EE 394V: Analysis of Power Systems with Renewable Energy Sources

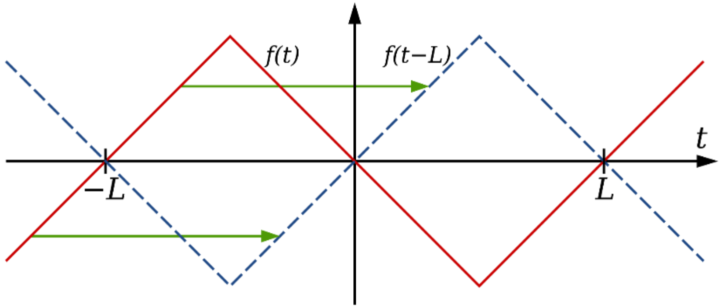
Final Project: Distribution Circuit Modeling for Harmonics

Soham Roy and Fernando Osorio

Motivation

- Non-linear loads and inverter-based generation (e.g. solar PVs) in distribution grid

- Harmonics (3rd, 5th, 7th…) produced by power electronic devices (i.e. rectifiers, inverters, VFDs)
  - Elements of the Fourier series of any periodic signal
  - Occur at multiples ($h \times f_1$) of the fundamental frequency (f_1)
  - Even order harmonics (2nd, 4th, 6th…) usually absent due to half-wave symmetric waveforms: $f(t) = -f(t - L)$

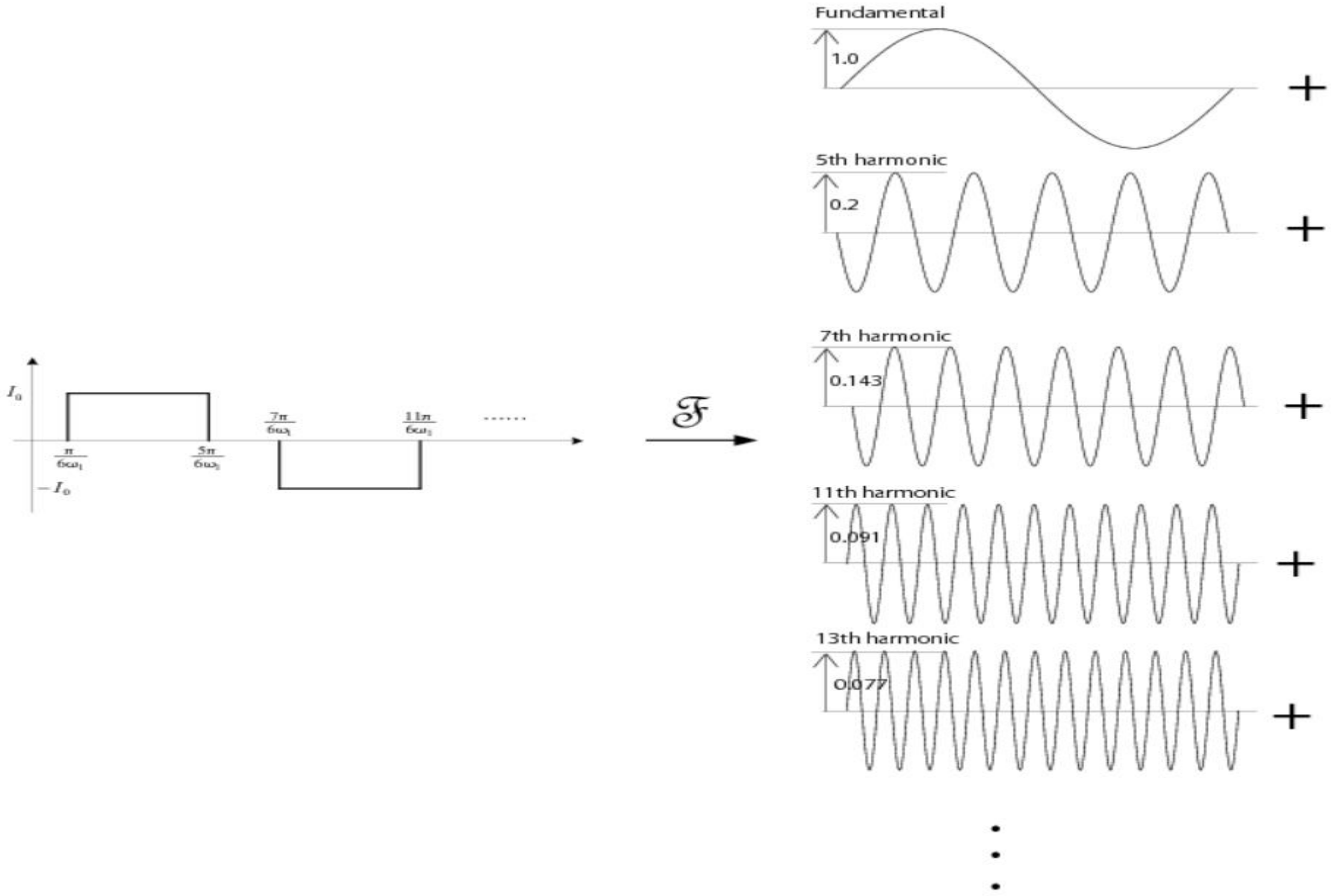


Half-wave symmetric waveform [1]

- Distribution circuit models can be expanded to incorporate harmonics

[1] "Signals and Systems/Periodic Signals" ,WikiBooks [Online]. Available: https://en.wikibooks.org/wiki/Signals_and_Systems/Periodic_Signals#Half-wave_Symmetry

Background: Fundamentals of Harmonics



6-pulse Full Bridge Rectifier: non-sinusoidal current waveform is decomposed into its Fourier series. Harmonic currents are constituent of the Fourier series [2]

[2] S. Santoso, Fundamentals of Electric Power Quality, Winter 2010 Ed

Background: Harmonic phase sequences for 3-phase balanced power system [2]

$$i_a(t) = \sum_{h=1,2,3}^{\infty} I_h \sin(h\omega_1 t + \theta_h)$$

$$i_b(t) = \sum_{h=1,2,3}^{\infty} I_h \sin\left(h\omega_1 t + \theta_h - h\frac{2\pi}{3}\right)$$

$$i_c(t) = \sum_{h=1,2,3}^{\infty} I_h \sin\left(h\omega_1 t + \theta_h + h\frac{2\pi}{3}\right)$$

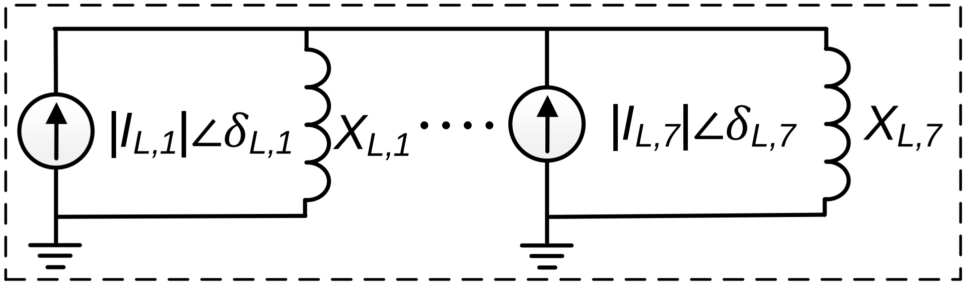
Harmonic order	Phase sequence	Harmonic order	Phase sequence	Harmonic order	Phase sequence
1	+	7	+	13	+
2	-	8	-	14	-
3	0	9	0	15	0
4	+	10	+	16	+
5	-	11	-	17	-
6	0	12	0	18	0

Triplen (3rd, 6th, 9th…) harmonics have zero sequence behavior and add up in the neutral of a balanced power system

[2] S. Santoso, Fundamentals of Electric Power Quality, Winter 2010 Ed

Background: Current Source Model (CSM) for harmonics

- Non-linear loads and renewable energy sources: modeled using current source models (CSMs) to represent power electronics
- CSM reads current spectrum data and injects current
- Harmonic Norton equivalent impedances:
  - Challenging to compute
  - Usually very large; represented as open circuit to simplify simulations



CSM for harmonic source

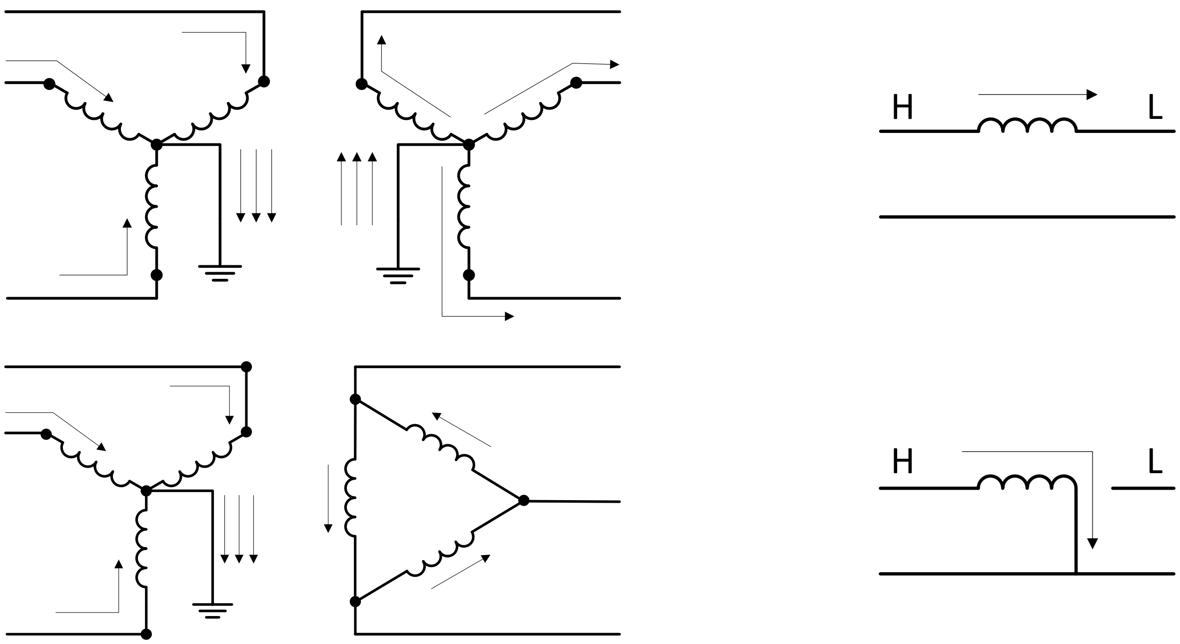
Objective

- Expand distribution line and transformer models in MATLAB to include harmonics: $Yprim_{line(h)}$ and $Yprim_{Xfmr(h)}$
- Validate using OpenDSS and steady-state simulations in EMTP-RV

Three-phase transformer diagrams [2]

Grounded wye-grounded wye (Yg-Yg)

Grounded wye-delta (Yg-D)



Winding diagrams

Zero Sequence Connections

MATLAB Approach: Obtaining Ybus for harmonics and LF solution

Distribution lines:

- Replace $(R + jX)$ by $(R + jhX)$ in $\hat{z}$ matrix to obtain $\hat{z}_{(h)}$
- No change in A matrix
- Obtain $Yprim_{line(h)} = A^T\left(\hat{z}_{(h)}l\right)^{-1}A$

$\hat{z}_{(h)}$: harmonic phase impedance matrix

Distribution Xfmr:

- Replace $Z = R + jX$ by $Z_{(h)} = R + jhX$; accordingly $Z_{b(h)}$ is obtained
- No change in A, B and N matrices
- Calculate $Y_{1(h)} = B\left(Z_{b(h)}\right)^{-1}B^T$ and $Y_{w(h)} = NY_{1(h)}N^T$
- Obtain $Yprim_{Xfmr\,(h)} = AY_{w(h)}A^T$

$Z_{(h)}$: harmonic impedances

$Z_{b(h)}$: harmonic impedance matrix

$Y_{1(h)}$: harmonic nodal primitive matrix

$Y_{w(h)}$: harmonic winding admittance matrix

Ybus: $Ybus_{(h)}$ is obtained by appropriately combining $Yprim_{line(h)}$ and $Yprim_{Xfmr(h)}$ for each harmonic frequency

Multifrequency load flow (LF) analysis for harmonics [3]:

$I_{(h)} = Ybus_{(h)}V_{(h)}$ using H-bus method

[3] W. Xu, J. R. Marti and H. W. Dommel, "A multiphase harmonic load flow solution technique," in *IEEE Transactions on Power Systems*, vol. 6, no. 1, pp. 174-182, Feb. 1991.

OpenDSS Approach: Harmonic LF solution

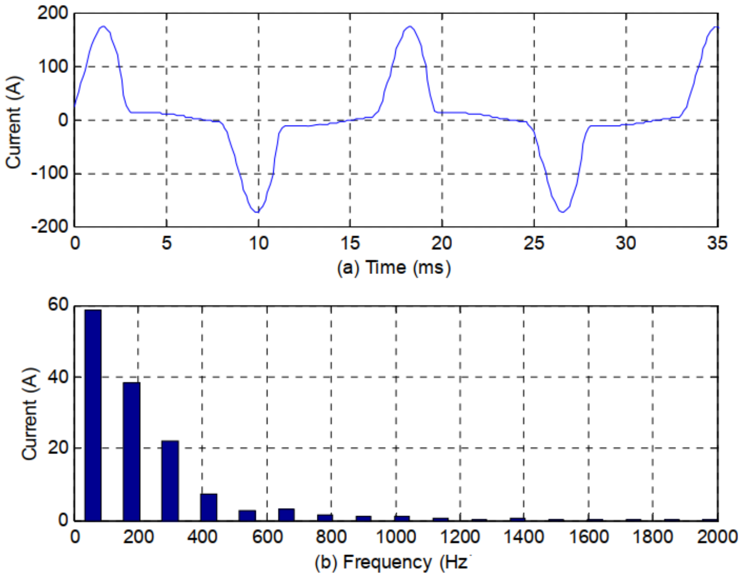
New "Spectrum.Spectrum_Load_a" NumHarm=4 CSVFile=Spectrum_Load_a.csv

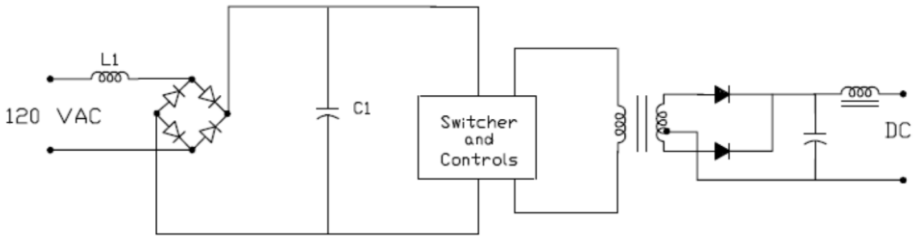
	A	B	C
1	1	100	-58.8314
2	3	65.7	-162.494
3	5	37.7	84.8432
4	7	12.7	-39.8196

!Non-linear load
New Load.Non_linear_load bus=n4.1.2.3 Phases=3 conn=wye Kv=4.16
Kva=421.5119 Model=5 spectrum=Spectrum_load_a
Set neglectloadY=yes

!Solve without harmonics
solve
!Solve with harmonics
set mode=harmonics
solve

Case study: Spectrum for CSM of non-linear Load [2]



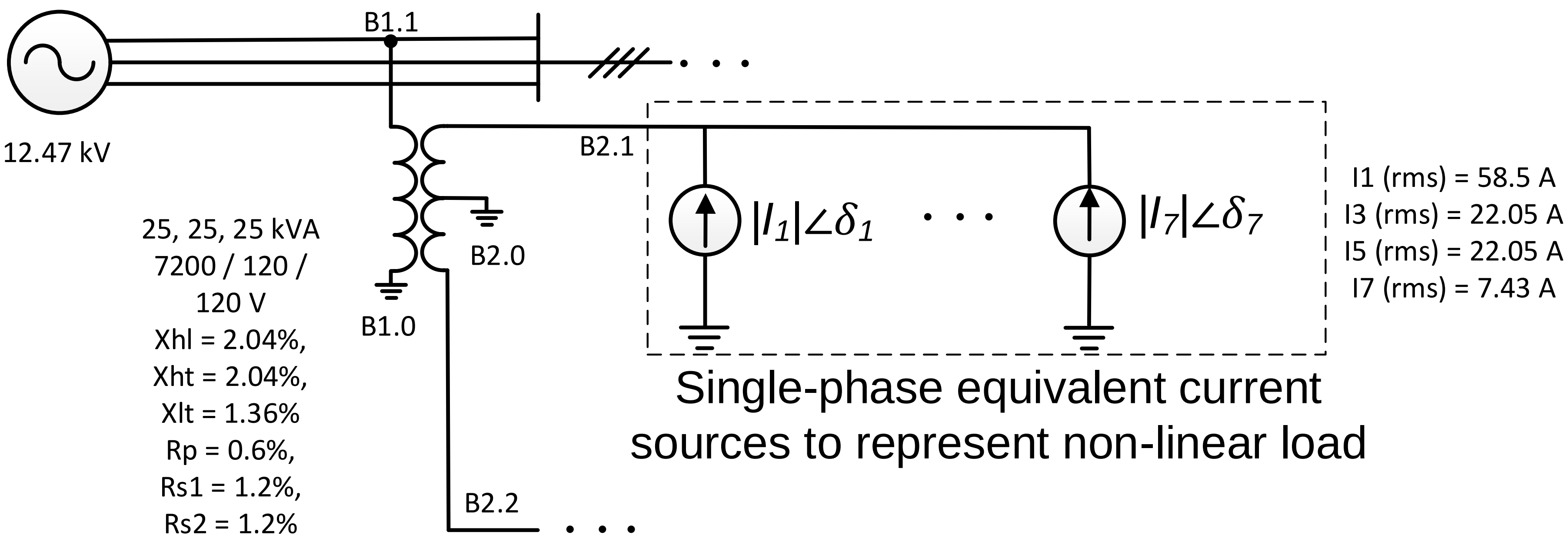


h	% of IRMS [A]	Phase [deg]
1	100	-28
3	65.7	-71
5	37.7	-123
7	12.7	173

Fundamental current (rms): 58.5 A
Fundamental frequency: 60 Hz
Fundamental voltage: 120 V

[2] S. Santoso, Fundamentals of Electric Power Quality, Winter 2010 Ed

Case study **A**: 7.2kV/120V/120V **Center-tapped** transformer



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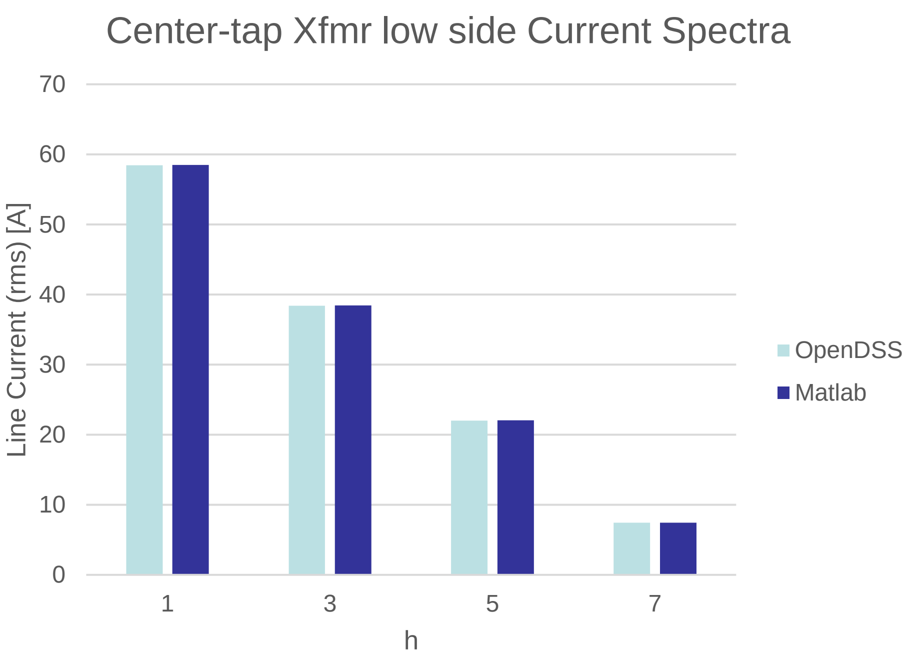

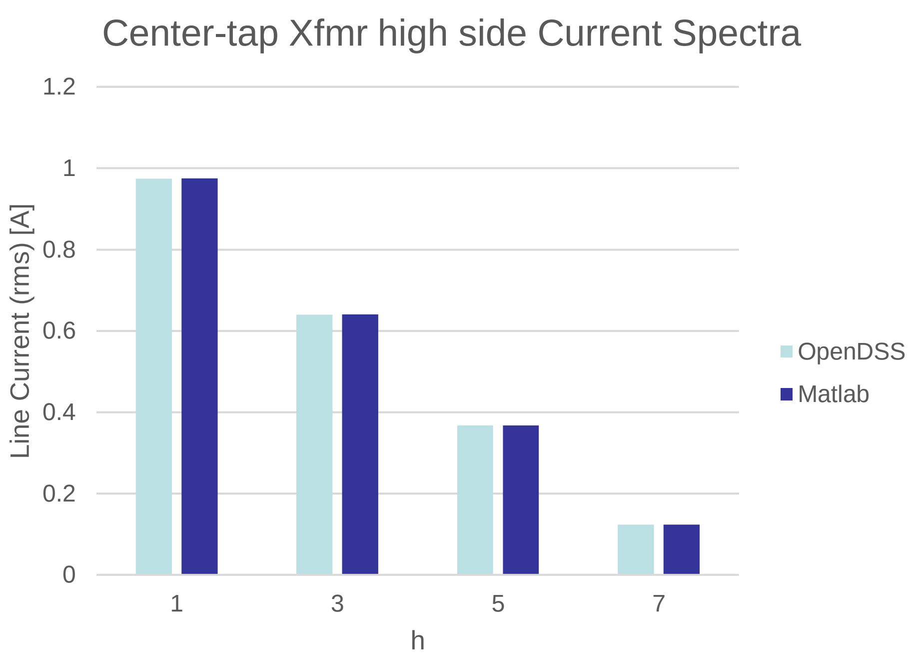

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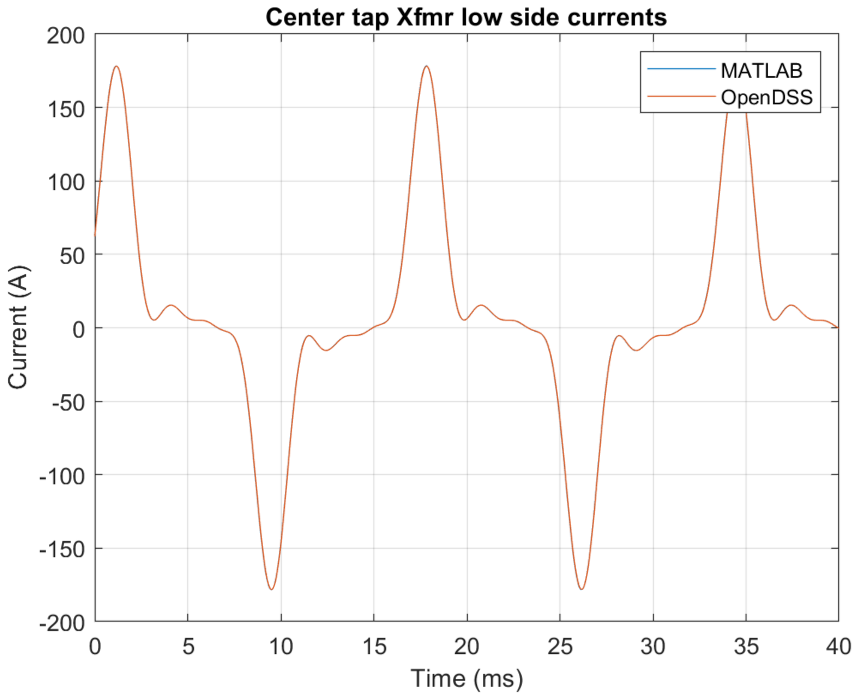

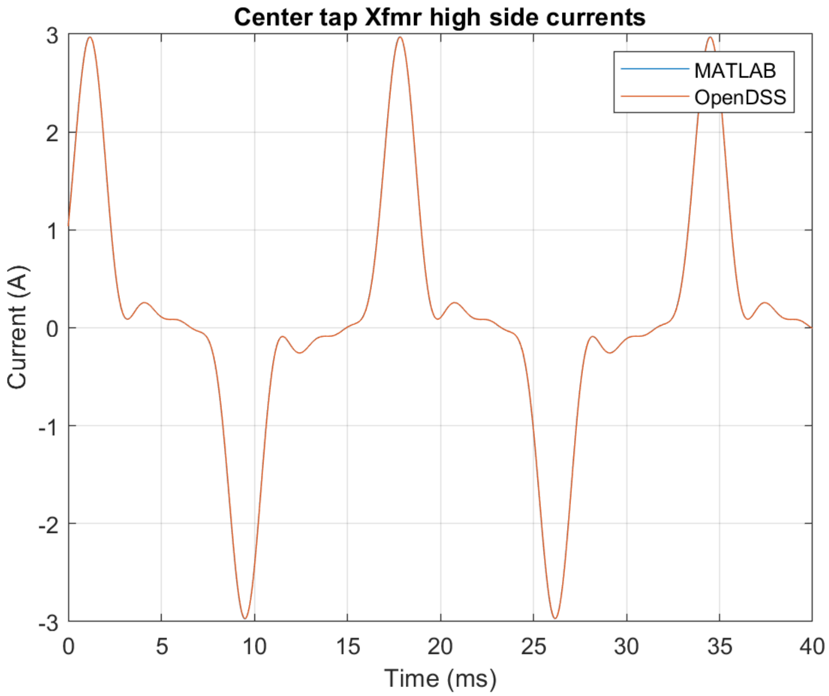

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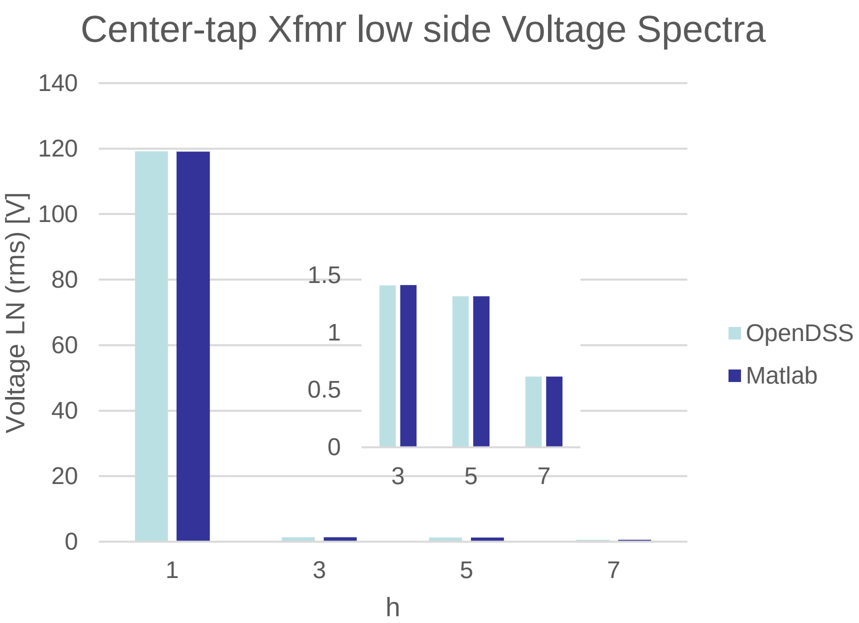
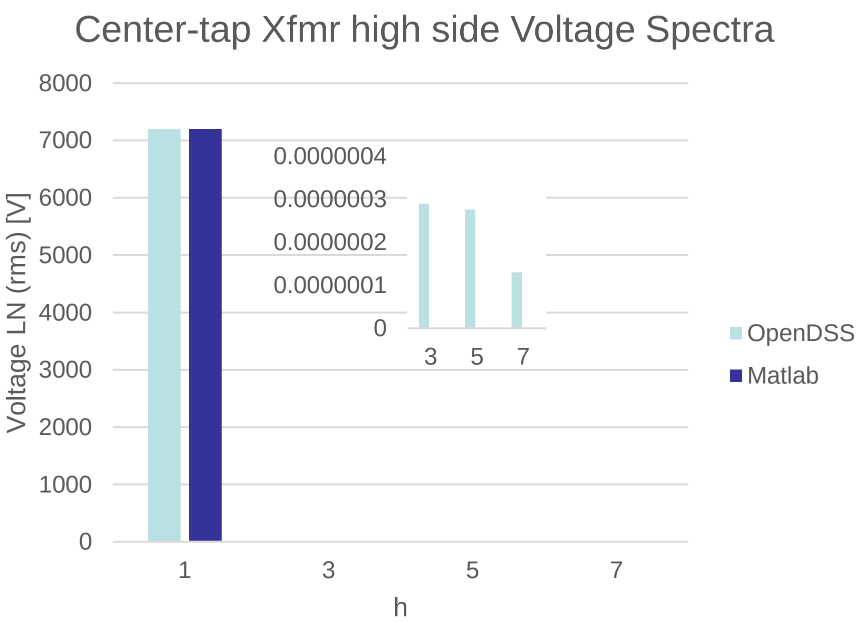
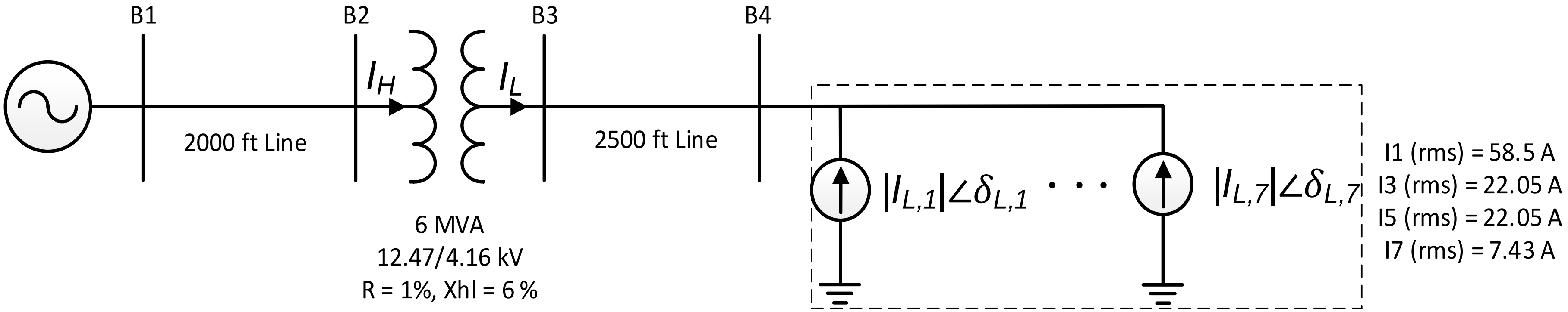


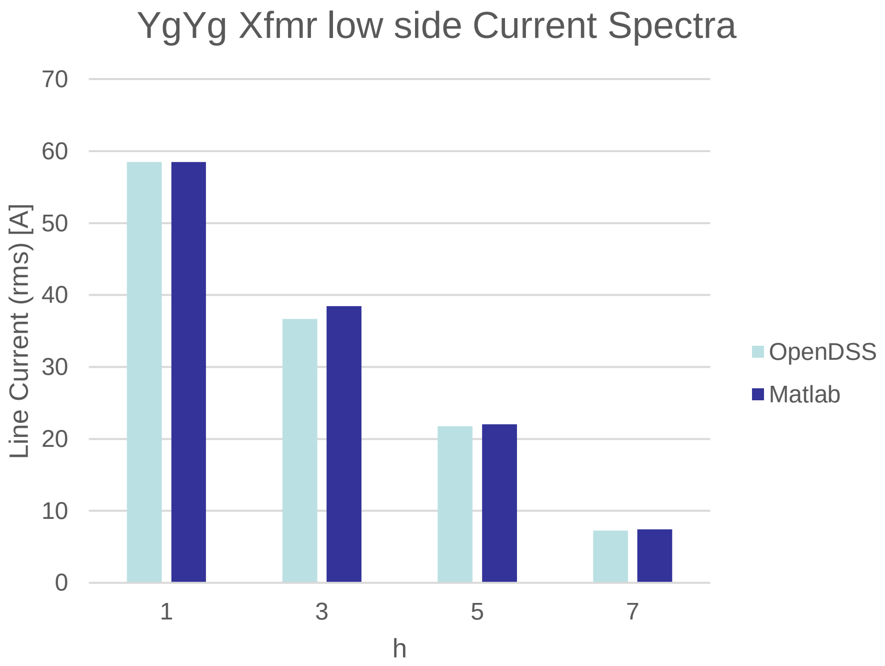


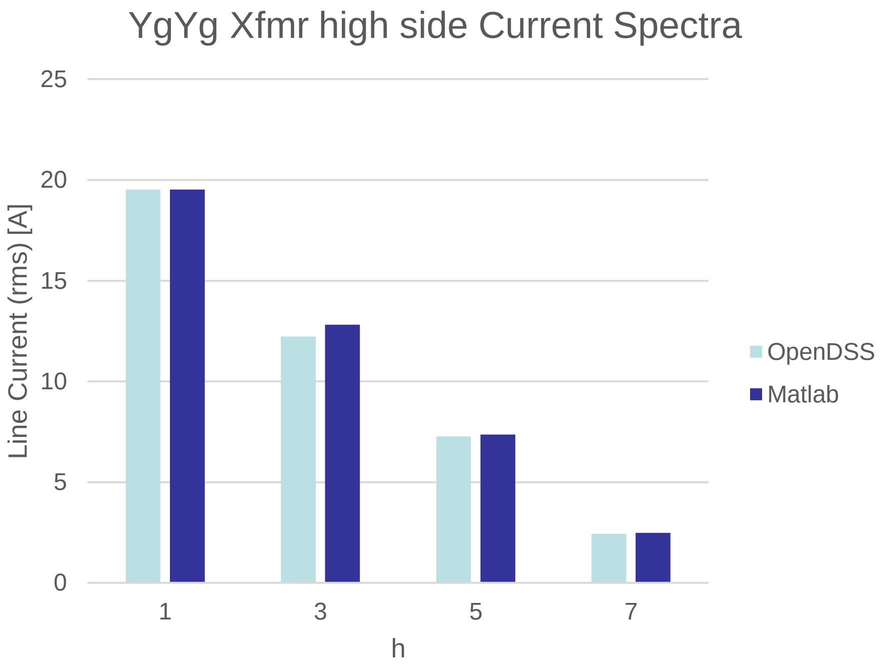
Case study **B**: IEEE 4 bus system with non-linear load



Equivalent current sources to represent non-linear loads

Case study **B1**: IEEE 4 bus system with grounded wye-grounded wye (**YgYg**) Xfmr





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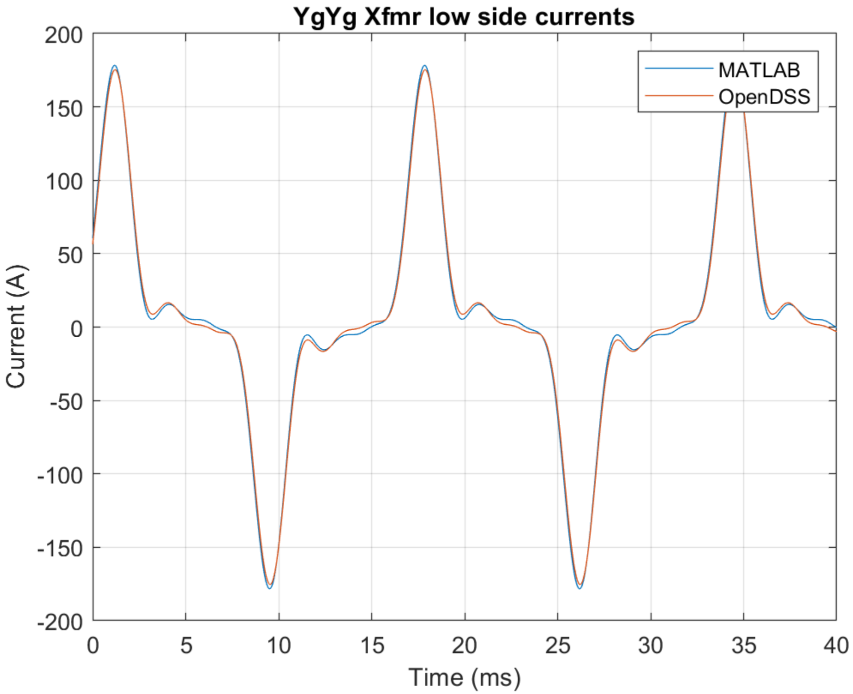

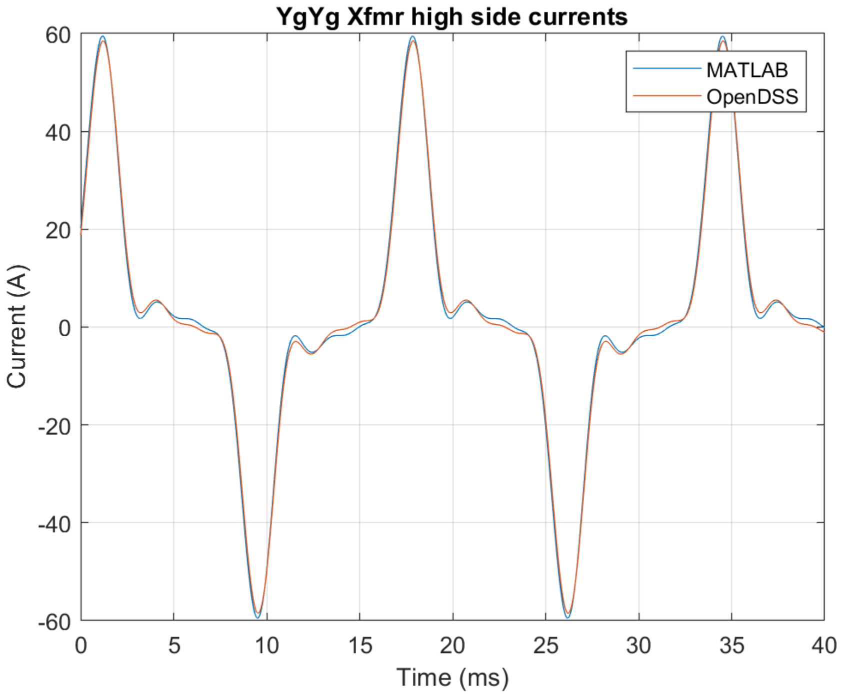

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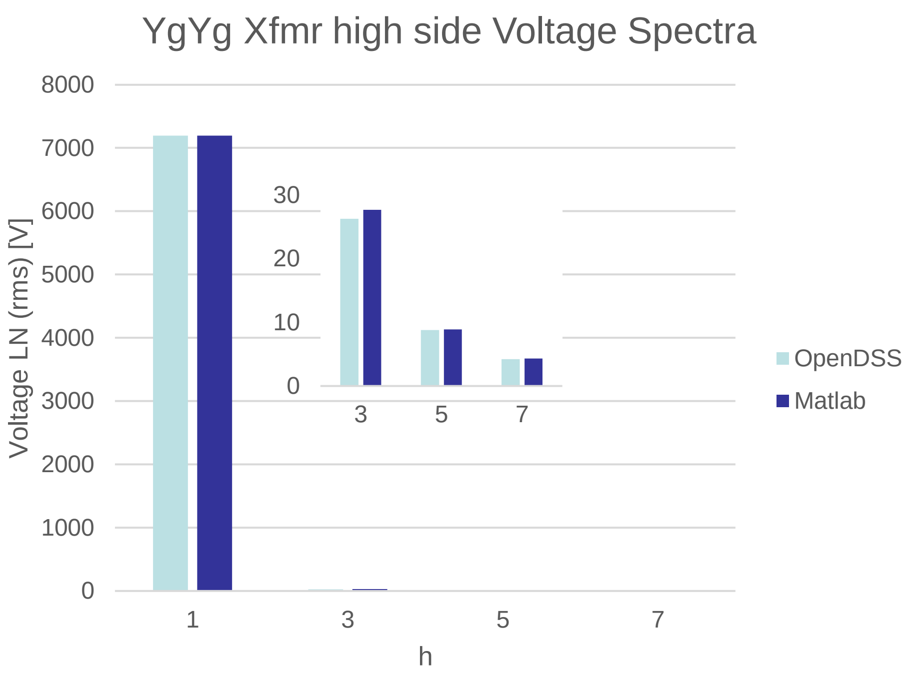
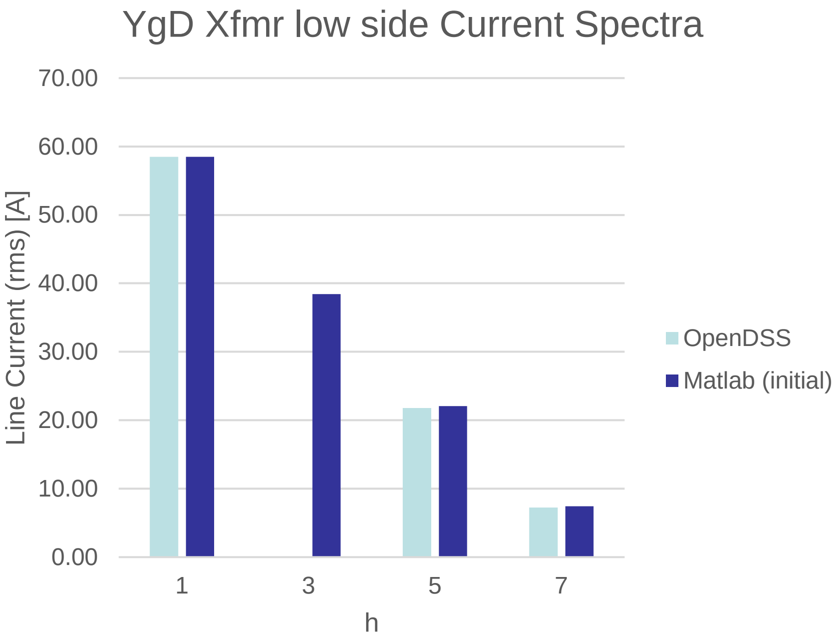
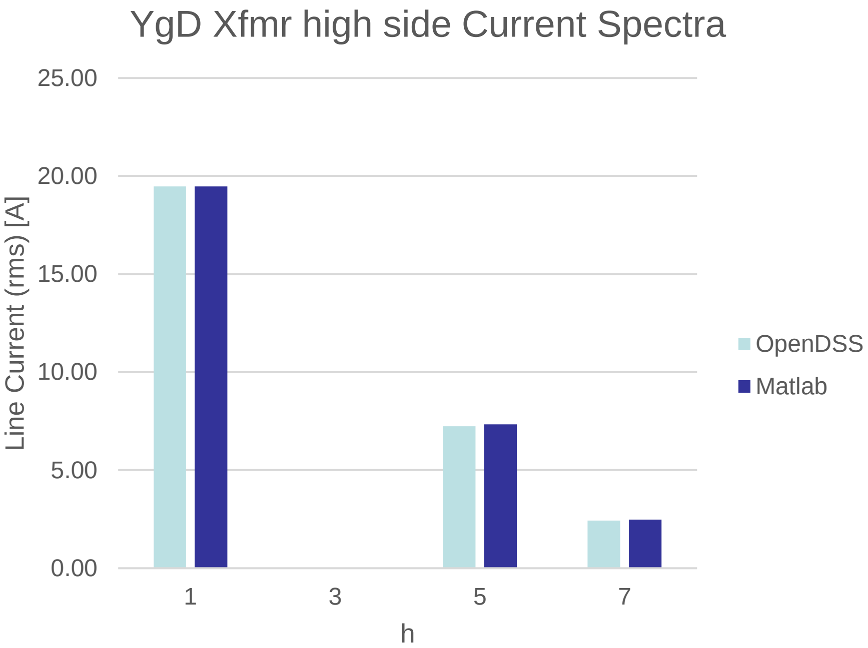


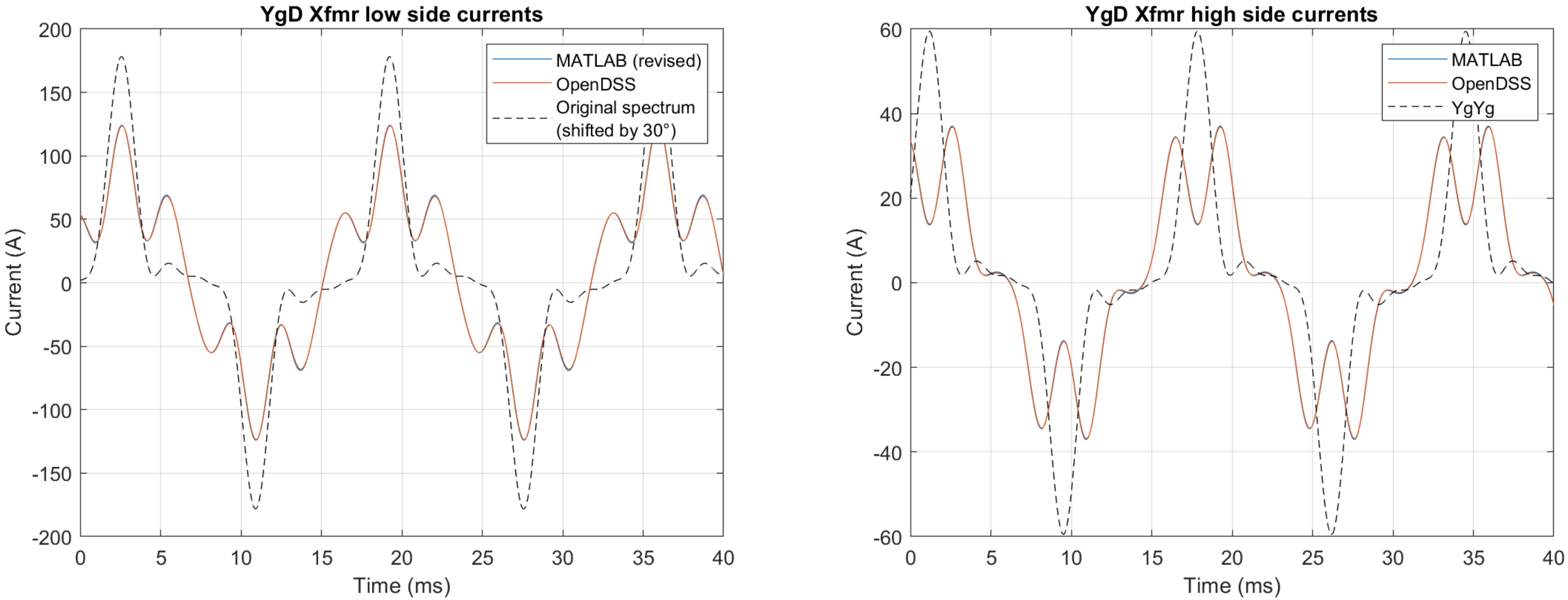
Case study **B2**: IEEE 4 bus system with grounded wye-delta (**YgD**) Xfmr





The 3rd harmonic is inherently nullified by OpenDSS even on the low voltage (delta) side

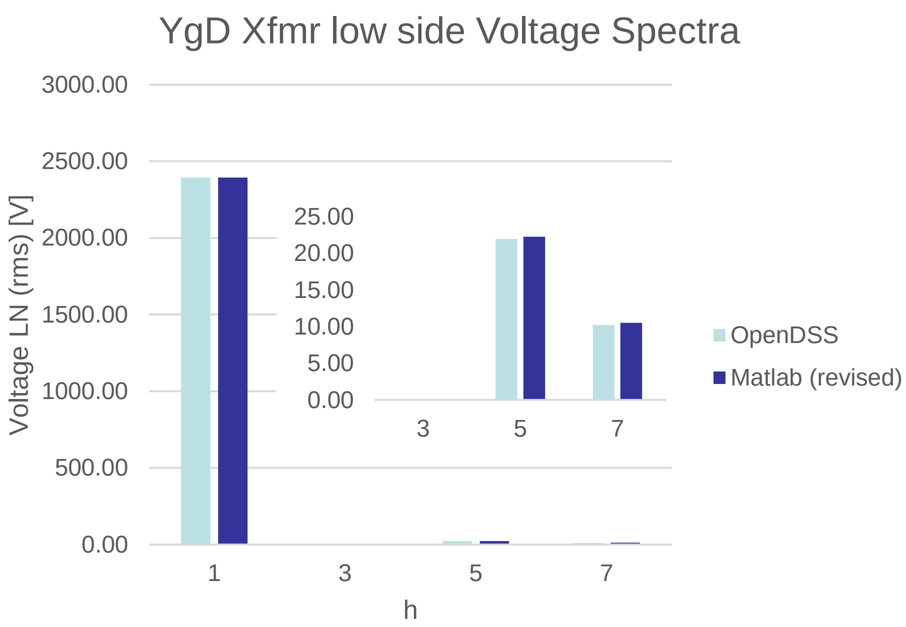
Case study **B2**: IEEE 4 bus system with grounded wye-delta (**YgD**) Xfmr

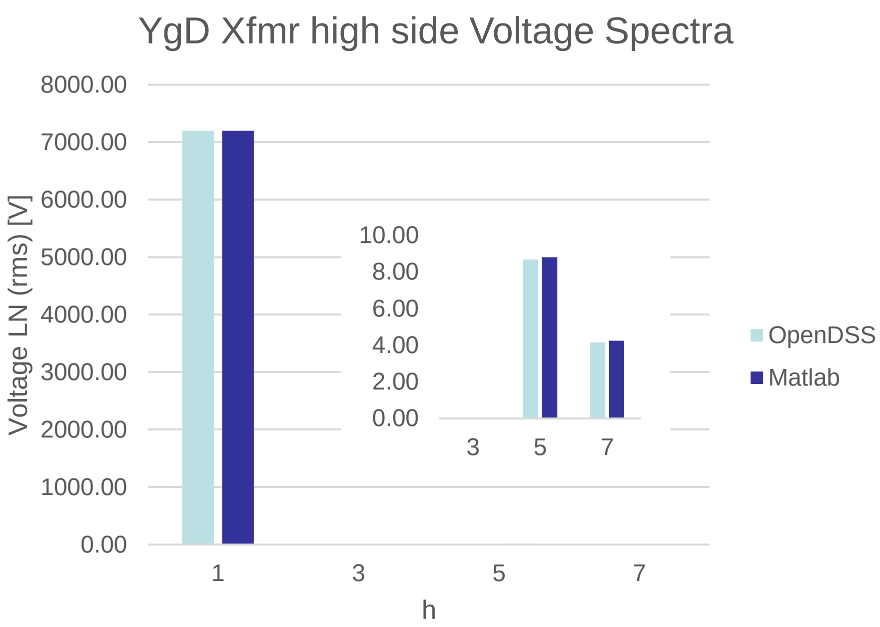


Wave shape changes from low side to high side because of different phase sequences:

- Fundamental: shifted by +30° from low to high side (positive sequence)
- 3rd harmonic: cancelled due to delta configuration (zero sequence)
- 5th harmonic: shifted by -30° from low to high side (negative sequence)
- 7th harmonic: shifted by +30° from low to high side (positive sequence)

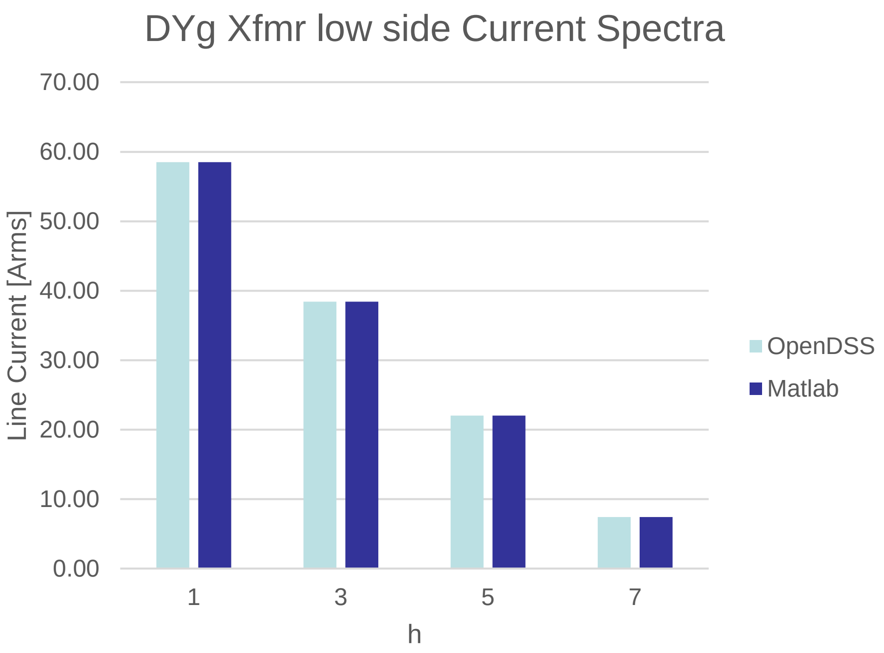
Case study **B2**: IEEE 4 bus system with grounded wye-delta (**YgD**) Xfmr

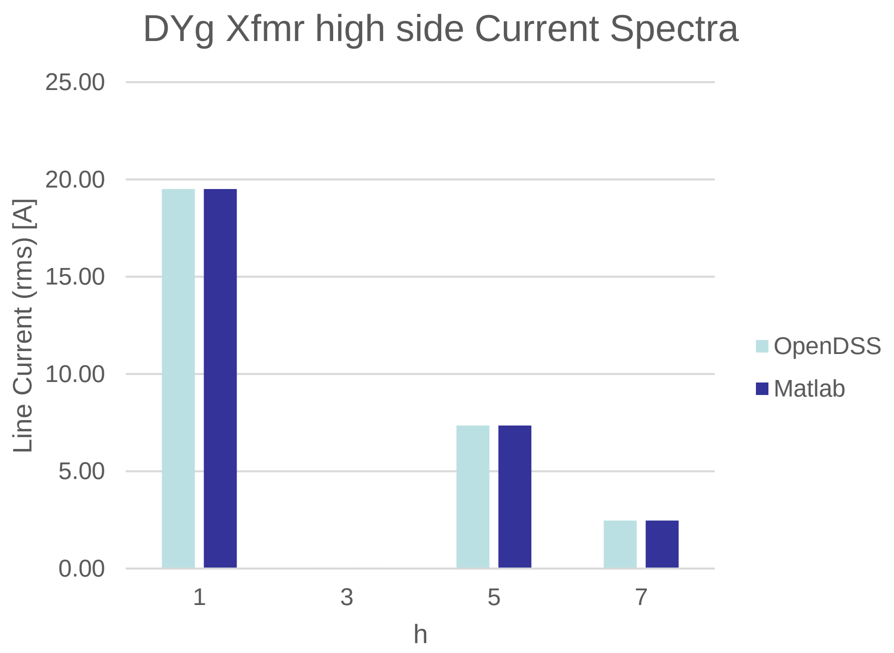




The 3rd order harmonic current causes a sharp voltage resonance at the delta side of the Xfmr; this is due to the lack of a phase-to-ground path to drain the harmonic current. The 3rd harmonic voltage is excluded from the low side results due to its unrealistic magnitude.

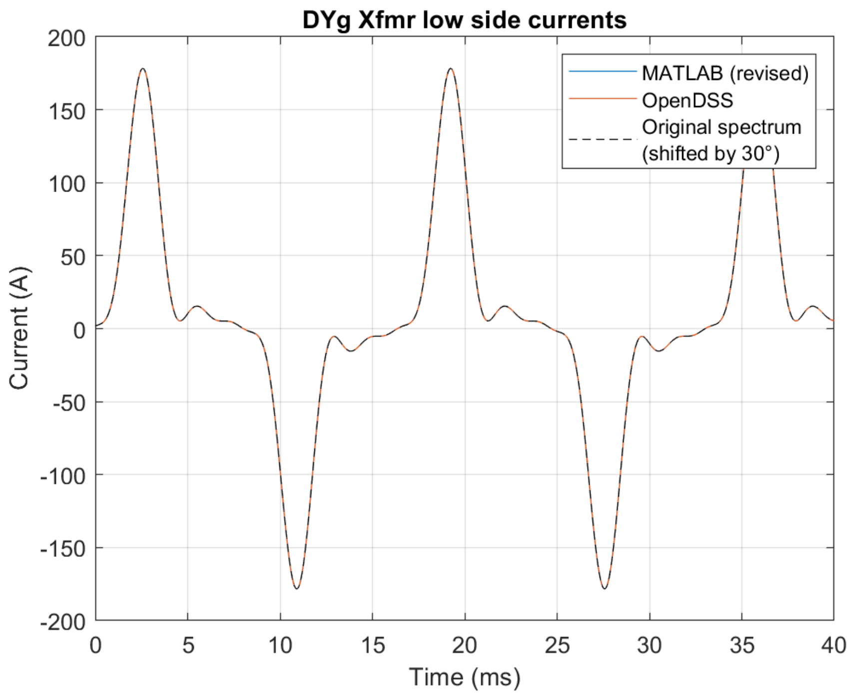
Case study **B3**: IEEE 4 bus system with delta-grounded wye (**DYg**) Xfmr

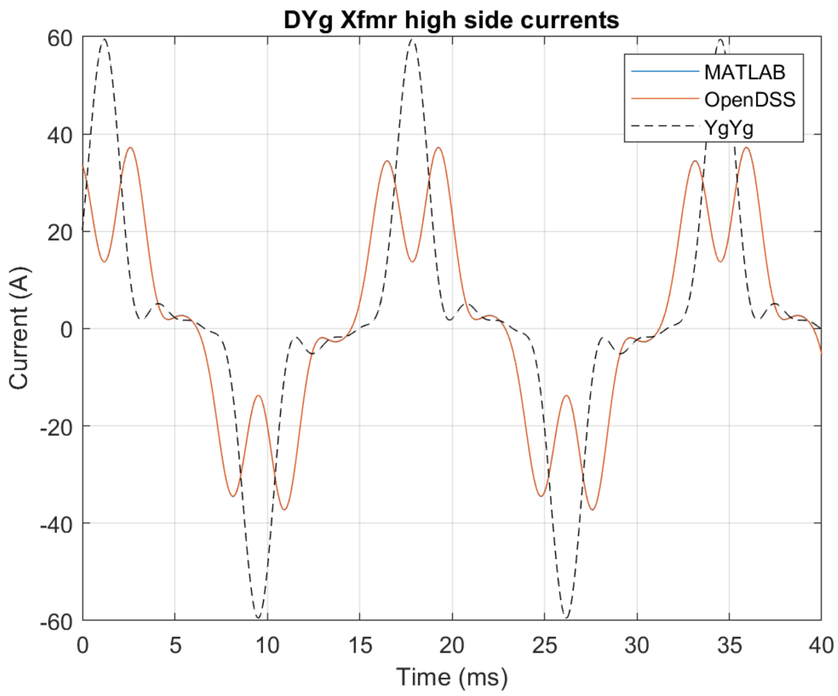




The 3rd harmonic is **NOT** inherently nullified by OpenDSS on the low voltage (wye) side, unlike the YgD case

Case study **B3**: IEEE 4 bus system with delta-grounded wye (**DYg**) Xfmr





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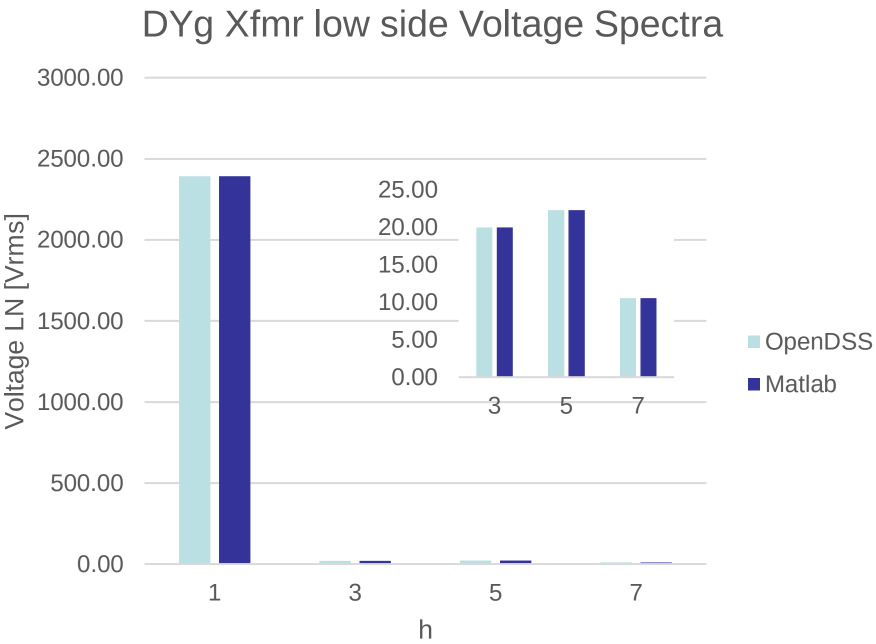
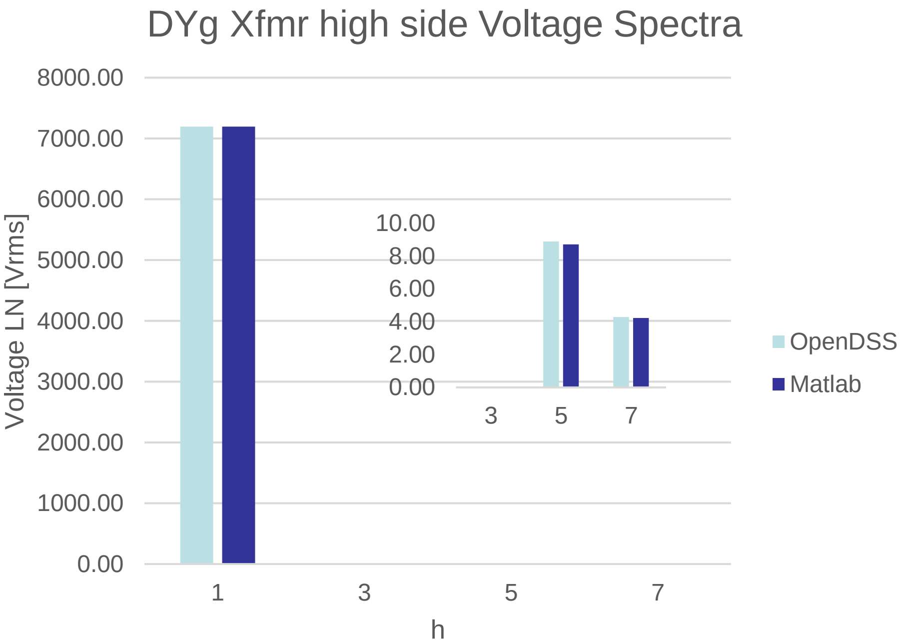
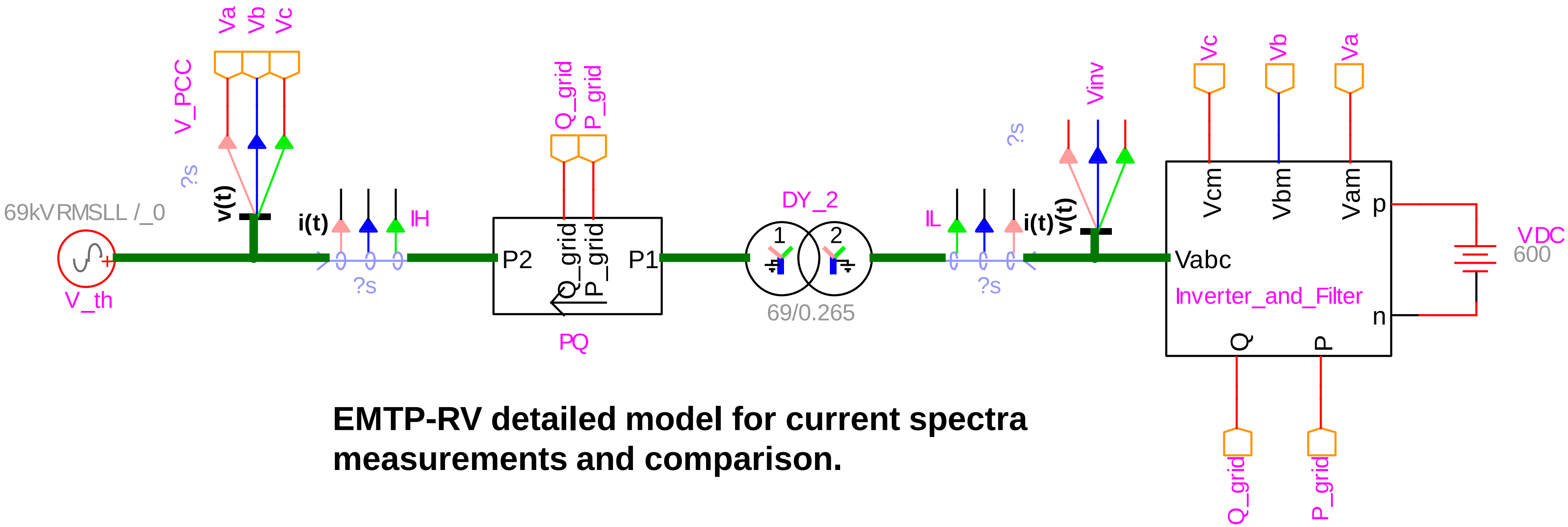




Case study **C1**: Inverter-Based Generation Steady-State Harmonic Simulation - YgYg



EMTP-RV detailed model for current spectra measurements and comparison.

IL – Low side Current Spectrum

h	IRMS [A]	Phase [deg]
1	724.89659446	0.11621776
3	3.61852208	-86.18331333
5	60.59393845	123.78444976
7	0.60369343	153.70402571

The current spectrum for IL is obtained from the detailed model of a PV inverter involving power electronic switches

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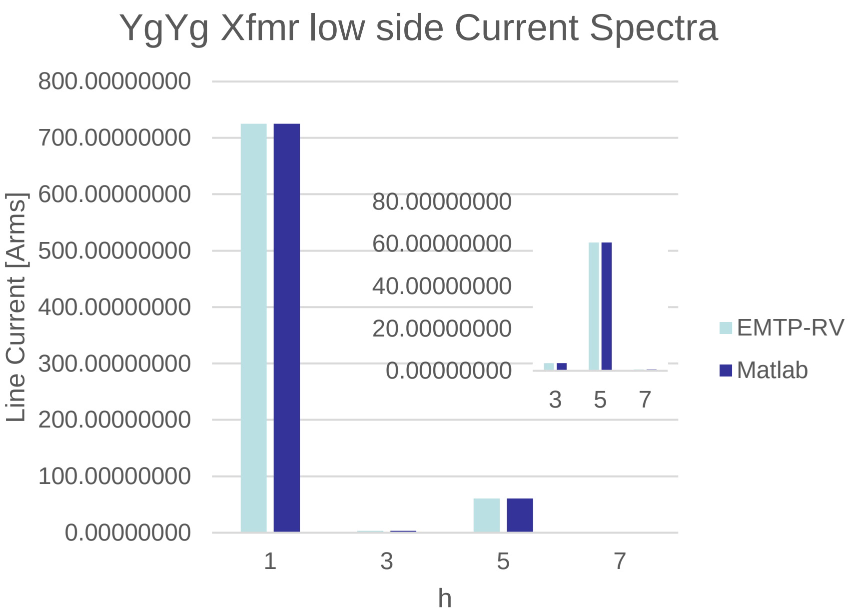

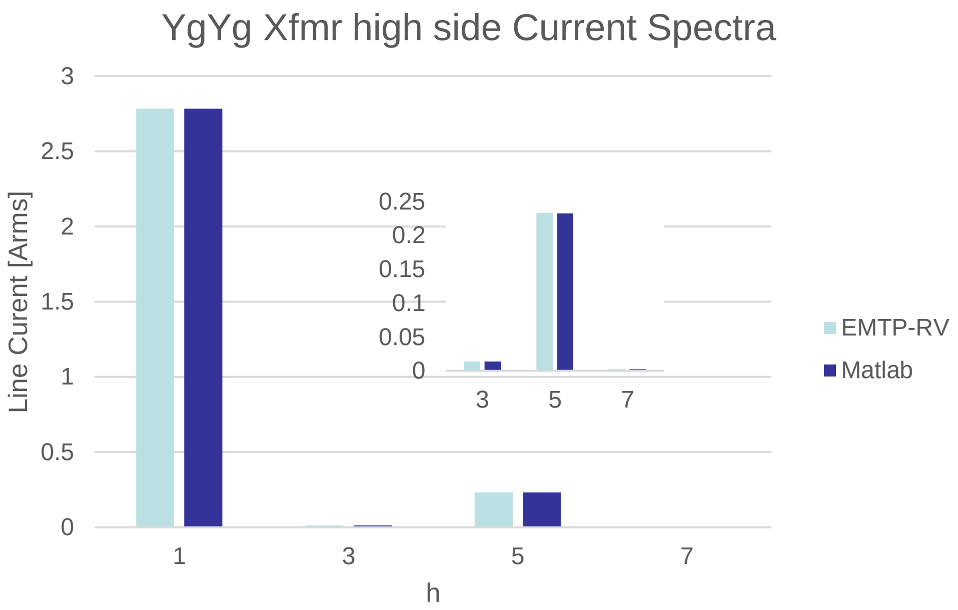

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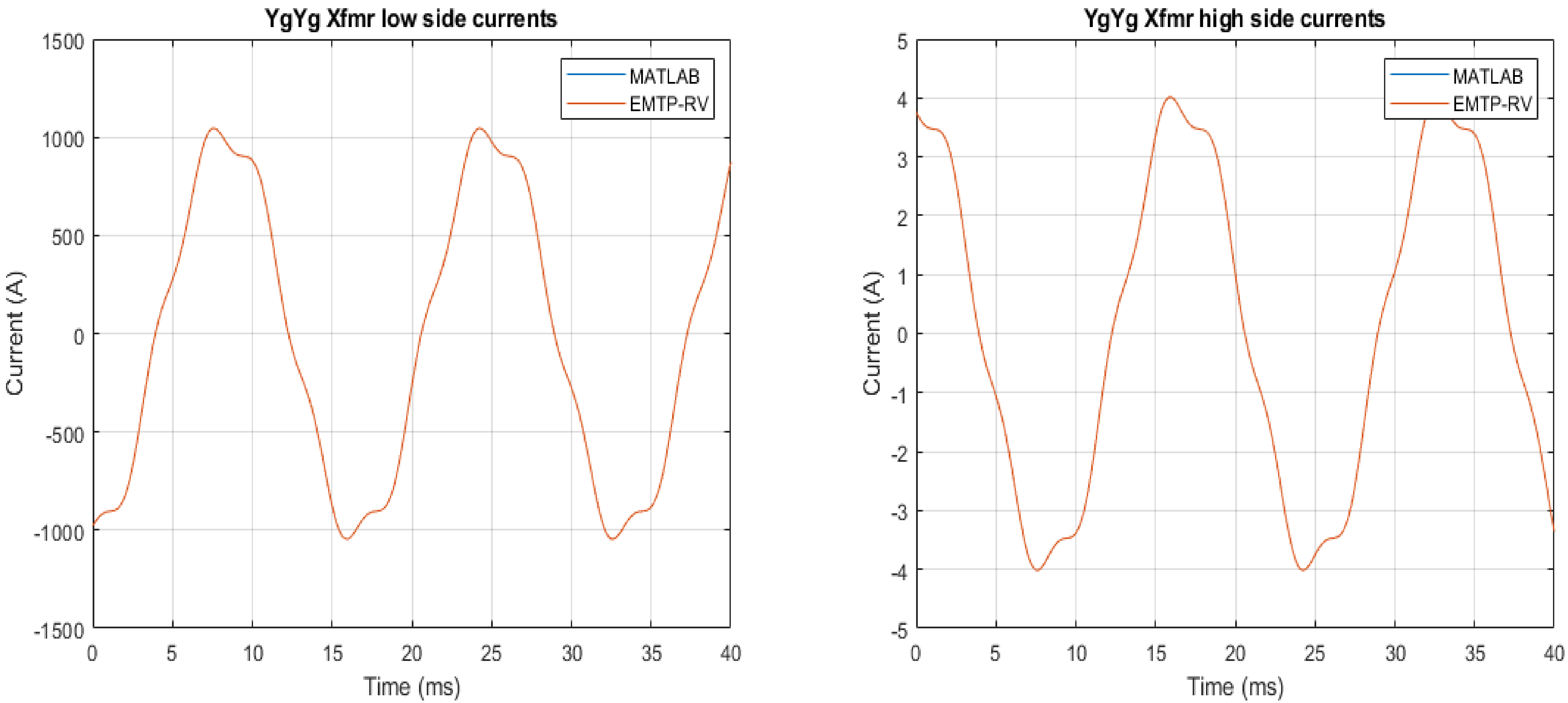

Both currents waveshapes match very well – the MATLAB model is validated

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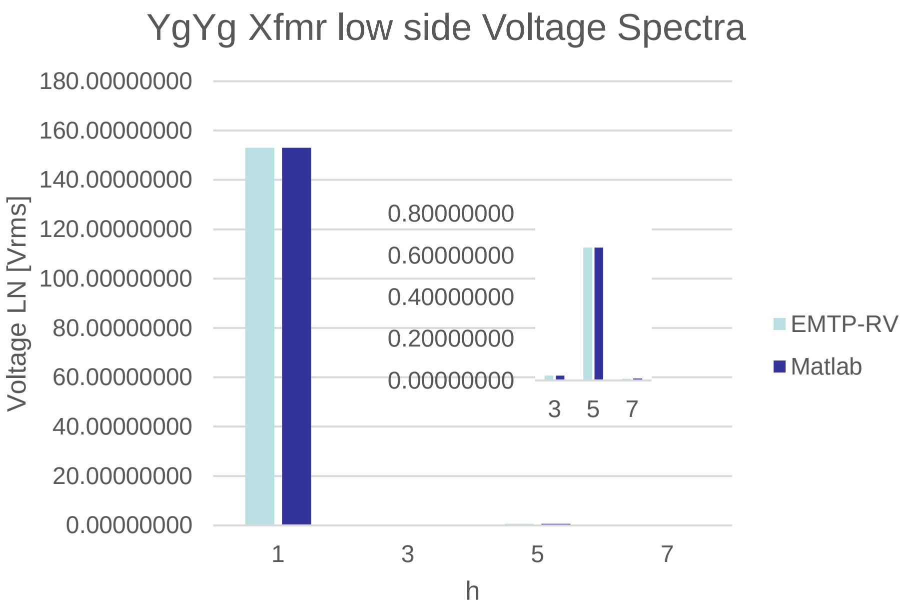
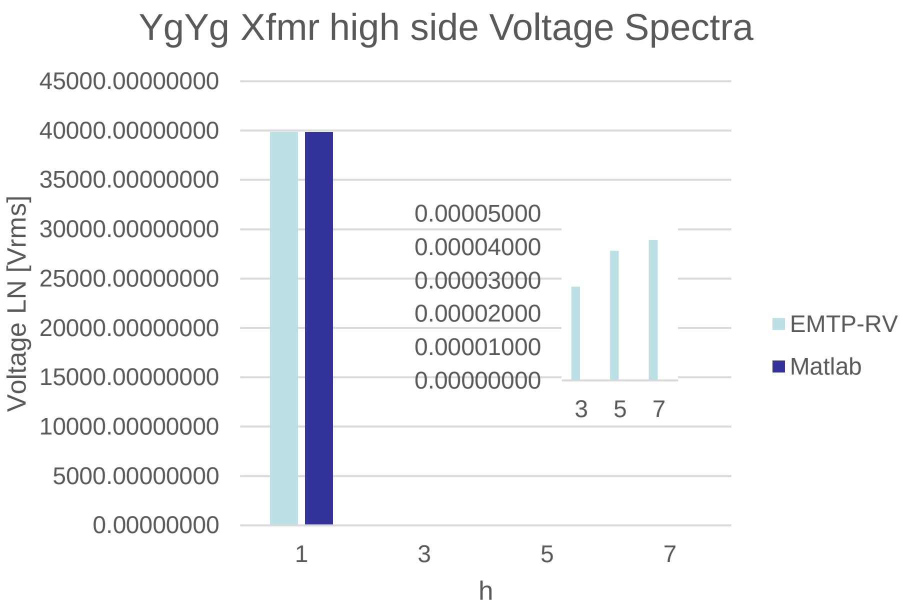
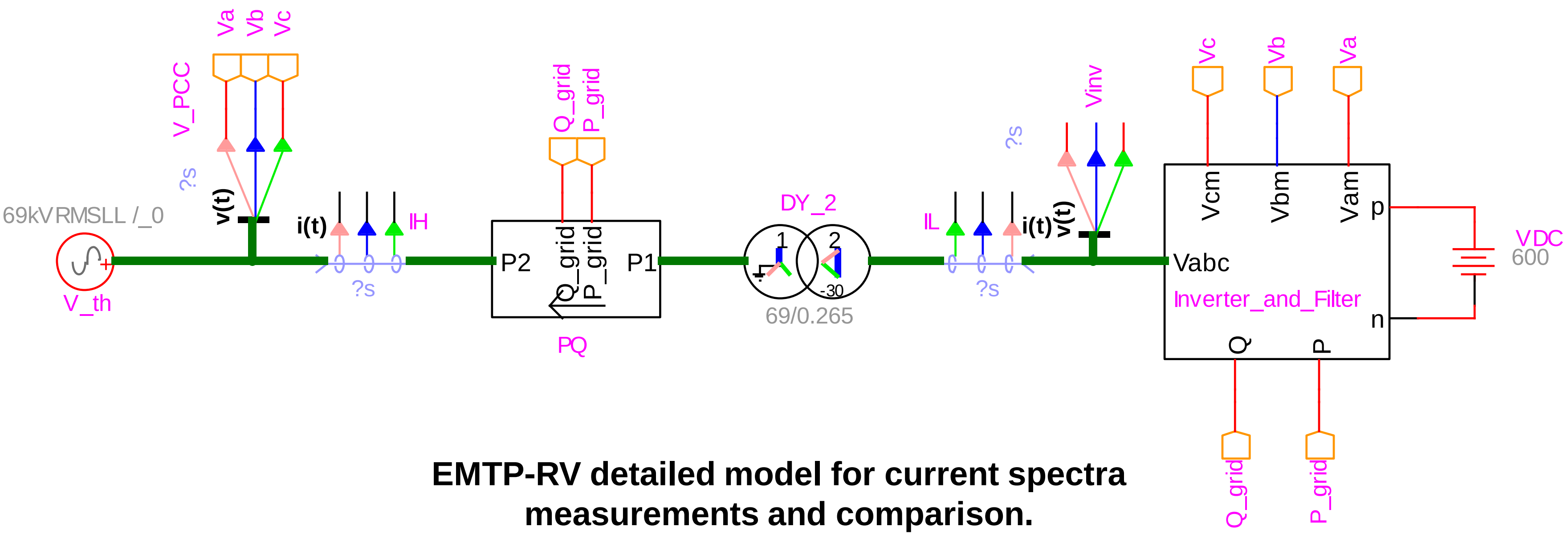




Case study **C2**: Inverter-Based Generation Steady-State Harmonic Simulation – YgD

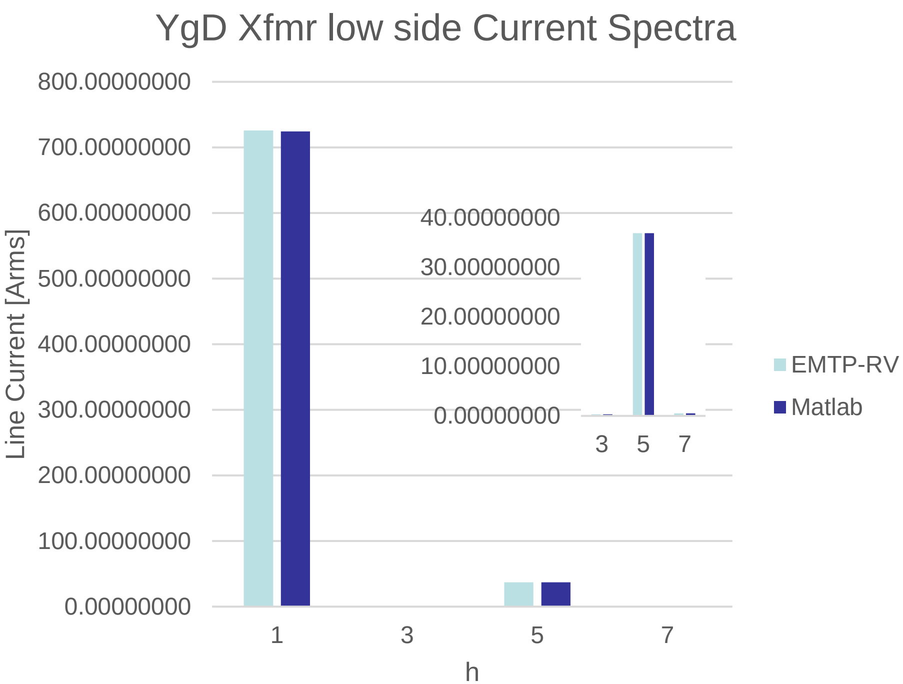


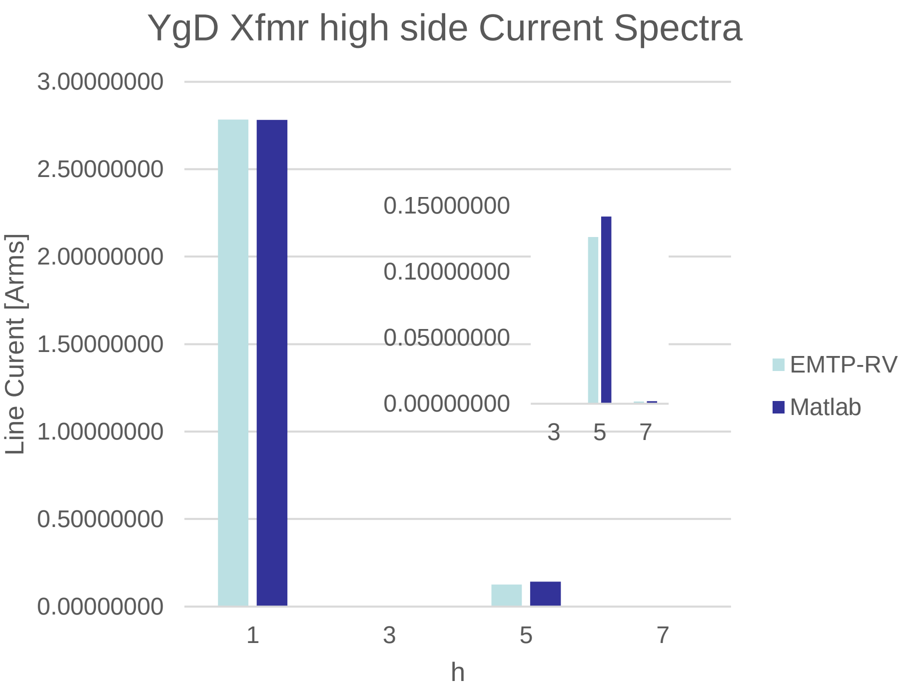
EMTP-RV detailed model for current spectra measurements and comparison.

IL – Current Spectrum

h	IRMS [A]	Phase [deg]
1	725.49423181	-29.90098730
3	0.31181659	-98.22515297
5	36.88252625	-15.09932240
7	0.50247343	-54.64784741

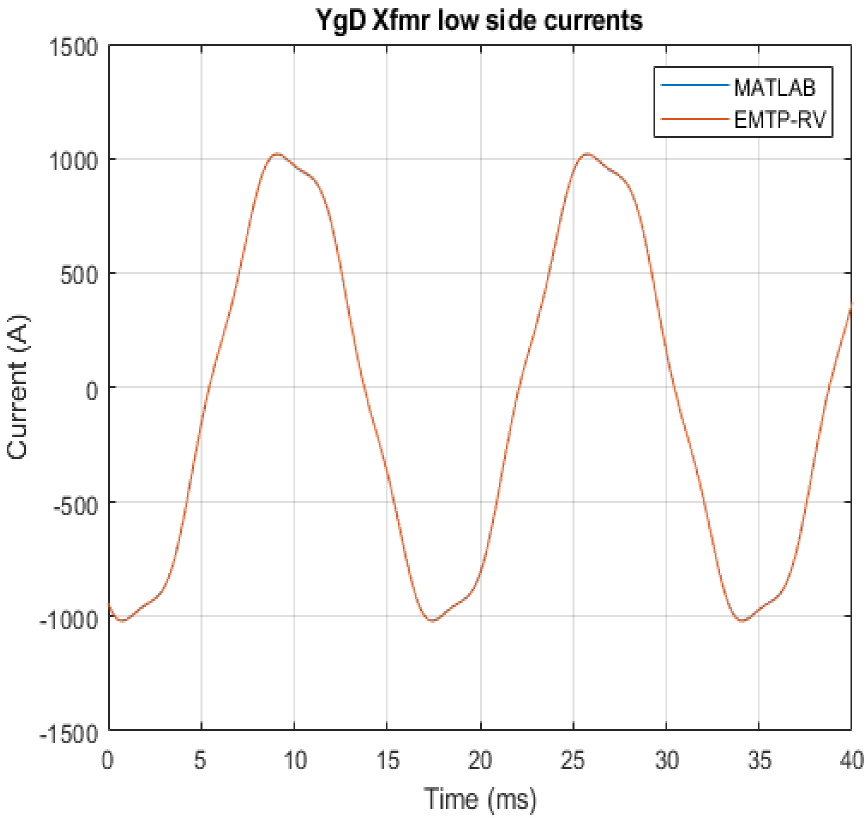
Case study **C2**: Inverter-Based Generation Steady-State Harmonic Simulation – YgD

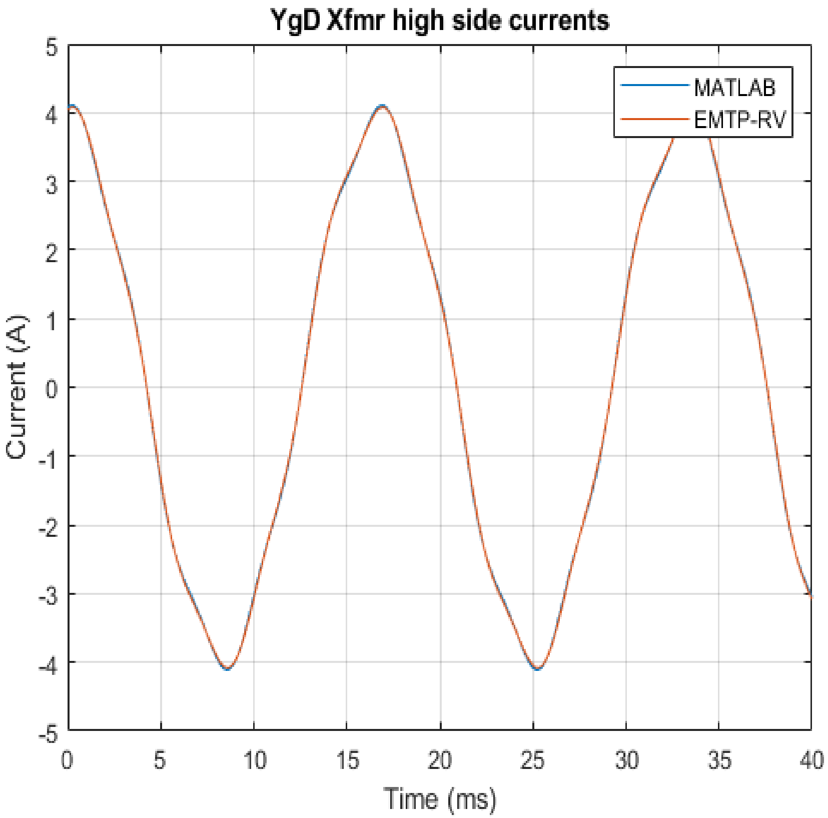




- Slightly different results obtained on the currents at the high side of the Xfmr
- The Matlab script assumes balanced conditions, whereas the EMTP-RV detailed model is inherently unbalanced

Case study **C2**: Inverter-Based Generation Steady-State Harmonic Simulation – YgD





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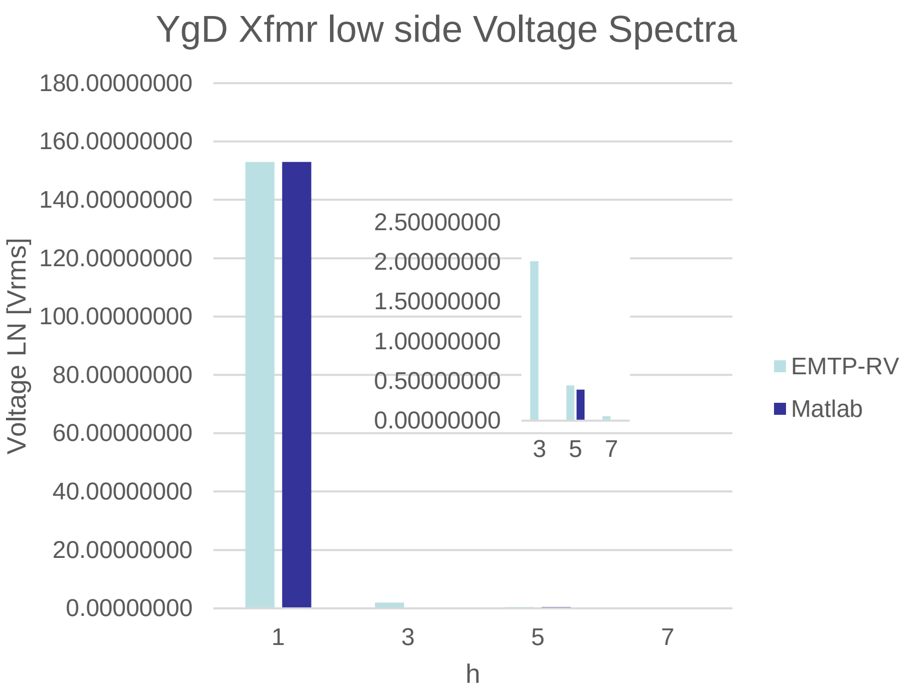

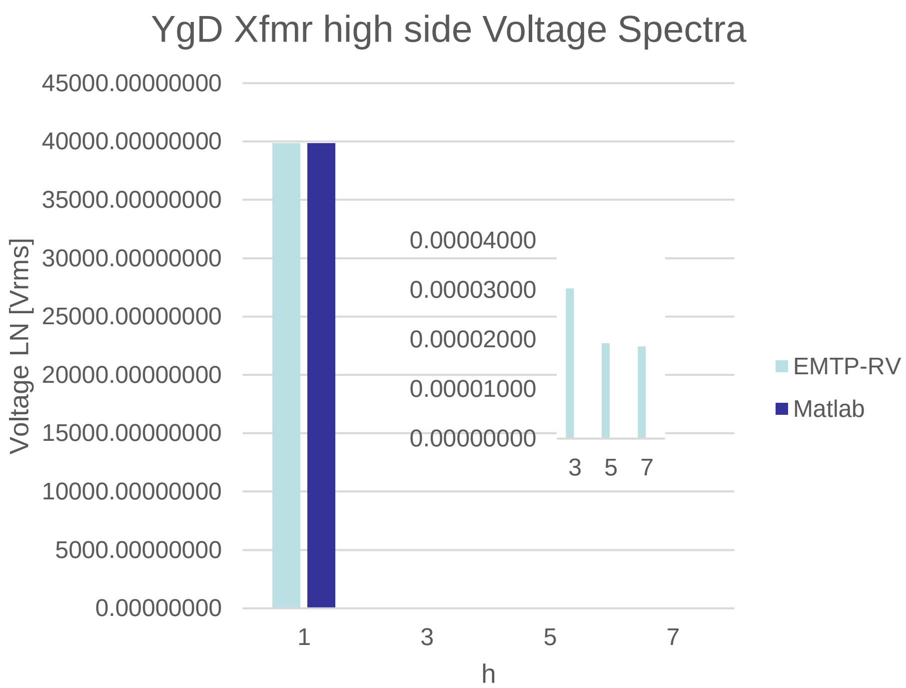

The EMTP-RV detailed model is inherently unbalanced, this causes the 3rd order harmonic to flow from low to high side of the Xfmr without causing a sharp voltage resonance. Matlab voltage results at the 3rd harmonic are excluded from the results due to its unrealistic magnitude.

Conclusions

- Power system network models studied in class can successfully be expanded to simulate harmonic currents in steady-state. The Yprim of each element requires adjustment depending on the harmonic frequency.
- Harmonic load-flow can be achieved by running separate simulations at each harmonic frequency, including the fundamental.
- YgYg Xfmr lets all harmonic currents flow through its windings.
- YgD Xfmr works as a filter for the triplen (3^{rd}, 6^{th}, 9^{th}…) harmonic currents.
- Triplen harmonic currents cause a sharp voltage resonance in the delta side of a DYg/YgD Xfmr; this is due to the lack of a phase-to-ground path to drain the triplen harmonic currents.
- When triplen harmonic currents are injected in the wye side of a YgD/DYg Xfmr, the current can flow from the lines to the ground without causing a voltage resonance. No triplen harmonic current is observed in the delta side of the Xfmr since it is an open circuit for zero-sequence currents.