Harmonics Mitigation Project –

Work Package 2: Algorithm Design, Development and Implementation for Single Inverter Control

Issue 1 17/11/2020

Section 1.1 - Overview

- The aim of Work Package 2 (WP2) is to develop and validate a control algorithm intended to utilise existing photovoltaic (PV) inverters as active filters (AF). This functionality is in addition to the main task performed by these devices, that is to deliver active power from the PV panels to the power grid.
- The development of the active filter functionality consisted of determining appropriate control algorithms along with their control parameters that allows the PV inverter to inject harmonic current components equal in magnitude and opposite in phase with respect to existing harmonics on a feeder used as the measuring point on the grid. As a result, cancellation of network harmonic currents is obtained, leading to reduced distortion in the upstream network.
- The effectiveness of the proposed algorithm was tested with varying harmonic levels, varying levels of irradiance and for unbalanced network conditions. Additional controls were added to ensure that the PV inverter rating and the associated power transformer rating are not exceeded when harmonics are injected.
- The impact of the proposed control on system technical performance was evaluated by using the EMT simulation model developed as part of WP1. This model is a close representation of system operating conditions for the month of October 2019. Harmonic levels were compared for the original case, and for the case where active filter functionality is deployed.
- The following slides will set out the specification for the work; describe the developed algorithm; outline testing undertaken to confirm functionality; and evaluate the impact on harmonic levels within the Tiverton 33 kV Network.

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Section 1.2 – Specification and Scope

- The developed algorithm will take feeder current measurements as inputs and regulate inverter switching to inject anti-phase harmonic currents to achieve harmonic cancellation.
- Factors such as phase shift of any interface transformer and delays in the acquisition of measurement data will be considered
- The algorithm will not cause any thermal, voltage, fault level or other constraint in the network, and will not cause the power rating of the inverter to be exceeded.
- The algorithm will be demonstrated via an individual inverter under different operating conditions, including changing inverter output power and changing system harmonic levels.
- The benefits of the algorithm will shown through a detailed comparison of modelled system harmonic performance with and without the harmonic mitigation algorithm.
- Work Package 2 documentation will include a copy of the full developed algorithm code.

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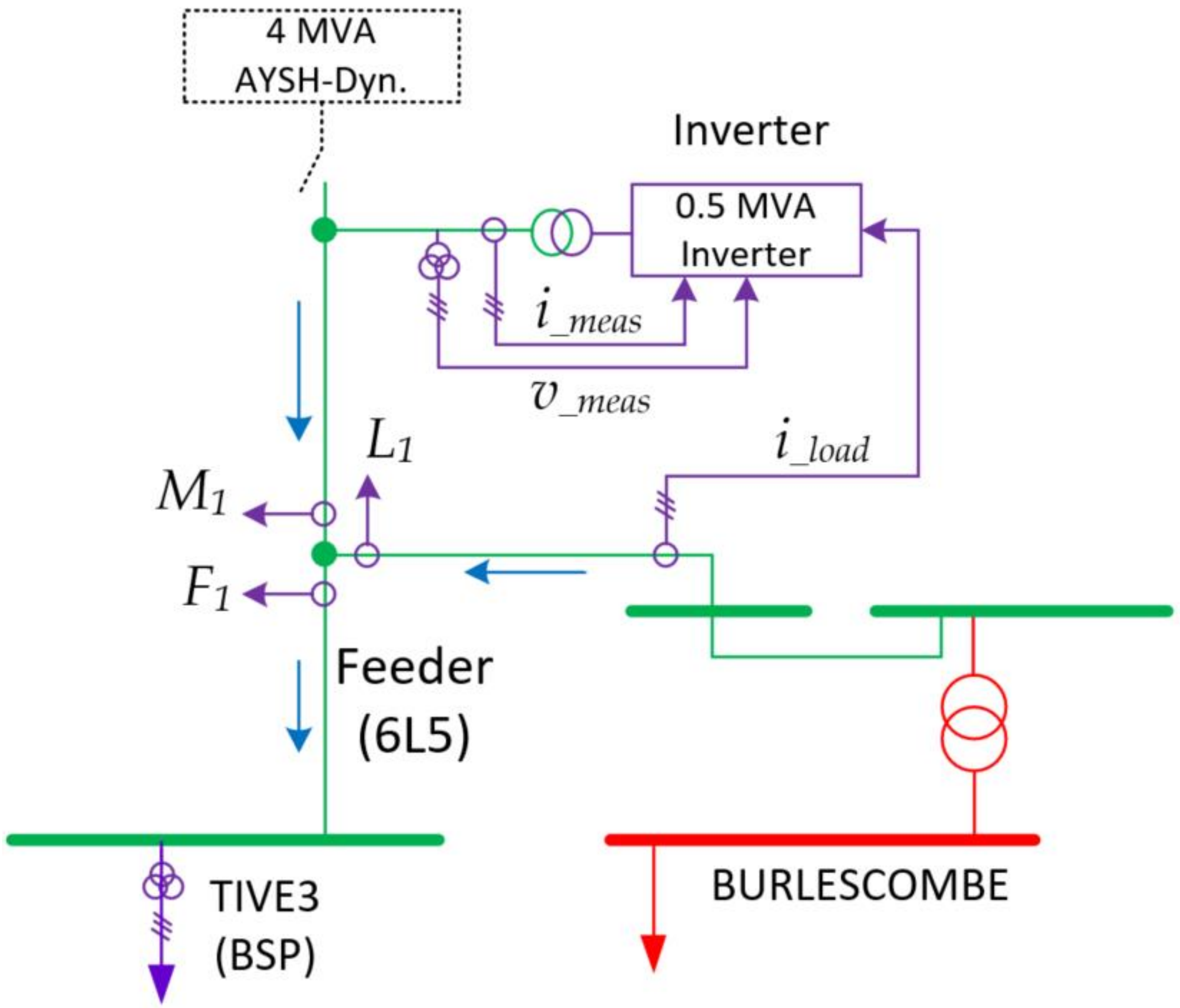
Section 1.3 - Measurements Points

- The Ayshford 500 kVA PV inverter is considered for the development of the algorithm. This converter is connected to a 33/0.4 kV step-up transformer with the same rated power.
- The PV inverter, the equivalent model of the PV farm (4 MVA), and the surrounding power system are shown in the figure to the right. The wider Tiverton Network is not shown for simplicity.
- The current and voltage measured on the high side of the transformer and the load current are used as feedback signal for the control ($i_{\_meas}$, $v_{\_meas}$ and $i_{\_load}$).
- The effectiveness of AF operation is tested by monitoring the following quantities:
  - M1 - PV inverter current
  - L1 - load current
  - F1 - feeder current
  - TIVE3 – voltage at the BSP



Section 2 - Design and development

- The following slides in Section 2:
  - describe the key functional elements of the active filter (AF) algorithm (Section 2.1);
  - summarise issues that were encountered and overcome during development (Section 2.2); and
  - detail testing of the developed algorithm (Section 2.3).

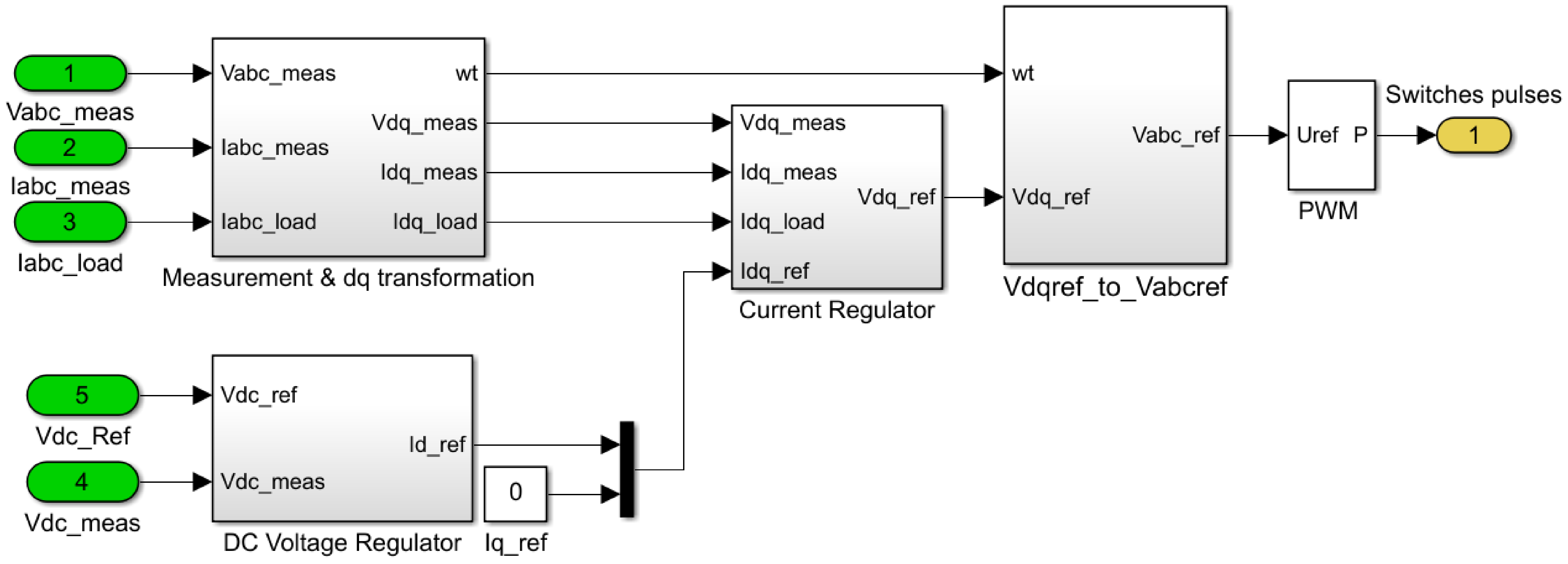
Note: the AF algorithm is designed to be added to an existing fundamental power controller

2.1 Key functional elements
Control Algorithm – Overview

The control algorithm consists of five main blocks as shown in the screenshot:

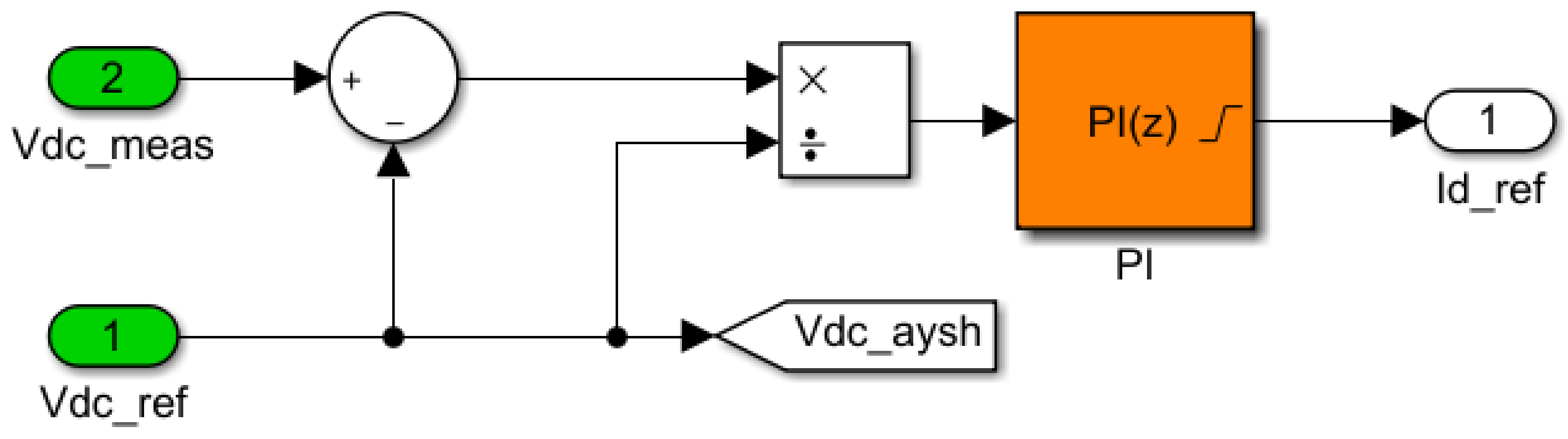
- DC voltage Regulation.
- Measurements and dq transformation.
- Current Regulation.
- Reference voltage transformation from dq frame to abc frame.
- Pulse Width Modulation (PWM).

In the following slides, the first three blocks are described in detail. An extensive discuss of the functionality within blocks D and E can be found in WP1a report (Literature Review).



A. DC voltage regulator

- The DC voltage regulator is a standard block of PV inverter control and allows calculating the reference current for the inverter at fundamental frequency (Id_ref), based on solar irradiance.
- When AF operation is implemented, additional harmonic current components are superposed to the fundamental component, and the dc voltage follows the fluctuations in the output current. Therefore, voltage ripples are observed, that cause suboptimal operation of the controller. To mitigate this issue, the dc voltage reference is increased from 580 to 700 V, thus reducing the impact of the oscillations on the controller.
- The proposed DC voltage reference value is well within the maximum permissible rating, and within the dc voltage range permissible during normal infeed operation. Additionally, this inverter is equipped with overvoltage protection activated when Vdc > 1 kV, again well above the proposed reference value.
- Based on the above, the proposed change in Vdc ref is acceptable and will not cause any issues on the PV inverter operation.

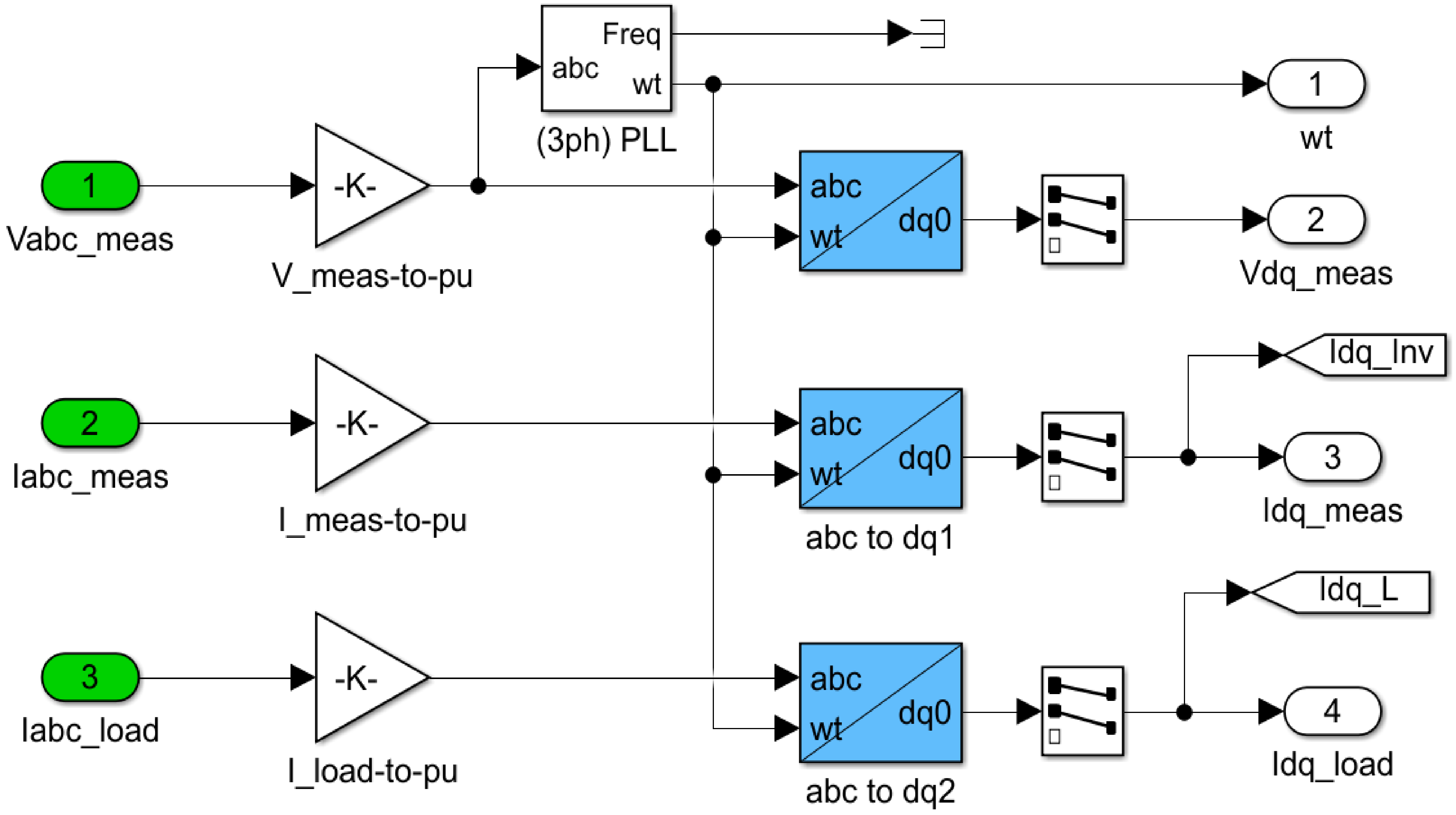


Input voltage / on the DC side

• for the start of the infeed operation	V	350
• for possible infeed operation	V	350…950
• nominal value	V	600
• maximum permissible	V	1,000

B. Measurement and dq transformation (1/2)

- The measurement block contains three input variables: inverter voltage, inverter current, and load current (see Section 1.3). These variables are firstly converted to pu values.
- Then, a phase-lock-loop (PLL) is used to estimate the grid voltage phase angle and frequency.
- The Park transformation is then applied to transfer the input variables from the abc to the dq reference frame. This is a common approach adopted for control of three-phase systems, as it allows simplifying the control analysis reducing the number of variables from three (abc) to two (direct and quadrature components)



B. Measurement and dq transformation (2/2)

Following translation to the dq reference frame:

- For 5th order harmonics:
  - Balanced currents (250 Hz in abc, with only negative-sequence components) are seen only at 300Hz (in dq)
  - Unbalanced currents[1] are seen at 200 Hz (dq) for positive-sequence components and at 300 Hz (dq) for negative-sequence components
- For 7th order harmonics:
  - Balanced currents (350 Hz in abc, with only positive-sequence components) are seen only at 300Hz (in dq)
- For 11th order harmonics:
  - Balanced currents (550 Hz in abc, with only negative-sequence components) are seen only at 600Hz (in dq)
- For 13th order harmonics:
  - Balanced currents (650 Hz in abc, with only positive-sequence components) are seen only at 600Hz (in dq)

1 – Not including zero sequence components

Working in the dq frame:

- A controller operating at 200 Hz affects positive sequence 5th order harmonics
- A controller operating at 300 Hz affects:
  - Negative-sequence 5th order harmonics; AND
  - Positive-sequence 7th order harmonics
  - i.e. 300Hz (dq) controller influences balanced 5th and 7th order harmonics
- A controller operating at 600Hz affects:
  - Negative-sequence 11th order harmonics, AND
  - Positive-sequence 13th order harmonics
  - i.e. 600Hz (dq) controller influences balanced 11th and 13th order harmonics

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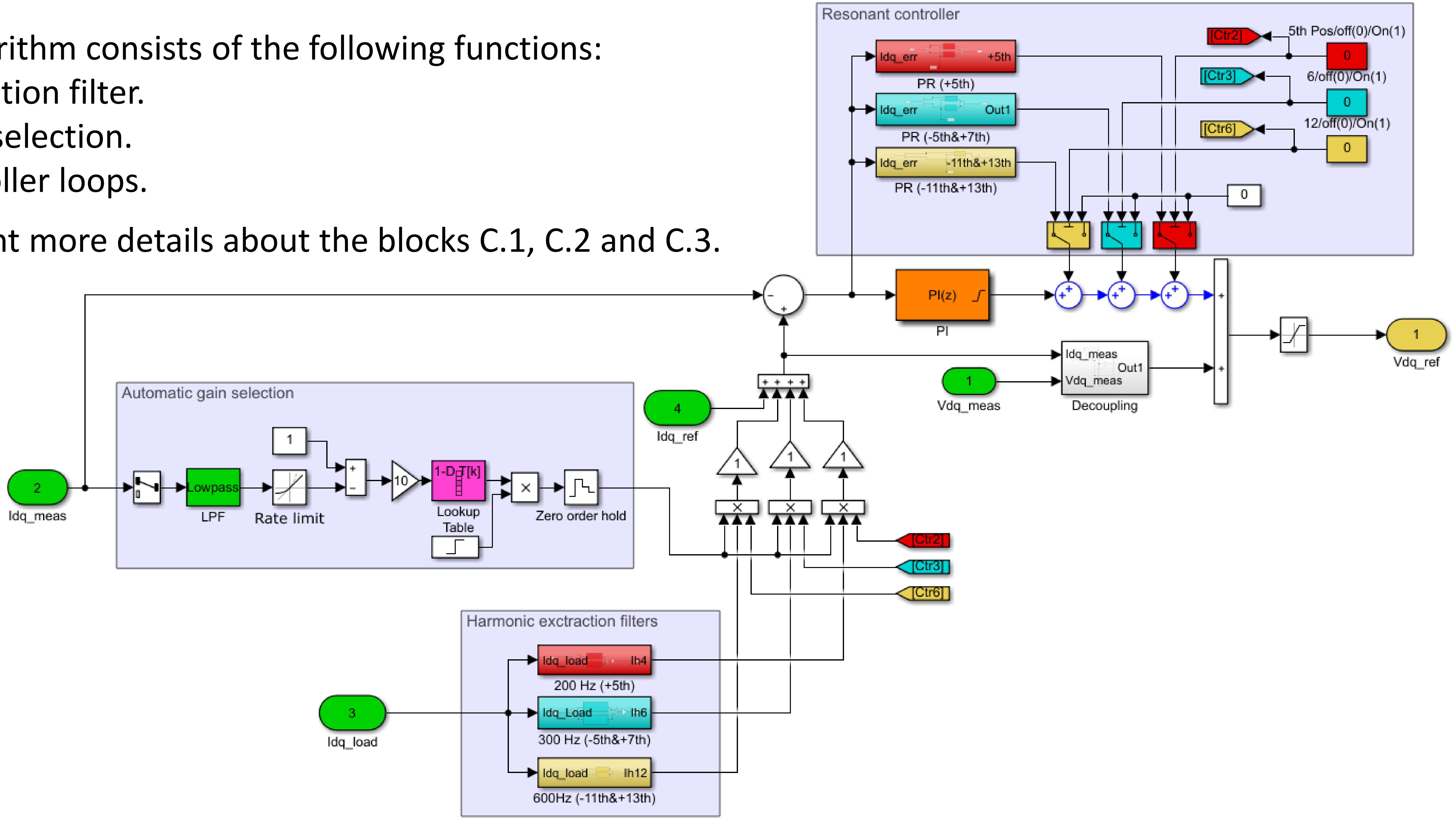
C. Current regulator

The current regulator algorithm consists of the following functions:

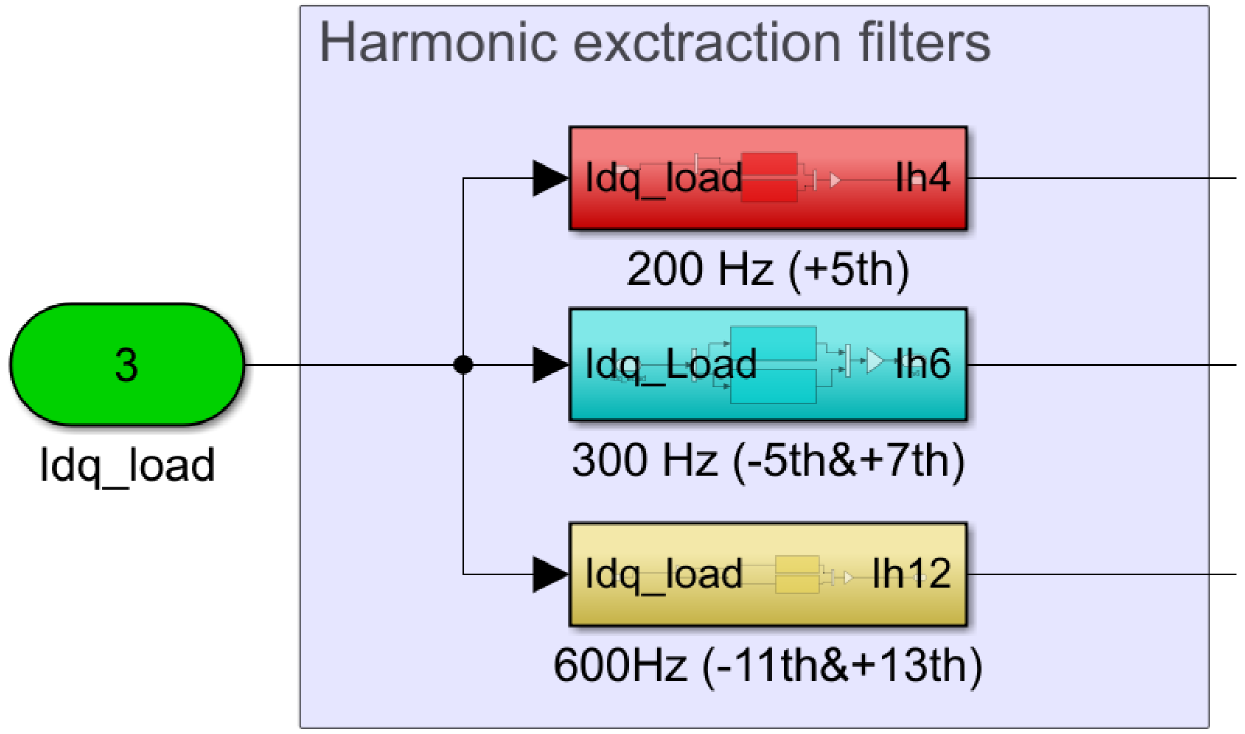
- C.1 Harmonic extraction filter.
- C.2 Automatic gain selection.
- C.3 PI and PR controller loops.

The following slides present more details about the blocks C.1, C.2 and C.3.



C.1 Harmonic extraction filter (1/2)

- The harmonic extraction block consists of three notch filters. These filters pass a specified frequency component while blocking others. The input signal to the filters is the load current in the dq reference frame (Idq_load).
- For this project, four harmonic components are considered: 5th, 7th, 11th and 13th. These harmonics have been chosen based on the measurement data recorded on the Tiverton Network.
- The following sequence components have been chosen: positive- and negative-sequence 5th harmonic components; positive-sequence 7th harmonic component; negative-sequence 11th order component and positive-sequence 13th harmonic component.
- Both negative- and positive-sequence 5th harmonic components were considered to demonstrate the validity of the proposed approach when unbalance harmonic components are present.
- For the other harmonics, only balanced components were assumed because these harmonics are smaller and the measurement data show only small unbalance in the system.



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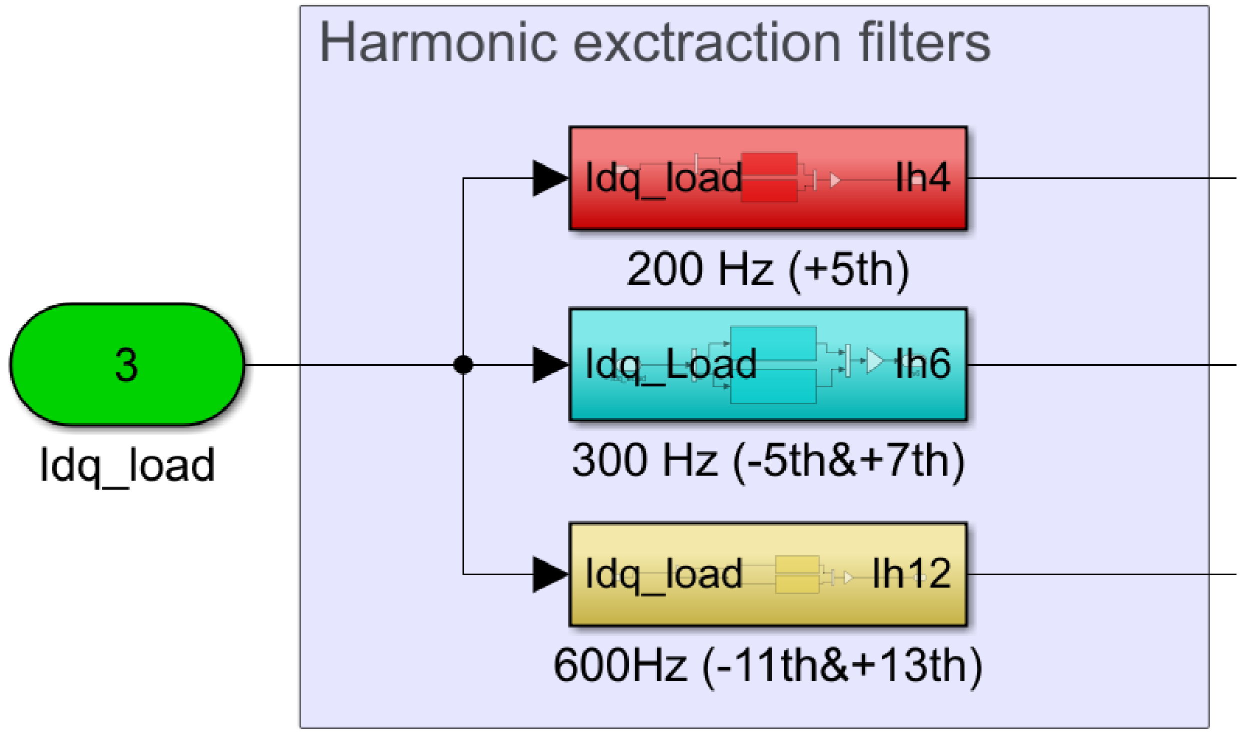
C.1 Harmonic extraction filter (2/2)

- The harmonic components listed above translate to three frequencies in the dq reference frame:
  - **200** Hz obtained from the positive-sequence 5th order harmonic component. This component is included in the algorithm since this component is observed in practical measurements.
  - **300** Hz obtained from the negative-sequence 5th order harmonic component and the positive-sequence 7th harmonic component;
  - **600** Hz obtained from the negative-sequence 11th order harmonic component and the positive-sequence 13th harmonic component
- The three harmonic components extracted from the filters are then used to calculate the inverter reference current.
- The amount of harmonics that can be compensated depends on the inverter available capacity, and is calculated as shown in the next slide.



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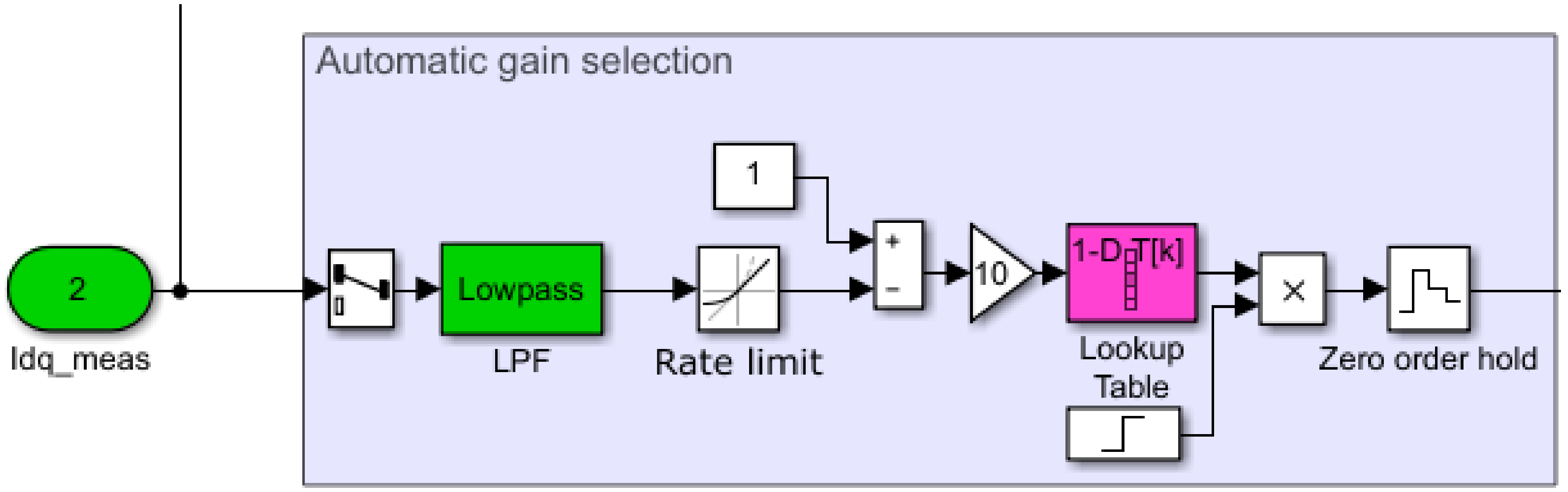
C.2 Automated gain control



- The measured fundamental output current of the inverter (Id_meas) is used to select the gain and to modulate each individual harmonic component injected by the inverter. Iq_meas is equal to zero because the PV inverter operates at unity power factor.
- The measured fundamental current of the inverter is passed through a low-pass filter (LPF), and then a rate limiter is used to reduce the fluctuation in the current signal. The output of the rate limiter is a modified fundamental output current signal, which is used to calculate the available capacity for harmonic compensation.
- Based on the available capacity to compensate, the gain value is selected from a lookup table, and then passes through the zero-order hold to setup a time limit for step change. Adjustment of the gain over time is limited to prevent rapid set-point fluctuations, this is set to be–adjusted every 10 minutes to match the aggregation window used for 95 percentile in IEC-61000-4-30.
- The gain value is varying between (0 and 1), where (0) means no-compensation and (1) means fully compensation.
- The final gain is then multiplied by the extracted harmonics to evaluate the amount of harmonic mitigation required for injection into the controller (as shown on the current control overview diagram).

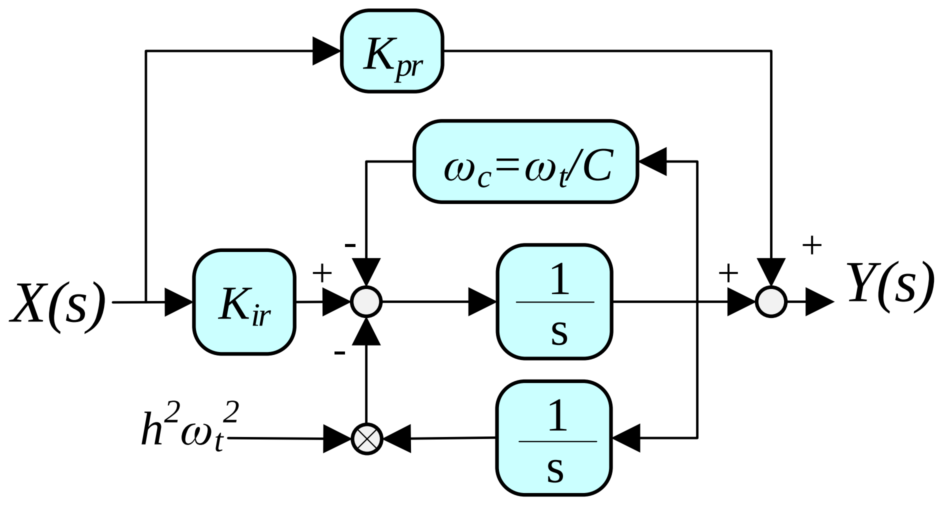
C.3 Proportional-Resonant controller (theory)

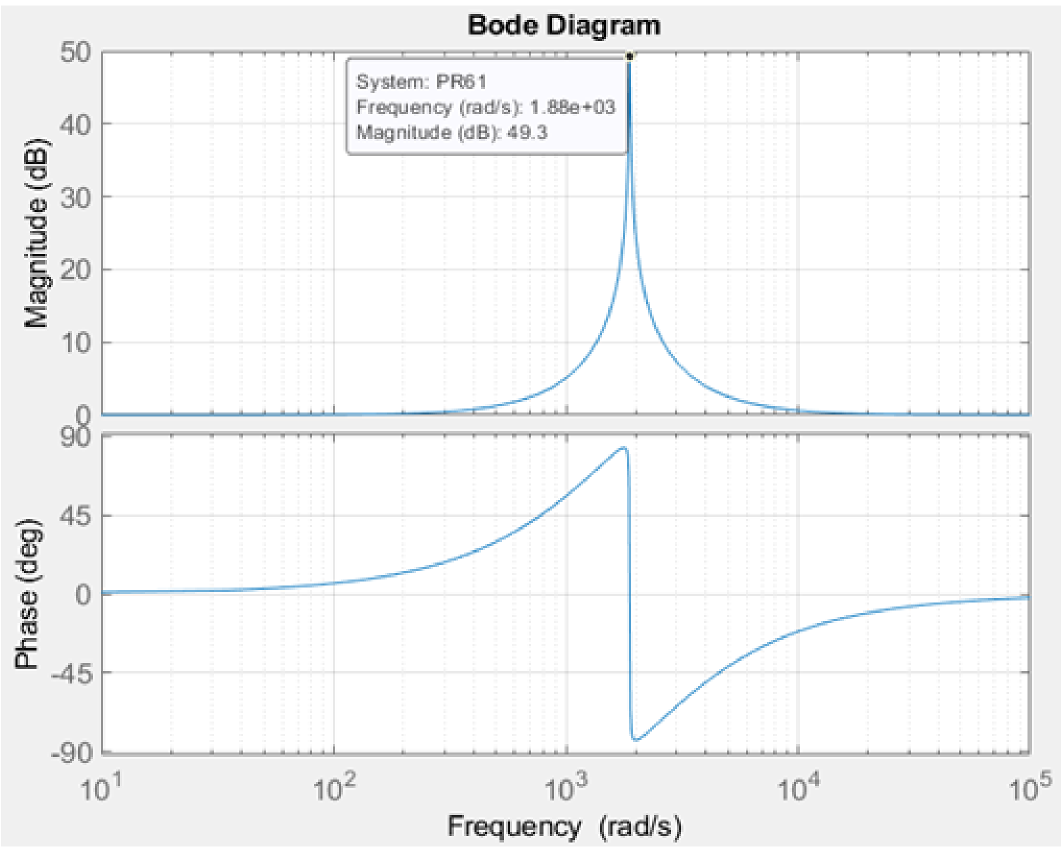
- The transfer function of the proportional-resonant (PR) controller is:

$$G_{PR} = K_{pr} + \frac{2K_{ir}\omega_c S}{S^2 + 2\omega_c S + (h\omega_t)^2}$$

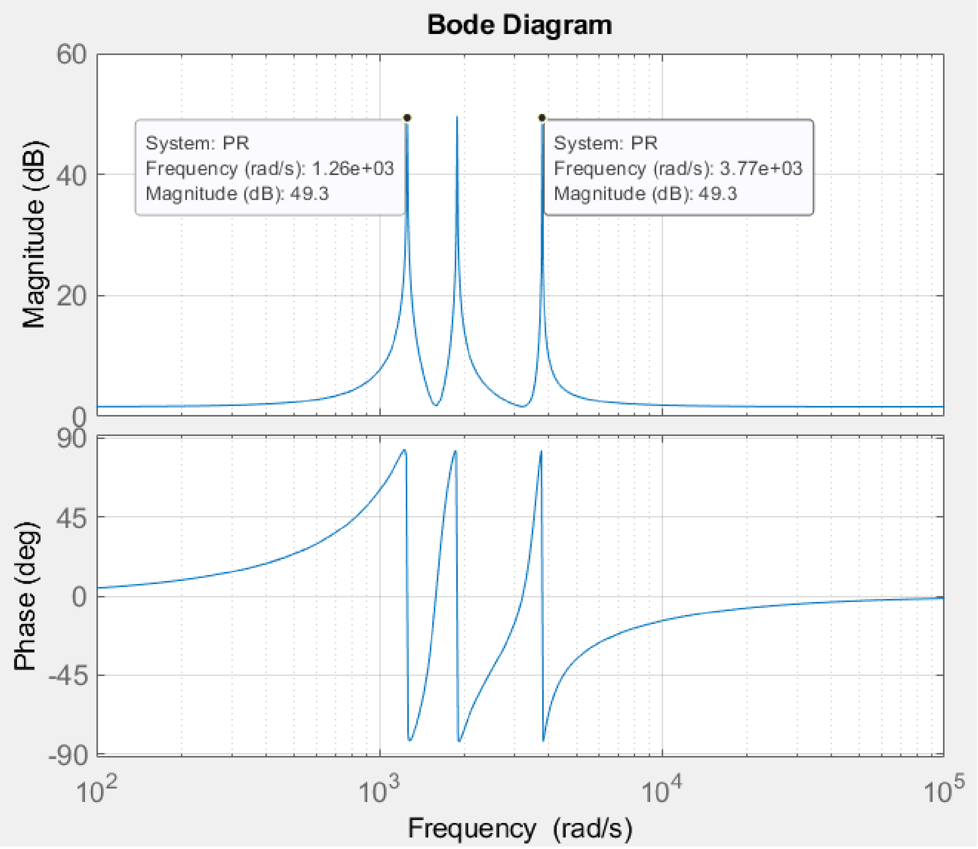
where, K_{pr} is the proportional gain, K_{ir} is the resonant gain, ω_c is the cutting frequency, and ω_t the fundamental frequency, h the selected harmonic.

- The frequency response of the PR controller above is given in the Bode Diagram on the left.
- In this project, three frequencies are considered: 200 Hz, 300 Hz and 600 Hz as discussed previously. Therefore, the implemented PR controller is shown in the Bode Diagram on the right.





Frequency response of the PR controller shown above, assuming a resonant frequency of 300 Hz



Frequency response of the combined PR controllers used in this project (200 Hz, 300 Hz and 600 Hz)

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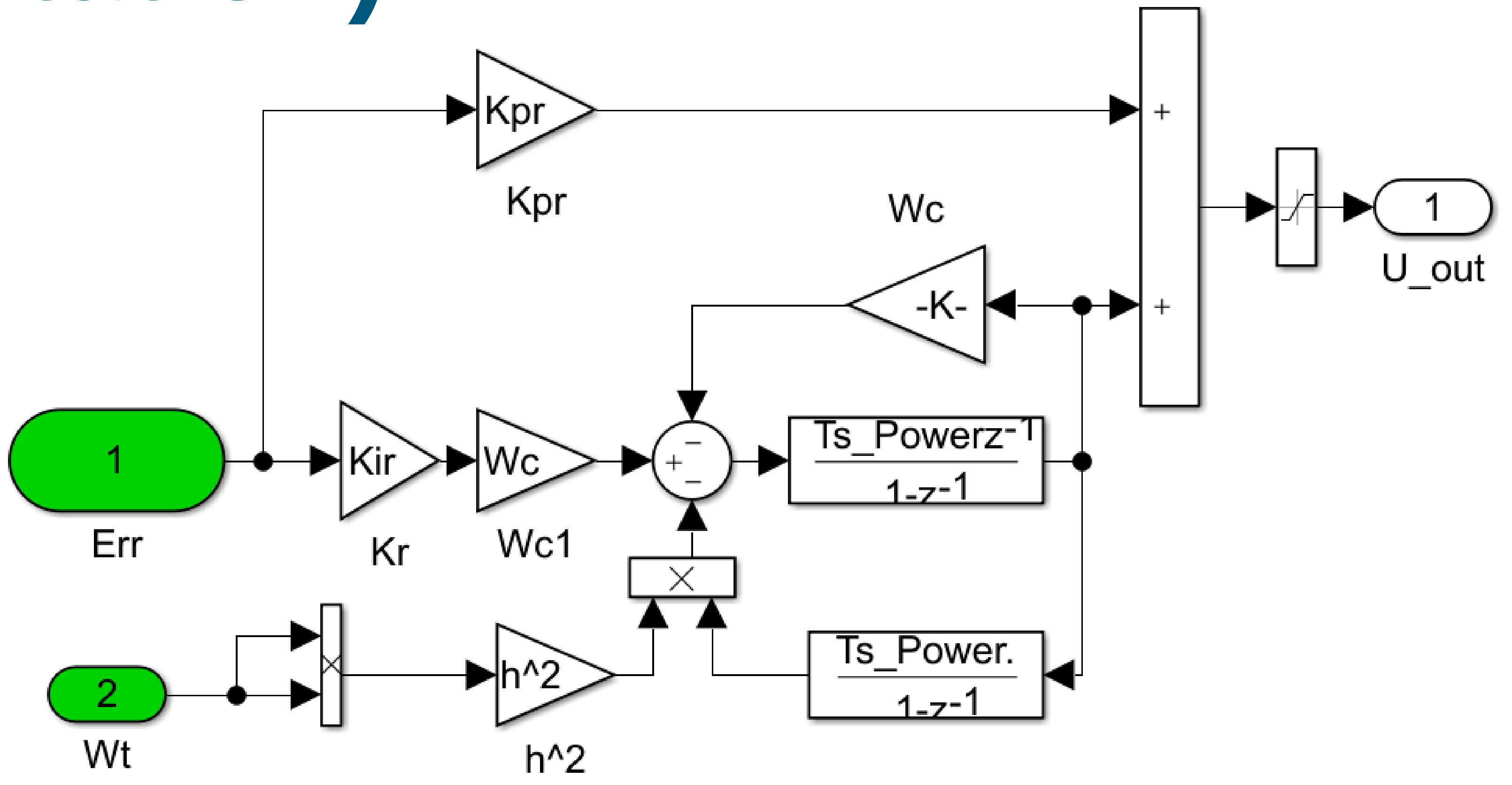
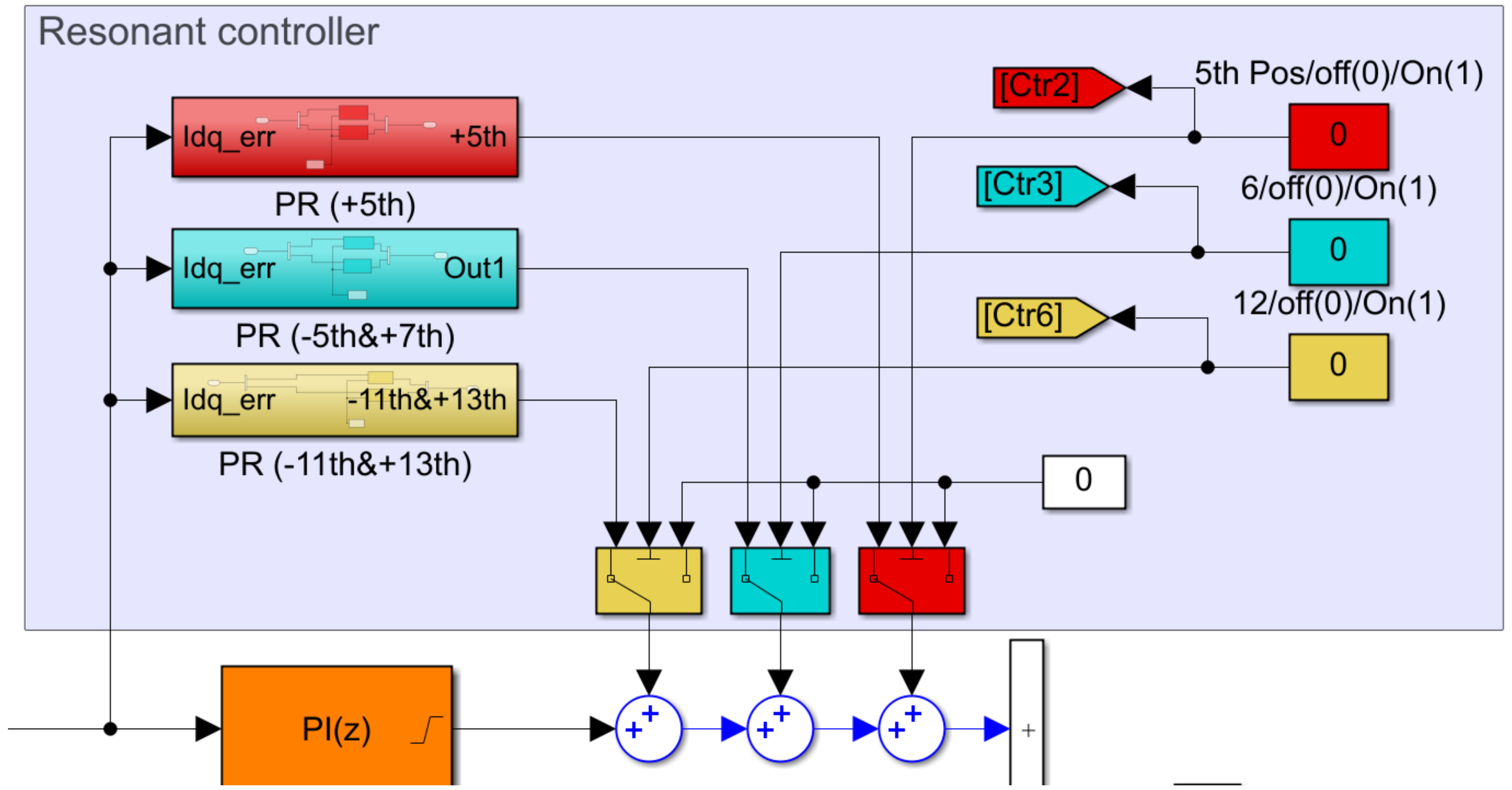
C.3 Resonant controller (implementation)

- The simulation model of the proportional resonant (PR) controller transfer function is shown in the top right figure, while the figure on the bottom shows the parallel connection between the resonant and proportional-integral (PI) controller. The PI controller is used to regulate the fundamental frequency current component.
- Each PR controller is designed to compensate one frequency, obtained from the harmonic extraction filters described earlier:
  - Red, for 200 Hz
  - Blue, for 300 Hz
  - Yellow, for 600 Hz

  The PI controller controls the fundamental power component.
- The switches in the figure allow manual inclusion or exclusion of individual harmonic compensation and have been used thorough the testing and development phase.





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2.1 Key issues that shaped the development (1/3)

Item	Solution
Initial version of the low pass filter used for harmonic extraction was causing oscillations in the harmonic reference signal. This was because the filter was not effective in isolating the different harmonic components present in the signal.	The low pass filter has been replaced by a notch filter, thus leading to a better performance of the algorithm – Section C.1
High harmonic current mitigation values injected by the inverter caused overcompensation in cases of high irradiance. This was because the high gain resulting in reference voltages leading to over-modulation.	Automatic gain adjustment was developed to prevent overcompensation during high irradiance – Section C.2
Poor compensation was observed for 11th and 13th harmonic compared to 5th and 7th components. This was because the gain value used for the 11th and 13th components were initially the same as those for the 5th and 7th components and was not suitable for the 11th and 13th components.	Various 'harmonic groups' are created, for each frequency component in the dq domain, allowing the gain to be set appropriate for the harmonic group – Section C.1

2.1 Key issues that shaped the development (2/3)

Item	Solution
A Proportional Integral (PI) controller initially used to generate harmonic mitigation signals was not effective. This is because PI controllers are only effective for dc components in the dq domain (corresponding to fundamental frequency in the abc domain).	Proportional resonant (PR) controller added for each 'harmonic group'. Section C.3
The initial control system was not able to compensate both positive- and negative-sequence components for the fifth harmonic. This was because the positive-sequence fifth harmonic results in a different harmonic frequency in the dq domain compared to the negative-sequence.	Additional filter added to compensate positive-sequence 5th harmonic current. Section C.3
When AF operation is considered, oscillatory components are shown in the direct-component current reference at fundamental frequency. This is tracked down to oscillations in the dc voltage reference due to additional harmonic components in the current reference.	The dc voltage reference was modified. Section A

2.1 Key issues that shaped the development (3/3)

Item	Solution
The approach of time compression within the simulation causes the rate of irradiance change to be higher than in the real system. Within the modelling this leads to frequent and sudden changes in the harmonic gain value, and to short duration bursts of harmonic injections from the inverters.	A modified irradiance value profile was developed using a rate limiter and a sample and hold, to ensure that the gain value is held for at least 10 minutes. Section C.2
Harmonic spectrum analysis of time-varying signals for the full time period show ‘side bands’, i.e. additional harmonic components, with smaller amplitude, surrounding the expected harmonic components *.	Shorter time windows are considered and aggregated where required using the rms approach. The harmonic spectra for various operating conditions are shown in Section 2.3 and Section 3.

* This is not an issue related to the control system development, but rather to evaluation of the impact (in other words, the FFT is not used within the control but only to display and allow evaluation of the results).

2.3 Testing and validation

- The following slides show the testing carried out validate basic operation of the proposed algorithm.
- Tests have been performed for individual harmonics, for each harmonic group and then for all harmonic components.
- Unbalanced fifth harmonic currents were also considered.
- The individual tests run in this section assume a constant irradiance value and a constant harmonic magnitude. No other harmonic sources were included.
- The results of time varying irradiance and/or harmonic current magnitude are covered in Section 3.

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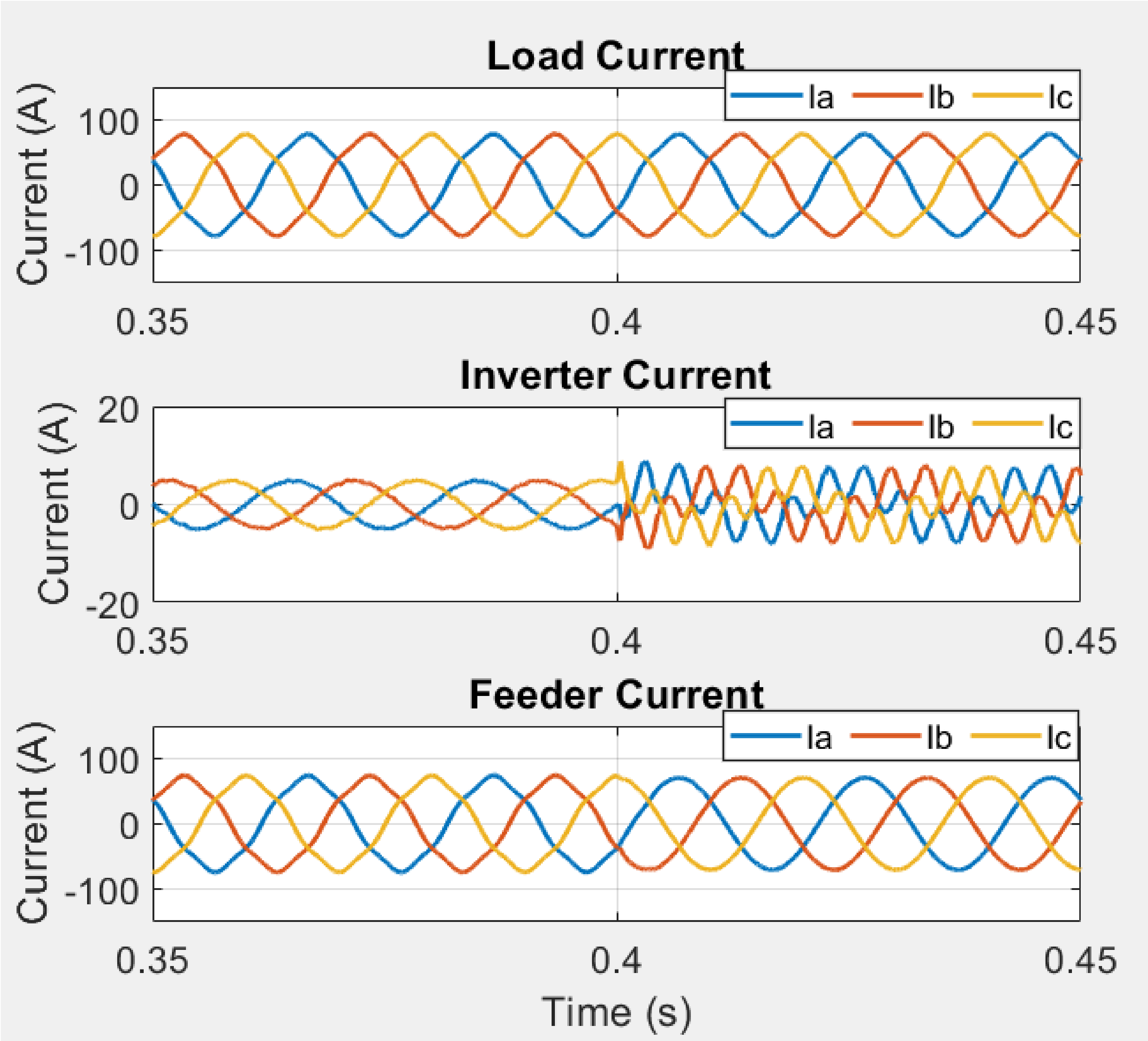
Overview of the tests

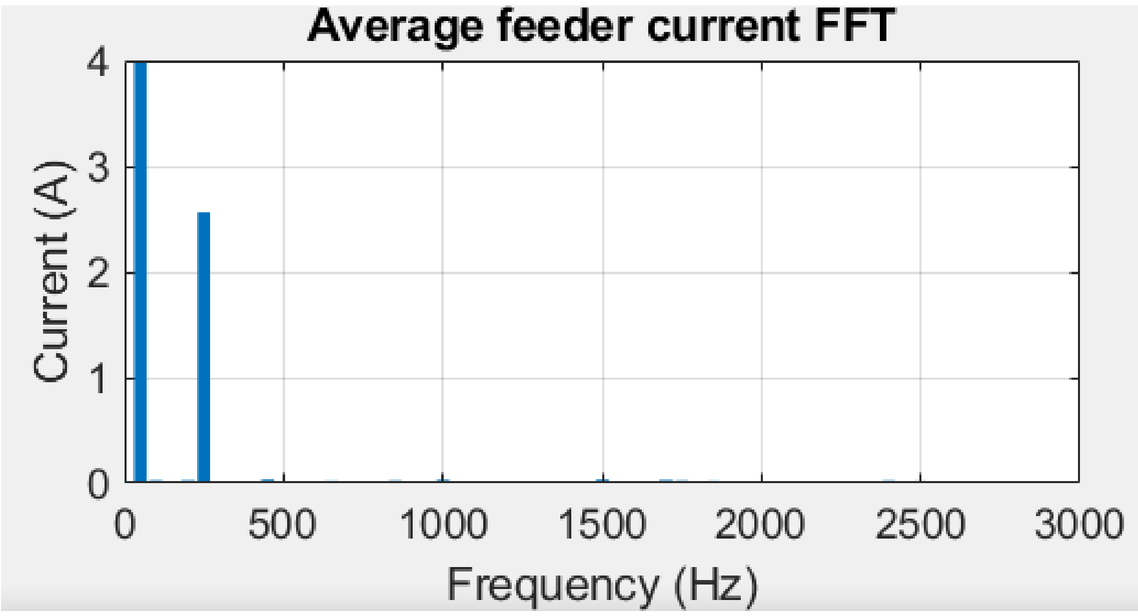
- The table below shows the amplitude of the harmonic current components used for each test. All values listed are rms components.
- The current amplitude of 2.5 A is a typical value for the 5th and the 7th harmonic, while 11th and 13th harmonics are much smaller. However, when performance of the controller for individual harmonics was tested, larger values of the 11th and 13th harmonic were used to verify the robustness of the algorithm at these frequencies.
- The inverter is running at 50% fundamental power output for these tests.

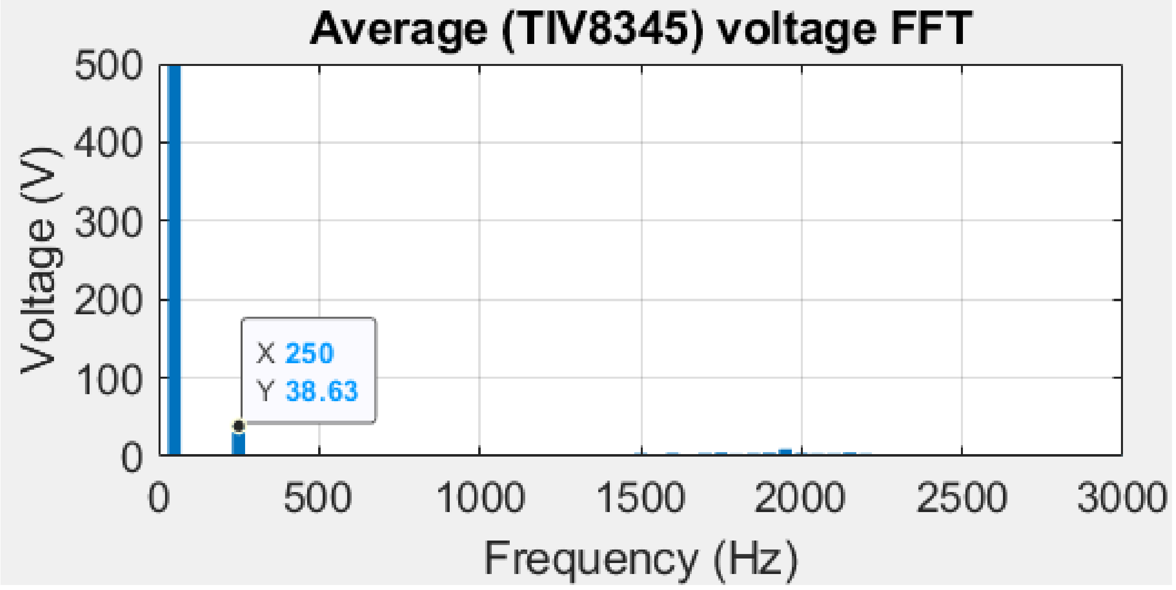
Harmonic current	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
5th	2.5 A (-)	1.25 A (-) 1.25 A (+)	1.25 A (-) 1.25 A (+)		2.5 A (-)				2.5 A (-)
7th				2.5 (+)	2.5 A (+)				2.5 A (+)
11th						2.5 A (-)		2.5 A (-)	0.37 A (-)
13th							2.5 (+)	2.5 A (+)	0.19 A (+)

Test 1: Balanced 5th harmonic current

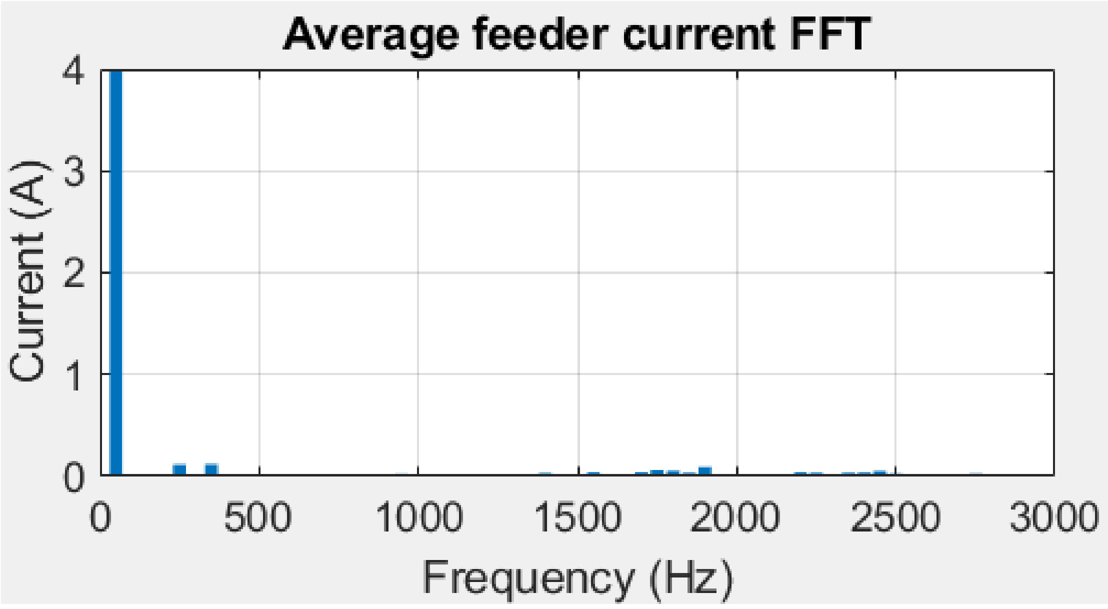


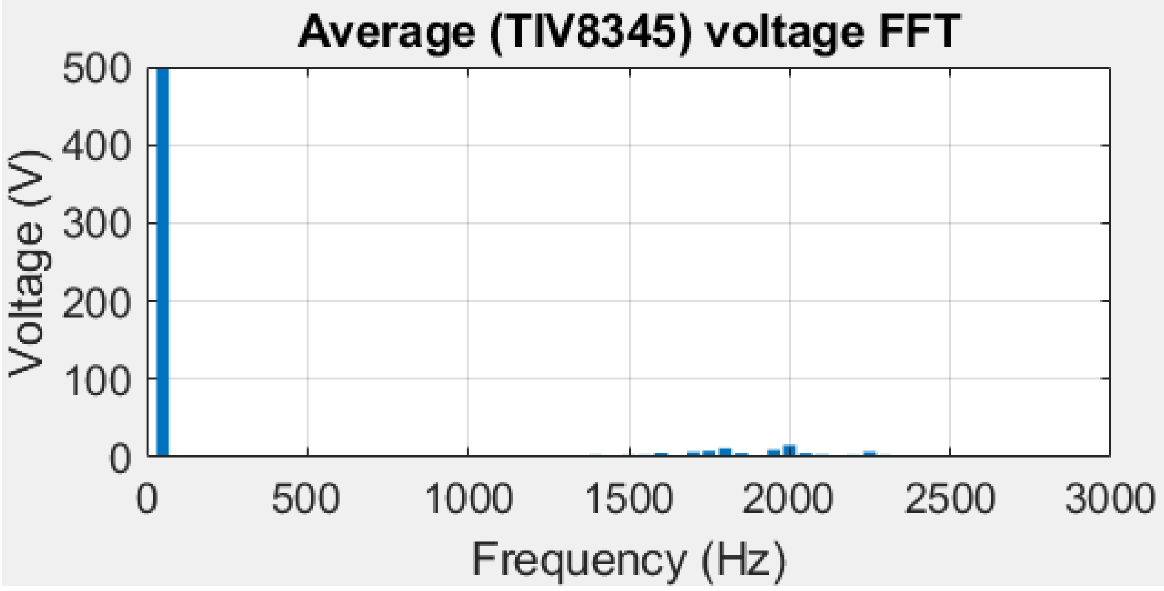
Current waveforms before and after compensation with balanced 5th harmonic only.





Feeder current (Left) and TIVE8345 voltage (Right) harmonics without compensation.

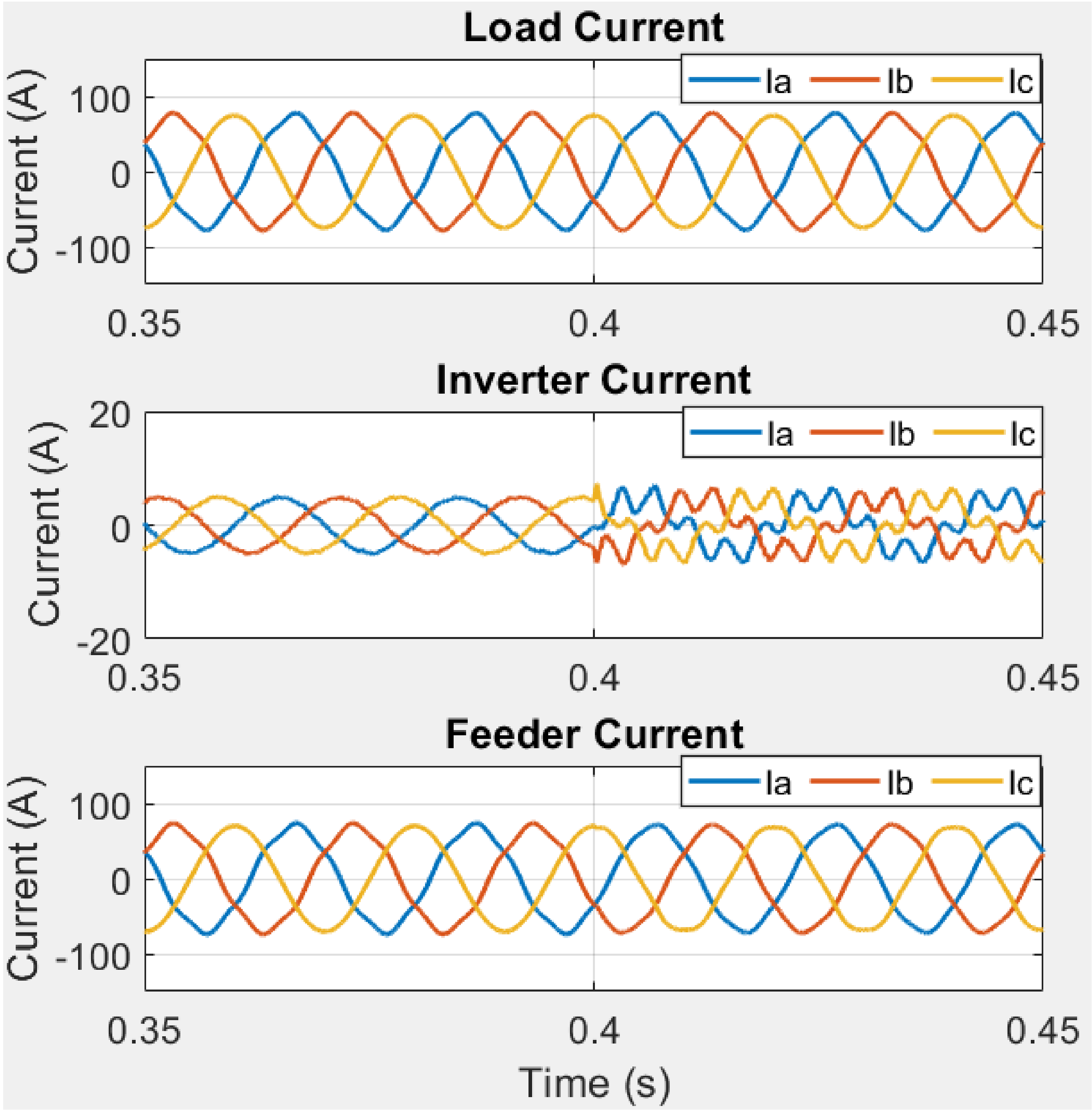




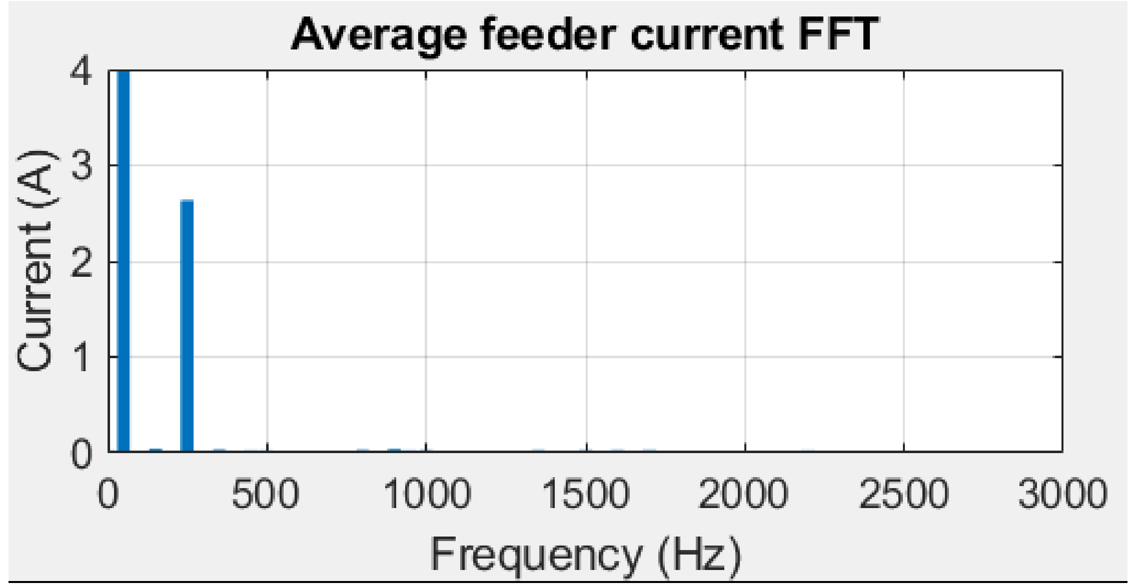
Feeder current (Left) and TIVE8345 voltage (Right) harmonics with compensation.

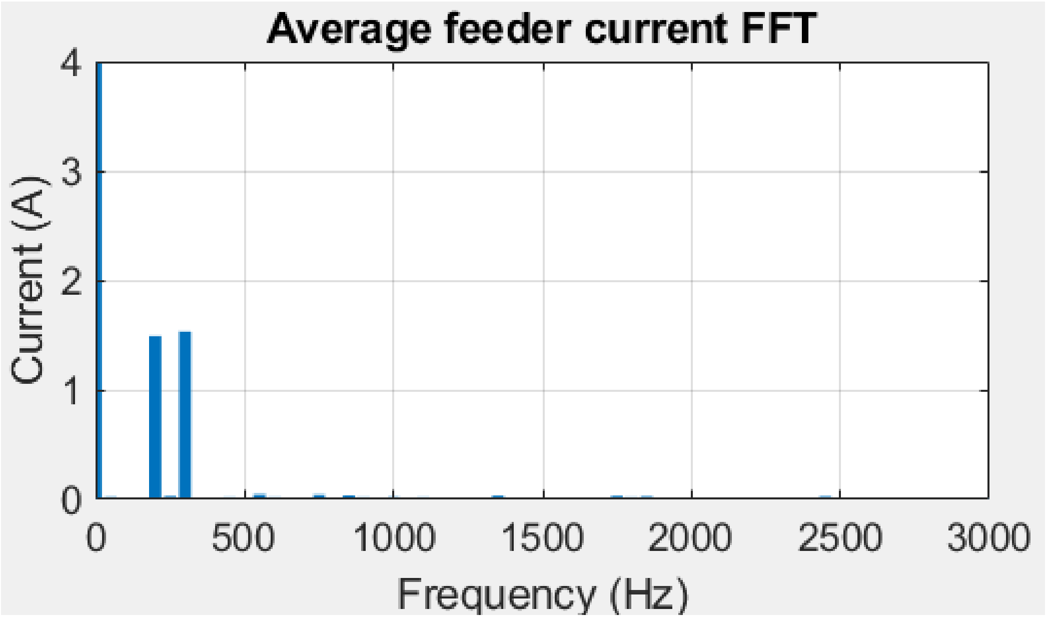
Test 2: Unbalanced 5th harmonic current

Initially only negative-sequence components are included in compensation algorithm.

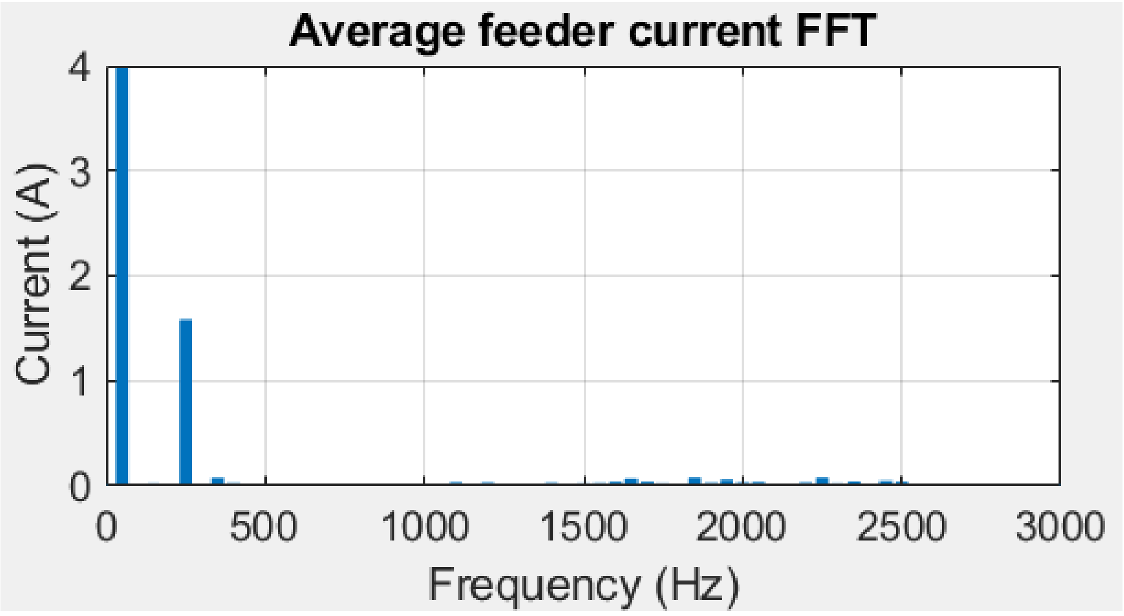


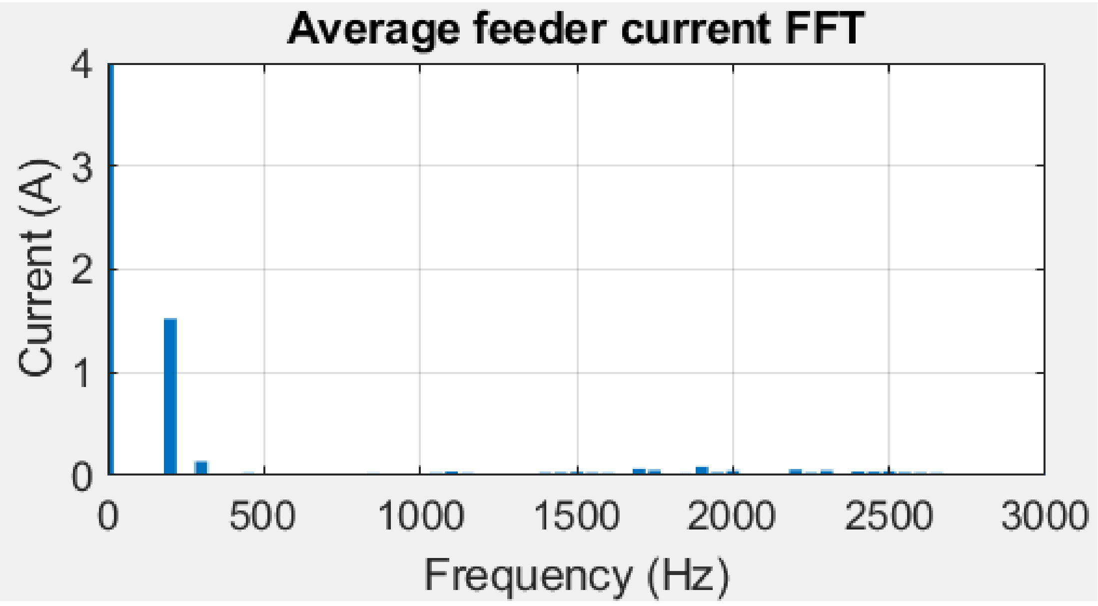
Current waveforms before and after compensation with unbalanced 5th harmonic current.





Feeder current before compensation, abc-frame (Left), dq-frame (Right).





Feeder current after compensation, abc-frame (Left), dq-frame (Right).

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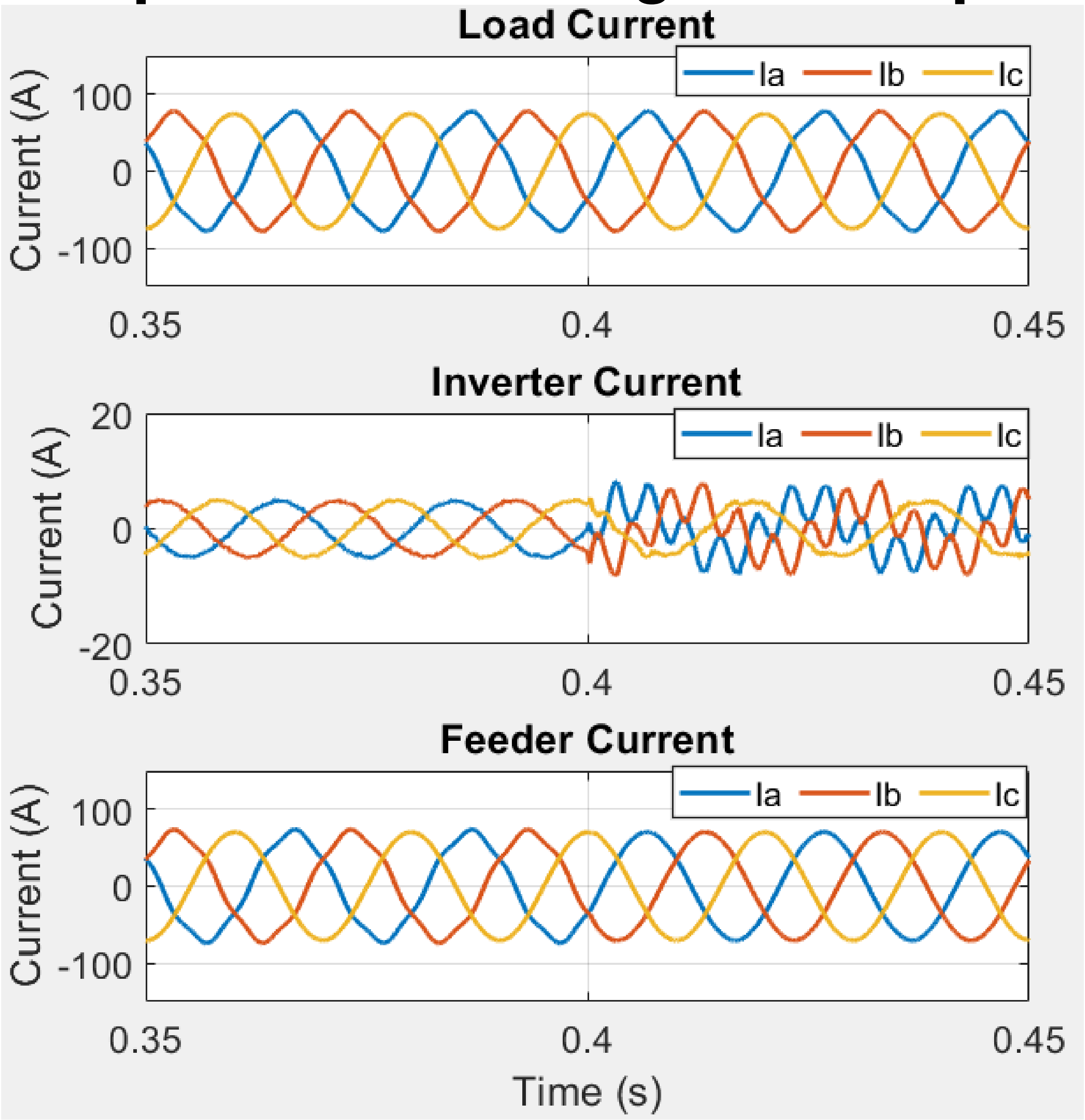
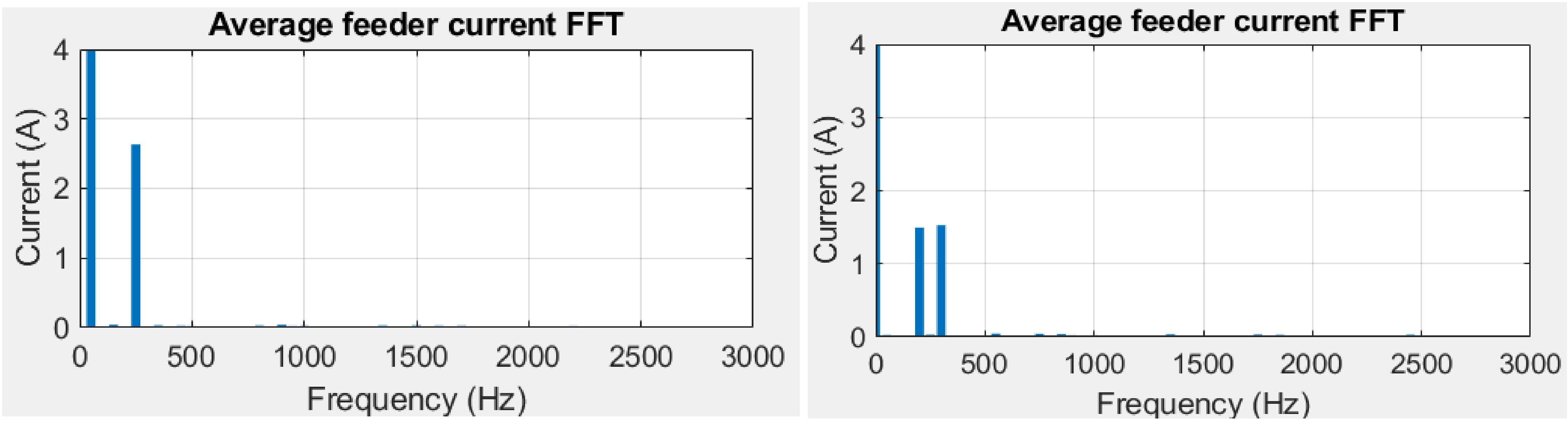
Test 3: Unbalanced 5th harmonic current

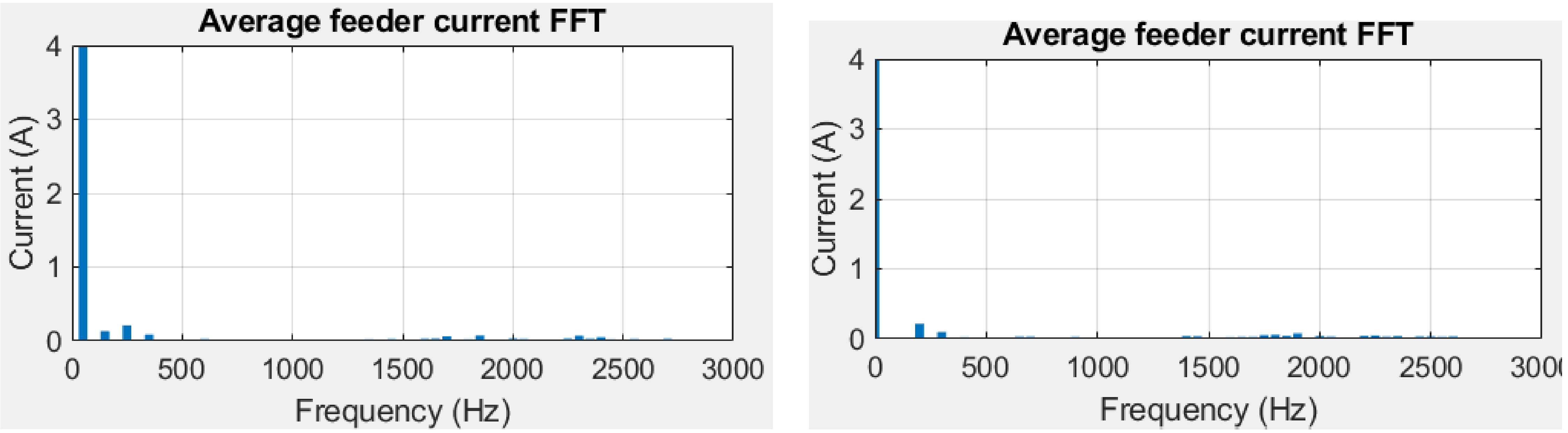
Both positive-and negative-sequence components are included in compensation algorithm.



Current waveforms before and after compensation with unbalanced 5th harmonic current.

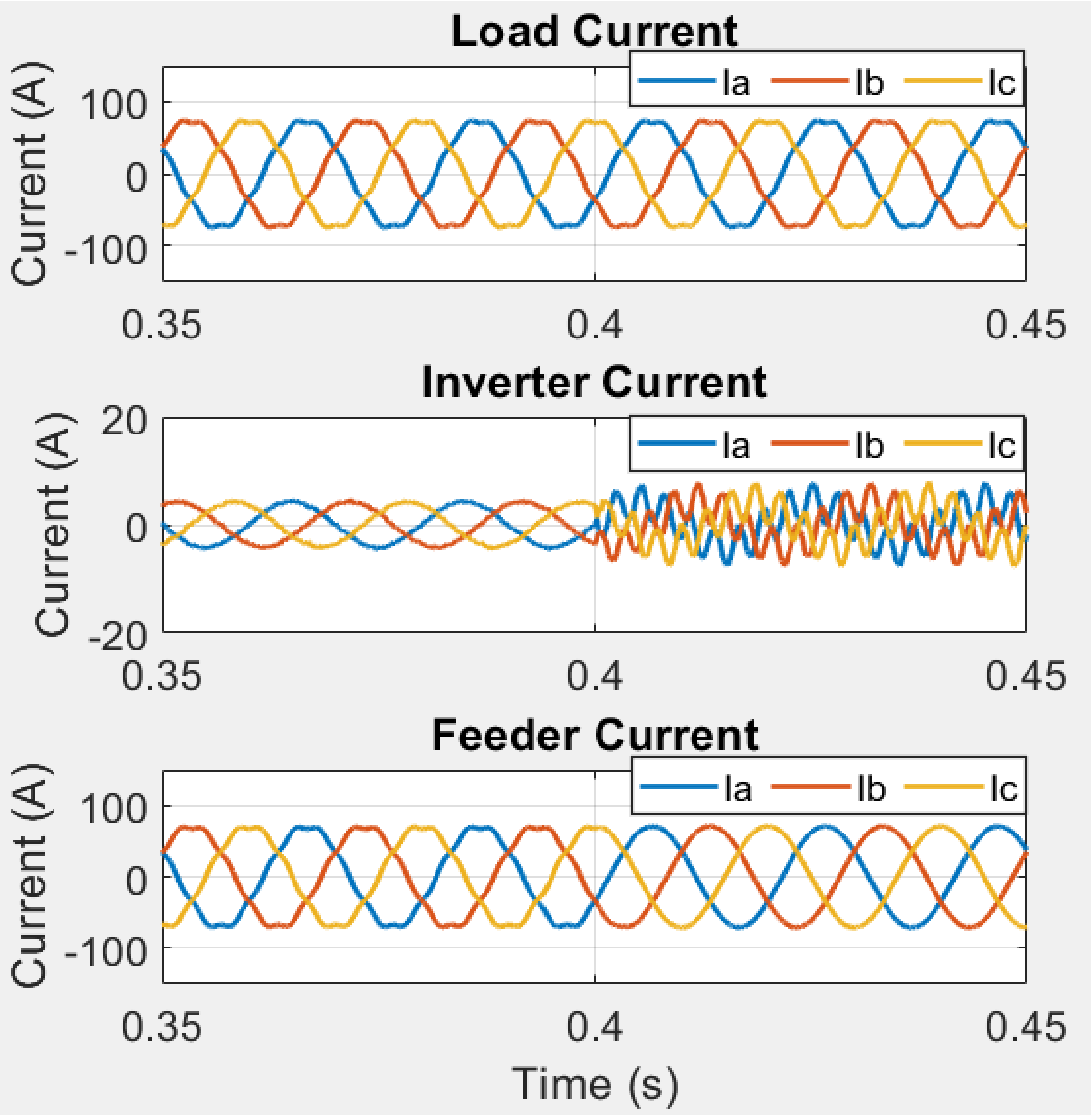


Feeder current before compensation, abc-frame (Left), dq-frame (Right).

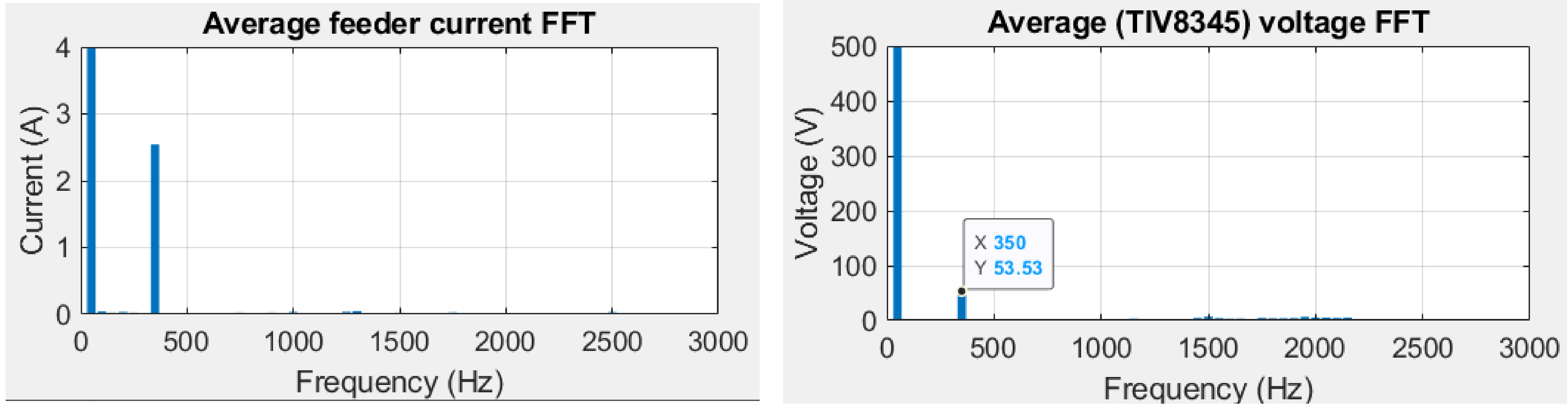


Feeder current after compensation, abc-frame (Left), dq-frame (Right).

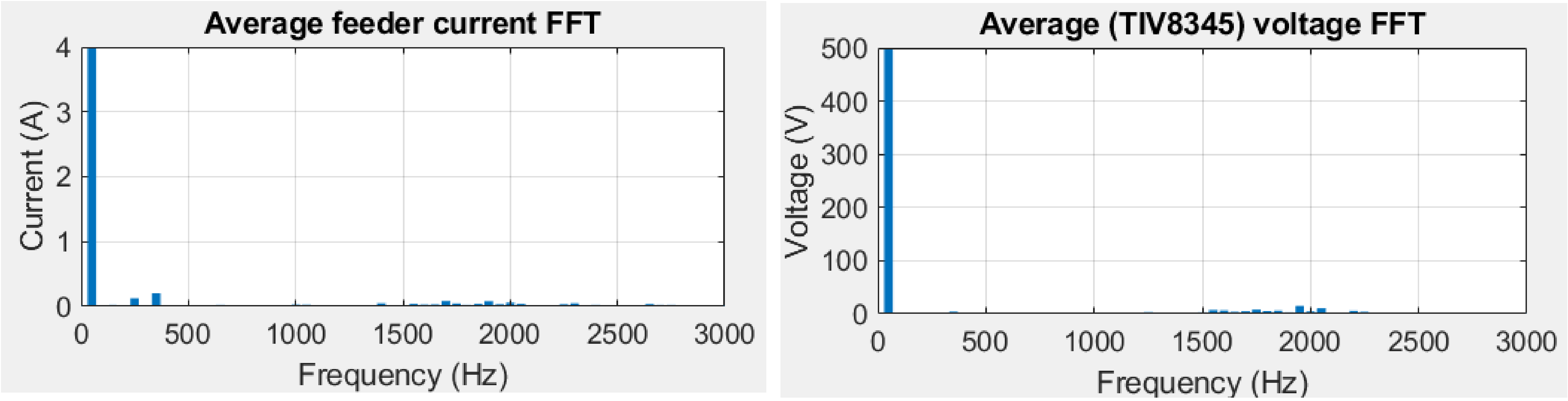
Test 4: Balanced 7th harmonic current



Current waveforms before and after compensation with balanced 7th harmonic current.

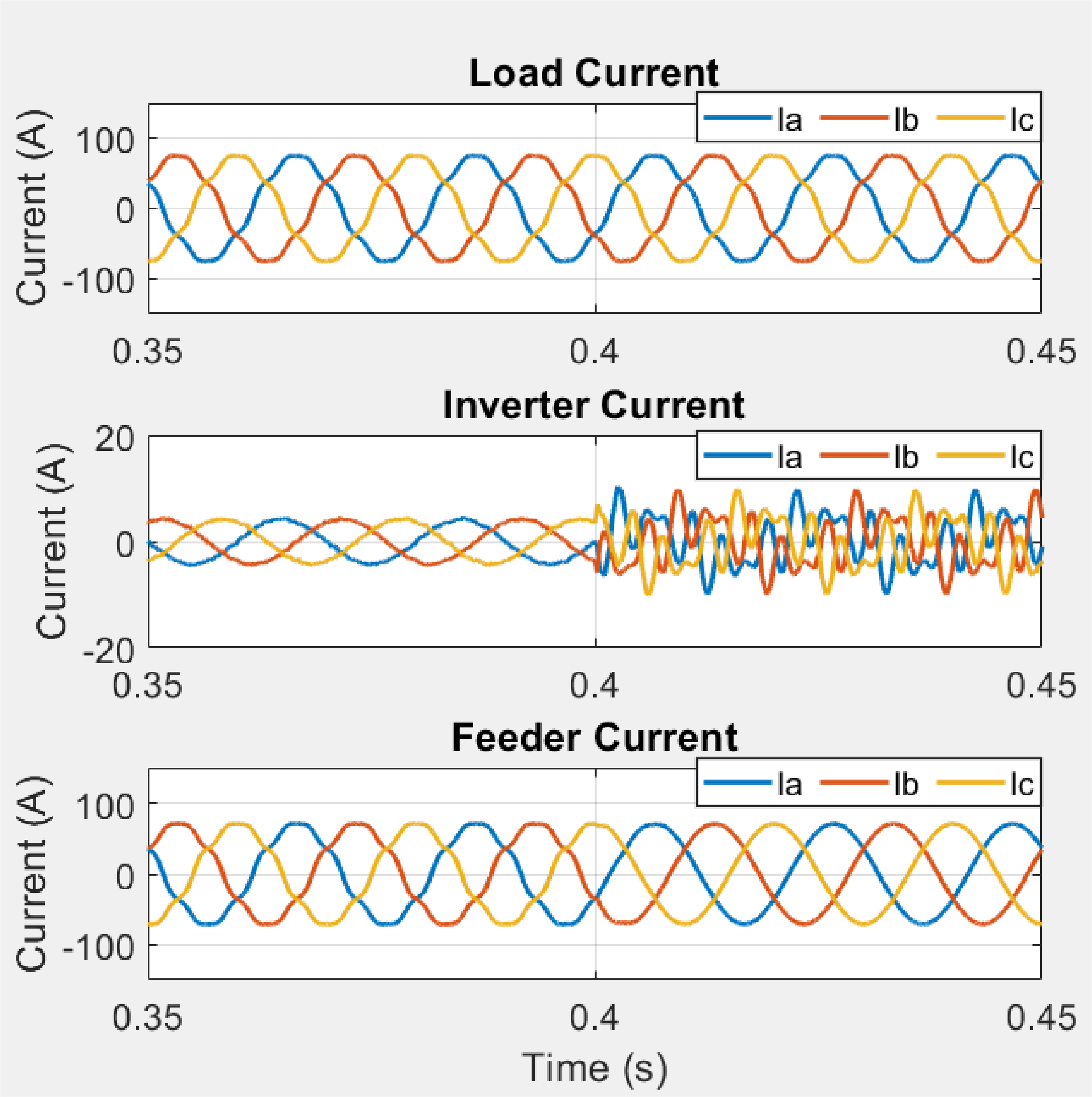


Feeder current (Left) and TIVE8345 voltage (Right) harmonics without compensation.

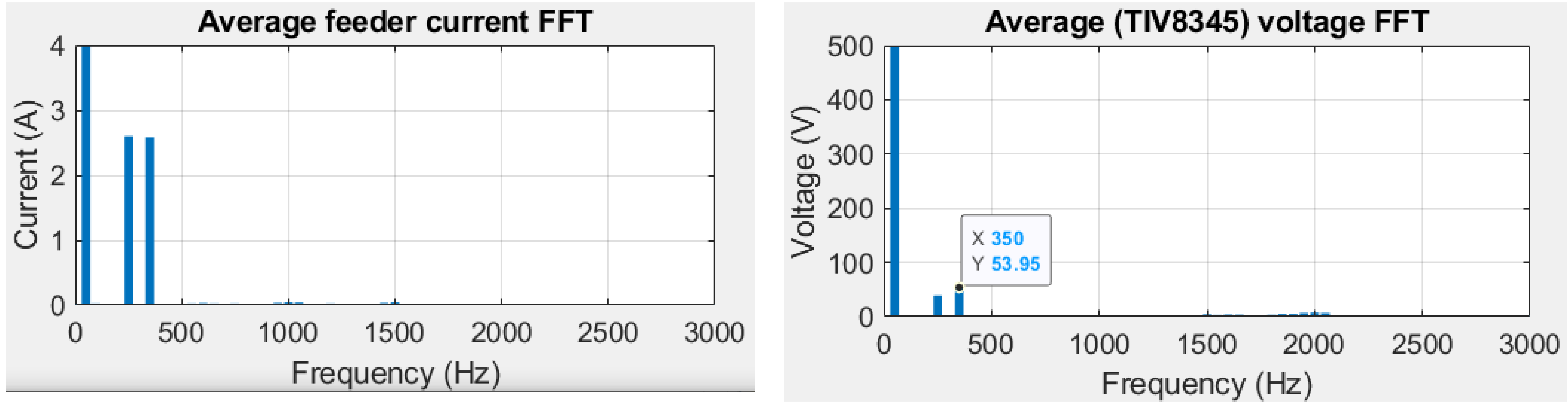


Feeder current (Left) and TIVE8345 voltage (Right) harmonics with compensation.

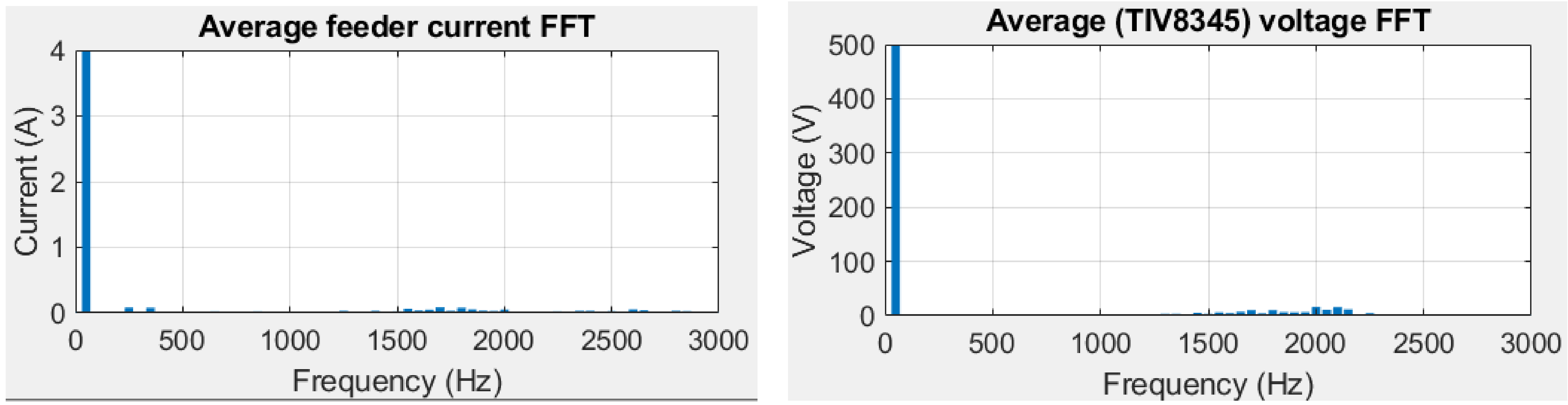
Test 5: Balanced 5th and 7th harmonic current



Current waveforms before and after compensation with balanced 5th and 7th harmonic current.

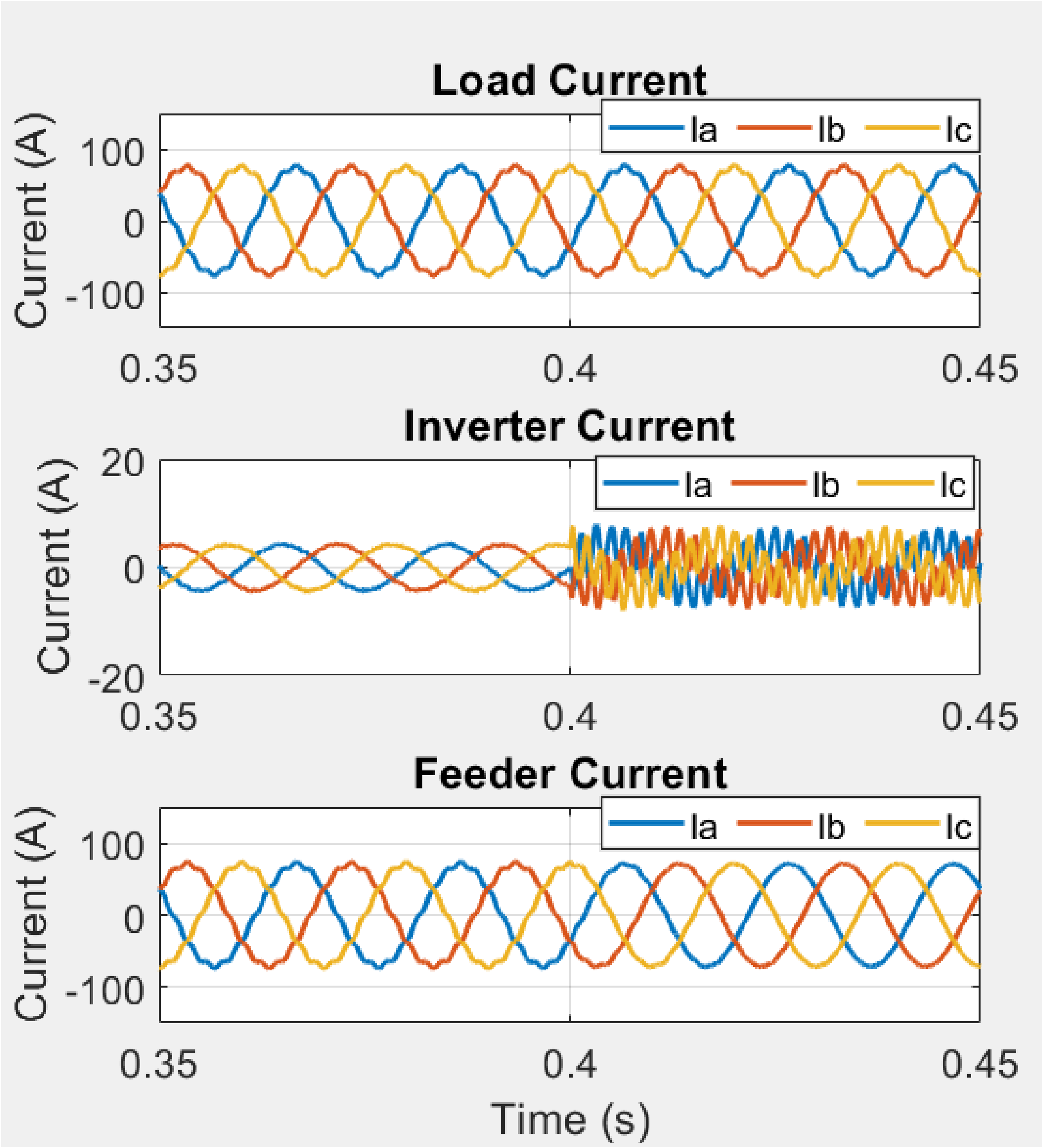


Feeder current (Left) and TIVE8345 voltage (Right) harmonics without compensation.

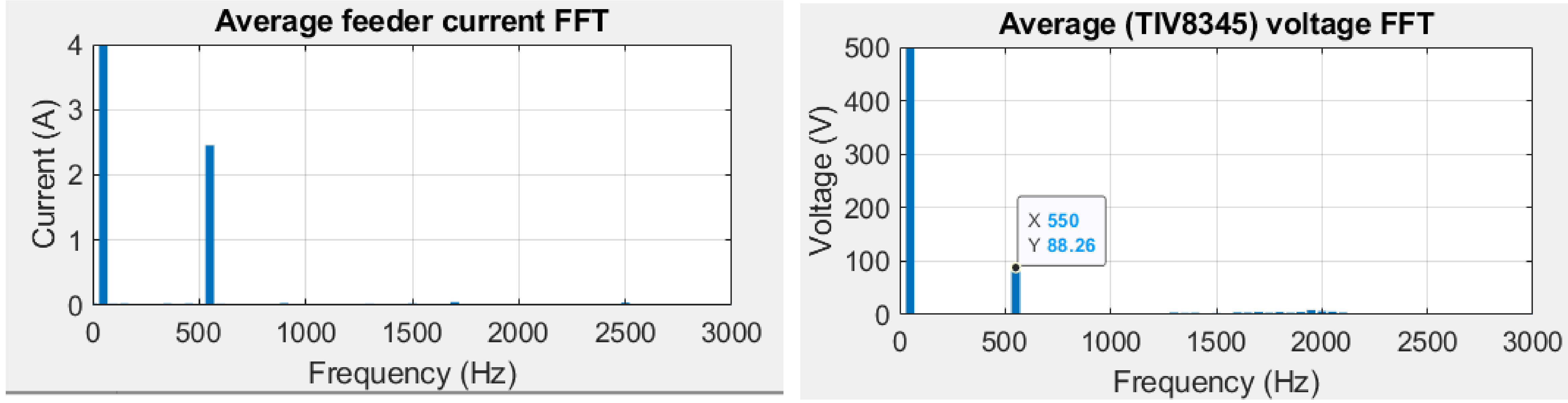


Feeder current (Left) and TIVE8345 voltage (Right) harmonics with compensation.

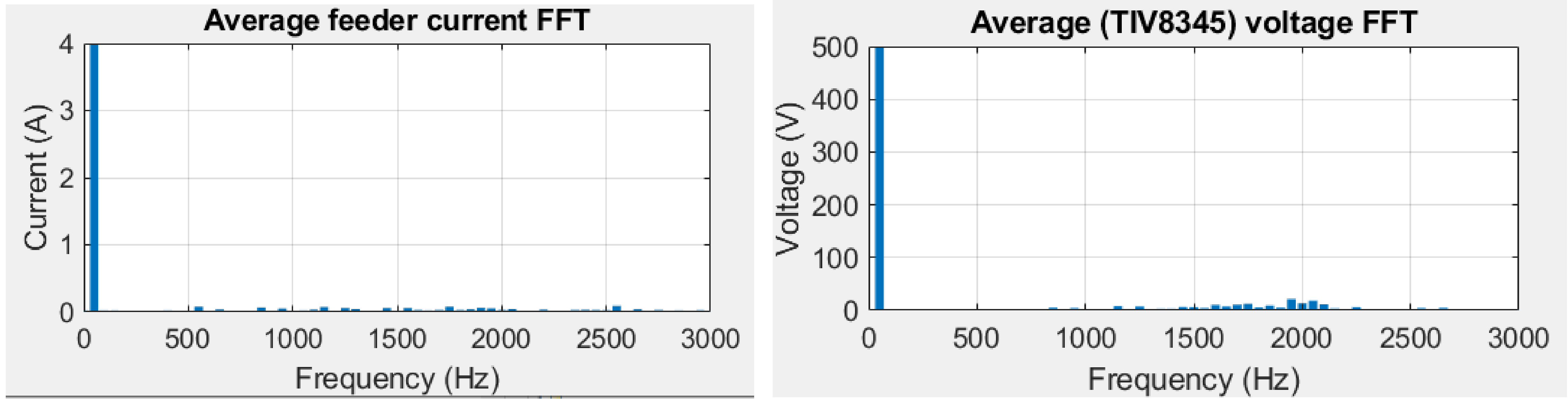
Test 6: Balanced 11th harmonic current



Current waveforms before and after compensation with balanced 11th harmonic current.



Feeder current (Left) and TIVE8345 voltage (Right) harmonics without compensation.



Feeder current (Left) and TIVE8345 voltage (Right) harmonics with compensation.

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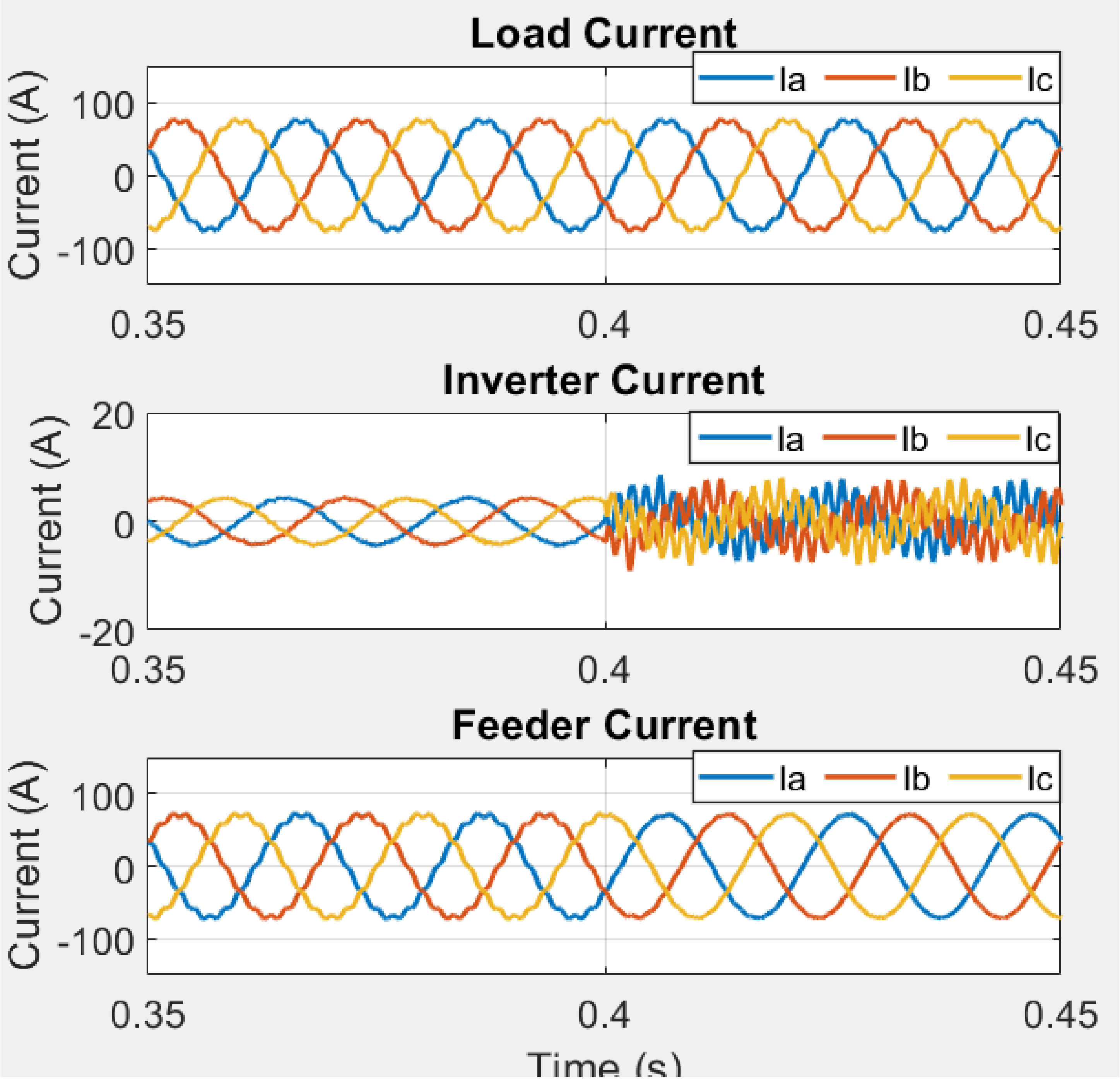
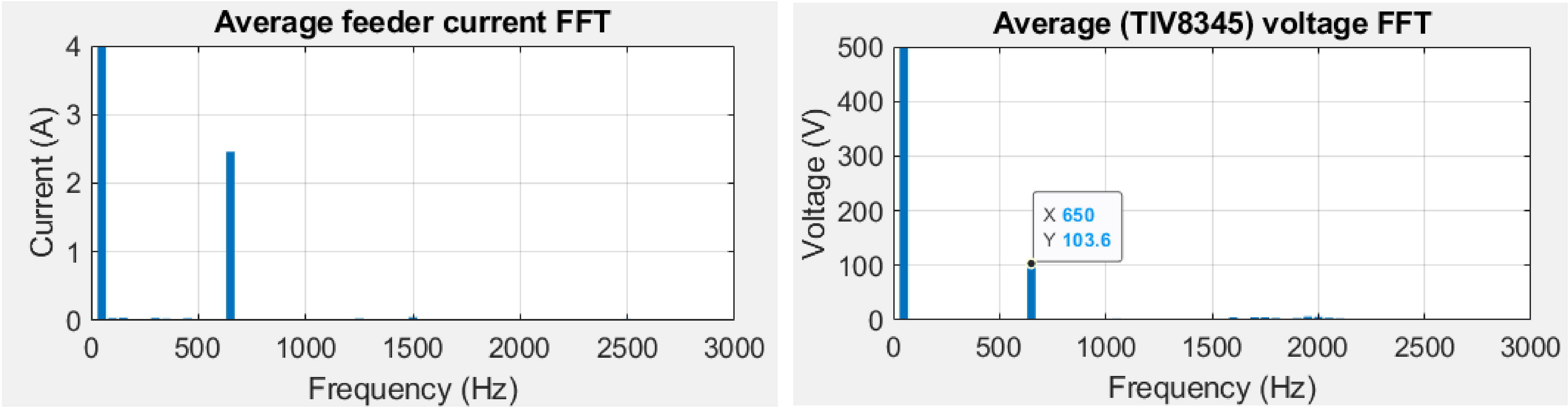
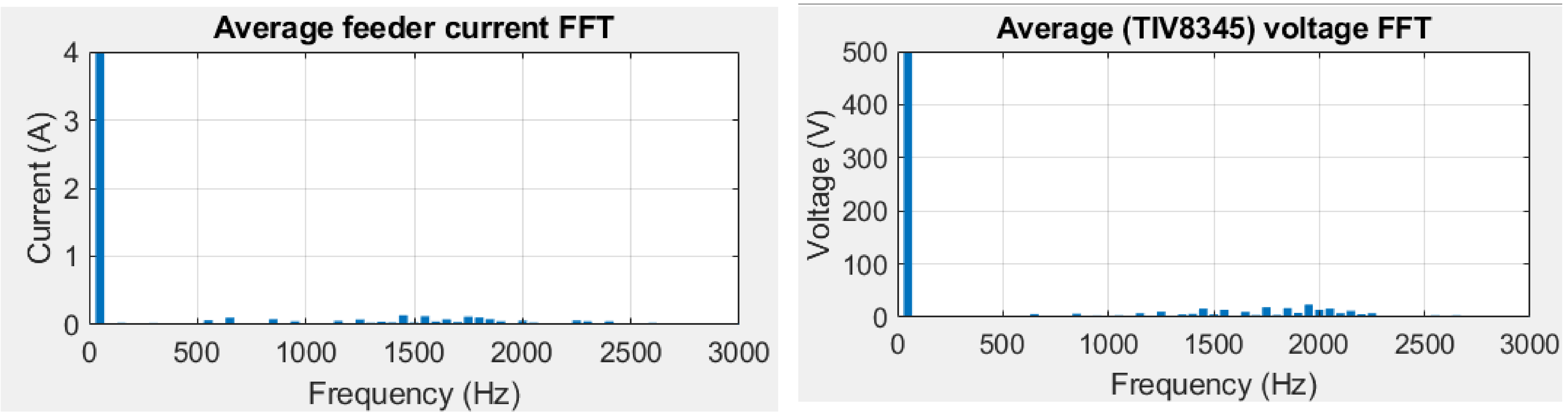
Test 7: Balanced 13th harmonic current



Current waveforms before and after compensation with balanced 13th harmonic current.

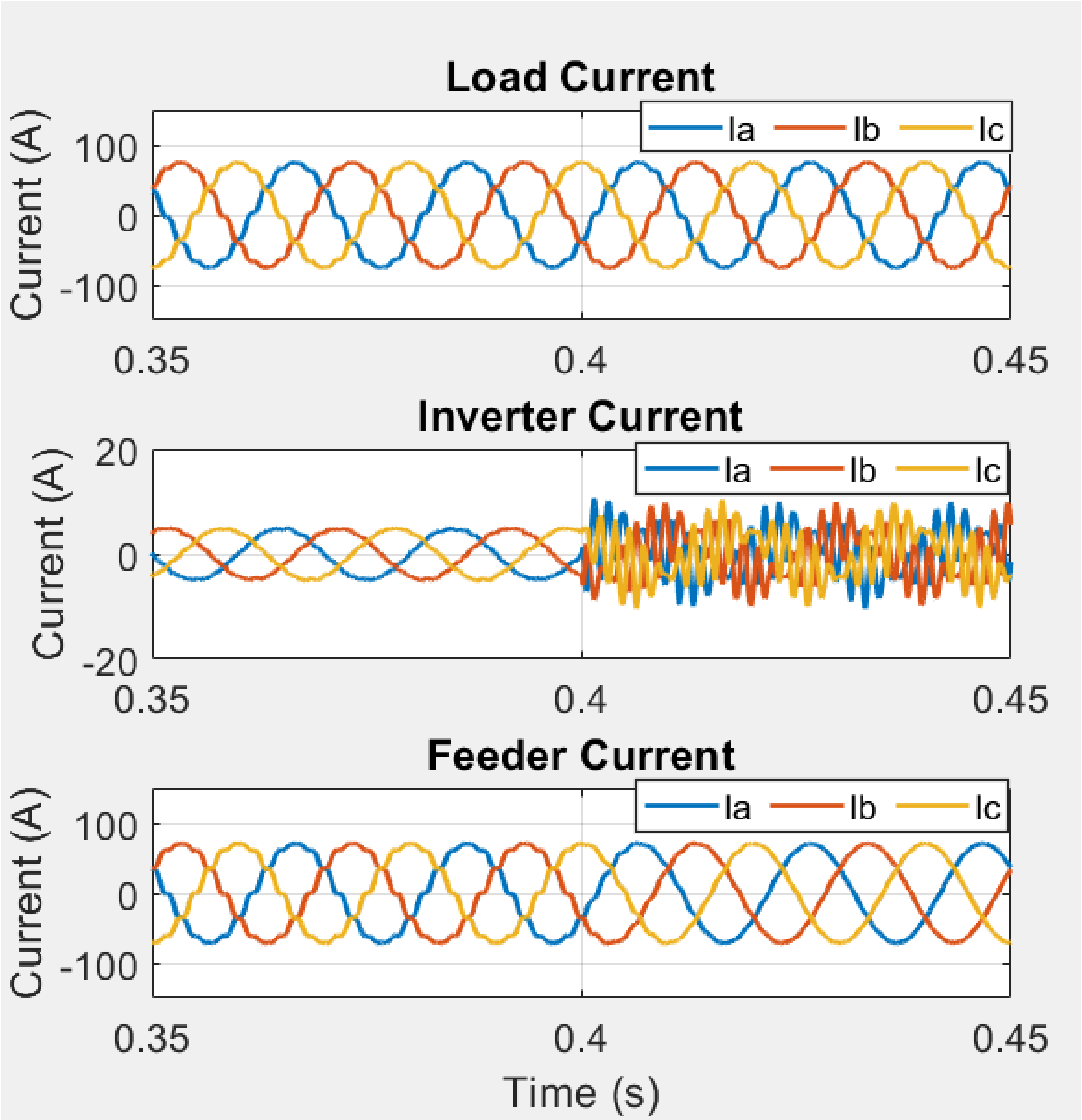


Feeder current (Left) and TIVE8345 voltage (Right) harmonics without compensation.

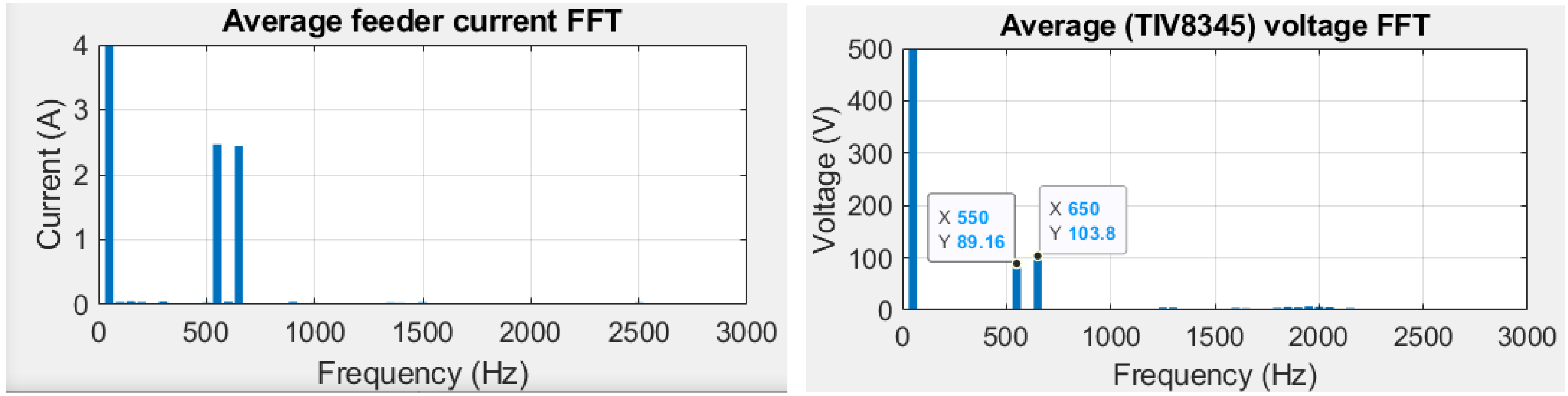


Feeder current (Left) and TIVE8345 voltage (Right) harmonics with compensation.

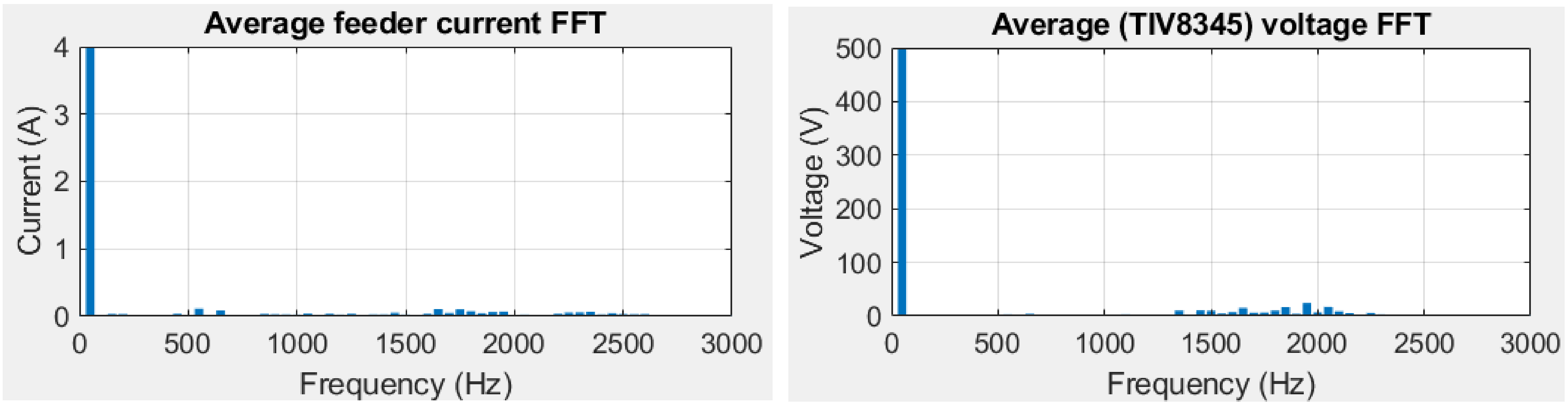
Test 8: Balanced 11th and 13th harmonic current



Current waveforms before and after compensation with balanced 11th and 13th harmonic current.



Feeder current (Left) and voltage (Right) harmonics without compensation.



Feeder current (Left) and voltage (Right) harmonics with compensation.

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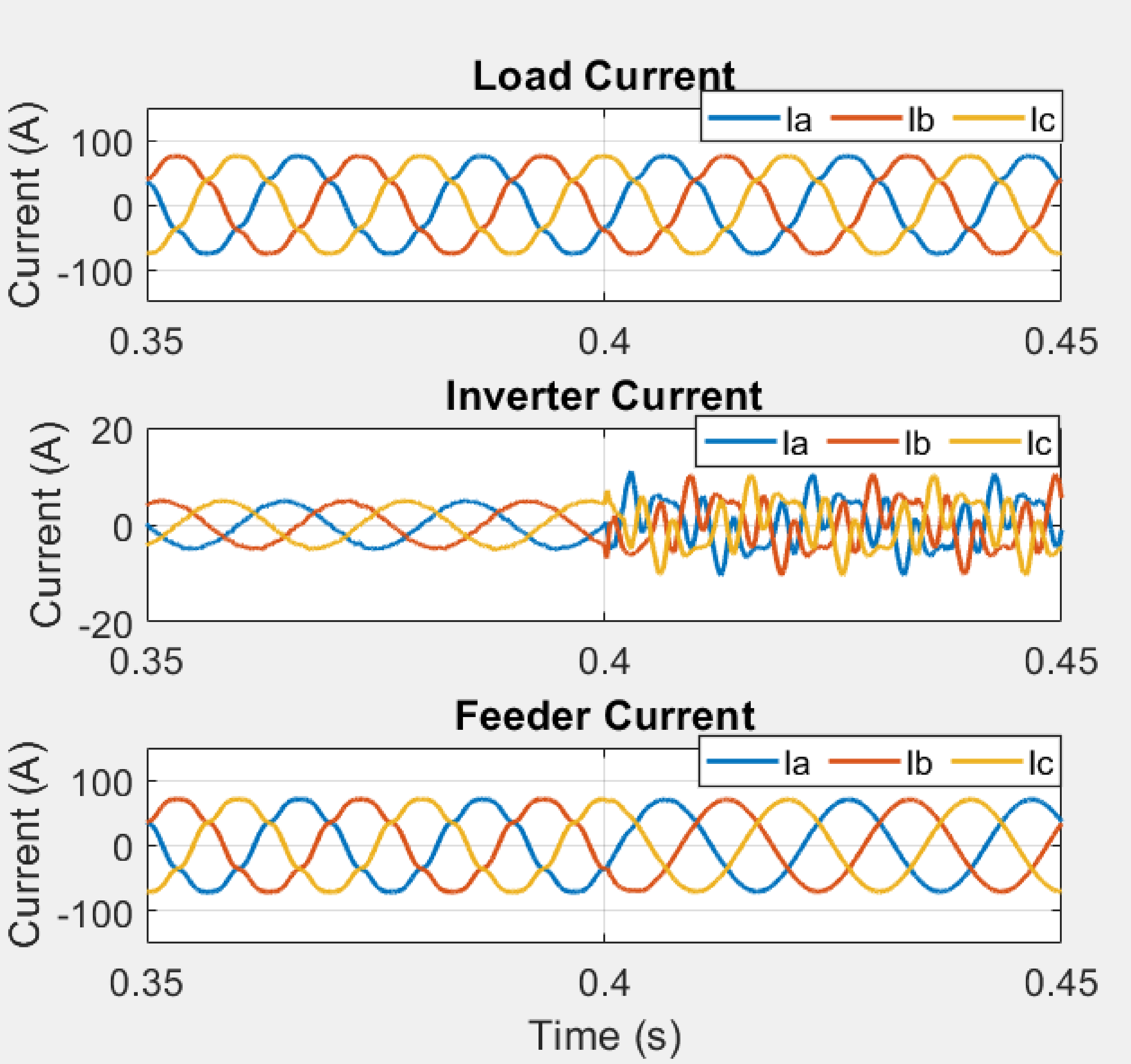
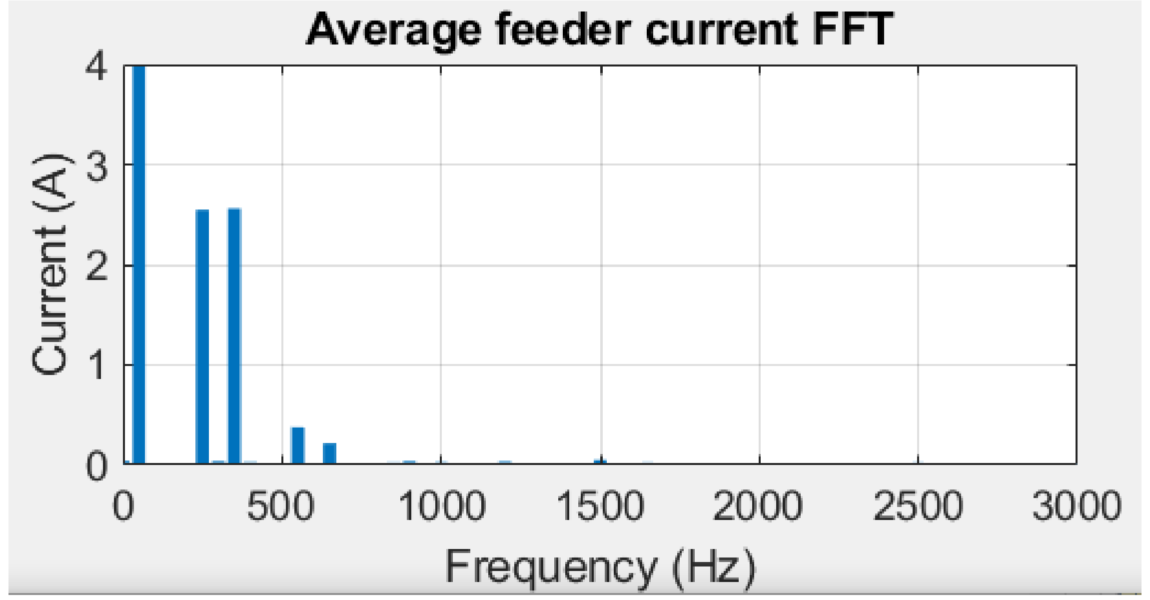
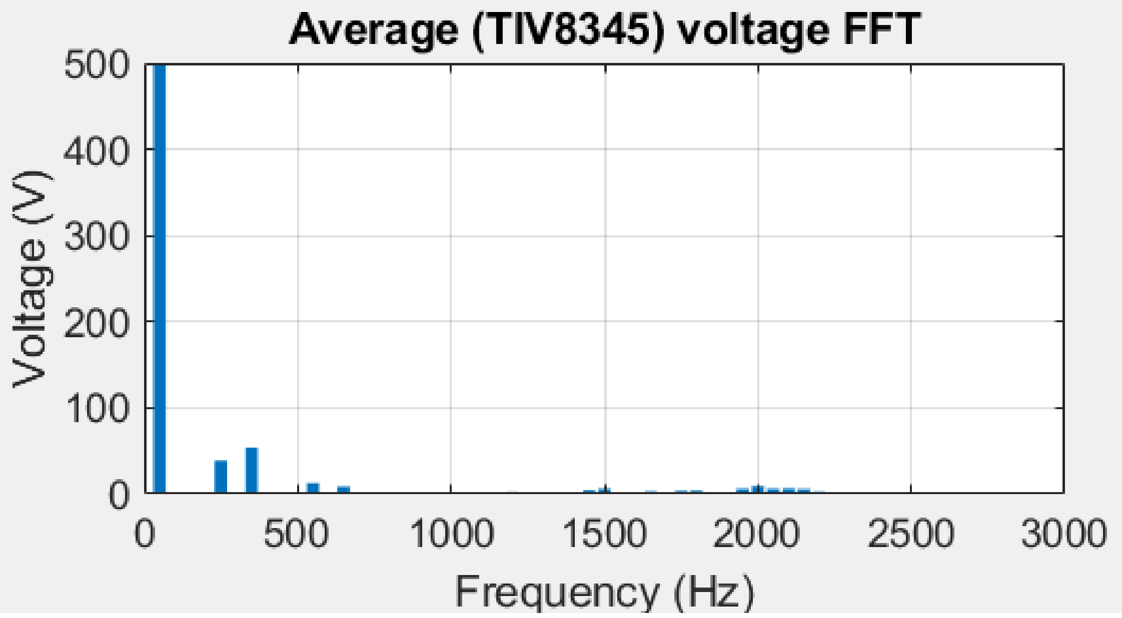
Test 9: All (balanced) harmonic components simultaneously

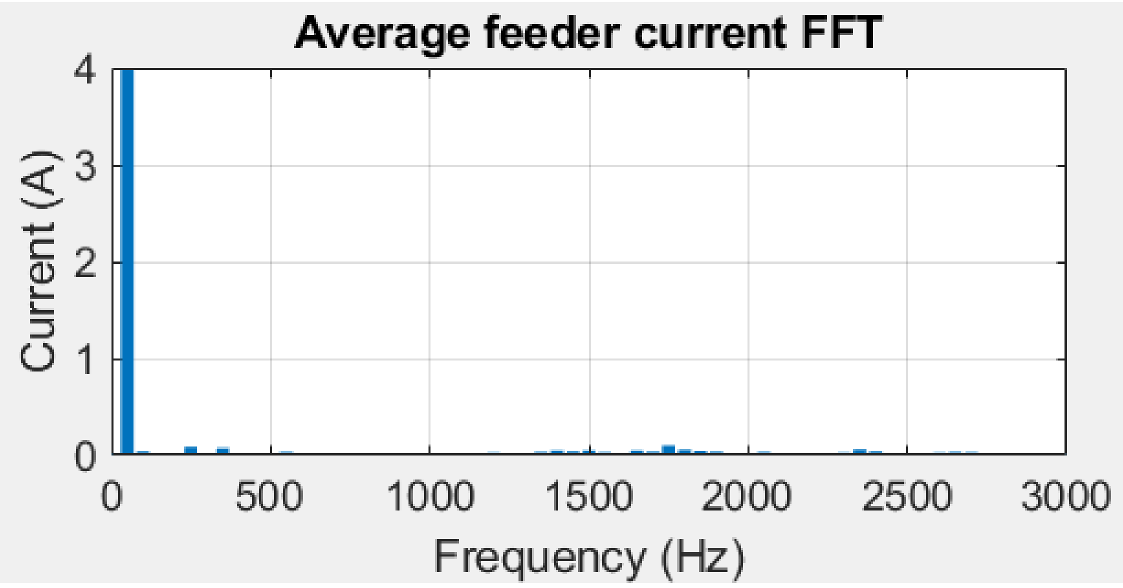


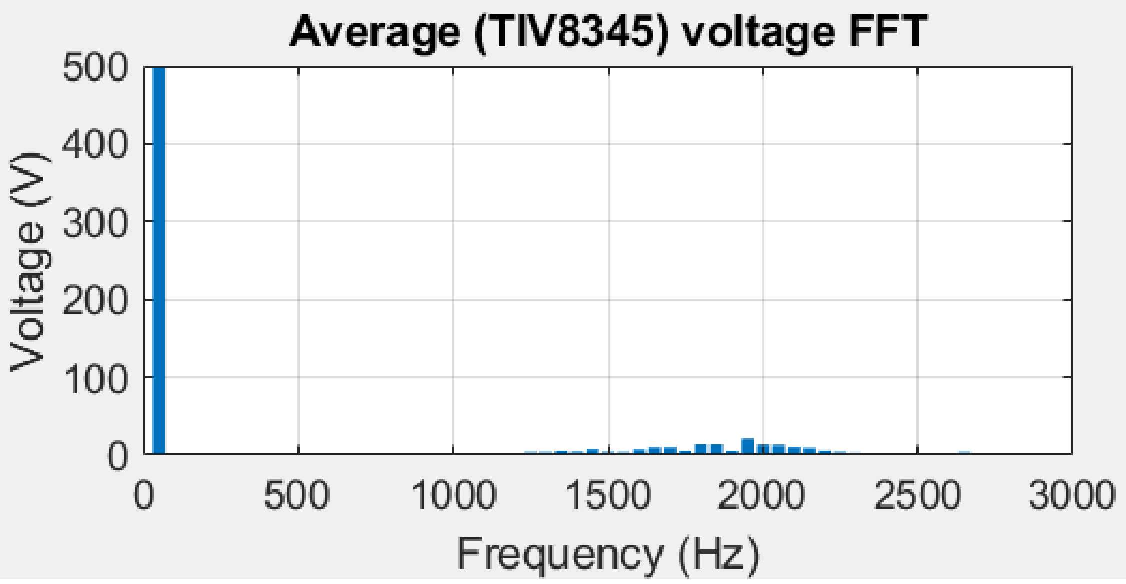
Current waveforms before and after compensation with all four harmonics (amplitudes close to feeder current).





Feeder current (Left) and TIVE8345 voltage (Right) harmonics without compensation.





Feeder current (Left) and TIVE8345 voltage (Right) harmonics with compensation.

2.4 Conclusions

- A novel control algorithm to perform harmonic compensation has been developed that operates alongside existing fundamental current control.
- The main components of the active filter algorithm consist of: notch filters, proportional resonant controllers and gain selection.
- The proposed approach has been assessed for the main harmonic components identified on the Tiverton Network (5^{th}, 7^{th}, 11^{th} and 13^{th}) and found to almost eliminate these harmonics when the algorithm is in operation, and lower irradiance occurs.
- Small residual (5^{th}, 7^{th}, 11^{th} and 13^{th}) harmonics are observed, and represent the limit of the controller action that has been achieved.
- It is also noted that small levels of harmonics are generated at higher orders (>1500 Hz) as a result of the inverter action. The levels are low, with no material impact on grid operation.

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3. Studies – operation of the algorithm using October 2019 data

- Section 3 shows the results of tests carried out using the dynamic model developed in WP1.
- The dynamic model represents the system for the period of October 1st – October 21st 2019.
- Validation of the proposed algorithm was carried out by comparing the harmonic distortion in the system under two operating conditions: 1) running the model with no harmonic mitigation; and 2) running the model with the harmonic mitigation algorithm deployed at the inverter within the Ayshford PV farm.
- The impact of the algorithm was assessed by:
  1. Comparing frequency distribution charts of harmonic current magnitude (for each harmonic components). A successful result sees the a reduction in the number of instances of higher harmonic magnitude periods (and a corresponding increase in the number of instances of low current magnitude periods).
  2. Comparing FFT charts (without and with mitigation) for voltage at the 33kV BSP and for current measured on the feeder – these charts show average moving window FFT results for the full time period.
  3. Assessing the impact on voltage THD.
  4. Assessing the impact on losses in the interface transformer.

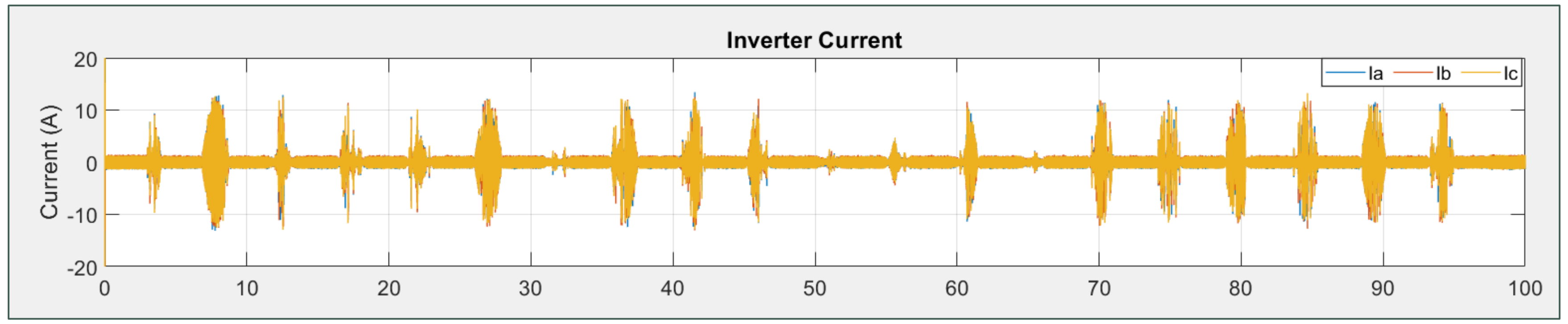
3.1 Inverter current

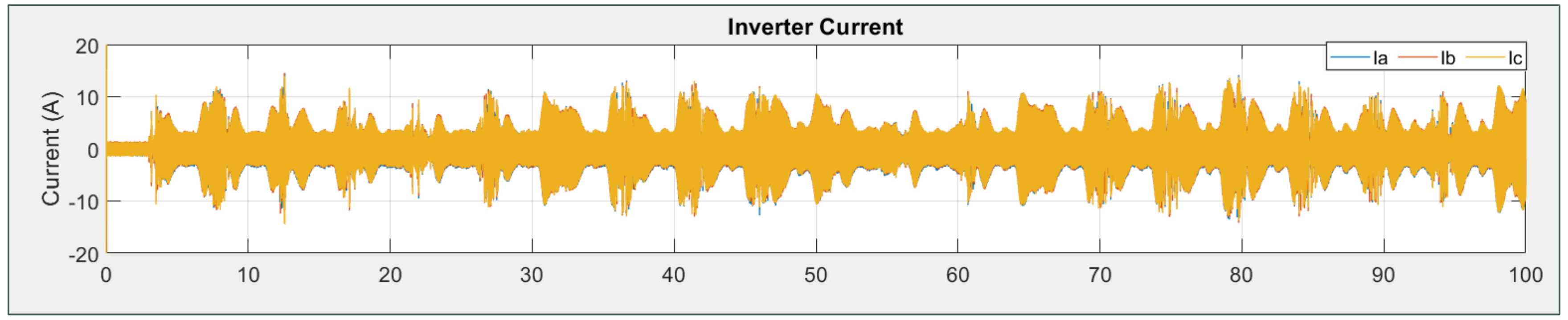
- The inverter current is monitored for the entire simulation time under two operating scenarios:
  - Original model, with no AF algorithm implemented.
  - Modified model, with AF algorithm implemented and operating.
- This test was done with the following aims:
  - To verify that the inverter rated current is not exceeded throughout the simulation time
  - To confirm that harmonics are not injected when the inverter is operating at high power levels.
- Simulation results are shown in the next slides.

3.1 Inverter current (1/3)

Original model | **With AF operation**

Entire simulation time (three weeks)



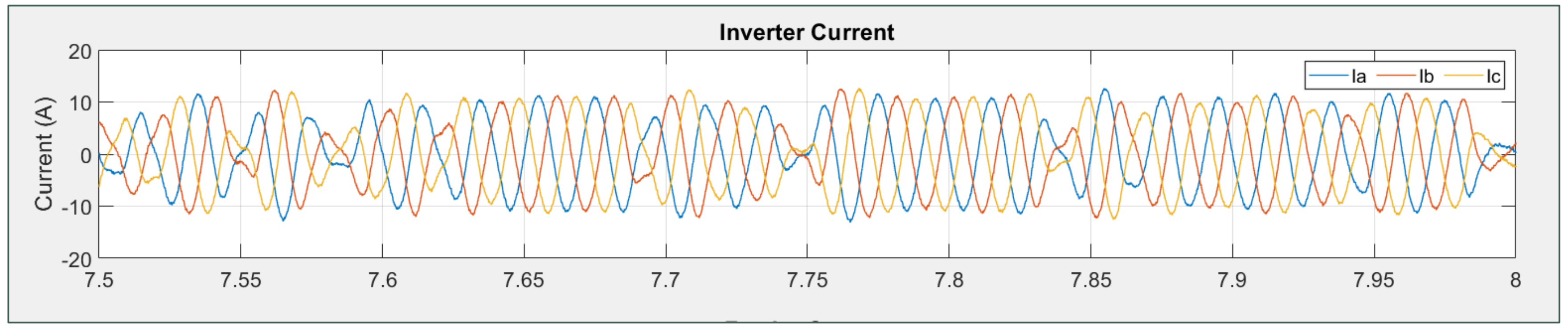


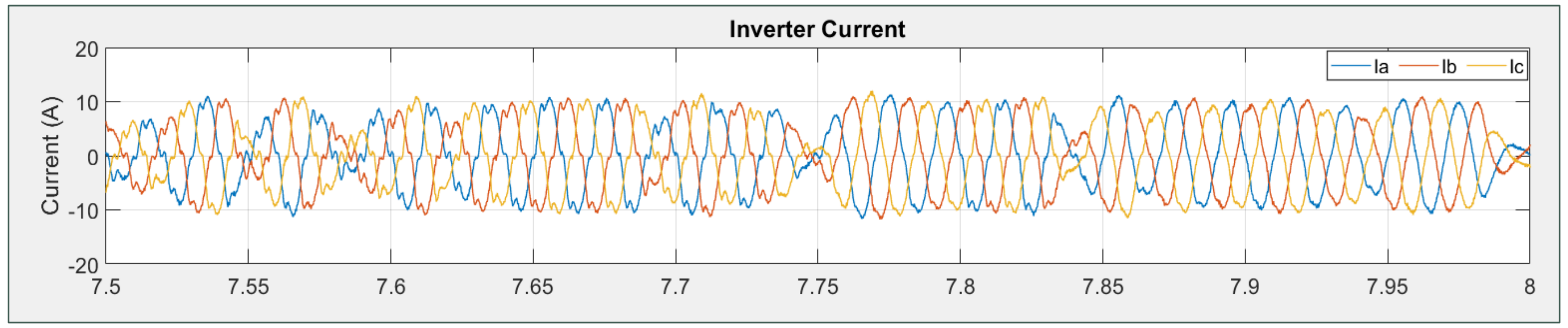
- The charts above show the modelled inverter current without and with AF functionality operating over a three week period. It is clear that:
  - the inverter is much more “active” with the AF functionality operating; and
  - harmonic mitigation does not drive peak inverter current beyond levels seen without AF operation.

3.1 Inverter current (2/3)

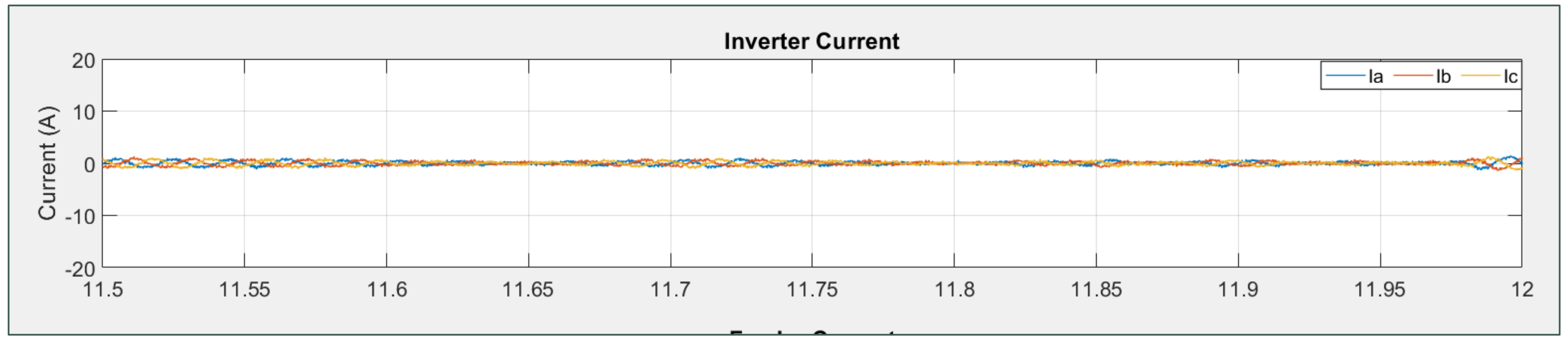
Original model | **With AF operation**

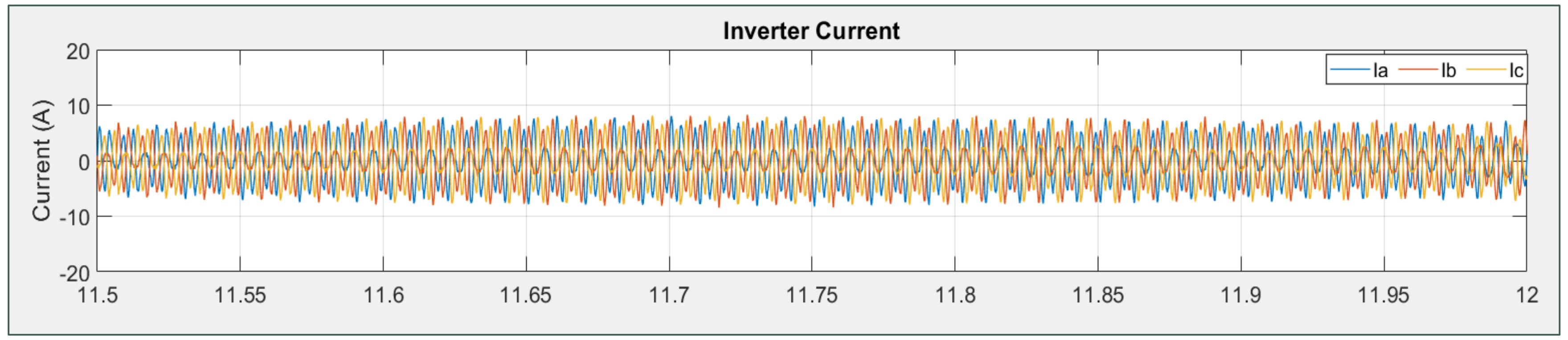
High irradiance window





Low irradiance window

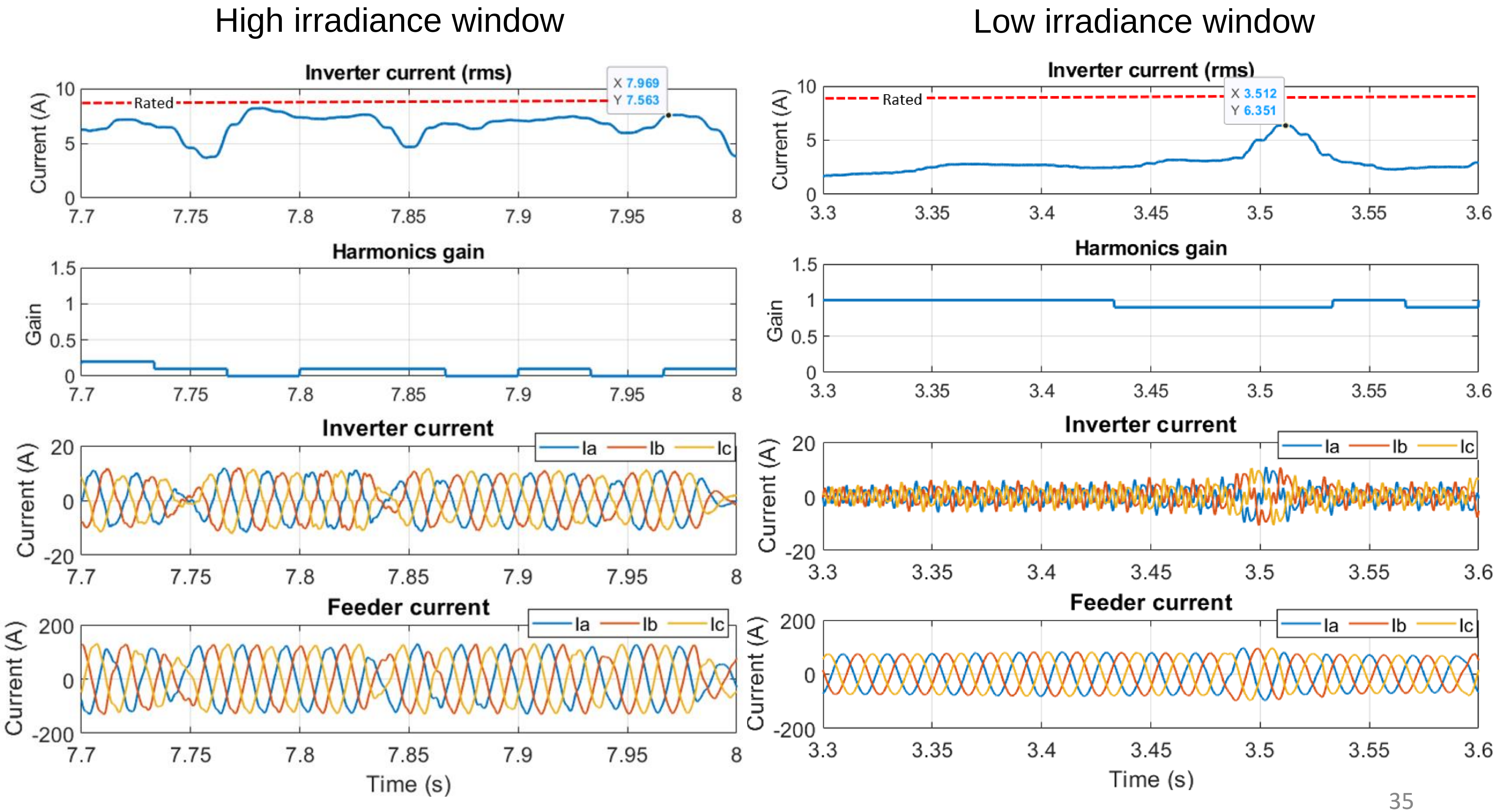




- The charts above show the modelled inverter current without and with AF functionality during a high irradiance period (upper charts) and during a low irradiance period (lower chart). It is clear that the inverter is much more “active” with harmonic mitigation during low irradiance periods, when capacity exists to carry out the mitigation

3.1 Inverter current (3/3)

- The charts on this page shows more in details inverter operation during high irradiance and low irradiance.
- When the inverter is operating under high the harmonic gain is close to zero. Therefore, no compensation is applied.
- At low irradiance conditions, there is plenty of room for the inverter to inject harmonics, which can be again determined by high harmonic gain.
- Under both conditions, the inverter rms current is not exceeded.
- The harmonic gain value is varying between 0 to 1, with a 10 min time interval.



3.2 Feeder current - Frequency distribution charts

- Frequency distribution (FD) charts have been prepared for each harmonic of interest.
- These charts represent the variation of feeder harmonic current magnitudes for the original case and for the case with harmonic compensation.
- The charts are shown for the following operating conditions:
  3.2.a – The entire simulation time.
  3.2.b – A day with low irradiance and a day with high irradiance.

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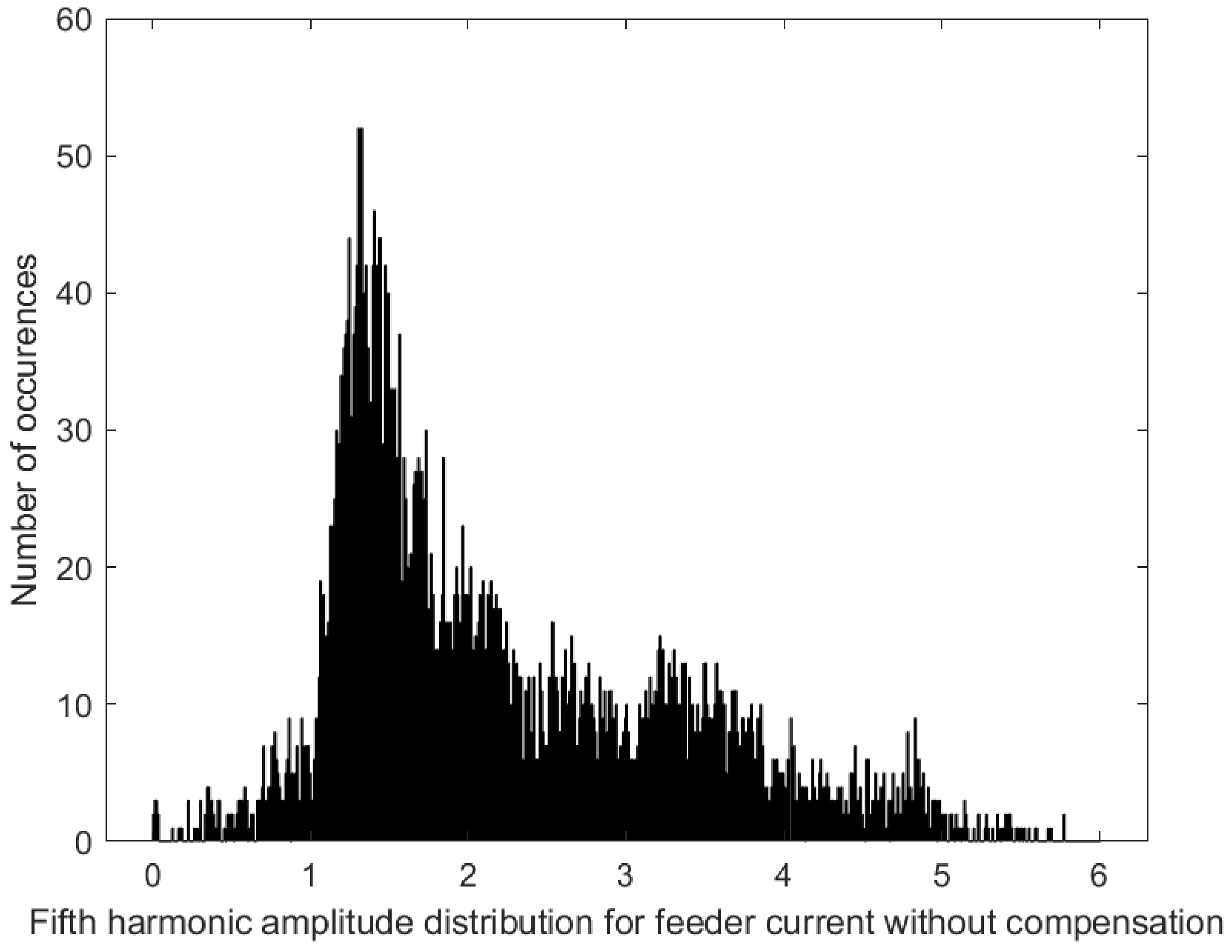
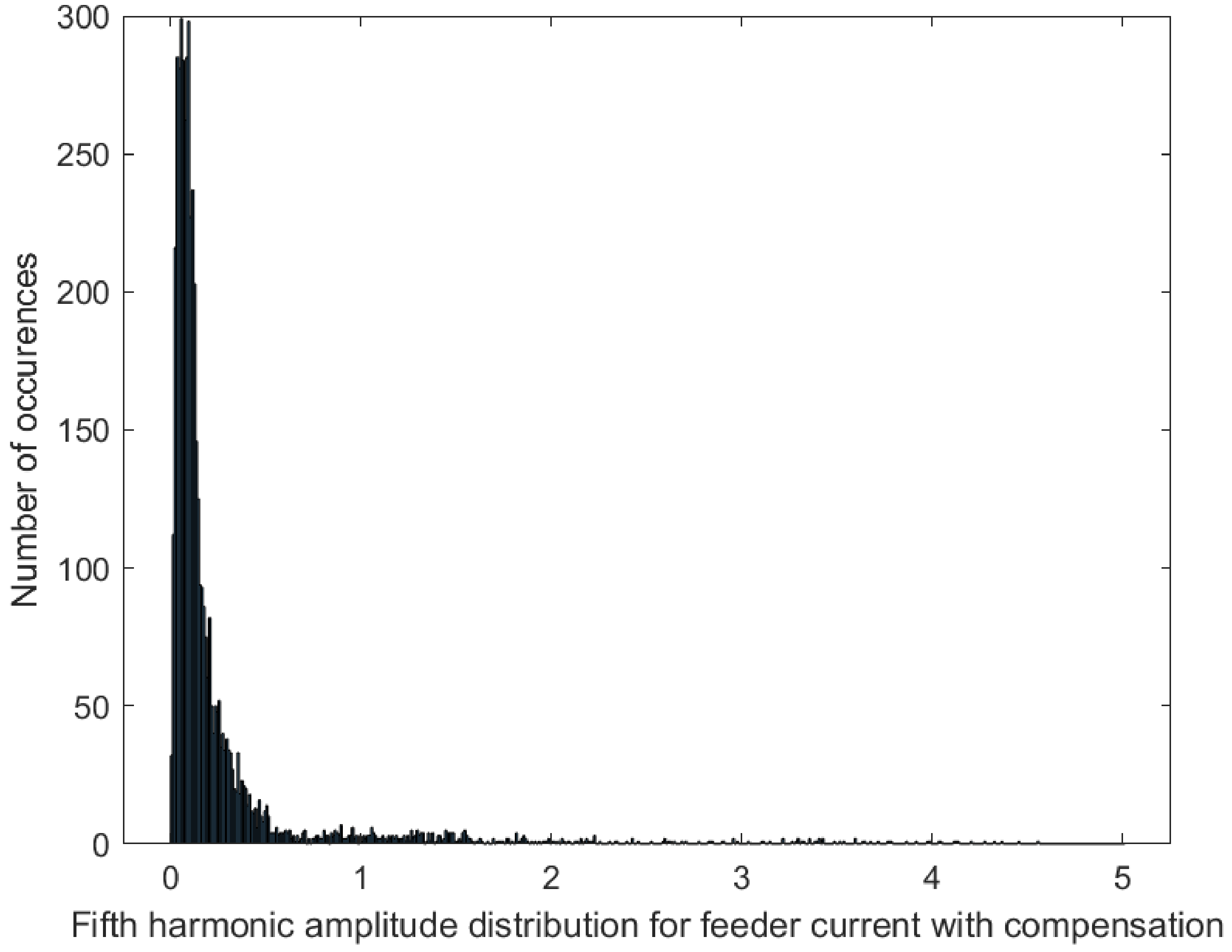
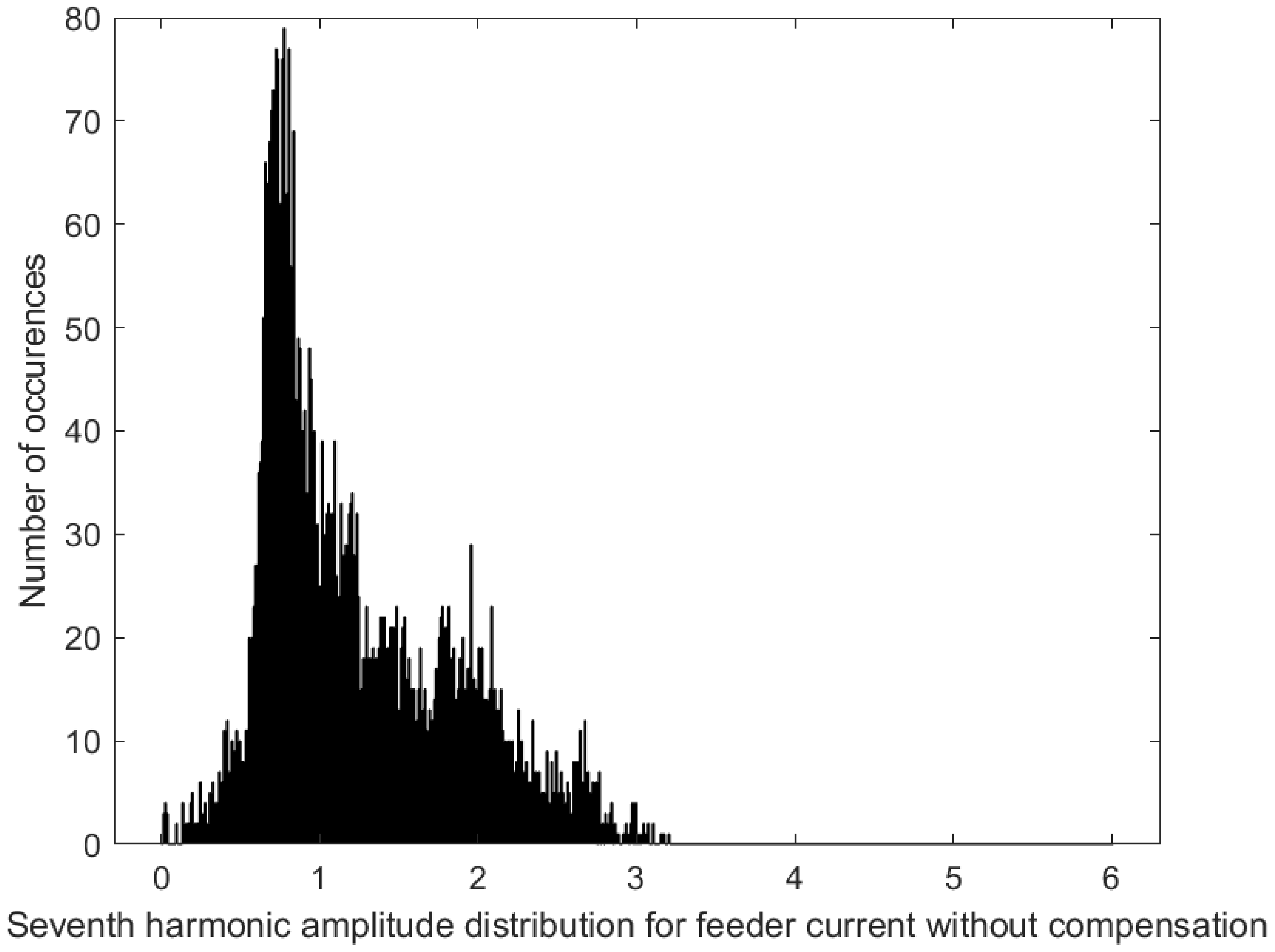
3.2.a FD charts for three weeks – 5th harmonic

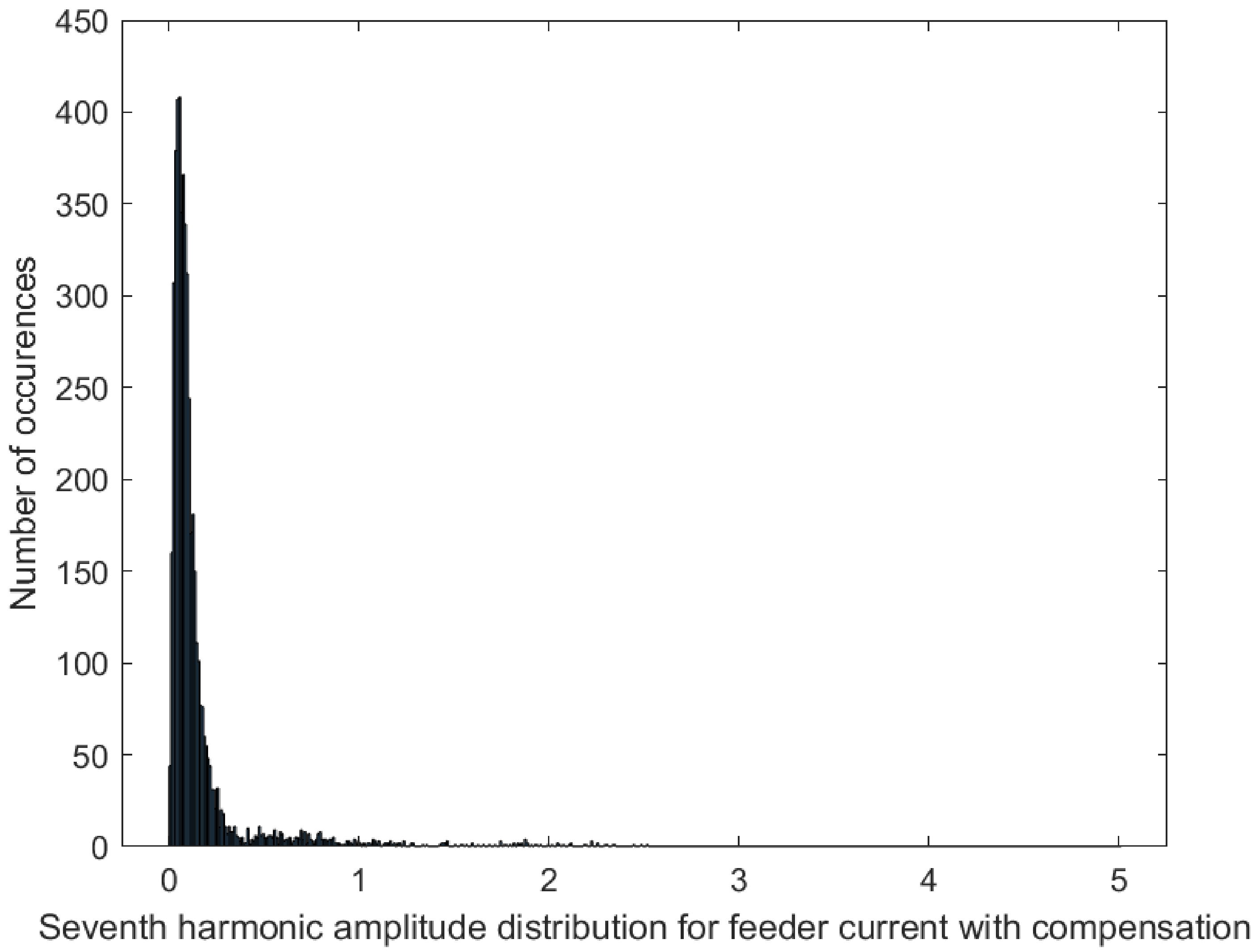




- These charts show the impact of AF operation on 5th harmonic current in the 33 kV feeder over the three week period. In left chart it can be seen that the most frequent 5th harmonic current magnitude is ~1.3 A, and that currents of up to ~5.8 A occur, though the number of instances diminishes as the current magnitude increases.
- With the AF functionality operating (right hand chart), a significantly different pattern of harmonic currents occurs. Only a very few instances of harmonic current above ~0.5 A occur, and the most frequent 5th harmonic current becomes ~0.1 A.
- The very few instances of higher harmonic current magnitude are associated with periods of higher solar irradiance, when the inverter does not have sufficient capacity to convert PV fundamental power and mitigate harmonics at the same time.

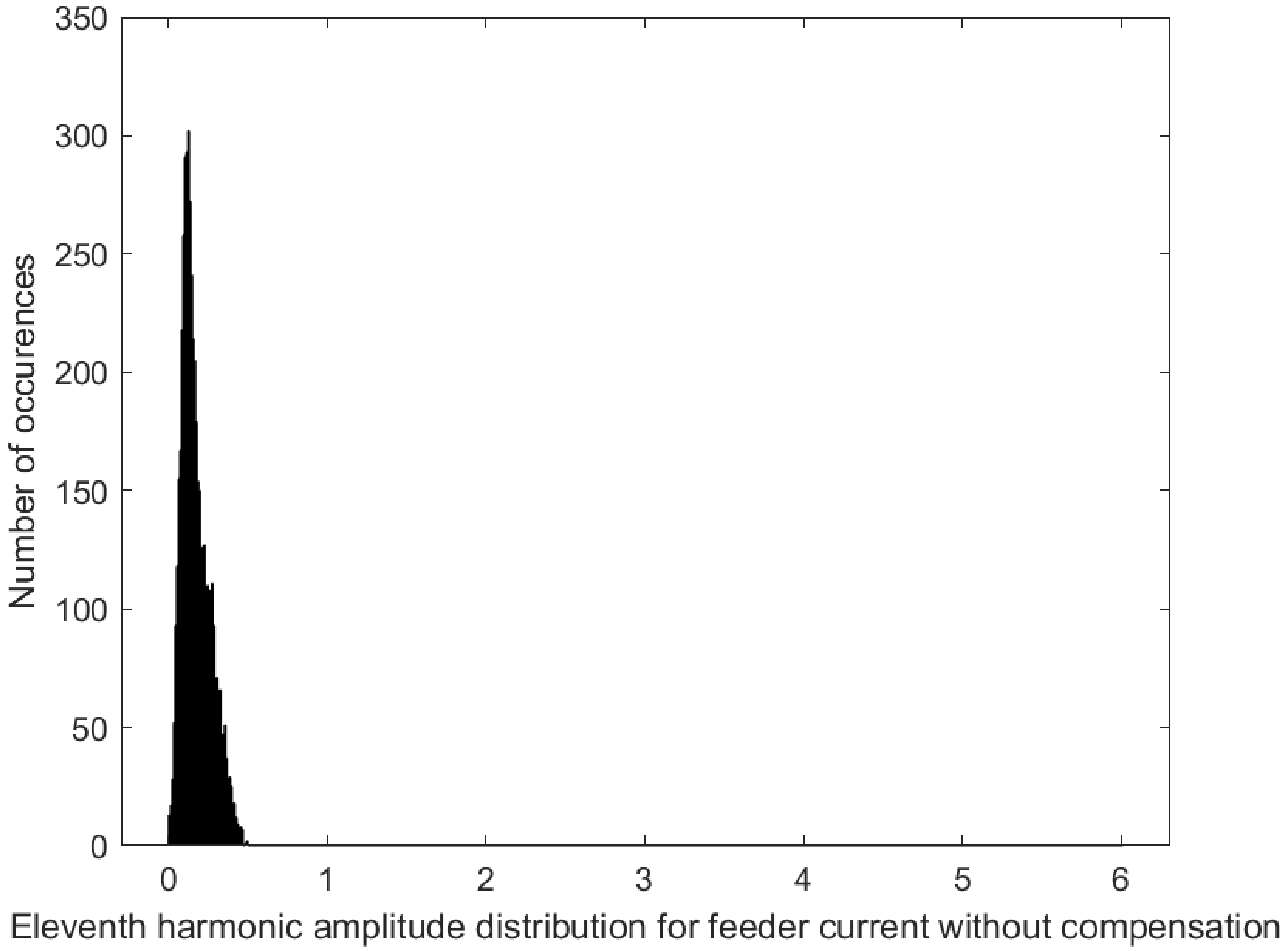
3.2.a FD charts for three weeks – 7th harmonic

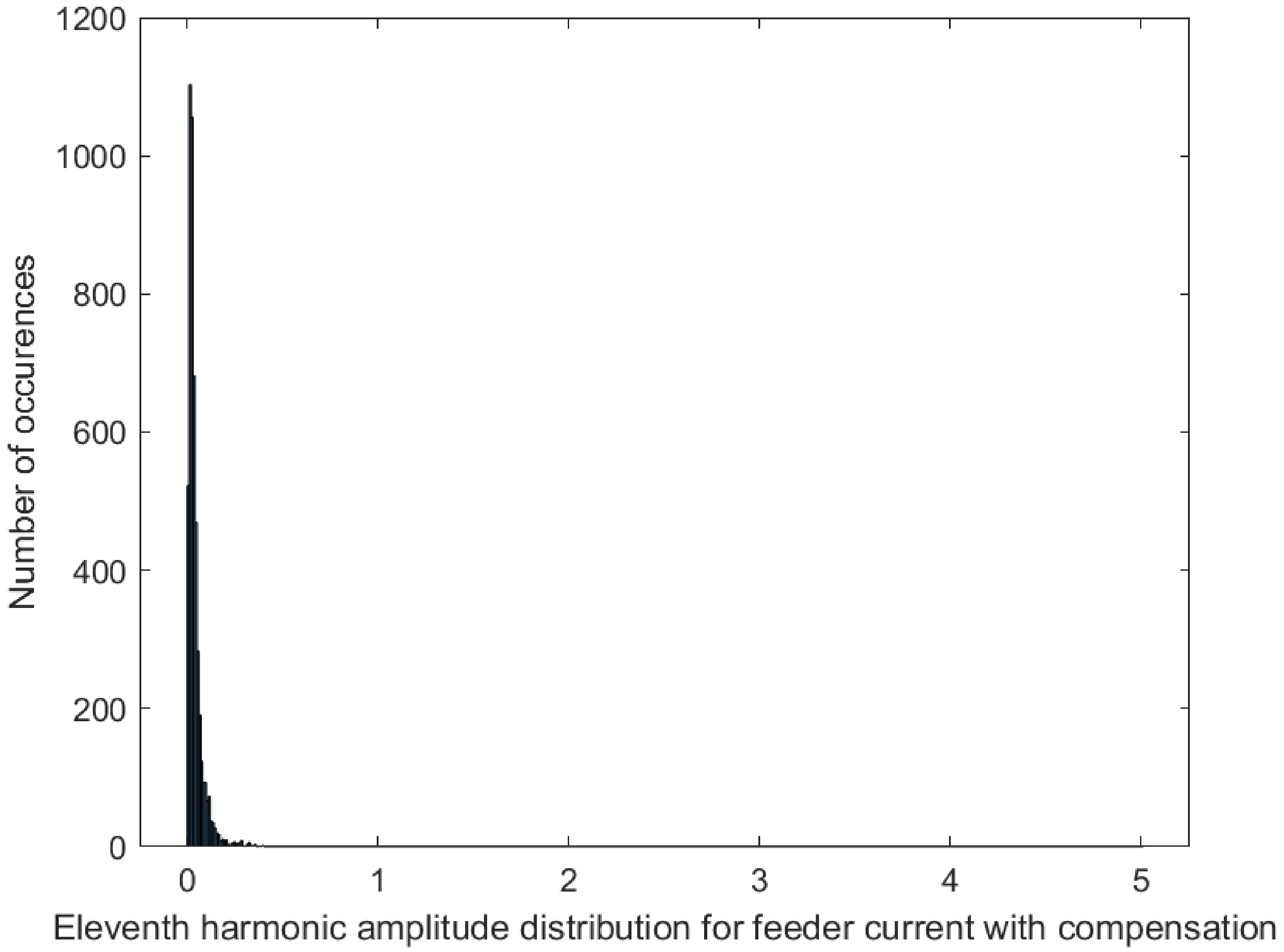




- A similar result to the previous slide is shown here for the 7th harmonic.

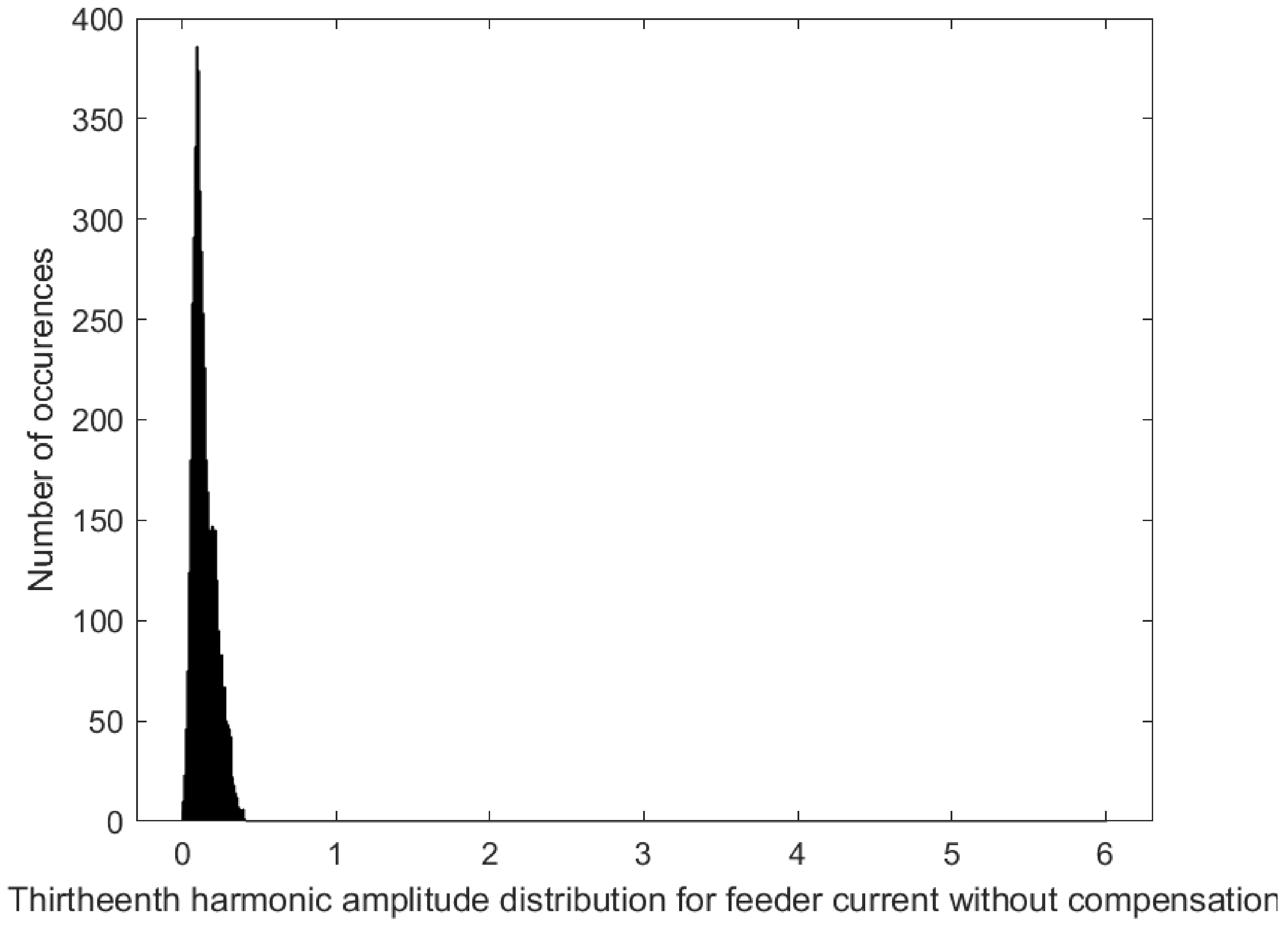
3.2.a FD charts for three weeks – 11th harmonic

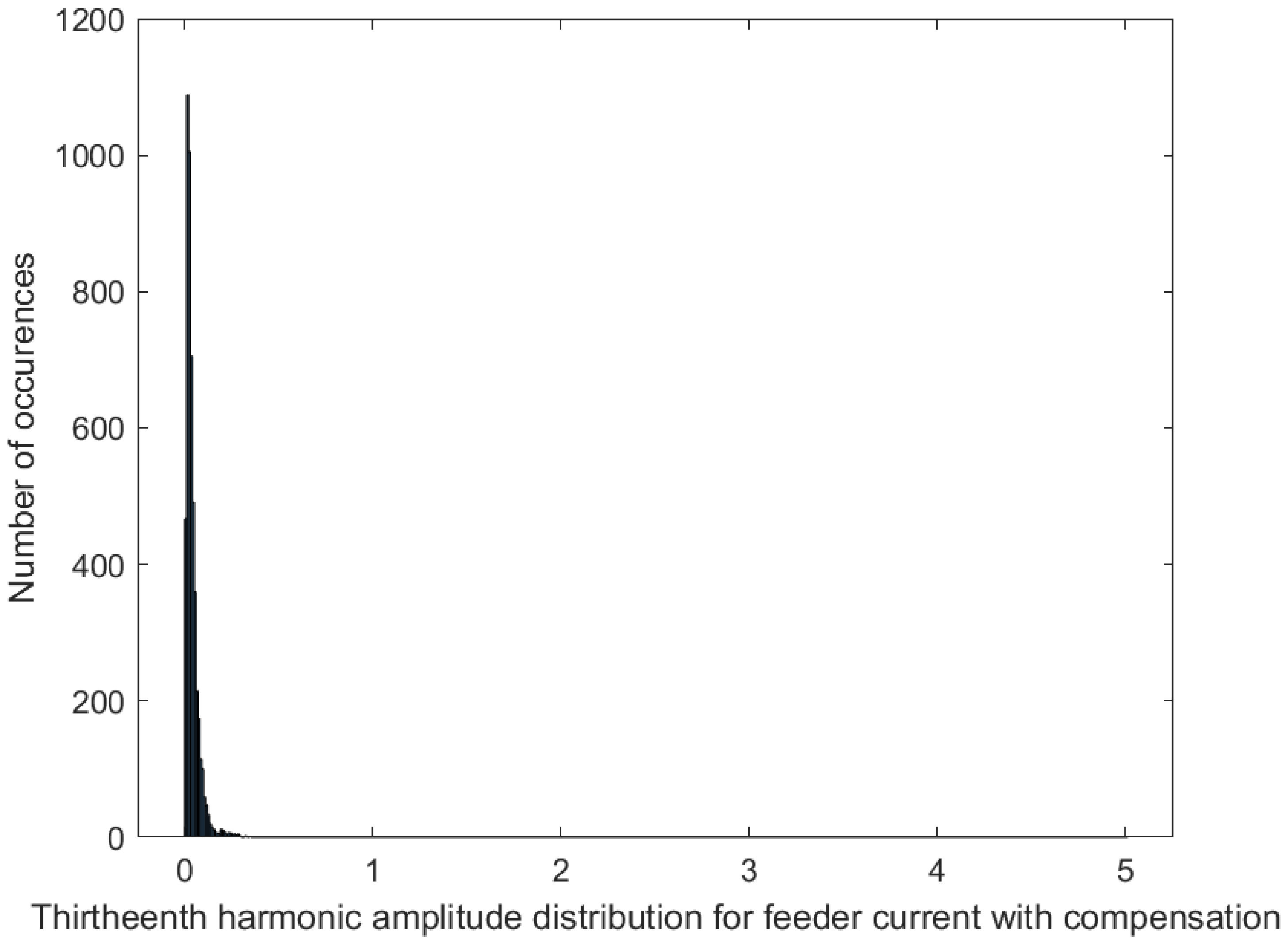




- The 11th and 13th harmonics are much smaller in magnitude compared to the 5th and the 7th. Therefore, the chart to the left shows few instances of high amplitude 11th harmonic component.
- In spite of the relatively small current amplitude, the algorithm is able to compensate for these harmonics too.

3.2.a FD charts for three weeks – 13th harmonic





- The behaviour for the 11th harmonic is similar to the 13th harmonic shown in the previous slide.

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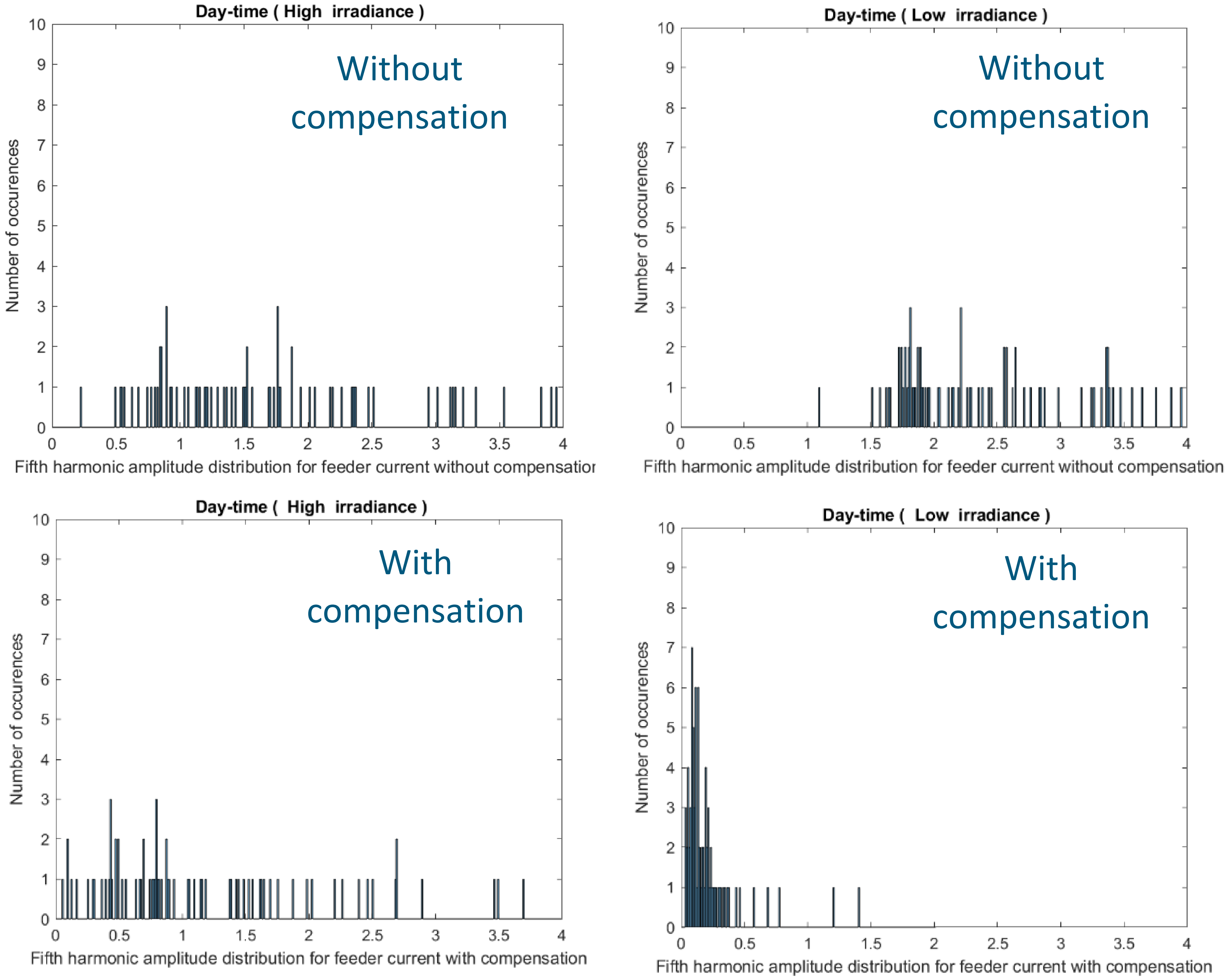
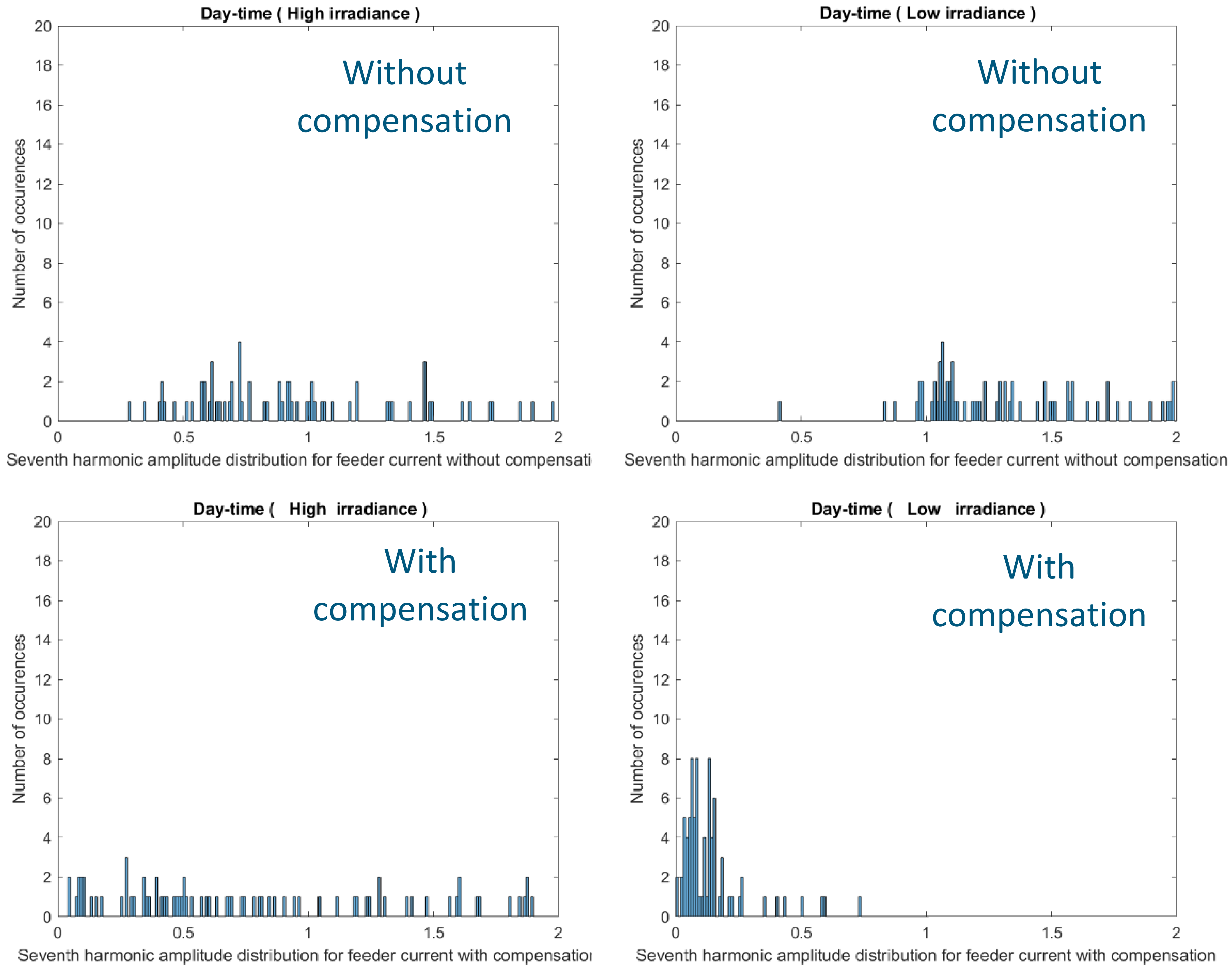
3.2.b FD charts for high and low irradiance day – 5^{th} harmonic

- These graphs are obtained by considering a 7 hours window (9 am till 4 pm for a single day).
- When low irradiance conditions are met, the harmonic compensation algorithm can very effectively mitigate feeder harmonics. Under high irradiance condition, the feeder current shows high values of harmonic current because less harmonic mitigation takes place under these conditions.



3.2.b FD charts for high and low irradiance day – 7th harmonic

- The results for remaining harmonics, shown on this slide and the next ones are similar to the 5th harmonic.



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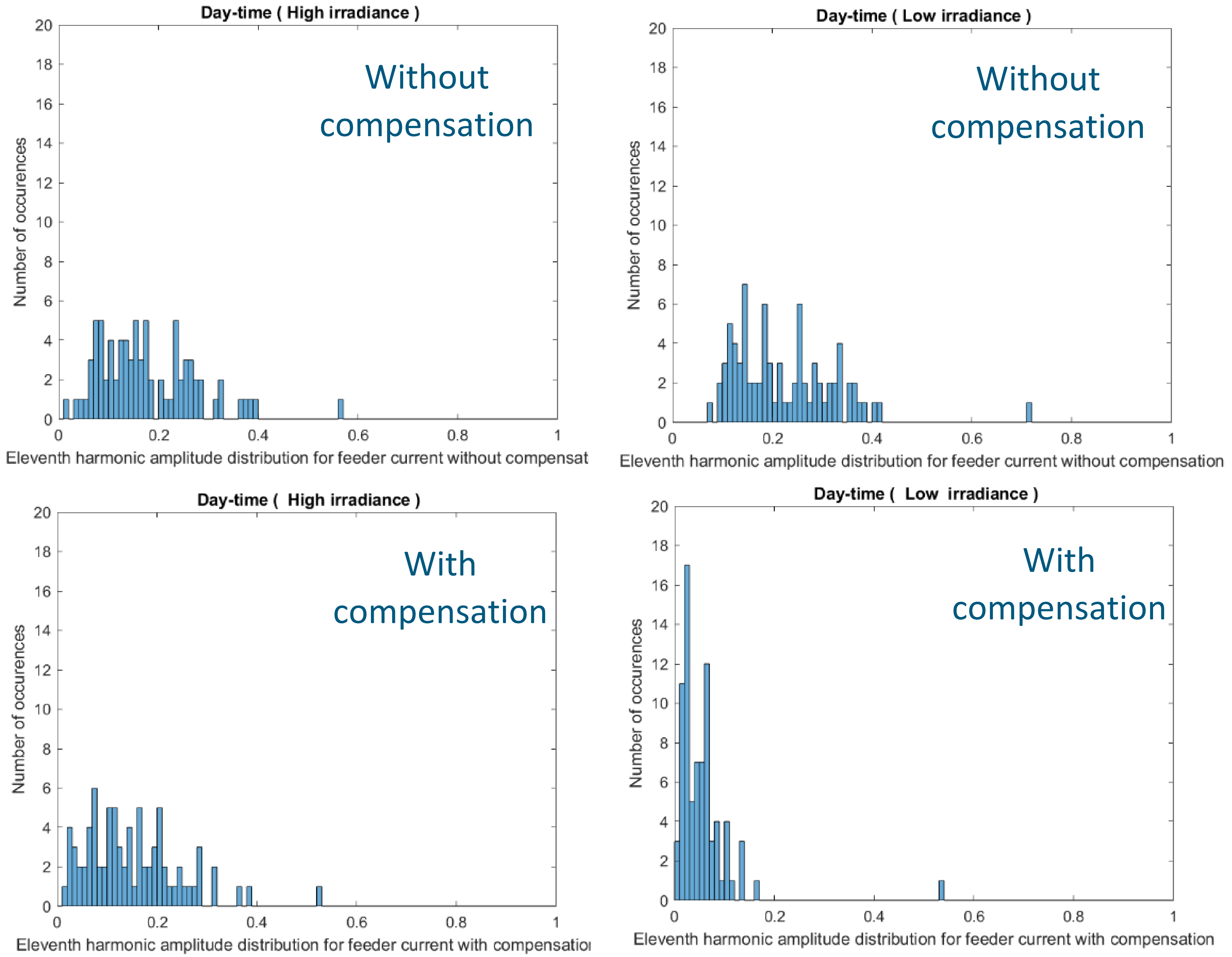
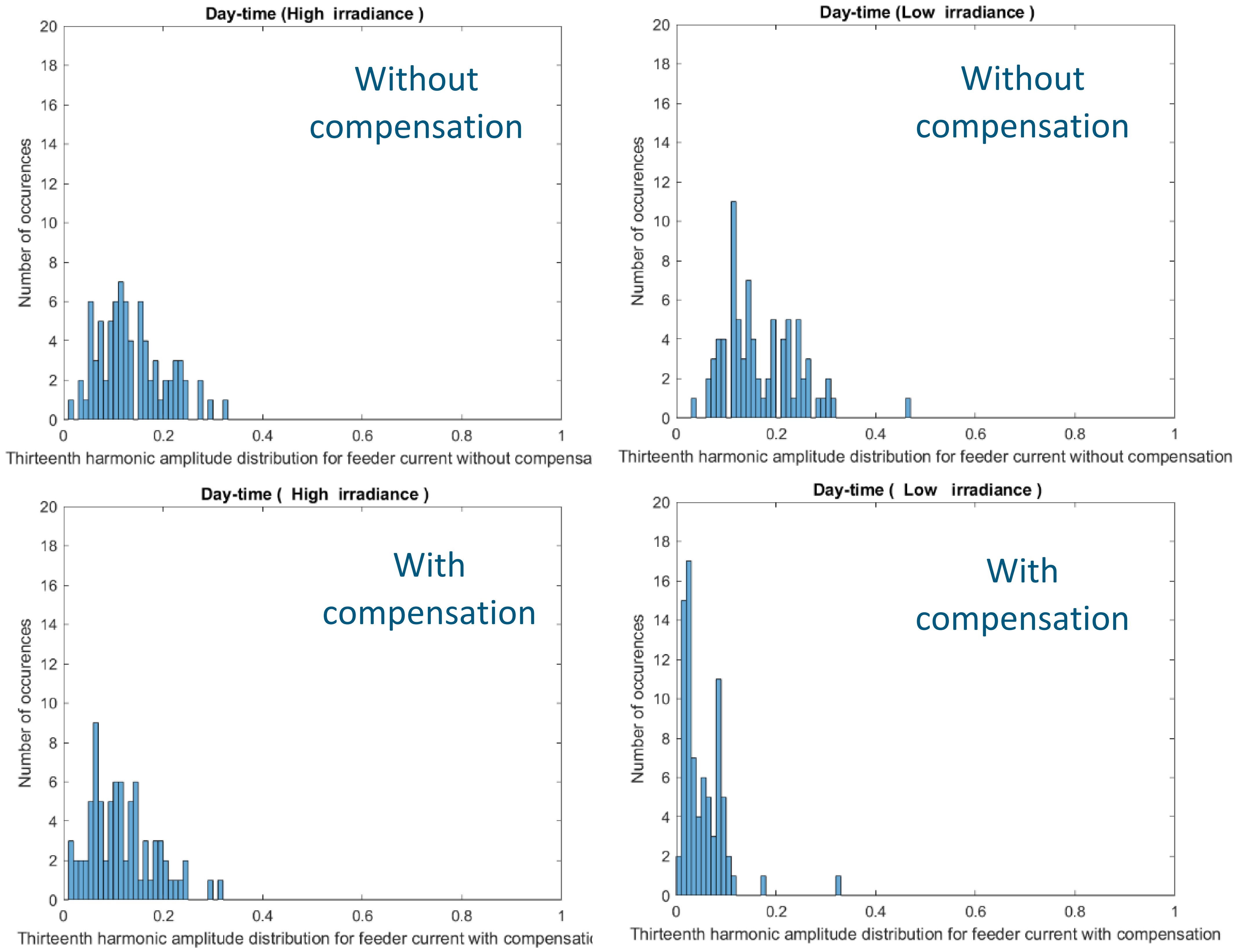
3.2.b FD charts for high and low irradiance day – 11th harmonic



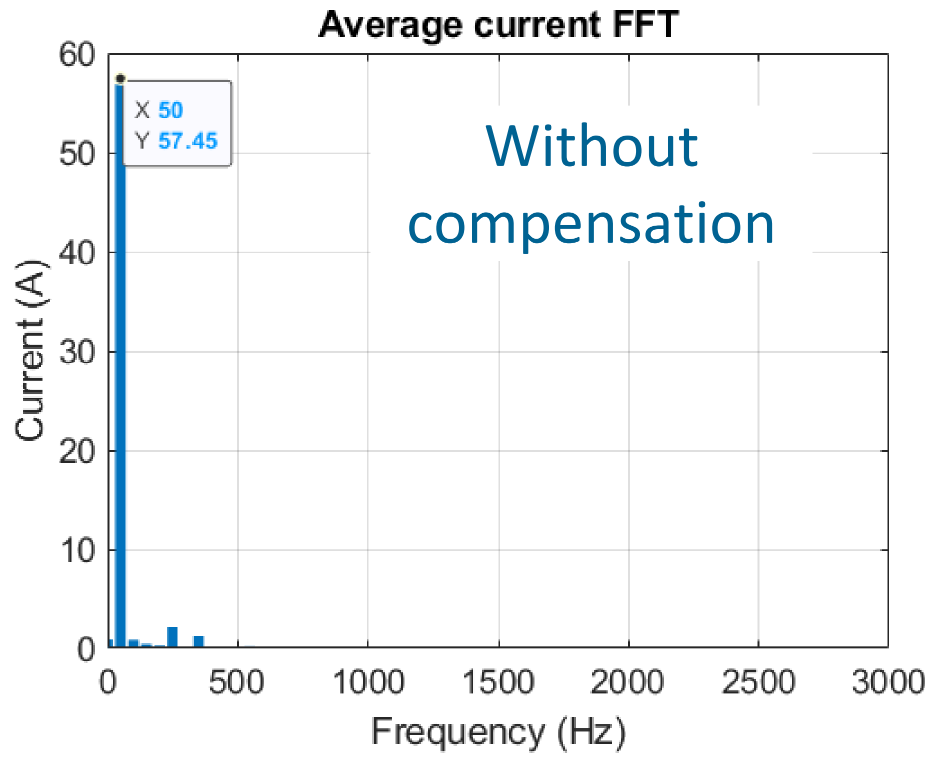
3.2.b FD charts for high and low irradiance day – 13th harmonic

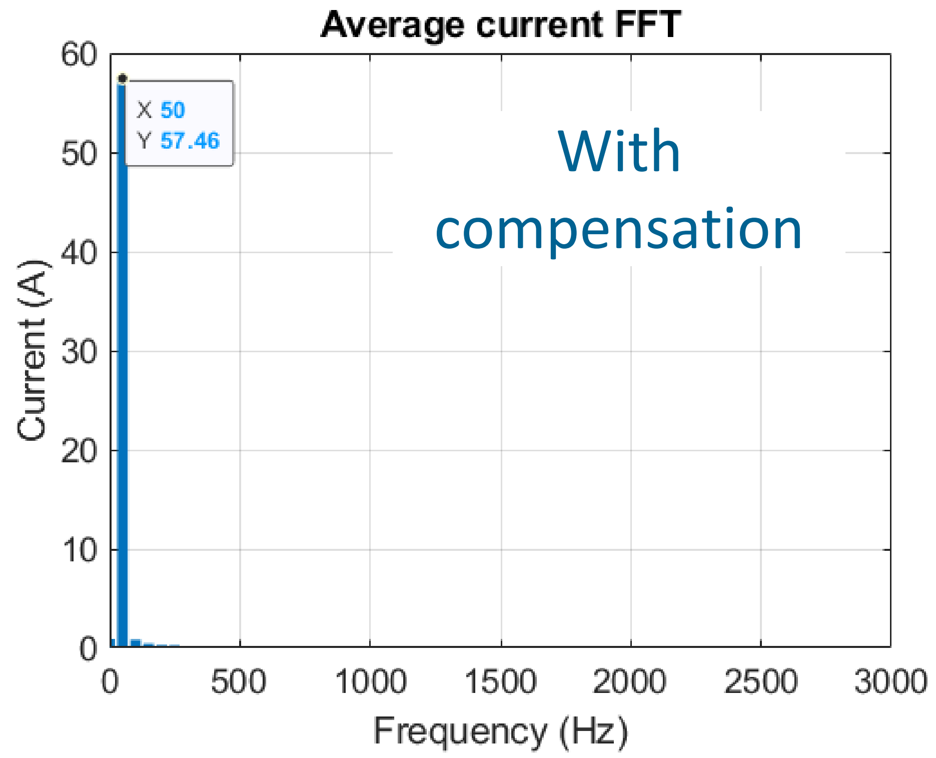


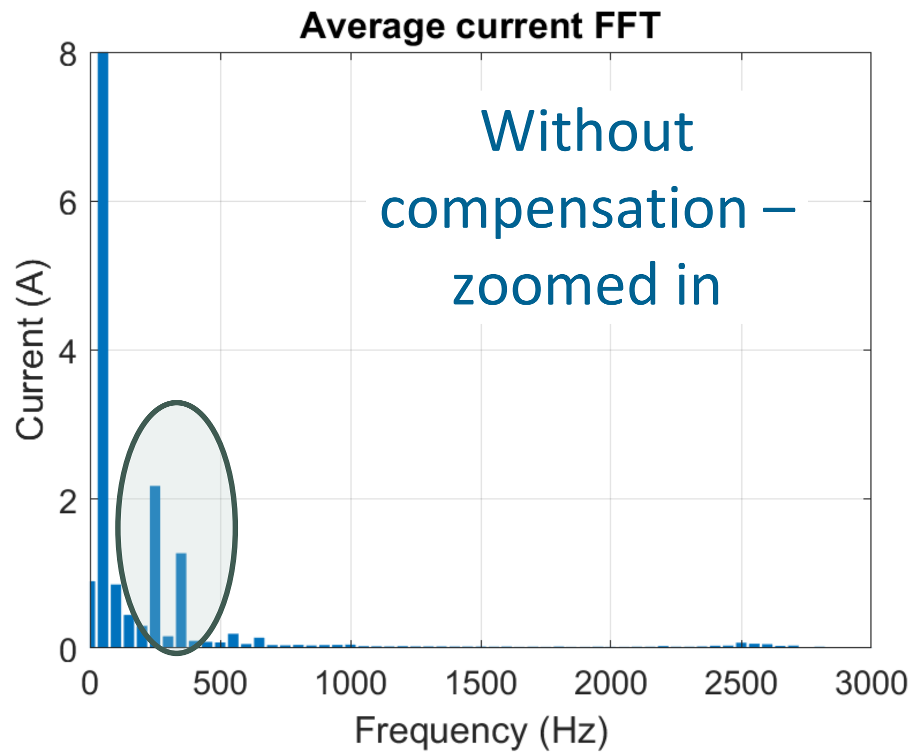
3.2.c Feeder current average FFT for three weeks

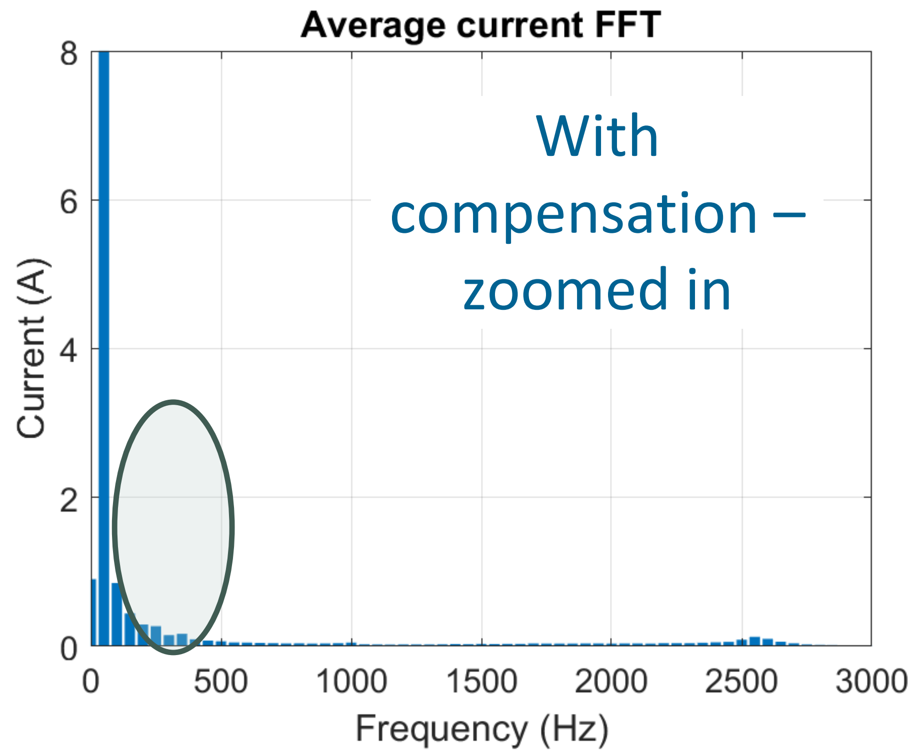
- Current FFT on the feeder is compared in the charts to the right.
- These charts present an rms average of FFT calculated across a three weeks period.
- The table below quantifies the reduction of the harmonic components.
- Small sidebands are visible when zooming in, due to the continuous variations of the fundamental current amplitude and the compressed time scale of the simulation.

Harmonic	Without compensation	With compensation	Percentage reduction (%)
1st	57.45	57.46	-
5th	2.178	0.269	87.7
7th	1.275	0.168	86.8
11th	0.194	0.053	72.6
13th	0.142	0.047	66.9









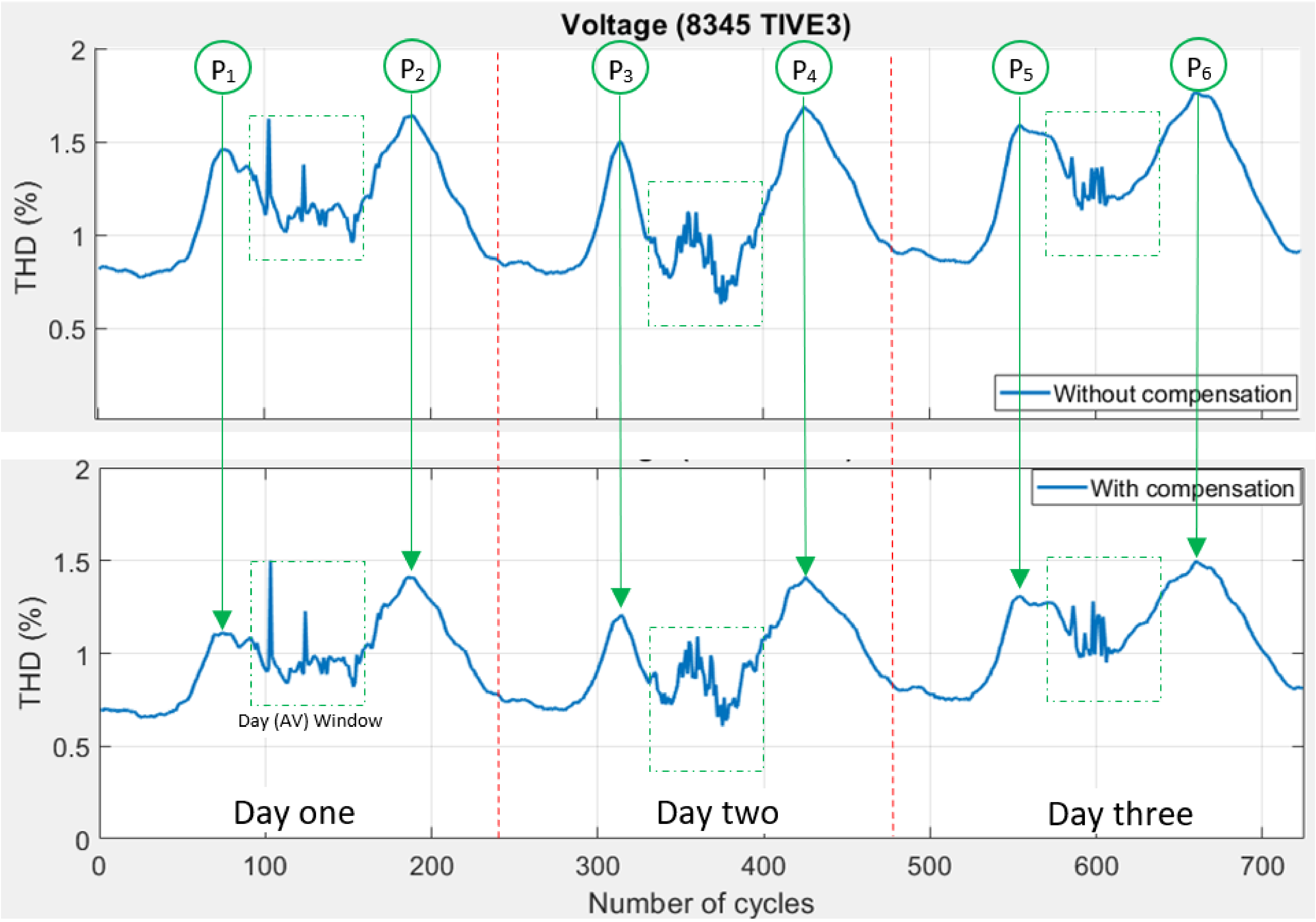
3.3 Time variation of voltage THD at the BSP

- Voltage THD at the BSP (TIVE3) is monitored within the model.
- The voltage THD (according to G5/5) is calculated without and with AF operation, and the results for the entire simulation time (three weeks) are as follows:
  - Without AF compensation, the rms voltage THD is 1.199%
  - With AF compensation, rms voltage THD is 1.043 %
  - Therefore, an overall reduction of 15.7% is observed.
  - The maximum compensation observed over a THD peak is 33.8% .
- In the next slide, detailed simulation results are shown for an observation period of three simulation days: this window has been selected for clarity and to allow displaying annotations, and it is illustrative of the typical variations of irradiance and harmonic levels observed in the Tiverton Network over the full period.

Voltage THD calculation

- The table below shows a detailed comparison of THD values for three simulation days:
  - Six peak values have been compared (P1- P6), and they occur-during night time periods.
  - The average THD calculation through day time (for a duration of 7 hours) is shown.
- The compensation is more effective at night than during the day because of low irradiance levels.

Data points	without comp.	With comp.	Voltage THD reduction (%)
P1 (X73)	1.457	1.119	33.8
P2 (X186)	1.637	1.417	22
P3 (X314)	1.498	1.208	29
P4 (X424)	1.688	1.413	27.5
P5 (X555)	1.59	1.314	27.6
P6 (X660)	1.764	1.496	26.8
Day one (Av) 9am-4pm	1.2432	1.0026	24.06
Day two (Av) 9am-4pm	0.9131	0.8464	6.67
Day three (Av) 9am-4pm	1.3439	1.1403	20.36
Total Three Days average	1.1594	1.0003	15.91

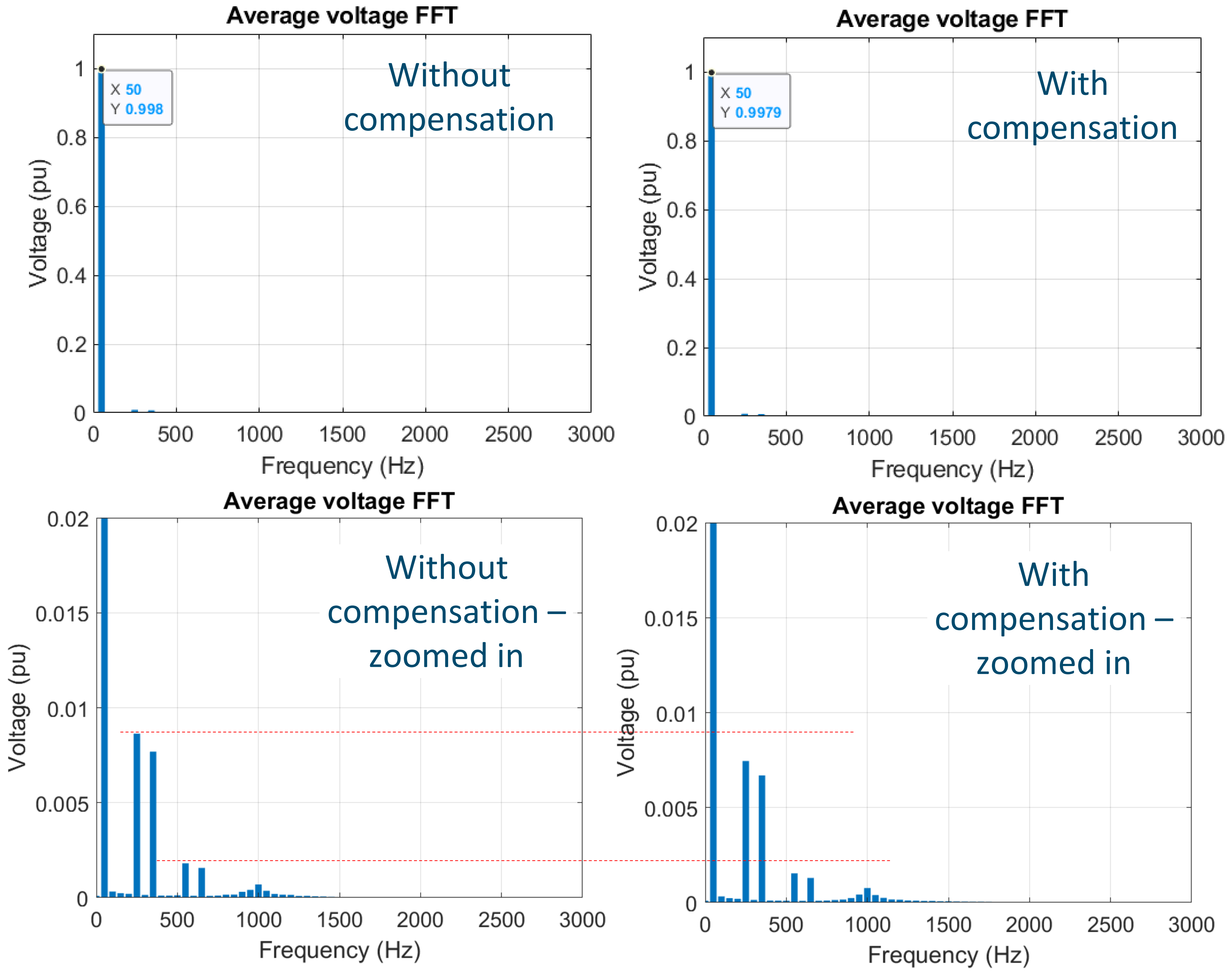


- Maximum reduction is 33.8%
- Average reduction is 15.91%

3.3 Harmonic Voltages at TIVE3

- While the voltage THD provides an indication of the overall impact on harmonic levels, it is important to look at individual harmonics also.
- FFT analysis on voltage has been undertaken before and after implementation of the AF algorithm.
- This analysis determines the rms value of each frequency component across the entire simulation time, based on IEC 61000-3-34.

Harmonic	Without compensation	With compensation	Percentage reduction (%)
1st	0.9980	0.9979	-
5th	0.0086	0.0074	13.7
7th	0.0076	0.0066	12.9
11th	0.0018	0.0015	15.1
13th	0.0015	0.0012	17.2



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3.4 Transformer losses

- The main effect of AF operation on the transformer is related to the copper losses.
- The losses are proportional to the square of the rms current and they are calculated using the following equation:

$$P_{Cu} = I_1^2 R_1 + I_5^2 R_5 + I_7^2 R_7 + I_{11}^2 R_{11} + I_{13}^2 R_{13}$$

- where R_1, R_5, R_7, R_{11} and R_{13} are frequency-dependant resistances calculated by using Method 1 described in CIGRE TB 766.

- The next slide presents the comparison between the fundamental losses and the total losses for three simulation days.

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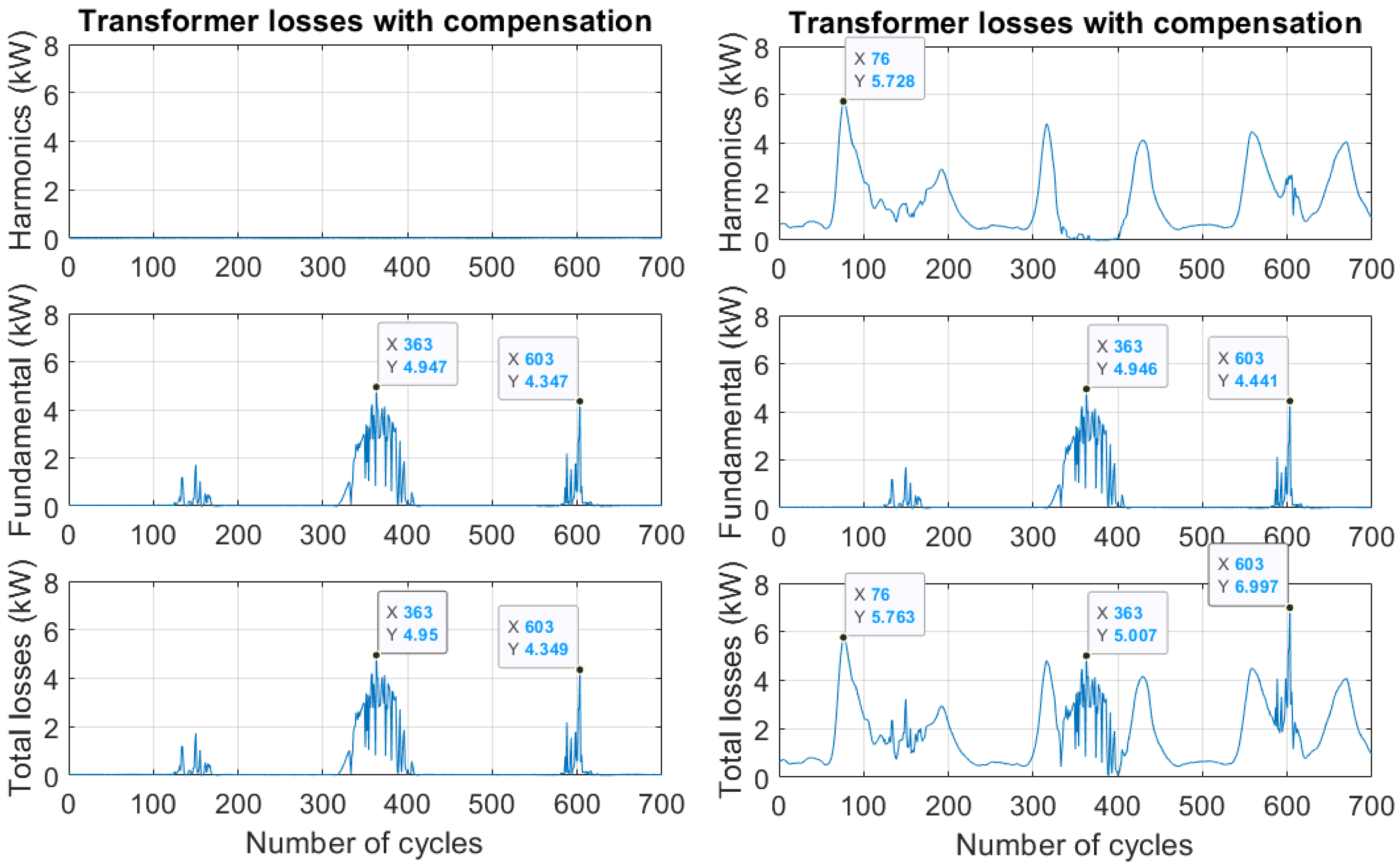
3.4 Transformer losses

- The figure to the right shows transformer losses without and with compensation implemented.
- Clearly the transformer losses increase with AF functionality (comparison of lower left and lower right charts)
- Under the majority of operating circumstances the losses are lower than full fundamental load losses of the transformer (~5kW).
- On a small number of occasions, and for short periods of time the transformer losses can be up to 15% above full load values.
- In practice this is very unlikely to drive hotspot temperatures to levels that would greatly accelerate insulation ageing. However, further limits on harmonic mitigation will be introduced during Work Package 3 to prevent full load losses being exceeded, and thereby take a conservative approach to the thermal impact on the transformer



3.5 Conclusions

- Tests run with the complete dynamic model over a 21 day period demonstrated that the harmonic current levels on the system are significantly reduced due to the action of the AF algorithm.
- The controller is more effective in mitigating harmonic feeder currents under low-irradiance conditions, because priority is always given to fundamental power injection. Therefore, under high-irradiance conditions, fundamental power flow has precedence on harmonic injection.
- Provided that irradiance levels are sufficiently low, the controller will mitigate up to 8.7 A rms of harmonic current to virtually zero.
- The frequency distribution charts show the positive impact that the algorithm has on harmonic levels in the feeder over the full time period
- At this stage in the work programme only one inverter is used to compensate the entire harmonic amplitude measured on the feed, but the controller design allows scaling the amount of compensation provided by an individual inverter, and therefore spreading the loading between multiple units.
- The voltage THD at the BPS is reduced up to 33.8%. The impact on this metric is less than the impact on harmonic currents at the considered feeder because the voltage at the BSP is affected by harmonic loads connected to other feeders and by the background harmonic distortion.

WP2 Conclusions

- The developed algorithm takes feeder current measurements as inputs and regulates inverter switching to inject anti-phase harmonic currents to achieve harmonic cancellation. The algorithm operation has been demonstrated initially through functional tests, and then by using a dynamic model of Tiverton Network to evaluate impact of a 3-week operating period.
- Factors such as phase shift of the interface transformer and delays in the acquisition of measurement data were considered. Because harmonic measurements are taken on the delta-connected side of the transformer, and harmonic injection takes place on the wye-side, an adequate phase shift has been included in the dq transformation. The final implemented design allows changing the harmonic gain every 10 minutes and therefore masks the effect of delays due to data acquisition.
- The algorithm does not cause any thermal, voltage, fault level or other constraint in the network, and does not cause the power rating of the inverter to be exceeded. Thermal behaviour has been verified through transformer losses. The impact on voltage fundamental amplitude is negligible as shown by average voltage FFT. Fault level is not impacted due to the current limiter included in the control. Inverter rating is not exceeded due to the harmonic gain control.
- The algorithm was demonstrated with an individual inverter under different operating conditions, including changing inverter output power and changing system harmonic levels. The benefits of the algorithm were shown through a detailed comparison of modelled system harmonic performance with and without the harmonic mitigation algorithm.
- Detailed screenshots of the proposed algorithm have been included in this report, and they are accompanied by a computer model.