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.

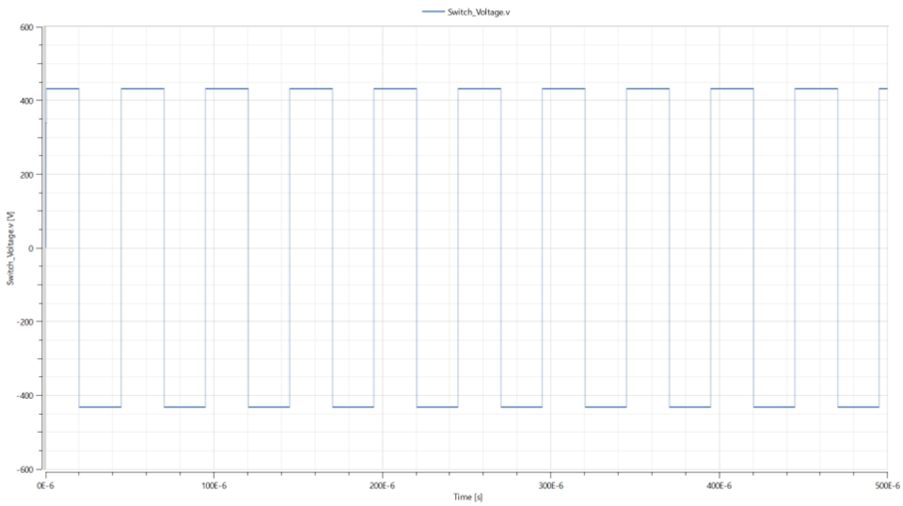

Figure 1: Bipolar Switching Test

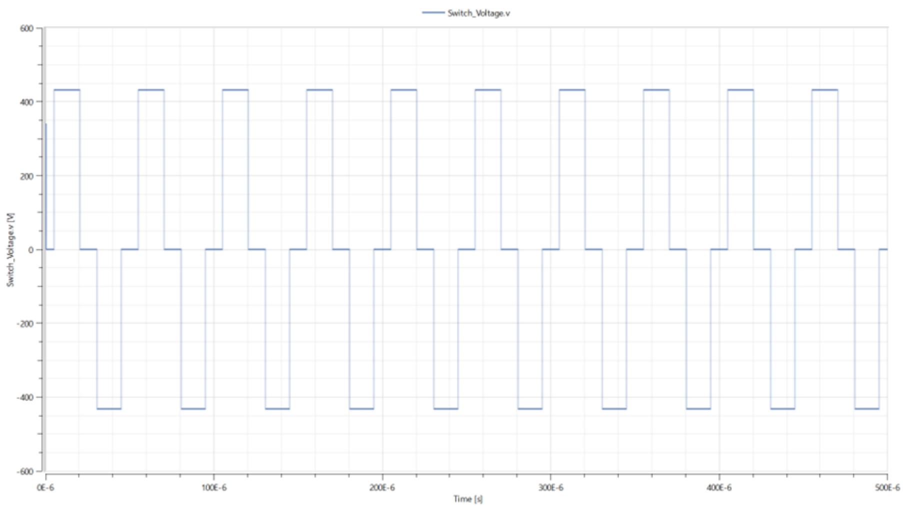

Figure 2: Unipolar Switching Test

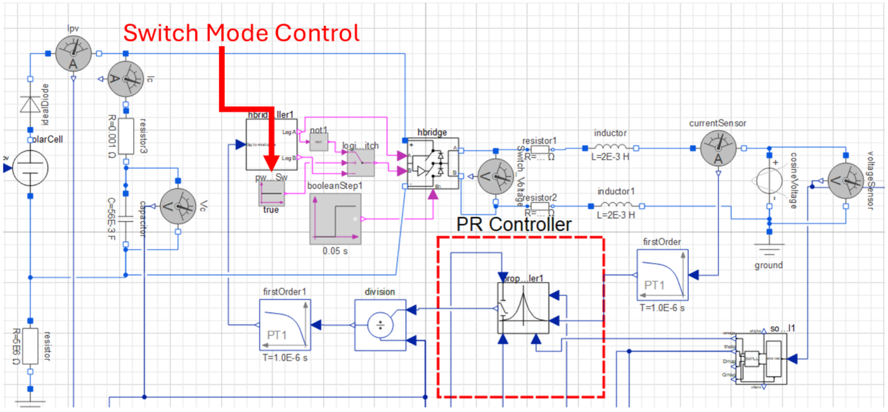

Figure 3: How to set bipolar and unipolar switching

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

1.2 Results

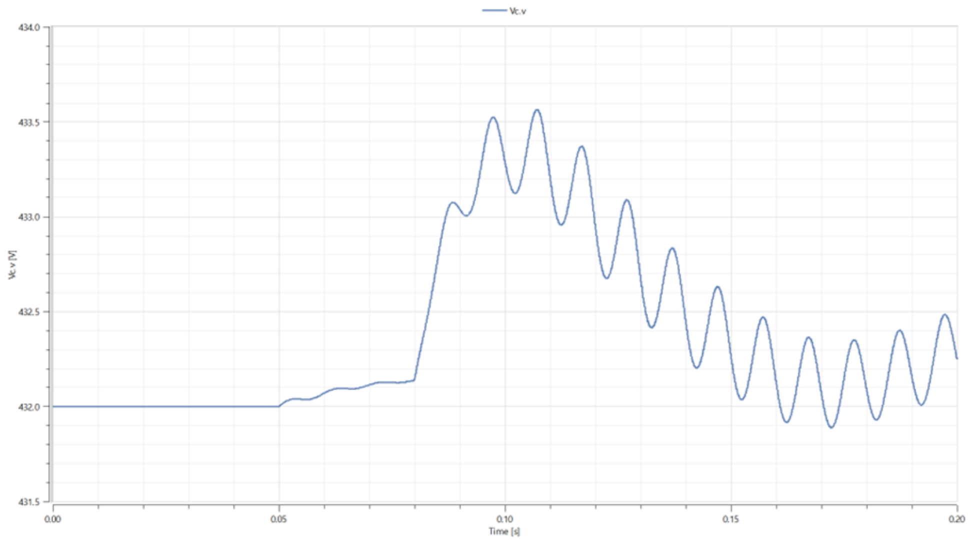

Figure 4: Bipolar V_c, capacitor voltage (PV to GND), Sim Time = 0.2 s

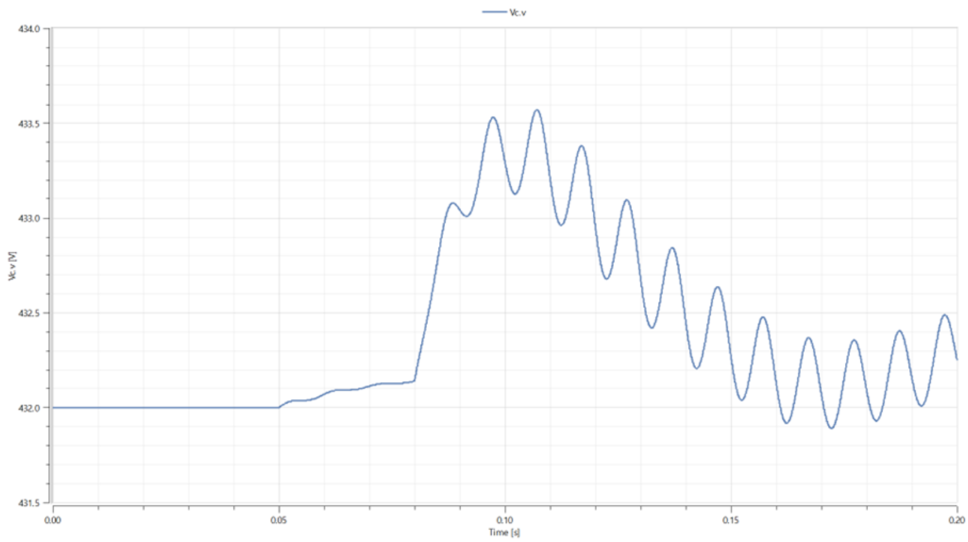

Figure 5: Unipolar V_c, capacitor voltage (PV to GND), Sim Time = 0.2 s

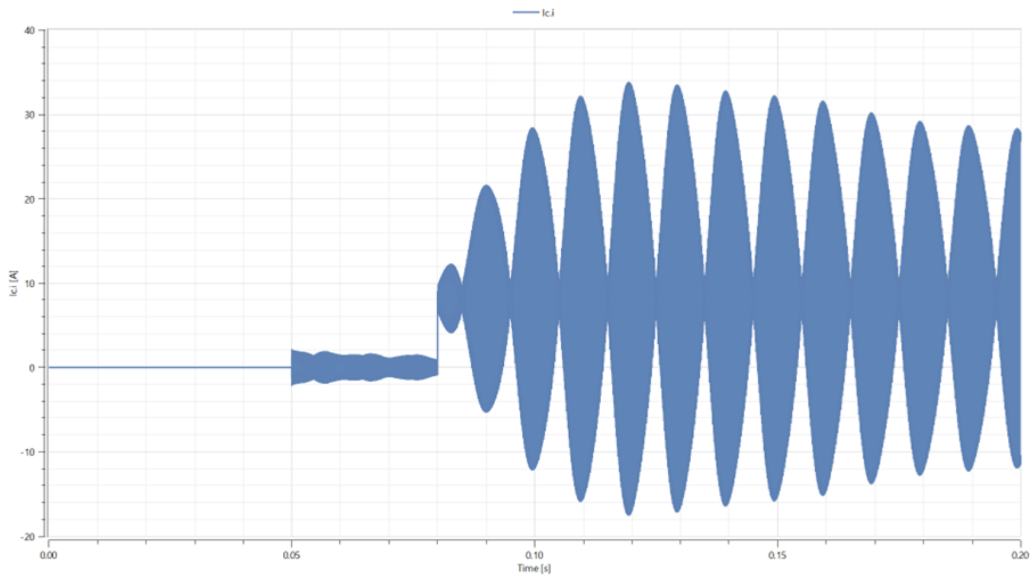

Figure 6: Bipolar I_c, current through capacitor, Sim Time = 0.2 s

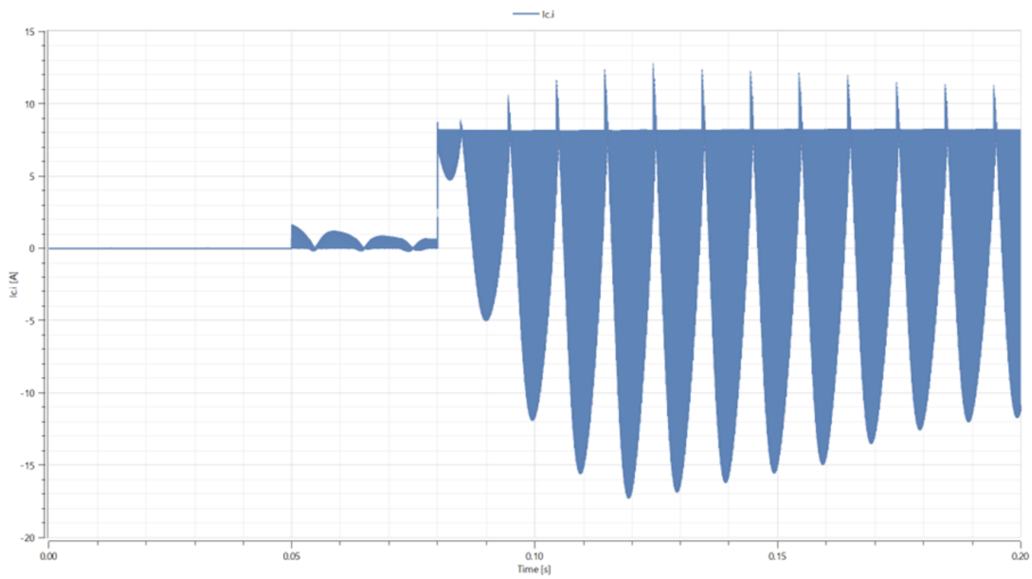

Figure 7: Unipolar I_c, current through capacitor, Sim Time = 0.2 s

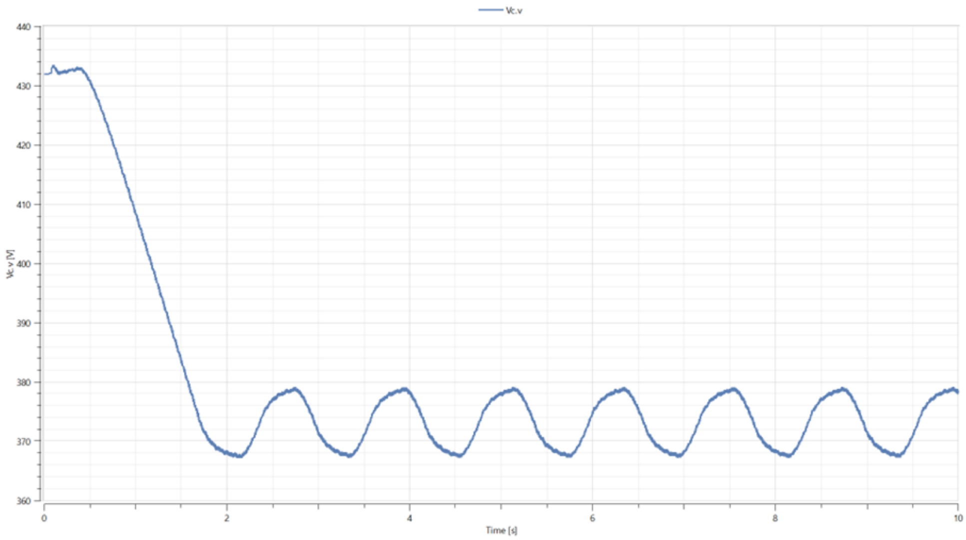

Figure 8: Bipolar V_c, capacitor voltage (PV to GND), Sim Time = 10 s

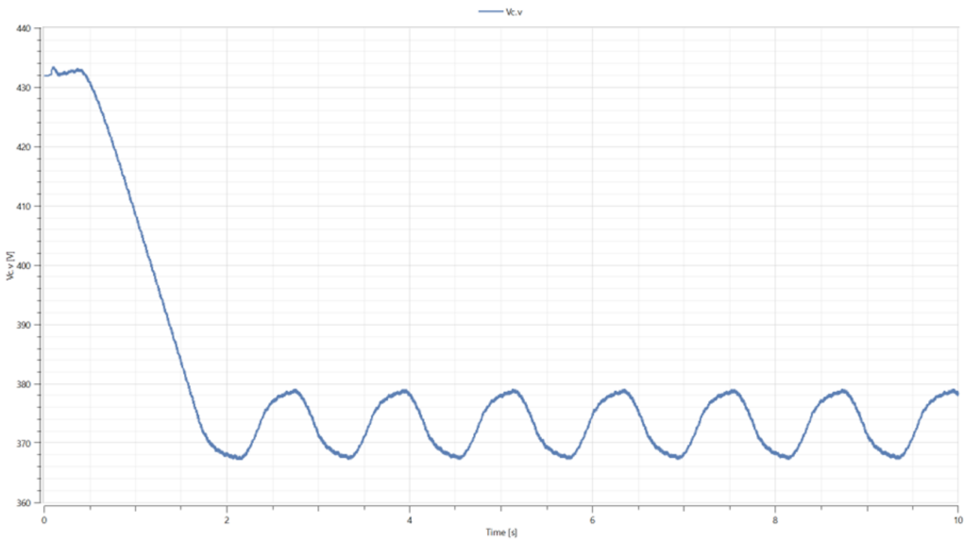

Figure 9: Unipolar V_c, capacitor voltage (PV to GND), Sim Time = 10 s

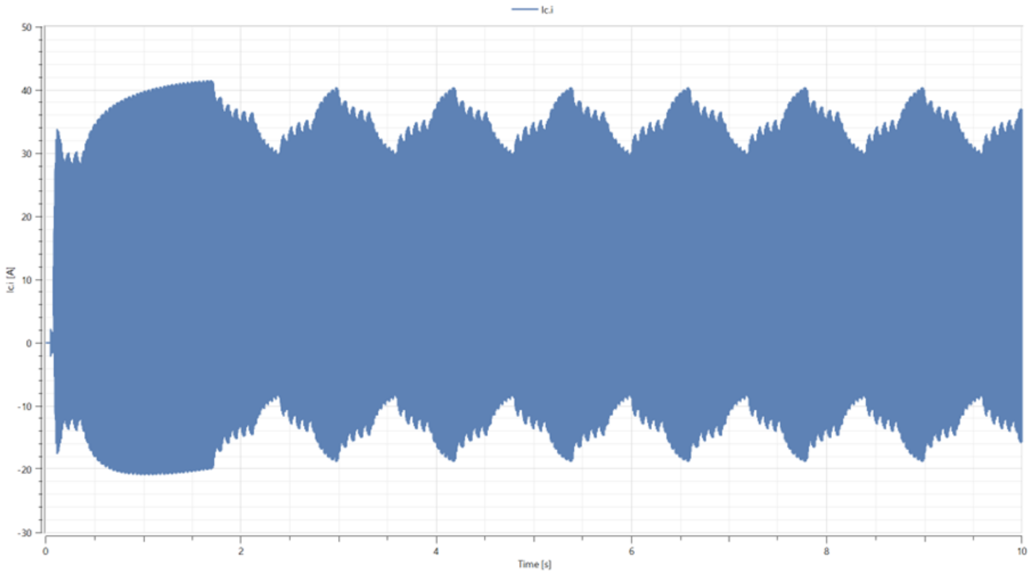

Figure 10: Bipolar I_c, current through capacitor, Sim Time = 10 s

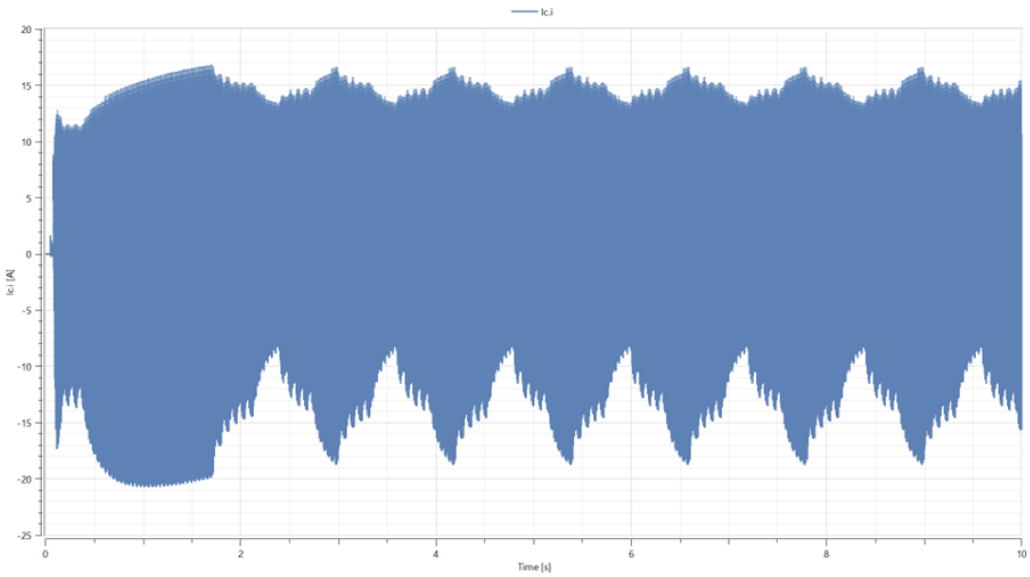

Figure 11: Unipolar I_c, current through capacitor, Sim Time = 10 s

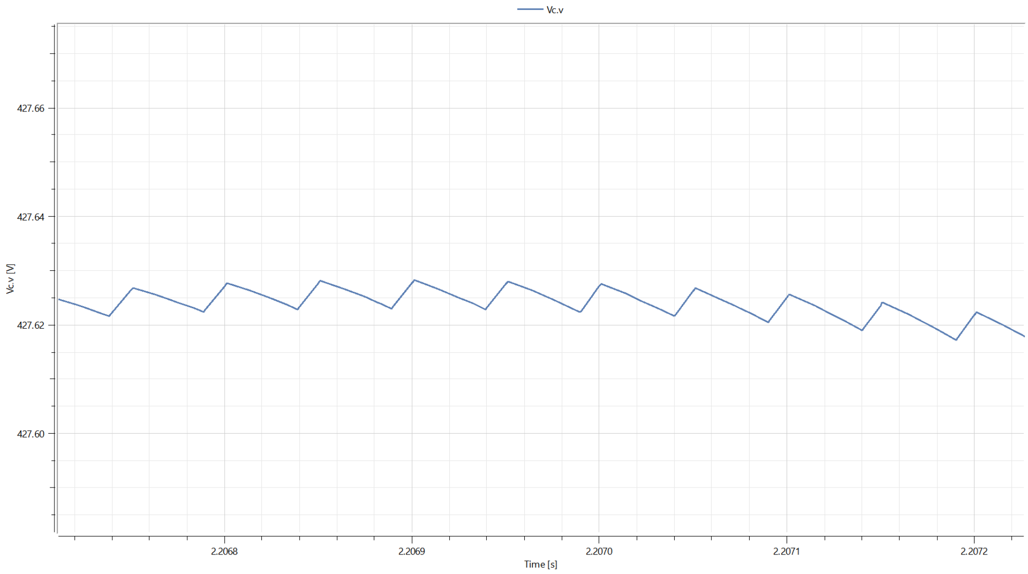

Figure 12: Bipolar, voltage ripple $\Delta V_c = 0.0054$ V, manual zoom

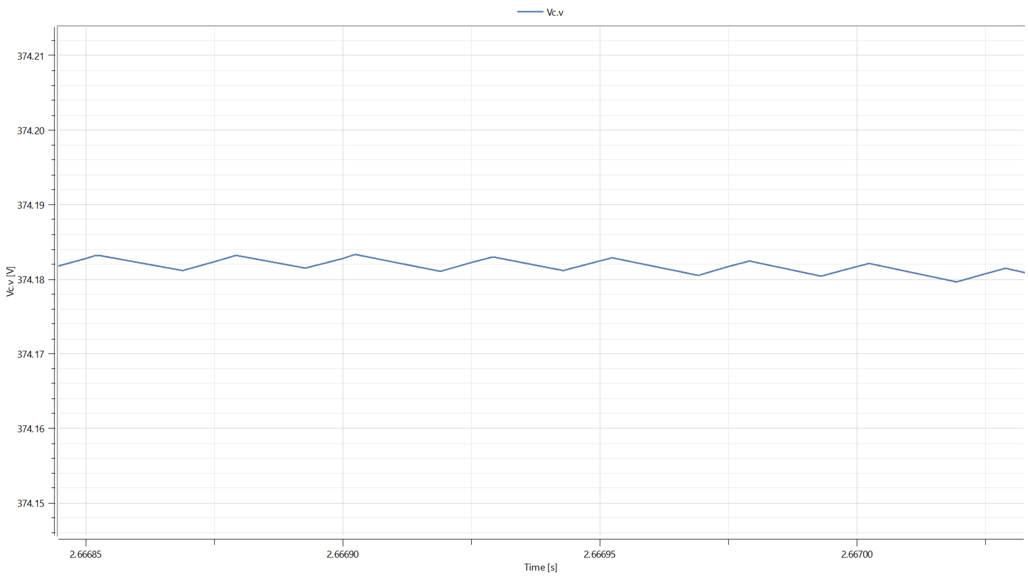

Figure 13: Unipolar, voltage ripple $\Delta V_c = 0.0022$ V, manual zoom

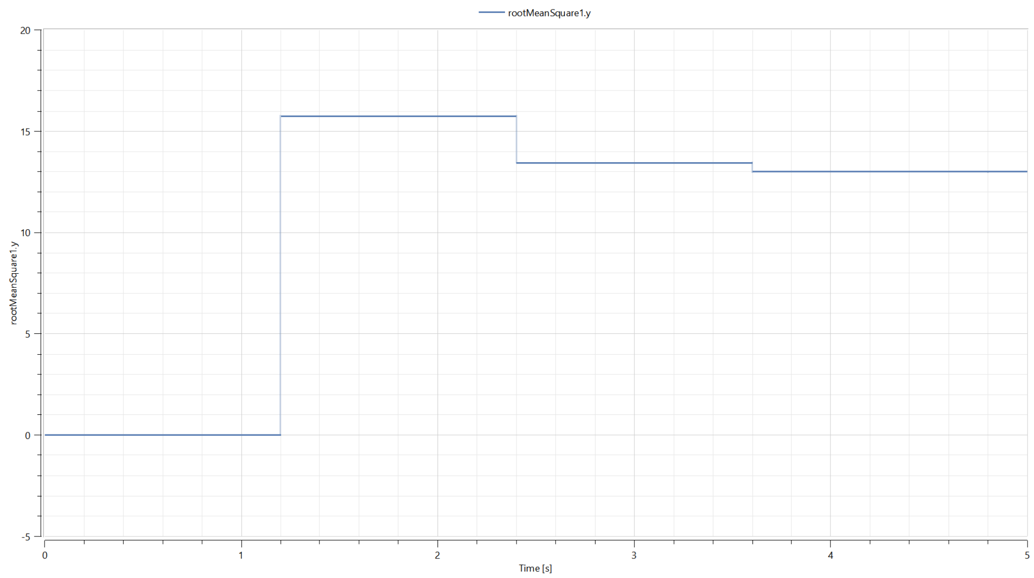

Figure 14: Bipolar, RMS capacitor current, $I_c = 13\ A_{RMS}$ at steady state, Sim Time = 5s

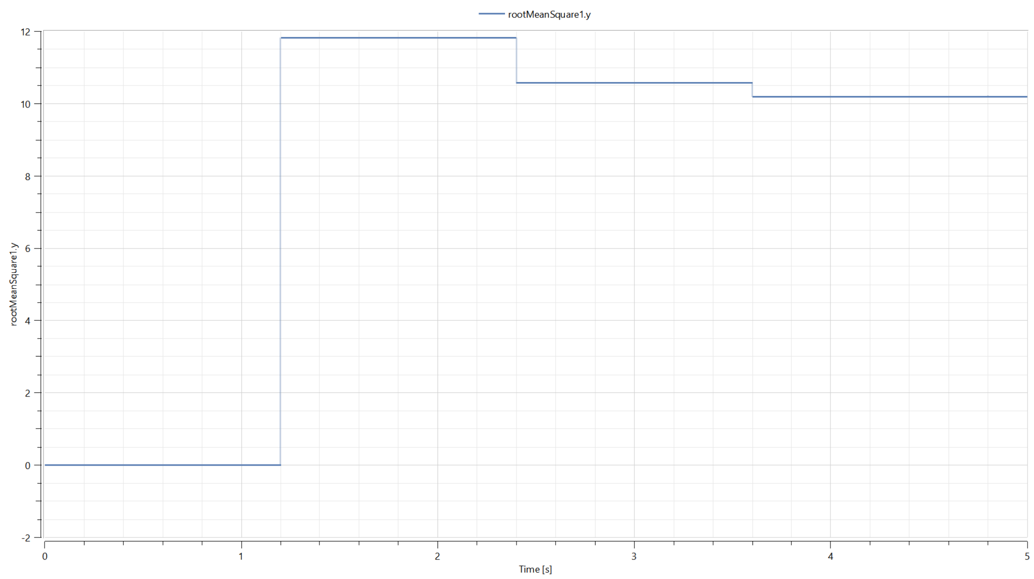

Figure 15: Bipolar, RMS capacitor current, $I_c = 10.2\ A_{RMS}$ at steady state, Sim Time = 5s

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 4 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 the grid sinusoid, 6. This f, is 100 Hz. The grid connected voltage 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. 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 it is a harmonic multiple. The period, is about 1.2 s which was estimated by counting periods within the 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 when converted to discrete is this,

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

Using 7, An estimate of the period and ΔV_c for each component can be determined using wolfram simulation centre plots 12, 4, 8. Subbing in for bipolar switching 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 is gathered the same but using 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 as the each have a 3rd and 5th harmonic. Even if that was the case, there may still be an error as higher order harmonic components, while much smaller in magnitude, do exist and will make noise. This could make up for the missing error percentages.

2 Grid Connected Inverters

2.1 Method

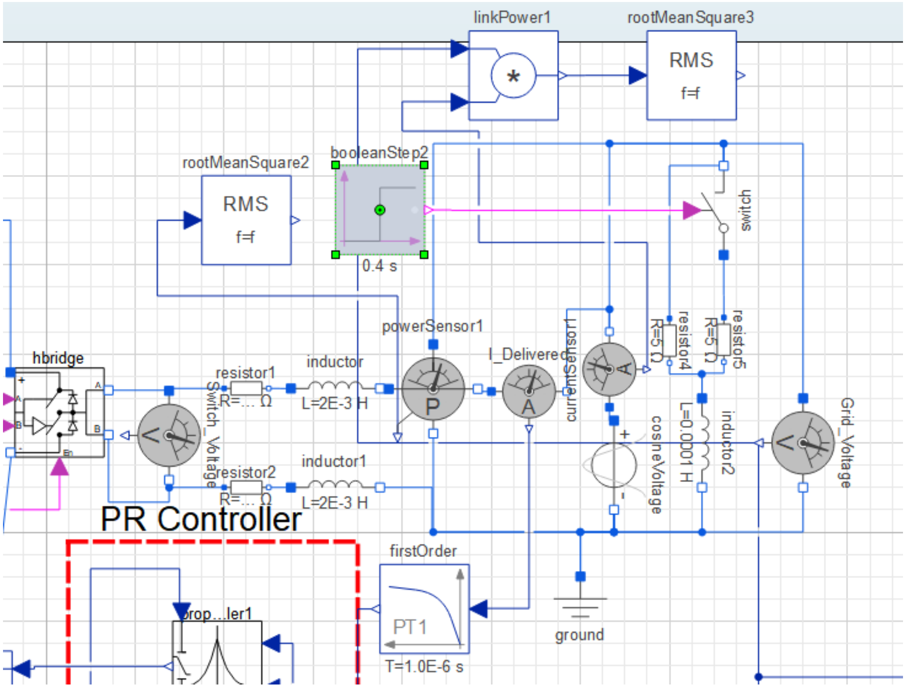

Figure 16: Set Up to confirm grid connected inverter control

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 0.4s. 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. This is changed for the MPPT section, at the end. This allowed more accurate simulations so the current did not do a massive jump initially.

To check the power factor alignment, the simulation was changed manually to a different inductance for different simulations. The inclusion of the switch like for the resistor did not work. The system took too long to adjust. For the MPPT section, the initial capacitor voltage was set to 432 V.

2.2 Results

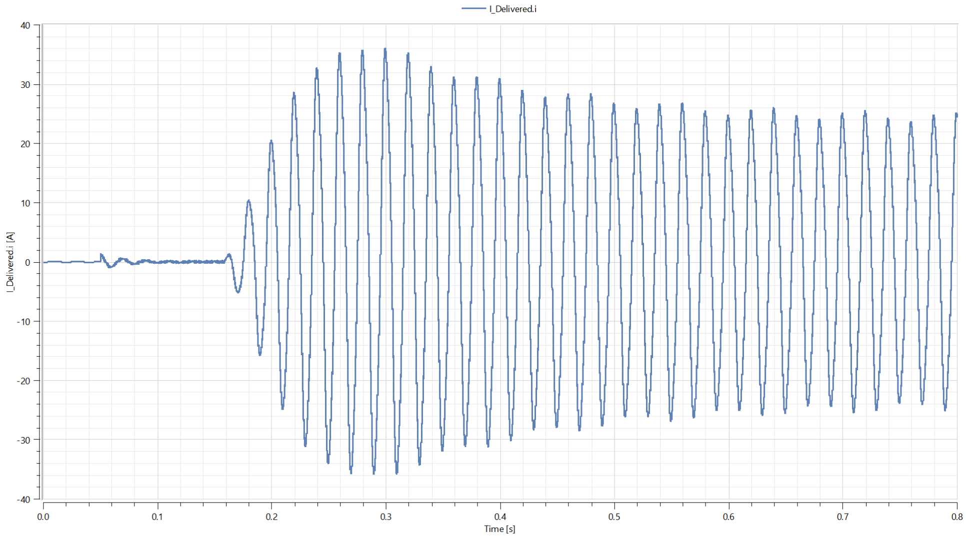

Figure 17: Changing Real, Current delivered from inverter, Sim Time = 1 s

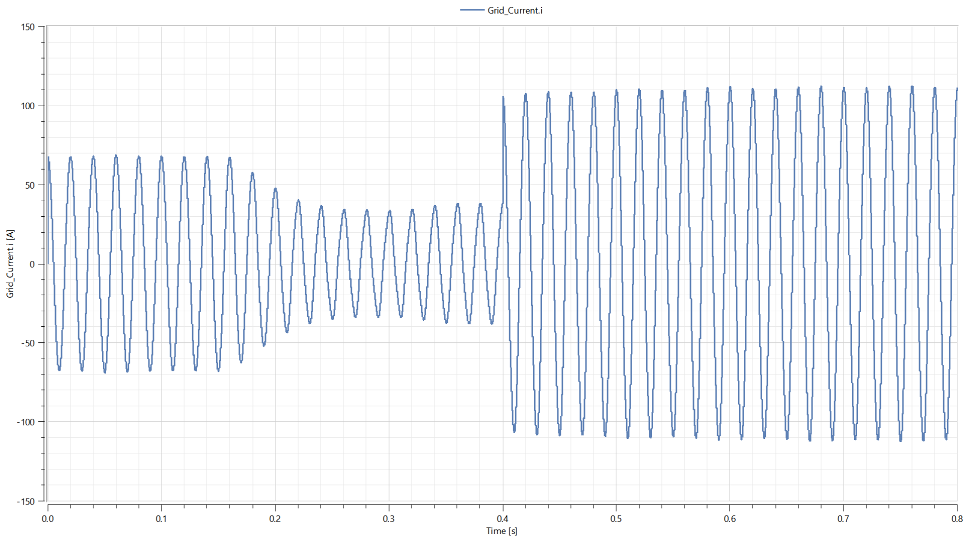

Figure 18: Changing Real, Current delivered to load from grid voltage source, Sim Time = 1 s

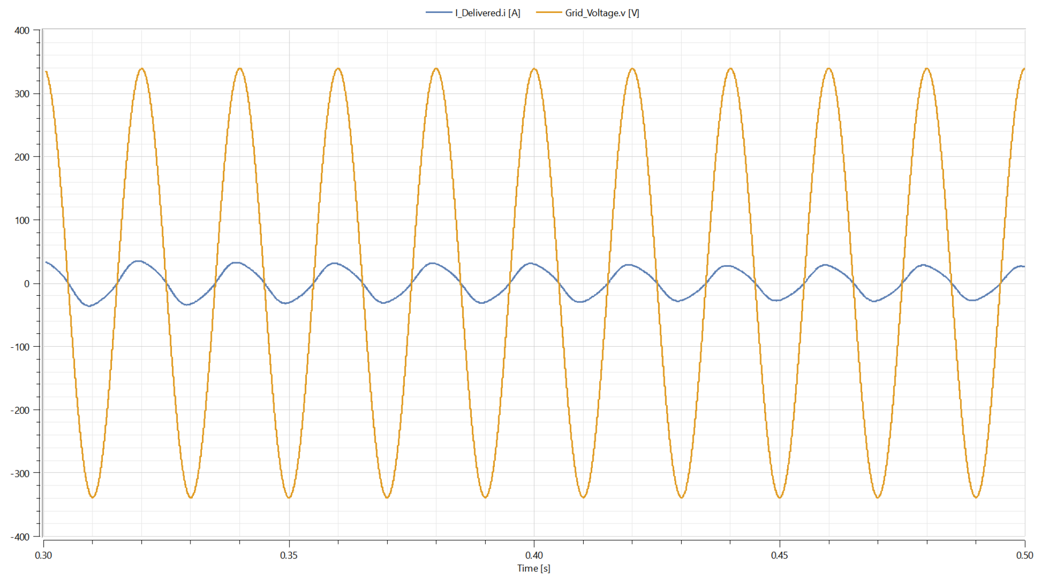

Figure 19: Changing Real, Grid Voltage and Delievered Current, Sim Time = 0.3 - 0.5 s

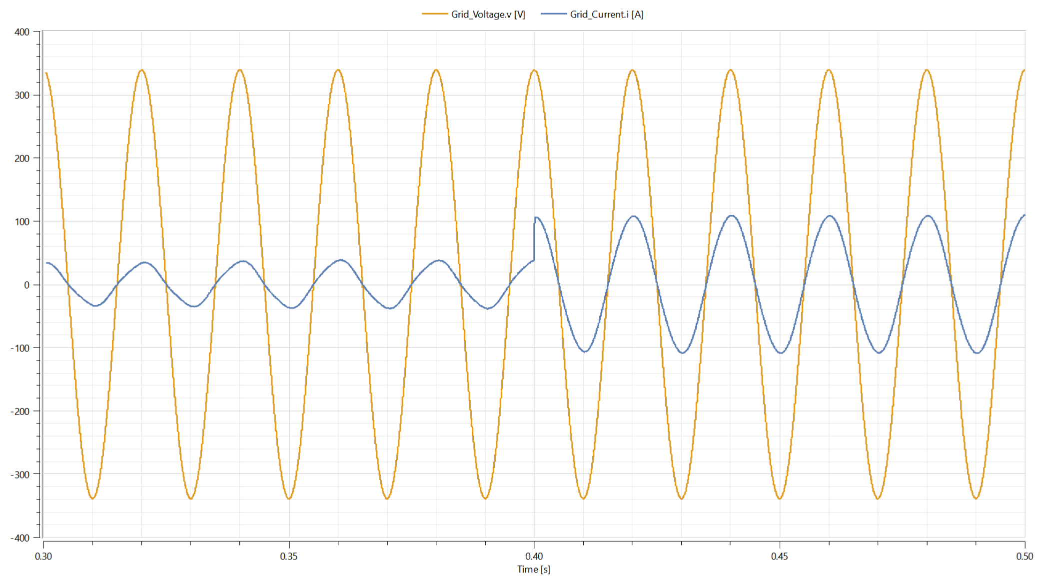

Figure 20: Changing Real, Grid Voltage and Grid Current, Sim Time = 0.3 - 0.5 s

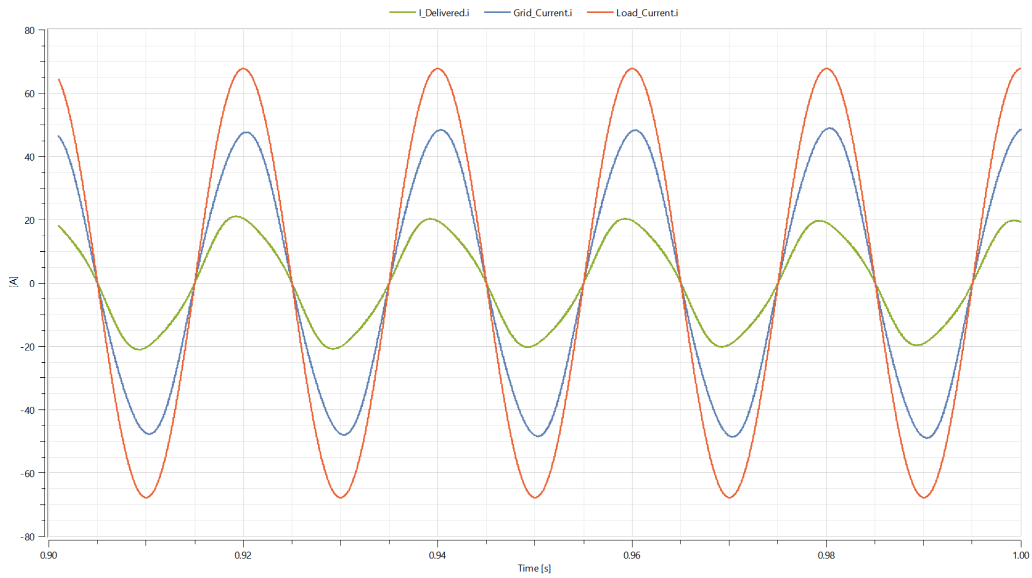

Figure 21: Currents Low Inductance, 0.00001H

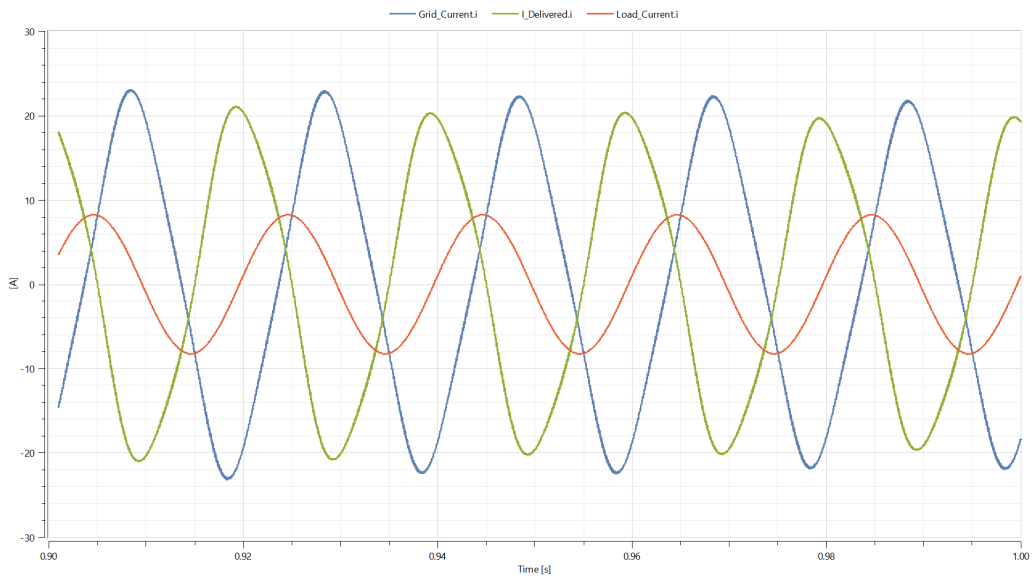

Figure 22: Currents High Inductance, 0.08 H

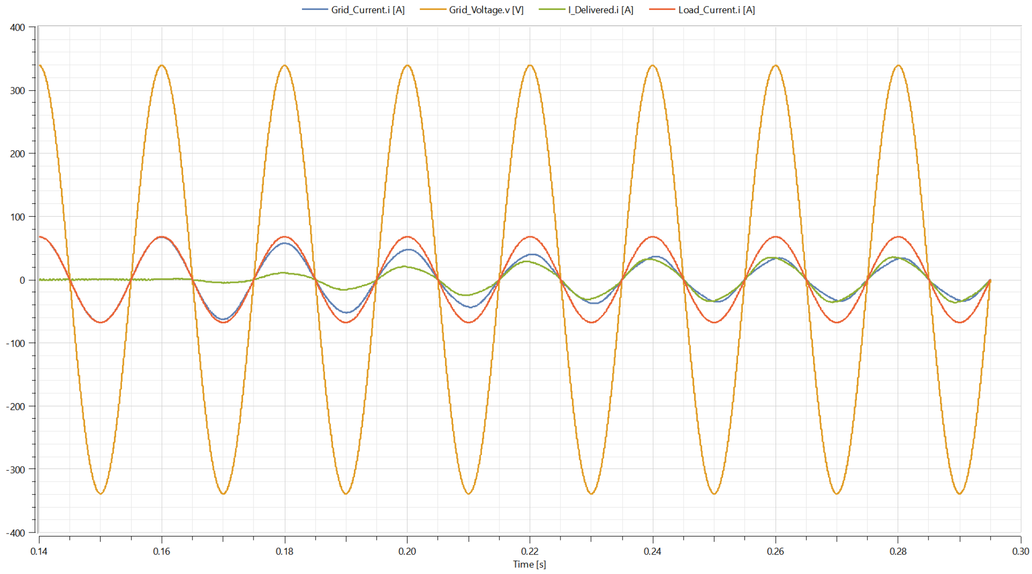

Figure 23: Power Factor Test, Low Inductance, 0.00001 H

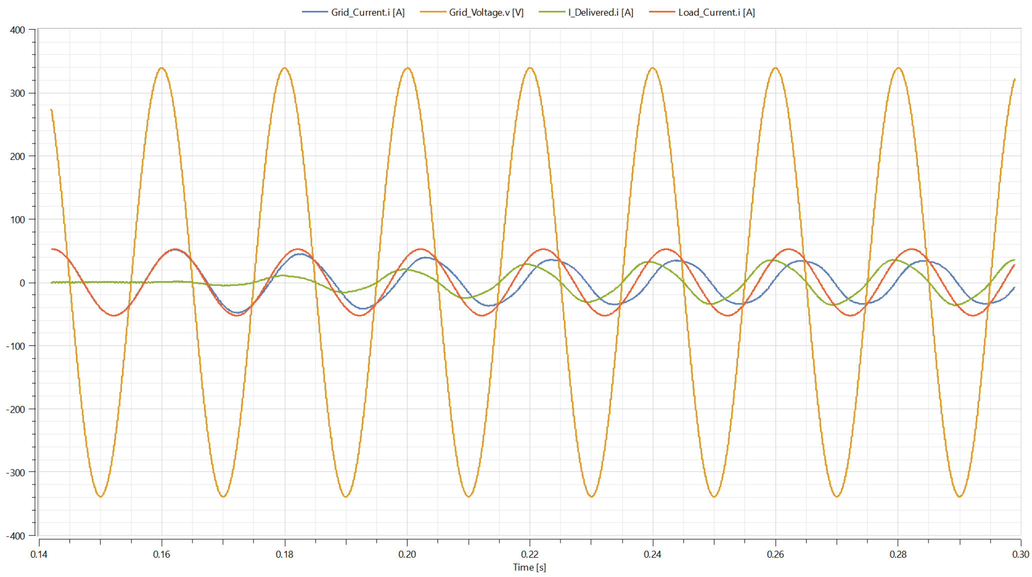

Figure 24: Power Factor Test, High Inductance, 0.013 H

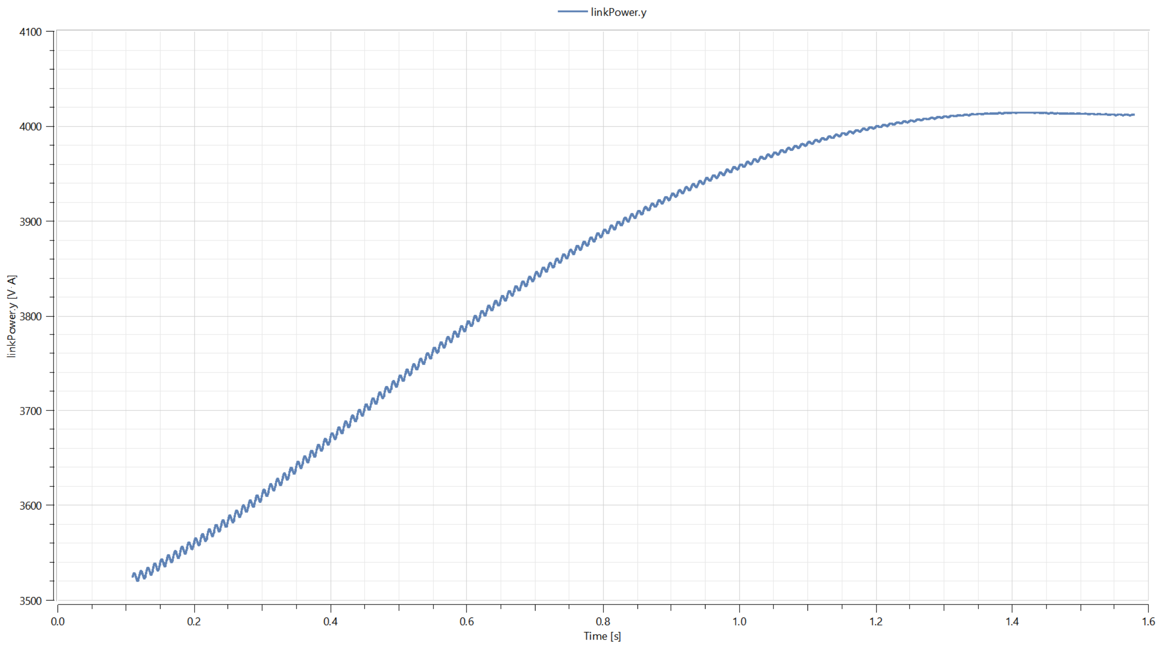

Figure 25: MPPT, P_{PV}

2.3 Discussion

The control system tracks the reference voltage. The system stays constant upon disturbances, 19. The grid has to adjust instead of inverter, 20. This keeps the voltage and power the same, maximising the output power by the solar panels. When an inductive load is added in, the same occurs 24. The inverter tracks the reference and controls the current so that it stays in line with the voltage. This maximises output power.

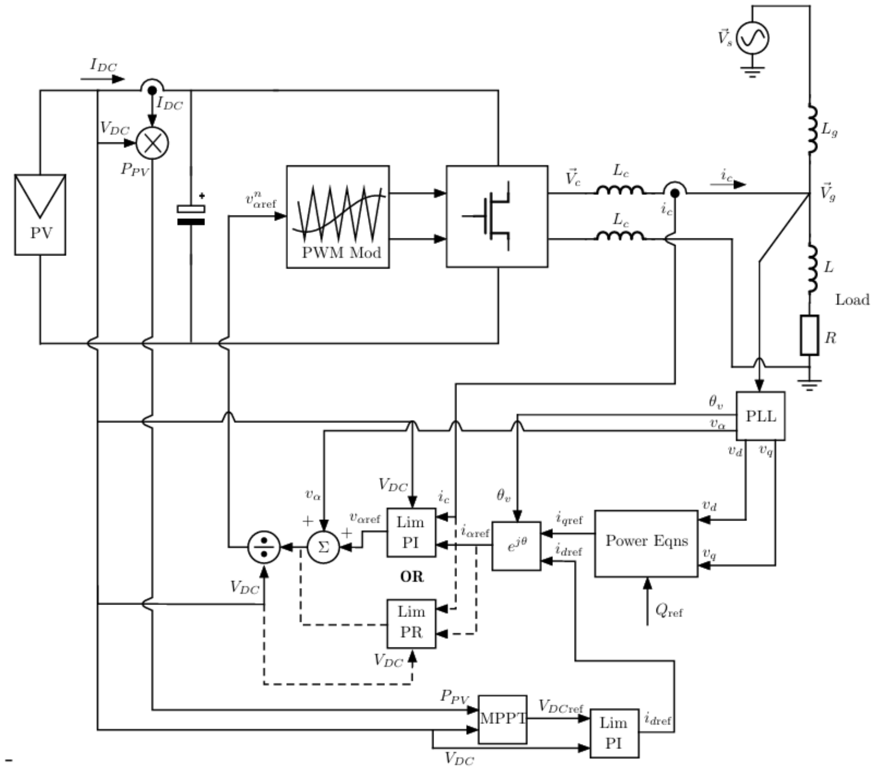

Figure 26: Control System Block Diagram, from [1]

The inverter can be broken into three parts. The Phase Locked Loop, The Controller, and MPPT. The phase locked loop tracks the reference, the grid supply. This gives the contoller the information required to create a varying PWM that mimics a sinusoid after filtering. The MPPT tracks the output power by the PV cell. PV cells aren't constant voltage like a battery. The voltage can vary based on the load resistance or based on the current. The MPPT tracks the current and the voltage to maximise output power, finding the optimal point. The output, a desired current, is fed through the main controller. The delivered current, has some noise to it, 22. This is likely due the 3rd and 5th harmonics, referenced 1.3 and possibly due to control system delays.

For the MPPT, it occurred in the 10 s simulations from the first part, 8. Even though it started at 432 V, it optimised the system for maximum power output and brought the voltage down to the steady state of 376.5 V_{RMS}. The MPPT can be seen maximising the output by looking at the link power, 25.

Everything else in the inverter that is not the PV cells, the Hbridge, the grid and the load is the outputs and inputs to the blocks within the inverter. It is only information, and might require a conversion, for example the park transform but it is still the same information, just in a different form. The information and conversions required depend on the type of controller. This was simulated using the proportional resonant controller, but using space vectors and park transforms it is possible to just use a PI controller.

References

[1] R. Betz, “Supplementary notes - ass 2 2017.” [Online]. Available: https://canvas.newcastle.edu.au/courses/29167/files/7575759?wrap=1