Project Report

Single Phase Grid-tied Inverter with passive damping of the LCL filter utilizing a grid current control with Capacitor current feedback and Grid voltage feedforward.

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Abstract

This project report delves into the comprehensive analysis and implementation of advanced control strategies for single-phase grid-tied inverters featuring LCL filters. The primary focus is on the utilization of a passive damping approach through grid current control, incorporating Capacitor Current Feedback and Grid Voltage Feedforward techniques. The report begins with the development of a Simulink model for a full-bridge inverter using unipolar Sine-PWM, providing a detailed explanation of the model components and their interconnections. Subsequently, the controller design is explored, incorporating equations for the reference grid current and details of the feedback loop, proportional-integral (PI) controller, and capacitor current feedback.

The system study section investigates the behavior of the inverter under different scenarios. Initially, simulations are conducted assuming constant active power with sinusoidal grid voltage, demonstrating the system's response to setpoint changes in power. The report then explores the impact of distorted grid voltage, introducing 3rd and 5th harmonics. Remarkably, the grid current controller proves effective in mitigating the impact of harmonics on the grid current. The final set of simulations examines the system's response at lower power (1 kW) and unity power factor, showcasing the influence of the proportional and derivative components in the grid feedforward. The results highlight the significance of including the derivative component in fully eliminating distortions caused by grid voltage harmonics on the grid current.

In summary, this project provides a comprehensive exploration of advanced control strategies for grid-tied inverters, offering valuable insights into the design and performance of such systems under varying operating conditions. The findings contribute to the optimization of grid-tied inverter control in the presence of challenging grid conditions, laying the groundwork for further advancements in renewable energy integration.

Step 1: Simulink model of the full-bridge inverter with unipolar Sine-PWM.

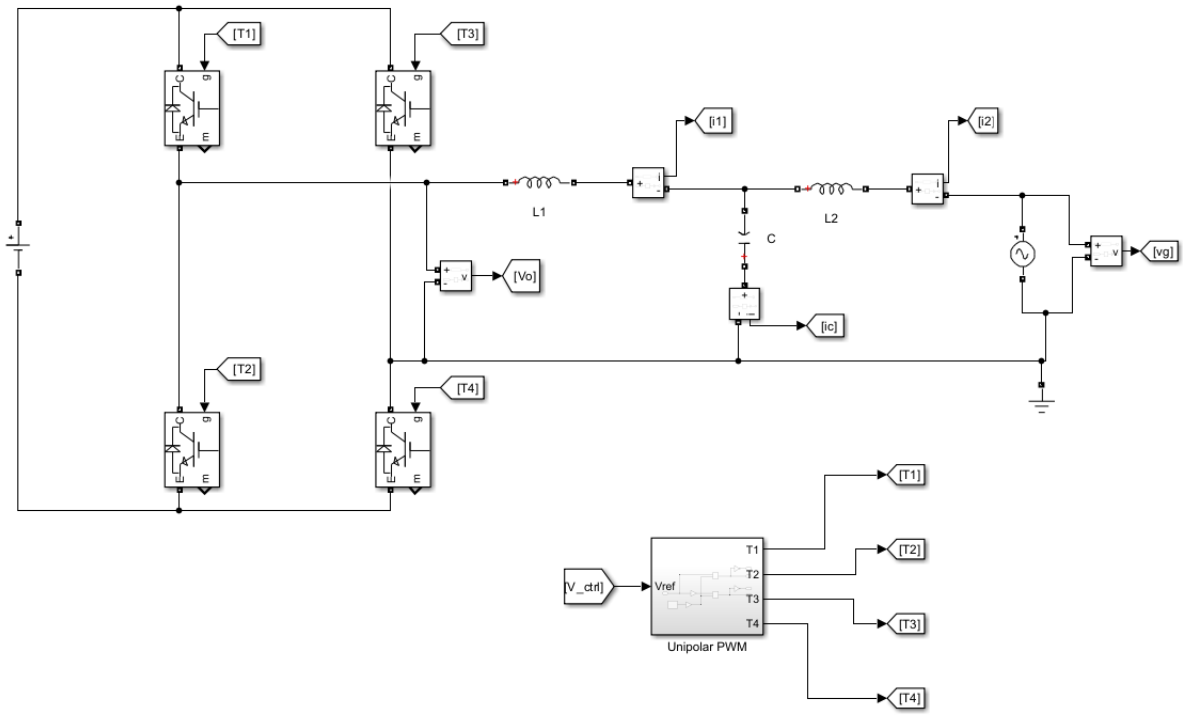

Figure 1 Grid tied inverter with Unipolar PWM

The full bridge inverter was built using the components of the Simscape library. The DC voltage source is used to provides a stable DC voltage input of 500 Volts. IGBTs with antiparallel Diodes have been used as the switches and their gate signals T1, T2, T3 and T4 are generated using unipolar PWM subsystem. The values of the LCL filter components are L1 = 2.6mH, L2 = 0.7 mH and C = 5 uH and they are initialized into the workspace using a Matlab script. An AC voltage source is used to represent the sinusoidal grid voltage and is set at an amplitude of 325 V and 50 Hz frequency. The current and voltage measurement blocks are used to provide the system important variables.

Inside the Unipolar PWM subsystem, the following circuit is modeled.

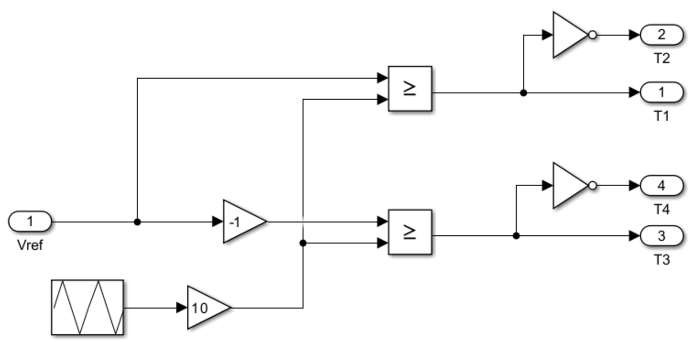

Figure 2 Unipolar PWM subsystem

The reference voltage V_{ref} is the control voltage realized from the Control loop. This is compared to a triangular carrier signal whose amplitude is set to 10 using the consecutive gain block and has 20 KHz frequency.

Step 2: Controller design

The power feed is defined using a constant block. The step inputs in the model are used to give a setpoint step change of the grid power from 4 kW to 3.5 kW and from 3.5 kW to 4 kW at their specified times which are discussed in the simulation exercise later in this report.

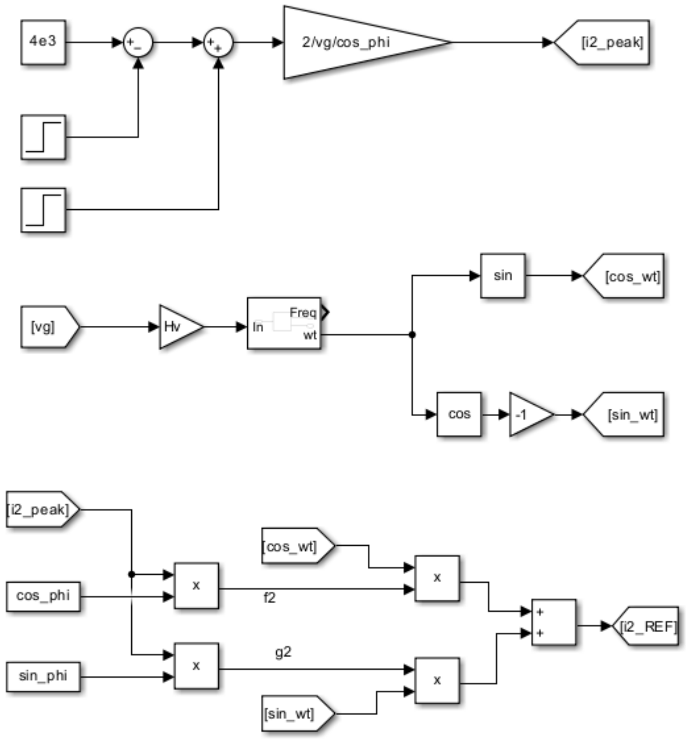

Figure 3 Generation of reference grid current

In figure 4, the control loop used to generate the control voltage $\boldsymbol{V_{ctrl}}$ which is applied for generating gate signals at the unipolar PWM subsystem is presented:

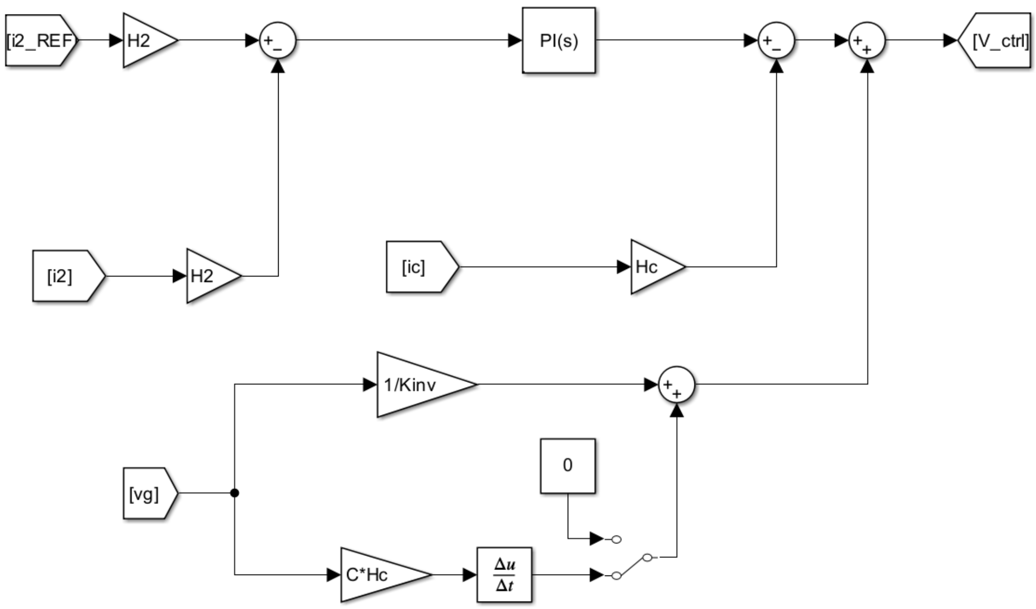

Figure 4 Generation of V_ctrl

The grid current is measured through a sensor of gain $\boldsymbol{H_2} = \mathbf{0.15}$ and is added to the reference grid current $\boldsymbol{i_{2,REF}}$ (measured using the same sensor) through a feedback loop. The resulting signal is the input to the PI controller.

The derivative element of the grid feedforward $\boldsymbol{sCH_c}$ is implemented using a gain block of value $\boldsymbol{CH_c}$ connected to a derivative block. A manual switch is used to select this derivative component or to deselect it.

3. System Study

Case 1

In this case, the simulation time considered is 0.05 seconds. The setpoint to reduce the power to 3.5 kW is at 0.035 seconds and the setpoint to increase it to 4 KW is at 0.045 seconds. The following plots of system variables are obtained:

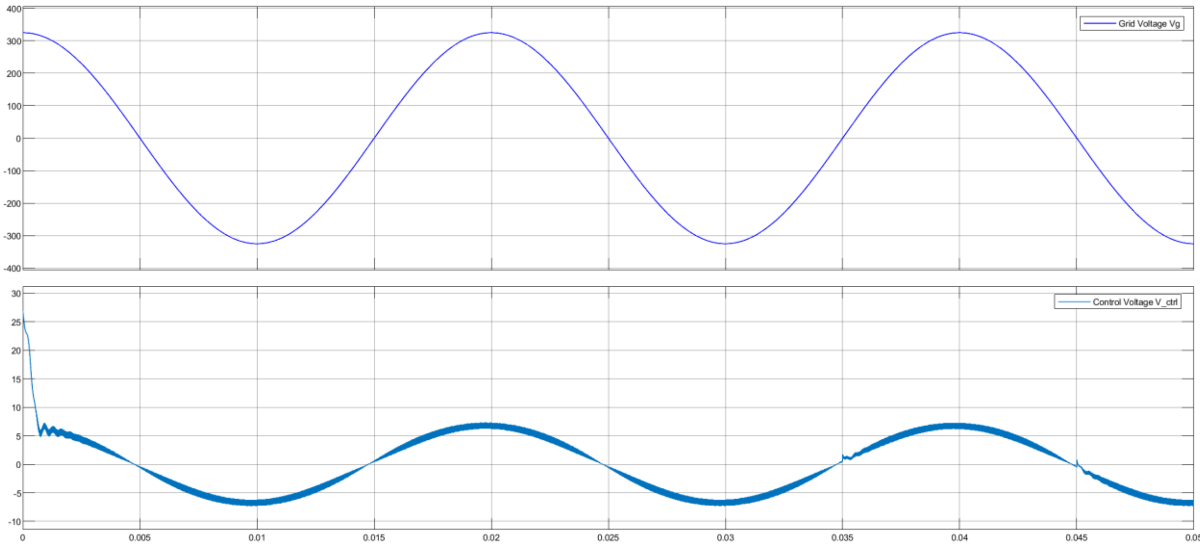

Figure 5 Plot of Grid voltage and Control voltage at Pac = 4 KW and power factor of 0.9

Figure 5 above shows the grid voltage to be a perfect sinusoid. The plot at the bottom shows the control voltage. The waveform reveals distortions in the beginning before the system gets to a steady state. When the power step changes occur at times 0.035 and 0.045s, distortions occur again in the control voltage.

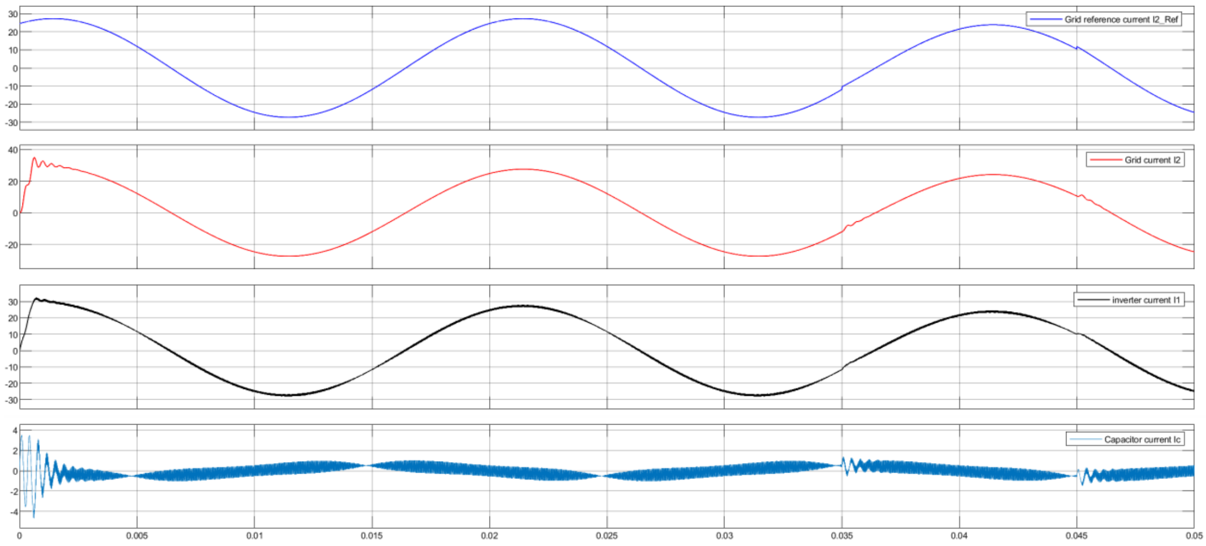

Figure 6 Plot of system currents at Pac = 4 KW and power factor of 0.9 leading

At the top of Figure 6 above, the synchronized reference grid current is shown. It is not in phase with the grid voltage since the power factor is not at unity. There is a reduction in amplitude when the step reduction of power from 4kW to 3.5kW occurs at 0.035s and a consecutive increase in amplitude when the step increment of power from 3.5kW to 4kW occurs at 0.045s. The grid current waveform (red waveform) has distortions in the beginning before a steady state is reached. When power step changes occur, the effect on the grid current is captured by distortions at times 0.035s and 0.045s.

The inverter current waveform (black waveform) reveals the presence of current ripples which are eliminated by the filter capacitor. They are represented as the capacitor current on the bottom plot.

<u>Case 2</u>

3rd and 5th Harmonics have been introduced to the grid voltage by adding two ac voltage sources to the grid voltage one with 180 degrees phase shift at 5% amplitude with a frequency of 150 Hz and another with 150 degrees phase shift at 6% amplitude with frequency of 250 Hz.

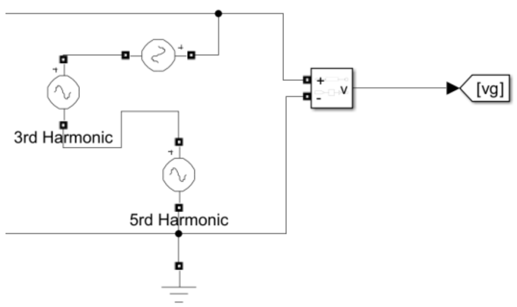

Figure 7 Harmonics addition

The following plots of system variables are obtained:

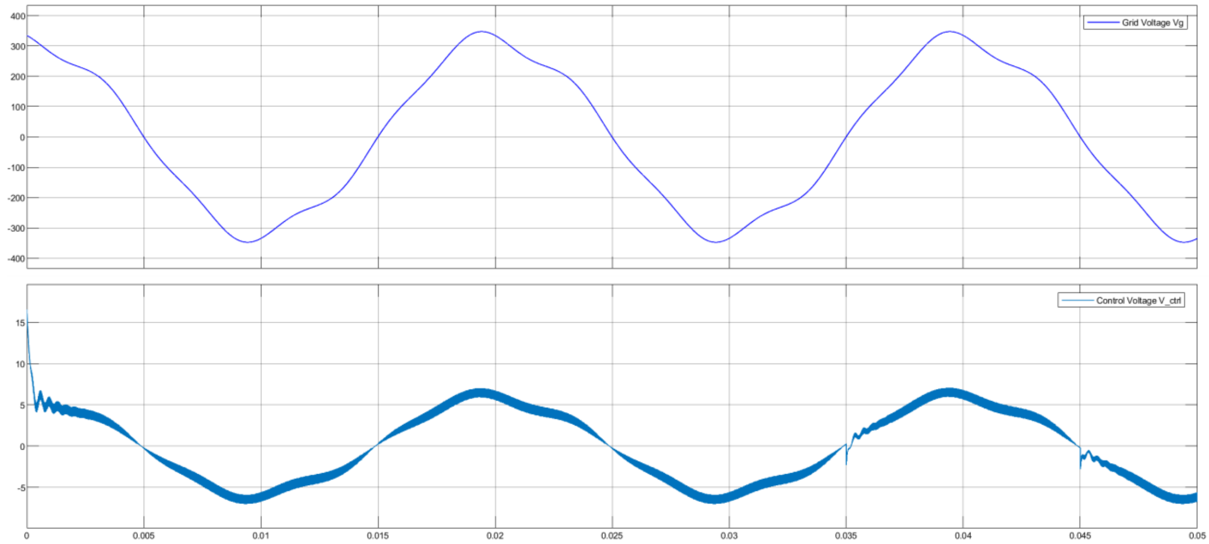

Figure 8 System voltages with addition of 3rd and 5th harmonics

Figure 8 above shows the grid voltage with the 3rd and 5th Harmonics. The plot at the bottom shows the control voltage considering the harmonics. The waveform reveals distortions in the beginning before the system gets to a steady state. When the power step changes occur at times 0.035 and 0.045s, distortions occur again in the control voltage.

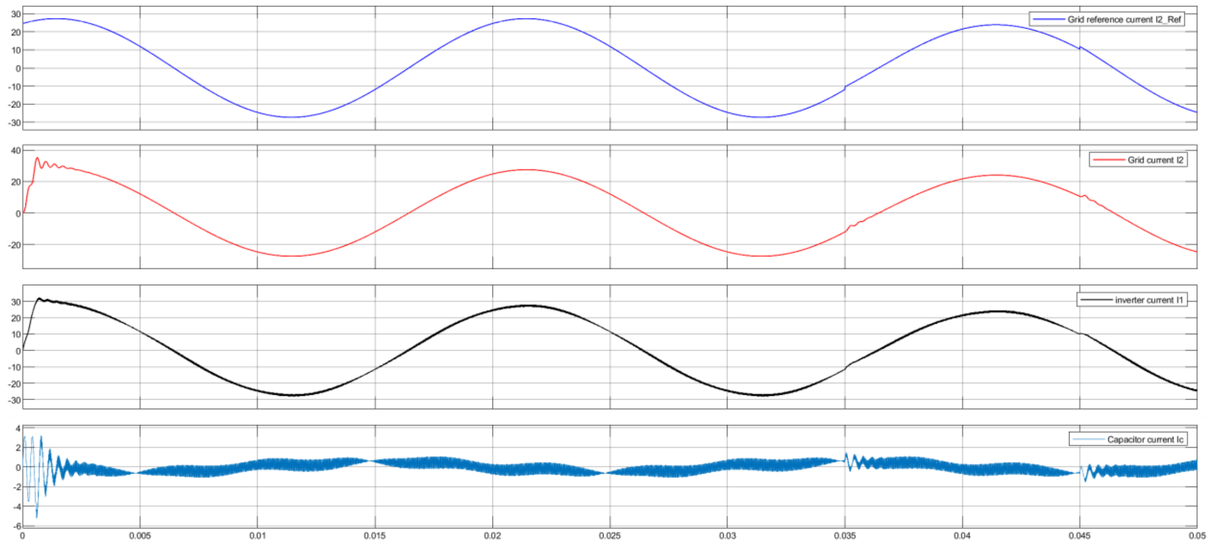

Figure 9 System currents with addition of 3rd and 5th harmonics

At the top of Figure 9 above, the synchronized reference grid current is shown. It is not in phase with the grid voltage since the power factor is not at unity. The harmonics on the grid voltage do not appear on this waveform since it only synchronized to the fundamental component of the grid voltage. The grid current waveform (red waveform) in steady state operation is not distorted by the grid voltage harmonics. This shows that the grid current controller implemented worked well to mitigate the impact of grid voltage harmonics on the grid current. The step changes in power at 0.035 and 0.045s are captured by distortions and reduction and increase in current amplitudes respectively.

Case 3

The power feed as shown in figure 3 is changed to 1 kW. The derivative component is deselected from the feedforward using a manual switch as shown in figure 4. The 3rd and 5th Harmonics are considered in the grid voltage. The following plots of system variables are obtained:

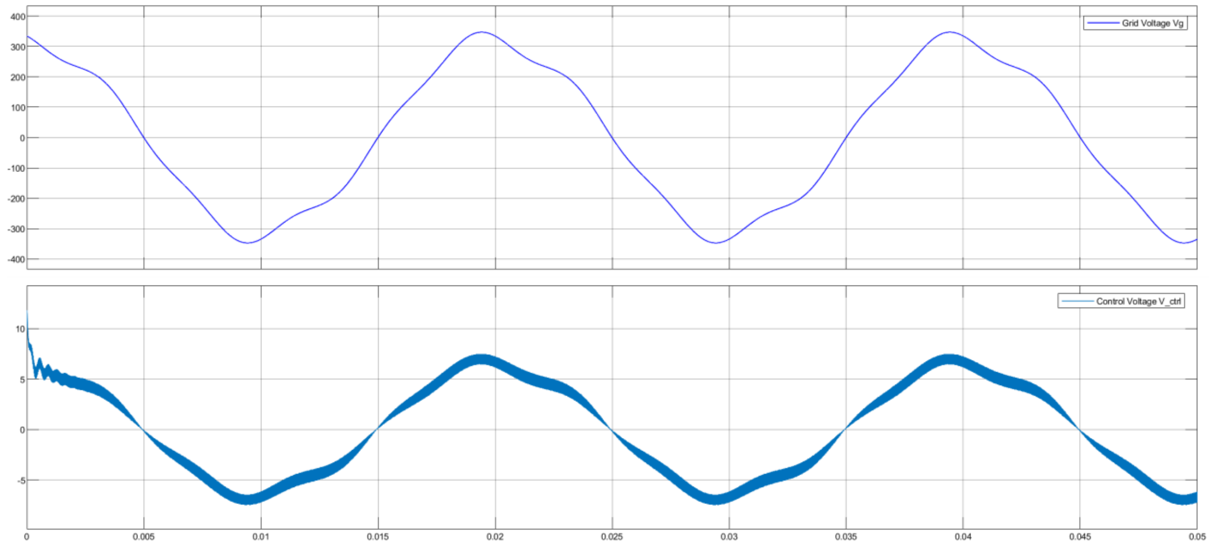

Figure 10 System voltages with Pac = 1 kW, power factor = 1, Proportional component only in $G_{ff}(s)$

Figure 10 above shows the grid voltage with the 3rd and 5th Harmonics at power input of 1 kW at power factor of 1. The plot at the bottom shows the control voltage considering the harmonics. The waveform reveals distortions in the beginning before the system gets to a steady state.

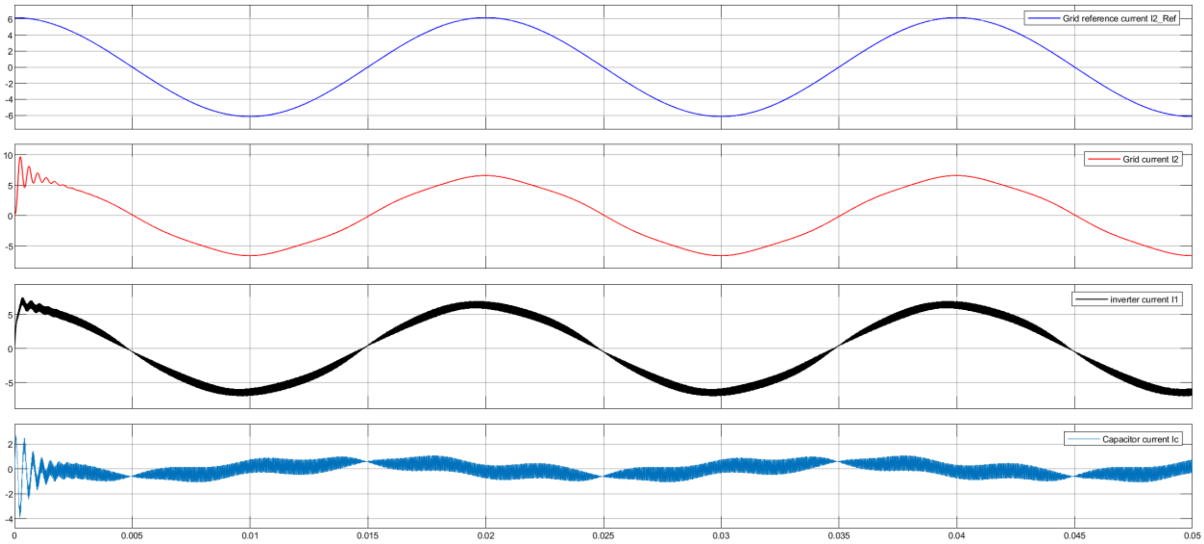

Figure 11 System currents with Pac = 1 kW, power factor = 1, Proportional component only in $G_{ff}(s)$

At the top of Figure 11 above, the synchronized reference grid current is shown. It is important to note that it is in phase with the grid voltage since the power factor is at unity. Its amplitude level has dropped now to 6A for a lower input power of 1 kW. The harmonics on the grid voltage do not appear on this waveform since it only synchronized to the fundamental component of the grid voltage. The grid current waveform (red waveform) in steady state operation reveals a considerable amount of distortions by the grid voltage harmonics since it is not perfectly sinusoidal. This shows that the grid current controller implemented only with the proportional component of the Grid feedforward is not optimized to mitigate the impact of grid voltage harmonics on the grid current. The Derivative component is needed to fully cancel out the effect of the grid voltage harmonics on the grid current as investigated in part (b) in the next subsection.

<u>Case 4</u>

The derivative component is included in the feedforward using a manual switch as shown in figure 4. The 3rd and 5th Harmonics are considered in the grid voltage. The following plots of system variables are obtained:

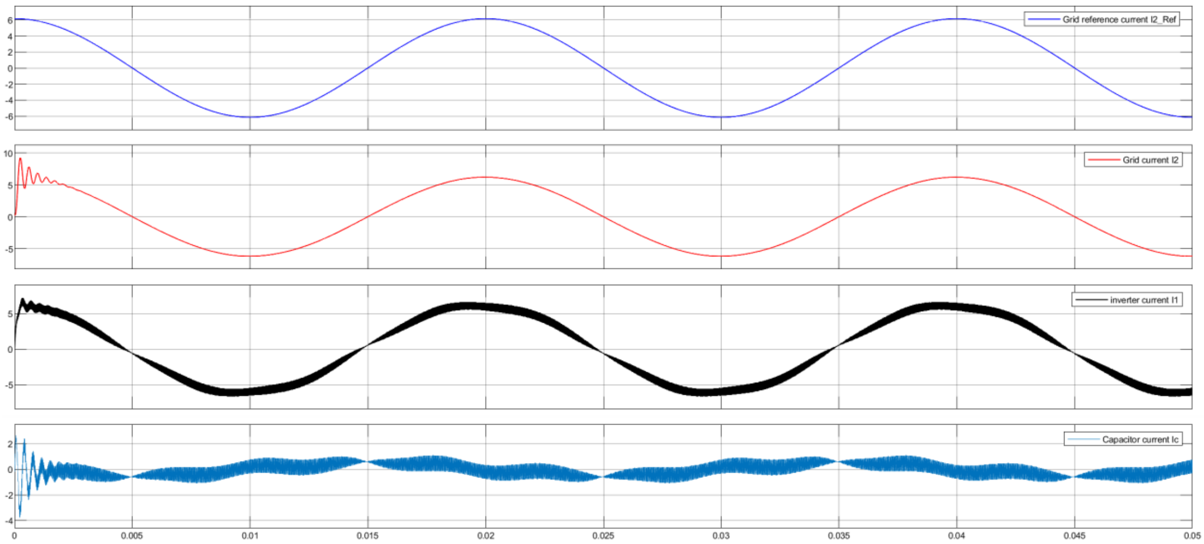

Figure 12 System currents with Pac = 1 kW, power factor = 1, Proportional and Derivative components in Gff(s)

In figure 12 above, the system current waveforms when both proportional and Derivative components in the feedforward are applied have been presented. The grid current waveform (red waveform) in steady state operation has no distortions by the grid voltage harmonics since it is perfectly sinusoidal. This shows that the grid current controller implemented with both the proportional and derivative components of the Grid feedforward is optimized to mitigate the impact of grid voltage harmonics on the grid current. The Derivative component plays a key role in the complete elimination of the grid voltage harmonics effects on the grid current.