School of Electrical and Computer Engineering
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ELEC3251
Assignment 2

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Analysis of Switching Harmonics and Grid Connected Inverters

1 PV Voltage and Switching Harmonics

1.1 Method

To determine the correct switching output, a test was performed at the H-bridge output to confirm that both switching strategies can be achieved. This test involved setting a constant sinusoid input at the H-bridge controller.

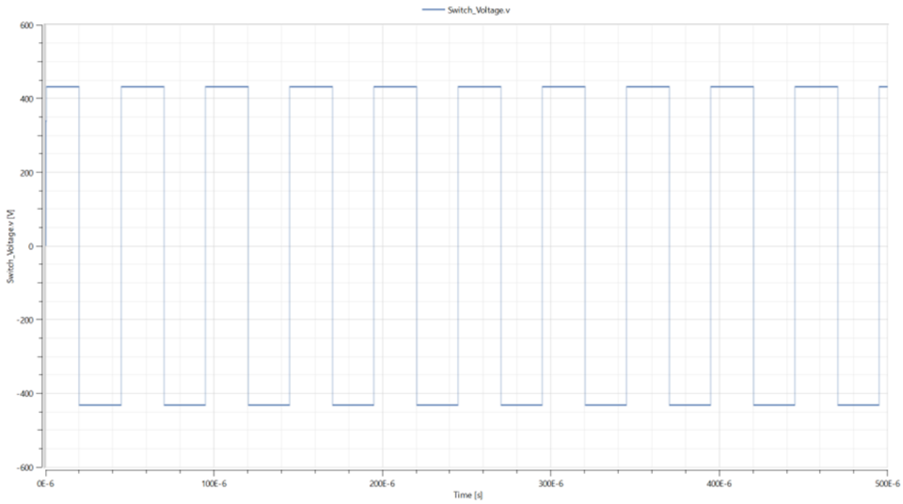

Figure 1: Bipolar Switching Test

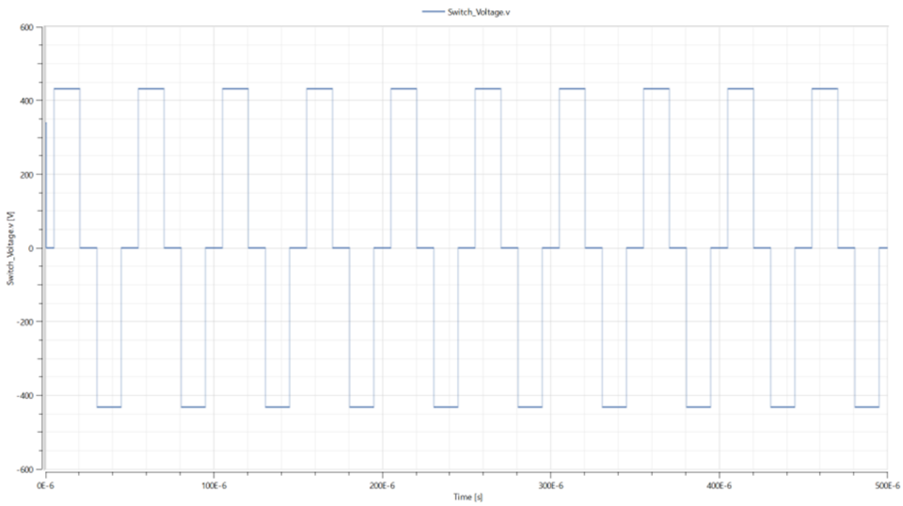

Figure 2: Unipolar Switching Test

The switching frequency was set to 20 kHz. The current sensor, Ic was added to measure

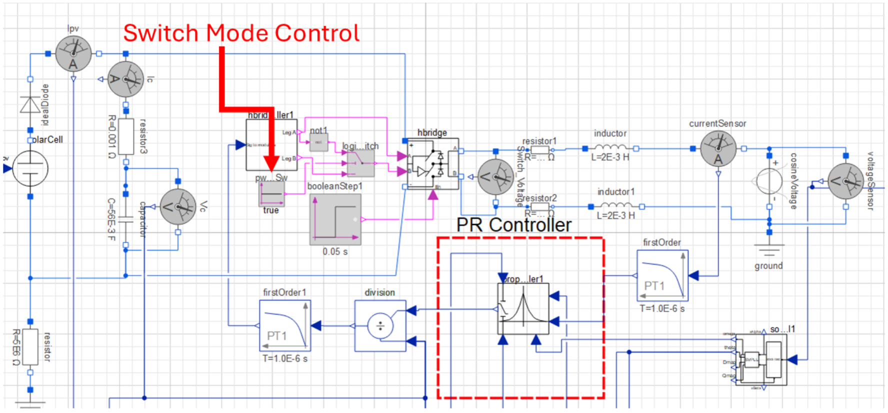

Figure 3: How to set bipolar and unipolar switching

current through the capacitor. The voltage sensor for the capacitor was named Vc. The simulation was run twice, at 0.2 s and at 10 s. This allows the viewing of different frequency components. The numbers of cells in series for the solar cell was 850. The capacitance was set to 56 mF. The some experimentation, it was found that the input supply was 5kW.

1.2 Results

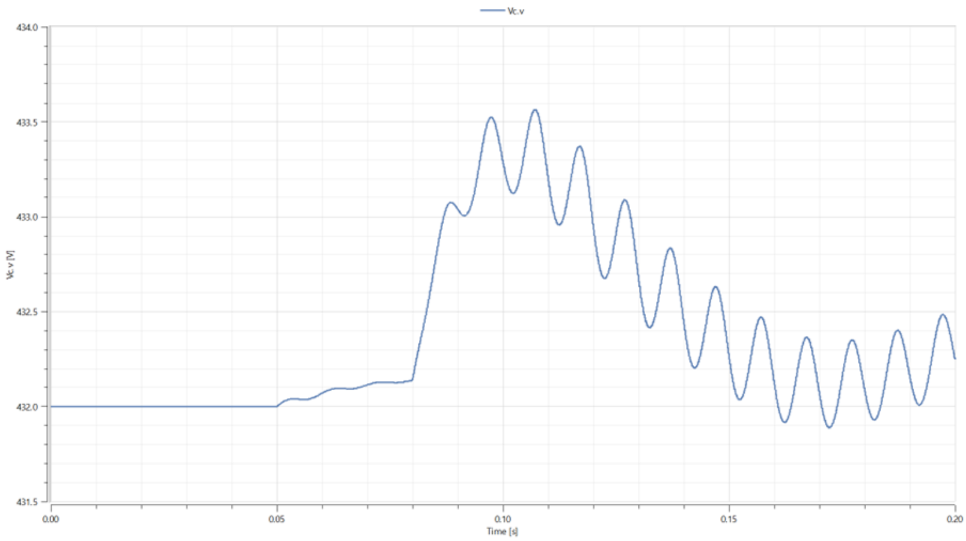

Figure 4: Bipolar V_c, capacitor voltage (PV to GND), Sim Time = 0.2 s

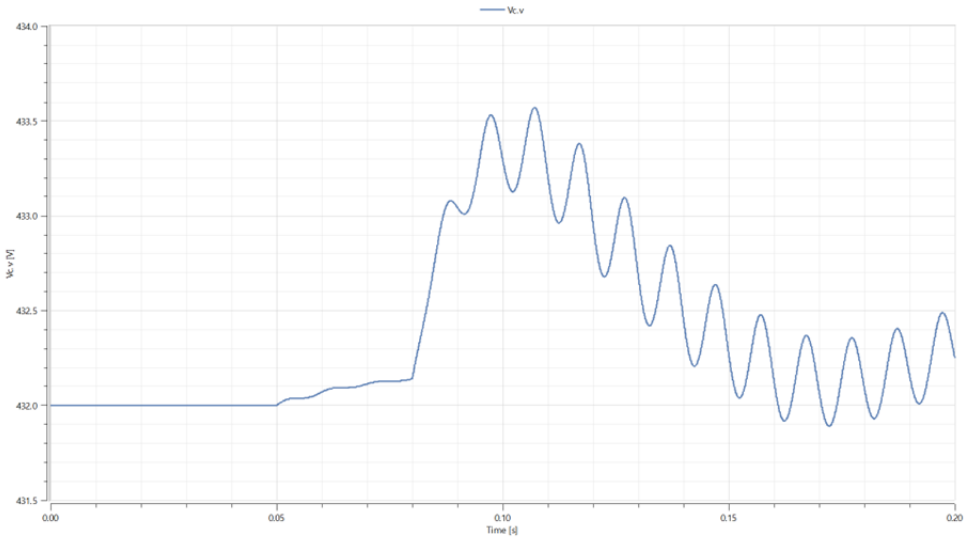

Figure 5: Unipolar V_c, capacitor voltage (PV to GND), Sim Time = 0.2 s

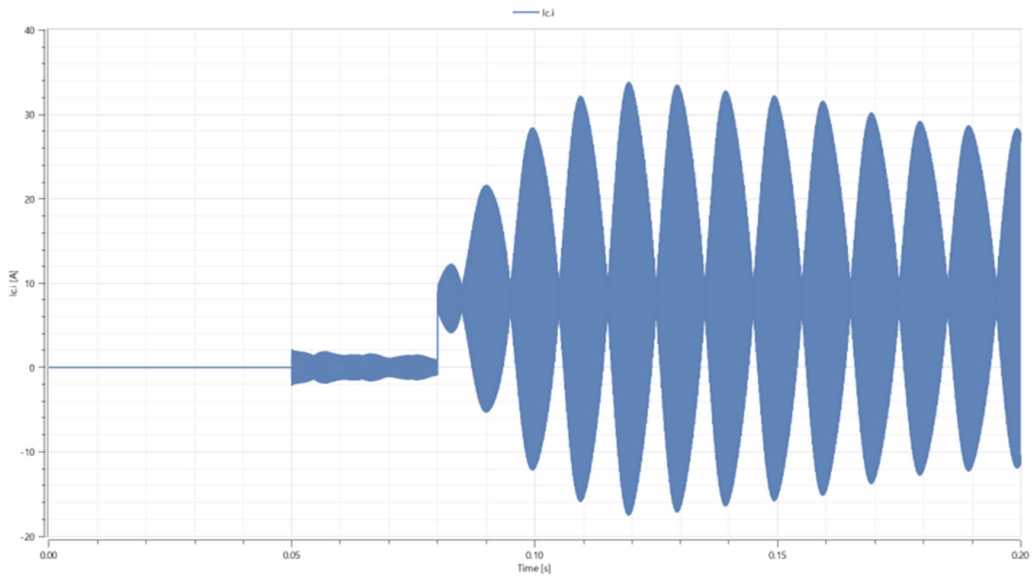

Figure 6: Bipolar I_c, current through capacitor, Sim Time = 0.2 s

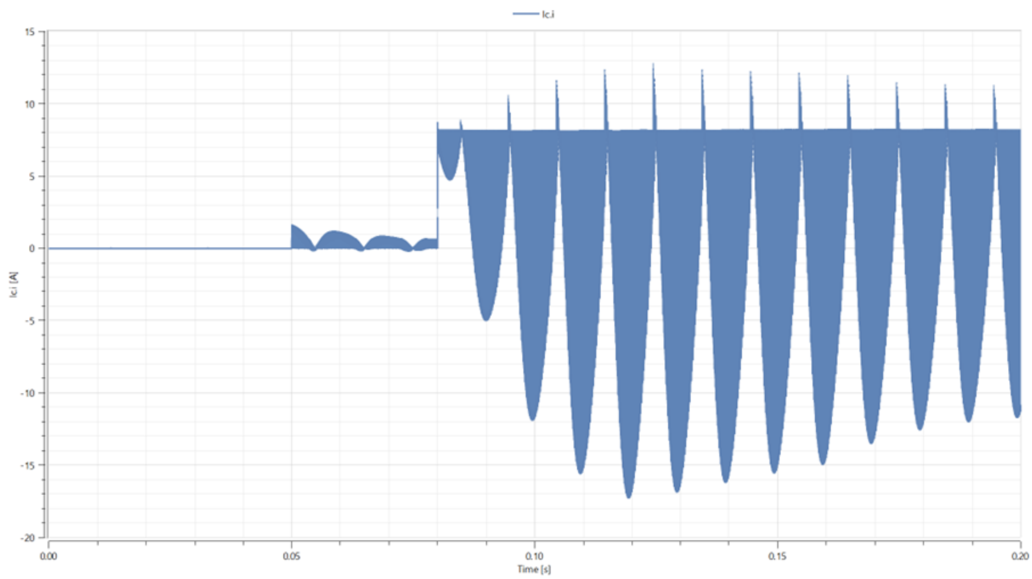

Figure 7: Unipolar I_c, current through capacitor, Sim Time = 0.2 s

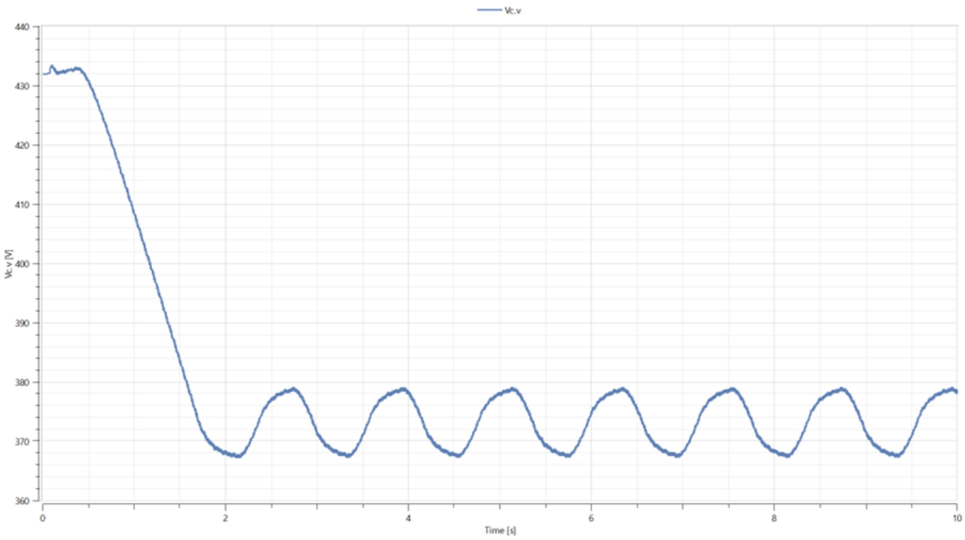

Figure 8: Bipolar V_c, capacitor voltage (PV to GND), Sim Time = 10 s

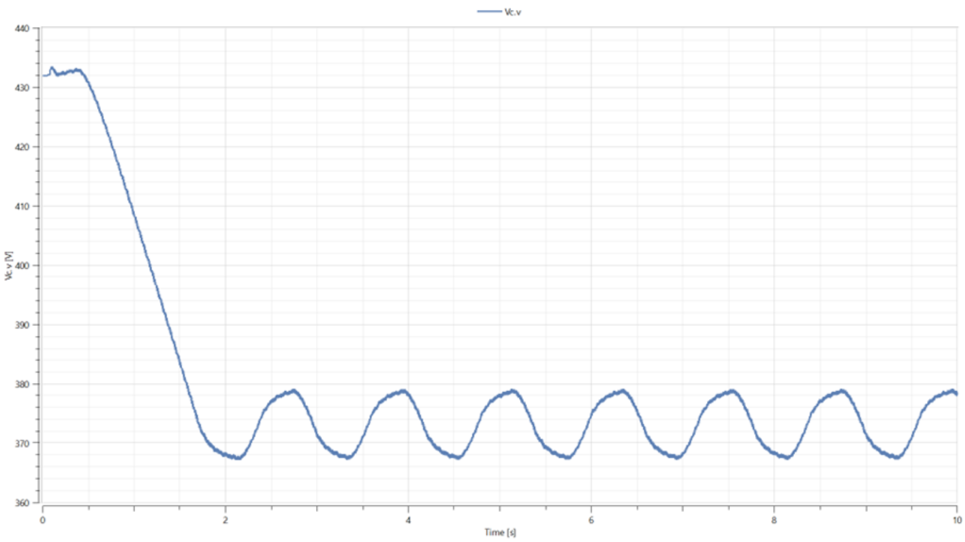

Figure 9: Unipolar V_c, capacitor voltage (PV to GND), Sim Time = 10 s

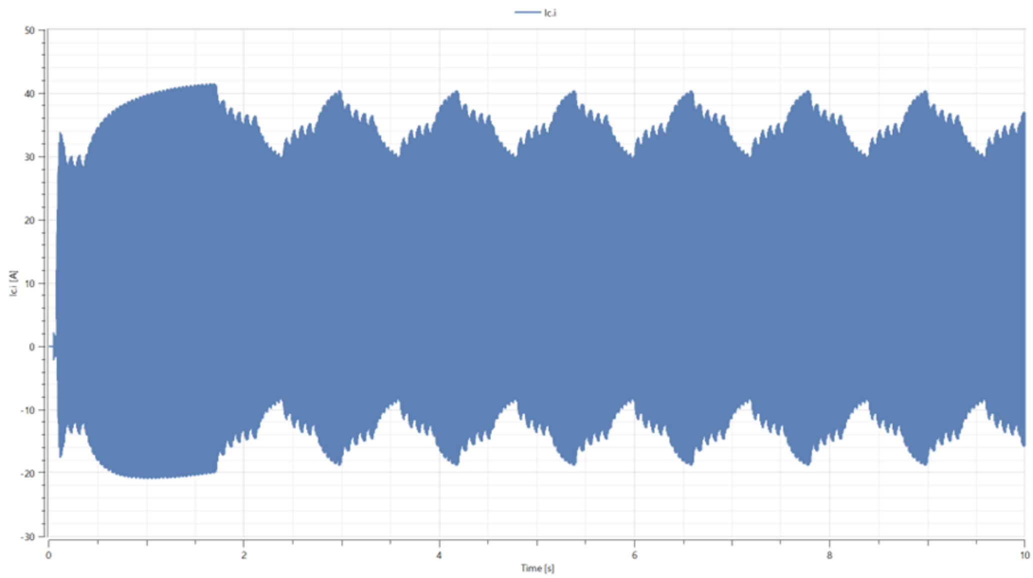

Figure 10: Bipolar I_c, current through capacitor, Sim Time = 10 s

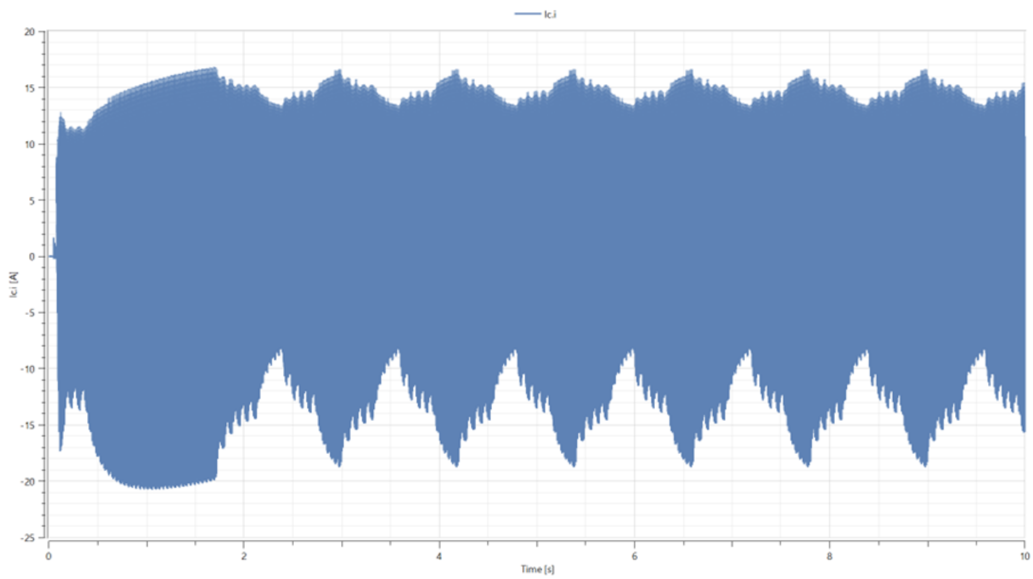

Figure 11: Unipolar I_c, current through capacitor, Sim Time = 10 s

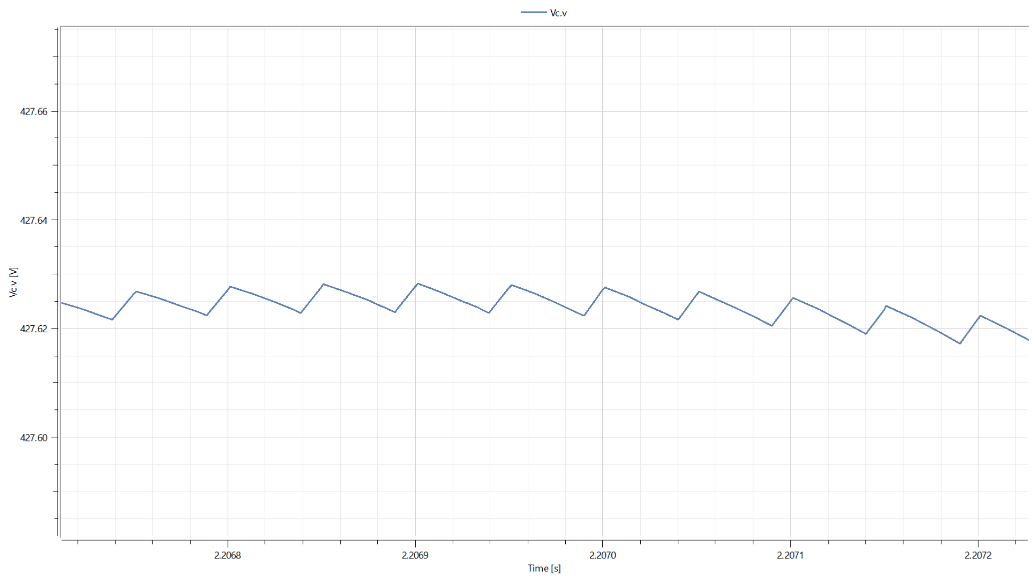

Figure 12: Bipolar, voltage ripple $\Delta V_c = 0.0054$ V, manual zoom

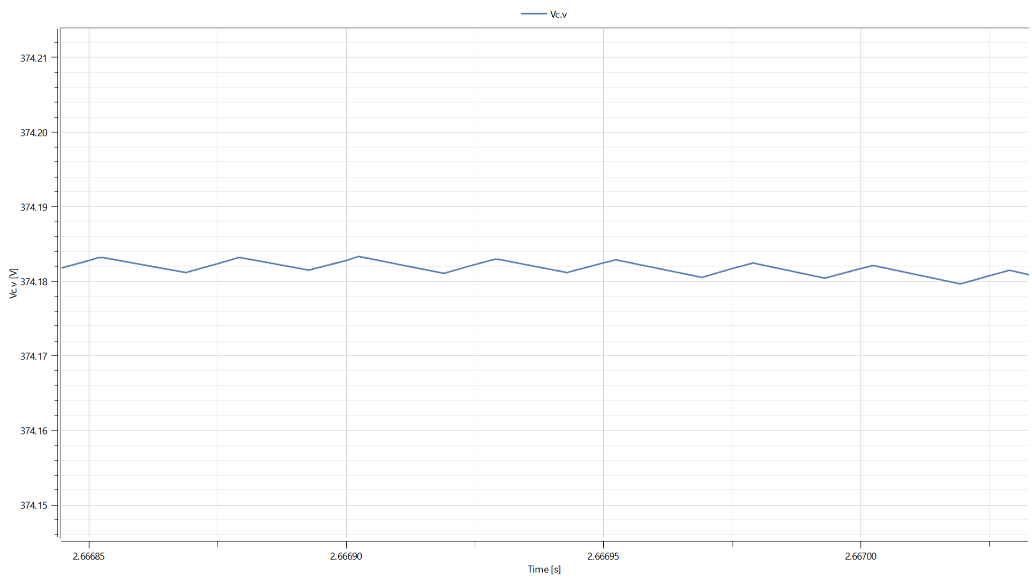

Figure 13: Unipolar, voltage ripple $\Delta V_c = 0.0022$ V, manual zoom

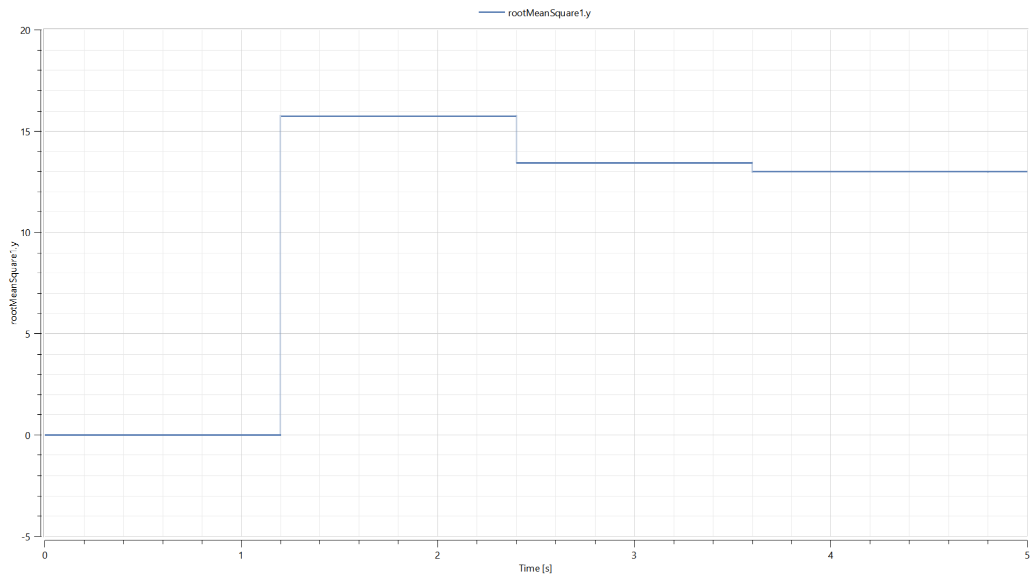

Figure 14: Bipolar, RMS capacitor current, $I_c = 13\ A_{RMS}$ at steady state, Sim Time = 5s

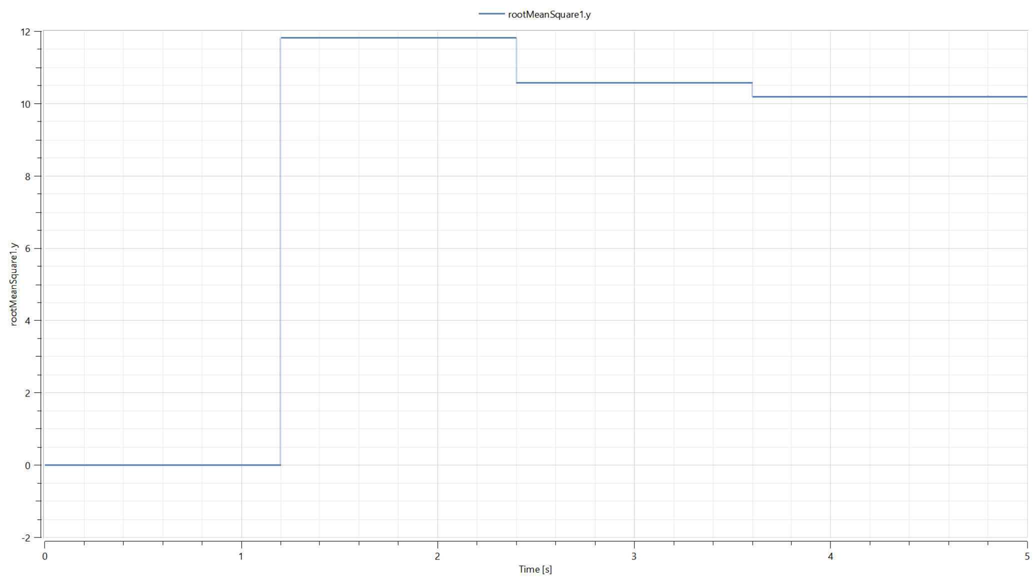

Figure 15: Bipolar, RMS capacitor current, $I_c = 10.2\ A_{RMS}$ at steady state, Sim Time = 5s

1.3 Discussion

Comparing both switching methods, the capacitor voltage (PV) was basically equal, see Figure 4. At time 0.05 s the H-bridge starts switching to produce a current. For the PV cell, the aim is to obtain 5kW of output power. If power, P is

$$P = IV \tag{1}$$

and the grid voltage is 240 V_{RMS}, then the current must be,

$$I = \frac{P}{V} = \frac{5 \cdot 10^3}{240} = 20.83\, A_{RMS} \tag{2}$$

This makes sense, because later simulations show that the supply current at steady state is 29.5 A_p. From 9, a steady state value can be inferred from the PV voltage or capacitor voltage, V_c. This is 373 ± 5 V. For its RMS,

$$373 + \frac{5}{\sqrt{2}} = 376.5\, V_{RMS} \tag{3}$$

This steady state voltage is the MPP (Maximum Power Point). For this simulation, it happened to be 3.8 kW.

An analysis of the different V_c plots show many different frequency components. The first frequency component is the switching frequency, 12 and 13. The second frequency component comes from switching trying to match the grid sinusoid, 6. This f, is 100 Hz. This comes from the grid connected voltage. This is 50 Hz, that makes this signal, the second harmonic. The same frequency can be seen from the current plots, Figure 6. There is a distinct difference between the plots, due to the different switching modes, see Figure 7. This is expected, as harmonic disturbance should be less under unipolar switching. The greatest piece of evidence, can be inferred from the magnitudes of the current plots. As the magnitude of the harmonics is from 40 to -20 for bipolar and from 15 to -20 for unipolar. This can be proved by calculating and plotting rms capacitor current which is performed below. The last frequency component was at the steady state, 8. This frequency component is harmonic distortion. We can confirm this by checking for a common denominator as this means its an harmonic multiple. The period, is about 1.2 s which was estimated by counting periods within a 2-8 s window. For the common denominator information that matters,

$$\frac{T_{max}}{a \cdot T_{small}} = \mathbb{N} \qquad\qquad a = 1, 3, 5, 7, 11... \tag{4}$$

The answer must be a postive integer, it is denoted as a natural number. If it is not, that means the prime number max is known. For the 100 Hz frequency component, $a_{max} = 5$,

$$\frac{1.2}{5 \cdot 0.01} = 24$$

For the switching frequency f_s, the 20 kHz component, $a_{max} = 5$ as well,

$$\frac{1.2}{5 \cdot 5 \cdot 10^{-5}} = 4800$$

This is expected as the 3rd and 5th harmonics cause the most harmonic noise within a single phase system. This means that by removing the 3rd and 5th harmonic, it would remove the majority of the harmonic disturbance at the output.

The frequency components can be added together to estimate the capacitor current using the capacitor equation,

$$i_c = C\frac{dV}{dt} \tag{5}$$

To add all the frequency components together, the capacitor equation is expanded like this,

$$i_c = C\left(\frac{dV_1}{dt} + \frac{dV_2}{dt} + \frac{dV_3}{dt}\right) \tag{6}$$

which to discrete,

$$i_c = C\left(\frac{\Delta V_1}{T_1} + \frac{\Delta V_2}{0.5T_2} + \frac{\Delta V_3}{0.5T_3}\right) \tag{7}$$

Using 7, Estimates of the period and ΔV_c for each component from plots 12, 4, 8 for bipolar leads to this,

$$i_c = 56 \cdot 10^{-3}\left(0.0054 \cdot 20000 + \frac{0.5}{0.5 \cdot 0.01} + \frac{10}{0.5 \cdot 1.2}\right) = 12.58\ A_{RMS}$$

This can be confirmed by plotting the RMS i_c current, 14. This is set by connecting an RMS block to the current sensor, then setting the RMS block to frequency $1/1.2\ Hz$. The simulated RMS current is 13 A. This makes an error 3.34%.

For the unipolar simulation, information from plots 13, 5, 9

$$i_c = 56 \cdot 10^{-3}\left(0.0022 \cdot 20000 + \frac{0.5}{0.5 \cdot 0.01} + \frac{10}{0.5 \cdot 1.2}\right) = 8.98\ A_{RMS}$$

Checking against the simulation, 15, RMS capacitor current is 10.2 A. This makes an error of of 13.59%. This is to be expected, as this was an estimate. Technically,

$$\frac{\Delta V_3}{0.5T_3} = \frac{\Delta V_{3rd}}{0.5T_{3rd}} + \frac{\Delta V_{5th}}{0.5T_{5th}} \tag{8}$$

This is true for the switching and grid noise components. If more time was given, an FFT would have been simulated.

2 Grid Connected Inverters

2.1 Method

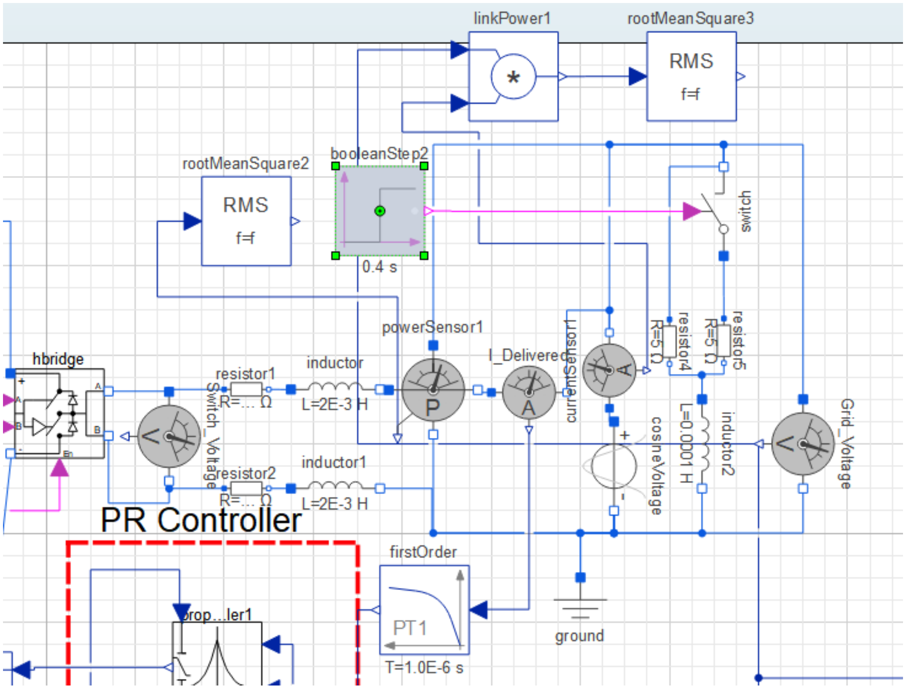

Figure 16: Set Up to confirm grid connected inverter control

This simulation tests the control systems ability to perform output disturbance rejection. If the load chabnges, how does the system react. This simulation changes the real part of the load from 5 to 2.5 Ω at 0.25s. The control system starts at 0.005 s. The H-bridge starting switching at 0.05 s. To reach steady state earlier, the capacitor initialisation voltage was set to 360 V.

2.2 Results

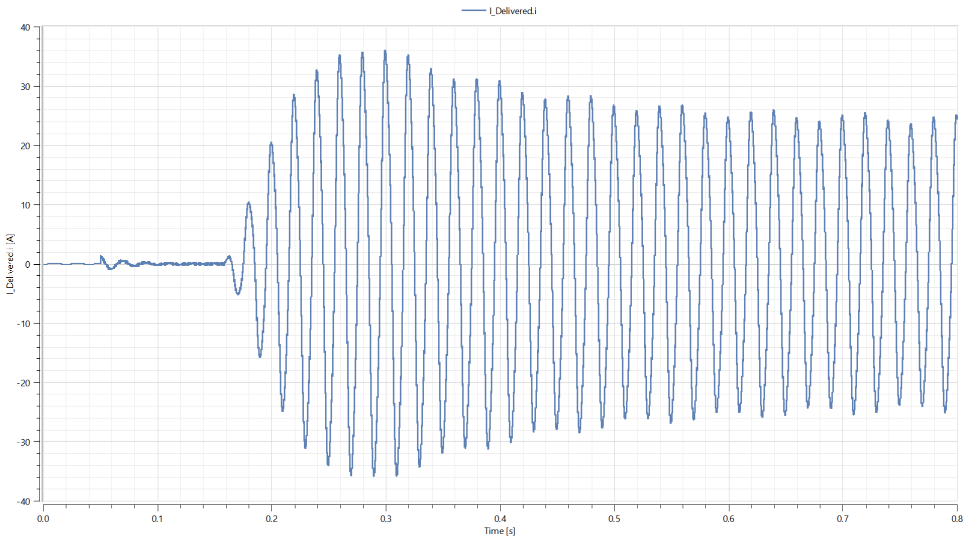

Figure 17: Current delivered from inverter

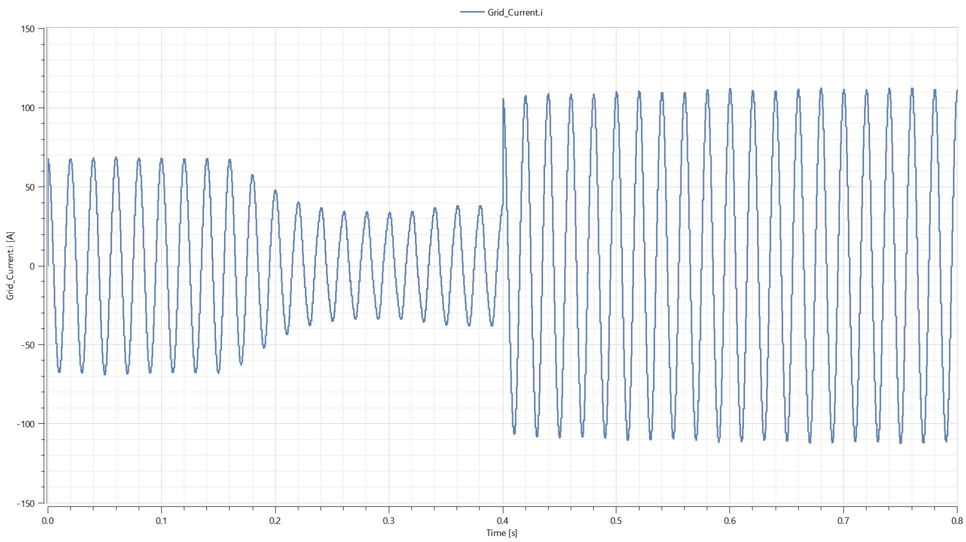

Figure 18: Current delivered to load from grid voltage source

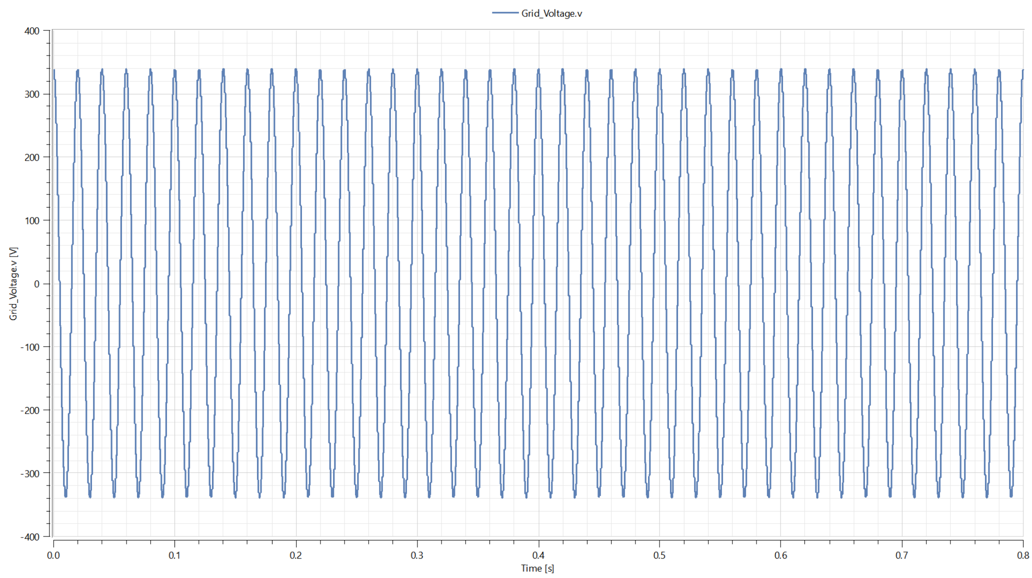

Figure 19: Grid Voltage

2.3 Discussion

References