Development Teams

Typhoon HIL

Grupo de Eletrônica
de Potência e Controle

Universidade Federal de Santa Maria

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Controllers for Grid-Tied Converters: A Test-Driven Design on Typhoon HIL

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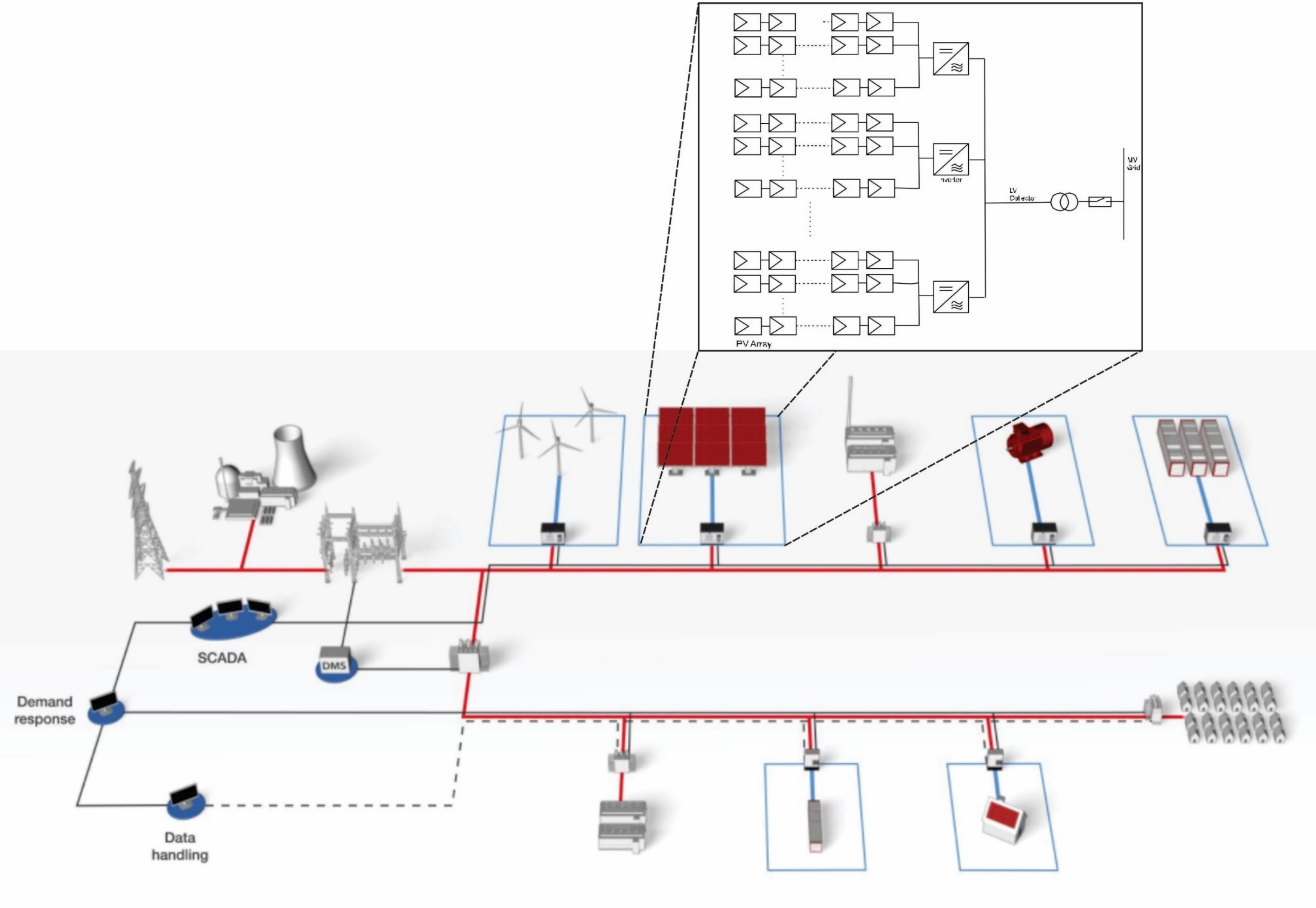
ntroduction to Grid Tied Inverter Design



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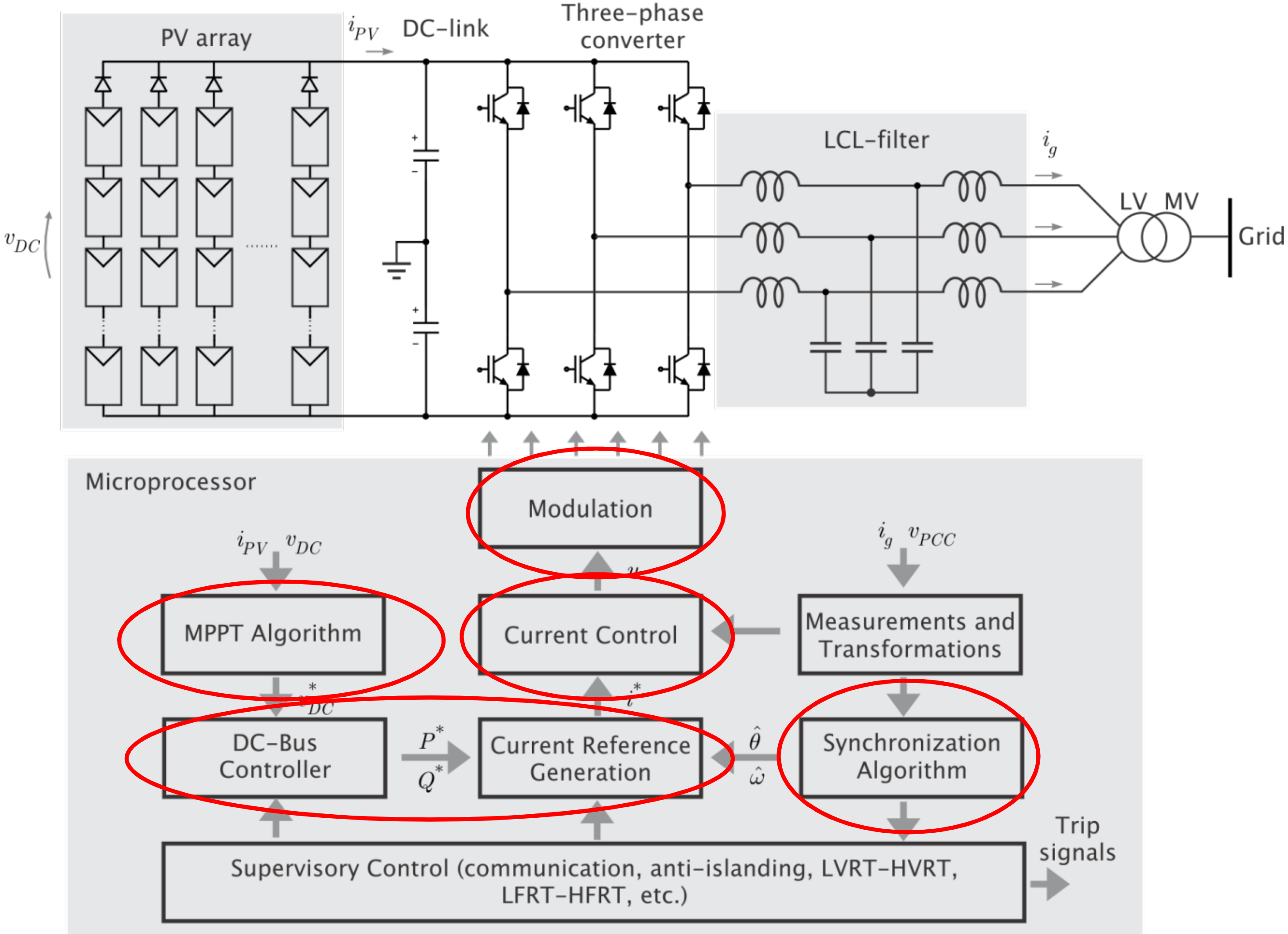

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MODULE 3

Modulation strategies for grid-tied inverters

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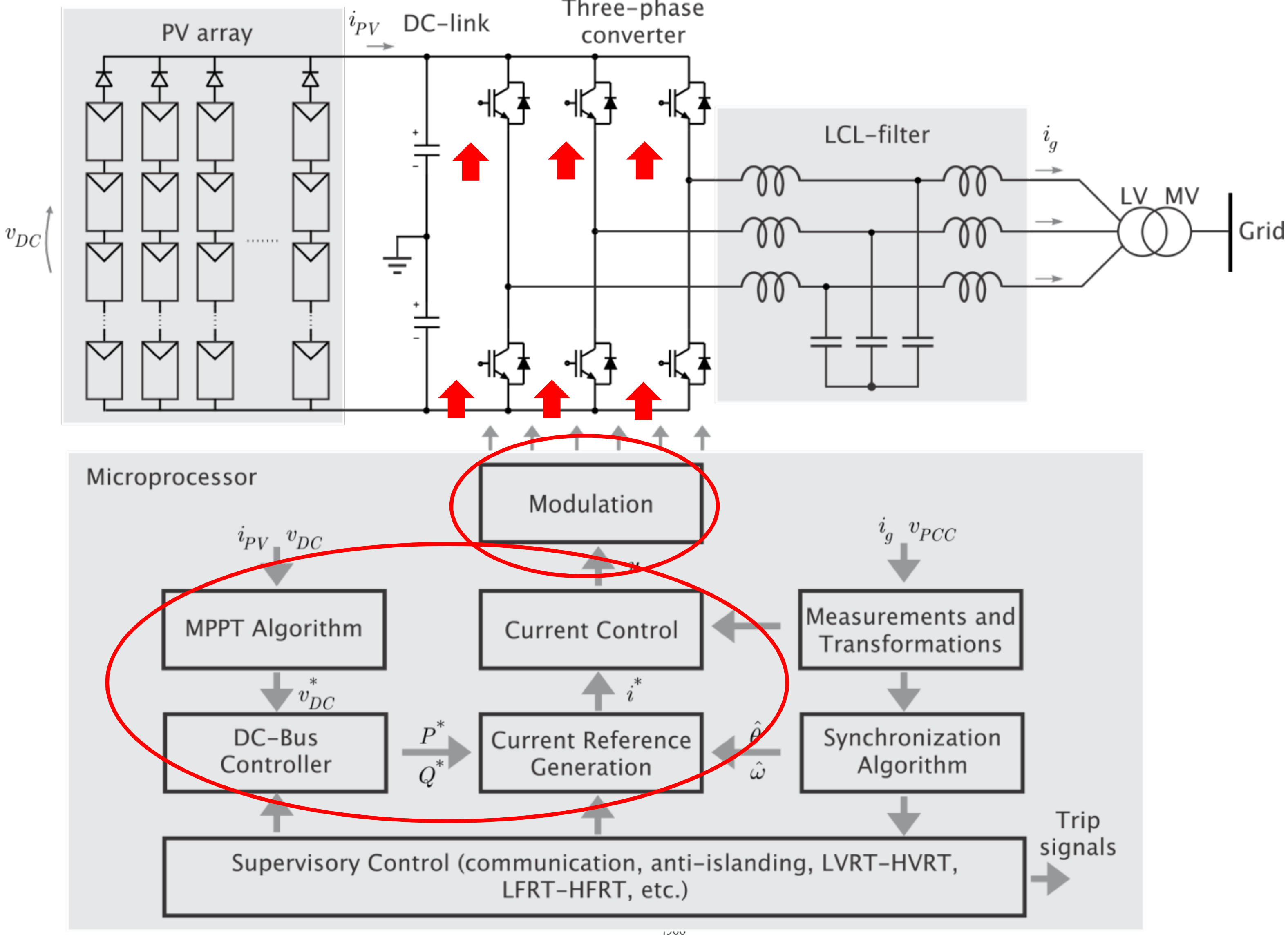
Introduction to Grid Tied Inverter Design

Modulation approaches for grid-tied inverters



Course Goals

By the end of this module you should be able to:

- ☐ Understand different modulation strategies;
- ☐ Apply these modulation strategies for two and three level grid-tied inverters;
- ☐ Design the inverter L or LCL output filter;
- ☐ Employ a test-driven approach to benchmark different modulation strategies and output filters

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Modulation approaches for grid-tied inverters

1. Three-Phase Inverter Topologies for PV Systems

Overview of PV Systems

- ☐ Microinverters or module integrated inverters

- ☐ String inverters or multi-string inverters;

- ☐ Centralized inverters;

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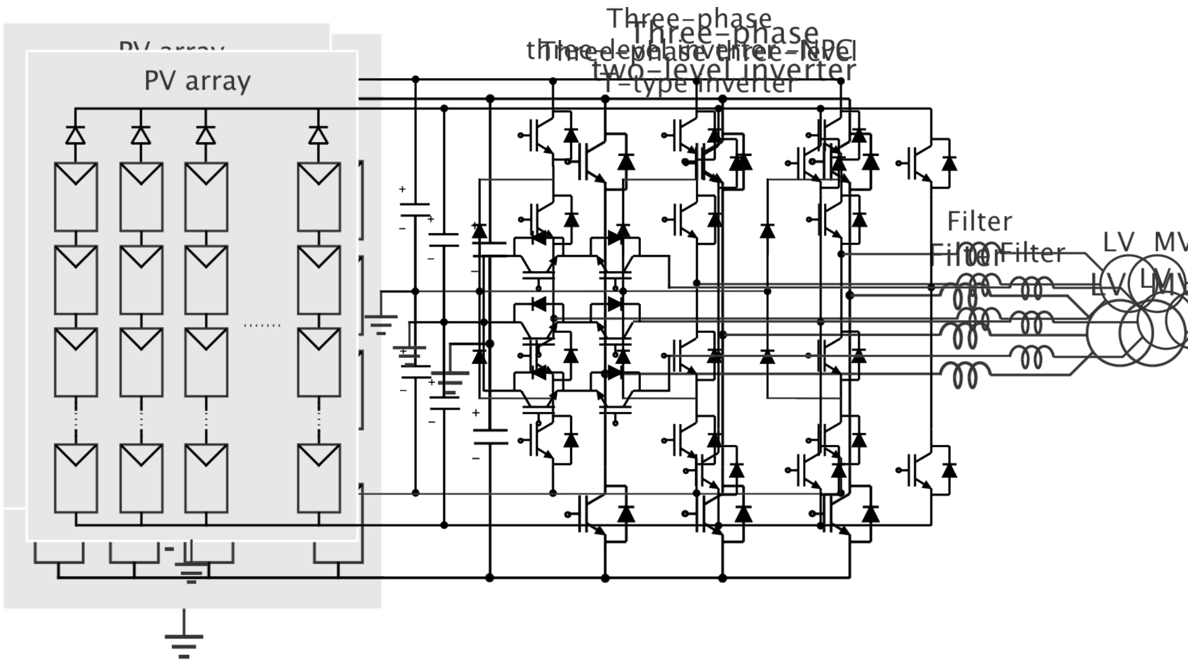
Three-Phase Inverter Topologies for PV Systems

- Two-level VSI;
- Neutral Point Clamped (NPC) inverter;
- T-Type inverter;
- Others (Cascaded H-Bridge Inverter - CHB , Multilevel Flying Capacitor Inverter, etc.)



Modulation approaches for voltage-source grid-tied inverters

- Sinusoidal PWM;
- Carrier-based Modulation with Commom-mode Voltage Injection;
- Space Vector Modulation - SVM;
- Selective Harmonic Elimination – SHE and Synchronous Optimal Pulsewidth Modulation;
- Nearest Voltage Level - NVL;
- Others;

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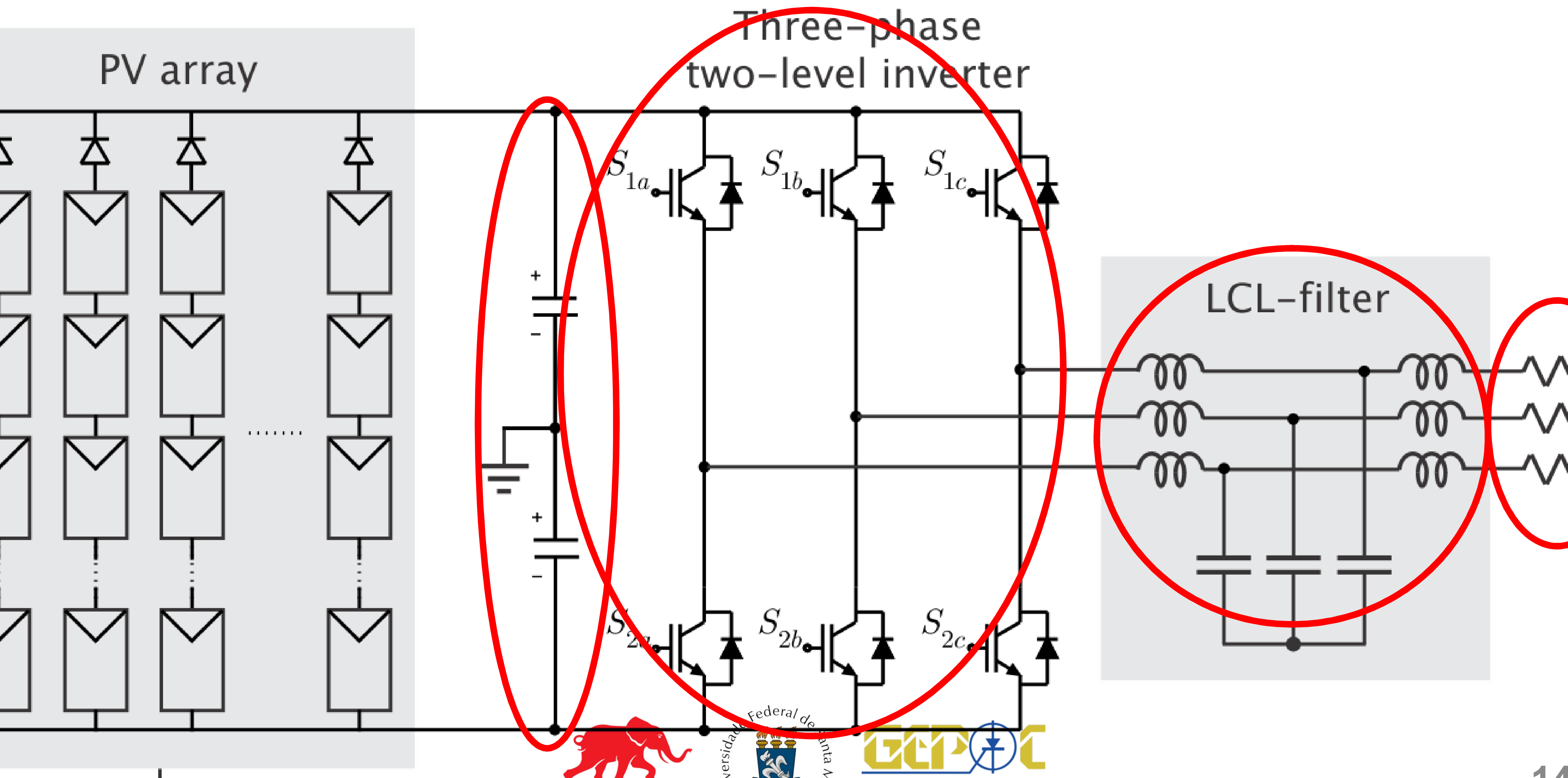
Modulation approaches for grid-tied inverters

2. Modulation Strategies and Filter Design for the Three-Phase Two-Level Inverter

Modulation approaches for two-level inverters

- ☐ Carrier-Based Sinusoidal PWM;
- ☐ Carrier-based Modulation with Common-Mode Voltage Injection;
- ☐ Space Vector Modulation - SVM;

Modulation Strategies for Two-level inverter



Modulation approaches for grid-tied inverters

2.1. Carrier-Based Sinusoidal Modulation – Two-level inverter

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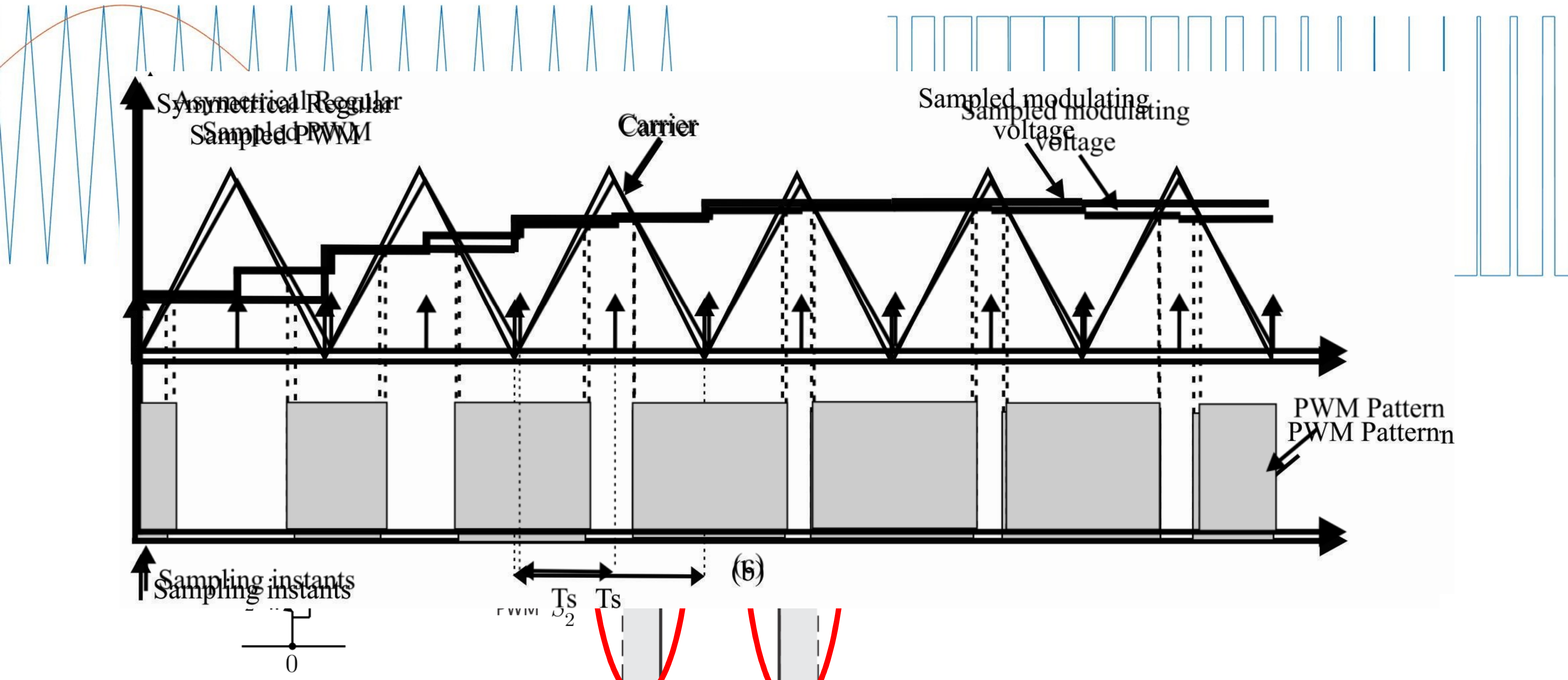
2.1 - Carrier-Based Sinusoidal Modulation – Two-level inverter



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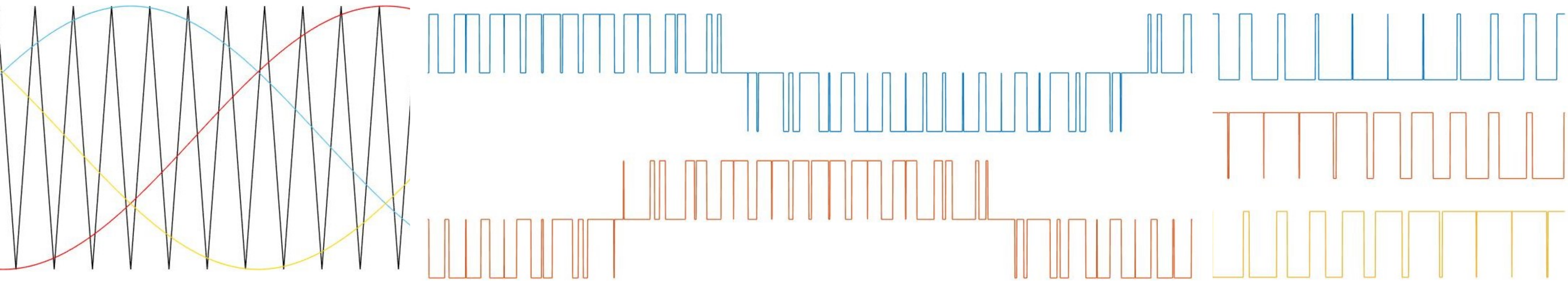
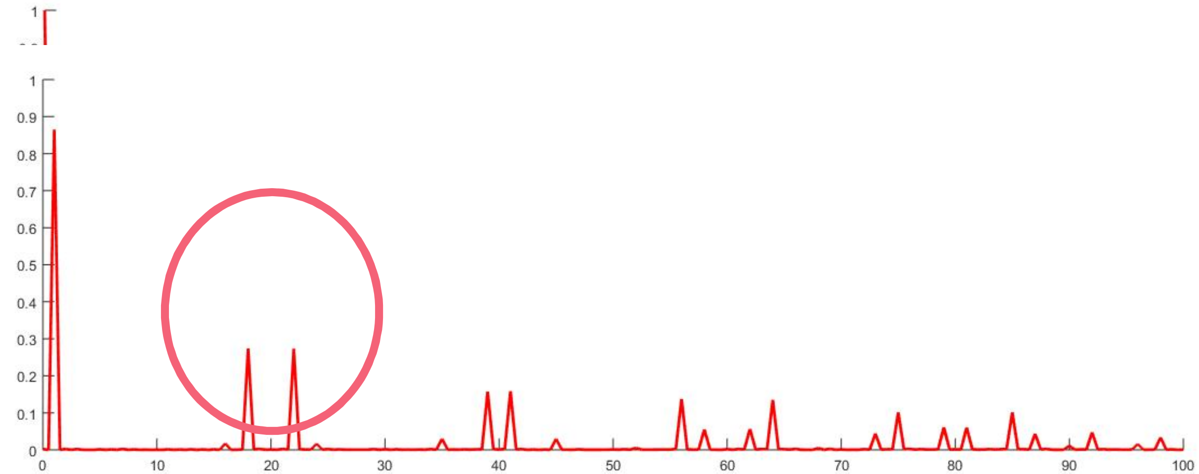
2.1 - Carrier-Based Sinusoidal Modulation – Two-level inverter



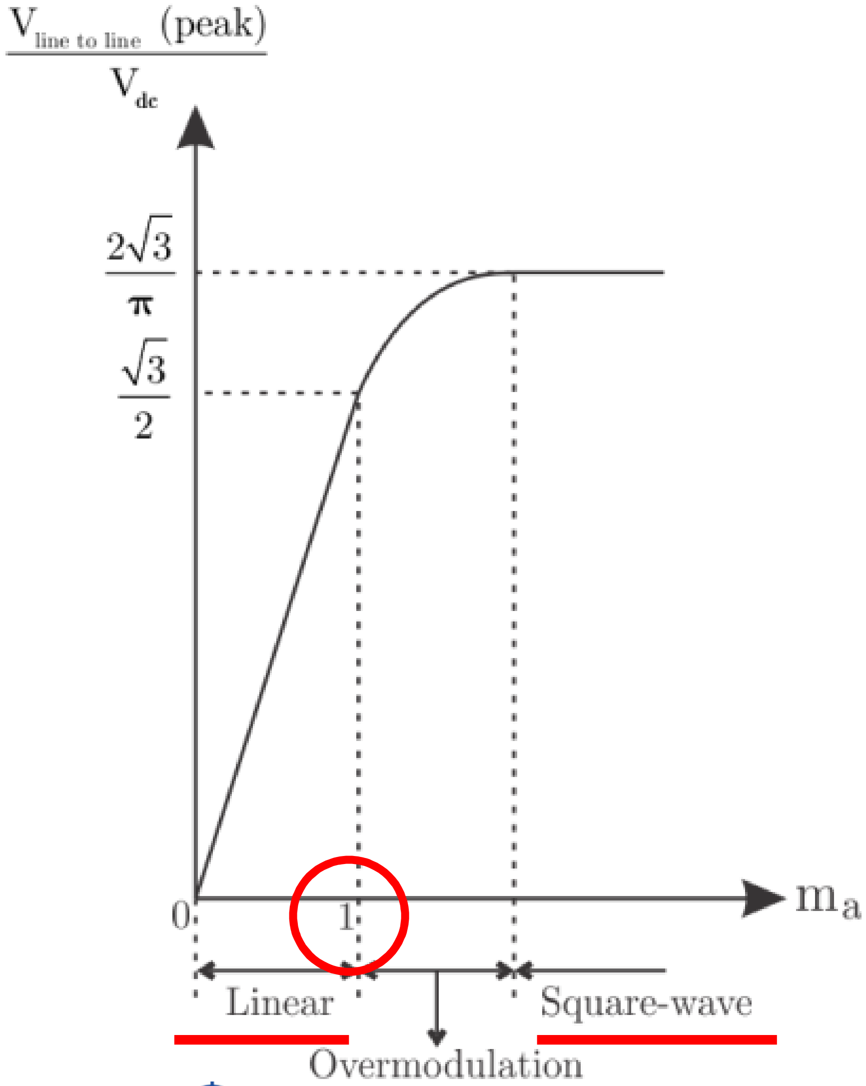
$$= \sqrt{3}\,\frac{V_{dc}}{2} = 0.866V_{dc}$$



2.1 - Carrier-Based Sinusoidal Modulation – Two-level inverter

$$m_a = \frac{V}{0.5TPER}$$

$$m_f = \frac{f_c}{f_1}$$



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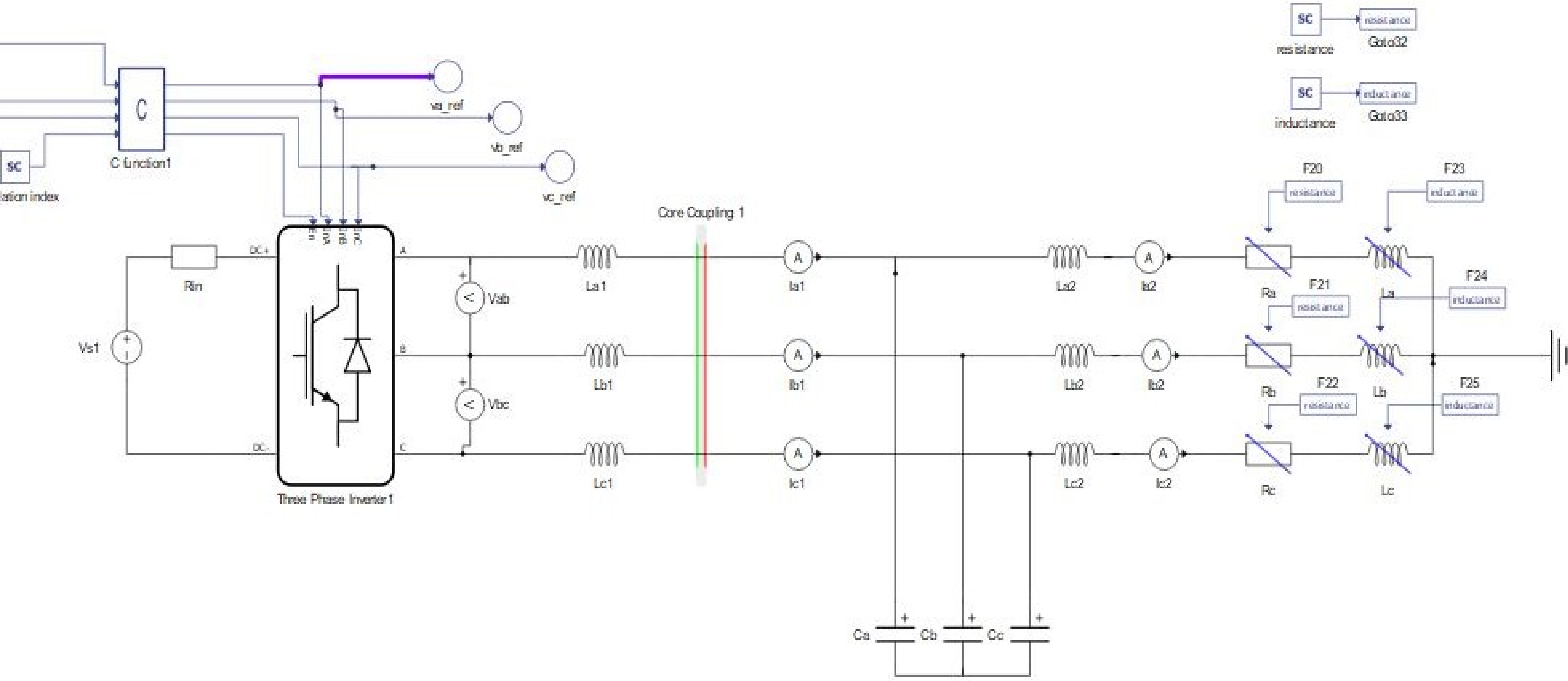
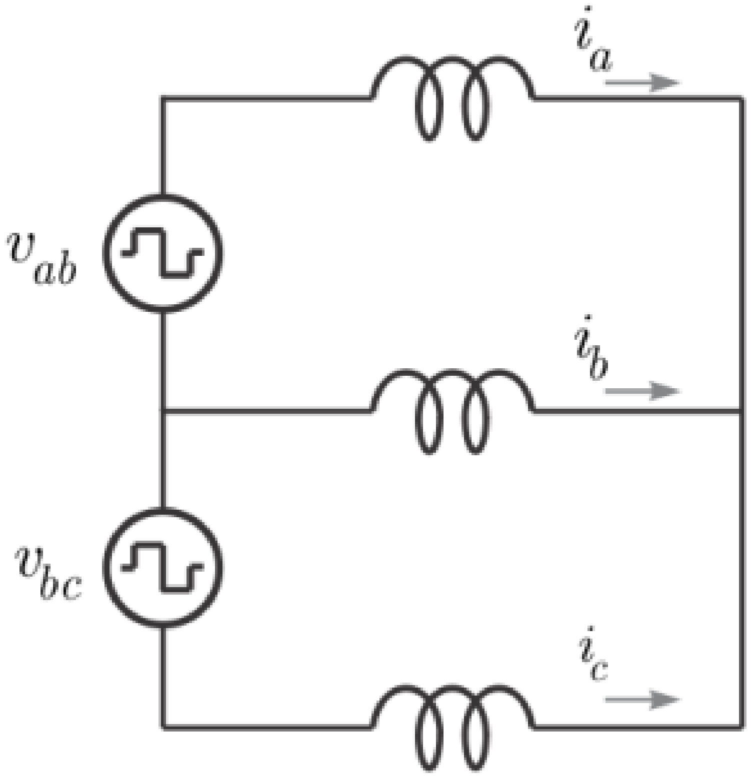

SC
resistance
Goto32
SC
inductance
Goto33
C
C function1
SC
va_ref
vb_ref
vc_ref
Core Coupling 1
F20
resistance
F23
inductance
F21
resistance
F24
inductance
F22
resistance
F25
inductance
DC+
DC-
A
B
C
Rin
Vs1
Vab
Vbc
Three Phase Inverter1
La1
Lb1
Lc1
Ia1
Ib1
Ic1
La2
Lb2
Lc2
Ia2
Ib2
Ic2
Ra
Rb
Rc
La
Lb
Lc
Ca
Cb
Cc

2.1 - Carrier-Based Sinusoidal Modulation – L Filter Design



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2.1 - Carrier-Based Sinusoidal Modulation – L Filter Design

$$\begin{bmatrix} i_a(s) \\ i_b(s) \\ i_c(s) \end{bmatrix} = \frac{1}{3sL}\begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix}\begin{bmatrix} v_{ab}(s) \\ v_{bc}(s) \end{bmatrix}$$

$$i_a(jw) = \frac{1}{3(jw)L}\left(2v_{ab}(jw) + v_{bc}(jw)\right)$$

$$L = \frac{1}{3w}h$$

$$h = \frac{\sqrt{\sum_h \left|2v_{ab}(jw) + v_{bc}(jw)\right|^2}}{aI_{rated}}$$

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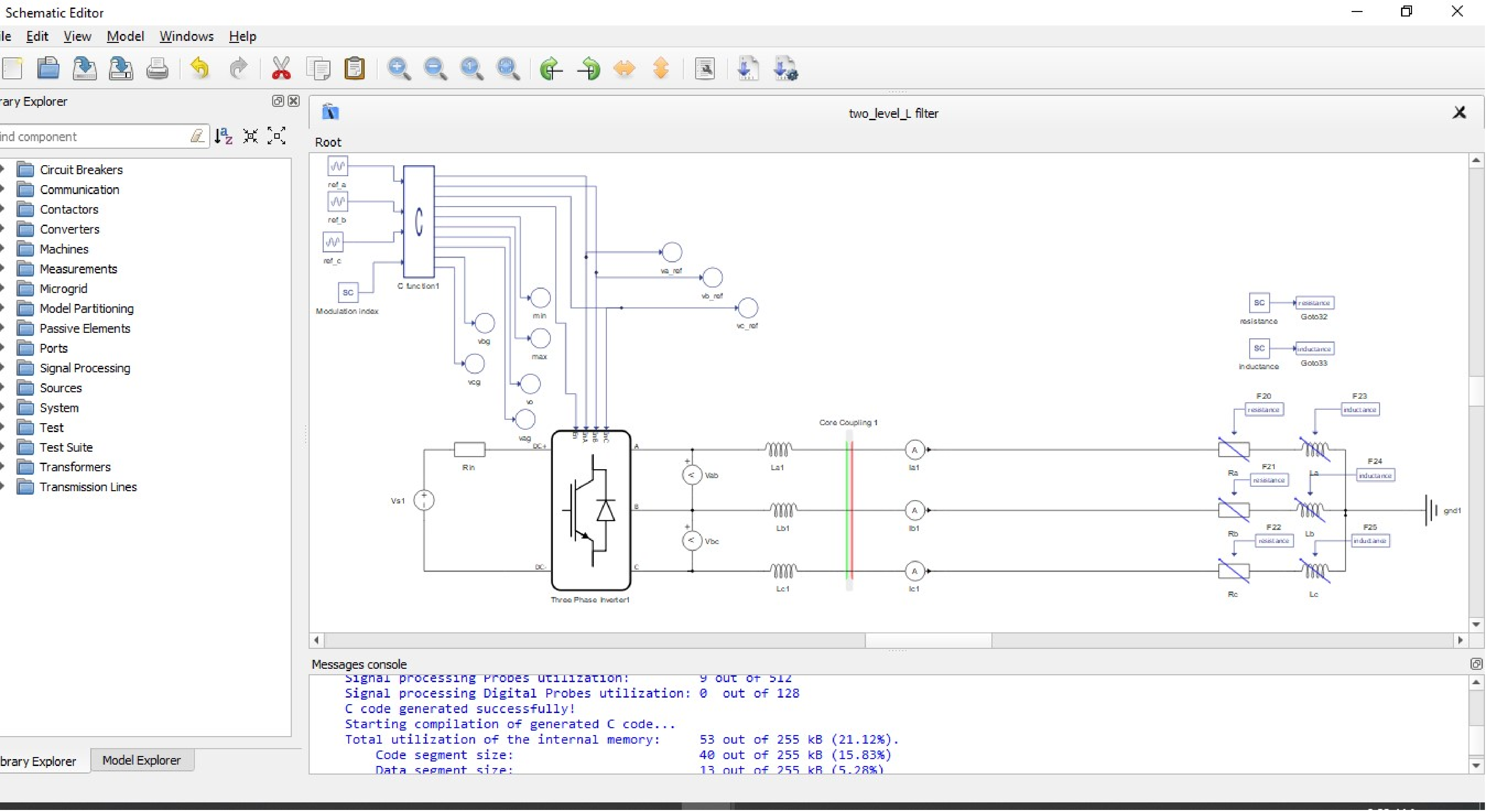

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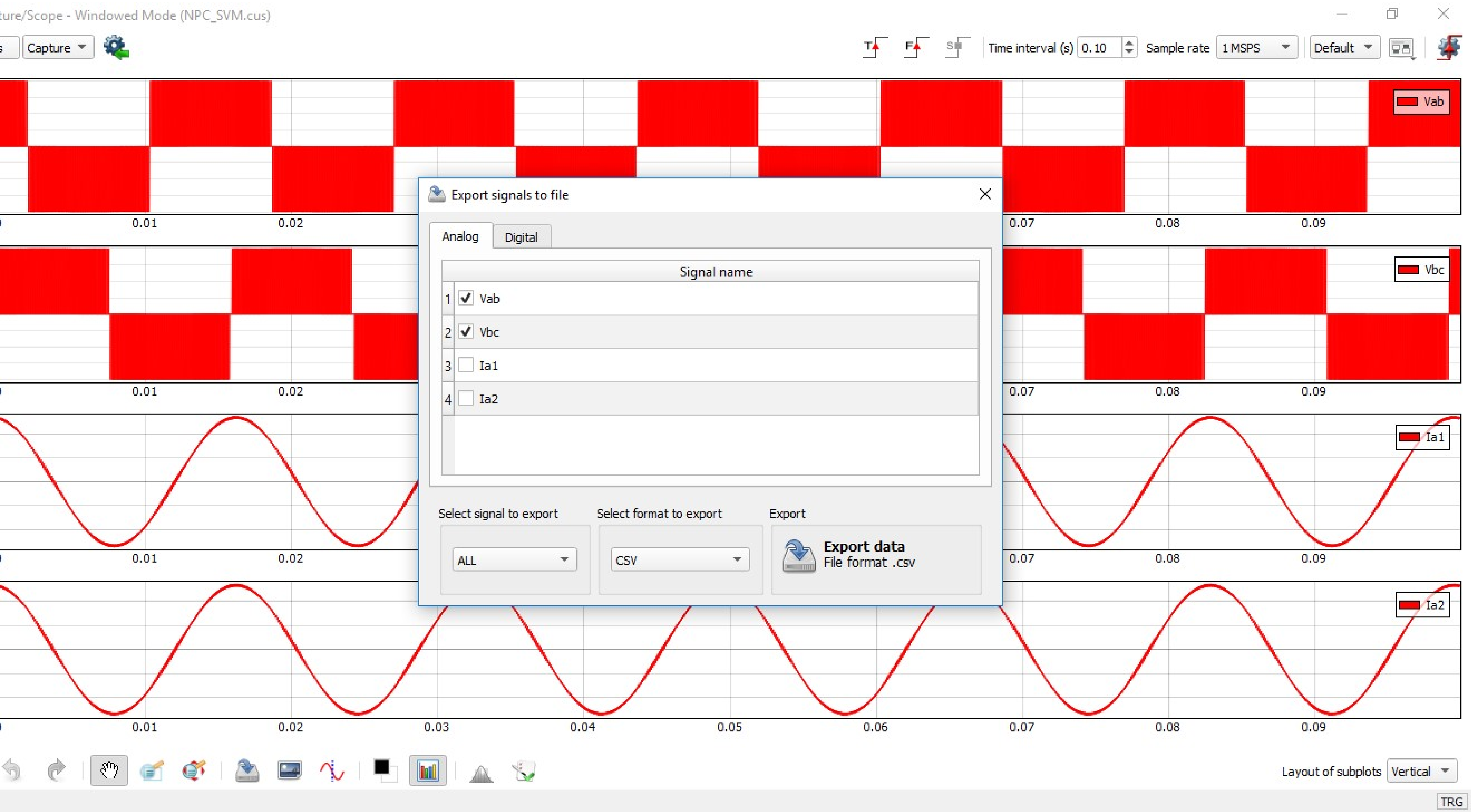

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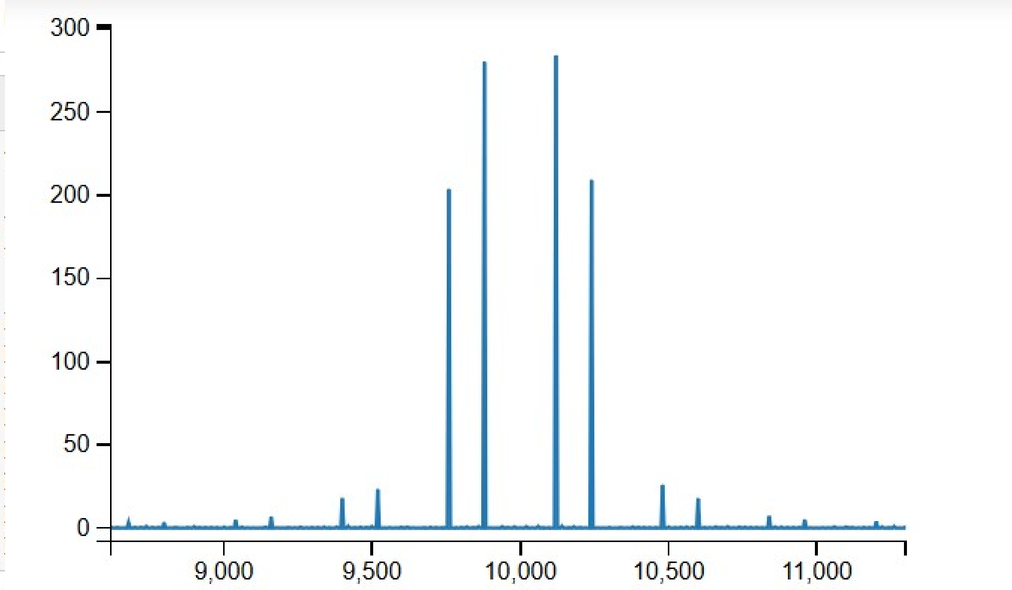
2.1 - Carrier-Based Sinusoidal Modulation – L Filter Design

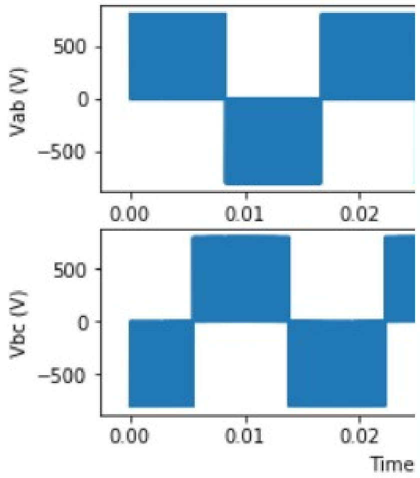
Step 1:

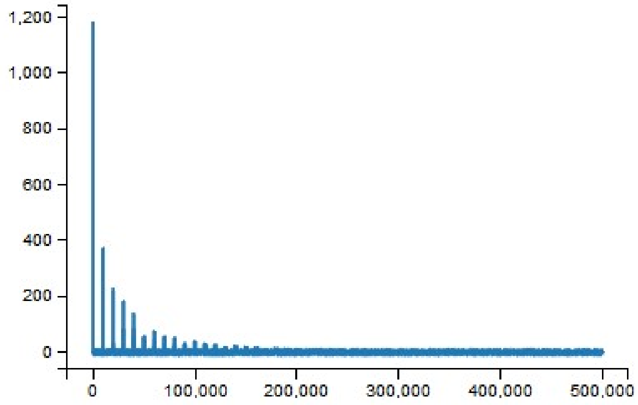


utput voltage ($2v_{ab} + v_{bc}$)

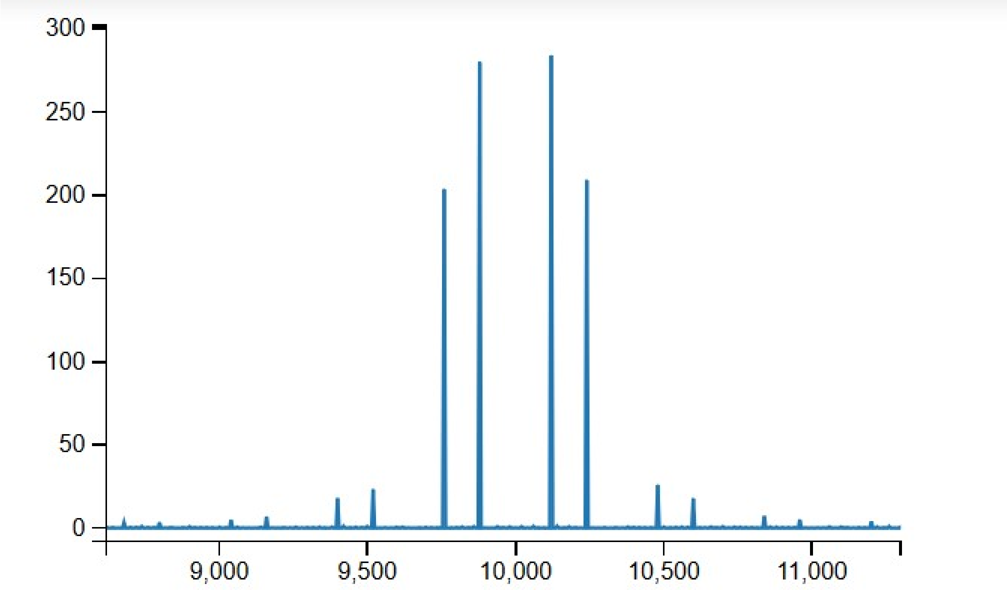
```
ge)
vab)/2)]/(n/2)
]
```

Out[4]: [<matplotlib.lines.Line2D at 0x1b540661358>]





2.1 - Carrier-Based Sinusoidal Modulation – L Filter Design



3]:

```
SumVh=np.sqrt(270*270*2+210*210*2+40*40*4)  # values obtained from the spectrum of 
omega=2*np.pi*fs
alpha=0.005   #
eta=SumVh/(alpha*Irated)
L=1/(3*omega)*eta
print(L)
```

2.1 - Carrier-Based Sinusoidal Modulation – L Filter Design

In [10]:

Slide Type Slide

```
print('Nominal power ',repr(round(P_rated/1000,2)), 'kW')
print('Nominal line-to-line voltage',repr(round(V_line,2)), 'V')
print('Nominal rms current',repr(round(Iref/np.sqrt(2),2)), 'A rms')
print('Grid nominal frequecy',repr(round(fo,2)), 'Hz')
print('Dc bus voltage',repr(round(Udc,2)), 'V')
print('Switching frequency,  fsw=',repr(round(fs/1000,2)), 'kHz')
print('Current first group of high order harmonic amplitude', repr(round(alpha*100,4)), '%')
print('L=', repr(round(L*1000,2)), 'mH')
print ('Inductance per phase ',repr(round(L/Lb,2)),'pu')
```

```
Nominal power  100.0 kW
Nominal line-to-line voltage 380 V
Nominal rms current 151.93 A rms
Grid nominal frequecy 60 Hz
Dc bus voltage 800 V
Switching frequency,  fsw= 10.0 kHz
Current first group of high order harmonic amplitude 1.0 %
L= 1.21 mH
Inductance per phase  0.32 pu
```

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2.1 - Carrier-Based Sinusoidal Modulation – LCL Filter Design

- The maximum total per phase inductance should be less than 0.1 pu

- The resonance frequency of the filter should be in a range between $10f_o$ and $0.5f_s$

- The filter capacitance should be limited to 10% of the base reactance

- The converter-side inductor is designed to limit the maximum current ripple

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2.1 - Carrier-Based Sinusoidal Modulation – LCL Filter Design

Step 1 :

$$L_1 \geq \frac{U_{dc}}{8 f_s (b I_{rated})}$$

In [6]: Slide Type Sub-Slide

```
# Step 1
ripple=30;
beta=ripple/100;
# Compute L1
L1 = Udc/(8*fs*beta*Irated) # select this line for two level converter
##L1 = Udc/(16*fs*beta*Irated) # select this line for three level converter
```

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2.1 - Carrier-Based Sinusoidal Modulation – LCL Filter Design

Step 2 :

$$C_f \leq 0.1C_b$$

In [18]: Slide Type Sub-Slide

```
# Step 2

Cf=Cb*0.1

print("L1=", repr(round(L1*1000,2)), 'mH')
print("Cf=", repr(round(Cf*1000000,2)), 'uF')
```

```
L1= 0.08 mH
Cf= 183.7 uF
```

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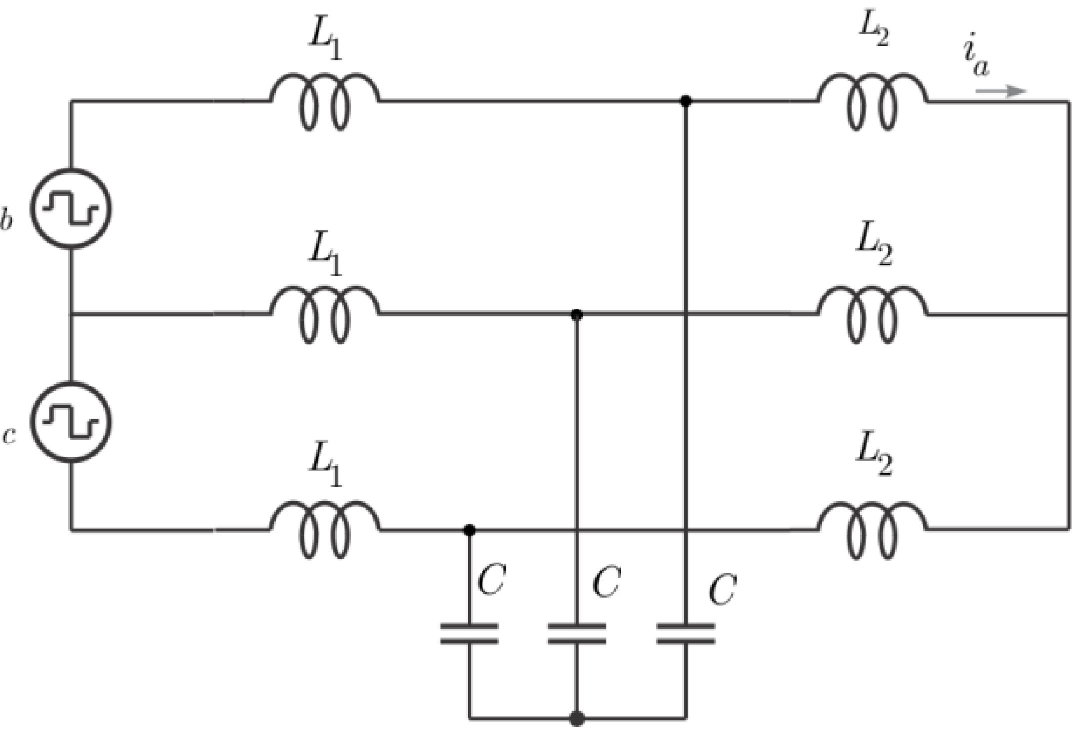
2.1 - Carrier-Based Sinusoidal Modulation – LCL Filter Design

Step 3 :



$$3C_f L_1 L_2 w_h \left(w_h^2 - \frac{L_1 + L_2}{C_f L_1 L_2} \right) = h\left(w_h, I_h\right)$$

$$h\left(w_h, I_h\right) = \frac{\left|2v_{ab}\left(jw_h\right) + v_{bc}\left(jw_h\right)\right|}{I_h}$$

$$I_h = \sqrt{2}\,\frac{0.09S_{SC}}{h}\,\frac{20000}{V_{line}}$$

2.1 - Carrier-Based Sinusoidal Modulation – LCL Filter Design

Step 3 :

$$L_2 = \max\left(\frac{h(w_h, I_h) + 3L_1 w_h}{3C_f L_1 w_h^3 - 3w_h}\right)$$

In [8]:

Slide Type Sub-Slide

```
N_cap= 12 ##  number of fundamental cycles captured from HIL Scada
h_from=N_cap*40
h_to=N_cap*470
omega=2*np.pi*freq[h_from:h_to]
I_h=np.sqrt(2)*0.09*S_sc*20000/V_line/(omega/(2*np.pi*60))
Sum2VabVbch=np.abs(fft_x1[h_from:h_to])
eta=Sum2VabVbch/I_h
L2_h=(eta+3*L1*omega)/(3*Cf*L1*omega*omega*omega-3*omega)
plt.plot(omega/2/np.pi,L2_h*1000)
plt.title(' L2 inductance (mH) versus Harmonic Order')
L2=np.max(L2_h)
print ( 'Frequency range considered for the L2 design')
print ('f_min=',repr(round(np.min(omega/2/np.pi)/1000,2)),'kHz','        f_max=',repr(round(np.max(omega/2/np.pi)/1000,2)),'kH
print('L2=',repr(round(L2*1000,2)),'mH')
```

```
Frequency range considered for the L2 design
f_min= 2.4 kHz          f_max= 28.2 kHz
L2= 0.34 mH
```

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Carrier-Based Sinusoidal Modulation – LCL Filter Design

In [9]: Slide Type Sub-Slide

```python
print('Nominal Power ',repr(round(P_rated/1000,2)), 'kW')
print('Nominal Voltage',repr(round(V_line,2)), 'V')
print('Grid nominal frequecy',repr(round(fo,2)), 'Hz')
print('Dc bus voltage',repr(round(Udc,2)), 'V')
print('Switching frequency,  fsw=',repr(round(fs/1000,2)), 'kHz')
print('Inverter current ripple   ', repr(round(beta*100,4)), '%')
print('L1=', repr(round(L1*1000,2)), 'mH')
print('Cf=', repr(round(Cf*1000000,2)),'uF')
print('L2=', repr(round(L2*1000,2)), 'mH')
print('LCL resonant frequency fr=',repr(round(np.sqrt((L2+L1)/(L1*L2*Cf))/2/np.pi/1000,2)), 'kHz')
print ('Total inductance per phase,',repr(round((L1+L2)/Lb,2)),'pu')
print ('Capacitance per phase, ',repr(round(Cf/Cb,2)),'pu')
```

```
Nominal Power  100.0 kW
Nominal Voltage 380 V
Grid nominal frequecy 60 Hz
Dc bus voltage 800 V
Switching frequency,  fsw= 10.0 kHz
Inverter current ripple    30.0 %
L1= 0.16 mH
Cf= 183.7 uF
L2= 0.34 mH
LCL resonant frequency fr= 1.14 kHz
Total inductance per phase, 0.13 pu
Capacitance per phase,  0.1 pu
```

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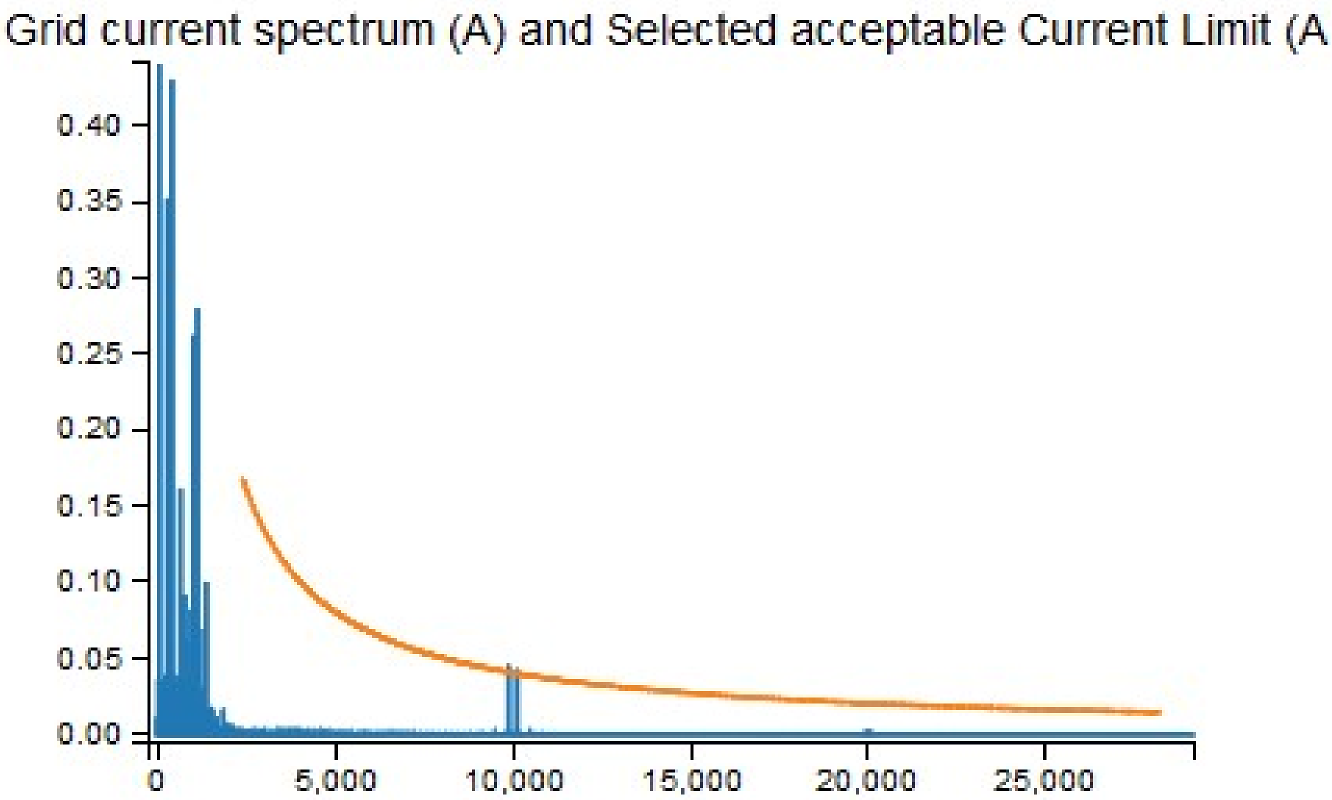
.1 - Carrier-Based Sinusoidal Modulation – LCL Filter Design

Design Validation

In [25]:

```
currents = pd.read_csv('HIL_190212_19111
iga=currents.loc[:, "Ia2"]
ia_inv=currents.loc[:, "Ia1"]


fft_iga = np.fft.fft(iga)
n = len(fft_iga)
fft_x2 = fft_iga[0:int(len(fft_iga)/2)]/
n3 = len(fft_x2)
freq = np.fft.fftfreq(n, 1/f_s)
freq1 = freq[0:int(len(freq)/2)]
mpld3.enable_notebook()
plt.plot(freq1,np.abs(fft_x2),omega/2/np.
plt.title('Grid current spectrum (A) and
```



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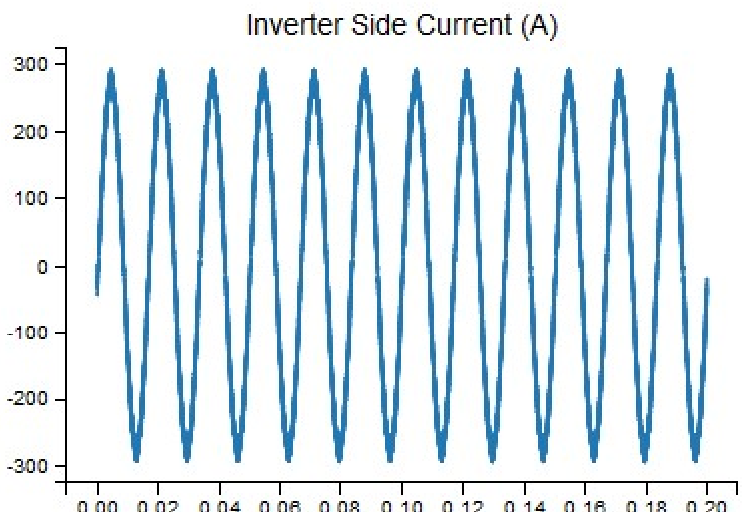
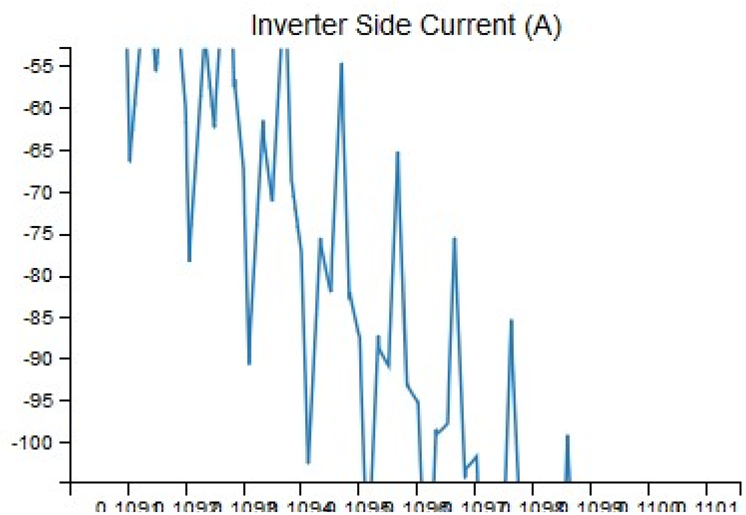
.1 - Carrier-Based Sinusoidal Modulation – LCL Filter Design

Design Validation





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```
beta_real=(-55-(-105))/Iref
print('beta measured =', repr(round(beta_real,3)), '     Designed beta =',beta)
```

```
beta measured = 0.233      Designed beta = 0.3
```

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Modulation approaches for grid-tied inverters

2.2. Carrier-Based Modulation with Common-Mode Injection

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2.2 - Carrier-based Modulation with Common-Mode Voltage Injection

$$v_{ag} = v_{an} + v_o$$
$$v_{bg} = v_{bn} + v_o$$
$$v_{cg} = v_{cn} + v_o$$

$$v_{ab} = v_{ag} - v_{bg}$$
$$v_{bc} = v_{bg} - v_{cg}$$
$$v_{ab} + v_{bc} + v_{ca} = 0$$

$$\begin{bmatrix} v_{ab} \\ v_{bc} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} v_{ag} \\ v_{bg} \\ v_{cg} \end{bmatrix}$$

$$\begin{bmatrix} v_{ab} \\ v_{bc} \\ v_o \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 1/3 & 1/3 & 1/3 \end{bmatrix} \begin{bmatrix} v_{ag} \\ v_{bg} \\ v_{cg} \end{bmatrix}$$

$$\begin{bmatrix} v_{ag} \\ v_{bg} \\ v_{cg} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & 3 \\ -1 & 1 & 3 \\ -1 & -2 & 3 \end{bmatrix} \begin{bmatrix} v_{ab} \\ v_{bc} \\ v_o \end{bmatrix}$$

$$v_{an} + v_{bn} + v_{cn} = 0$$

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2.2 - Carrier-based Modulation with Common-Mode Voltage Injection

$$0 \leq v_{ag} \leq V_{dc}$$
$$0 \leq v_{bg} \leq V_{dc}$$
$$0 \leq v_{cg} \leq V_{dc}$$

$$0 \leq \frac{2}{3}v_{ab} + \frac{1}{3}v_{bc} + v_0 \leq V_{dc}$$
$$0 \leq -\frac{1}{3}v_{ab} + \frac{1}{3}v_{bc} + v_0 \leq V_{dc}$$
$$0 \leq -\frac{1}{3}v_{ab} - \frac{2}{3}v_{bc} + v_0 \leq V_{dc}$$

$$\Longrightarrow$$

$$-\frac{2}{3}v_{ab} - \frac{1}{3}v_{bc} \leq v_0 \leq V_{dc} - \frac{2}{3}v_{ab} - \frac{1}{3}v_{bc}$$
$$\frac{1}{3}v_{ab} - \frac{1}{3}v_{bc} \leq v_0 \leq V_{dc} + \frac{1}{3}v_{ab} - \frac{1}{3}v_{bc}$$
$$\frac{1}{3}v_{ab} + \frac{2}{3}v_{bc} \leq v_0 \leq V_{dc} + \frac{1}{3}v_{ab} + \frac{2}{3}v_{bc}$$

2.2 - Carrier-based Modulation with Common-Mode Voltage Injection

$$c_1 = V_{dc} - \frac{2}{3}v_{ab} - \frac{1}{3}v_{bc}$$
$$c_2 = V_{dc} + \frac{1}{3}v_{ab} - \frac{1}{3}v_{bc}$$
$$c_3 = V_{dc} + \frac{1}{3}v_{ab} + \frac{2}{3}v_{bc}$$
$$c_4 = -\frac{2}{3}v_{ab} - \frac{1}{3}v_{bc}$$
$$c_5 = \frac{1}{3}v_{ab} - \frac{1}{3}v_{bc}$$
$$c_6 = \frac{1}{3}v_{ab} + \frac{2}{3}v_{bc}$$

$\min(c_1, c_2, c_3) \rightarrow$ upper limit of the linear region
$\max(c_4, c_5, c_6) \rightarrow$ lower limit of the linear region

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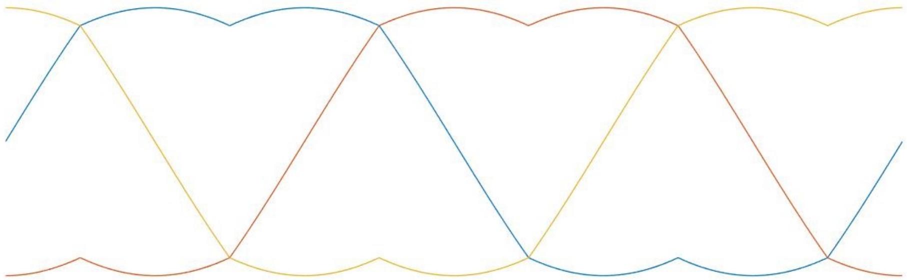
2.2 - Carrier-based Modulation with Common-Mode Voltage Injection

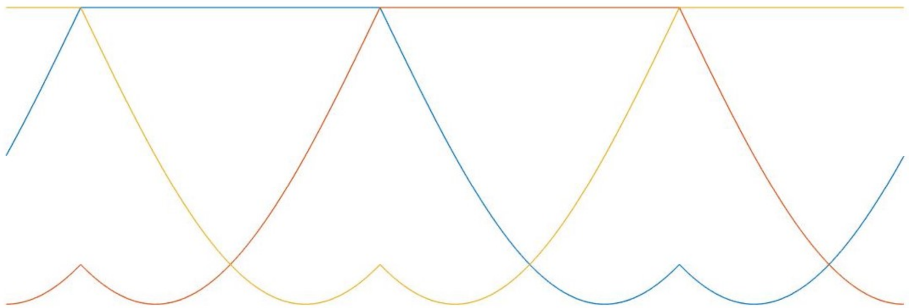
$$_g = v_{an} + v_o$$
$$_g = v_{bn} + v_o$$
$$_g = v_{cn} + v_o$$

$$v_o = \frac{\min(\,) + \max(\,)}{2}$$



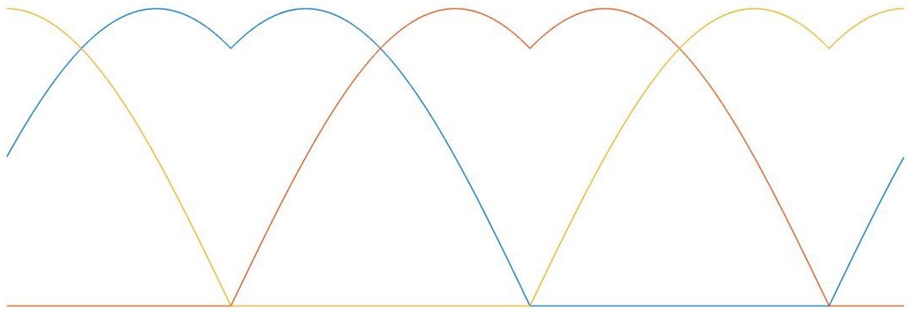
$$0 \leq v_{ag}^{*} \leq TPER$$
$$0 \leq v_{bg}^{*} \leq TPER$$
$$0 \leq v_{cg}^{*} \leq TPER$$

$$v_o = \max(\,)$$



$$v_{ag}^{*} = \frac{v_{ag}}{V_{dc}} TPER$$
$$v_{bg}^{*} = \frac{v_{bg}}{V_{dc}} TPER$$
$$v_{cg}^{*} = \frac{v_{cg}}{V_{dc}} TPER$$

$$v_o = \min(\,)$$



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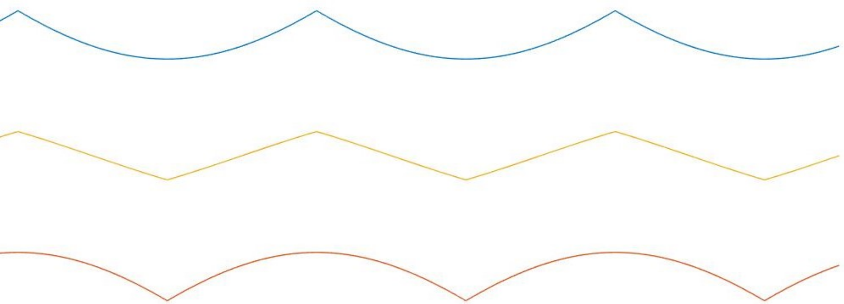
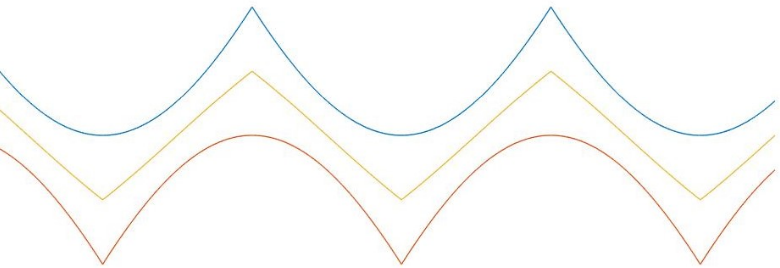
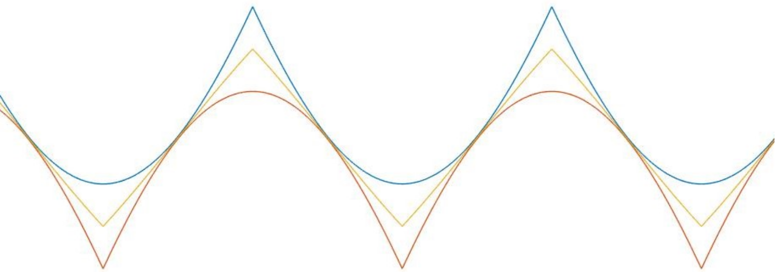
2.2 - Carrier-based Modulation with Common-Mode Voltage Injection



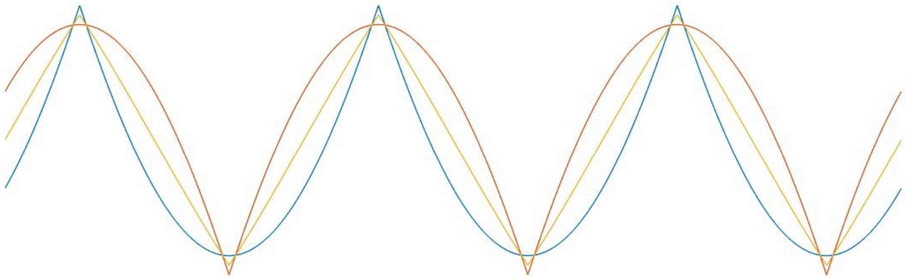
m_a =0.5



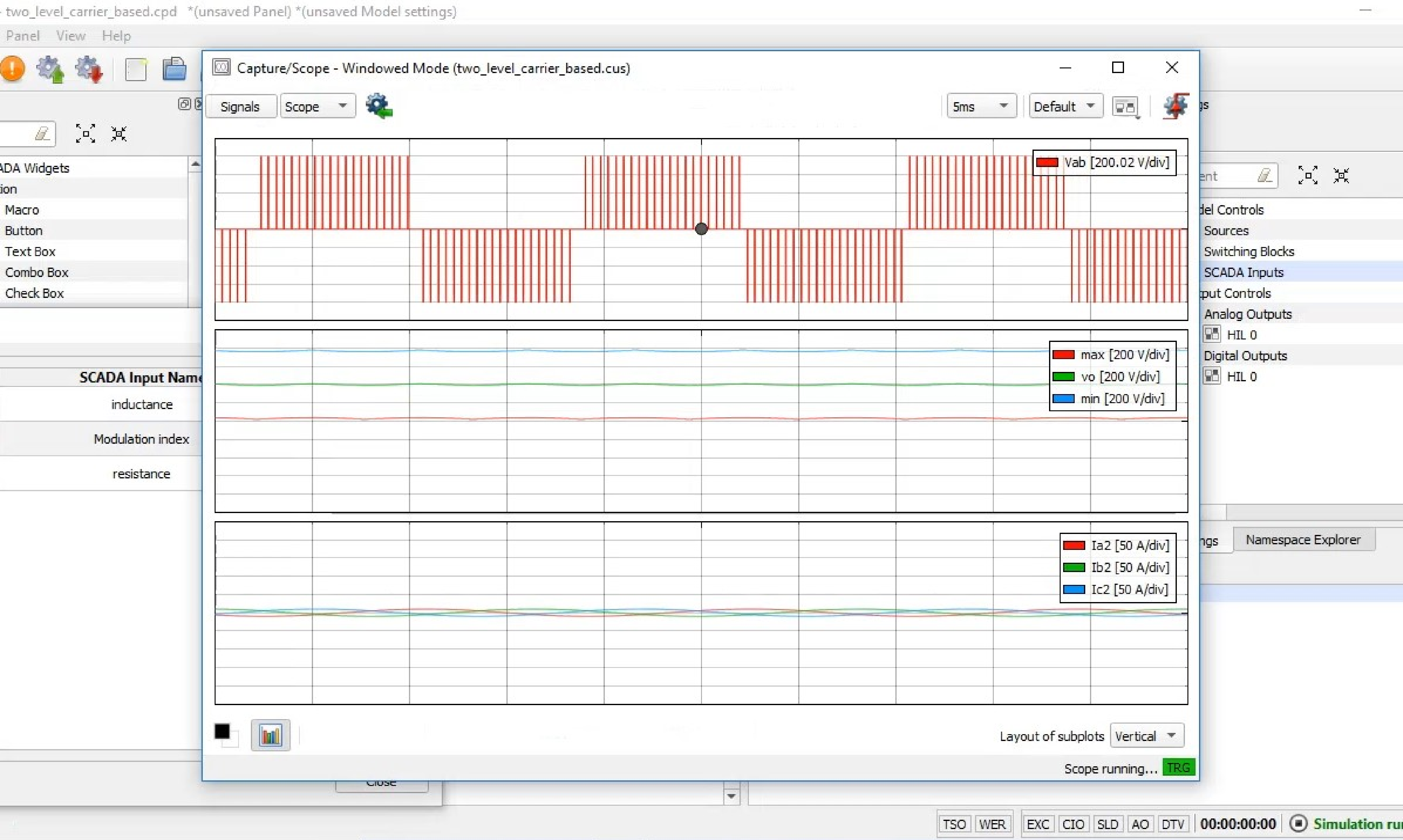
m_a =1.0



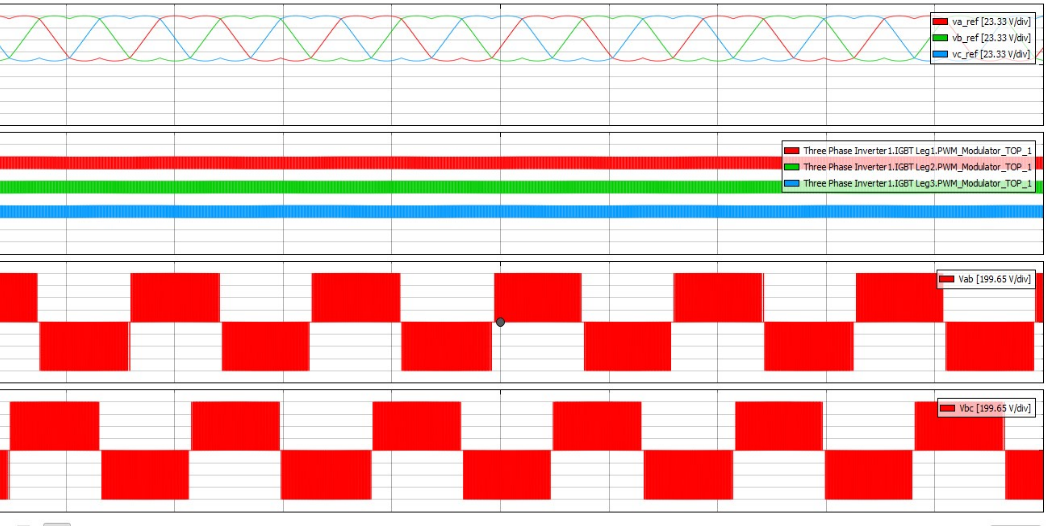
m_a =1.15

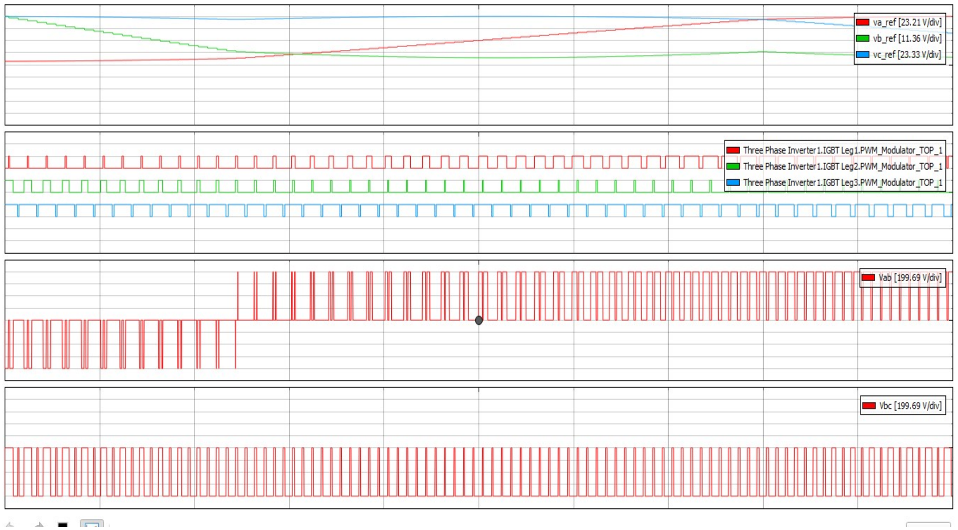


m_a =


two_level_carrier_based.cpd *(unsaved Panel) *(unsaved Model settings)
Panel View Help
Capture/Scope - Windowed Mode (two_level_carrier_based.cus)
Signals
Scope
5ms
Default
Vab [200.02 V/div]
max [200 V/div]
vo [200 V/div]
min [200 V/div]
Ia2 [50 A/div]
Ib2 [50 A/div]
Ic2 [50 A/div]
Layout of subplots
Vertical
Scope running...
TRG
Macro
Button
Text Box
Combo Box
Check Box
SCADA Input Name
inductance
Modulation index
resistance
Sources
Switching Blocks
SCADA Inputs
Analog Outputs
HIL 0
Digital Outputs
HIL 0
Namespace Explorer
TSO WER EXC CIO SLD AO DTV
00:00:00:00

2.2 - Carrier-based Modulation with Common-Mode Voltage Injection – LCL Filter Design





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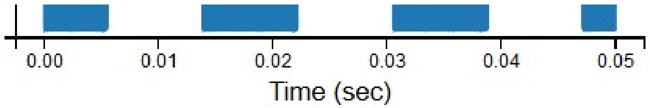
2.2 - Carrier-based Modulation with Common-Mode Voltage Injection – LCL Filter Design

9]:

Slide Type Sub-Sl

```
print('Nominal Power ',repr(round(P_rated/1000,2)), 'kW')
print('Nominal Voltage',repr(round(V_line,2)), 'V')
print('Grid nominal frequecy',repr(round(fo,2)), 'Hz')
print('Dc bus voltage',repr(round(Udc,2)), 'V')
print('Switching frequency,  fsw=',repr(round(fs/1000,2)), 'kHz')
print('Inverter current ripple    ', repr(round(beta*100,4)), '%')
print('L1=', repr(round(L1*1000,2)), 'mH')
print('Cf=', repr(round(Cf*1000000,2)),'uF')
print('L2=', repr(round(L2*1000,2)), 'mH')
print('LCL resonant frequency fr=',repr(round(np.sqrt((L2+L1)/(L1*L2*Cf))/2/np.pi/1000,2)), 'kHz')
print ('Total inductance per phase,',repr(round((L1+L2)/Lb,2)),'pu')
print ('Capacitance per phase, ',repr(round(Cf/Cb,2)),'pu')
```

```
Nominal Power  100.0 kW
Nominal Voltage 380 V
Grid nominal frequecy 60 Hz
Dc bus voltage 800 V
Switching frequency,  fsw= 10.0 kHz
Inverter current ripple    30.0 %
L1= 0.16 mH
Cf= 183.7 uF
L2= 0.28 mH
LCL resonant frequency fr= 1.18 kHz
Total inductance per phase, 0.11 pu
Capacitance per phase,  0.1 pu
```



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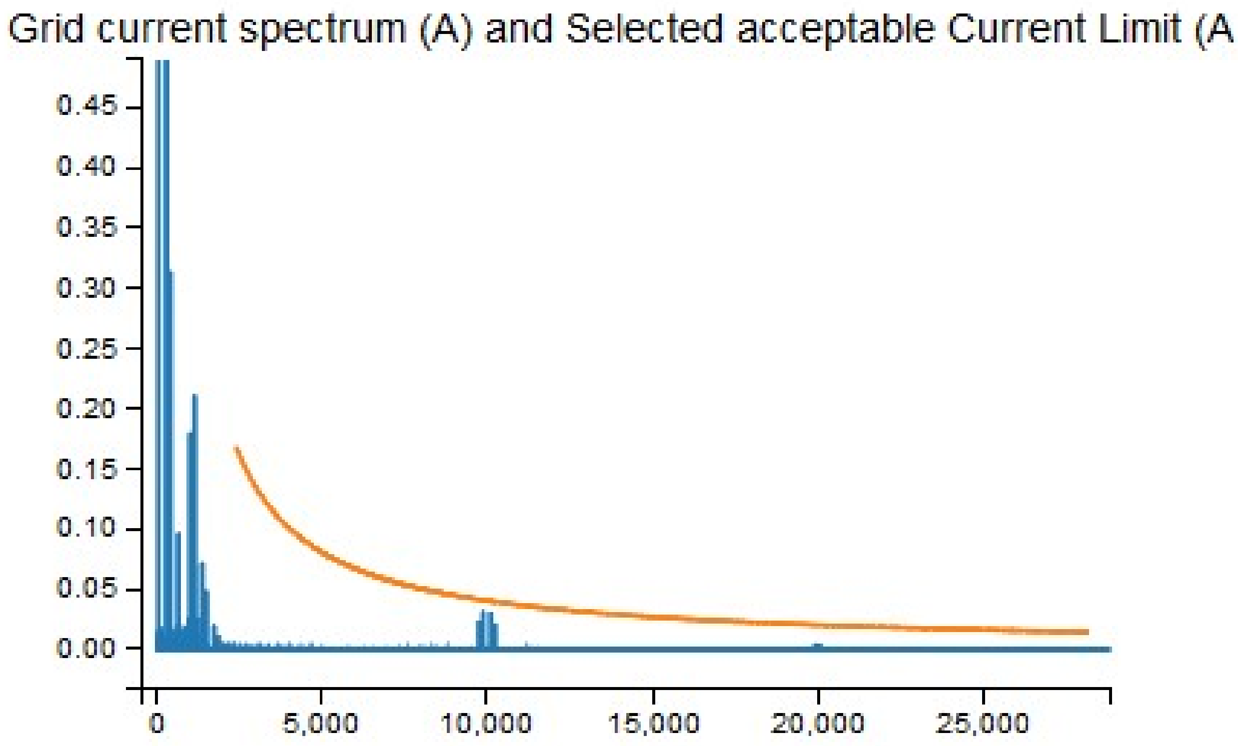
2.2 - Carrier-based Modulation with Common-Mode Voltage Injection – LCL Filter Design



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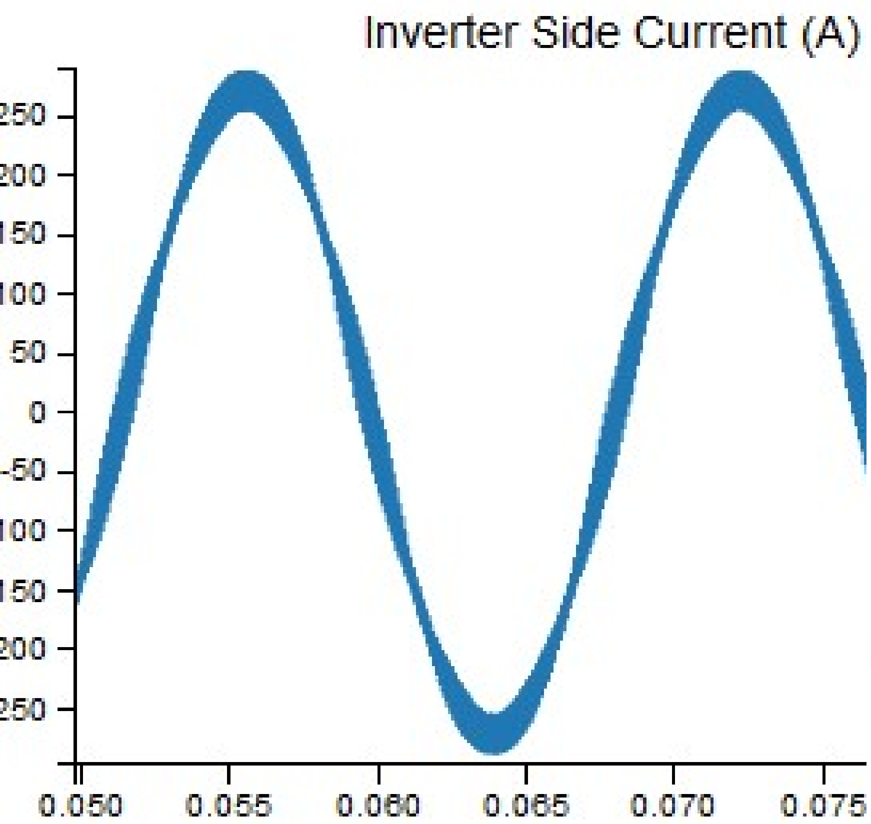
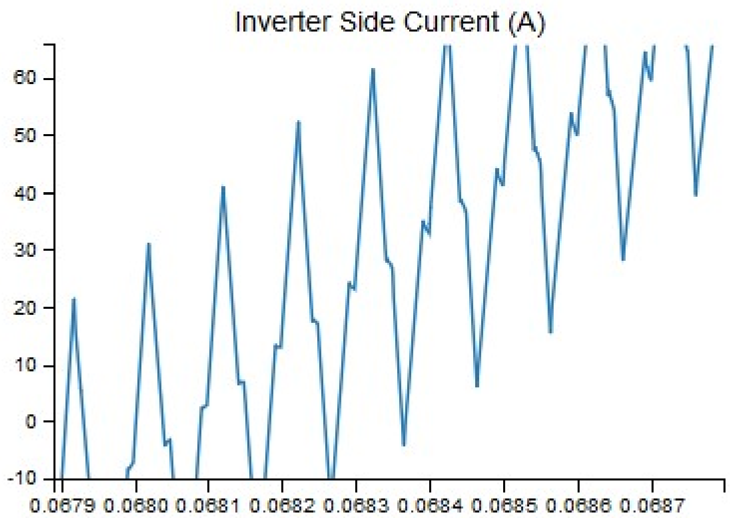
2.2 - Carrier-based Modulation with Common-Mode Voltage Injection – LCL Filter Design





In [14]:

```
beta_real=(65-(-10))/Iref
print('beta measured =', repr(round(beta_real,3)), '     Designed beta =',bet
```

```
beta measured = 0.349      Designed beta = 0.3
```

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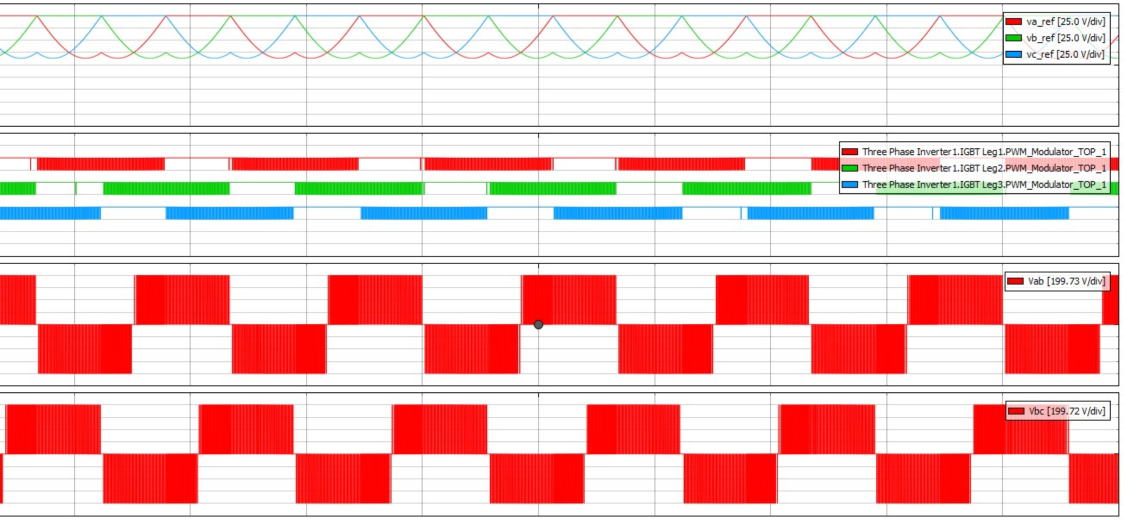
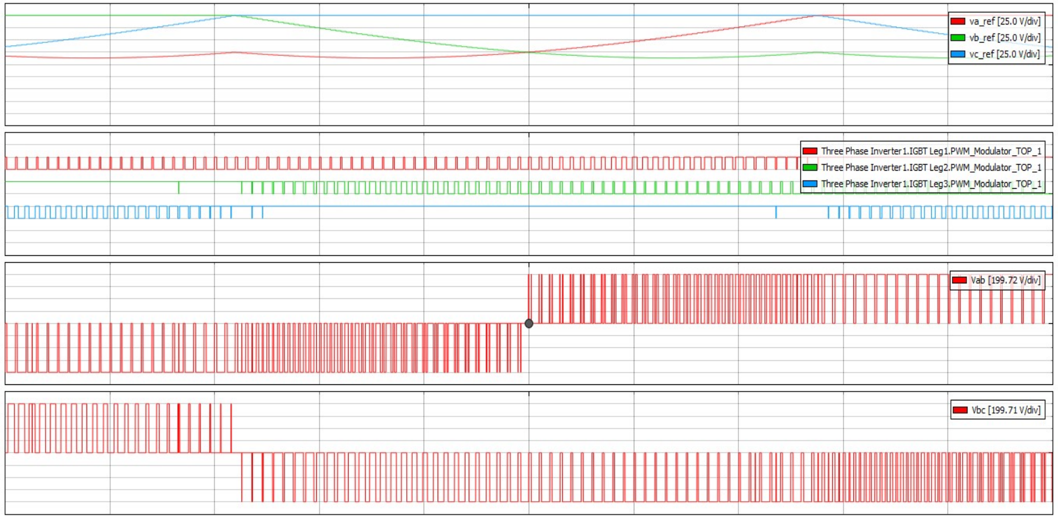
2.2 - Carrier-based Modulation with Common-Mode Voltage Injection – LCL Filter Design





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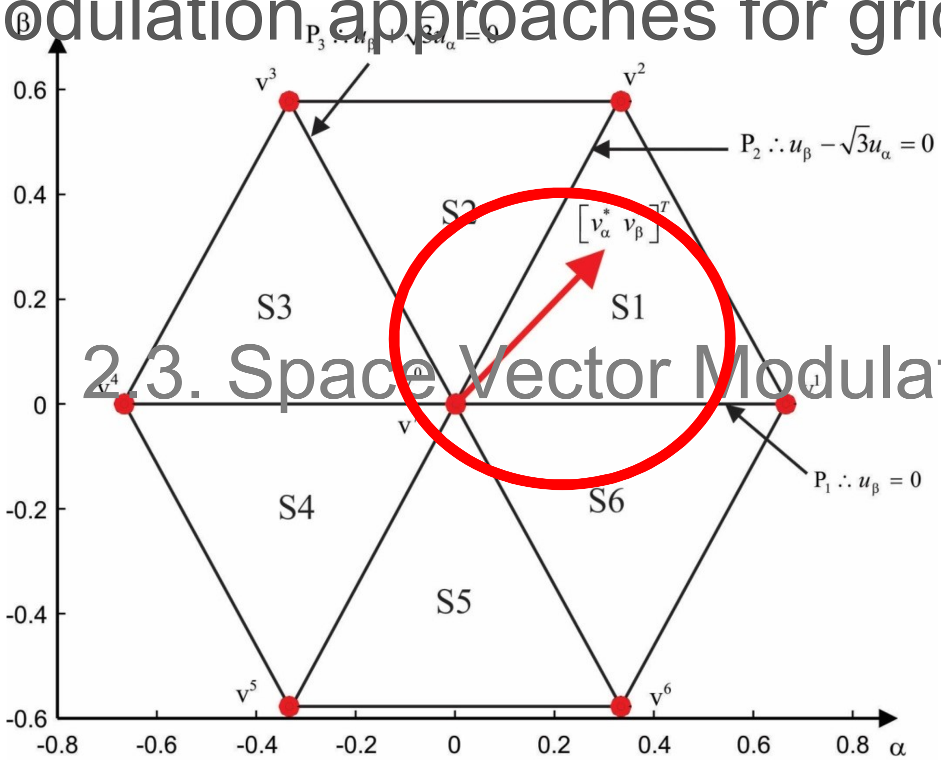
Modulation approaches for grid-tied

2.3. Space Vector Modulation - SVM



	$\mathbf{v}^0$	$\mathbf{v}^1$	$\mathbf{v}^2$	$\mathbf{v}^7$
s_{1a}	0	1	1	1
s_{1b}	0	0	1	1
s_{1c}	0	0	0	1

	$\mathbf{v}^0$	$\mathbf{v}^3$	$\mathbf{v}^2$	$\mathbf{v}^7$
s_{1a}	0	0	1	1
s_{1b}	0	1	1	1
s_{1c}	0	0	0	1

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2.3 - Space Vector Modulation - SVM

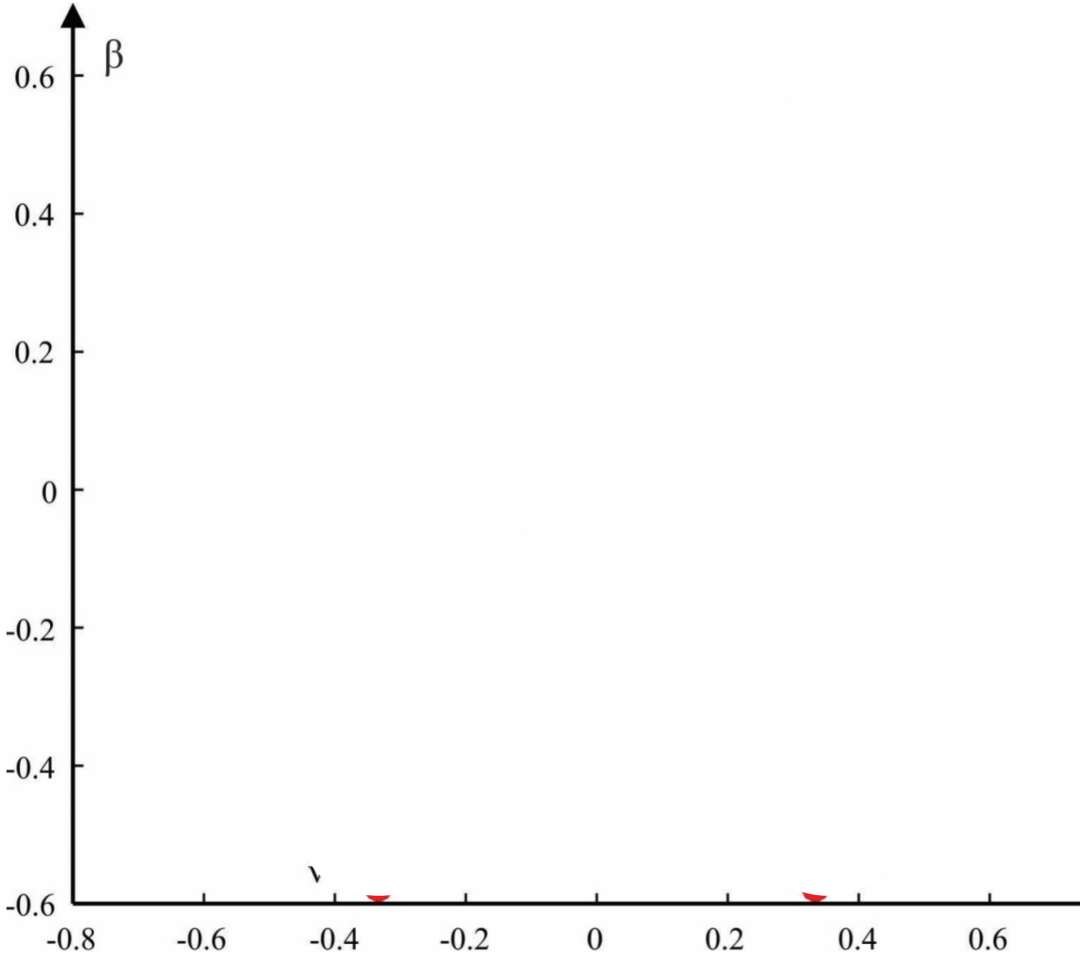
$$\begin{bmatrix} u_\alpha^* \\ u_\beta^* \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}_{abc} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}_{\alpha\beta} \qquad \mathbf{v}^3 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}_{abc} = \begin{bmatrix} -0.333 \\ 0.577 \end{bmatrix}_{\alpha\beta}$$

$$\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}_{abc} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}_{\alpha\beta} \qquad \mathbf{v}^4 = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}_{abc} = \begin{bmatrix} -0.667 \\ 0 \end{bmatrix}_{\alpha\beta}$$

$$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}_{abc} = \begin{bmatrix} 0.667 \\ 0 \end{bmatrix}_{\alpha\beta} \qquad \mathbf{v}^5 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}_{abc} = \begin{bmatrix} -0.333 \\ -0.667 \end{bmatrix}_{\alpha\beta}$$

$$\begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}_{abc} = \begin{bmatrix} 0.333 \\ 0.577 \end{bmatrix}_{\alpha\beta} \qquad \mathbf{v}^6 = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}_{abc} = \begin{bmatrix} 0.333 \\ -0.577 \end{bmatrix}_{\alpha\beta}$$



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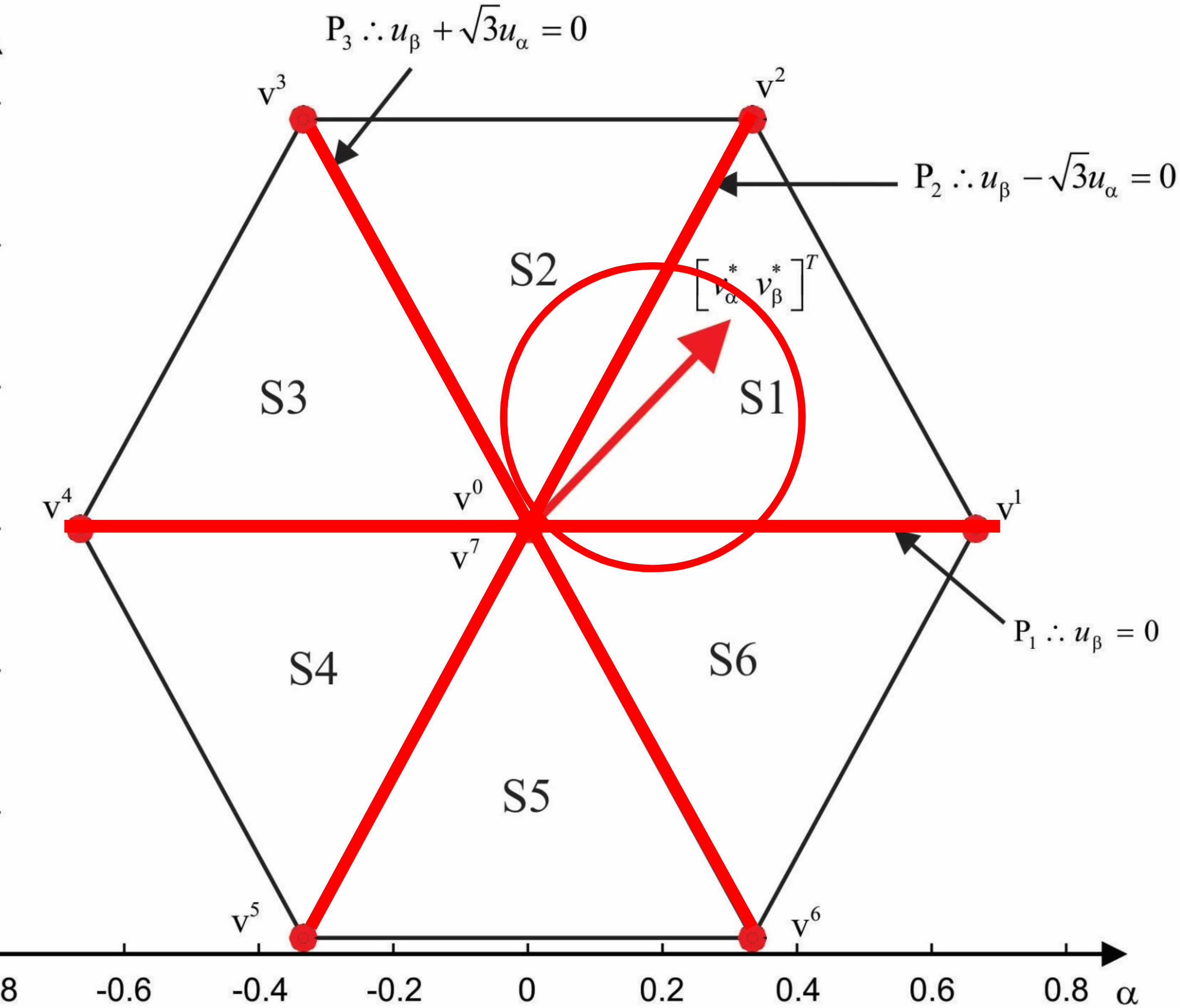
2.3 - Space Vector Modulation - SVM



$$\mathbf{u} = \frac{1}{T_s}\left[\int_0^{t_1} \mathbf{v}^1 dt + \int_{t_1}^{t_2} \mathbf{v}^2 dt + \int_{t_2}^{t_3} \mathbf{v}\right.$$

$$\mathbf{v}^0 \Delta t_0 + \mathbf{v}^1 \Delta t_1 + \mathbf{v}^2 \Delta t_2 = 0.5\mathbf{u}$$

2.3 - Space Vector Modulation - SVM

$$\underbrace{\begin{bmatrix} \cdots & \mathbf{v}^2 & \mathbf{v}^0 \\ \cdots & 1 & 1 \end{bmatrix}}_{\mathbf{M}} \begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \Delta t_0 \end{bmatrix} = \begin{bmatrix} \mathbf{u} \\ 1 \end{bmatrix} T_s \Rightarrow \begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \Delta t_0 \end{bmatrix} = \mathbf{M}^{-1} \begin{bmatrix} \mathbf{u} \\ 1 \end{bmatrix} T_s$$

$$\begin{bmatrix} \cdots_0 \\ \cdots_1 \\ \cdots_2 \end{bmatrix} = \begin{bmatrix} \Delta t_0 \\ \Delta t_1 \\ \Delta t_2 \end{bmatrix} \frac{1}{T_s}$$

$$\textbf{Sector 1} \rightarrow \mathbf{M}^{-1} = \begin{bmatrix} \mathbf{v}^1 & \mathbf{v}^2 & \mathbf{v}^0 \\ 1 & 1 & 1 \end{bmatrix} \qquad \textbf{Sector 4} \rightarrow \mathbf{M}^{-1} = \begin{bmatrix} \mathbf{v}^4 & \mathbf{v}^5 & \mathbf{v}^0 \\ 1 & 1 & 1 \end{bmatrix}$$

$$\textbf{Sector 2} \rightarrow \mathbf{M}^{-1} = \begin{bmatrix} \mathbf{v}^2 & \mathbf{v}^3 & \mathbf{v}^0 \\ 1 & 1 & 1 \end{bmatrix} \qquad \textbf{Sector 5} \rightarrow \mathbf{M}^{-1} = \begin{bmatrix} \mathbf{v}^5 & \mathbf{v}^6 & \mathbf{v}^0 \\ 1 & 1 & 1 \end{bmatrix}$$

$$\textbf{Sector 3} \rightarrow \mathbf{M}^{-1} = \begin{bmatrix} \mathbf{v}^3 & \mathbf{v}^4 & \mathbf{v}^0 \\ 1 & 1 & 1 \end{bmatrix} \qquad \textbf{Sector 6} \rightarrow \mathbf{M}^{-1} = \begin{bmatrix} \mathbf{v}^6 & \mathbf{v}^1 & \mathbf{v}^0 \\ 1 & 1 & 1 \end{bmatrix}$$

2.3 - Space Vector Modulation - SVM

Sector 1

	$\mathbf{v}^0$	$\mathbf{v}^1$	$\mathbf{v}^2$	$\mathbf{v}^7$
s_{1a}	0	1	1	1
s_{1b}	0	0	1	1
s_{1c}	0	0	0	1

$$\mathrm{COMP}s_{1a} = 0.5d_0 TPER$$
$$\mathrm{COMP}s_{1b} = (0.5d_0 + d_1)TPER$$
$$\mathrm{COMP}s_{1c} = (0.5d_0 + d_1 + d_2)TPER$$

Sector 2

	$\mathbf{v}^0$	$\mathbf{v}^3$	$\mathbf{v}^2$	$\mathbf{v}^7$
s_{1a}	0	0	1	1
s_{1b}	0	1	1	1
s_{1c}	0	0	0	1

$$\mathrm{COMP}s_{1a} = (0.5d_0 + d_1)TPER$$
$$\mathrm{COMP}s_{1b} = (0.5d_0)TPER$$
$$\mathrm{COMP}s_{1c} = (0.5d_0 + d_1 + d_2)TPER$$

Sector 3

	$\mathbf{v}^0$	$\mathbf{v}^3$	$\mathbf{v}^4$	$\mathbf{v}^7$
s_{1a}	0	0	0	1
s_{1b}	0	1	1	1
s_{1c}	0	0	1	1

$$\mathrm{COMP}s_{1a} = (0.5d_0 + d_1 + d_2)TP$$
$$\mathrm{COMP}s_{1b} = (0.5d_0)TPER$$
$$\mathrm{COMP}s_{1c} = (0.5d_0 + d_1)TPER$$

Sector 4

	$\mathbf{v}^0$	$\mathbf{v}^5$	$\mathbf{v}^4$	$\mathbf{v}^7$
s_{1a}	0	0	0	1
s_{1b}	0	0	1	1
s_{1c}	0	1	1	1

$$\mathrm{COMP}s_{1a} = (0.5d_0 + d_1 + d_2)TPER$$
$$\mathrm{COMP}s_{1b} = (0.5d_0 + d_1)TPER$$
$$\mathrm{COMP}s_{1c} = (0.5d_0)TPER$$

Sector 5

	$\mathbf{v}^0$	$\mathbf{v}^5$	$\mathbf{v}^6$	$\mathbf{v}^7$
s_{1a}	0	0	1	1
s_{1b}	0	0	0	1
s_{1c}	0	1	1	1

$$\mathrm{COMP}s_{1a} = (0.5d_0 + d_1)TPER$$
$$\mathrm{COMP}s_{1b} = (0.5d_0 + d_1 + d_2)TPER$$
$$\mathrm{COMP}s_{1c} = (0.5d_0)TPER$$

Sector 6

	$\mathbf{v}^0$	$\mathbf{v}^1$	$\mathbf{v}^6$	$\mathbf{v}^7$
s_{1a}	0	1	1	1
s_{1b}	0	0	0	1
s_{1c}	0	0	1	1

$$\mathrm{COMP}s_{1a} = 0.5d_0 TPER$$
$$\mathrm{COMP}s_{1b} = (0.5d_0 + d_1 + d_2)TP$$
$$\mathrm{COMP}s_{1c} = (0.5d_0 + d_1)TPER$$

Summary

- SPWM is simple but it does not explore the entire voltage syntheses capability;
- Carrier-based Modulation with Common-Mode Voltage Injection overcome the limitations of SPWM;
- Space Vector Modulation – SVM addresses the problem of modulation on a inverter output space.

Modulation approaches for grid-tied inverters

3. Modulation Strategies and Filter Design for the Three-Phase Three-level Inverter

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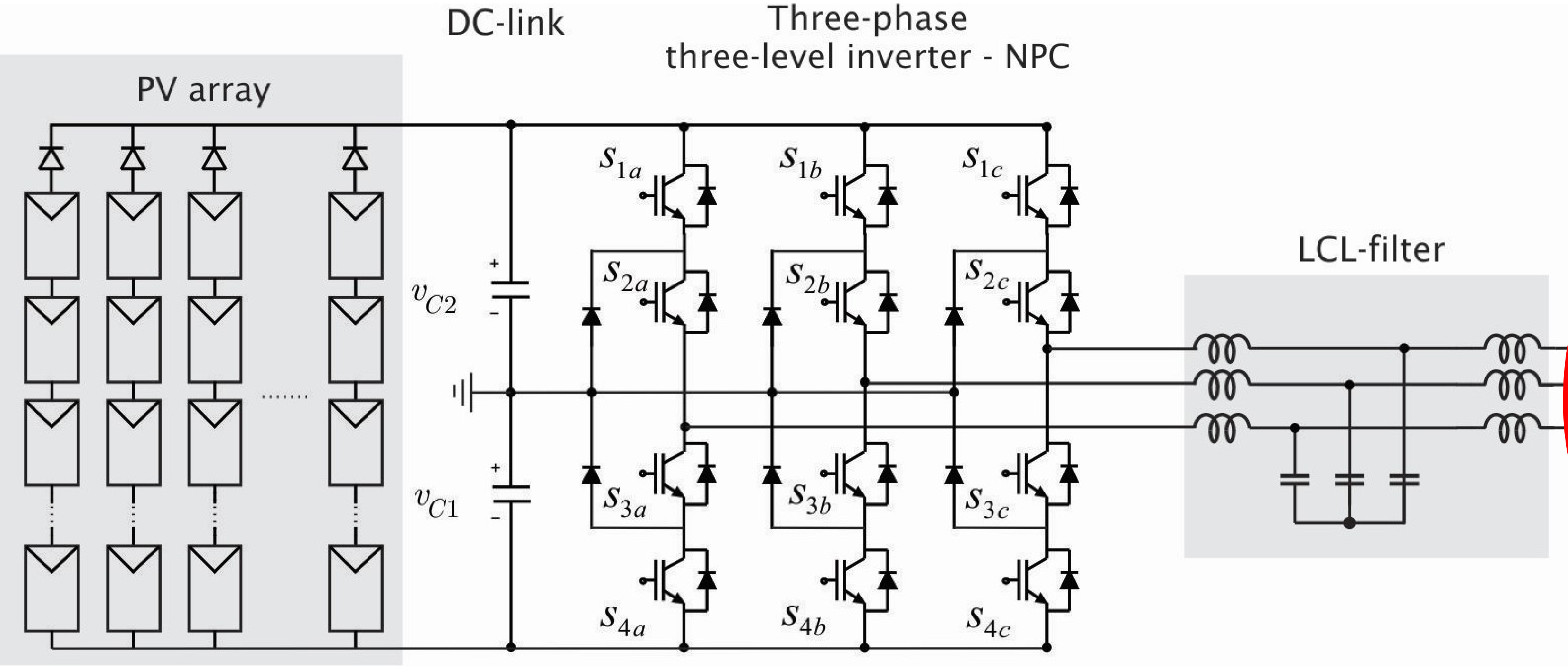
Modulation Strategies for Three-Level Inverters

- Carrier-Based Sinusoidal PWM;

- Carrier-based Modulation with Common-Mode Voltage Injection;

- Space Vector Modulation - SVM;

Modulation Strategies for Three-Level Inverters



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Modulation Strategies for NPC Inverters

S1x	S2x	Leg Voltage	iox
1	1	Vdc/2	0
0	1	0	-ix
0	0	-Vdc/2	0
1	0	Not allowed	0

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Modulation approaches for grid-tied inverters

3.1. Carrier-Based Sinusoidal Modulation implemented with Phase Disposition

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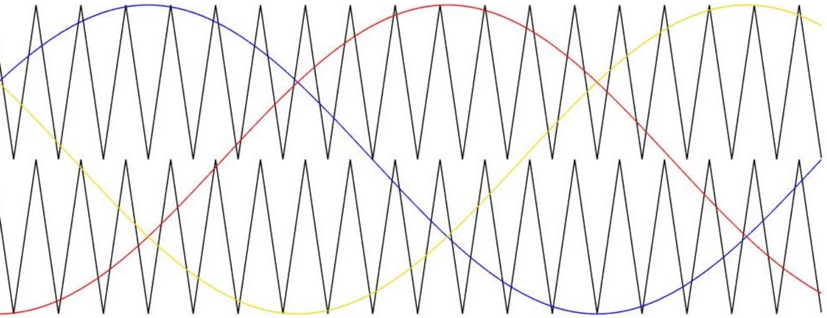
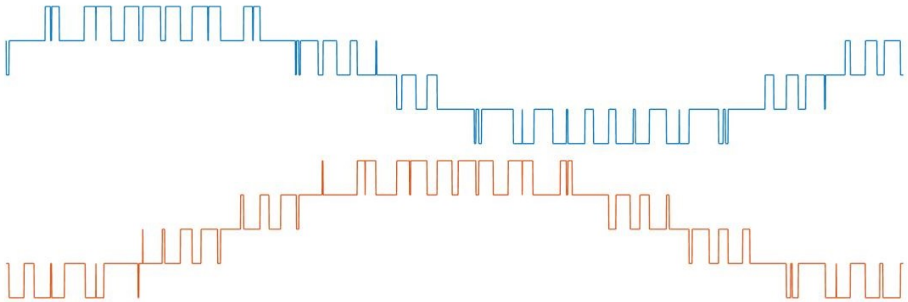
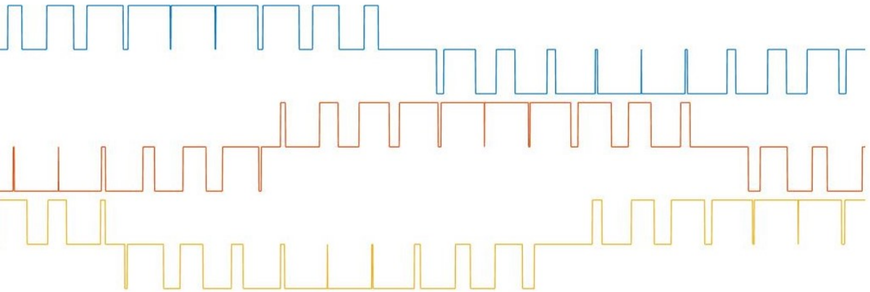
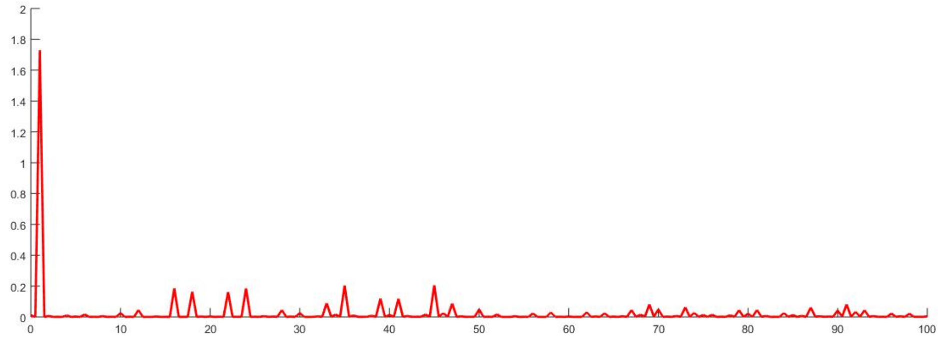
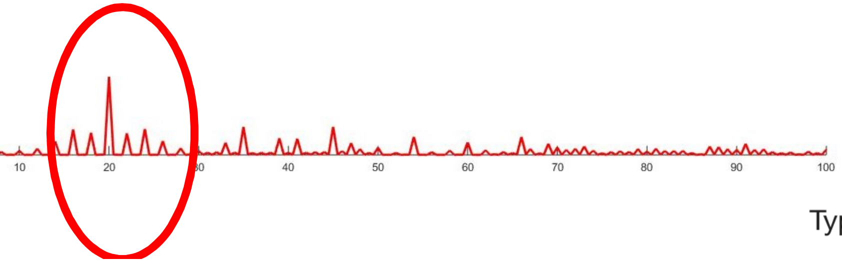
3.1 - Carrier-Based Sinusoidal Modulation – Three-level NPC inverter











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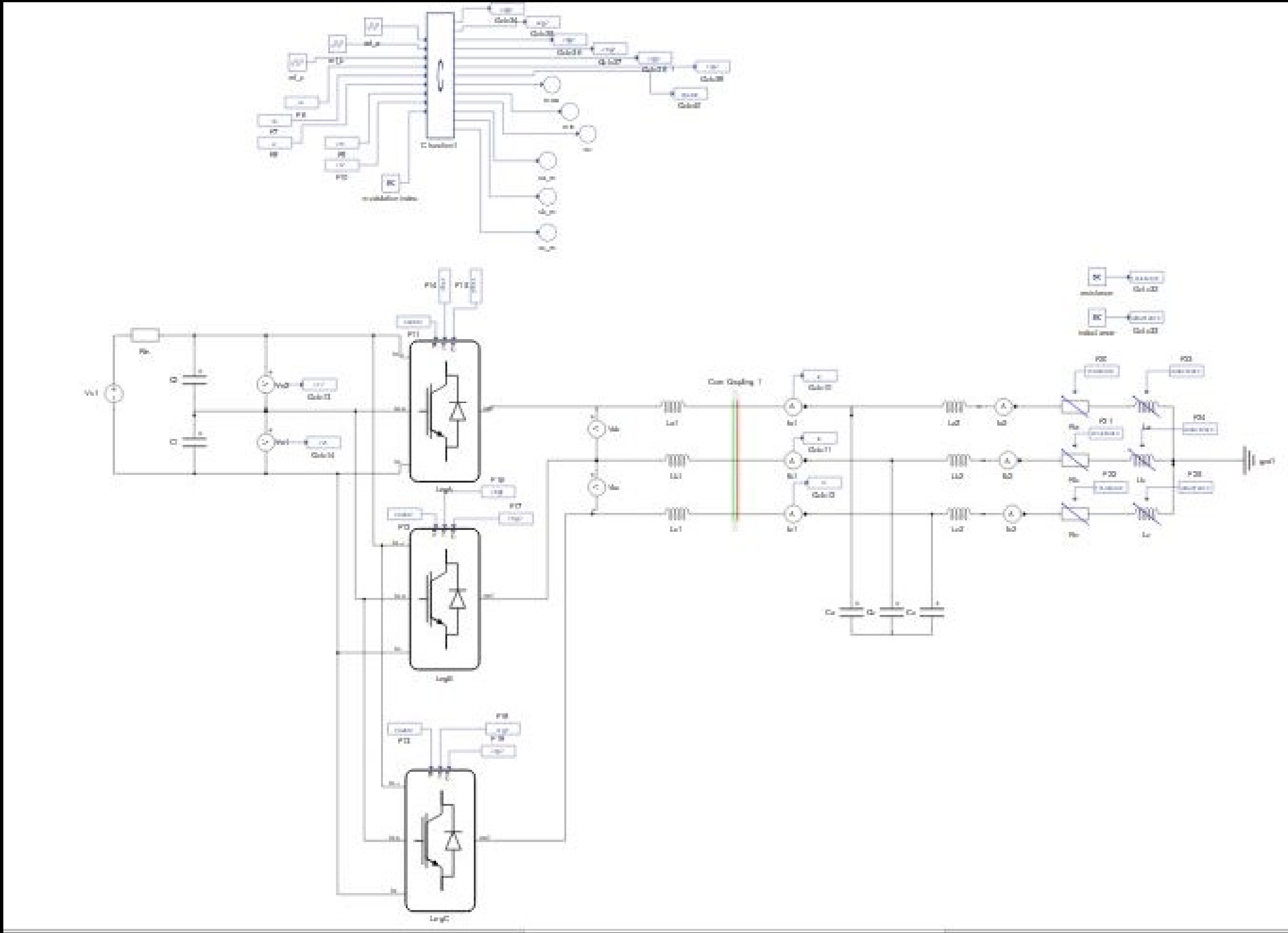

Modulation approaches for grid-tied inverters

3.2. Carrier-based Modulation with Common-Mode Voltage Injection

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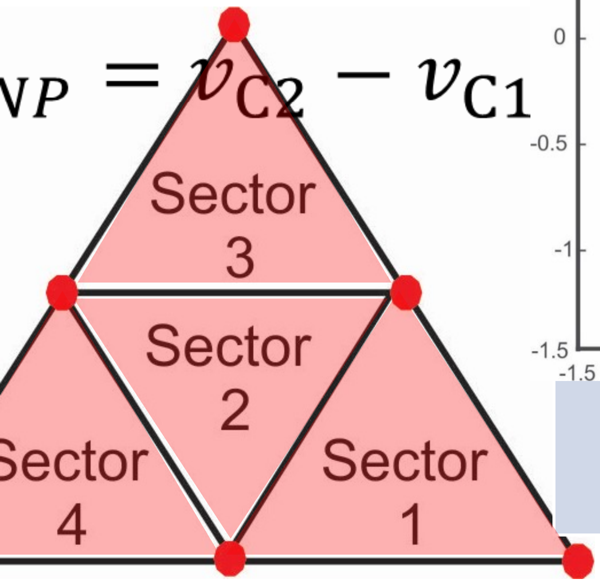
3.2 - Carrier-based Modulation with Common-Mode Voltage Injection

3.2 - Carrier-based Modulation with Common-Mode Voltage Injection

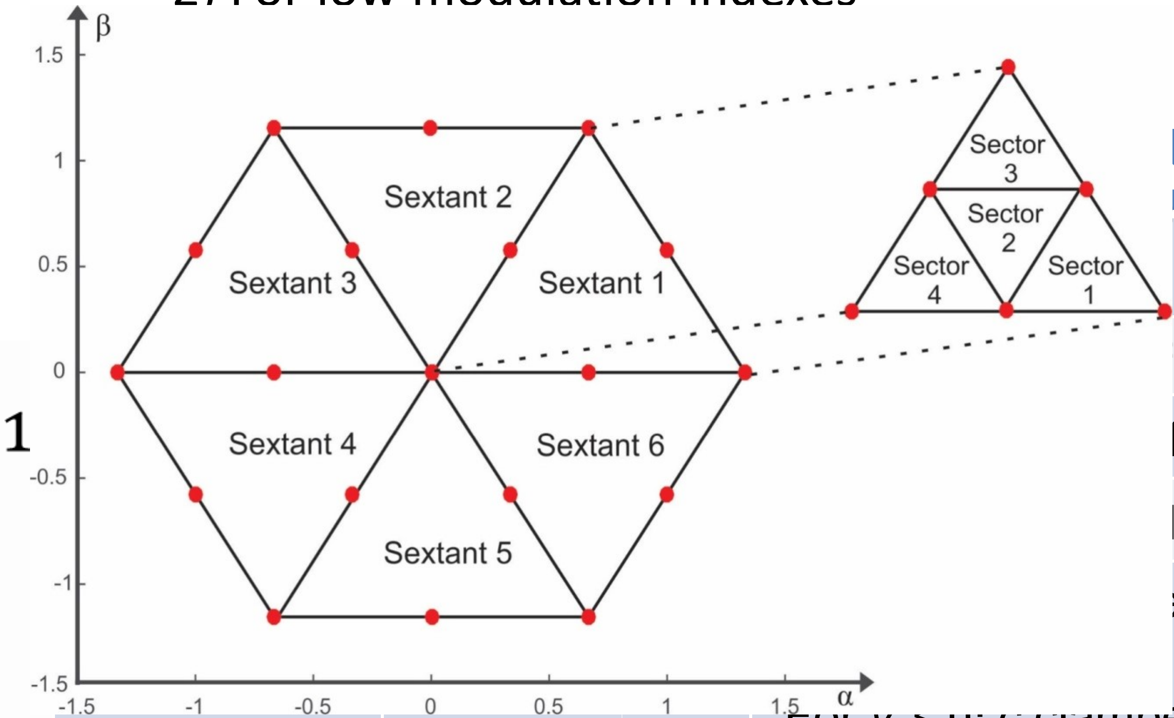
$_a, i_b, i_c$

$_{C1}, v_{C2}$

$_{NP} = v_{C2} - v_{C1}$



2) For low modulation indexes



t 4)	
$-v_a$ $-v_b$	**offset**
0 $-v_c$	$-v_b$
[-1]	$+1-v_a$ [-1 $-v_a$
[-1]	$-1-v_c$ [+1 $-v_c$
ed to +1 to +1]	For v_b>0: +1-v_a [+
For $v_b \leq 0$: c clamped to -1 [a clamped to -1]	For $v_b \leq 0$: -1-v_c [-

es extracted from “A carrier-based PWM strategy with zero-sequence voltage injection for a three-level neutral-point-ped converter”

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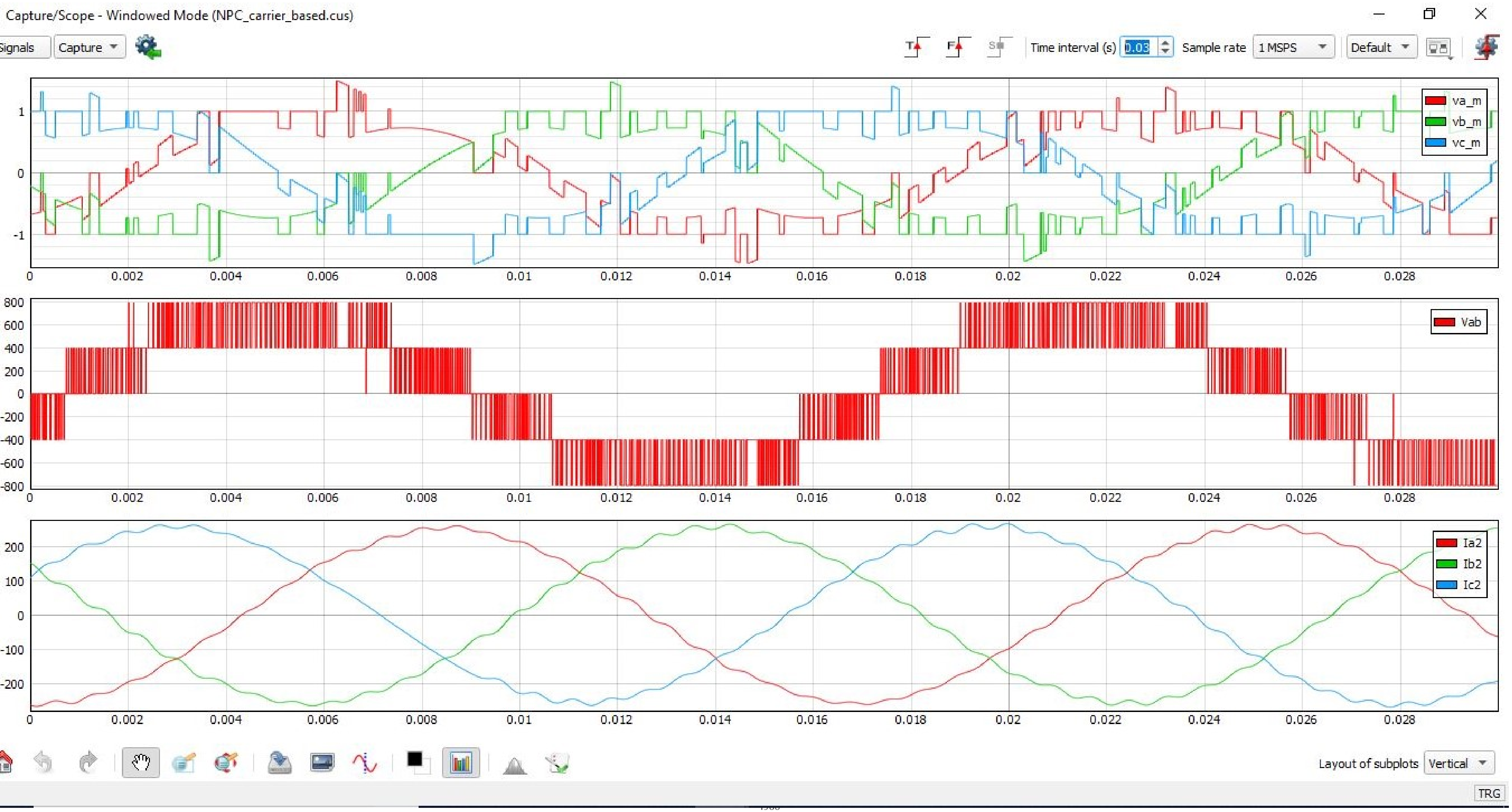
3.2 - Carrier-based Modulation with Common-Mode Voltage Injection



3.2 - Carrier-based Modulation with Common-Mode Voltage Injection

$$-0.5V_{dc} \le v_{ag} \le 0.5V_{dc}$$
$$-0.5V_{dc} \le v_{bg} \le 0.5V_{dc}$$
$$-0.5V_{dc} \le v_{cg} \le 0.5V_{dc}$$

$$V_{dc} \le \frac{2}{3}v_{ab} + \frac{1}{3}v_{bc} + v_0 \le 0.5V_{dc}$$
$$_{dc} \le -\frac{1}{3}v_{ab} + \frac{1}{3}v_{bc} + v_0 \le 0.5V_{dc}$$
$$_{dc} \le -\frac{1}{3}v_{ab} - \frac{2}{3}v_{bc} + v_0 \le 0.5V_{dc}$$

$$-0.5V_{dc} - \frac{2}{3}v_{ab} - \frac{1}{3}v_{bc} \le v_0 \le 0.5V_{dc} - \frac{2}{3}v_{ab} -$$
$$-0.5V_{dc}\frac{1}{3}v_{ab} - \frac{1}{3}v_{bc} \le v_0 \le 0.5V_{dc} + \frac{1}{3}v_{ab} -$$
$$-0.5V_{dc}\frac{1}{3}v_{ab} + \frac{2}{3}v_{bc} \le v_0 \le 0.5V_{dc} + \frac{1}{3}v_{ab} +$$

3.2 - Carrier-based Modulation with Common-Mode Voltage Injection

$$c_1 = 0.5V_{dc} - \frac{2}{3}v_{ab} - \frac{1}{3}v_{bc}$$
$$c_2 = 0.5V_{dc} + \frac{1}{3}v_{ab} - \frac{1}{3}v_{bc}$$
$$c_3 = 0.5V_{dc} + \frac{1}{3}v_{ab} + \frac{2}{3}v_{bc}$$
$$c_4 = -0.5V_{dc} - \frac{2}{3}v_{ab} - \frac{1}{3}v_{bc}$$
$$c_5 = -0.5V_{dc} \frac{1}{3}v_{ab} - \frac{1}{3}v_{bc}$$
$$c_6 = -0.5V_{dc} \frac{1}{3}v_{ab} + \frac{2}{3}v_{bc}$$

$\min(c_1, c_2, c_3) \rightarrow$ upper limit of the linear region

$\max(c_4, c_5, c_6) \rightarrow$ lower limit of the linear region

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3.2 - Carrier-based Modulation with Common-Mode Voltage Injection

$$v_{ag} = v_{an} + v_o$$
$$v_{bg} = v_{bn} + v_o$$
$$v_{cg} = v_{cn} + v_o$$

$$v_o = \min$$

$$v_o = \max$$

$$0 \leq v_{ag}^* \leq TPER$$
$$0 \leq v_{bg}^* \leq TPER$$
$$0 \leq v_{cg}^* \leq TPER$$

$$\Rightarrow$$

$$v_{ag}^* = \frac{v_{ag}}{V_{dc}} TPER + TPER$$
$$v_{bg}^* = \frac{v_{bg}}{V_{dc}} TPER + TPER$$
$$v_{cg}^* = \frac{v_{cg}}{V_{dc}} TPER + TPER$$

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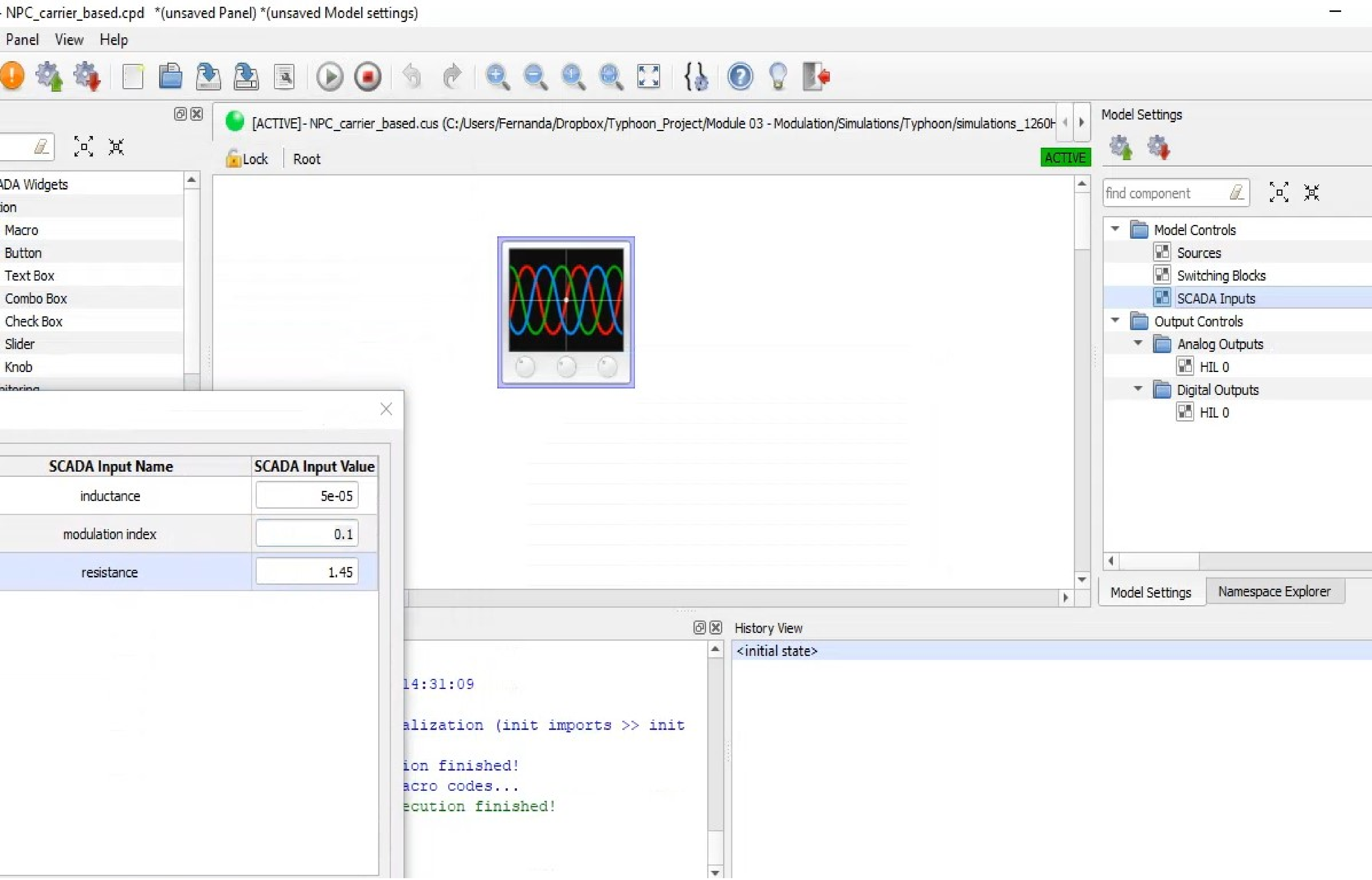
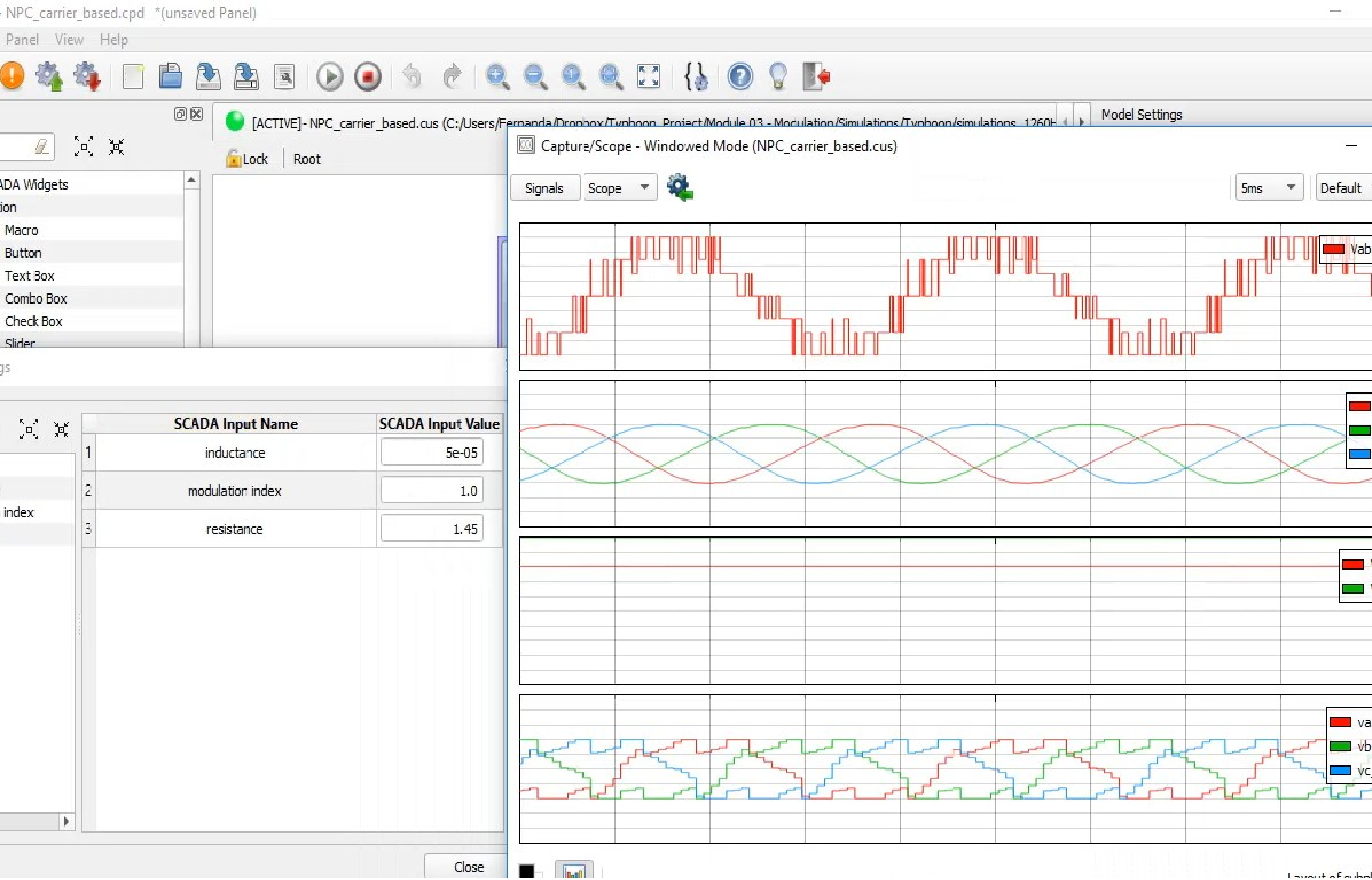
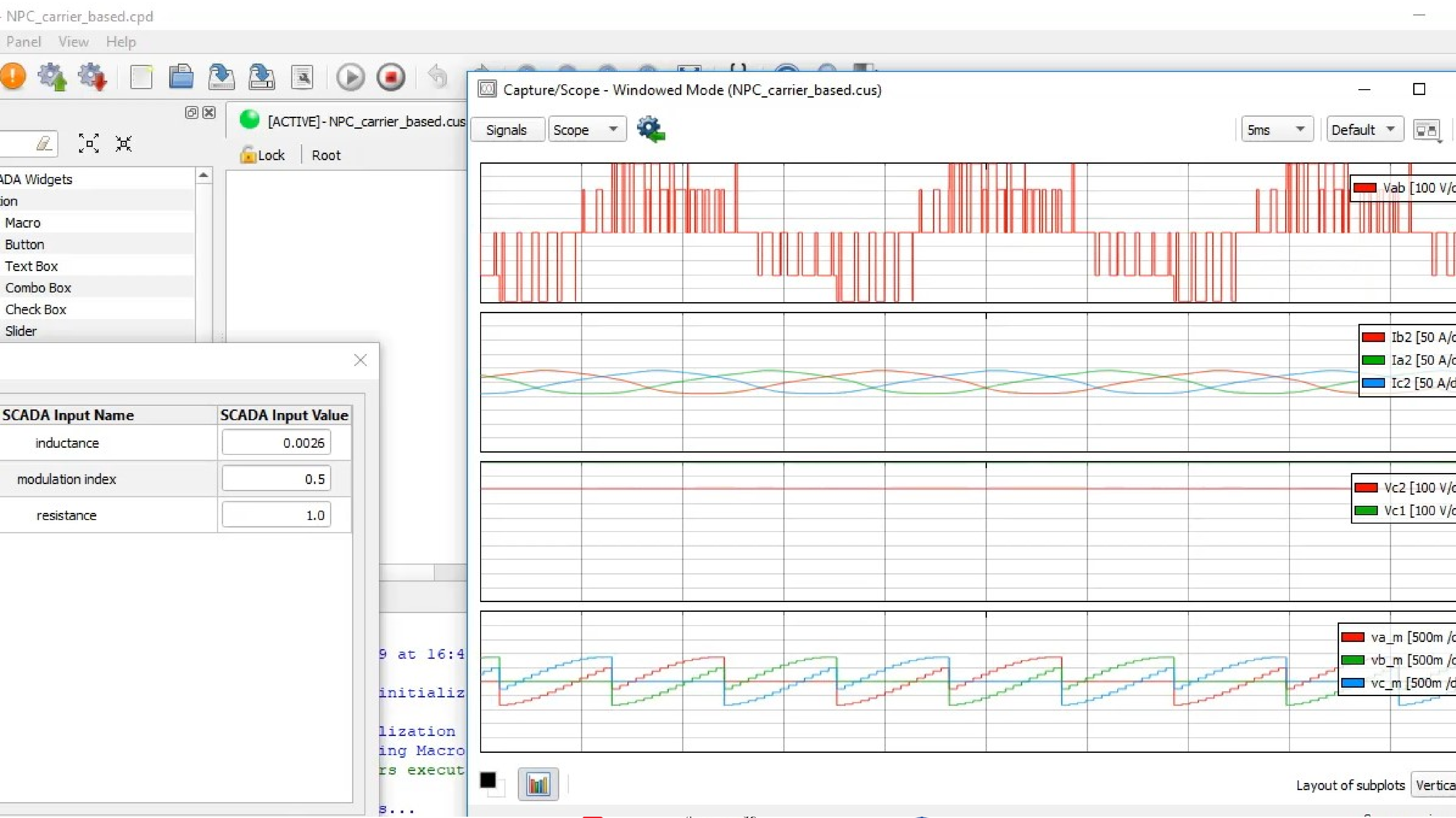

NPC_carrier_based.cpd *(unsaved Panel) *(unsaved Model settings)
Panel View Help
[ACTIVE]- NPC_carrier_based.cus (C:/Users/Fernanda/Dropbox/Typhoon_Project/Module 03 - Modulation/Simulations/Typhoon/simulations_1260H
Lock
Root
ACTIVE
Model Settings
find component
Model Controls
Sources
Switching Blocks
SCADA Inputs
Output Controls
Analog Outputs
HIL 0
Digital Outputs
HIL 0
Model Settings
Namespace Explorer
ADA Widgets
ion
Macro
Button
Text Box
Combo Box
Check Box
Slider
Knob
SCADA Input Name
SCADA Input Value
inductance
5e-05
modulation index
0.1
resistance
1.45
14:31:09
alization (init imports >> init
ion finished!
acro codes...
ecution finished!
History View
<initial state>



NPC_carrier_based.cpd *(unsaved Panel)
Panel View Help
[ACTIVE] - NPC_carrier_based.cus (C:/Users/Fernanda/Dropbox/Typhoon_Project/Module 03 - Modulation/Simulations/Typhoon/simulations_1260H
Model Settings
Lock
Root
Capture/Scope - Windowed Mode (NPC_carrier_based.cus)
Signals
Scope
5ms
Default
ADA Widgets
ion
Macro
Button
Text Box
Combo Box
Check Box
Slider
gs
index
SCADA Input Name
SCADA Input Value
1 inductance 5e-05
2 modulation index 1.0
3 resistance 1.45
Close
Vab
va
vb
vc



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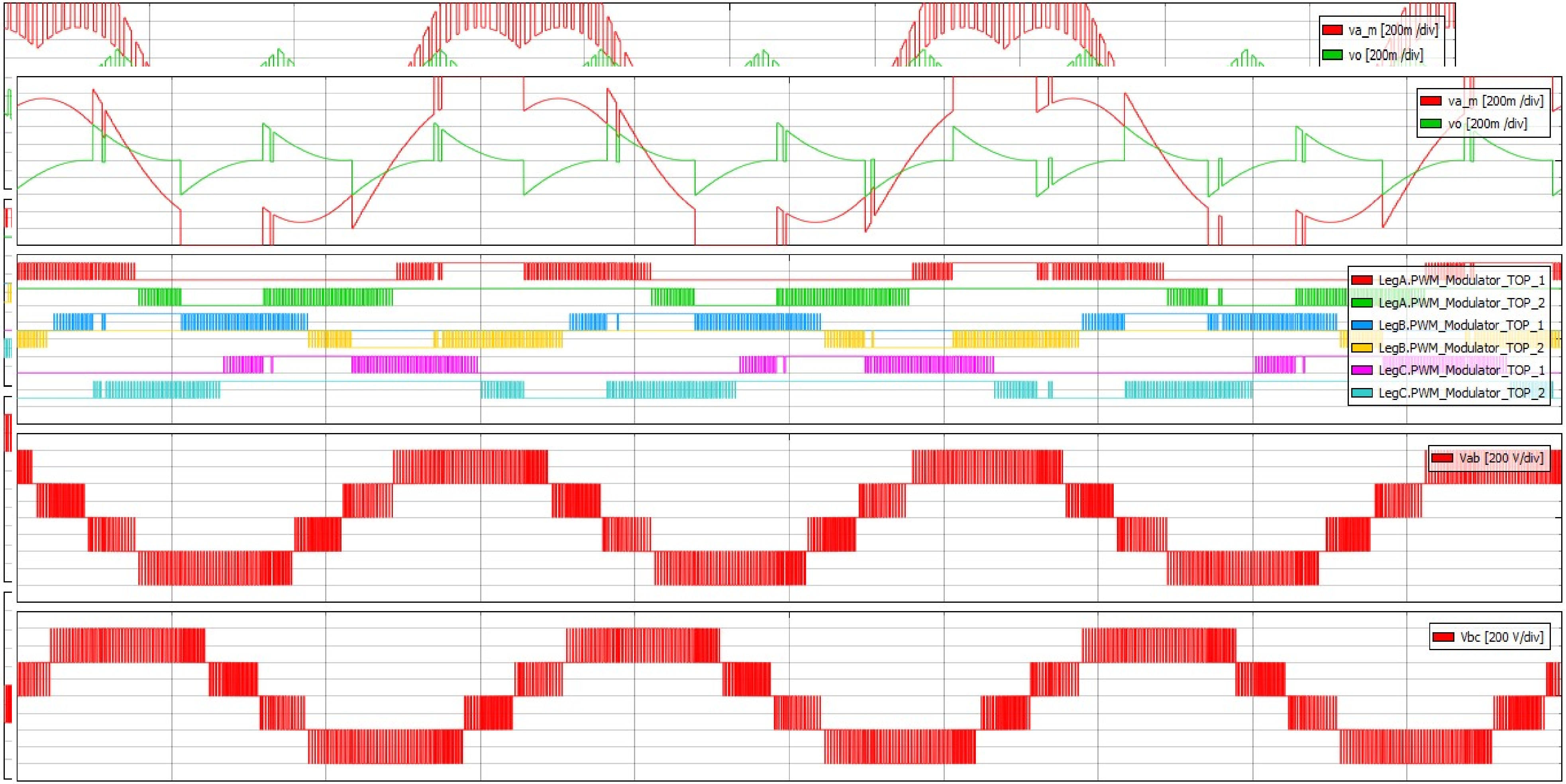
3.2 - Carrier-based Modulation with Common-Mode Voltage Injection

LCL Filter Design



L=50uH
R=1.45
PF=1
ma=1

L=2.65m
R=1.0
PF=0.7
ma=1

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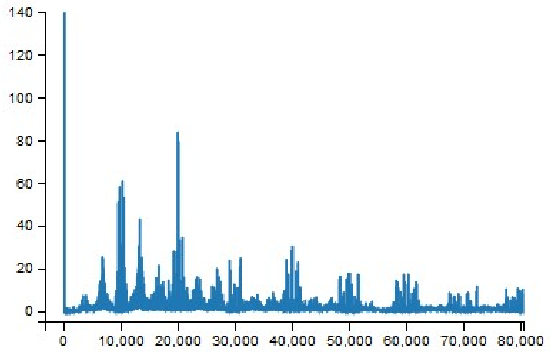
3.2 - LCL Filter Design

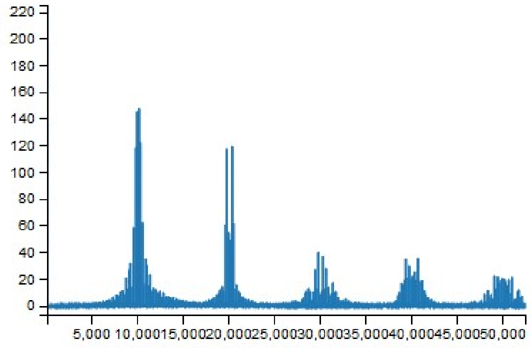
The inverter with LCL filter main parameters are:

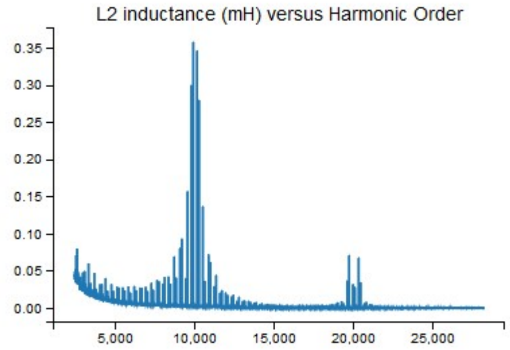
]: Slide Typ

```
print('Nominal Power ',repr(round(P_rated/1000,2)), 'kW')
print('Nominal Voltage',repr(round(V_line,2)), 'V')
print('Grid nominal frequecy',repr(round(fo,2)), 'Hz')
print('Dc bus voltage',repr(round(Udc,2)), 'V')
print('Switching frequency,  fsw=',repr(round(fs/1000,2)), 'kHz')
print('Inverter current ripple   ', repr(round(beta*100,4)), '%')
print('L1=', repr(round(L1*1000,2)), 'mH')
print('Cf=', repr(round(Cf*1000000,2)),'uF')
print('L2=', repr(round(L2*1000,2)), 'mH')
print('LCL resonant frequency fr=',repr(round(np.sqrt((L2+L1)/(L1*L2*Cf))/2/np.pi/1000,2)), 'kHz')
print ('Total inductance per phase,',repr(round((L1+L2)/Lb,2)),'pu')
print ('Capacitance per phase, ',repr(round(Cf/Cb,2)),'pu')
```

```
Nominal Power  100.0 kW
Nominal Voltage 380 V
Grid nominal frequecy 60 Hz
Dc bus voltage 800 V
Switching frequency,  fsw= 10.0 kHz
Inverter current ripple    30.0 %
L1= 0.08 mH
Cf= 183.7 uF
L2= 0.36 mH
LCL resonant frequency fr= 1.47 kHz
Total inductance per phase, 0.11 pu
Capacitance per phase,  0.1 pu
```







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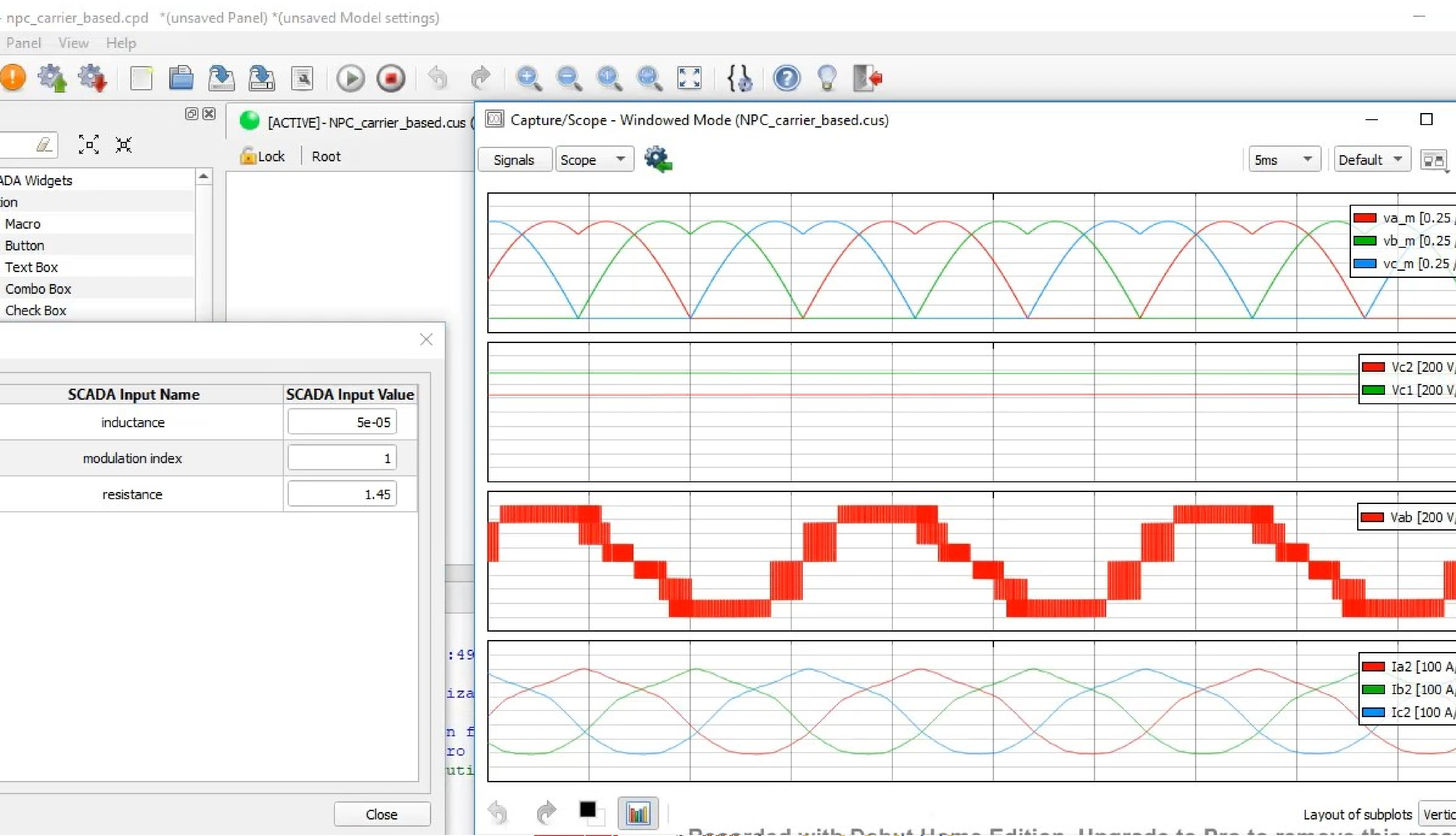

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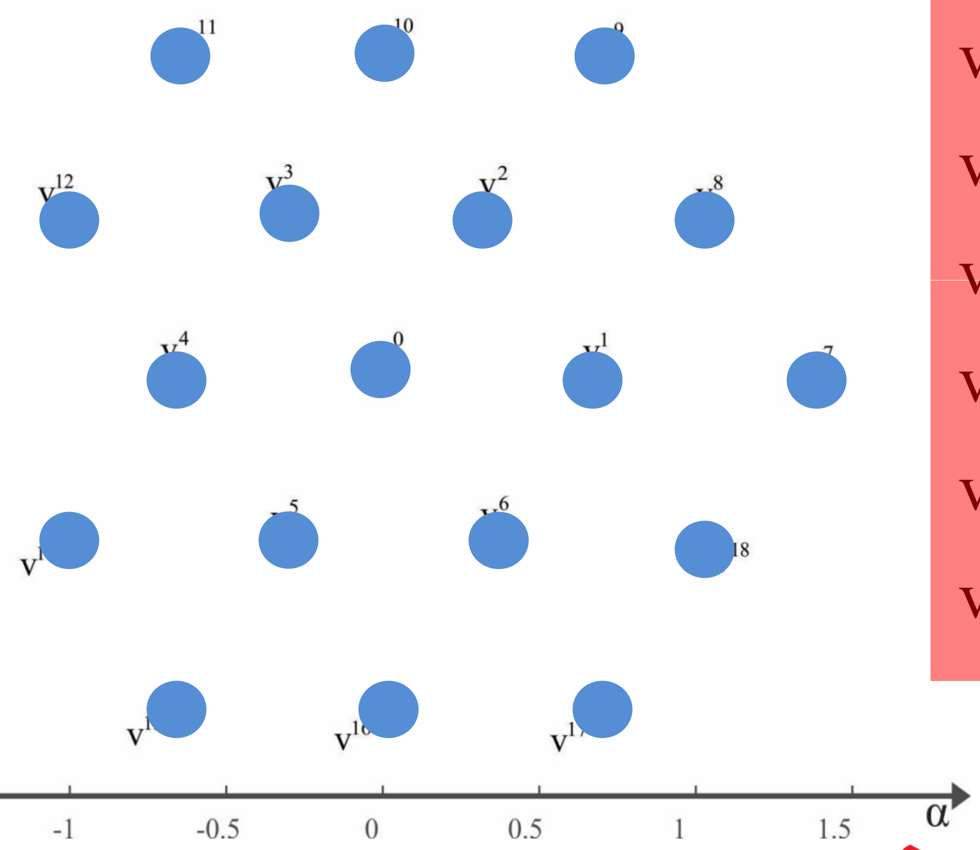
Modulation approaches for grid-tied inverters

3.3. Space Vector Modulation - SVM

3.3 - Space Vector Modulation - SVM

$$v^{00} = [1\ 1\ 1]^T;\ v^{0+} = [0\ 0\ 0]^T;\ v^{0-} = [-1\ -1\ -1]^T$$



$$v^{1+} = [1\ 0\ 0]^T;\ v^{1-} = [0\ -1\ -1]^T$$
$$v^{2+} = [1\ 1\ 0]^T;\ v^{2-} = [0\ 0\ -1]^T$$
$$v^{3+} = [0\ 1\ 0]^T;\ v^{3-} = [-1\ 0\ -1]^T$$
$$v^{4+} = [0\ 1\ 1]^T;\ v^{4-} = [-1\ 0\ 0]^T$$
$$v^{5+} = [0\ 0\ 1]^T;\ v^{5-} = [-1\ -1\ 0]^T$$
$$v^{6+} = [1\ 0\ 1]^T;\ v^{6-} = [0\ -1\ 0]^T$$

$$v^{8} = [1\ 0\ -1]^T$$
$$v^{10} = [0\ 1\ -1]^T$$
$$v^{12} = [-1\ 1\ 0]^T$$
$$v^{14} = [-1\ 0\ 1]^T$$
$$v^{16} = [0\ -1\ 1]^T$$
$$v^{18} = [1\ -1\ 0]^T$$

$$v^{7} = [1\ -1\ -1]^T$$
$$v^{9} = [1\ 1\ -1]^T$$
$$v^{11} = [-1\ 1\ -1]^T$$
$$v^{13} = [-1\ 1\ 1]^T$$
$$v^{15} = [-1\ -1\ 1]^T$$
$$v^{17} = [1\ -1\ 1]^T$$

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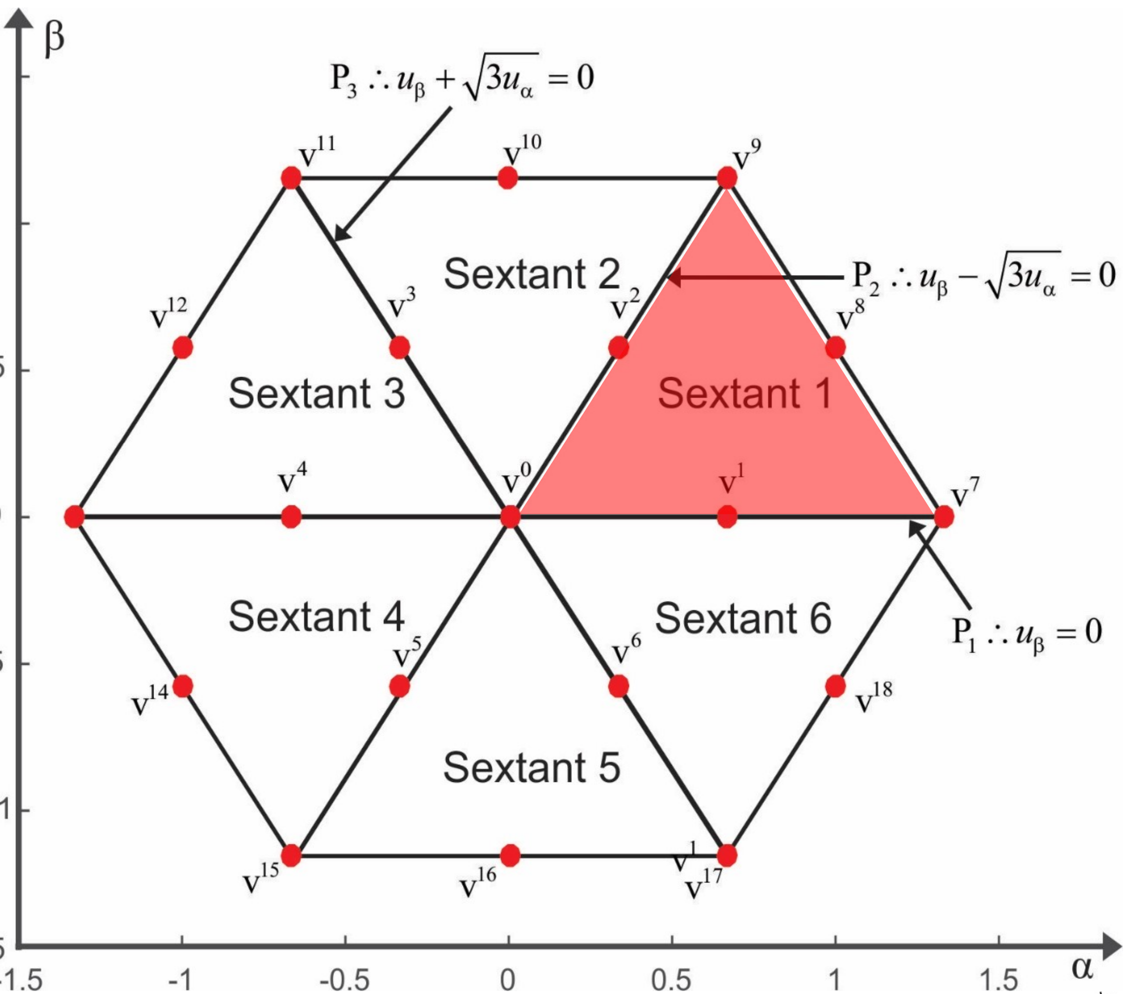
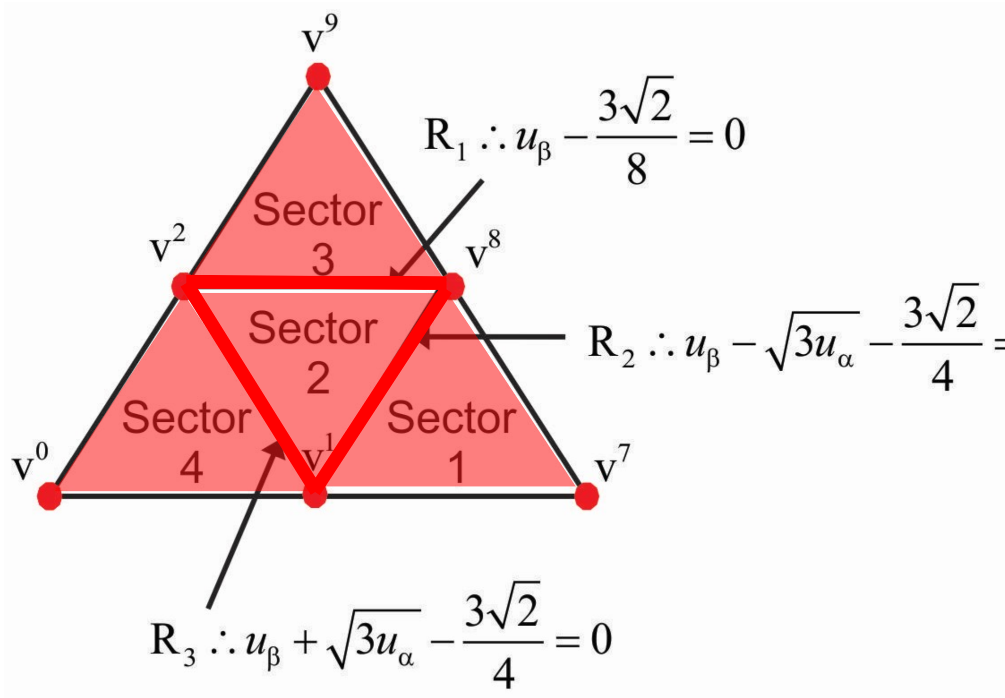
3.3 - Space Vector Modulation - SVM





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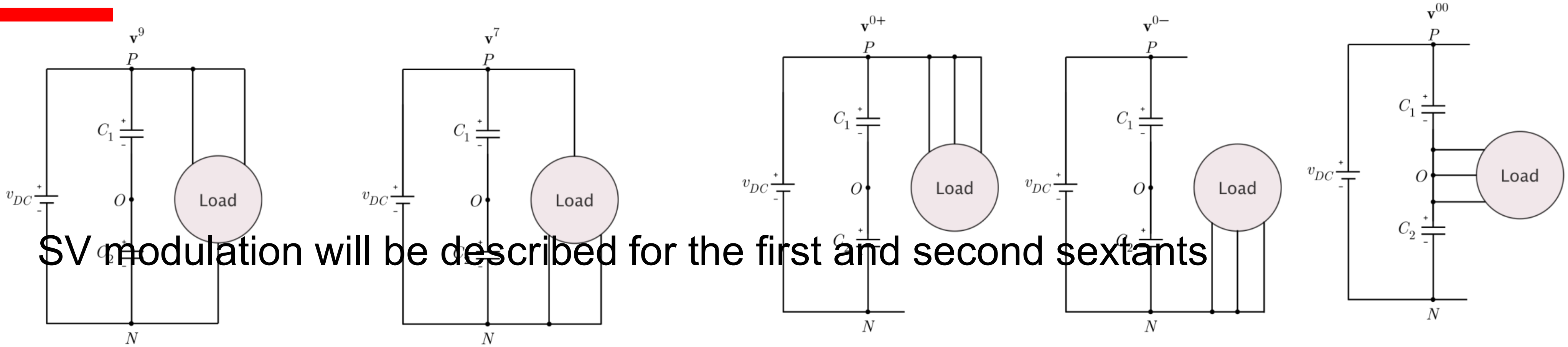
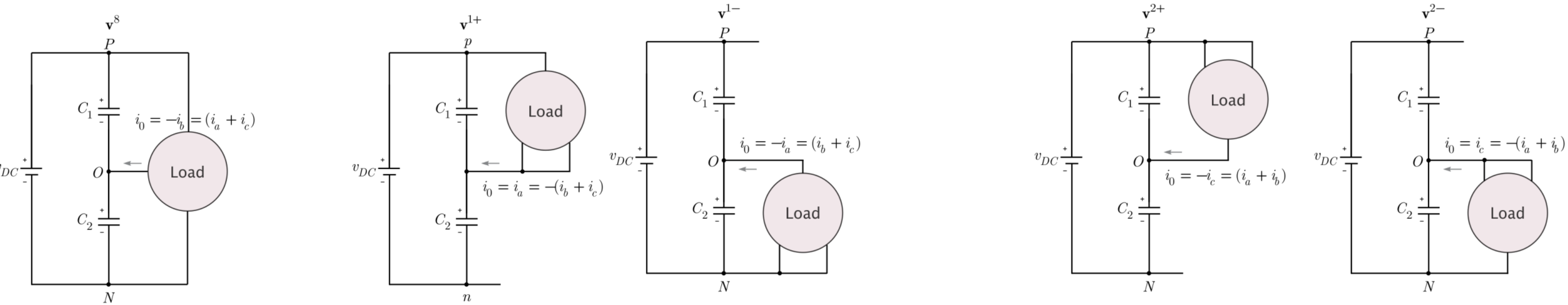
3.3 - Space Vector Modulation - SVM



SV modulation will be described for the first and second sextants

- Redundancies of the voltage vectors → balance the voltages of the dc bus capacitors



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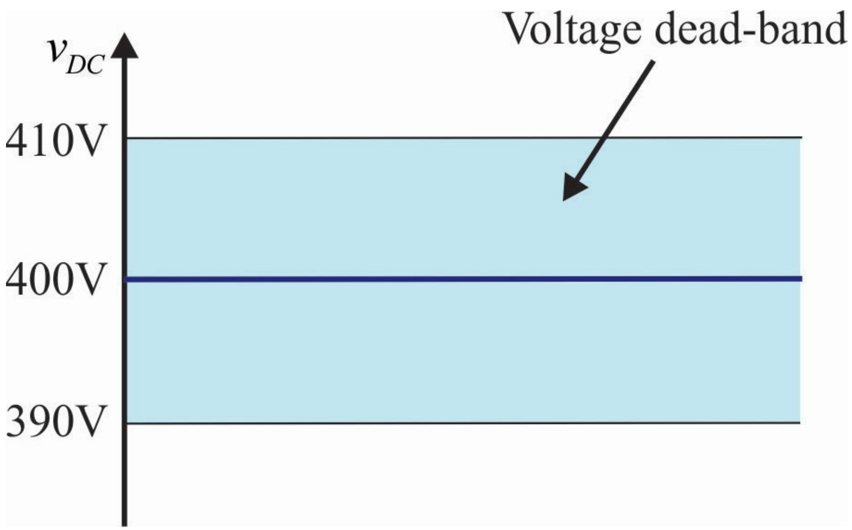
3.3 - Space Vector Modulation - SVM

rst Sextant

$\mathrm{v}^{0} \quad \mathrm{v}^{1} \quad \mathrm{v}^{2}$

ctor 1: Switching sequence for balanced voltages

$\mathrm{v}^{0+} \ \mathrm{v}^{2+} \ \mathrm{v}^{1+} \ \mathrm{v}^{00} \ \mathrm{v}^{2-} \ \mathrm{v}^{1-} \ \mathrm{v}^{0-}$



Sector 1: Switching sequence for unbalanced voltages

$$v_{c1},\ v_{c2},\ i_a,\ i_c$$

$v_{C2} > v_{C1}$	$i_a > 0$	$i_c > 0$	Switching Sequence
0	0	0	$\mathrm{v}^{1+}\ \mathrm{v}^{00}\ \mathrm{v}^{2-}$
0	0	1	$\mathrm{v}^{00}\ \mathrm{v}^{1+}\ \mathrm{v}^{2+}$
0	1	0	$\mathrm{v}^{2-}\ \mathrm{v}^{1-}\ \mathrm{v}^{0-}$
0	1	1	$\mathrm{v}^{2+}\ \mathrm{v}^{00}\ \mathrm{v}^{1-}$
1	0	0	$\mathrm{v}^{2+}\ \mathrm{v}^{00}\ \mathrm{v}^{1-}$
1	0	1	$\mathrm{v}^{2-}\ \mathrm{v}^{1-}\ \mathrm{v}^{0-}$
1	1	0	$\mathrm{v}^{00}\ \mathrm{v}^{1+}\ \mathrm{v}^{2+}$
1	1	1	$\mathrm{v}^{1+}\ \mathrm{v}^{00}\ \mathrm{v}^{2-}$

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3.3 - Space Vector Modulation - SVM

rst Sextant

v^{1} v^{7} v^{8}

ctor 2: Switching sequence for balanced voltages

v^{1+} v^{8} v^{7} v^{1-}

Sector 2: Switching sequenc
for unbalanced voltages

$v_{C2} > v_{C1}$	$i_a > 0$	Switchin Sequence
0	0	v^{1+} v^{8} v
0	1	v^{8} v^{7} v^{1-}
1	0	v^{8} v^{7} v^{1-}
1	1	v^{1+} v^{8} v

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First Sextant:

v^{1} v^{2} v^{8}

ctor 3: Switching sequence for balanced voltages

$v^{2+}\ v^{1+}\ v^{8}\ v^{2-}\ v^{1-}$

Sector 3: Switching sequence fo
unbalanced voltages

$v_{C2} > v_{C1}$	$i_a > 0$	$i_c > 0$	Switching Sequence
0	0	0	$v^{1+}\ v^{8}\ v^{2-}$
0	0	1	$v^{2+}\ v^{1+}\ v^{8}$
0	1	0	$v^{8}\ v^{2-}\ v^{1-}$
0	1	1	$v^{2+}\ v^{8}\ v^{1-}$
1	0	0	$v^{2+}\ v^{8}\ v^{1-}$
1	0	1	$v^{8}\ v^{2-}\ v^{1-}$
1	1	0	$v^{2+}\ v^{1+}\ v^{8}$
1	1	1	$v^{1+}\ v^{8}\ v^{2-}$

First Sextant

$$v^{2} \quad v^{8} \quad v^{9}$$

ctor 4: Switching sequence for balanced voltages

$$v^{2+} \; v^{9} \; v^{8} \; v^{2-}$$

Sector 4: Switching sequence for unbalanced voltages

$v_{C2} > v_{C1}$	$i_c > 0$	Switching Sequence
0	0	$v^{9}\ v^{8}\ v^{2-}$
0	1	$v^{2+}\ v^{9}\ v^{8}$
1	0	$v^{2+}\ v^{9}\ v^{8}$
1	1	$v^{9}\ v^{8}\ v^{2-}$

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3.3 - Space Vector Modulation - SVM

$$\frac{1}{T_s}\left[\int_0^{t_1} \mathbf{v}^1 dt + \int_{t_1}^{t_2} \mathbf{v}^2 dt + \int_{t_2}^{t_3} \mathbf{v}^0 dt\right]$$

$$\begin{bmatrix} \mathbf{v^1} & \mathbf{v^2} & \mathbf{v^0} \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \Delta t_0 \end{bmatrix} = \begin{bmatrix} \mathbf{u} \\ 1 \end{bmatrix} T_s \Rightarrow \begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \Delta t_0 \end{bmatrix} = \mathbf{M}^{-1}\begin{bmatrix} \mathbf{u} \\ 1 \end{bmatrix} T_s$$

$$\mathbf{v}^0 \Delta t_0 + \mathbf{v}^1 \Delta t_1 + \mathbf{v}^2 \Delta t_2 = \mathbf{u} T_s$$

$$\begin{bmatrix} d_0 \\ d_1 \\ d_2 \end{bmatrix} = \begin{bmatrix} \Delta t_0 \\ \Delta t_1 \\ \Delta t_2 \end{bmatrix} \frac{1}{T_s}$$

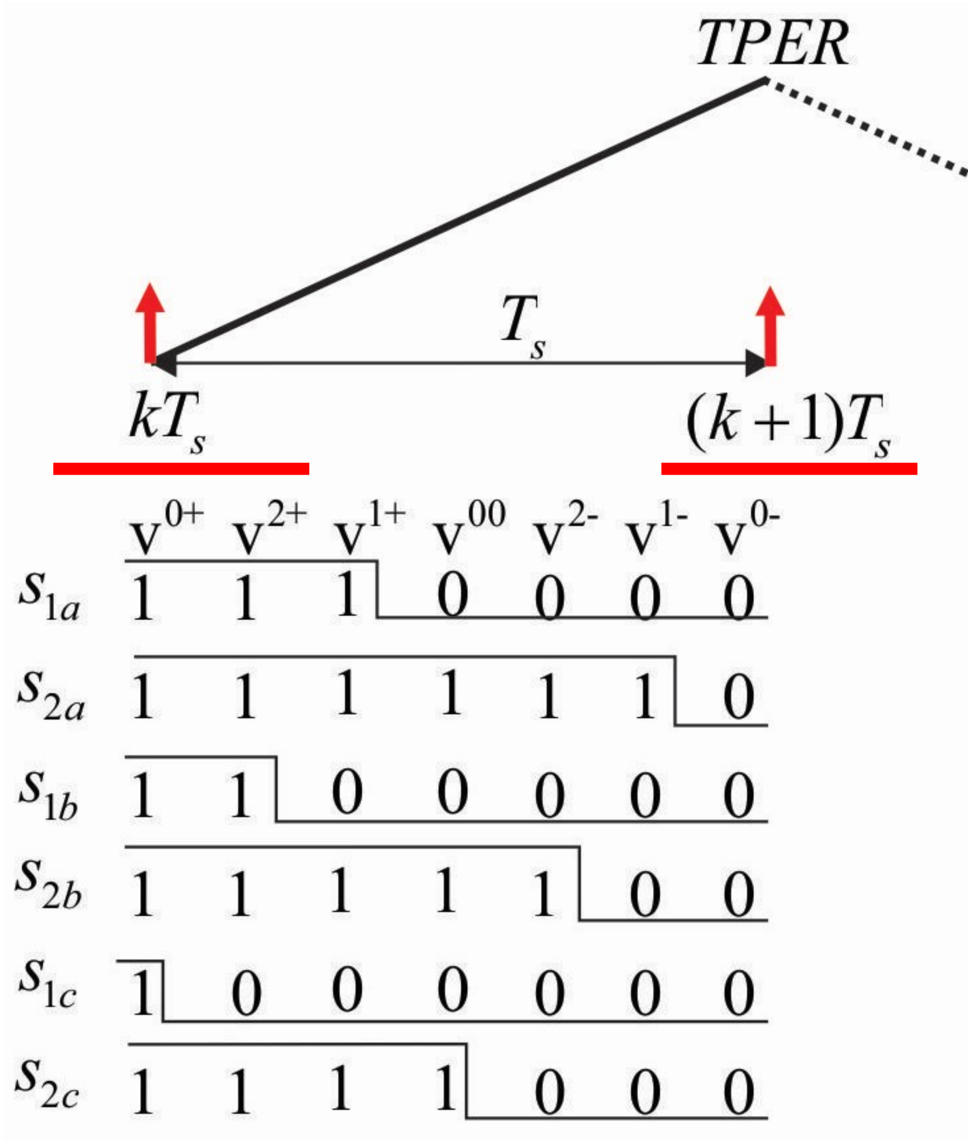
$$\mathrm{V}^{0+}\ \mathrm{V}^{2+}\ \mathrm{V}^{1+}\ \mathrm{V}^{00}\ \mathrm{V}^{2-}\ \mathrm{V}^{1-}\ \mathrm{V}^{0-}$$

3.3 - Space Vector Modulation - SVM

$$V^{0+} \quad V^{2+} \quad V^{1+} \quad V^{00} \quad V^{2-} \quad V^{1-} \quad V^{0-}$$

Sector 1

$$COMP_1 = COMPs_{1a} = (0.25d_0 + 0.5d_2 + 0.5d_1)TPER$$
$$COMP_2 = COMPs_{2a} = (0.75d_0 + d_2 + d_1)TPER$$
$$COMP_3 = COMPs_{1b} = (0.25d_0 + 0.5d_2)TPER$$
$$COMP_4 = COMPs_{2b} = (0.75d_0 + d_2 + 0.5d_1)TPER$$
$$COMP_5 = COMPs_{1c} = (0.25d_0)TPER$$
$$COMP_6 = COMPs_{2c} = (0.75d_0 + 0.5d_2 + 0.5d_1)TPER$$



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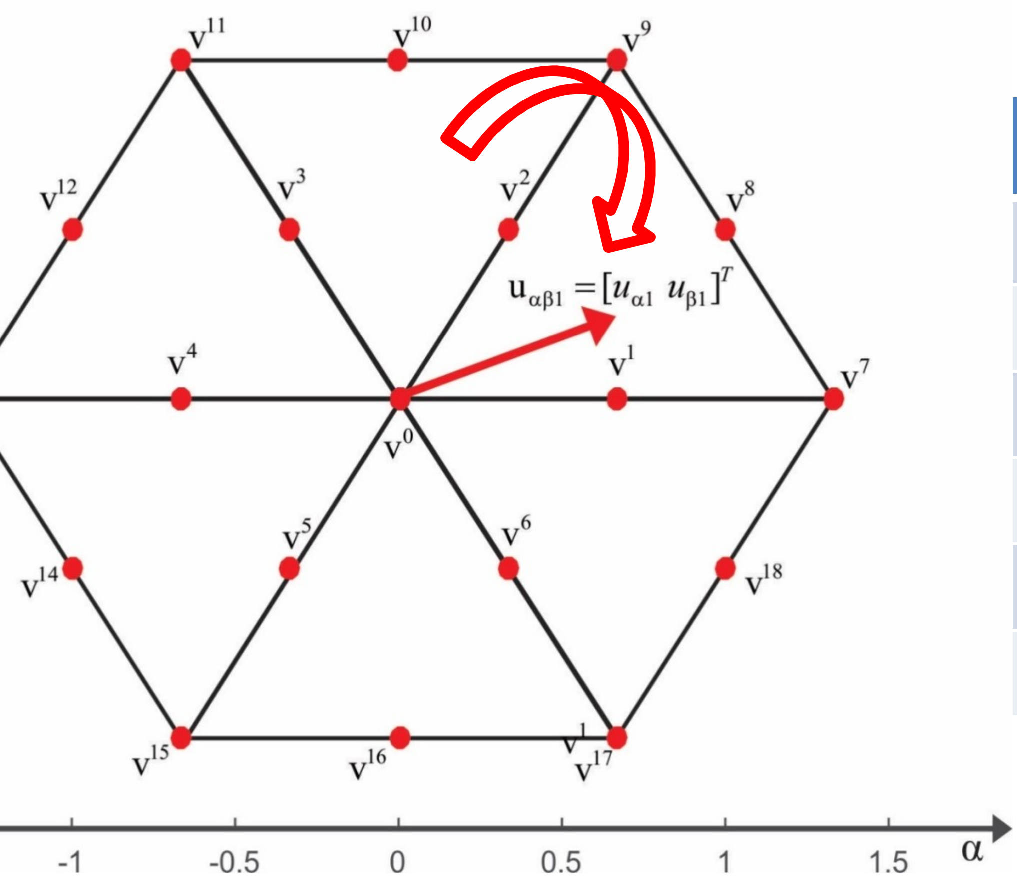
3.3 - Space Vector Modulation - SVM

$$\theta = \frac{\pi}{3}(\text{sextant}-1)$$

$$\begin{bmatrix} u_{\alpha 1} \\ u_{\beta 1} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} u_{\alpha} \\ u_{\beta} \end{bmatrix}$$



S1b	S2b	S1c	S2c	ic
COMP3	COMP4	COMP5	COMP6	ic
COMP3	COMP4	COMP5	COMP6	-ib
COMP1	COMP2	COMP3	COMP4	ia
COMP1	COMP2	COMP3	COMP4	-ic
COMP5	COMP6	COMP1	COMP2	ib
COMP5	COMP6	COMP1	COMP2	-ia

3.3 - Space Vector Modulation - SVM

econd Sextant:

$$v^{0} \quad v^{2} \quad v^{3} \quad v^{9} \quad v^{10} \quad v^{11}$$

$$i_a = -i_c$$

$$i_c = -i_b$$

ctor 1: Switching sequence for balanced voltages

$$v^{0+} \; v^{2+} \; v^{3+} \; v^{00} \; v^{2-} \; v^{3-} \; v^{0-}$$

Sector 1: Switching sequence fo
unbalanced voltages

$v_{C2} > v_{C1}$	$i_a > 0$	$i_c > 0$	Switching Sequence
0	0	0	v^{2+} v^{00} v^{3-}
0	0	1	v^{2+} v^{3+} v^{00}
0	1	0	v^{2-} v^{3-} v^{0-}
0	1	1	v^{3+} v^{00} v^{2-}
1	0	0	v^{3+} v^{00} v^{2-}
1	0	1	v^{2-} v^{3-} v^{0-}
1	1	0	v^{2+} v^{3+} v^{00}
1	1	1	v^{2+} v^{00} v^{3-}

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3.3 - Space Vector Modulation - SVM

Second Sextant:

v^2 v^9 v^{10}

ctor 2: Switching sequence for balanced voltages

v^{2+} v^9 v^{10} v^{2-}

Sector 2: Switching sequence for unbalanced voltages

$v_{C2} > v_{C1}$	$i_a > 0$	Switching Sequence
0	0	v^9 v^{10} v^{2-}
0	1	v^{2+} v^9 v^{10}
1	0	v^{2+} v^9 v^{10}
1	1	v^9 v^{10} v^{2-}

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3.3 - Space Vector Modulation - SVM

Second Sextant:

$$\vec{v}^{2} \quad \vec{v}^{3} \quad \vec{v}^{10}$$

ctor 3: Switching sequence for balanced voltages

$$\vec{v}^{2+} \ \vec{v}^{3+} \ \vec{v}^{10} \ \vec{v}^{2-} \ \vec{v}^{3-}$$

Sector 3: Switching sequence for unbalanced voltages

$v_{C2} > v_{C1}$	$i_a > 0$	$i_c > 0$	Switching Sequence
0	0	0	$\vec{v}^{2+}\ \vec{v}^{10}\ \vec{v}^{3-}$
0	0	1	$\vec{v}^{2+}\ \vec{v}^{3+}\ \vec{v}^{10}$
0	1	0	$\vec{v}^{10}\ \vec{v}^{2-}\ \vec{v}^{3-}$
0	1	1	$\vec{v}^{3+}\ \vec{v}^{10}\ \vec{v}^{2-}$
1	0	0	$\vec{v}^{3+}\ \vec{v}^{10}\ \vec{v}^{2-}$
1	0	1	$\vec{v}^{10}\ \vec{v}^{2-}\ \vec{v}^{3-}$
1	1	0	$\vec{v}^{2+}\ \vec{v}^{3+}\ \vec{v}^{10}$
1	1	1	$\vec{v}^{2+}\ \vec{v}^{10}\ \vec{v}^{3-}$

3.3 - Space Vector Modulation - SVM

Second Sextant:

v^{3} v^{10} v^{11}

ctor 4: Switching sequence for balanced voltages

v^{3+} v^{10} v^{11} v^{3-}

Sector 4: Switching sequence for unbalanced voltages

$v_{C2} > v_{C1}$	$i_c > 0$	Switching Sequence
0	0	v^{3+} v^{10} v^{11}
0	1	v^{10} v^{11} v^{3-}
1	0	v^{10} v^{11} v^{3-}
1	1	v^{3+} v^{10} v^{11}

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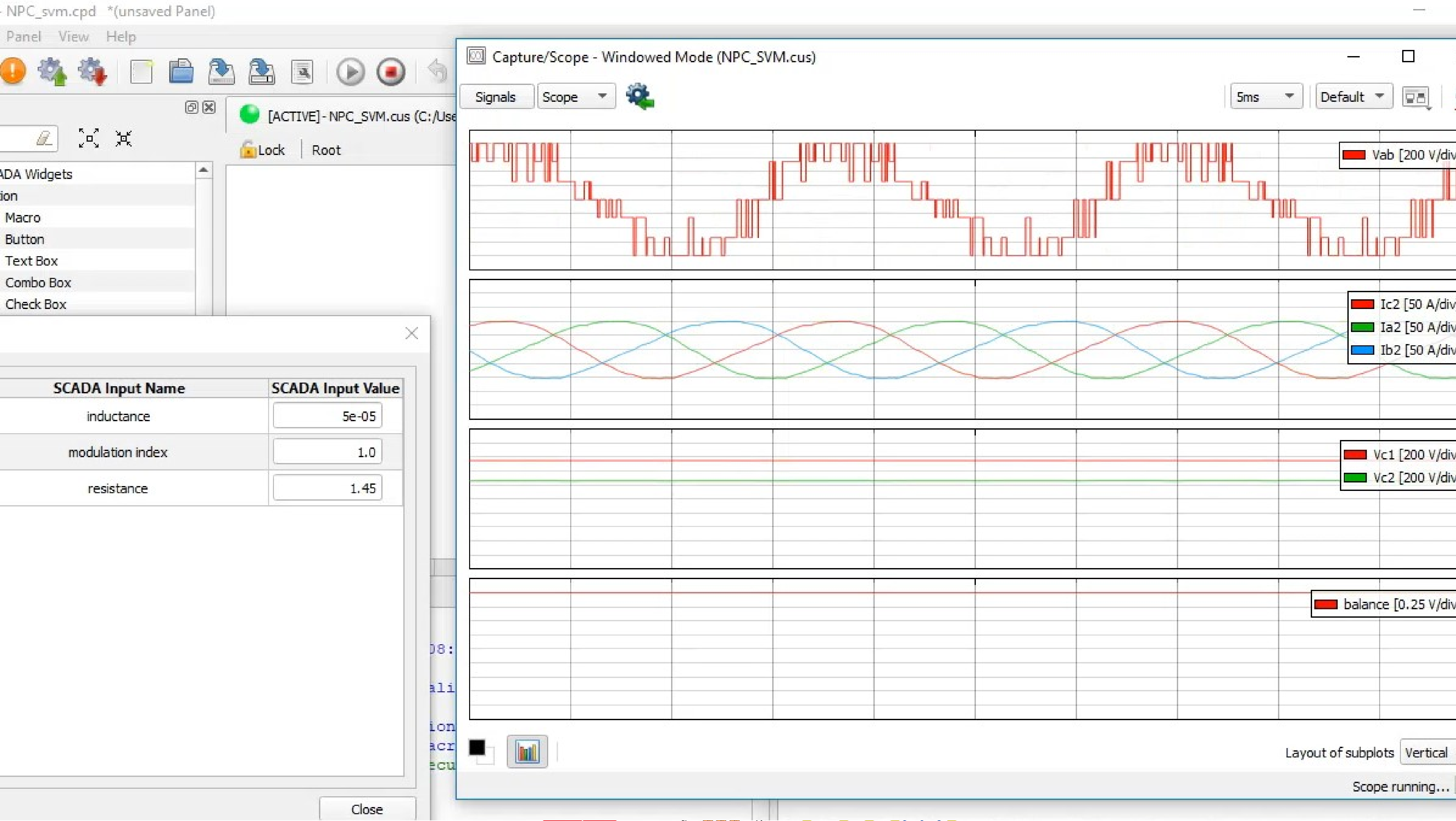

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3.3 - Space Vector Modulation – SVM LCL Filter Design

:

Slide Type Sub-Slide

```
print('Nominal Power ',repr(round(P_rated/1000,2)), 'kW')
print('Nominal Voltage',repr(round(V_line,2)), 'V')
print('Grid nominal frequecy',repr(round(fo,2)), 'Hz')
print('Dc bus voltage',repr(round(Udc,2)), 'V')
print('Switching frequency,  fsw=',repr(round(fs/1000,2)), 'kHz')
print('Inverter current ripple   ', repr(round(beta*100,4)), '%')
print('L1=', repr(round(L1*1000,2)), 'mH')
print('Cf=', repr(round(Cf*1000000,2)),'uF')
print('L2=', repr(round(L2*1000,2)), 'mH')
print('LCL resonant frequency fr=',repr(round(np.sqrt((L2+L1)/(L1*L2*Cf))/2/np.pi/1000,2)), 'kHz')
print ('Total inductance per phase,',repr(round((L1+L2)/Lb,2)),'pu')
print ('Capacitance per phase, ',repr(round(Cf/Cb,2)),'pu')
```

```
Nominal Power  100.0 kW
Nominal Voltage 380 V
Grid nominal frequecy 60 Hz
Dc bus voltage 800 V
Switching frequency,  fsw= 10.0 kHz
Inverter current ripple    30.0 %
L1= 0.08 mH
Cf= 183.7 uF
L2= 0.11 mH
LCL resonant frequency fr= 1.73 kHz
Total inductance per phase, 0.05 pu
Capacitance per phase,  0.1 pu
```

L=50uH
R=1.45
PF=1
ma=1

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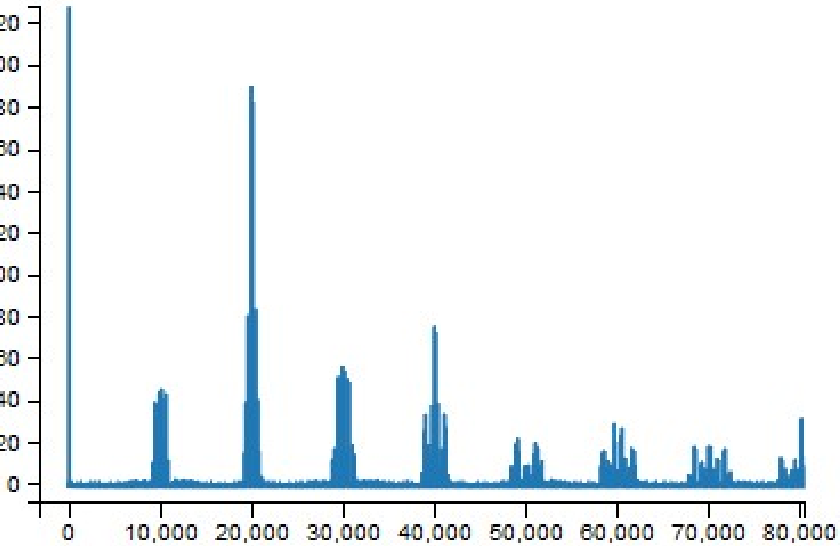
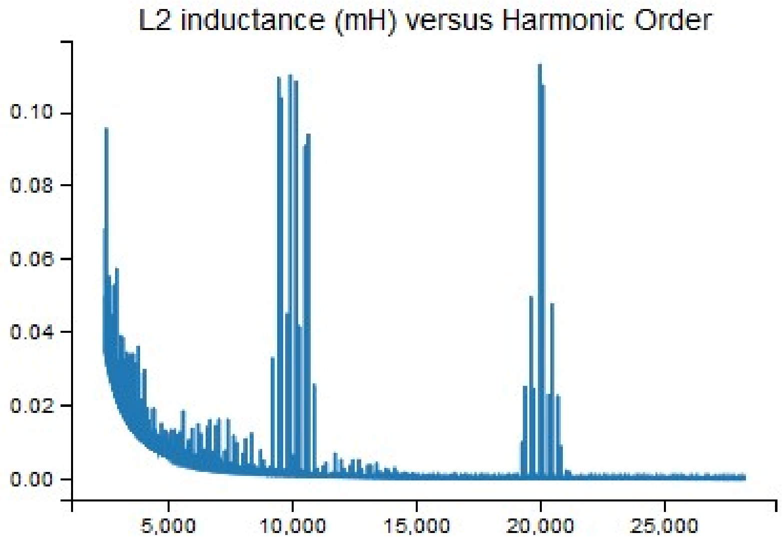
3.3 - Space Vector Modulation – SVM LCL Filter Design

L=2.6mH
R=1.0
PF=0.7
ma=1





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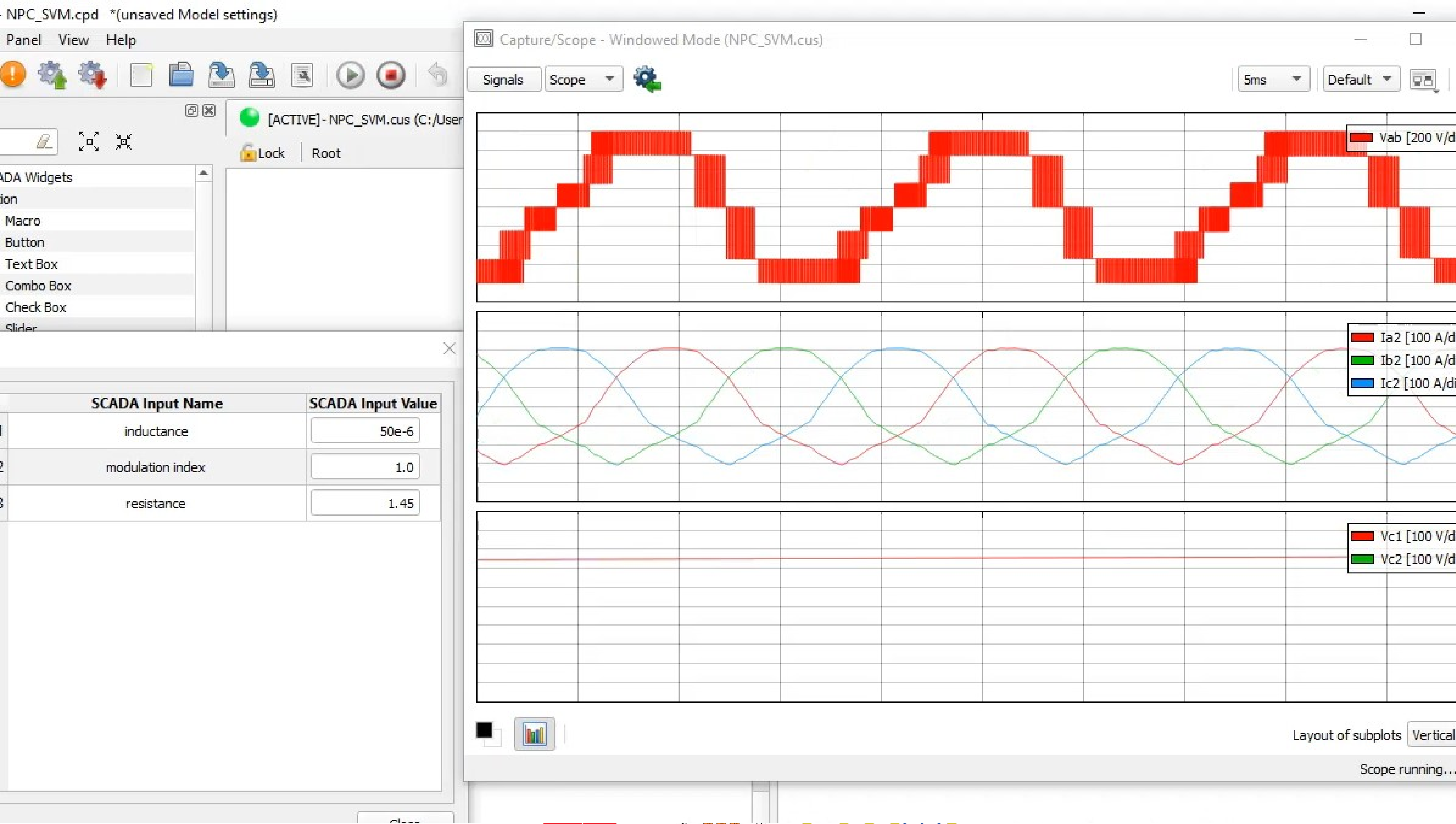
NPC_SVM.cpd *(unsaved Model settings)
Panel View Help
Capture/Scope - Windowed Mode (NPC_SVM.cus)
Signals
Scope
5ms
Default
[ACTIVE] - NPC_SVM.cus (C:/User
Lock
Root
ADA Widgets
ion
Macro
Button
Text Box
Combo Box
Check Box
Slider
SCADA Input Name
SCADA Input Value
inductance
50e-6
modulation index
1.0
resistance
1.45
Vab [200 V/d
Ia2 [100 A/d
Ib2 [100 A/d
Ic2 [100 A/di
Vc1 [100 V/d
Vc2 [100 V/d
Layout of subplots
Vertical
Scope running...

Summary

- SPWM with PD is not capable of balancing the dc bus capacitor voltages.

- The described Carrier-based Modulation with Common-Mode Voltage Injection make it possible to balance dc voltage but line to line voltage spectra are sensitive to the power factor and modulation index.

- With Space Vector Modulation – SVM the above mentioned limitations can be mitigated.

Modulation approaches for grid-tied inverters

3. Test-Driven Design

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Metrics to Compare Modulation Strategies

- Total Harmonic Distortion or filter required to meet grid code
- Number of commutations, semiconductor losses and losses distribution, semiconductors temperature.
- Stresses on converter internal variables
- Complexity of implementation

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Metrics selected to compare modulation strategies

- Total rated current distortion

$$\%TRD = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_{rated}} 100$$

- Weighted Total Harmonic Distortion

$$\%\,\mathrm{wTHD} = \frac{\sqrt{\sum_{h=2}^{50} \left(\frac{V_h}{h}\right)^2}}{V_{DC}} 100$$

- Number of commutation per semiconductor switch

- RMS current into the dc link capacitor midpoint

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Test Driven Design

Test 1: *ma* and PF vary.

Test 2: S and PF vary. *ma* is kept constant *ma*=1.

Test 3: Linearity

3.1 T

3.5 Test 2: a) Number of commutations per second

3 3.9 Test 3: Linearity of the modulation algorithm

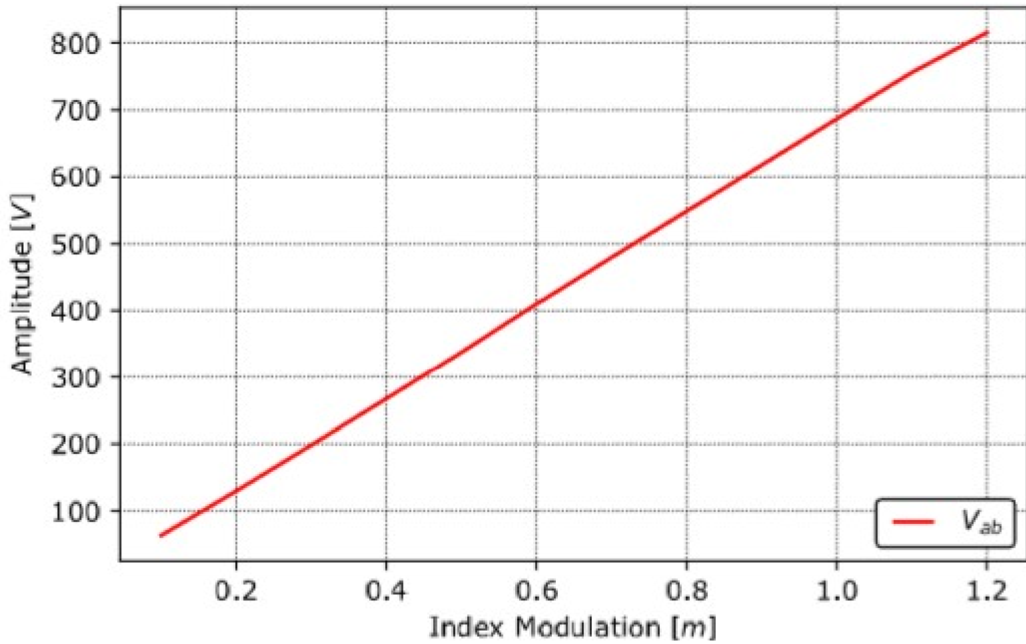

Figure 1 - Peak value of the fundamental amplitude of V_{ab} as a function of Index Modu

1.2	237.79	231.28	225.31	215.72	207.97	194.59	161.79	142.47	119.34

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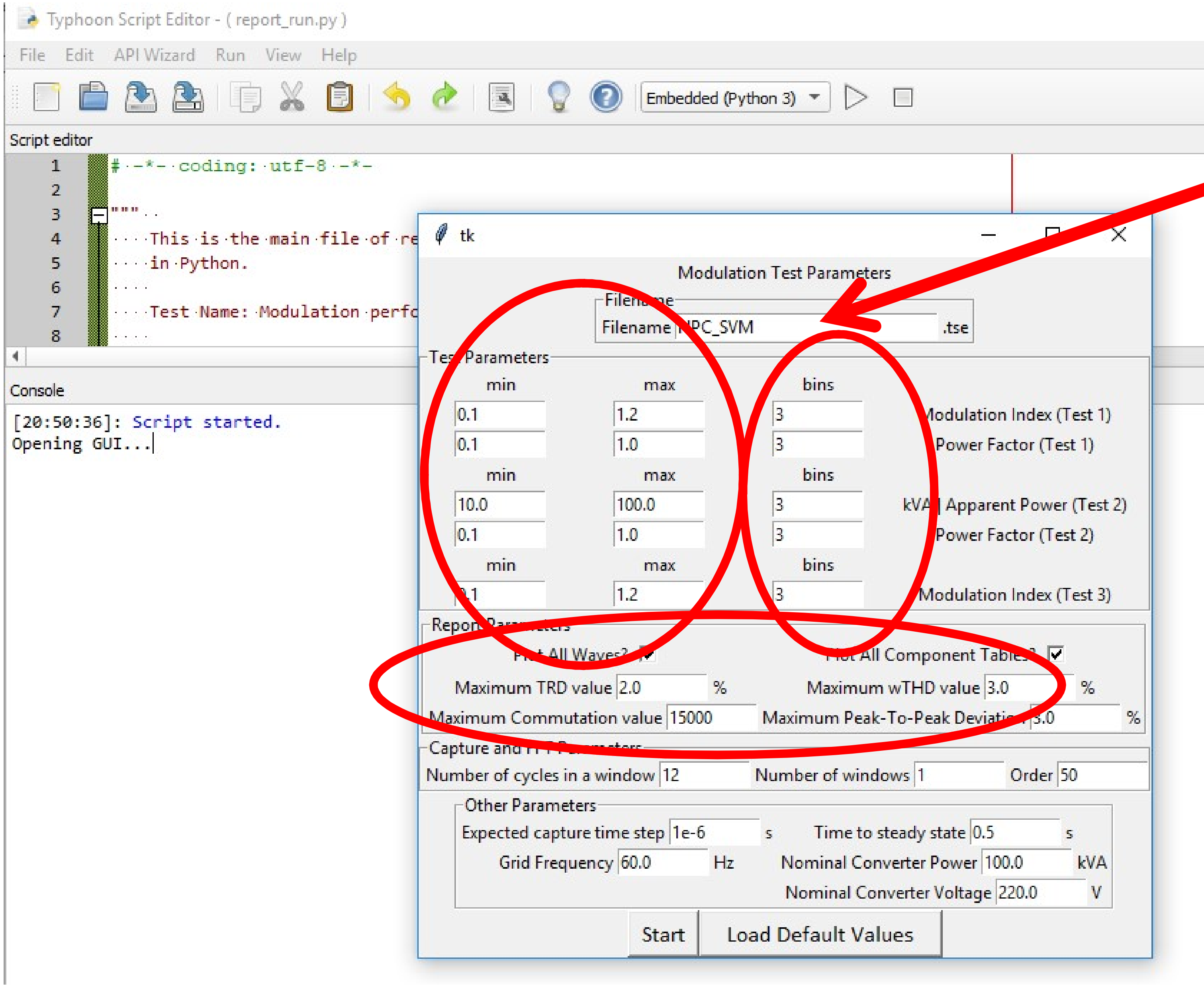
Tests parameters



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Test Driven Design for the NPC:
Carrier-based Modulation with Common-Mode Voltage Injection

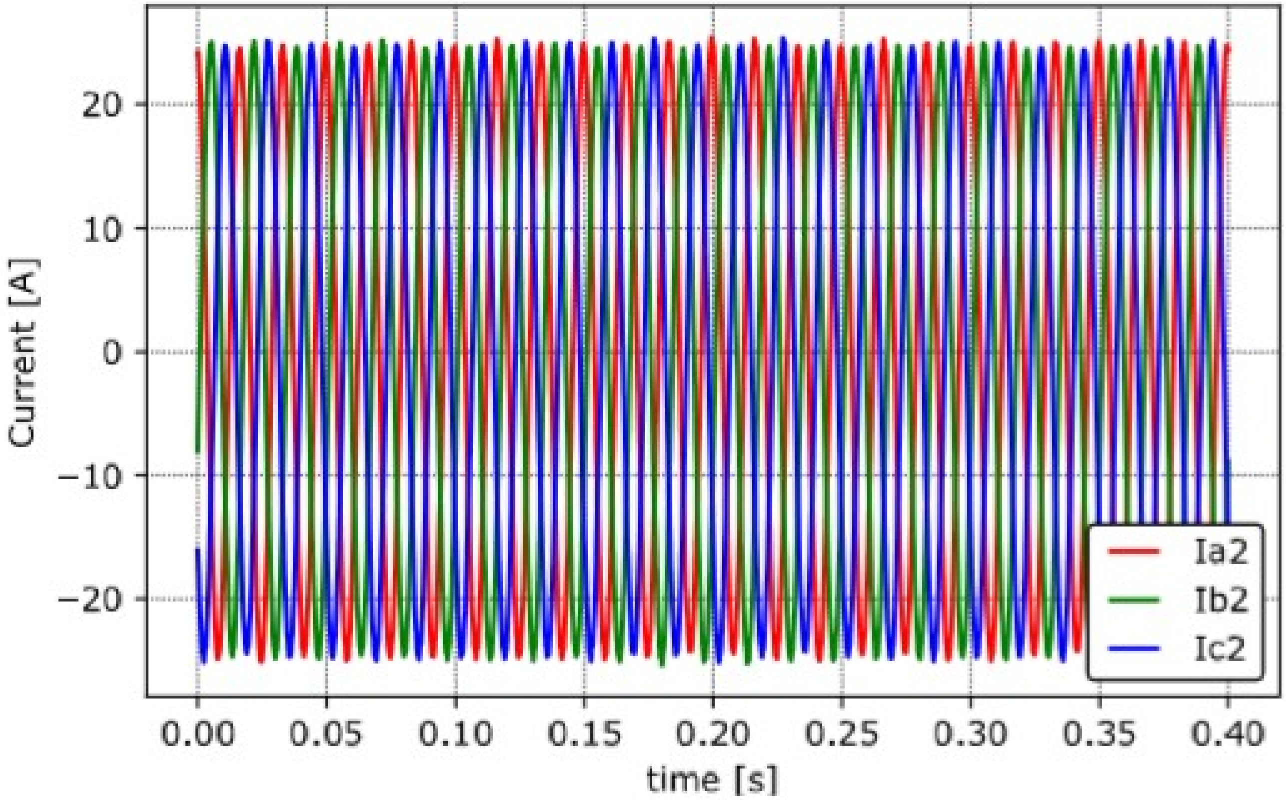

Figure 6 - Grid-side currents for the Test 1. power factor= 0.1 and modulation index= 0.1.

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Test Driven Design for the NPC:
Carrier-based Modulation with Common-Mode Voltage Injection

3.1 Test 1: a) Number of commutations per second

3.5 Test 2: a) Number of commutations per second

3.2 Test 1: b) Weighted Total Harmonic Distortion (wTHD)

3.7 Test 2: c) Total Rated-Current Distortion (TRD)

Table 17 - Average value of TRD in %. **Lines:** constant apparent power. **Columns:** constant power factor

	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
10 kVA	0.14	0.1	0.17	0.19	0.18	0.14	0.12	0.08	0.08	0.22
20 kVA	0.16	0.14	0.07	0.1	0.14	0.17	0.18	0.2	0.21	0.88
30 kVA	0.1	0.16	0.14	0.07	0.08	0.1	0.15	0.19	0.33	1.37
40 kVA	0.13	0.16	0.17	0.15	0.08	0.08	0.13	0.21	0.34	2.01
50 kVA	0.16	0.18	0.16	0.2	0.11	0.12	0.13	0.23	0.38	2.48
60 kVA	0.19	0.15	0.19	0.19	0.13	0.13	0.15	0.27	0.38	2.55
70 kVA	0.21	0.2	0.18	0.24	0.16	0.15	0.16	0.32	0.47	2.42
80 kVA	0.23	0.2	0.23	0.23	0.17	0.17	0.2	0.25	0.42	2.72
90 kVA	0.23	0.21	0.2	0.27	0.17	0.17	0.23	0.29	0.5	2.75
100 kVA	0.31	0.23	0.24	0.25	0.19	0.2	0.24	0.29	0.57	2.89

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Test Driven Design for the NPC:
Space Vector Modulation

3.1 Test 1: a) Number of commutations per second

3.5 Test 2: a) Number of commutations per second

3.6 Test 2: b) Weighted Total Harmonic Distortion (wTHD)

Table

10
20
30
40
50
60
70
80
90
100

3.7 Test 2: c) Total Rated-Current Distortion (TRD)

Table 17 - Average value of TRD in %. **Lines:** constant apparent power. **Columns:** constant power factor

	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
10 kVA	0.09	0.05	0.05	0.06	0.09	0.09	0.08	0.07	0.06	0.2
20 kVA	0.08	0.07	0.06	0.05	0.07	0.06	0.05	0.06	0.1	0.38
30 kVA	0.08	0.08	0.08	0.06	0.06	0.05	0.05	0.07	0.12	0.48
40 kVA	0.09	0.09	0.08	0.09	0.08	0.08	0.08	0.1	0.18	0.57
50 kVA	0.12	0.1	0.08	0.11	0.09	0.12	0.11	0.12	0.23	0.69
60 kVA	0.2	0.08	0.12	0.11	0.12	0.13	0.15	0.15	0.28	0.74
70 kVA	0.19	0.14	0.15	0.14	0.12	0.13	0.17	0.21	0.3	0.87
80 kVA	0.19	0.18	0.15	0.18	0.16	0.16	0.23	0.31	0.35	0.98
90 kVA	0.23	0.24	0.22	0.22	0.27	0.23	0.31	0.23	0.39	1.07
100 kVA	0.28	0.29	0.25	0.26	0.34	0.29	0.28	0.3	0.54	1.13

Test Driven Design for the NPC:
Space Vector Modulation

st Sextant

ctor 1: Switc

V^{2+} V^{1+}

TPER

ond Sexta

l_1)TPER

tor 1: Switch

).5d_1)TP

V^{2+} V^{3+}

3.1 Test 1: a) Number of commutations per second

Table 7 - Number of commutations per second for switches S1 and S3 of Phase A. **Lines:** constant modulation index. **Columns:** constant power factor

	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.1	13280	13280	13280	13280	13280	13280	13280	13280	13280	13280
0.2	13280	13280	13280	13280	13280	13280	13280	13280	13280	13280
0.3	13275	13280	13280	13280	13280	13280	13280	13280	13280	13280
0.4	13280	13280	13280	13280	13280	13280	13280	13280	13280	13280
0.5	13360	13360	13360	13360	13360	13360	13360	13360	13360	13355
0.6	13360	13360	13360	13355	13360	13360	13360	13360	13360	13360
0.7	12200	12200	12200	12200	12200	12200	12200	12200	12200	12200
0.8	11360	11360	11360	11360	11360	11360	11360	11360	11360	11360
0.9	10720	10720	10720	10720	10720	10720	10720	10720	10720	10720
1.0	10280	10280	10280	10280	10280	10280	10280	10280	10280	10280
1.1	9960	9960	9960	9960	9960	9960	9960	9960	9960	9960
1.2	5920	5920	5920	5920	5920	5920	5920	5920	5920	5920

Summary

- The modulation strategy has an impact on the performance of PWM inverters
- Carrier based approaches are straightforward to analyze and implement
- Space vector modulation is more general approach; however, for two level converters it may result in similar performance as its carrier based counterpart.
- In multilevel converters, the control of the internal variables plays a key role for the selection of the modulation approach.
- TDD demonstrated to be a valuable tool to benchmark modulation approach by covering a wide range of operating conditions.

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Credits

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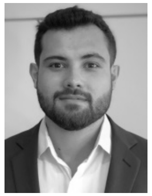
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