Final Assignment – Converter techniques (cohort 2025-04)

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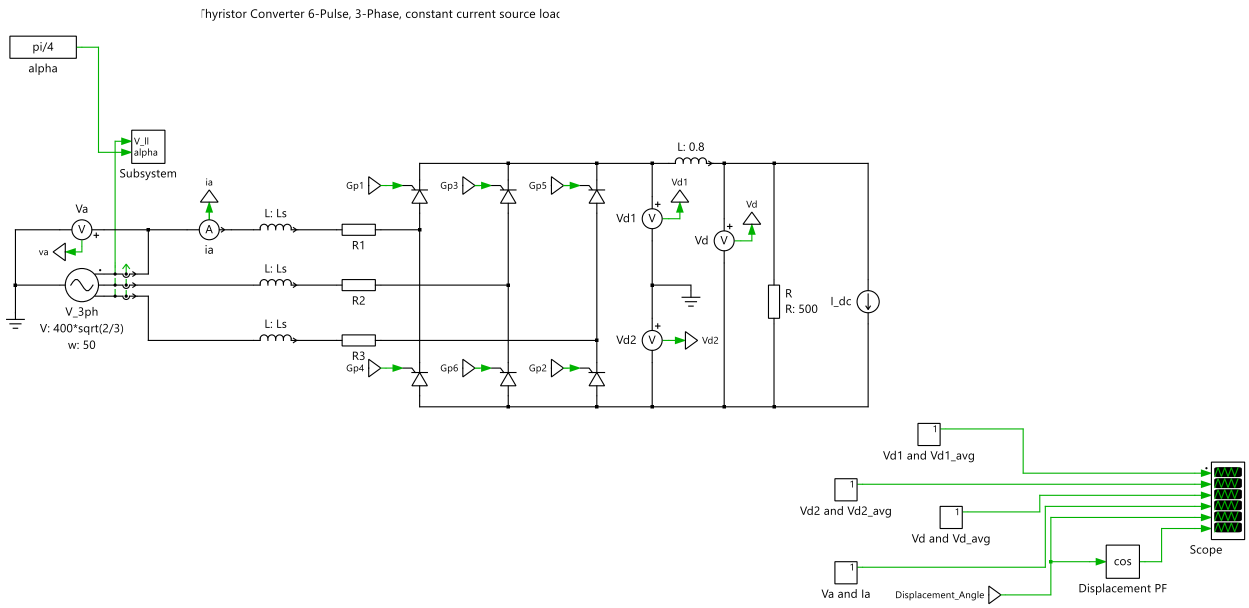
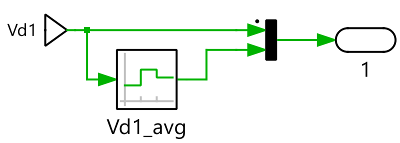
Exercise 1: Basic Concepts in 3-Phase Thyristor converters (Thy3_Concepts.plecs)

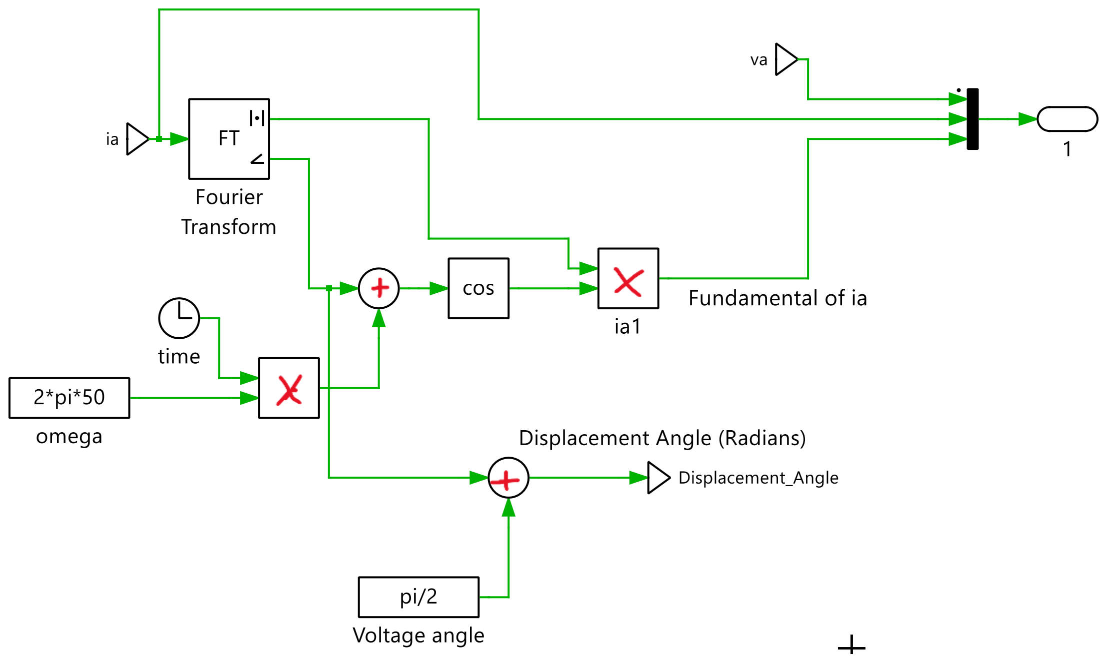
Simulation Model:



The subsystem of “Vd1 and Vd1_avg” is as below and the same model for other two subsystems: “Vd2 and Vd2_avg, Vd and Vd_avg”.

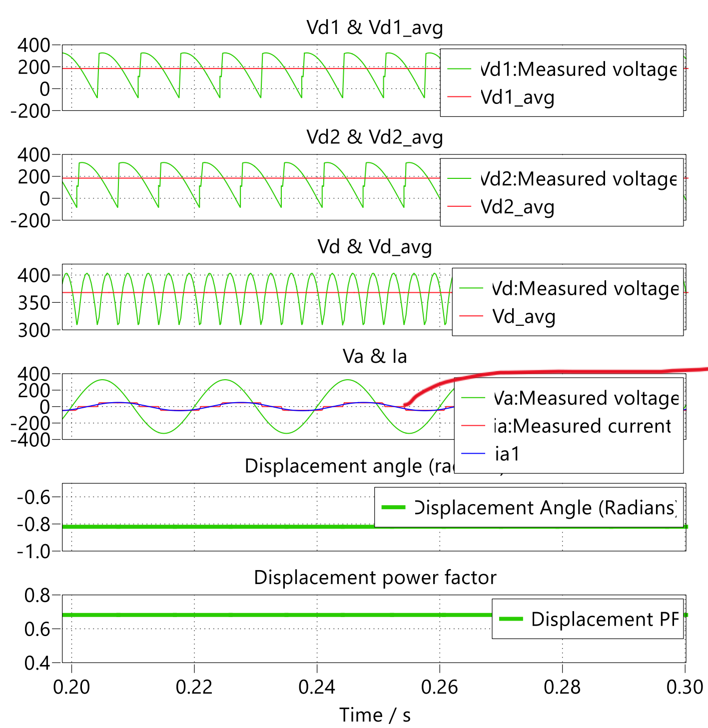


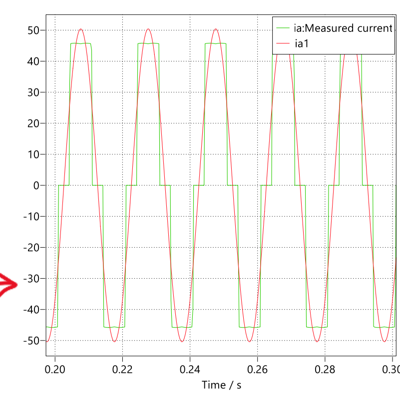
The subsystem of “Va and Ia” is as below. Based on FFT, the fundamental component of ‘ia’ is calculated and the same is plotted along with measured ‘va’ and ‘ia’.



Waveforms:

Case 1: Firing angle of 45 degrees





1. Average of Vd1 is 184.052 Volts.
2. Average of Vd2 is 184.051 Volts.
3. Average of Vd is 368.103 Volts.

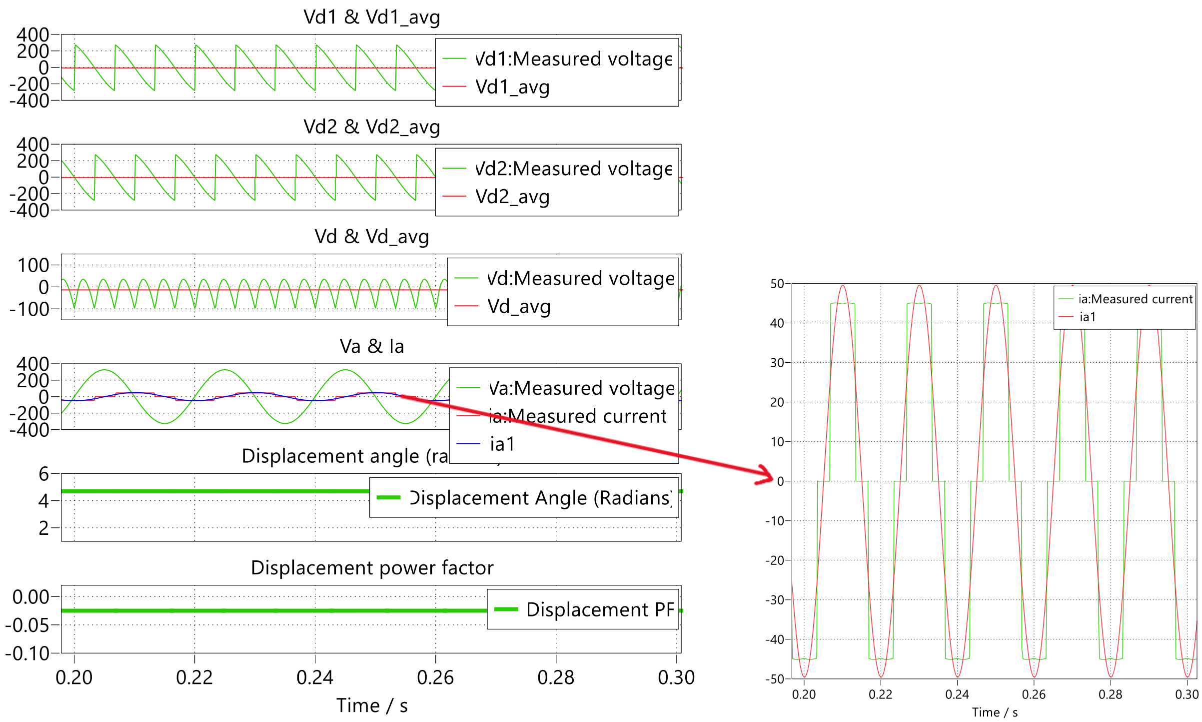
The average of Vd based on theoretical concept is

Vd_theory = $\left(\frac{3V_{LL,p}}{\pi}\cos\alpha\right) - \left(\frac{3*2\pi*50*L_s}{\pi} + R\right)I_0$ = $381.9718 - 13.545 = 368.4268$ Volts.

Therefore, the measured output voltage closely matches with the theoretical output voltage.

4. The measured displacement angle (The phase angle of fundamental current of ia with respect to va) is -0.820638 radians or 47.019 degrees. The measured displacement power factor is 0.68175 lag.
   Theoretical Displacement Power Factor (DPF) calculation:
   Power Factor (PF) = DPF * Distortion Factor (DF).
   Where DF = $\frac{I_{a1,rms}}{I_{a,rms}} = \frac{\left(\sqrt{6}/\pi\right)I_{0,dc}}{\left(\sqrt{2/3}\right)I_{0,dc}} = 0.955$
   PF = $\frac{P}{S} = \frac{V_{d,avg}*I_{0,dc}}{\sqrt{3}V_{LL}I_{a,rms}} = \frac{V_{d,avg}*I_{0,dc}}{V_{LL,p}*I_{0,dc}} = \frac{V_{d,avg}}{V_{LL,p}} = \frac{368.4268}{400*\sqrt{2}} = 0.6513$
   DPF = PF/DF = 0.6513/0.955 =0.68198 lag
   Therefore the measured DPF is same as with the calculated one.

Case 2: Firing angle of 90 degrees



1. Average of Vd1 is -6.83141 Volts.
2. Average of Vd2 is -6.83366 Volts.
3. Average of Vd is -13.6679 Volts.

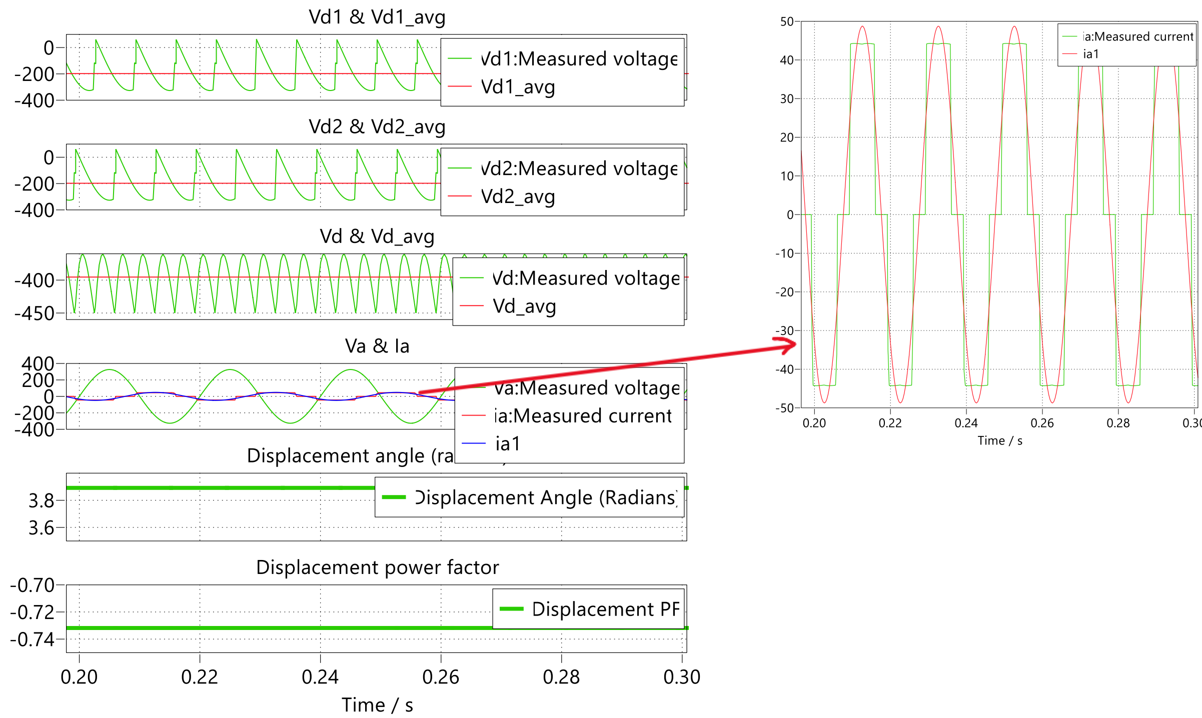
The average of Vd based on theoretical concept is

Vd_theory = $\left(\frac{3V_{LL,p}}{\pi}\cos\alpha\right) - \left(\frac{3*2\pi*50*L_s}{\pi} + R\right) I_0 = 0 - 13.545 = -13.545$ Volts.

Therefore, the measured output voltage closely matches with the theoretical output voltage.

4. The measured displacement angle (The phase angle of fundamental current of ia with respect to va) is 4.6874 radians or 268.568 (or 91.432) degrees. The measured displacement power factor is 0.025 lead.
   Theoretical Displacement Power Factor (DPF) calculation:
   Power Factor (PF) = DPF * Distortion Factor (DF).
   Where DF = $\frac{I_{a1,rms}}{I_{a,rms}} = \frac{\left(\sqrt{6}/\pi\right) I_{0,dc}}{\left(\sqrt{2/3}\right) I_{0,dc}} = 0.955$
   PF = $\frac{P}{S} = \frac{V_{d,avg}*I_{0,dc}}{\sqrt{3}V_{LL}I_{a,rms}} = \frac{V_{d,avg}*I_{0,dc}}{V_{LL,p}*I_{0,dc}} = \frac{V_{d,avg}}{V_{LL,p}} = \frac{-13.545}{400*\sqrt{2}} = -0.023944$
   DPF = PF/DF = -0.024/0.955 = -0.025 lag or 0.025 lead
   Therefore the measured DPF is same as with the calculated one.

Case 3: Firing angle of 135 degrees



1. Average of Vd1 is -197.693 Volts.
2. Average of Vd2 is -197.693 Volts.
3. Average of Vd is -395.382 Volts.

The average of Vd based on theoretical concept is

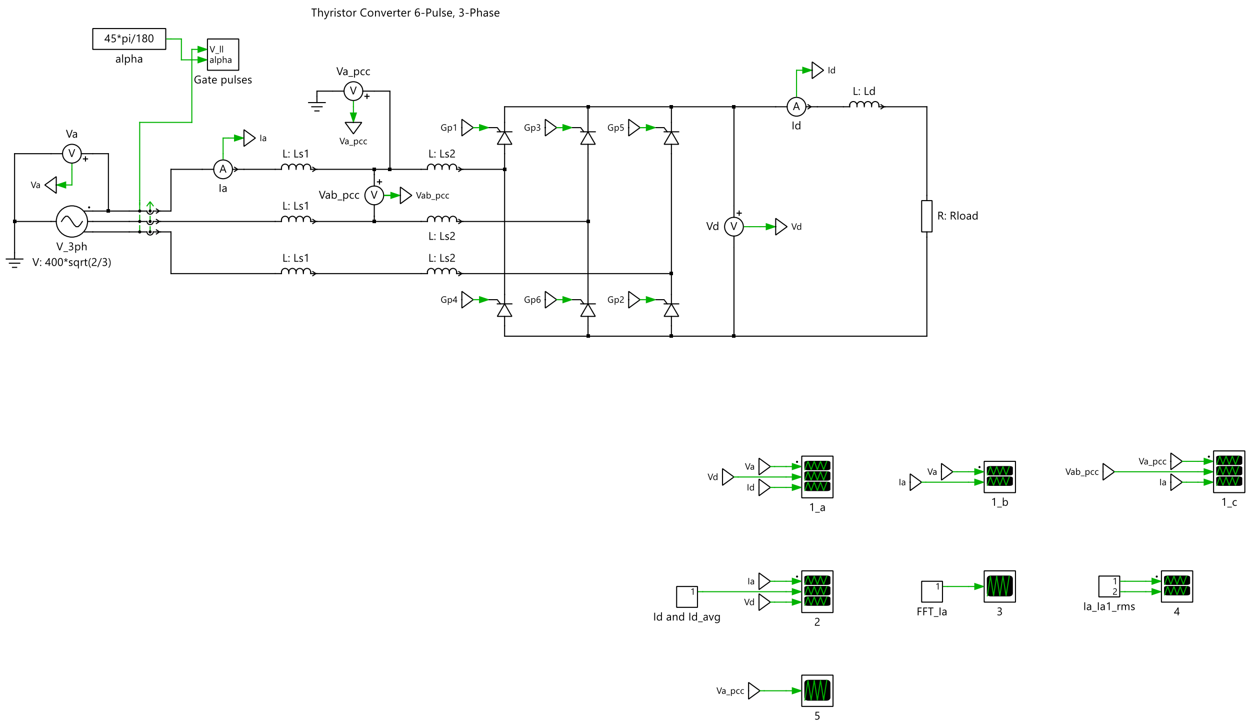
Vd_theory = $\left(\frac{3V_{LL,p}}{\pi}\cos\alpha\right) - \left(\frac{3*2\pi*50*L_s}{\pi} + R\right) I_0$ = $-381.972 - 13.545 = -395.516$ Volts.

Therefore, the measured output voltage closely matches with the theoretical output voltage.

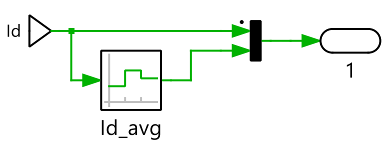
4. The measured displacement angle (The phase angle of fundamental current of ia with respect to va) is 3.8914 radians or 222.96 (or 137.04) degrees. The measured displacement power factor is 0.731822 lead.
   Theoretical Displacement Power Factor (DPF) calculation:
   Power Factor (PF) = DPF * Distortion Factor (DF).
   Where DF = $\frac{I_{a1,rms}}{I_{a,rms}} = \frac{\left(\sqrt{6}/\pi\right)I_{0,dc}}{\left(\sqrt{2/3}\right)I_{0,dc}} = 0.955$
   PF = $\frac{P}{S} = \frac{V_{d,avg}*I_{0,dc}}{\sqrt{3}V_{LL}I_{a,rms}} = \frac{V_{d,avg}*I_{0,dc}}{V_{LL,p}*I_{0,dc}} = \frac{V_{d,avg}}{V_{LL,p}} = \frac{-395.516}{400*\sqrt{2}} = -0.69918$
   DPF = PF/DF = -0.69918/0.955 = -0.732125 lag or 0.732125 lead
   Therefore the measured DPF is same as with the calculated one.

Exercise 2: 3-Phase Thyristor Rectifier Bridge (Thyrect3.plecs)

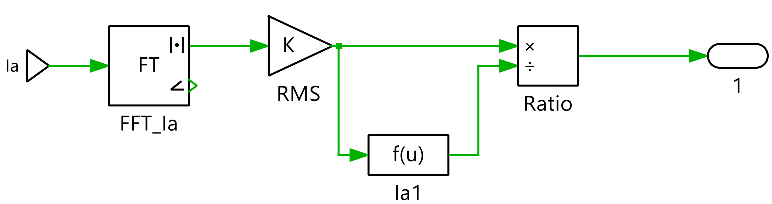
Simulation Model:



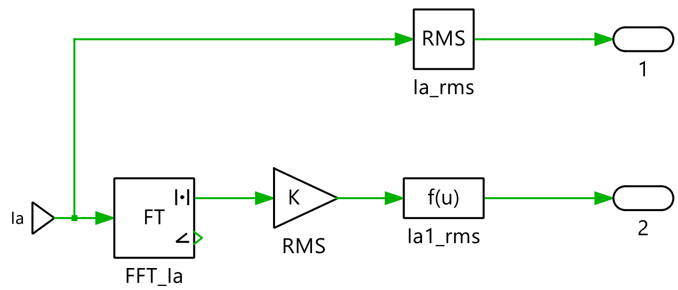
The subsystem of “Id and Id_avg” is as below.



The subsystem of “FFT_Ia” is as below.



The subsystem of “Ia_Ia1_rms” is as below.



Waveforms:

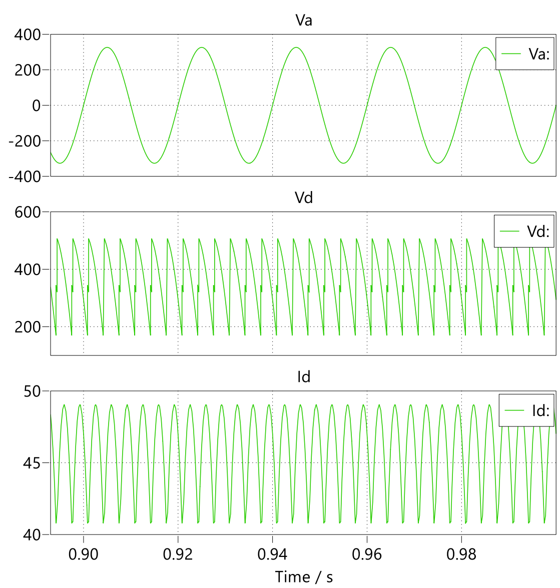
P1:

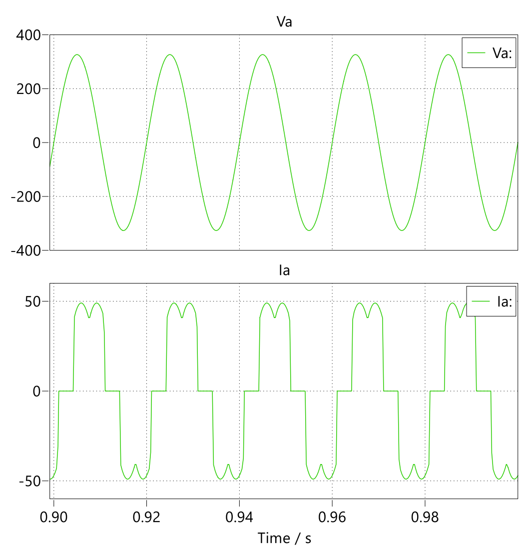
Data

Name	Cursor 1	Cursor 2	Mean
Time	0.92	0.96	
Va			
	1.36645e-08	*1.26232e-08*	2.01575e-09
Vd			
	295.04	*295.04*	367.266
Id			
	47.0447	*47.0448*	45.9082

Data

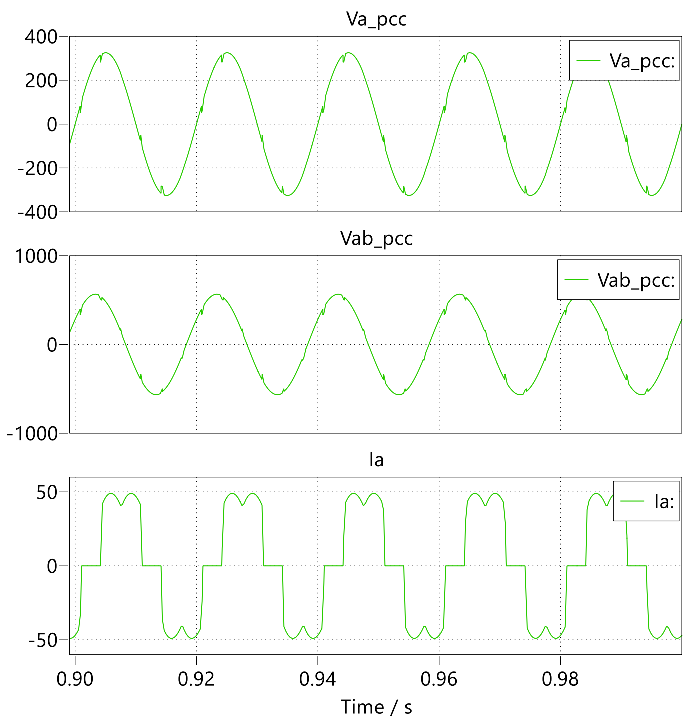
Name	Cursor 1	Cursor 2	RMS
Time	0.92	0.96	
Va			
	1.36645e-08	*1.26232e-08*	230.94
Ia			
	-47.0447	*-47.0448*	37.3753





Data

Name	Cursor 1	Cursor 2	RMS
Time	0.92	0.96	
Va_pcc			
Va_pcc:	-1.01647	-1.01648	229.408
Vab_pcc			
Vab_pcc:	281.826	281.826	397.346
Ia			
Ia:	-47.0447	-47.0448	37.3753



P2:

Commutation interval from the given equation is:

$$\cos(\alpha + u) = \cos\alpha - \frac{2wL_s}{\sqrt{2}V_{LL}} I_d$$

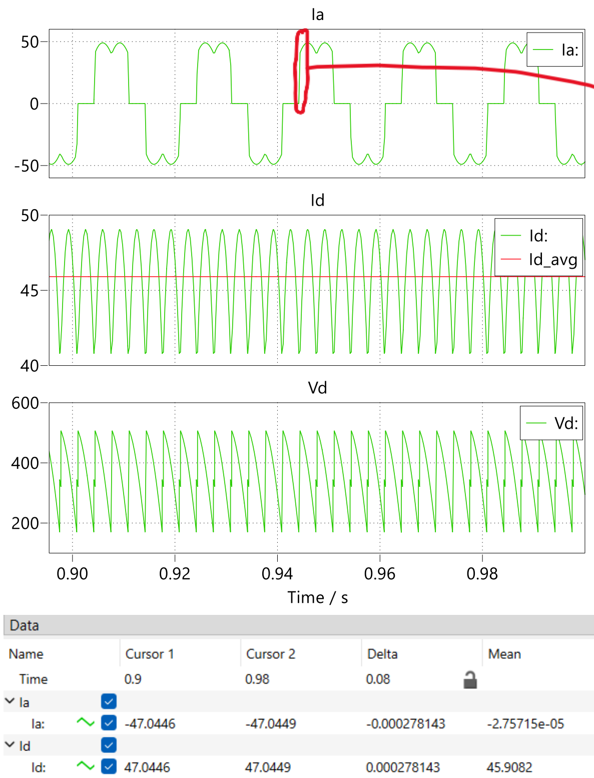
$$\cos(45^o + u) = \cos 45^o - \frac{2 * (2\pi * 50) * (0.2 + 1) * 10^{-3}}{\sqrt{2} * 400} * 45.9082$$

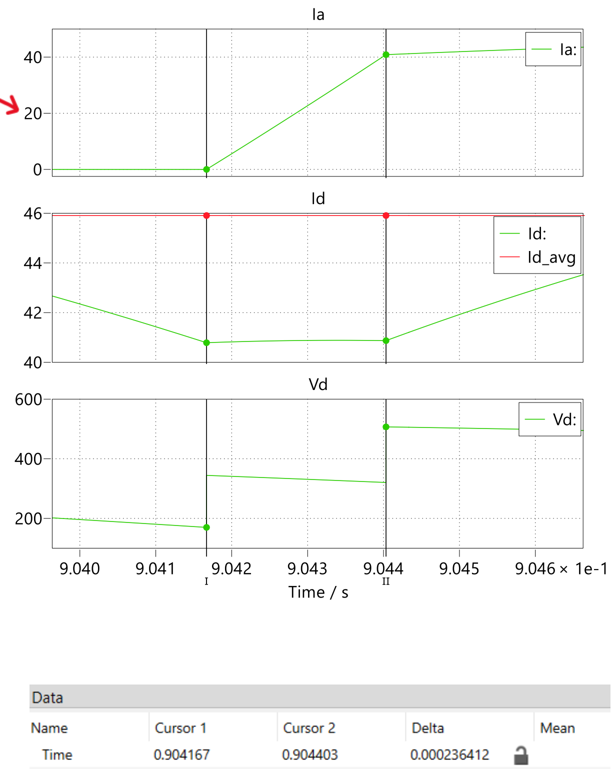
$$\cos\left(\frac{\pi}{4} + u\right) = \cos 45^o - 0.06118942755 = 0.64591735364$$

$$\frac{\pi}{4} + u = \cos^{-1} 0.64591735364 = 0.8706$$

$$u = 0.0852018\ radians$$

$$\boxed{u = 0.0852018 * \frac{0.01}{\pi} = 0.2712\ ms}$$





Id_avg value is 45.9082 A. The commutation interval from the plot is noted as u = 0.236412 ms.

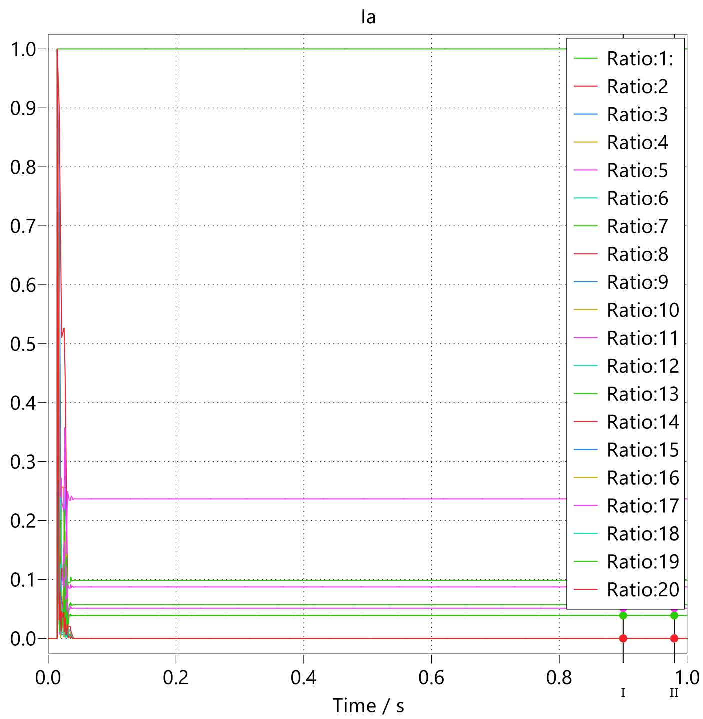
There is a considerable difference in u between the calculated and measured ones. This is because of difference in Id magnitude considered. In the measurement plot, commutation period is measured till id reaches 40.873 A whereas in the given equation id is considered as 45.9082.

If we consider Id = 40.873 in the given equation, we get

$$u = 0.0756\ radians$$

$$\boxed{u = 0.0756 * \frac{0.01}{\pi} = 0.2406\ ms}$$

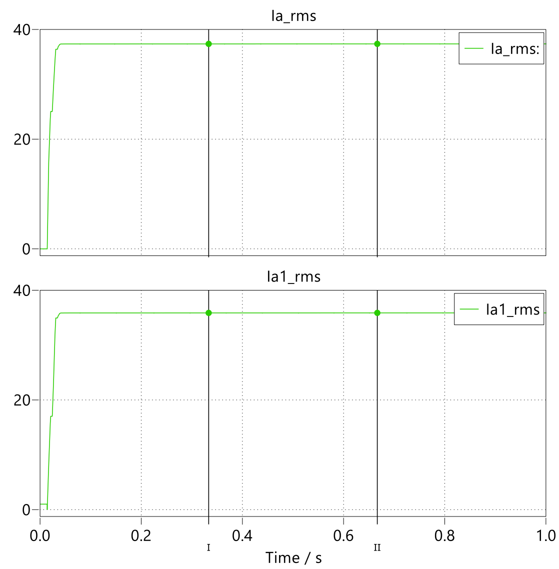
P3:



Name	Cursor 1	Cursor 2
Time	0.9	0.98
Ia		
Ratio:1:	1	1
Ratio:2	2.00141e-07	1.70523e-07
Ratio:3	1.00988e-07	8.60541e-08
Ratio:4	3.58158e-07	3.05171e-07
Ratio:5	0.236646	0.236645
Ratio:6	5.98083e-07	5.09593e-07
Ratio:7	0.0987365	0.0987372
Ratio:8	2.59477e-07	2.21084e-07
Ratio:9	1.69327e-07	1.4427e-07
Ratio:10	2.77074e-07	2.3608e-07
Ratio:11	0.0873471	0.0873471
Ratio:12	6.03085e-07	5.13854e-07
Ratio:13	0.0571182	0.0571184
Ratio:14	2.73835e-07	2.33322e-07
Ratio:15	2.10997e-07	1.79777e-07
Ratio:16	3.10871e-07	2.64874e-07
Ratio:17	0.051338	0.0513379
Ratio:18	5.57833e-07	4.75302e-07
Ratio:19	0.0389231	0.0389232
Ratio:20	2.2683e-07	1.93273e-07

The significant harmonic components are 5, 7, 11, 13, 17 and 19.

P4:



Name	Cursor 1	Cursor 2
Ia_rms:	37.3703	37.3738
Ia1_rms		
Ia1_rms	35.8719	35.8752

Power Factor (PF) = DPF * Distortion Factor (DF).

Where DF = $\frac{I_{a1,rms}}{I_{a,rms}} = \frac{35.8752}{37.3738} = 0.96$

PF = $\frac{P}{S} = \frac{V_{d,avg} * I_{0,dc}}{\sqrt{3} V_{LL} I_{a,rms}} = \frac{367.266 * 45.9082}{\sqrt{3} * 400 * 37.3738} = 0.651153$

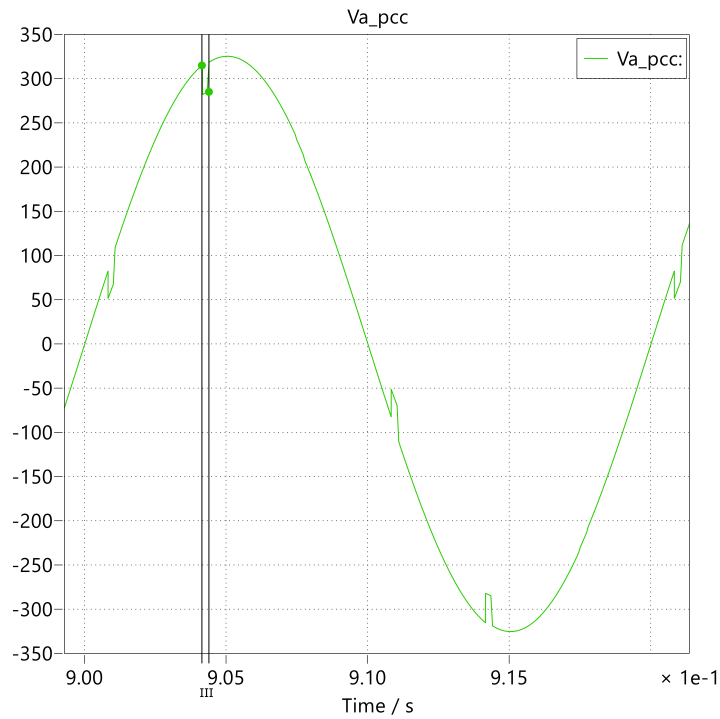
The values of $V_{d,avg}$, $I_{0,dc}$ are obtained from figures of P1.

DPF = PF/DF = 0.651153/0.96 = 0.67828 lag.

P5:

a. **Line-notch depth ρ(%)**

It is the ratio of peak-peak deviation from the actual voltage signal to the peak of actual voltage.

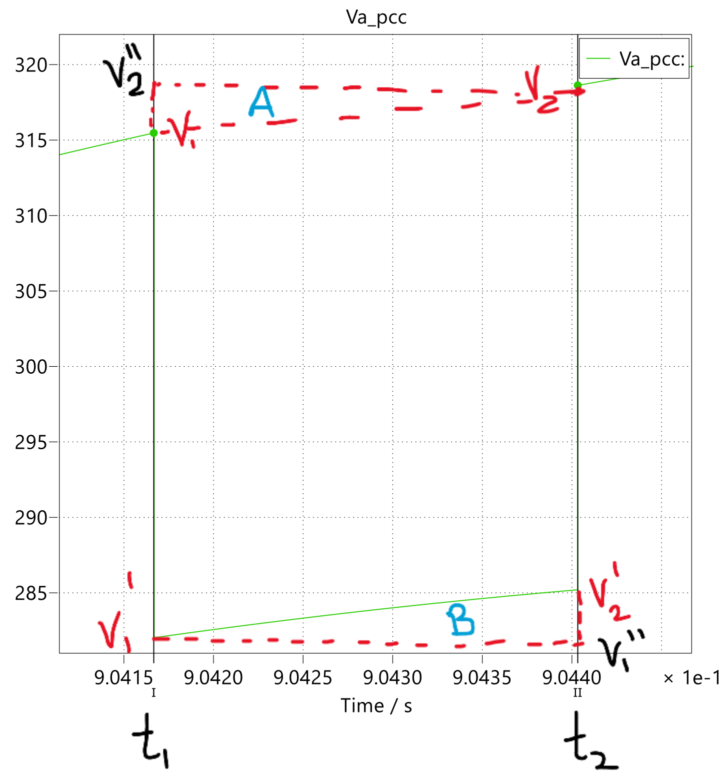


Name	Cursor 1	Cursor 2	Delta
Time	0.904148	0.904395	0.000247353
Va_pcc			
Va_pcc:	314.959	285.116	-29.8434

Peak to peak deviation is 29.8434 V and the peak of actual voltage is 325.32 V. So,

Line notch depth = $\frac{29.8434}{325.32} \times 100 = 9.1735\%$

b. Line-notch area



Name	Cursor 1	Cursor 2
Time	0.904167	0.904403
Va_p...		
	315.47	318.626

Line-notch area = Area of rectangle $V_1'V_1''V_2V_2''$

$= (V_2 - V_1'') * (t_2 - t_1)$

$= (318.626 - 282.027) * (0.904403 - 0.904167)$

$= 0.008637364\ voltsec$

P6:

The average value of Vd from the figures of P1 is 367.266 V.

The given equation for average of Vd is

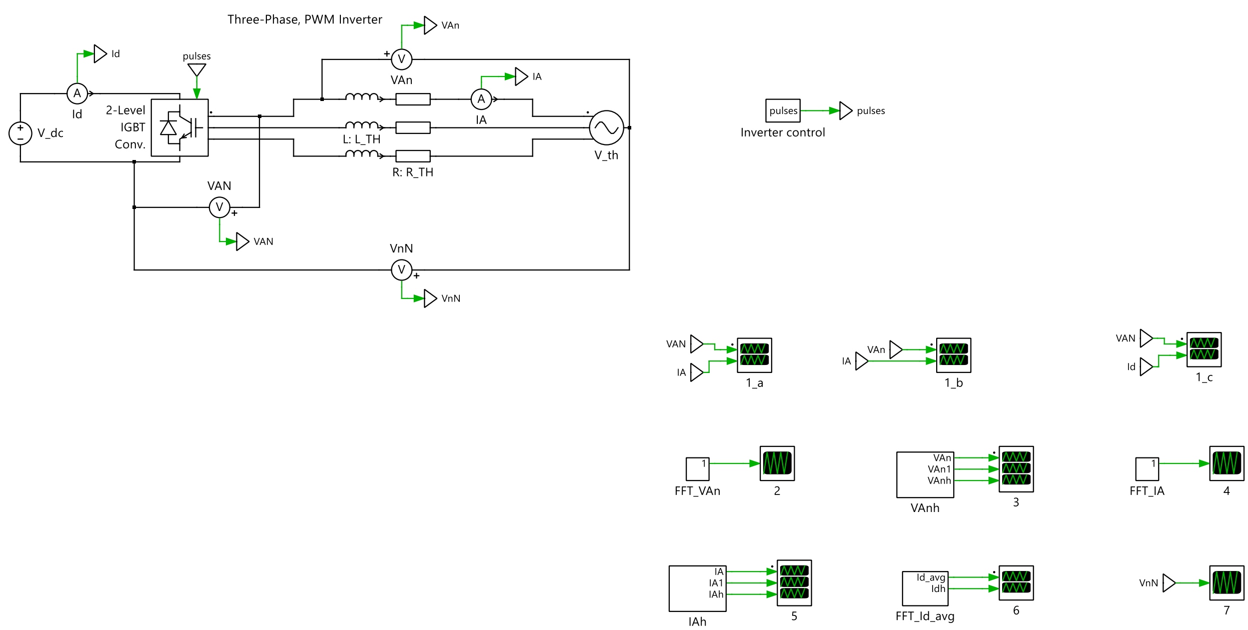
$$V_d = 1.35 V_{LL} \cos\alpha - \frac{3\omega L_s}{\pi} I_d$$

Substituting $V_{LL} = 400, \alpha = 45^o, \omega = 2\pi * 50, L_s = L_{s1} + L_{s2} = 1.2e^{-3}, I_d = 45.9082$ (from P1 figures), we get $V_{d\_avg} = 365.31\ V$.

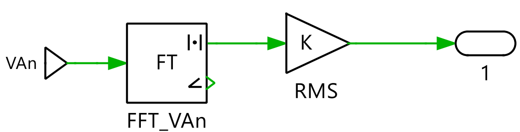
The calculated value matches close to the measured value.

Exercise 3: Three-Phase, PWM Inverter (PWINV3.plecs)

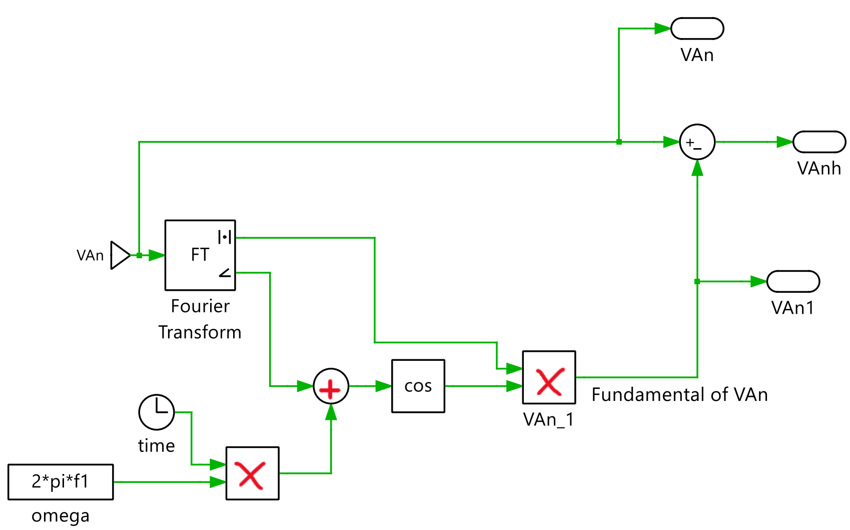
Simulation Model:



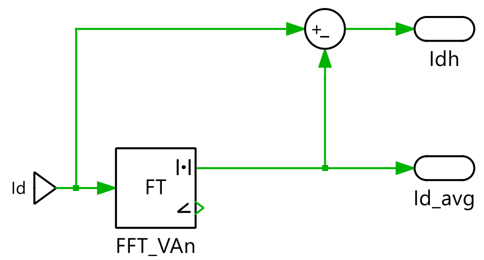
The subsystem of “FFT_VAn” is as below. The similar model is used in “FFT_IA” subsystem except the input which is IA instead of VAn.



The subsystem of “VAnh” is as below. The similar model is used in “IAh” subsystem except the input which is IA instead of VAn.

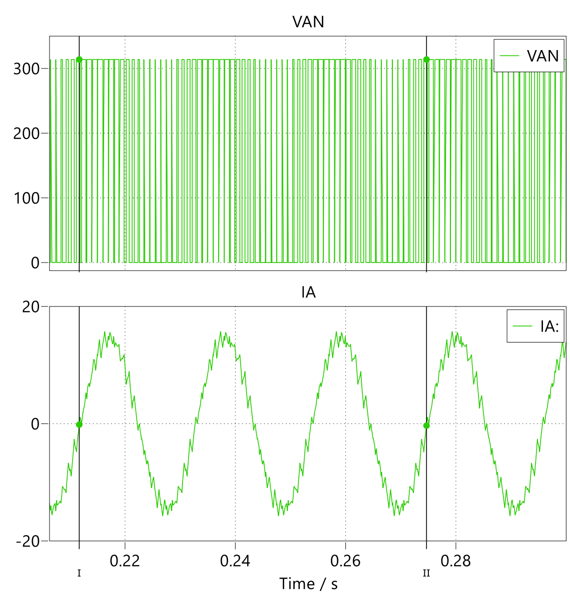


The subsystem of “FFT_Id_avg” is as below.

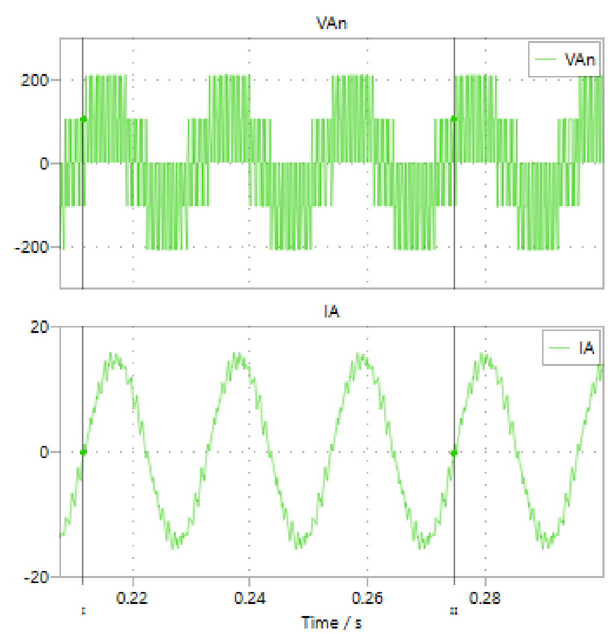


Waveforms:

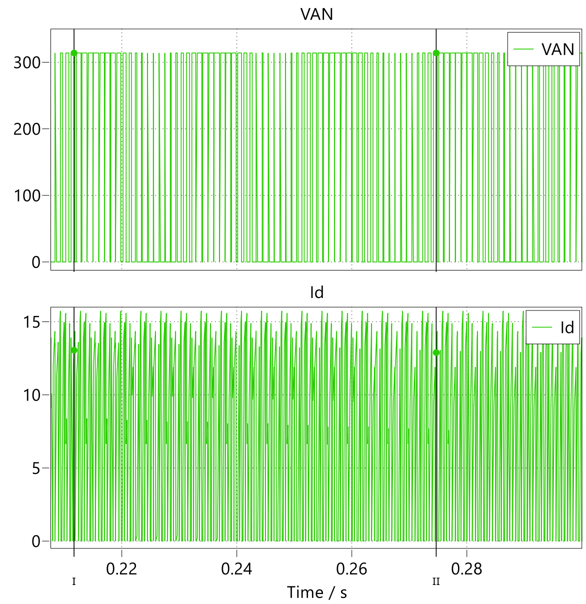
P1:



Name	Cursor 1	Cursor 2	RMS
Time	0.211693	0.274673	
VAN			
	313.97	313.97	221.975
IA			
	-0.156453	-0.326257	10.3125

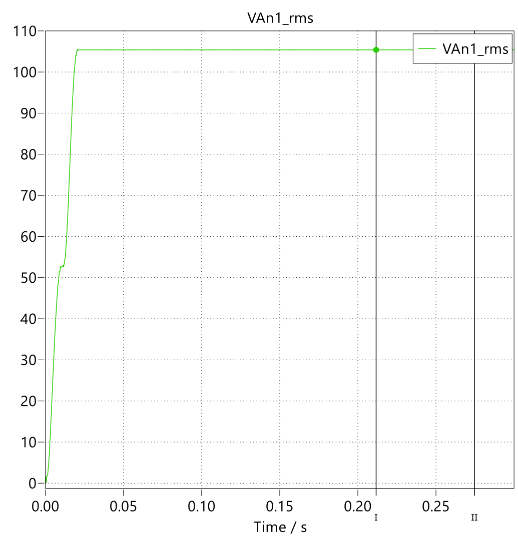


Name	Cursor 1	Cursor 2	RMS
Time	0.211693	0.274673	
VAn			
...	*104.657*	*104.657*	131.257
IA			
IA	*-0.15785*	*-0.327673*	10.3125



Name		Cursor 1	Cursor 2	Mean	RMS
Time		0.211693	0.274673		
VAN					
VAN		313.97	313.97	156.935	221.975
Id					
Id		13.055	12.8883	9.14061	10.6975

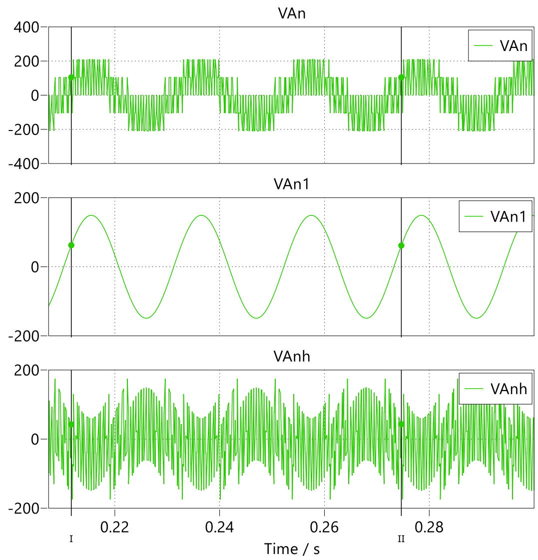
P2:



Name		Cursor 1	Cursor 2	RMS
Time		0.211693	0.274673	
VAn1_rms				
VAn1_rms		105.388	105.388	105.388

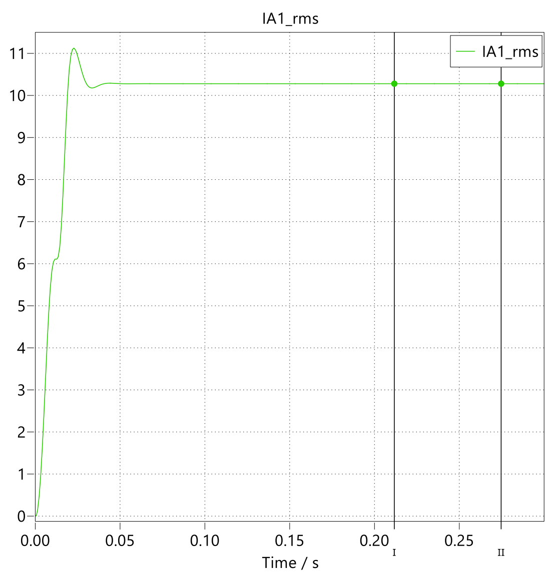
The measured fundamental voltage V_{An1}^{rms} $(f_1 = 47.619\ Hz)$ is same as the calculated i.e., 105.39 V.

P3:



Name	Cursor 1	Cursor 2	RMS
Time	0.211693	0.274673	
VAn			
VAn	104.657	104.657	131.257
VAn1			
VAn1	62.3589	61.5452	105.399
VAnh			
VAnh	42.2978	43.1115	78.237

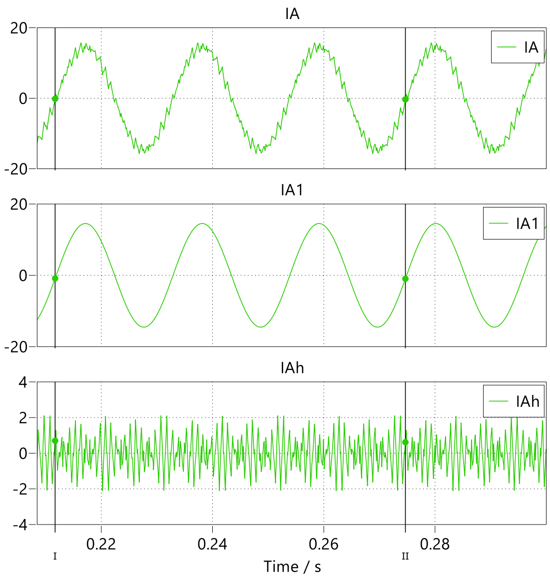
P4:



Name	Cursor 1	Cursor 2	RMS
Time	0.211693	0.274673	
IA1_rms			
IA1_rms	10.2793	10.2793	10.2793

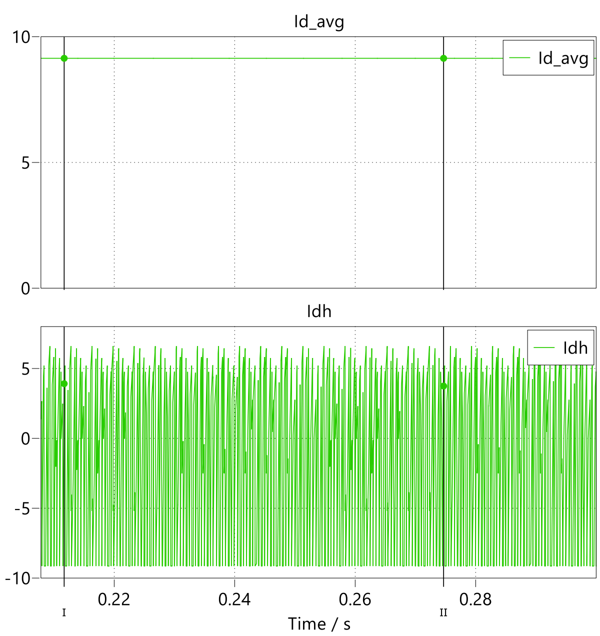
The measured fundamental current I_{A1}^{rms} $(f_1 = 47.619\ Hz)$ is same as the calculated i.e., 10 A.

P5:



Name			Cursor 1	Cursor 2	RMS
Time			0.211693	0.274673	
IA					
IA			-0.15785	-0.327673	10.3125
IA1					
IA1			-0.858458	-0.945553	10.2809
IAh					
IAh			0.700608	0.61788	0.806461

P6:



Name			Cursor 1	Cursor 2	Mean	RMS
Time			0.211693	0.274673		
Id_avg						
Id_avg			9.14184	9.14184	9.14184	9.14184
Idh						
Idh			3.91317	3.74648	-0.001233	5.55742

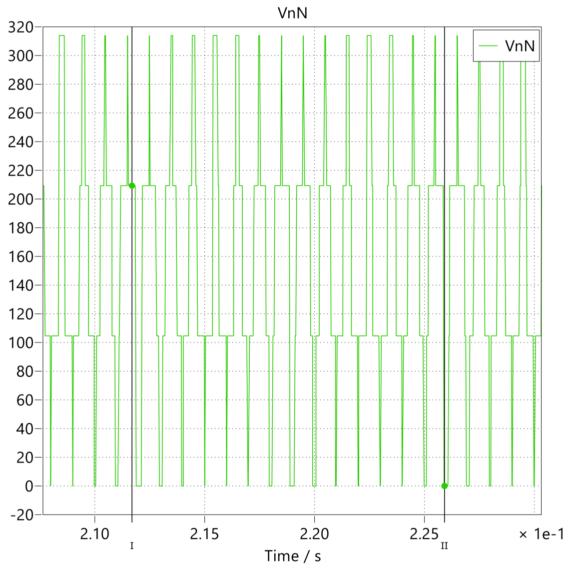
The average value is 9.14184 A and the ripple value is 5.55742 A.

P7:

The mid-point of the DC input voltage is assumed as its reference point N.

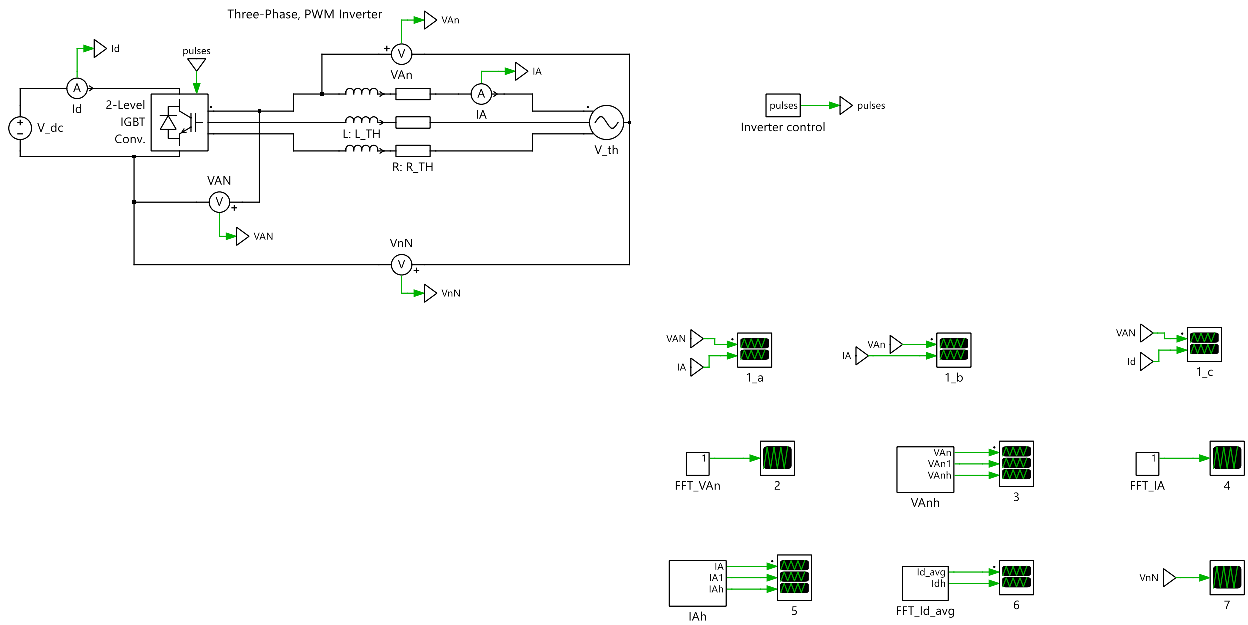
Name			Cursor 1	Cursor 2	RMS
Time			0.211693	0.225914	
VnN					
VnN			209.313	1.47438e-13	179.112

VnN is nothing but common mode voltage of the converter.

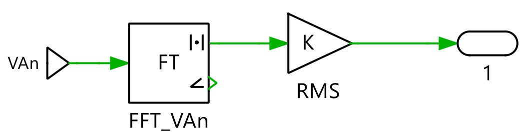


Exercise 4: Three-Phase, Square-Wave Inverter (SQINV3.plecs)

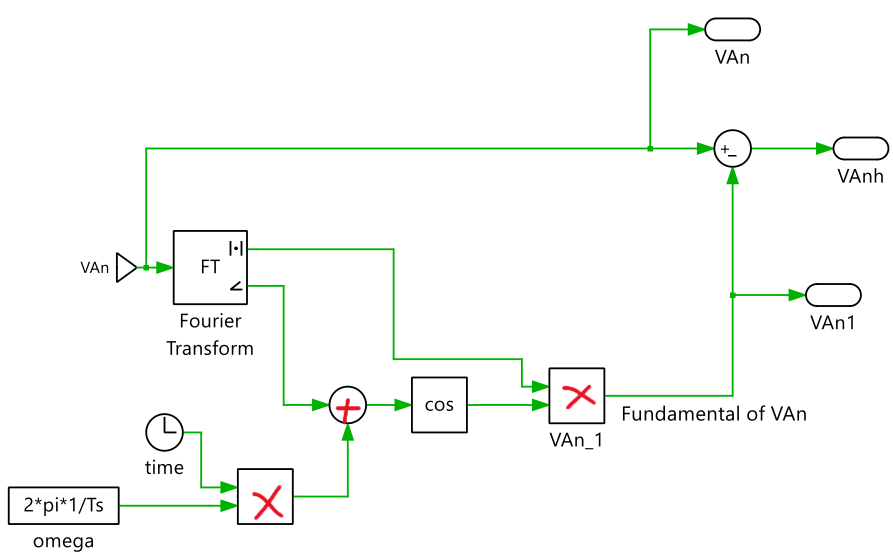
Simulation Model:



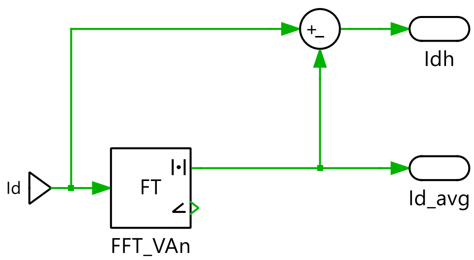
The subsystem of “FFT_VAn” is as below. The similar model is used in “FFT_IA” subsystem except the input which is IA instead of VAn.



The subsystem of “VAnh” is as below. The similar model is used in “IAh” subsystem except the input which is IA instead of VAn.



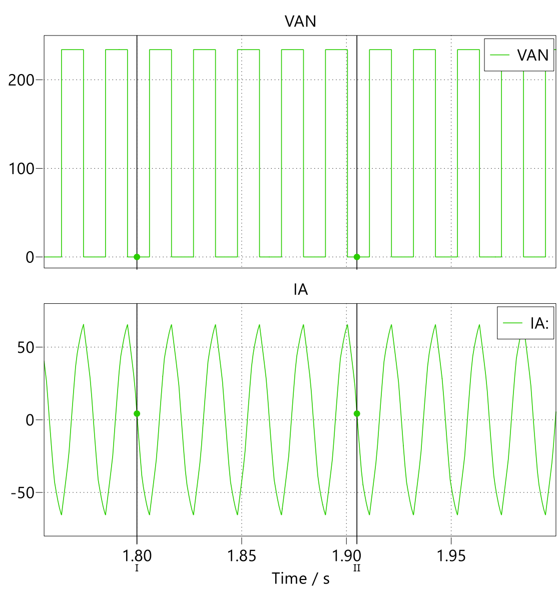
The subsystem of “FFT_Id_avg” is as below.



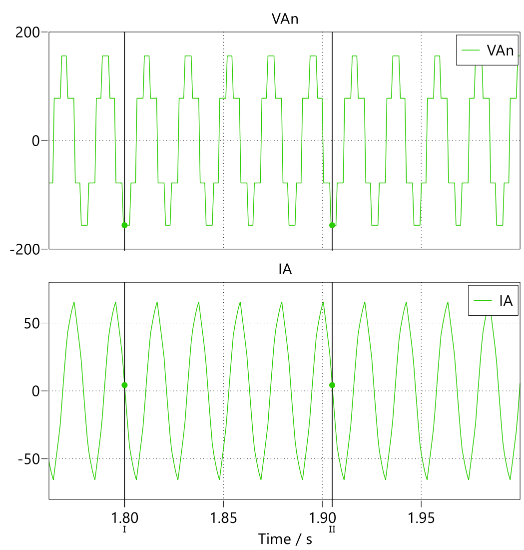
Fundamental frequency considered in all the applicable PLECS elements is $\frac{\mathbf{1}}{\boldsymbol{T_s}\mathbf{=21}\boldsymbol{e}\mathbf{-3}}$

Waveforms:

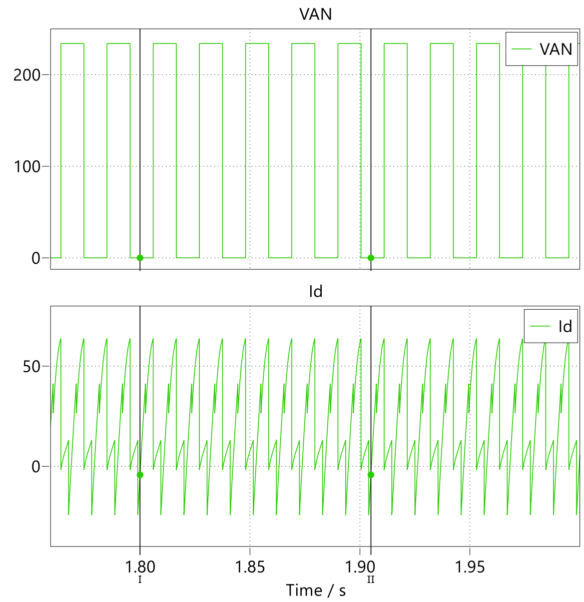
P1:



Name	Cursor 1	Cursor 2	RMS
Time	1.8	1.905	
VAN			
	0	0	165.484
IA			
	4.25193	4.25265	43.5731

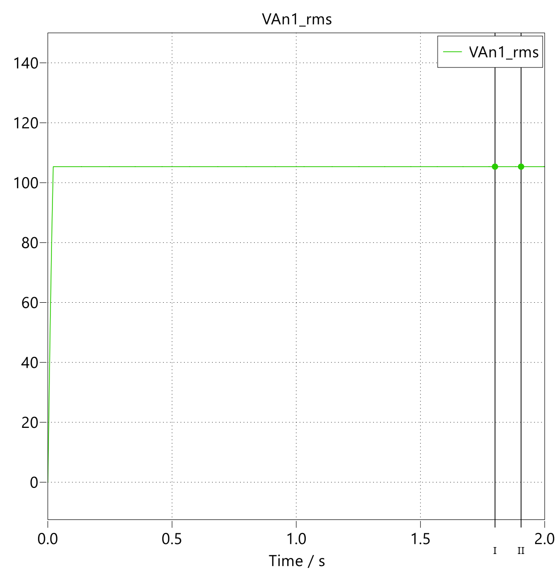


Name	Cursor 1	Cursor 2	RMS
Time	1.8	1.905	
VAn			
...	-156.02	-156.02	110.323
IA			
IA	4.25193	4.25265	43.5731



Name	Cursor 1	Cursor 2	Mean	RMS
Time	1.8	1.905		
VAN				
VAN	*0*	*0*	117.015	165.484
Id				
Id	*-4.25193*	*-4.25265*	22.0366	32.3119

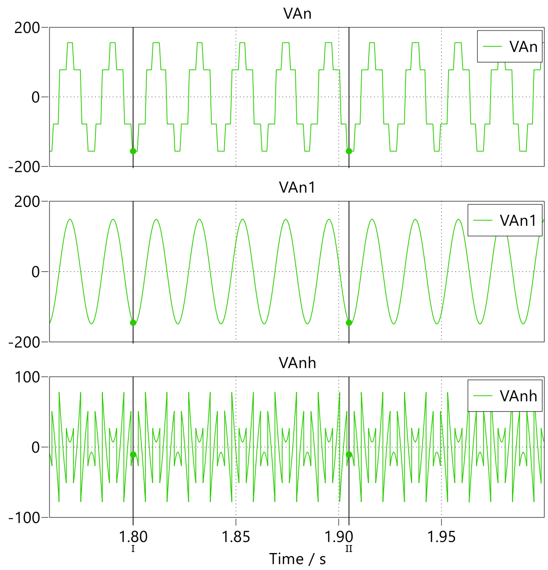
P2:



Name	Cursor 1	Cursor 2	RMS
Time	1.8	1.905	
VAn1_rms			
VAn1_rms	*105.351*	*105.351*	105.351

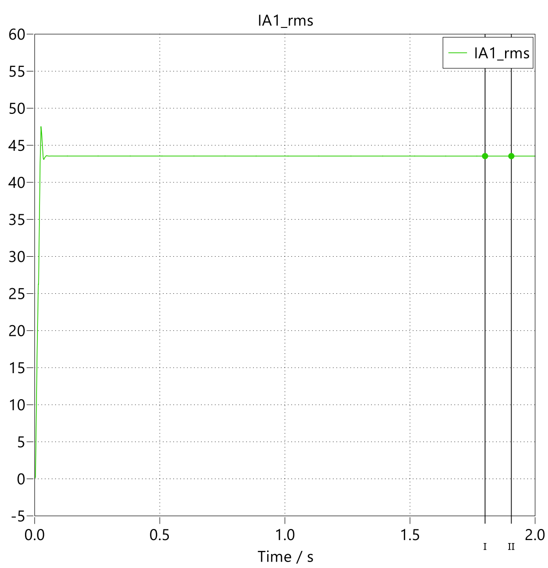
The measured fundamental voltage V_{An1}^{rms} $(f_1 = 47.619\ Hz)$ is same as the calculated i.e., $V_{LL1}^{rms} = 182.54\ V$ 1→ $V_{An1}^{rms} = \frac{V_{LL1}^{rms}}{\sqrt{3}} = 105.389$ V.

P3:



Name		Cursor 1	Cursor 2	RMS
Time		1.8	1.905	
VAn				
VAn		-156.02	-156.02	110.323
VAn1				
VAn1		-145.253	-145.253	105.35
VAnh				
VAnh		-10.7673	-10.7673	32.7474

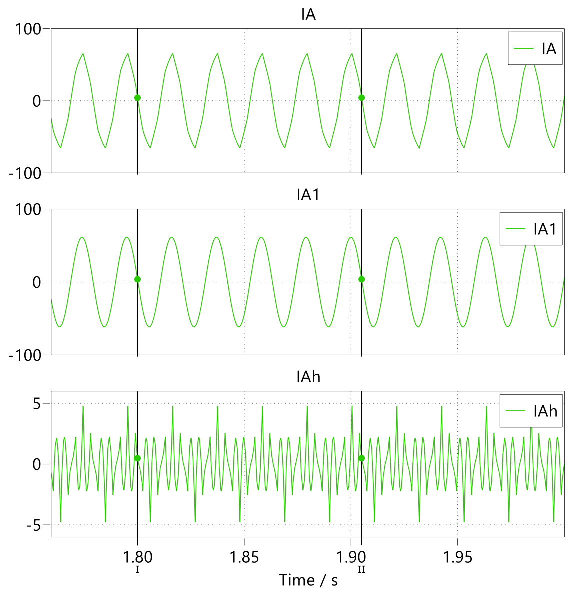
P4:



Name		Cursor 1	Cursor 2	RMS
Time		1.8	1.905	
IA1_rms				
IA1_rms		43.5432	43.5428	43.543

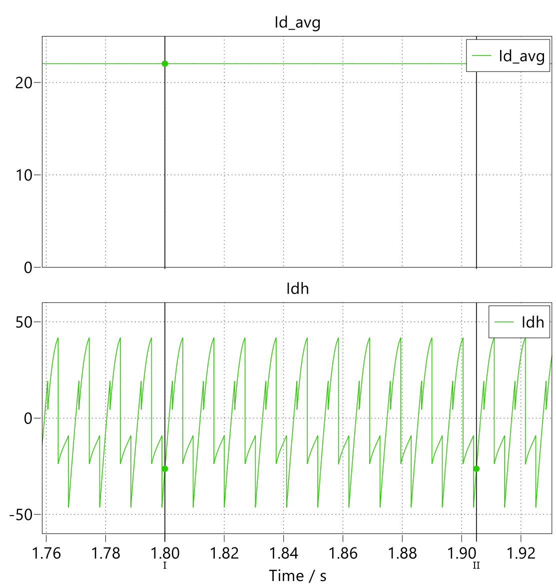
The measured fundamental current I_{A1}^{rms} $(f_1 = 47.619\ Hz)$ is not same as the calculated i.e., 10 A. This is due to mismatch in the common mode voltages (CMVs) as we used different PWM schemes. The fundamental RMS CMV in this example is 123.345 V which is less compared to in the previous example (179.059 V). These values could be noted from the figure of P7.

P5:



Name		Cursor 1	Cursor 2	RMS
Time		1.8	1.905	
IA				
IA		4.25193	4.25265	43.5731
IA1				
IA1		3.76824	3.76896	43.5429
IAh				
IAh		0.483693	0.483693	1.62081

P6:



Name		Cursor 1	Cursor 2	Mean	RMS
Time		1.8	1.905		
Id_avg					
Id_avg		22.0366	22.0366	22.0366	22.0366
Idh					
Idh		-26.2886	-26.2893	-7.5835e-06	23.6315

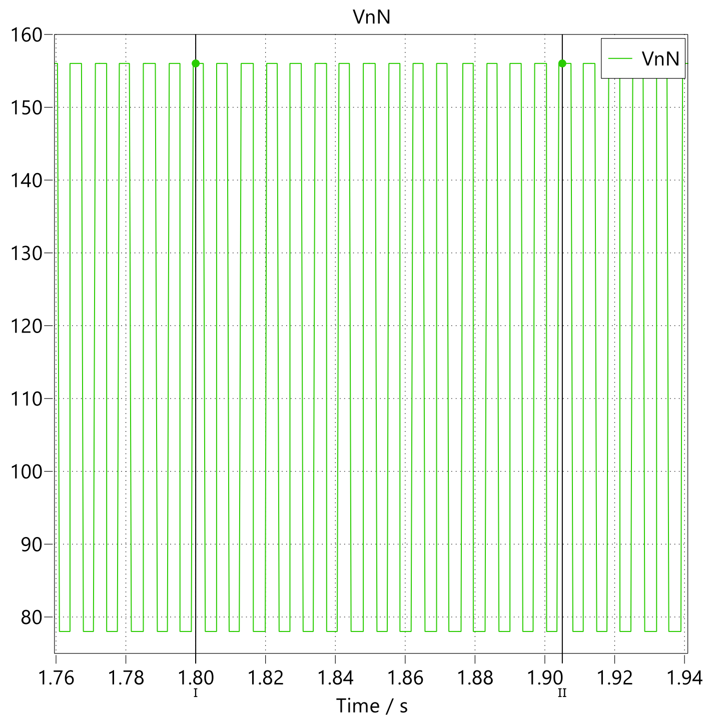
The average value is 22.0366 A and the ripple value is 23.6315 A.

P7:

The mid-point of the DC input voltage is assumed as its reference point N.

Name		Cursor 1	Cursor 2	RMS
Time		1.8	1.905	
VnN				
VnN		156.02	156.02	123.345

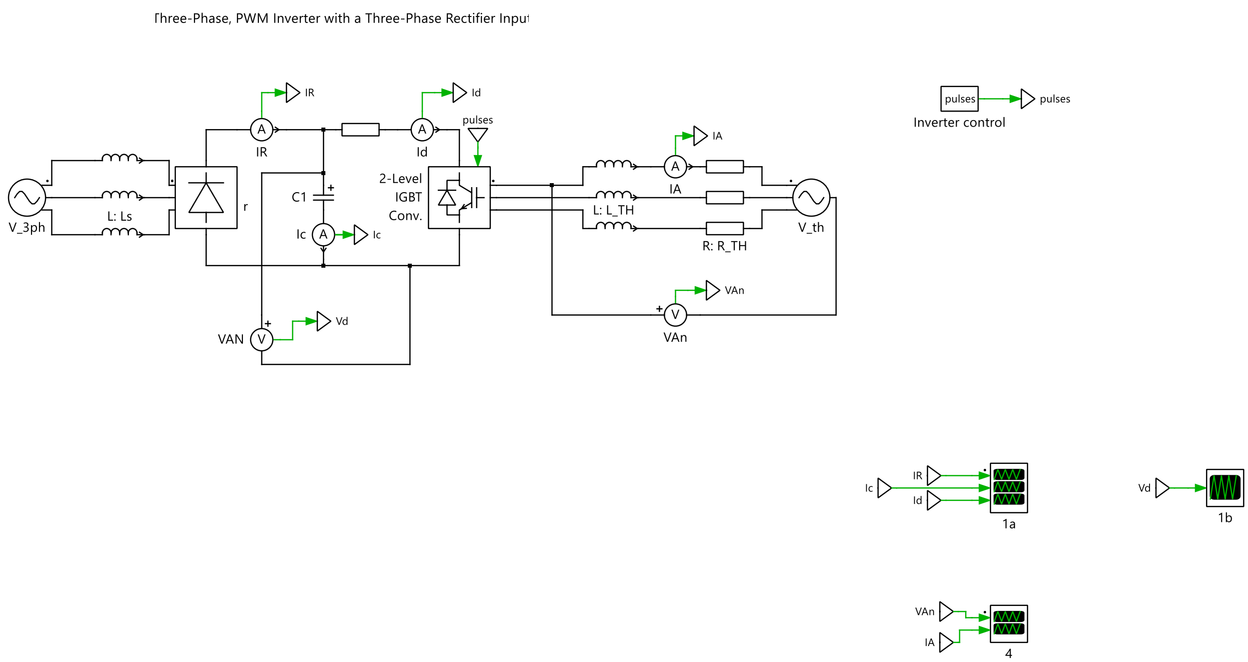
VnN is nothing but common mode voltage of the converter.



VnN
VnN
160
150
140
130
120
110
100
90
80
1.76
1.78
1.80
I
1.82
1.84
1.86
1.88
1.90
II
1.92
1.94
Time / s

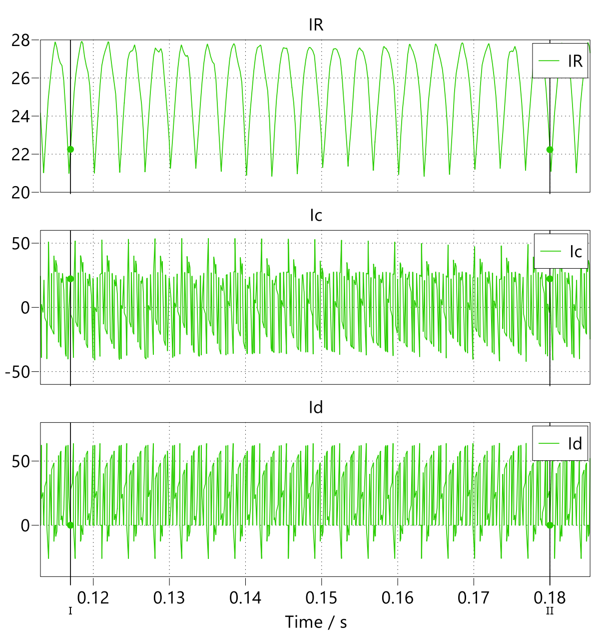
Exercise 5: Three-Phase, PWM Inverter with a Three-Phase Rectifier Input (PWMInv3_Rect.plecs)

Simulation Model:

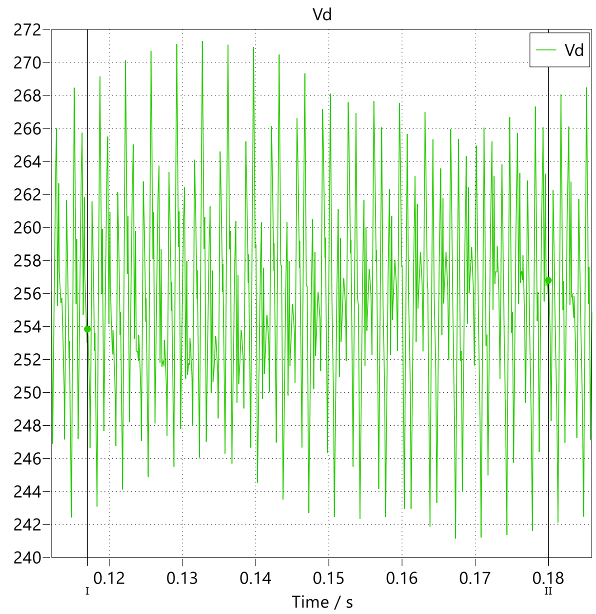


Waveforms:

P1:



Name	Cursor 1	Cursor 2	Mean	RMS
Time	0.117	0.18		
IR				
IR	22.2537	22.2377	25.5058	25.582
Ic				
Ic	22.2537	22.2377	0.0234613	23.5983
Id				
Id	0	0	25.4823	34.6055

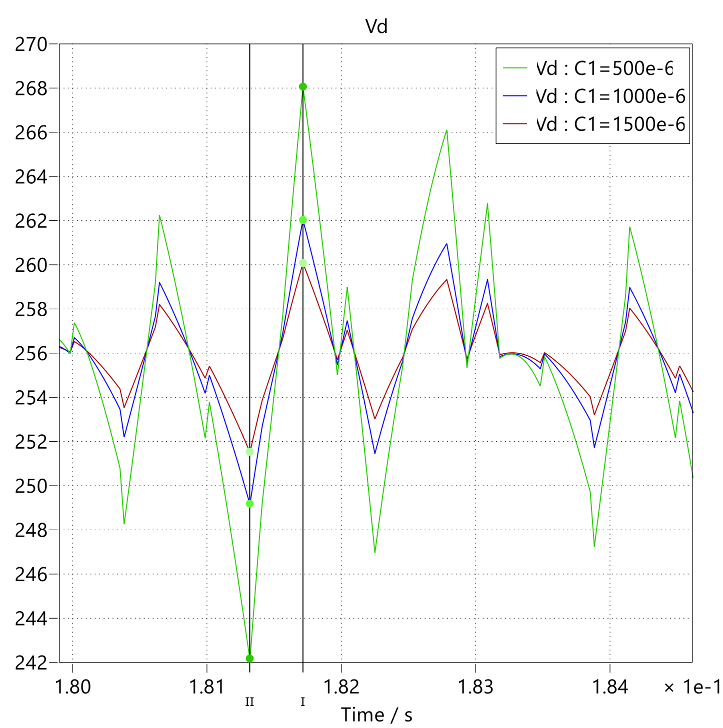


Name	Cursor 1	Cursor 2	Mean	RMS
Time	0.117	0.18		
Vd				
Vd	253.835	256.792	255.853	255.909

P2:

From the above figures, the RMS values of currents (i_R, i_c & i_d)are 25.582 A, 23.5983 A, and 34.6055 A respectively.

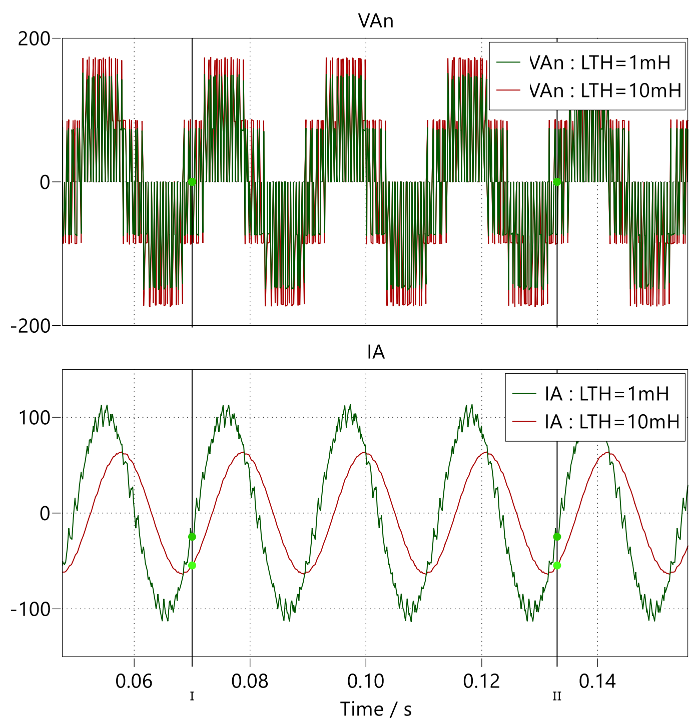
P3:



Name	Cursor 1	Cursor 2	Delta	Mean	RMS
Time	0.18132	0.181715	0.000394573		
Vd					
Vd	242.109	268.064	25.9548	255.29	255.392
	249.157	262.033	12.8764	255.698	255.723
	251.516	260.077	8.5615	255.865	255.877

The RMS and Average values of DC-link voltage are same for all capacitance values but the peak-peak voltage is inversely proportional to the capacitance value.

P4:

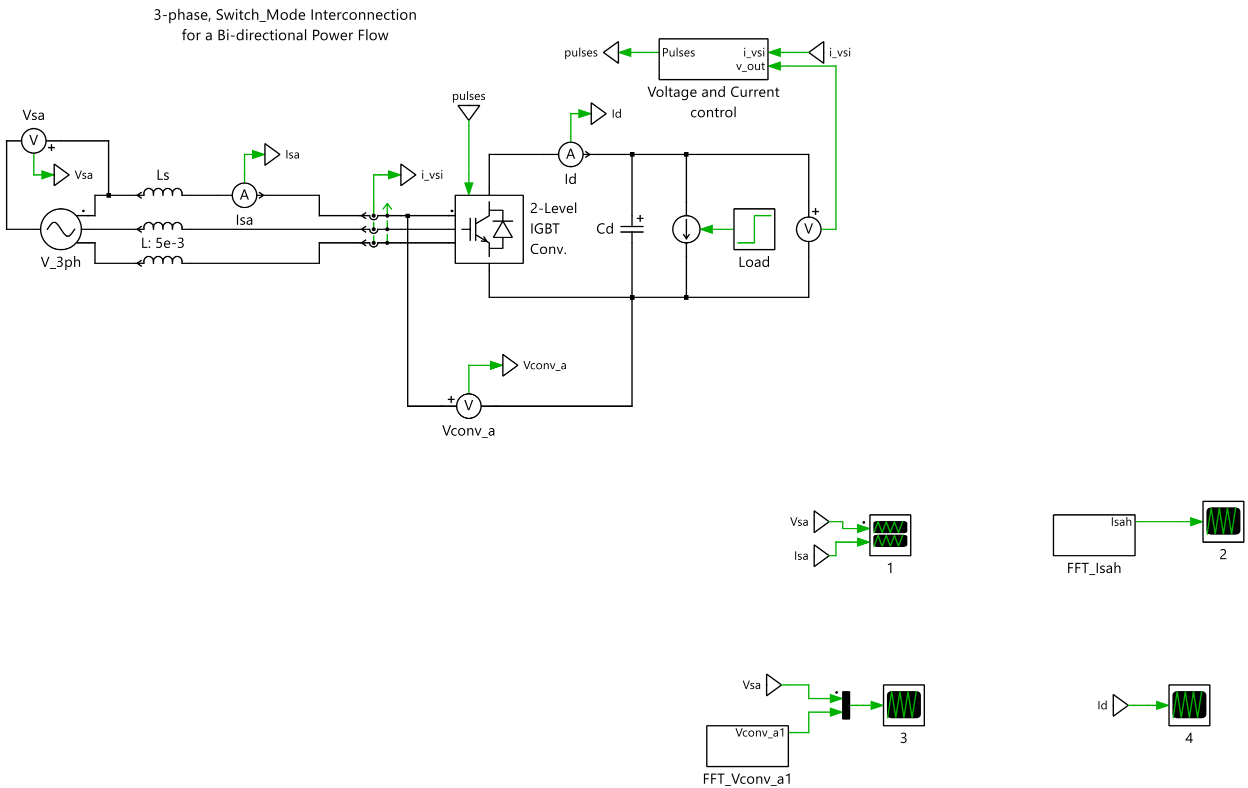


Name	Cursor 1	Cursor 2	Mean	RMS
Time	0.07	0.133		
VAn				
VAn	-7.10543e-15	7.10543e-15	0.00740513	91.7983
	-7.10543e-15	7.10543e-15	-0.017328	107.027
IA				
IA	-24.7867	-24.7572	0.00347102	73.6417
	-54.6829	-54.6964	-0.0075881	44.6689

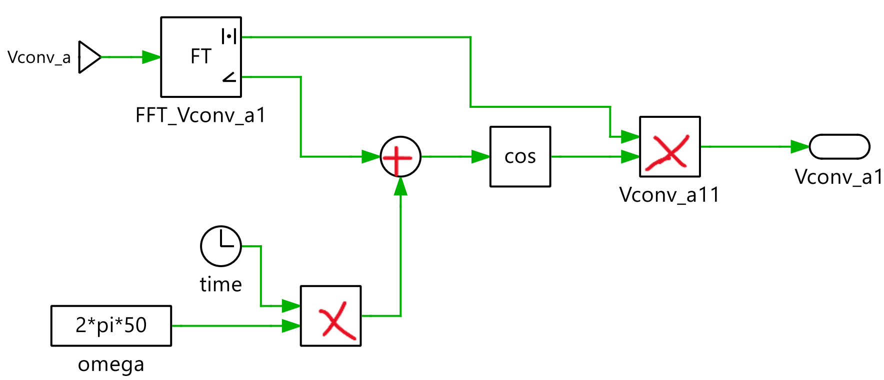
As the filter inductance increases, the current quality is improved.

Exercise 6: 3-Phase, Switch-Mode Interconnection for a Bi-directional-Power-Flow (3Ph_Conn.plecs)

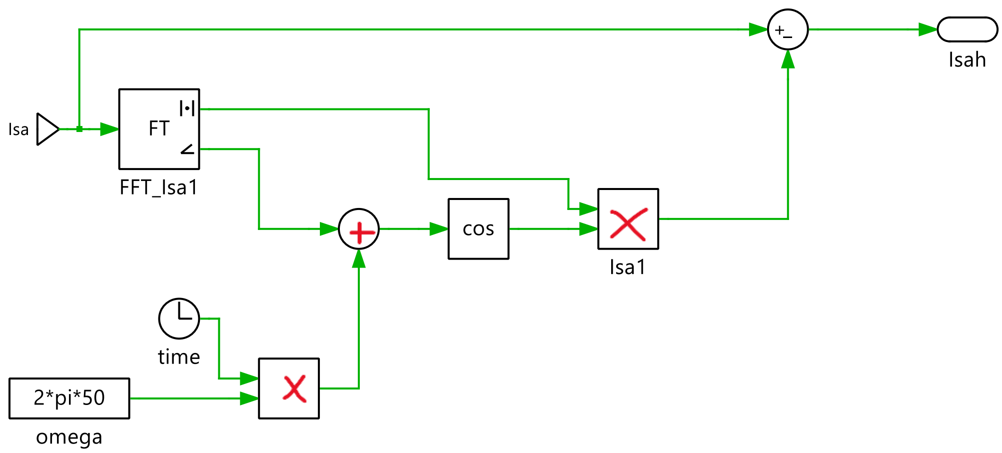
Simulation Model:



The subsystem of “FFT_Vconv_a1” is as below.

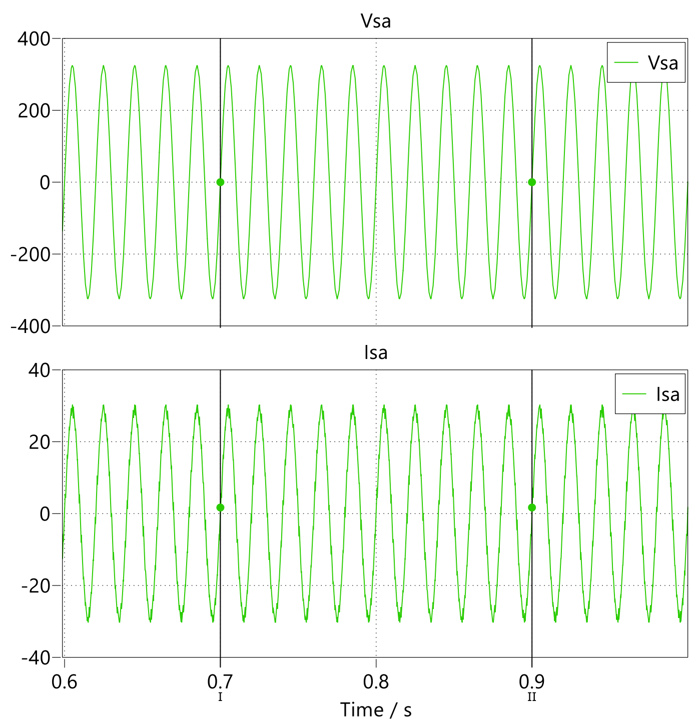


The subsystem of “FFT_Isah” is as below.



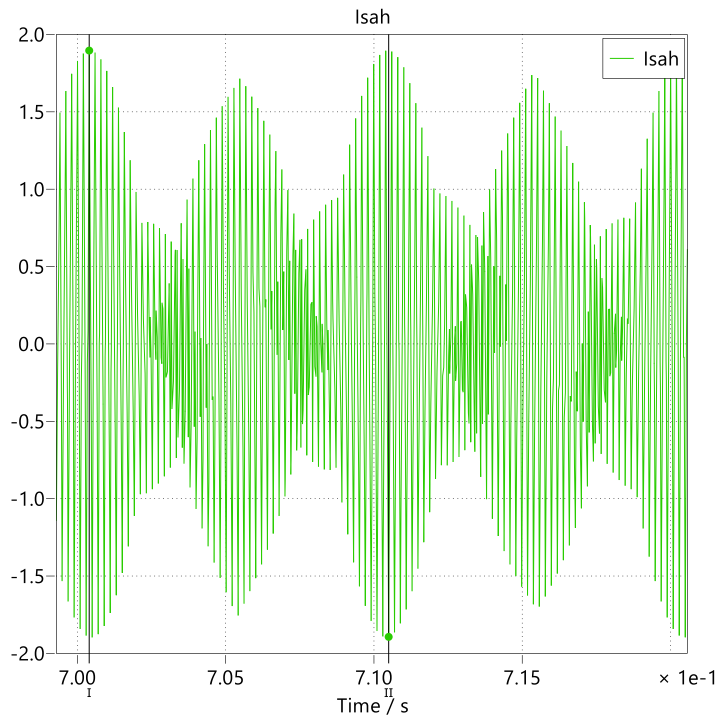
Waveforms:

P1:



Name	Cursor 1	Cursor 2	RMS
Time	0.7	0.9	
Vsa			
	-7.15872e-12	-1.27269e-12	229.785
Isa			
	1.69184	1.69184	20.3213

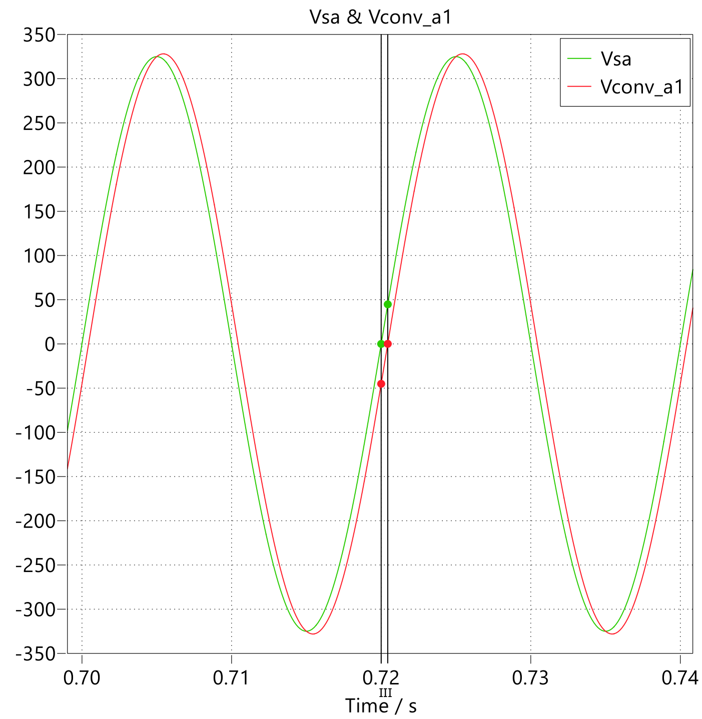
P2:



Name	Cursor 1	Cursor 2	Delta	RMS
Time	0.700398	0.710496	0.0100986	
Isah				
	1.89577	-1.89319	-3.78896	0.714661

So peak-peak ripple current is 3.78896 A.

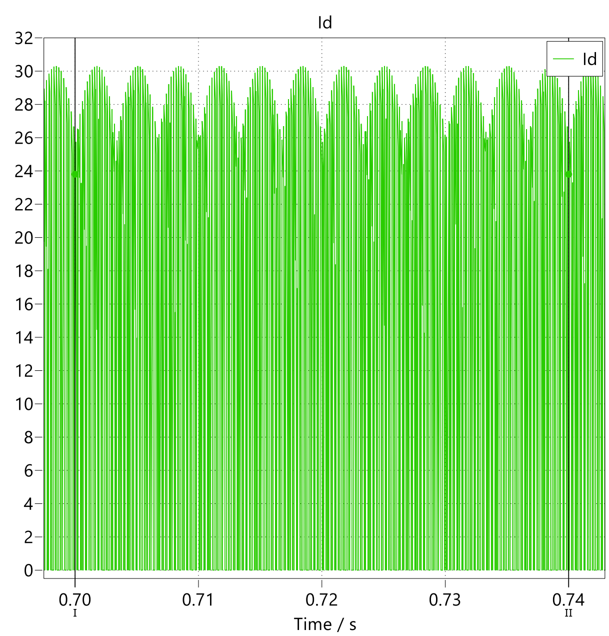
P3:



Name		Cursor 1	Cursor 2	Delta	RMS
Time		0.72	0.72044	0.000439977	
Vsa & Vconv_a1					
Vsa		-2.86537e-12	44.7748	44.7748	25.8837
Vconv_a1		-45.1161	0.089081	45.2052	26.0553

Vconv1 lags Vs by a time of 0.439977 ms and its equivalent angle in degrees is 7.919586.

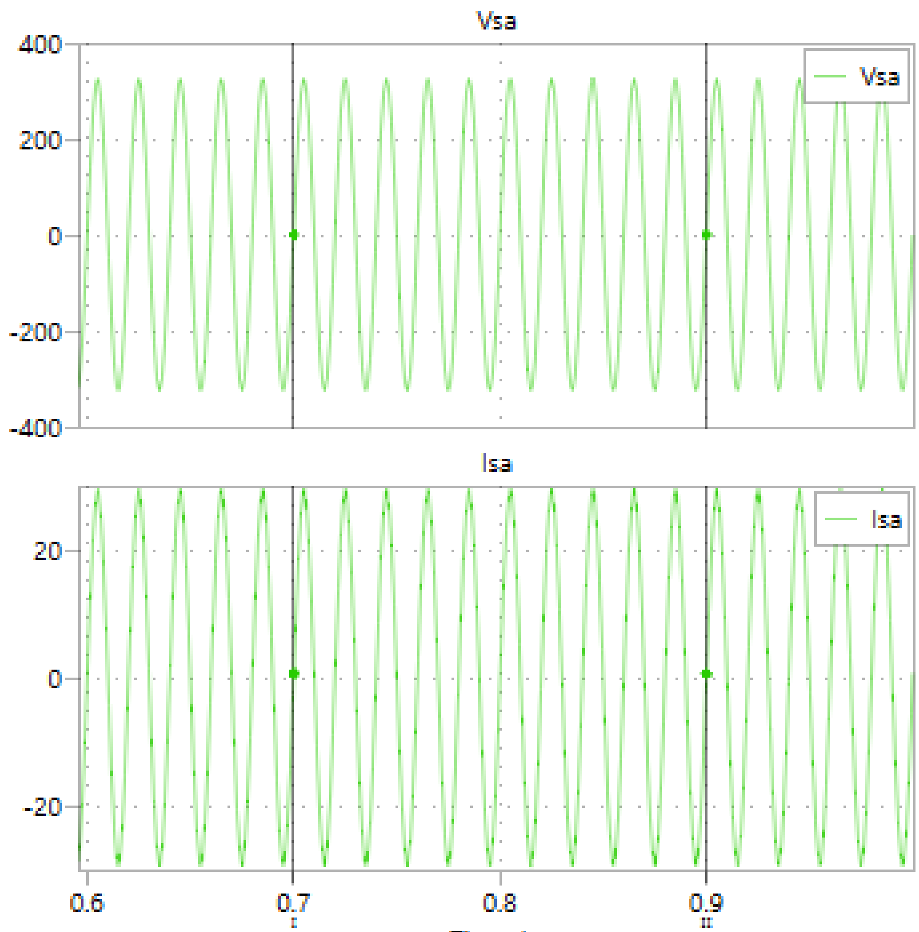
P4:



Name	Cursor 1	Cursor 2	Mean
Time	0.7	0.74	
Id			
	23.8011	23.8011	20

P5:

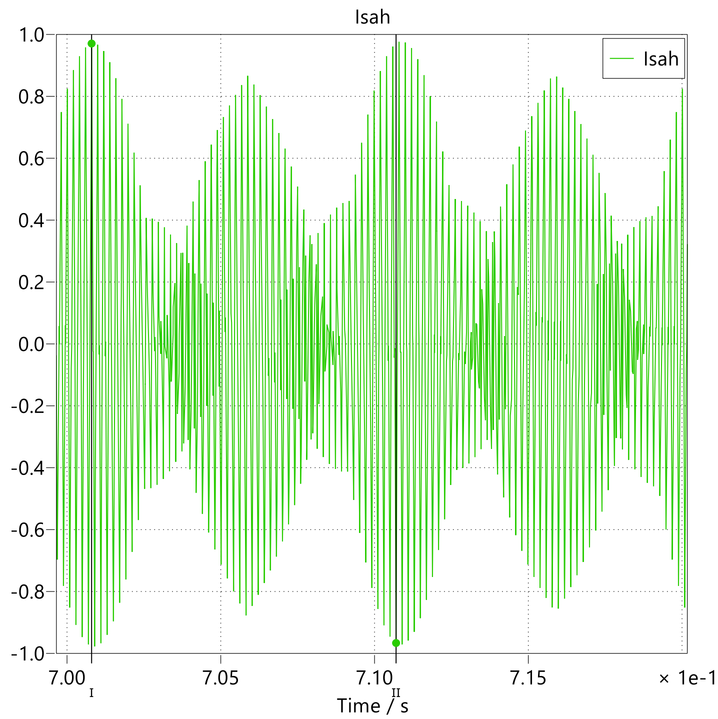
a.



Name	Cursor 1	Cursor 2	RMS
Time	0.7	0.9	
Vsa			
	-7.15872e-12	-1.27269e-12	229.785
Isa			
	0.660907	0.660907	20.3121

No change in fundamental RMS source current value with increase in filter inductance.

b.

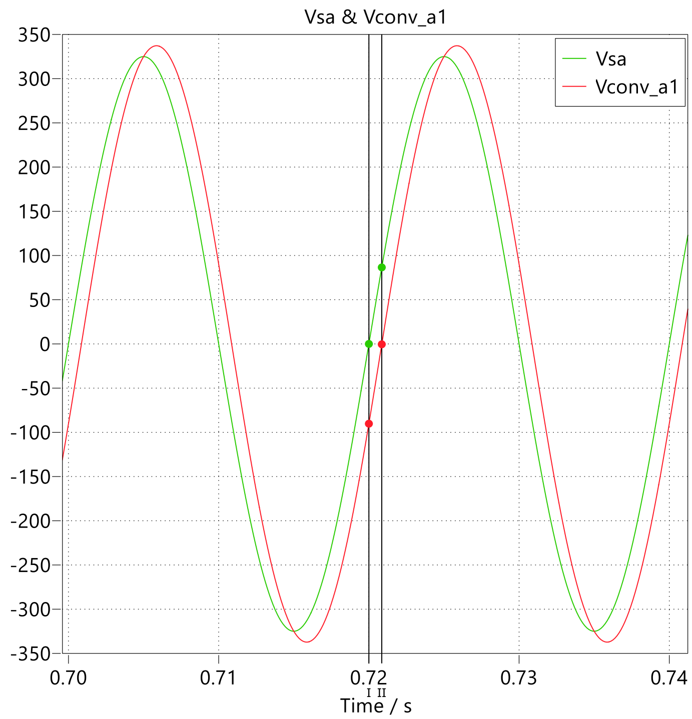


Name	Cursor 1	Cursor 2	Delta	RMS
Time	0.7008	0.710701	0.00990147	
Isah				
	0.970607	-0.966411	-1.93702	0.362793

The peak-peak ripple current is 1.93702 A which is almost half of the peakpeak ripple current with 5 mH filter inductance. The increased inductance helps in reducing the ripple in source currents.

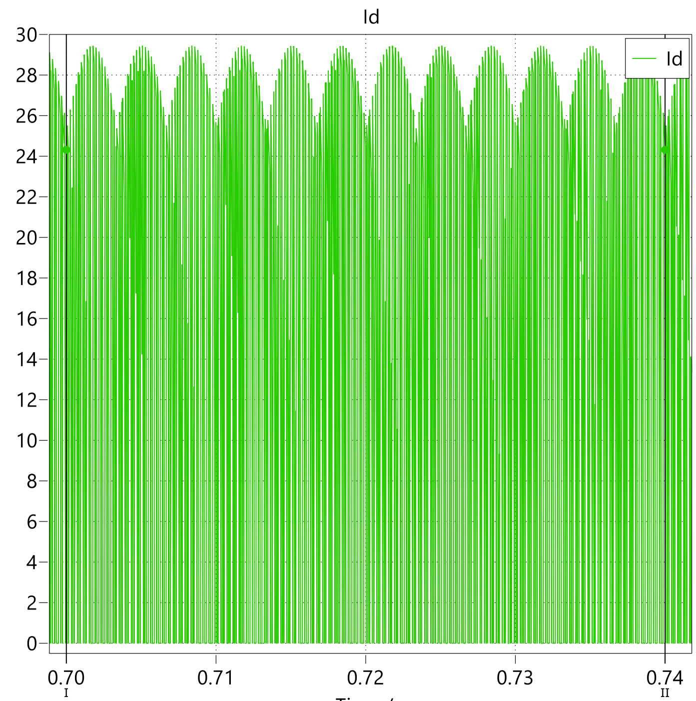
c.

Name	Cursor 1	Cursor 2	Delta	RMS
Time	0.72	0.720858	0.00085807	
Vsa & Vconv_a1				
Vsa	-2.86537e-12	86.544	86.544	50.2102
Vconv_a1	-90.2296	-0.426998	89.8026	52.4737



Vconv1 lags Vs by a time of 0.85807 ms and its equivalent angle in degrees is 14.44526 which is almost double that of with 5 mH filter inductance.

d.



Name	Cursor 1	Cursor 2	Mear
Time	0.7	0.74	
Id			
	24.3152	24.3152	20