Course Project Report

EENG 573

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A. Base case

Bases Per Unit System:

S_{BASE}	$\frac{5*10^6}{3} = 1.66\ MVA$
V_{BASE}	$\frac{4160}{\sqrt{3}} = 2401.77\ V$
Z_{BASE}	$\frac{(\frac{4160}{\sqrt{3}})^2}{\frac{5*10^6}{3}} = 3641.12\ \Omega$
I_{BASE}	$\frac{\frac{5*10^6}{3}}{\frac{4160}{\sqrt{3}}} = 693.93\ A$

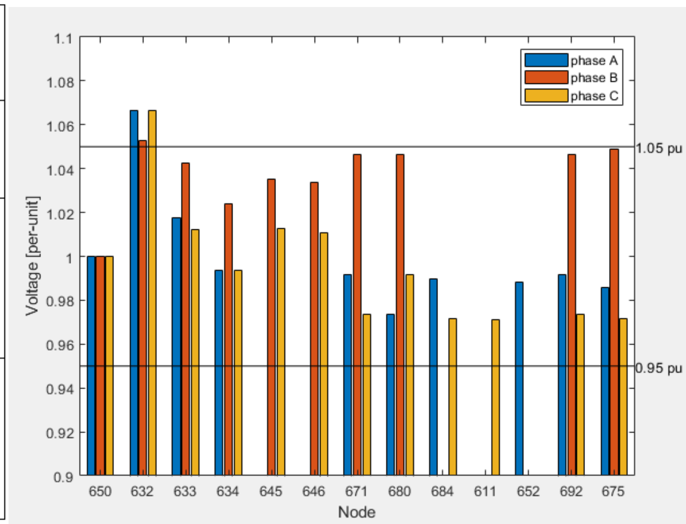


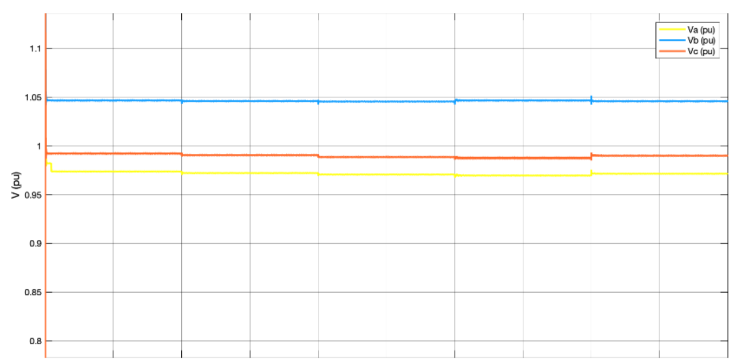
Figure 1: Voltage magnitudes in per-unit

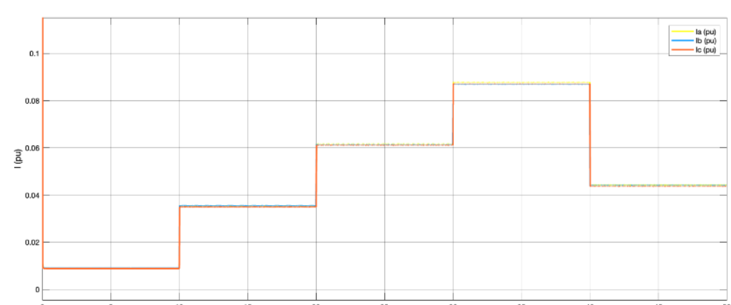
Active power supplied through PCC: 3580.352 kW

Reactive power supplied through PCC: 1749.8103 kVar

B. Electric Vehicle Charging Station (EVCS)

Voltage at node 680 (per unit) Current at node 680 (per unit)





C. Solar Park

The following figure displays the solar park model in Simulink:

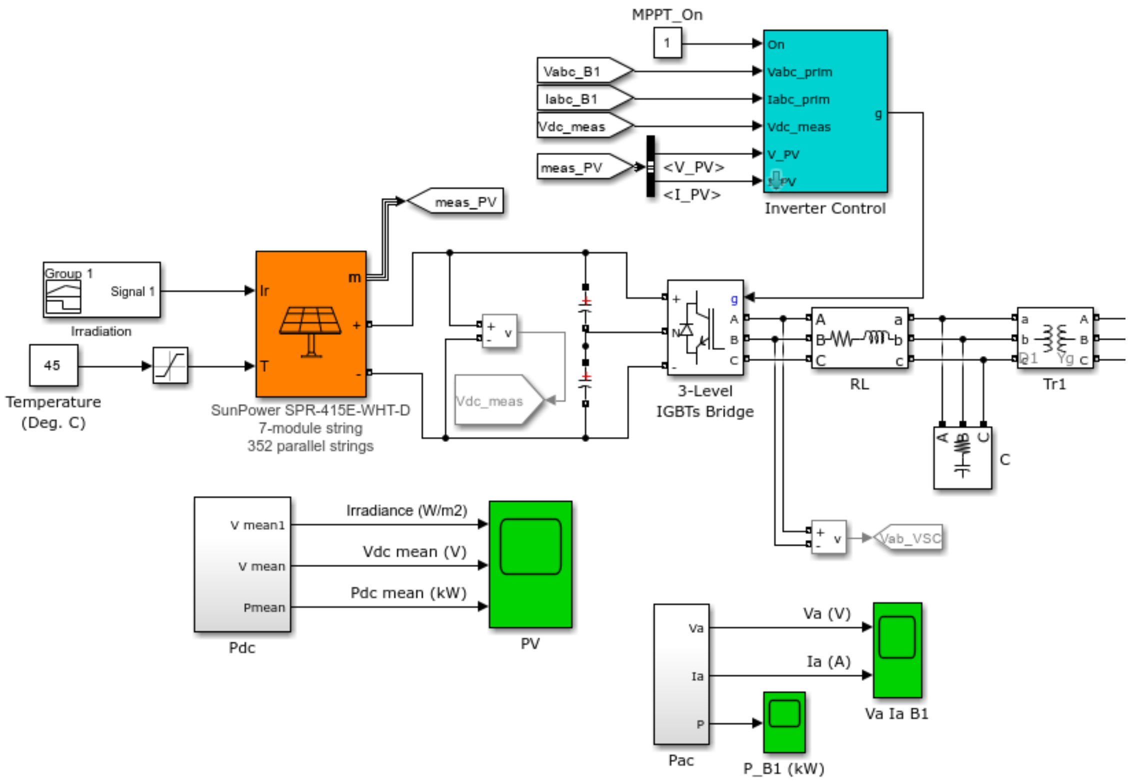


Figure 2: PV solar system

The components used:

- **PV Array**: The PV array consists of 352 parallel strings. Each string has 7 SunPower SPR-415E modules connected in series. At maximum power, they deliver 1 MW.
- **Three-phase DC/AC Inverter**: The converter is modeled using a 3-level IGBT bridge PWM-controlled. The inverter choke RL and a small harmonics filter C are used to filter the harmonics generated by the IGBT bridge.
- **Transformer**: 1 MVA 250V/4.16kV three-phase transformer is used to connect the inverter to the utility distribution system.
- **Inverter Control**: The control system contains five major Simulink®-based subsystems:
  - A. *MPPT Controller*: The Maximum Power Point Tracking (MPPT) controller is based on the 'Perturb and Observe' technique. This MPPT system automatically varies the VDC reference signal of the inverter VDC regulator in order to obtain a DC voltage which will extract maximum power from the PV array.
  - B. *VDC Regulator*: Determine the required I_d (active current) reference for the current regulator.
  - C. *Current Regulator*: Based on the current references I_d and I_q (reactive current), the regulator determines the required reference voltages for the inverter. In the example, the I_q reference is set to zero.
  - D. *PLL & Measurements*: Required for synchronization and voltage/current measurements.
  - E. *PWM Generator*: Generate firing signals to the IGBTs based on the required reference voltages. In our example, the carrier frequency is set to 1980 Hz (33×60).

The irradiance is modeled as a cloudy day, with 450W/m^2 as highest value. In Figure 3, irradiance increases in the morning, then the clouds cover the sun and, finally the sky clears in the afternoon. The Y-axis represents W/m^2 and the X-axis is a 24 hour day.

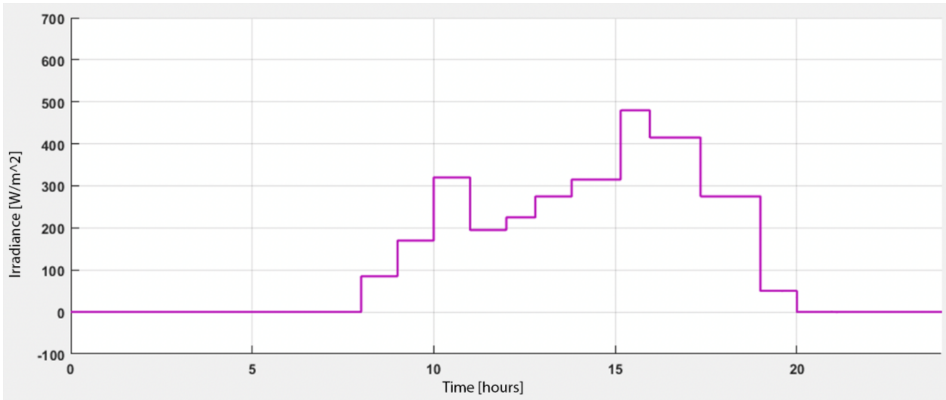


Figure 3: Irradiance signal

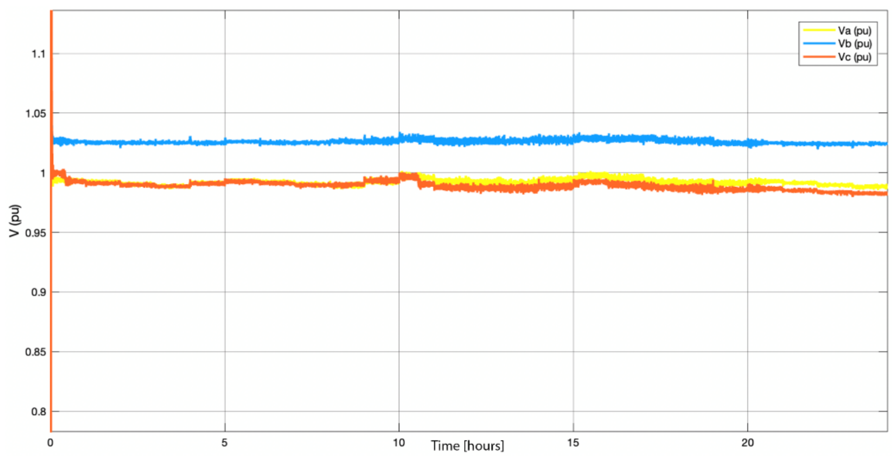


Figure 4: RMS voltage at node 671

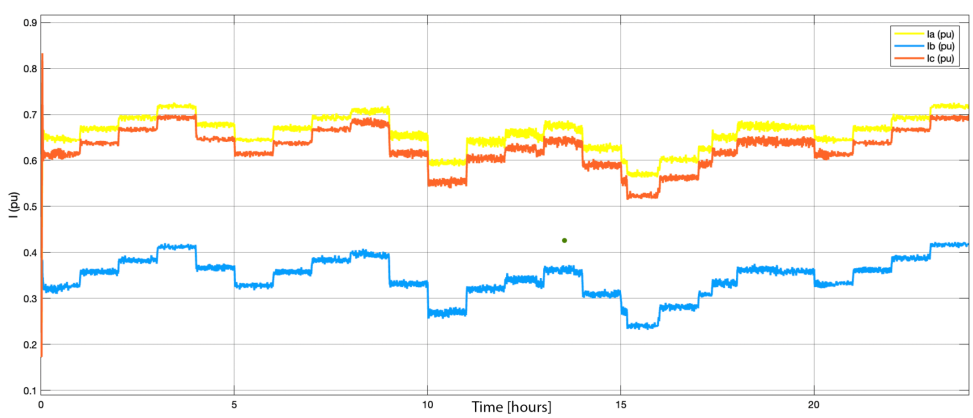


Figure 5: RMS current at node 671

D. Power Quality Analysis

Worst case Scenario

Node voltages, voltage harmonics/THD at the PCC, and current harmonics/TDD at the distribution transformers were analyzed for the worst-case scenario. In the figures and appendix, the team analyzed these measurements at each hour of the 24 hour simulation. Voltage harmonics were miniscule in magnitude and voltage THD was always nearly 0%, well within the IEEE 519 spec for THD and maximum for an individual voltage harmonic. Similarly, node voltages did not vary throughout the day. Current harmonics, however, did change throughout the simulation. Note at every hour corresponding to the maximum EV charging produces the greatest level of TDD, with most distortion coming from the 5th and 7th harmonics, as expected with a 6-pulse rectifier. The worst case occurs in the fourteenth hour, where TDD maxes out at 6.9% (average across the three phases), corresponding to an hour that has relatively high solar irradiance. There is also a minor overvoltage on node 632, however, this overvoltage was present in the base case as well, so there are no active measures to address it.

To check compliance with IEEE 519 current distortion limits, we calculated I_{SC} as 12.4 pu and $I_{L,1}$ as 0.61 pu, or a ratio of 20.3 (which is relatively weak). Our TDD of 6.9% is just within the 8% limit for TDD at this stiffness level, and our 5th and 7th harmonics are also within the maximum 7%.

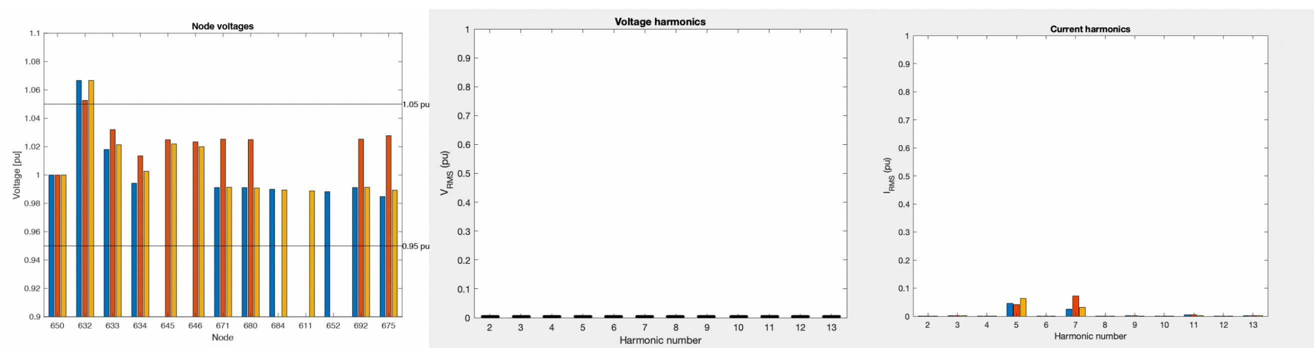


Figure 6. Worst case scenario, corresponding to the 14th hour.

	Phase A	Phase B	Phase C
Voltage THD (%)	1.725×10^{-13}	3.755×10^{-13}	3.755×10^{-13}
Current TDD (%)	5.33	8.34	7.08

E. Mitigation

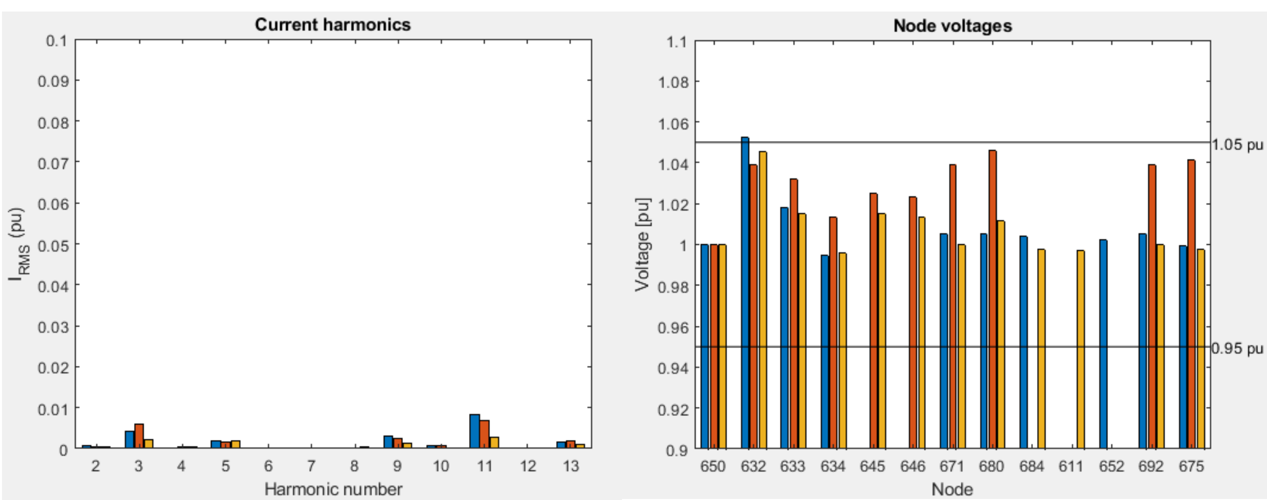
From Vinayagam et al.'s "Harmonics assessment and mitigation in a photovoltaic integrated network," there were different mitigation strategies explored with regards to addressing lower irradiance for PV systems. More specifically, some of the mitigation strategies explored involved possibly operating PV inverters at a higher power mode, by switching the battery storage on the DC side of the PV inverter. This is so that a reactive power contributor from a PV inverter can allow the PV inverter to operate at full apparent power capacity [1].

To mitigate 5th and 7th harmonic currents, a passive three-phase harmonic filter was inserted for each of these frequencies. With the addition of these filters, there are a couple potential downsides that need to be avoided. The addition of LC elements creates resonance frequencies, so that the resonance frequencies do not coincide with problematic harmonics. Also, over time (not an issue in our Simulink model but a real-world problem), these filters can detune and stop being effective. The team also considered converting our 6-pulse rectifier (for the EV charging station) to a 12-pulse rectifier which would cancel out the 5th and 7th harmonics, but the passive filters proved effective enough on their own.

The addition of these filters was successful in reducing the 5th and 7th current harmonics. The 7th goes away completely and the 5th is diminished to less than 0.01 per unit. The filters did end up adding a small amount of a 3rd current harmonic, as seen in Figure 7. However, total (average across the three phases) TDD is still much reduced, now only 0.8%. Voltage THD was essentially 0 before mitigation and still is. Figure 8 also displays that the overvoltage at node 632 has been fixed. As before, we are still in compliance with IEEE 519. Now we have to check IEEE 18-2012, specifically at our shunt power capacitors at nodes 611 and 675. We looked at the reactive power, voltage, and current through these capacitors, and their values were well within the IEEE limits.

The THD and TDD during the worst case (14th hour) now are as follows:

	Phase A	**Phase B**	**Phase C**
Voltage THD (%)	1.725×10^{-13}	3.757×10^{-13}	3.736×10^{-13}
Current TDD (%)	1.00	0.97	0.44



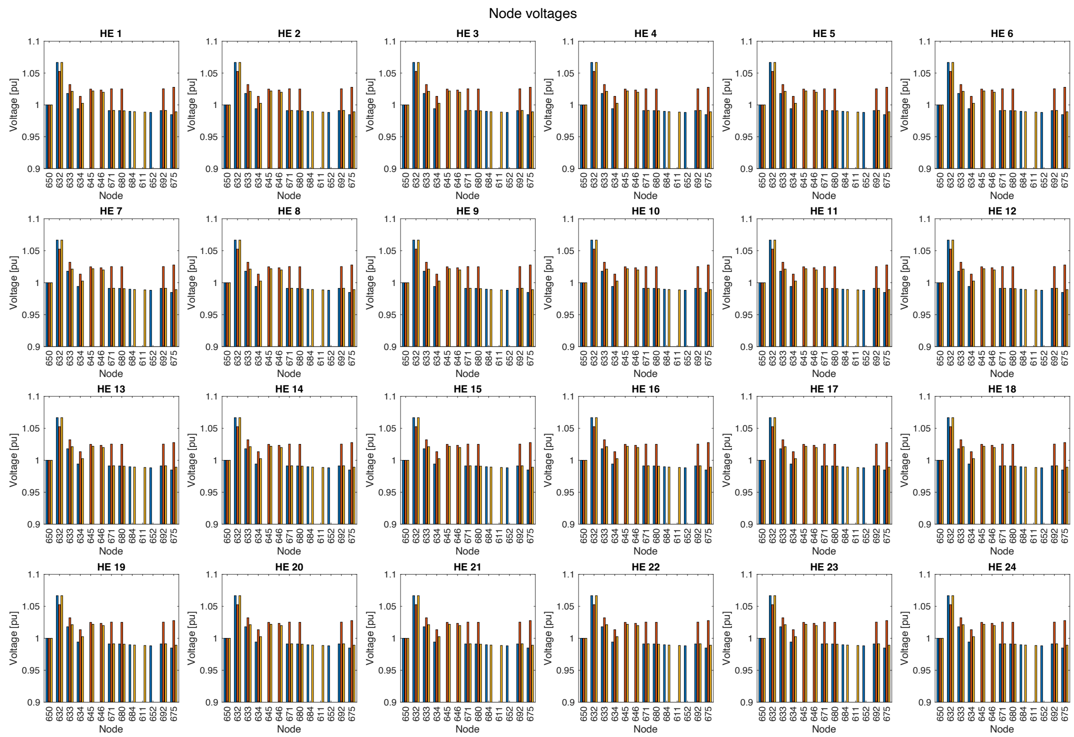
Figures 7 and 8: Current Harmonics (note the y-limit is 0.1 pu) and Node Voltages with the Worst-Case Scenario

References

[1] A. Vinayagam *et al.*, “Harmonics Assessment and mitigation in a Photovoltaic Integrated Network,” *Sustainable Energy, Grids and Networks*, vol. 20, p. 100264, Dec. 2019. doi:10.1016/j.segan.2019.100264

Appendix

In the bar graphs below, HE means hour ending at the given time, the, blue bar is phase A, red is phase B, yellow is phase C.



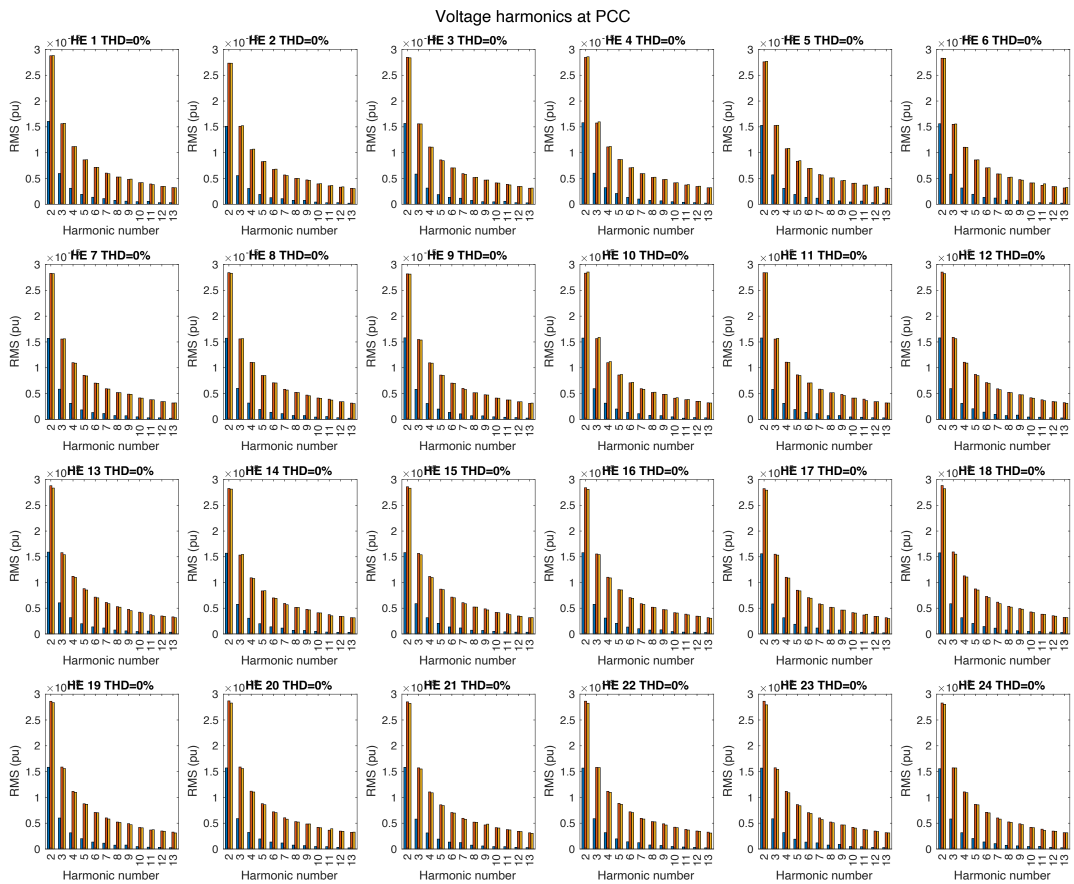
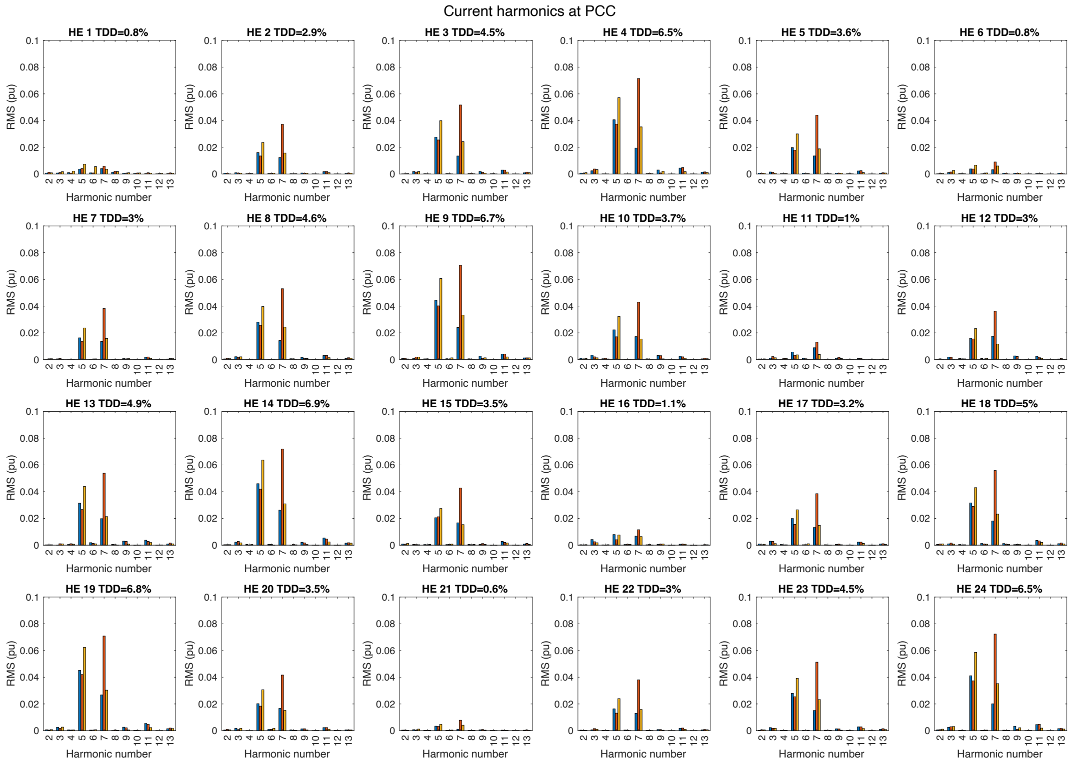


Figure 8. Note the y-scale of 10^-15


Current harmonics at PCC
HE 1 TDD=0.8%
HE 2 TDD=2.9%
HE 3 TDD=4.5%
HE 4 TDD=6.5%
HE 5 TDD=3.6%
HE 6 TDD=0.8%
HE 7 TDD=3%
HE 8 TDD=4.6%
HE 9 TDD=6.7%
HE 10 TDD=3.7%
HE 11 TDD=1%
HE 12 TDD=3%
HE 13 TDD=4.9%
HE 14 TDD=6.9%
HE 15 TDD=3.5%
HE 16 TDD=1.1%
HE 17 TDD=3.2%
HE 18 TDD=5%
HE 19 TDD=6.8%
HE 20 TDD=3.5%
HE 21 TDD=0.6%
HE 22 TDD=3%
HE 23 TDD=4.5%
HE 24 TDD=6.5%
RMS (pu)
Harmonic number