. **Take readings quickly for currents greater than 1.5A!**

Table 5.4: The load current (I_{out}) versus the MOSFET voltage (V_v)

I_{out} [A]	0.5	1	1.5	2	2.5	3
V_v [V]						

11) Turn off the Transformer Supply Voltage Cat. No. 726 80
12) Directly **plug in the INH port of the Control unit to 0V**. **Turn-off the 15V Power Supply!**

iii) An IGBT and a Diode in a Step-Down Converter

1) Replace the MOSFET (in the previous Figure; 5.5) with an IGBT (Cat. No. 735 346) having the same space requirement, as shown in the equivalent power circuit of Figure 5.7. Make sure that the diode polarity is correct. It must function as a free-wheeling diode and it must be ensured that it does not short-circuit the positive load voltage. With the IGBT and the diode, the RCD circuit must be connected by means of the bridging plug.

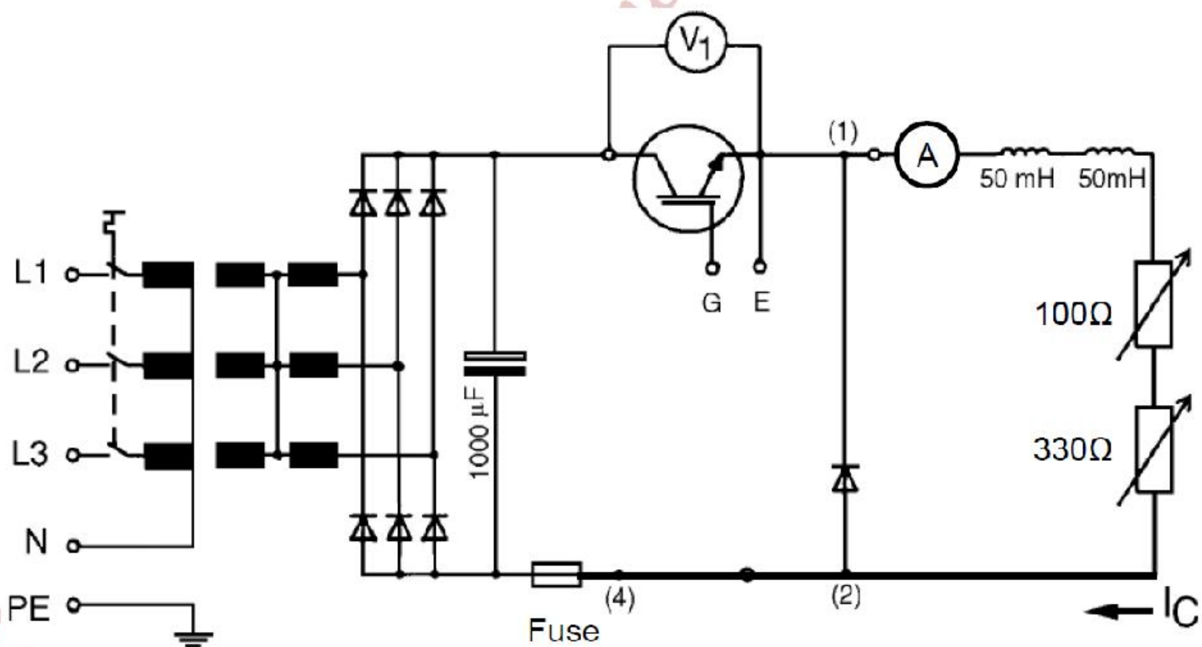


Figure 5.7 The equivalent power circuit of a Step-down converter implementing an IGBT and a diode

2) The Gate of the IGBT (G) is connected to + S1 port of the Control Unit PWM, and the Emitter of the IGBT (E) is connected to - S1 port of the Control Unit PWM.

3) The exact connection of control circuit, all power components and RMS meters are the same as Figure 5.6, but with an IGBT (Cat. No. 735 346) replacing the MOSFET. Use only one RMS meter to measure the valve voltage and the load current.
4) The current probe of an RMS meter (Cat. No. 727 10) is connected to measure the load current (I_{out}), set the RMS meter to "AV" and ("AC+DC"), and the voltage probe is connected to measure the voltage ("AC+DC") across the IGBT **(V_v).**
5) Note that, the Transformers' secondaries produce a phase-to-neutral voltage of **45V,** and the load is an RL type consisting **two series-inductors** (50mH each) **in series with two-series resistors** (100Ω in series with 330Ω). Initially, **set the resistors to their maximum values**.
6) Set the Setpoint Potentiometer to 10V, which is equivalent to a duty cycle of 100%.

Ask

7) Turn on the 15V Power Supply
8) Turn on the Transformer Supply Voltage Cat. No. 726 80
9) Unplug the INH port of the Control Unit; let it open!
10) Reduce the load resistor to increase the load current in steps of 0.5A, and measure the IGBT on-state voltage to fill in Table 5.5, **starting by reducing the 330Ω first to zero, then start reducing the 100Ω resistor**. **Take readings quickly for currents greater than 1.5A!**

Table 5.5: The load current (I_{out}) versus the IGBT voltage (V_v)

I_{out} [A]	0.5	1	1.5	2	2.5	3
V_v [V]						

11) Turn off the Transformer Supply Voltage Cat. No. 726 80
12) Directly **plug in the INH port of the Control unit to 0V**. **Turn-off the 15V Power Supply.** ***Keep the connections unchanged!***
13) Plot the output current versus the valve voltage for the data in Tables 5.3, 5.4 and 5.5 in one figure!
14) Compare the on-state voltage drop across the three devices (valves' voltages) for the three cases!

5.4 A Step-Down Converter Implementing an IGBT- PWM Control

1) Modify and connect the equipment to match the power circuit as shown in the Figure 5.8. Set the Transformers' secondaries for full voltage; produce a **phase-to-neutral voltage of 90V.** Ensure that the RCD circuits for the IGBT and diode are connected by means of the bridging plug!

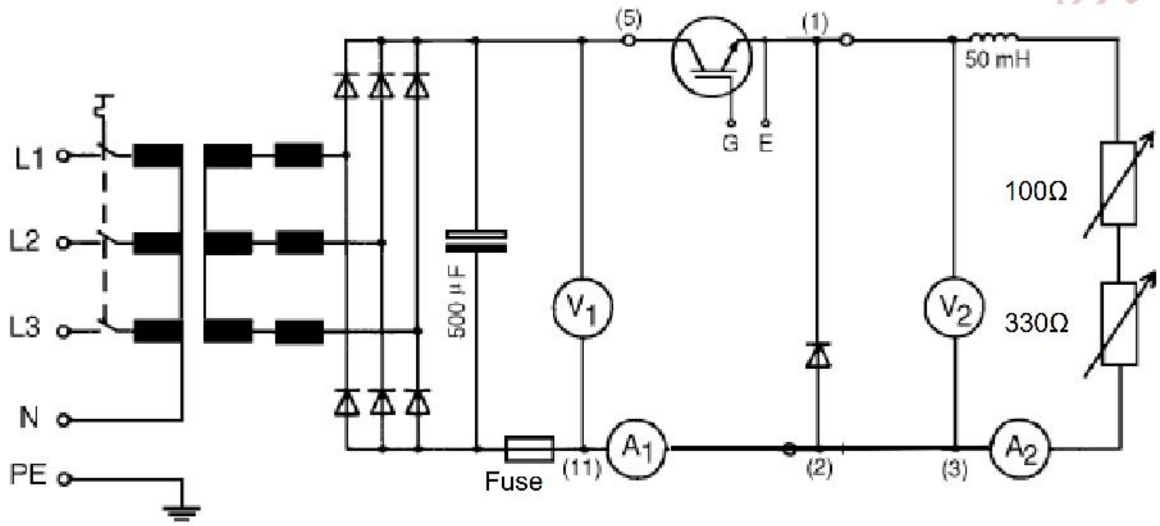


Figure 5.8 The equivalent power circuit of a Step-down converter implementing an IGBT-PWM control

2) The load impedance is set to maximum; 50mH and 430Ω.
3) The RMS meters are set to measure "AV" and "AC+DC".
4) The Gate is connected to S1+ and the Emitter is connected to S1- of the control circuit.
5) Ensure that **the INH port of the Control unit is plugged in to 0V!**
6) Make the necessary changes on the Cassy probes to plot the instantaneous control (gate-emitter) voltage of the IGBT!
7) Set the **Measured** time of "Cassy Lab software" to 2ms. It is the time interval of the waveform to display. The **Interval** (sampling time) is set to10µs. The latter affects the resolution of the waveform to display. Refer to **Appendix A** for Cassy setup help!
8) Set the frequency of the Control Unit to 1kHz, and set the Setpoint Potentiometer to 4V, which is equivalent to a duty cycle of 40%.

Ask

9) Turn on the 15V Power Supply and then turn on Transformer Supply Voltage Cat. No. 726 80
10) Unplug the INH port of the Control Unit; let it open!
11) Use the Cassy Software to plot the gate-emitter voltage, measure its turn-on and turn-off values! Take a screen shot! Measure the turn-on and turn-off times! Comment!

12) Turn off the Transformer Supply Voltage Cat. No. 726 80

13) Directly **plug in the INH port of the Control unit to 0V**. **Turn-off the 15V Power Supply. Keep the connections unchanged!**

14) Make the necessary changes on the Cassy probes to plot the instantaneous output voltage and output current of the Step-down converter.

Ask

15) Turn on the 15V Power Supply and then turn on Transformer Supply Voltage Cat. No. 726 80

16) Unplug the INH port of the Control Unit; let it open!

17) Plot the output voltage and output current, and measure their average values. Take a screen shot. Calculate the peak-to-peak ripple in the output current! Comment on the waveforms! Compare the value of the current ripple with that obtained in **part I) - step 38) -** with 50mH load inductance and a switching frequency of 200Hz. **What do you notice**?

Does the output voltage has a peak voltage, as that was with the Thyrsitor switch? Why?

18) Increase slowly the Setpoint Potentiometer to its maximum value (10V)

19) Maintain the output current at 1.0A, by decreasing the load resistance from its highest value (starting by decreasing the 330Ω resistor first). Take the RMS meters measurements to fill in Table 5.6. The on-time is decreased in steps of 0.1ms for other readings, whilst the load resistor is then decreased to maintain the output current at 1.0A. **After completing all measurements, adjust the load resistance immediately to the maximum value once again**!

Table 5.6: Control characteristics of a PWM Step-down converter at a constant output current (I_{out})

Measurement at I_{out} = 1.0A			Calculations	
t_{on} [ms]	V_{out} [V]	V_{in} [V]	$I_{in,\ ideal}$ [A]	$V_{out,\ ideal}$ [V]
1				
0.9				
0.8				
0.7				
0.6				
0.5				
0.4				
0.3				
0.2				

20) Turn off the Transformer Supply Voltage Cat. No. 726 80

21) Directly **plug in the INH port of the Control unit to 0V**. **Turn-off the 15V Power Supply. Keep the connections unchanged!**

22) Use the balance of power principle between input and output, to calculate $I_{in,\ ideal}$ and $V_{out,ideal}$

23) Plot the parameters in Table 5.6 versus the t_{on}.

24) Why there are discrepancies between ideal (theoretical) values and measured values?

25) Why does the input voltage vary with the reduction of t_{on}?

5.5 Ripple of the Output and Input Currents

For the circuit connected as was shown in Figure 5.8, and for the Potentiometer Setpoint is at 5V and a switching frequency set to 1kHz, examine the effect of various parameters on the output voltage and current ripple.

A) Smoothing Inductor

1) The load resistance is initially set to its maximum values; 430Ω. Initially, the smoothing inductance is 12.5mH.
2) Use the Cassy Lab Software to plot the voltage across the resistive load, and the output current.
3) Turn on the 15V Power Supply (Ask)
4) Turn on Transformer Supply Voltage Cat. No. 726 80.
5) Unplug the INH port of the Control Unit; let it open!
6) Adjust the load resistance, starting by adjusting the 330Ω resistor first, to maintain the output current at **1A** (measure its average using Cassy Lab Software)!
7) Using Cassy, measure peak-to-peak ripple in the output voltage (**Δv_{out}**) and output current **(Δi_{out})**! Take a screen shot!
8) Turn off the Transformer Supply Voltage Cat. No. 726 80
9) Directly **plug in the INH port of the Control unit to 0V**
10) Then adjust the value of the smoothing inductor, and for each value of smoothing inductor, shown in Table 5.7, repeat steps **4)** to **9)** to fill in the table. **Do not change the circuit connections while the power supplies are on!**

Table 5.7: Smoothing inductor effect on the ripple of output current and voltage

Smoothing Inductance [mH]	12.5	2X12.5	50	2X50
Δi_{out} [A]				
Δv_{out} [V]				

11) Turn-off the 15V Power Supply**. Keep the connections unchanged!**

12) Plot the output current ripple versus smoothing inductor, also plot the output voltage ripple versus smoothing inductor. Comment on figures and explain!

B) Switching Frequency

1) The load resistance is initially set to its maximum values; 430Ω. Initially, the smoothing inductance is **50mH,** and the Setpoint Potentiometer is at 5V.
2) Use Cassy Lab Software to plot the voltage across the resistive load, and also the output current.

Ask

3) Turn on the 15V Power Supply
4) Set the switching frequency to 250Hz
5) Turn on Transformer Supply Voltage Cat. No. 726 80
6) Unplug the INH port of the Control Unit; let it open!
7) Adjust the load resistance, starting by adjusting the 330Ω resistor first, to maintain the output current at **0.9A** (measure its average using Cassy Lab Software)!
8) Using Cassy, measure peak-to-peak ripple in the output voltage (**Δv_{out}**) and output current **(Δi_{out})**! Take a screen shot!
9) Then adjust the value of the switching frequency, as shown in Table 5.8, and take measurements of the current and voltage ripples to fill in the table!

Table 5.8: Switching frequency effect on the ripple of output current and voltage

Switching Frequency [Hz]	250	500	1000	2000
Δi_{out} [A]				
Δv_{out} [V]				

10) Turn off the Transformer Supply Voltage Cat. No. 726 80
11) Directly **plug in the INH port of the Control unit to 0V**.
12) Turn off the 15V Power Supply**. Keep the connections unchanged!**
13) Plot the output current ripple versus switching frequency, also plot the output voltage ripple versus switching frequency. Comment and Explain!

C) Duty Cycle Control

1) The load resistance is initially set to its maximum values; 430Ω, and the smoothing inductance is **50mH.** The switching frequency is 1kHz, and initially the Potentiometer Setpoint is at 9V.
2) Use the Cassy Lab Software to plot the voltage across the resistive load, and the output current.

Ask

3) Turn on the 15V Power Supply
4) Turn on Transformer Supply Voltage Cat. No. 726 80

5) Unplug the INH port of the Control Unit; let it open!
6) Adjust the load resistance, starting by adjusting the 330Ω resistor first, to maintain the output current at **1A** (measure its average using Cassy Lab Software)!
7) Measure the valve on time (t_{on}), the peak-to-peak ripple in the output voltage (**Δv_{out}**) and output current (**Δi_{out}**)! Take a screen shot!
8) Then, adjust slowly the value of the Potentiometer Setpoint voltage, as shown in Table 5.9, (**adjust accordingly the load resistance to maintain the output current at 1A**), then measure the on-time, the ripple in the output current and voltage to fill in the table.

Table 5.9: Duty cycle effect on the ripple of the output current and output voltage

Potentiometer Setpoint voltage [V]	9	7	5	3	1
t_{on} [ms]					
Δi_{out} [A]					
Δv_{out} [V]					

9) Turn off the Transformer Supply Voltage Cat. No. 726 80
10) Directly **plug in the INH port of the Control unit to 0V**.
11) Turn-off the 15V Power Supply**. Keep the connections unchanged!**
12) Plot the output current ripple versus Duty Cycle, also plot the output voltage ripple versus Duty Cycle.
13) What do you notice? Comment on results and explain!