

# **Transitorios por faltas num Sistema de Transmissão HVDC: LCC – VSC, 1000MW, 500kV, 2000 Km**

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## OBJETIVOS

### Objetivo Principal:

- ✓ Construir um Sistema de transmissão baseado em HVDC de topologia híbrida para um bipolo, especificamente uma configuração de terminais híbridos LCC-VSC, para 1000MW a 500 kV DC polo a polo.
- ✓ Realizar no Software ATP Draw a configuração bipolar considerando as unidades conversoras, ELO DC, compensadores de potência reativa, filtros AC e filtros DC.

### Objetivo Específico:

- ✓ Realizar faltas polo terra e no meio da linha, e reduzir os transitórios de sobretensões e picos de correntes produzidas pelo defeito.
- ✓ Medir a tensão DC e corrente DC no início, meio, e final da linha para analisar os transitórios.
- ✓ Medir a tensão AC e corrente AC nos barramentos dos transformadores antes e depois dos conversores.

# TEMARIO



Introdução



Modelagem e Topologias HVDC



Modelagem do Caso de Estudo do Sistema HVDC



Casos de estudo HVDC



Resultados



Conclusões



## Introdução

Source: ABB



### 1893

ABB starts providing power to the mining industry

Revolução industrial 1760 - 1840



### 1954

The world's first commercial HVDC link at Gotland, Sweden

The 20 MW, 100 kV



### 1997

The world's first VSC HVDC installation

The first experimental (VSC) HVDC system was tested in Hellisjón, Sweden. It was a 3-MW,  $\pm 10$ -kV overhead line two level VSC.



### 2013

Hybrid HVDC Breaker, solving a 100-year old technology puzzle enabling the DC-grids of the future.



### 2017

VSC HVDC highest performance ever – 3,000 MW, 640 kV, 2,000 km



### 1928

Dr Uno Lamm began developing HVDC in Ludvika, Sweden



### 1960s

Mercury arc valves replaced with thyristor semiconductor valves



### 2010

The world's first 800 kV UHVDC link at Xiangjiaba-Shanghai, China



### 2014

Complete 1,100 kV UHVDC system developed.



### The Future

DC support in AC grids  
DC grids

"The best way to predict the future is to create it"  
- Abraham Lincoln

- The world's first 1,100 kV transformer for the world's largest HVDC project in China
- Development, manufacturing and testing in the lead factory in Nuremberg
- The world's most powerful HVDC transformer with 587 MVA





## Introdução

HVDC – High Voltage Direct Current:

1. Tem desenvolvimento desde os 1954 (Sweden - Gotland) y atualmente tem madurez.
2. Existem mais de 200 conexiones de HVDC no mundo – Jovick, 2019.
3. São características por suas linhas de transmissão de longo comprimento. Torna-se tecnologicamente e economicamente viáveis sobre AC para 700 km – 800 km em OHL e 35-40km em cabos subterrâneos.
4. Transferência de grandes potências em grandes escalas sobre longas distancias.
5. Outras aplicações como transmissão de potência por cabos submarinos em sistemas fotovoltaicos, eólicos, sistemas isolado, offshore, wind farm ou oil platforms.
6. Facilita a interligações entre sistemas assíncronos AC: Itaipu, Brasil – Paraguay 50/60 Hz.
7. Interconexões entre mercados elétricos. Jovick, 2019.
8. Suporta maior estabilidade em AC e fornece resiliencia a black outs.
9. HVDC típicas  $\pm 500\text{kV}$  e UHVDC  $\pm 800\text{kV}$ , 4500 A.  
China - fases experimentais  $\pm 1100\text{kV}$ , 10-13GW, >2000 Km.





# Modelagem e Topologias HVDC

## Elementos do HVDC:

1. Conversor

2. Transformadores Conversores

3. ELO DC

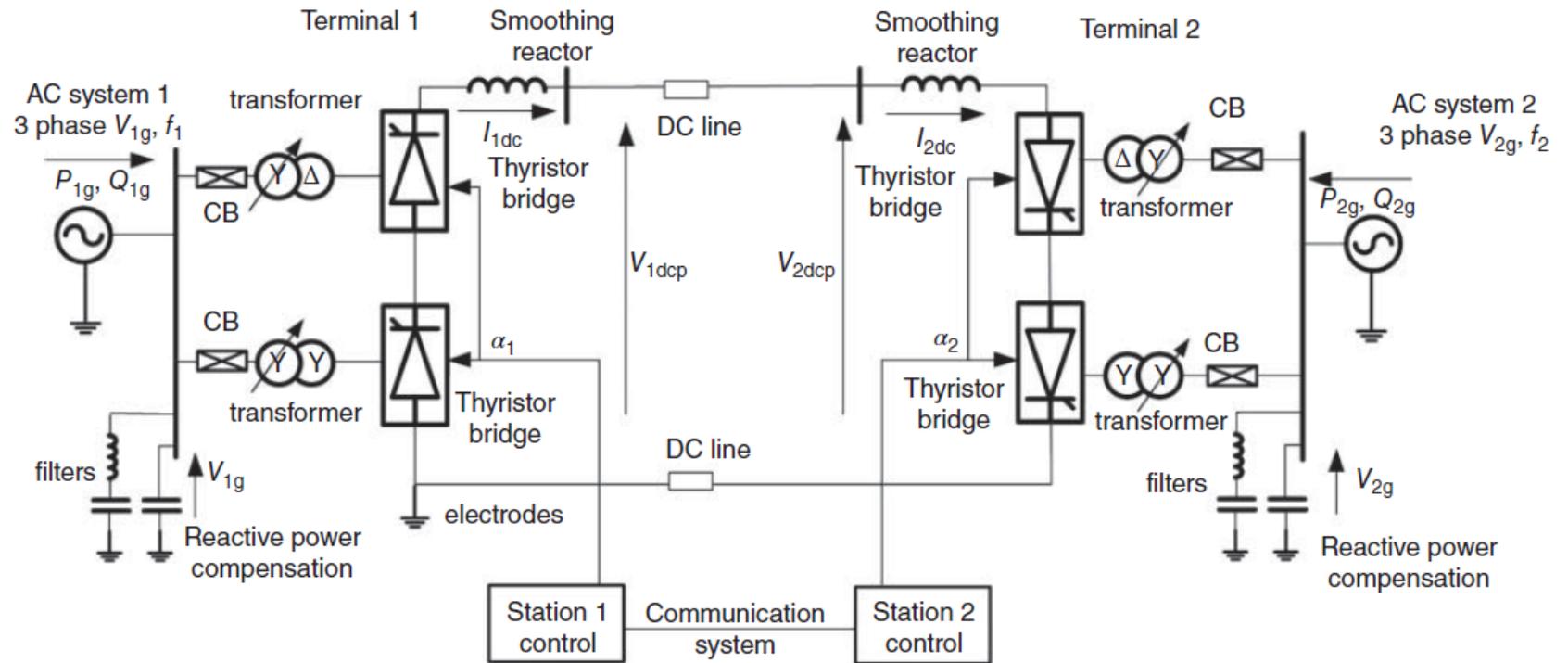
4. Reator de Alisamento

5. Compensadores Reativos

6. Filtros AC

7. Filtros DC

8. Controle e comunicação



Typical HVDC schematic (12-pulse monopole with metallic return). Jovick-2019

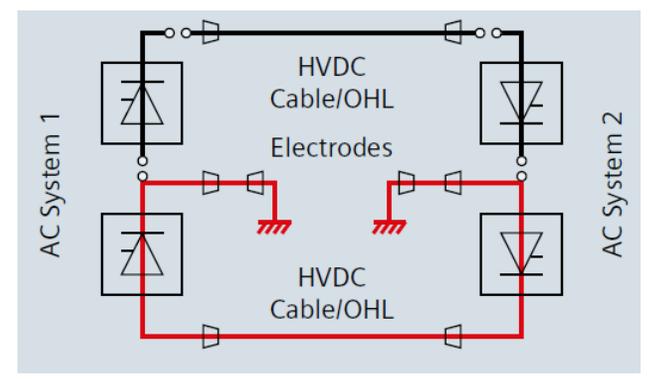
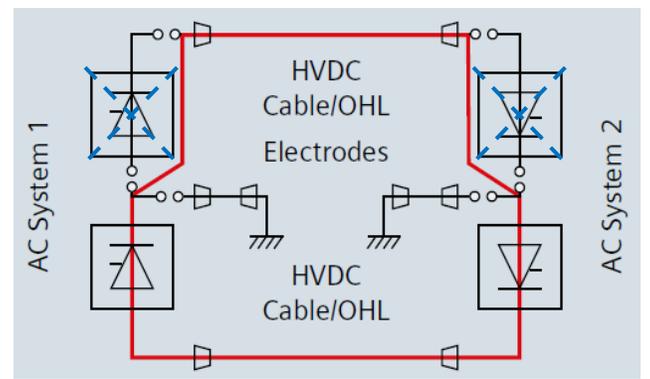
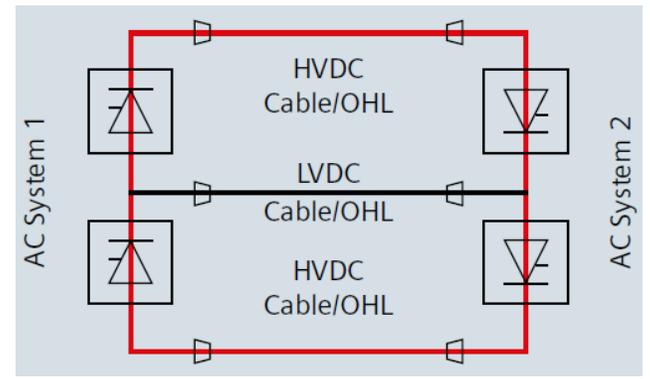
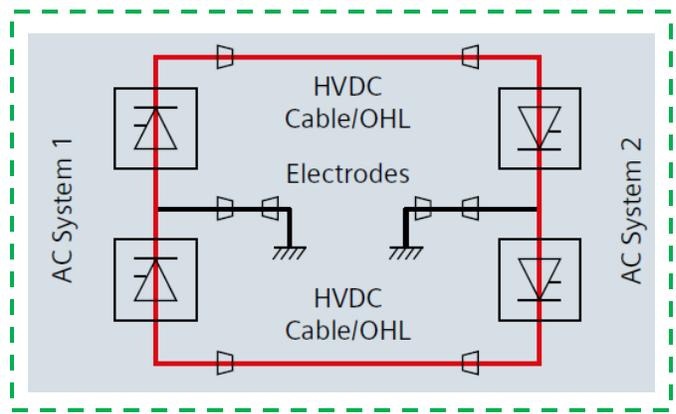
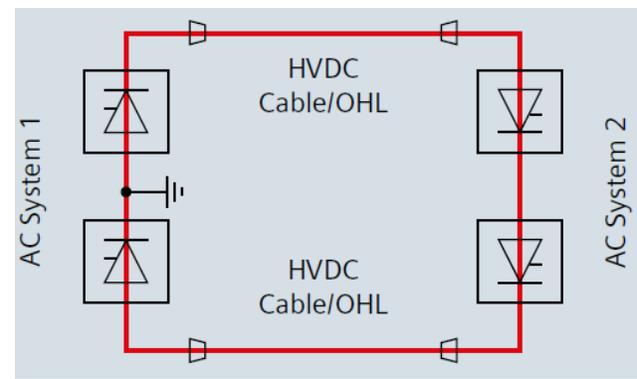
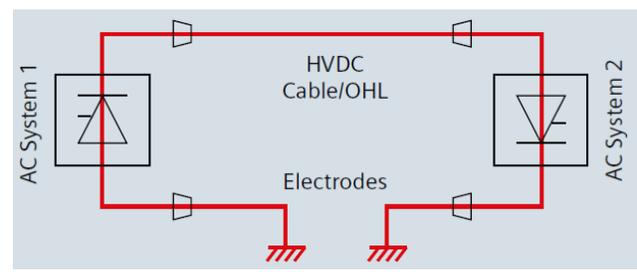


# Modelagem e Topologias HVDC

## Topologias

- 1.1 Monopolar com retorno por terra
- 1.2 Monopolar com retorno metálico
- 2.1 Bipolar com retorno por terra
- 2.2 Bipolar com retorno metálico
- 3.1 Back-to-back

Source: Siemens





## Basic topologies of four hybrid HVDC systems

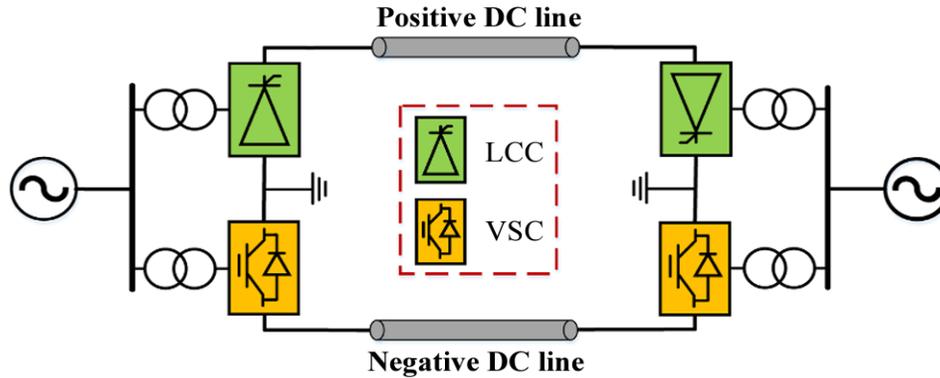
### Topologias Híbridas

1. Polo híbrido

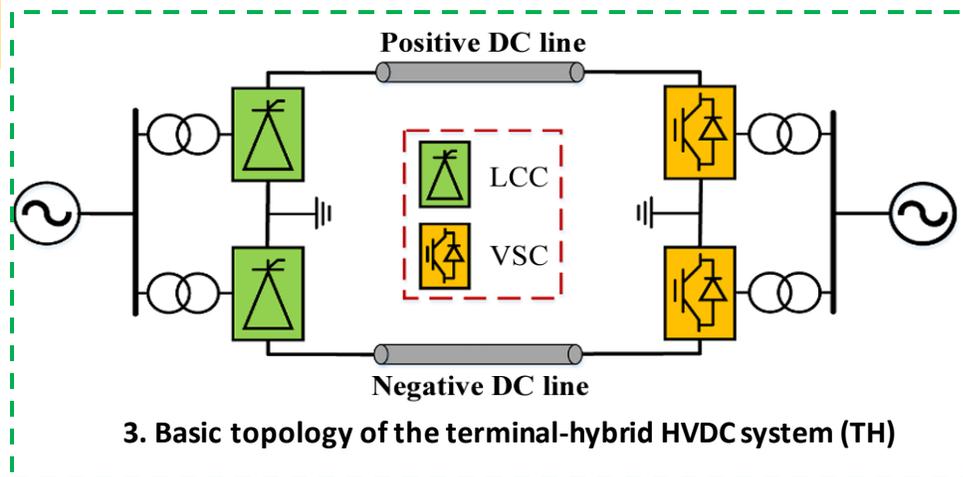
2. Serie híbrido

3. Terminal híbrido

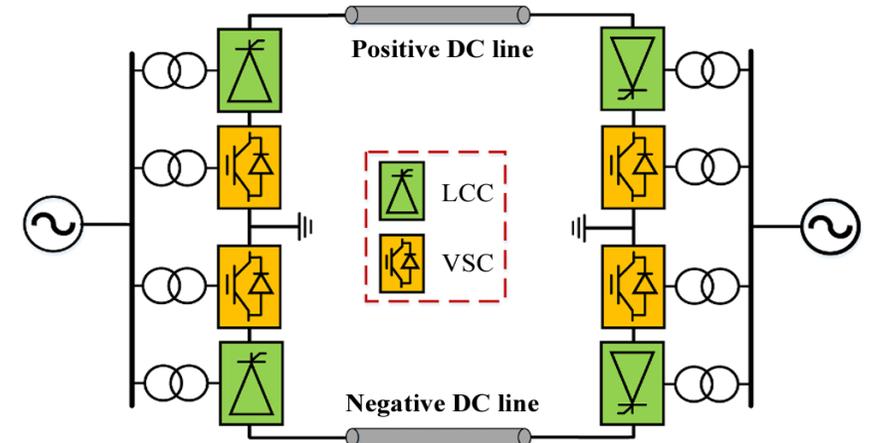
4. Paralelo híbrido



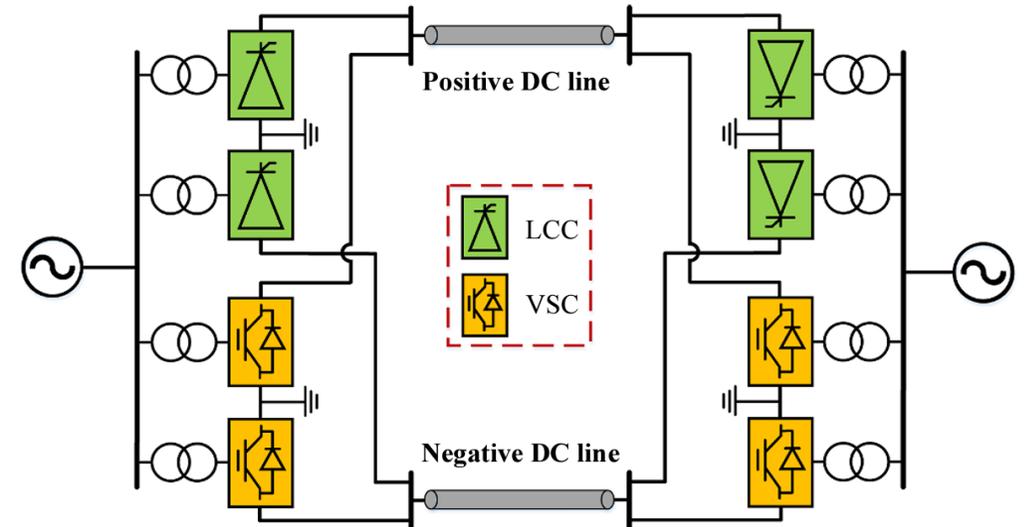
1. Basic topology of the pole-hybrid HVDC system (PH)



3. Basic topology of the terminal-hybrid HVDC system (TH)



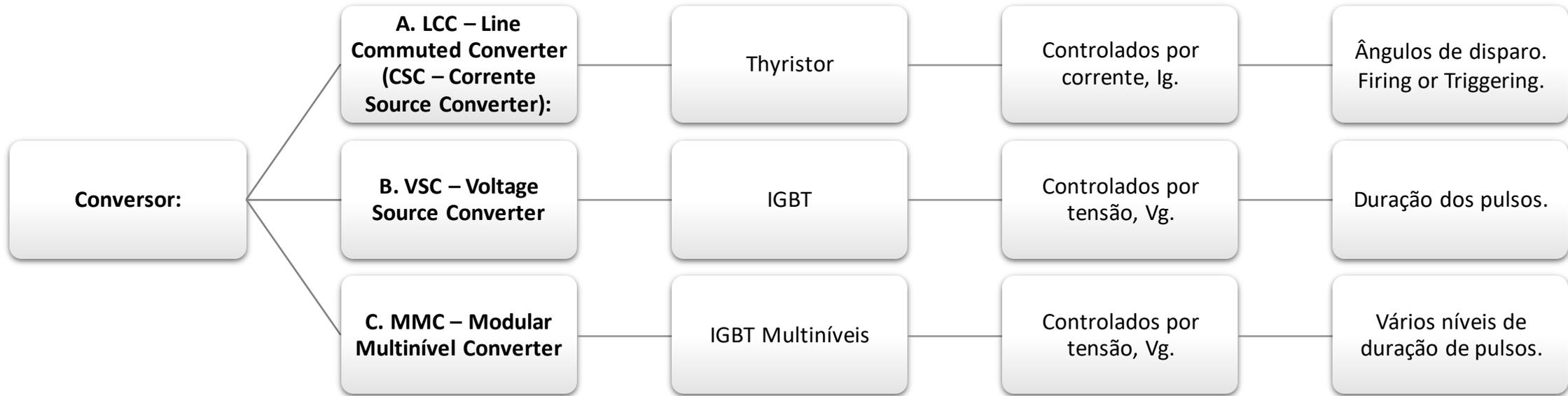
2. Basic topology of the series converter-hybrid HVDC system (SCH)



4. Basic topology of the parallel converter-hybrid HVDC system (PCH)



# Modelagem e Topologias HVDC

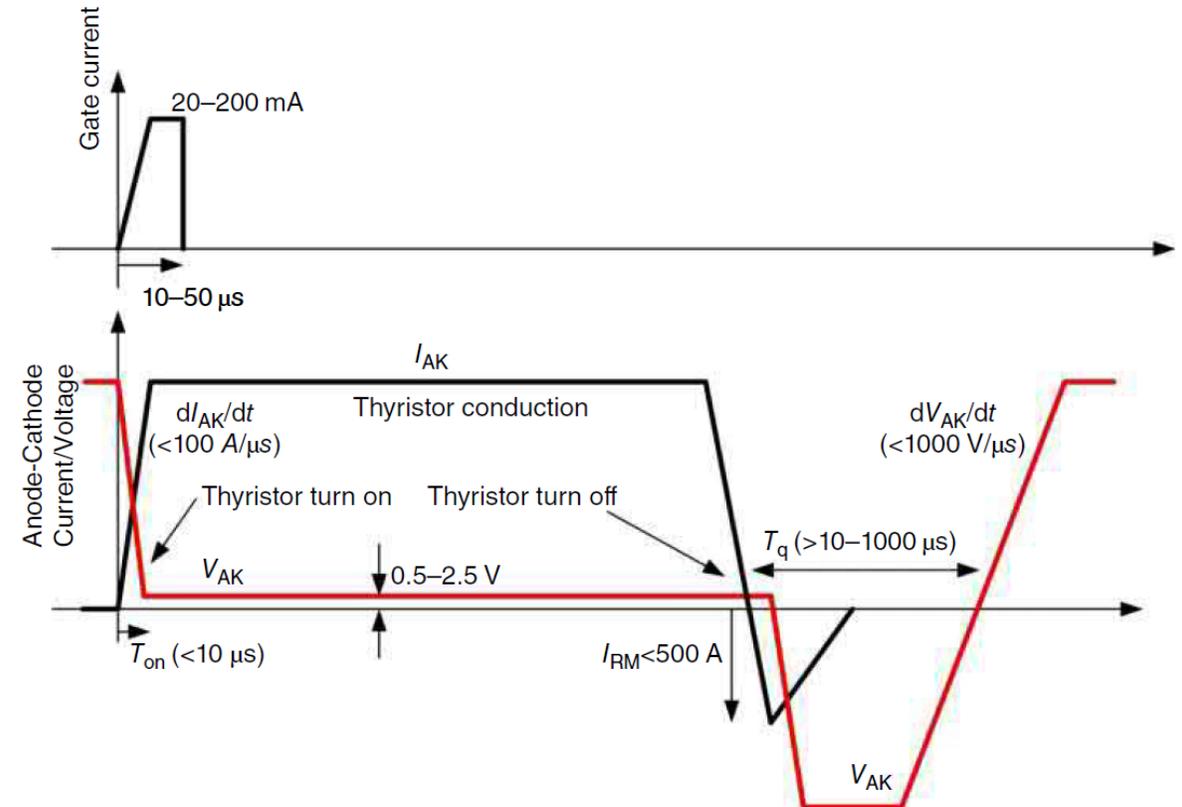
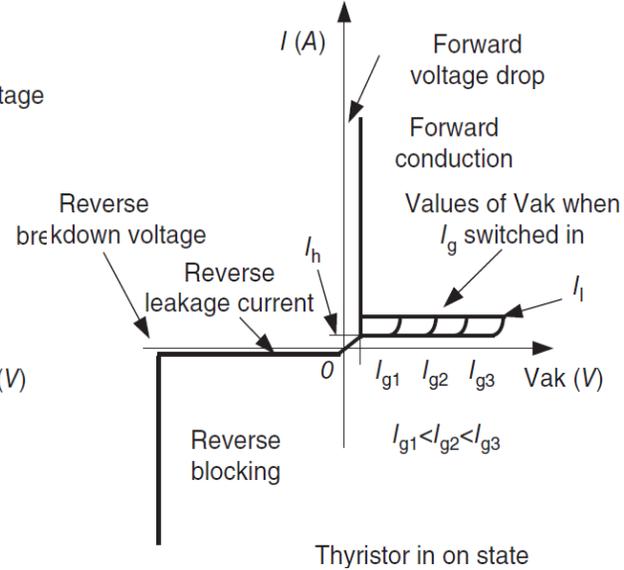
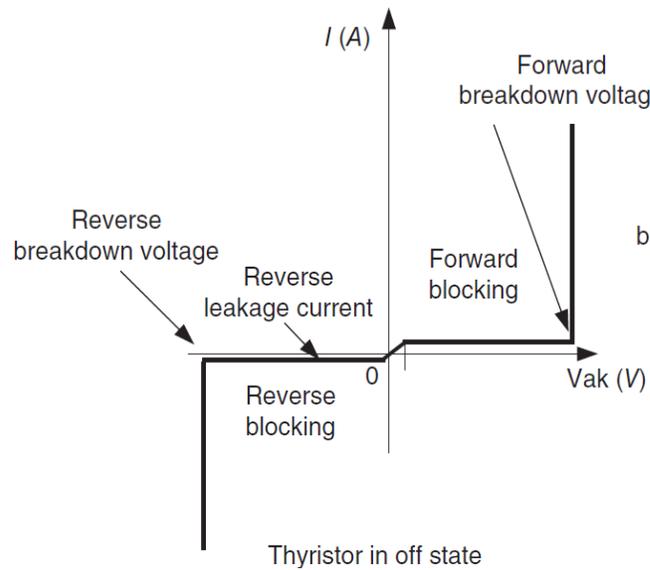
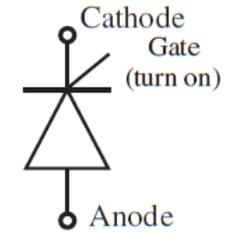
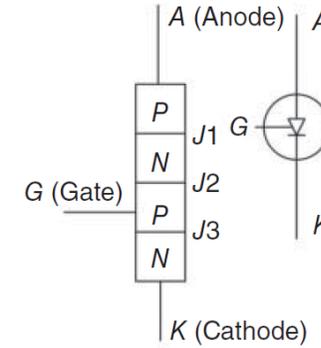
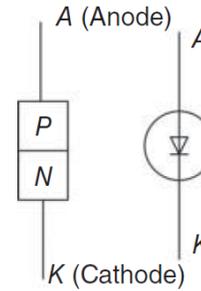




# Modelagem e Topologias HVDC

A. LCC – Line Commutated Converter

Thyristor





# Modelagem e Topologias HVDC

A. LCC – Line Commuted Converter

Thyristor



Date:- 30 Sept 2014  
Data Sheet Issue:- 2

## Fast Turn-off Thyristor Type P0295WC12x

### Absolute Maximum Ratings

|           | VOLTAGE RATINGS                                 | MAXIMUM LIMITS | UNITS |
|-----------|-------------------------------------------------|----------------|-------|
| $V_{DRM}$ | Repetitive peak off-state voltage, (note 1)     | 1200           | V     |
| $V_{DSM}$ | Non-repetitive peak off-state voltage, (note 1) | 1200           | V     |
| $V_{RRM}$ | Repetitive peak reverse voltage, (note 1)       | 1200           | V     |
| $V_{RSM}$ | Non-repetitive peak reverse voltage, (note 1)   | 1300           | V     |

|                | OTHER RATINGS                                                          | MAXIMUM LIMITS     | UNITS       |
|----------------|------------------------------------------------------------------------|--------------------|-------------|
| $I_{T(AV)}$    | Mean on-state current, $T_{sink}=55^{\circ}C$ , (note 2)               | 295                | A           |
| $I_{T(AV)}$    | Mean on-state current, $T_{sink}=85^{\circ}C$ , (note 2)               | 192                | A           |
| $I_{T(AV)}$    | Mean on-state current, $T_{sink}=85^{\circ}C$ , (note 3)               | 109                | A           |
| $I_{T(RMS)}$   | Nominal RMS on-state current, $T_{sink}=25^{\circ}C$ , (note 2)        | 599                | A           |
| $I_{T(D.C.)}$  | D.C. on-state current, $T_{sink}=25^{\circ}C$ , (note 4)               | 480                | A           |
| $I_{TSM}$      | Peak non-repetitive surge $t_p=10ms$ , $V_{RM}=0.6V_{RRM}$ , (note 5)  | 2.7                | kA          |
| $I_{TSM2}$     | Peak non-repetitive surge $t_p=10ms$ , $V_{RM}\leq 10V$ , (note 5)     | 2.97               | kA          |
| $I^2t$         | $I^2t$ capacity for fusing $t_p=10ms$ , $V_{RM}=0.6V_{RRM}$ , (note 5) | $36.5 \times 10^3$ | $A^2s$      |
| $I^2t$         | $I^2t$ capacity for fusing $t_p=10ms$ , $V_{RM}\leq 10V$ , (note 5)    | $44.1 \times 10^3$ | $A^2s$      |
| $(di/dt)_{cr}$ | Maximum rate of rise of on-state current (repetitive), (Note 6)        | 500                | A/ $\mu s$  |
| $(di/dt)_{cr}$ | Maximum rate of rise of on-state current (non-repetitive), (Note 6)    | 1000               | A/ $\mu s$  |
| $V_{RGM}$      | Peak reverse gate voltage                                              | 5                  | V           |
| $P_{G(AV)}$    | Mean forward gate power                                                | 1.5                | W           |
| $P_{GM}$       | Peak forward gate power                                                | 60                 | W           |
| $V_{GD}$       | Non-trigger gate voltage, (Note 7)                                     | 0.25               | V           |
| $T_{HS}$       | Operating temperature range                                            | -40 to +125        | $^{\circ}C$ |
| $T_{stg}$      | Storage temperature range                                              | -40 to +150        | $^{\circ}C$ |



Asymmetric - Capsule Type  
Series Details

Asymmetric Thyristors

$V_{DRM}$  (V): 2400, 2800

$V_{RRM}$  (V): 10, 30

$I_{TAV}$  @  $T_k=55^{\circ}C$  (A): 516, 1237



Distributed Gate - Capsule Type  
Series Details

Distributed Gate Thyristors

$V_{DRM}$  (V): 800, 1000, 1200, 1400, 1600, 1800, 2000, 2100, 2200, 2400 more

$V_{RRM}$  (V): 800, 1000, 1200, 1400, 1600, 1800, 2000, 2100, 2200, 2400 more

$I_{TAV}$  @  $T_k=55^{\circ}C$  (A): 472, 487, 577, 633, 717, 736, 809, 830, 878, 929 more



Fast Turn Off - Capsule Type  
Series Details

Fast Switching Thyristors

$V_{RRM}-V_{DRM}$  (V): 400, 600, 800, 1200

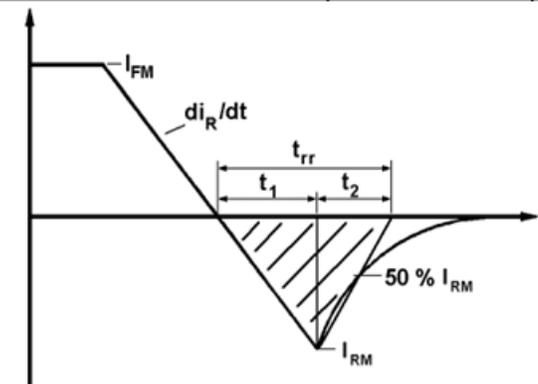
$I_{TAV}$  @  $T_k=55^{\circ}C$  (A): 295, 327, 366, 367, 389, 515, 848, 1007, 1110

$I_{TSM}$  10ms Half Sine Wave (A): 2700, 3250, 3600, 4700, 5000, 6500, 8750, 9500, 12300

### 4.0 Repetitive dv/dt

Higher dv/dt selections are available up to 1000V/ $\mu s$  on request.

|                |                                                                     |      |            |
|----------------|---------------------------------------------------------------------|------|------------|
| $(di/dt)_{cr}$ | Maximum rate of rise of on-state current (repetitive), (Note 6)     | 500  | A/ $\mu s$ |
|                | Maximum rate of rise of on-state current (non-repetitive), (Note 6) | 1000 | A/ $\mu s$ |

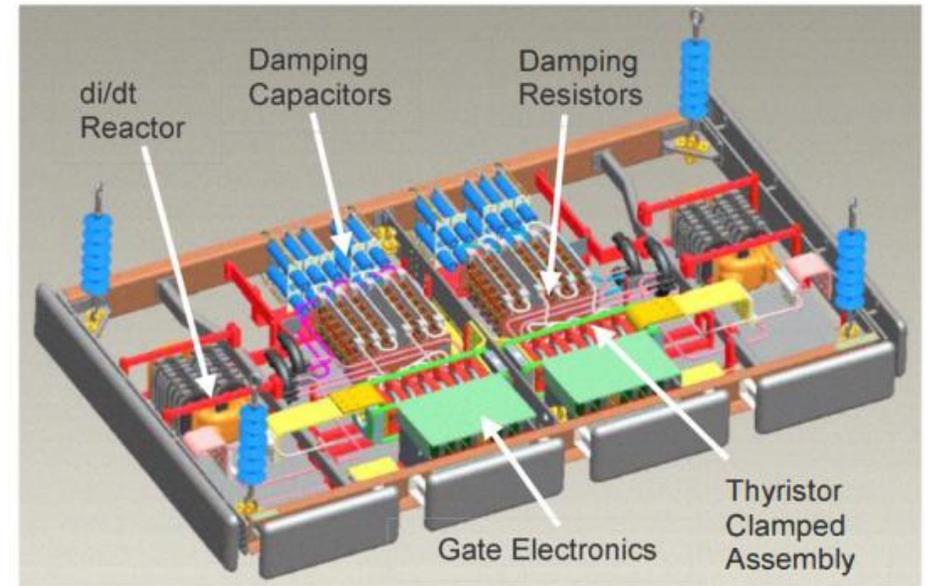
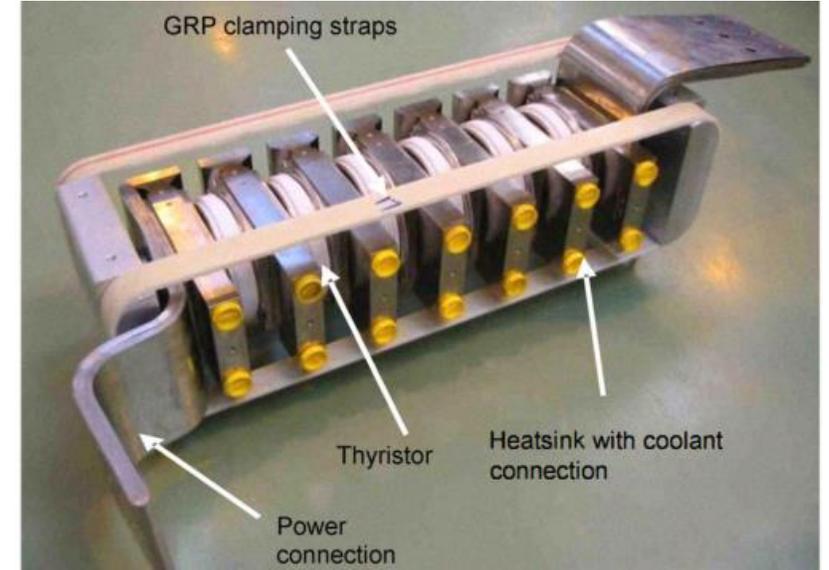
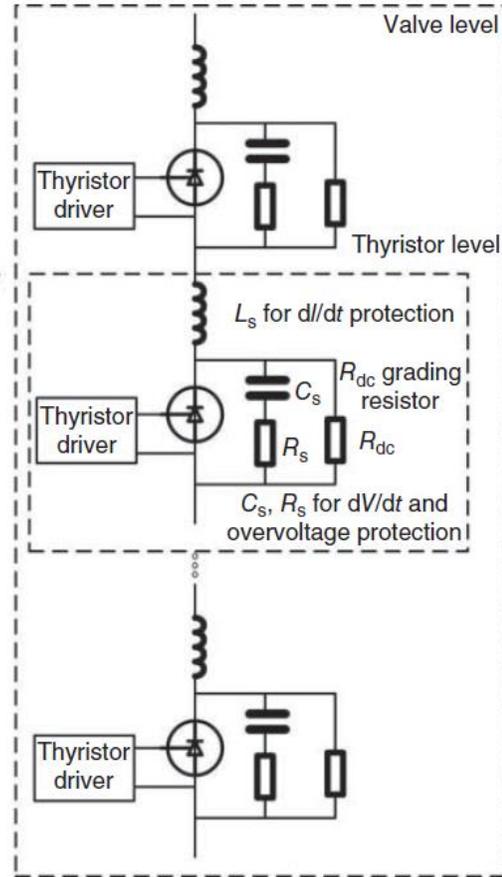
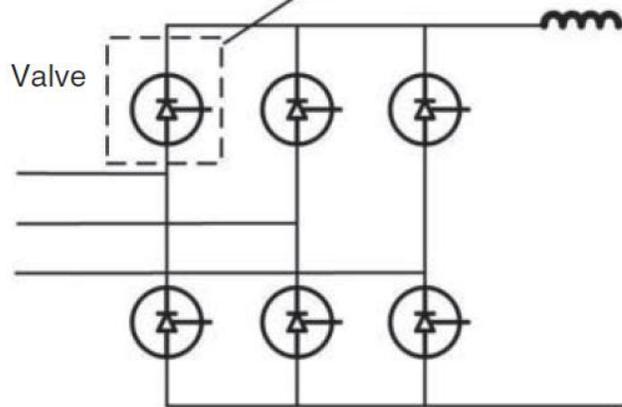




# Modelagem e Topologias HVDC

A. LCC – Line Commutated Converter

Thyristor



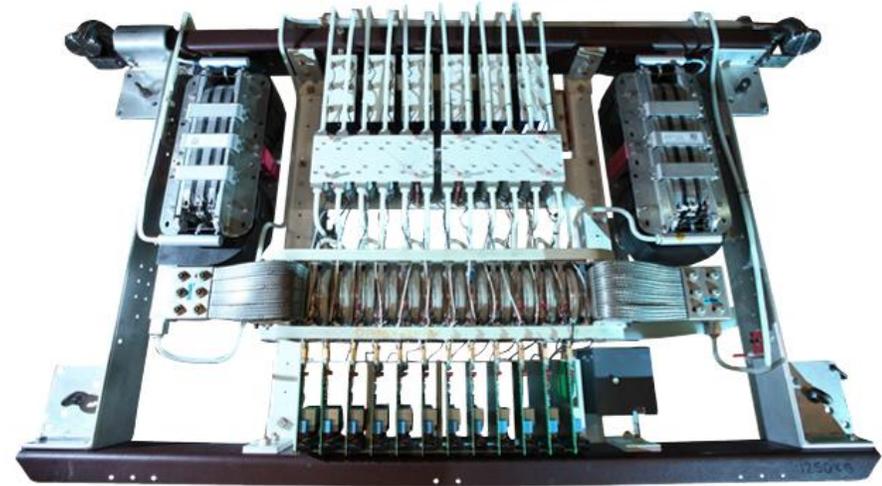


# Modelagem e Topologias HVDC

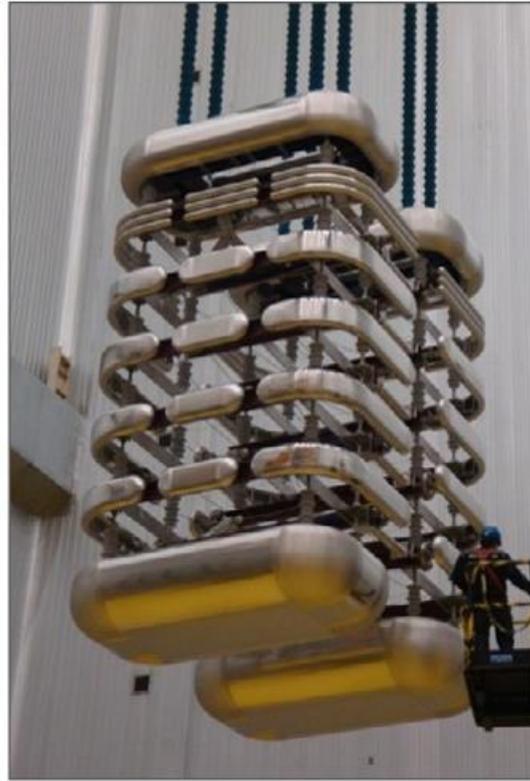
A. LCC – Line Commuted Converter

Thyristor

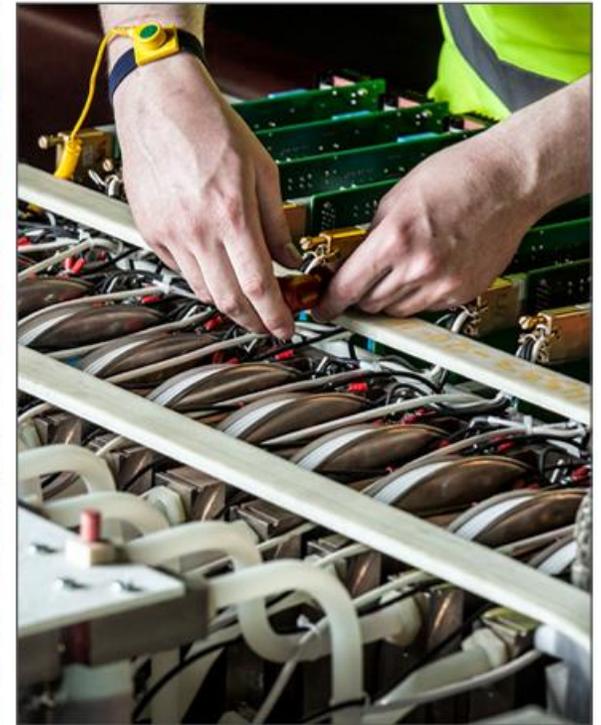
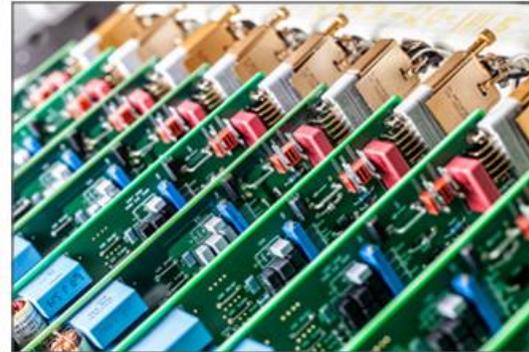
Construção



*In-line Arrangement*



*Square Arrangement*





# Modelagem e Topologias HVDC

A. LCC – Line Commutated Converter

Thyristor

Construção

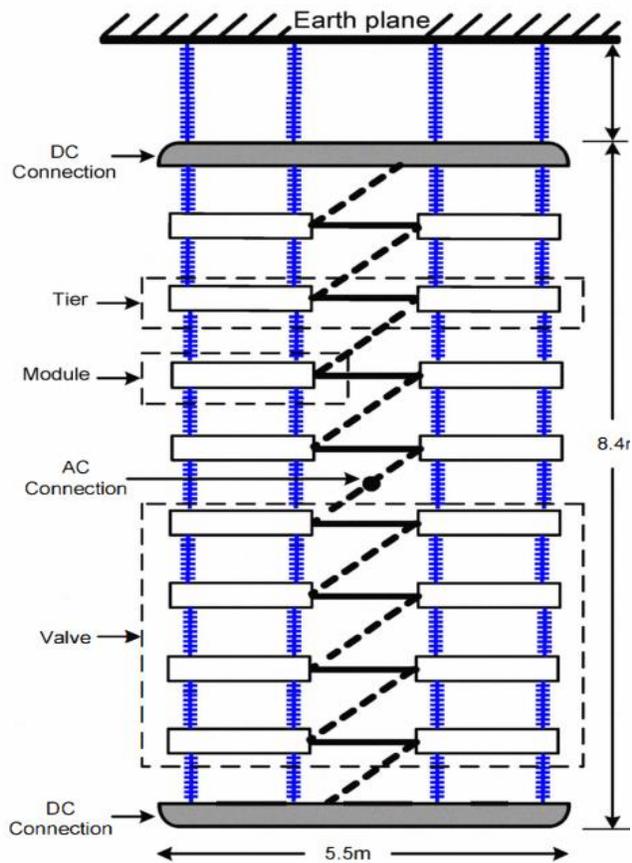


Diagrama de uma válvula dupla



ABB, HVDC

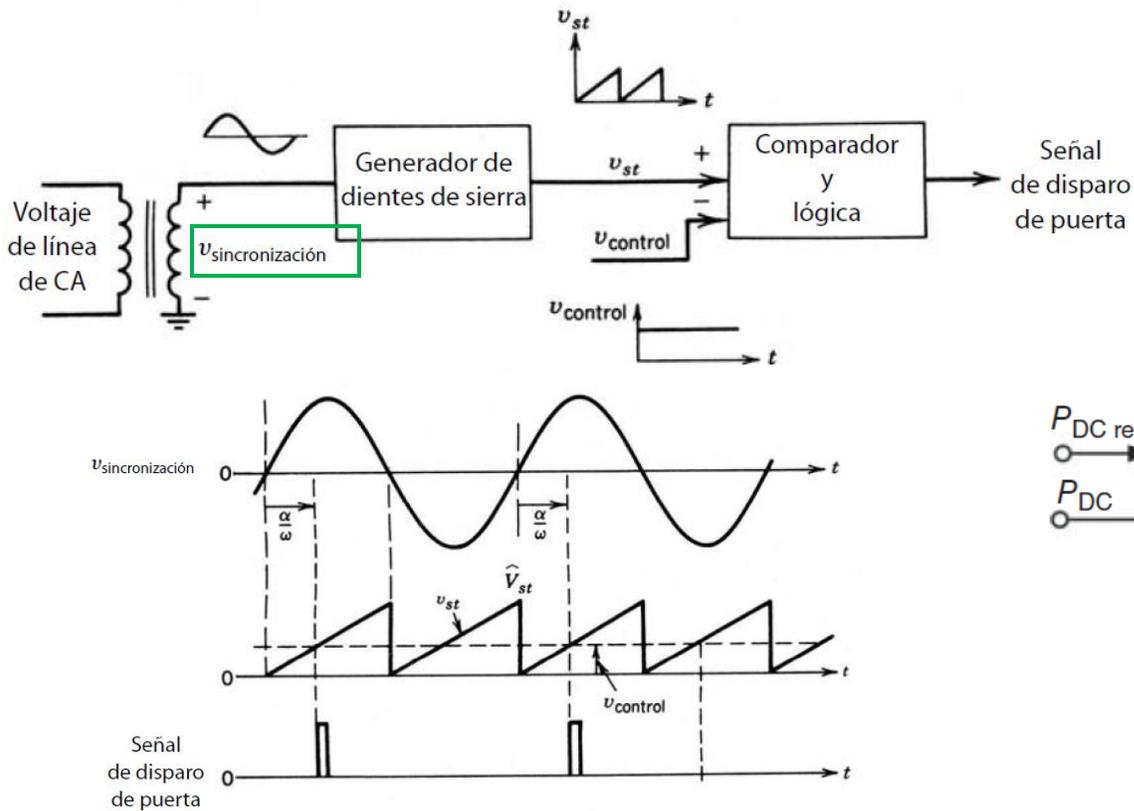


# Modelagem e Topologias HVDC

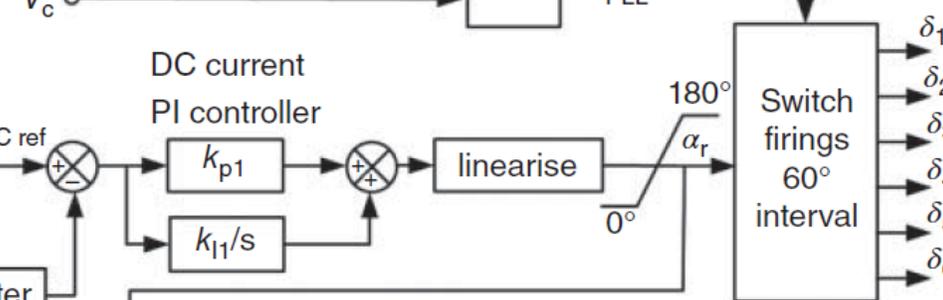
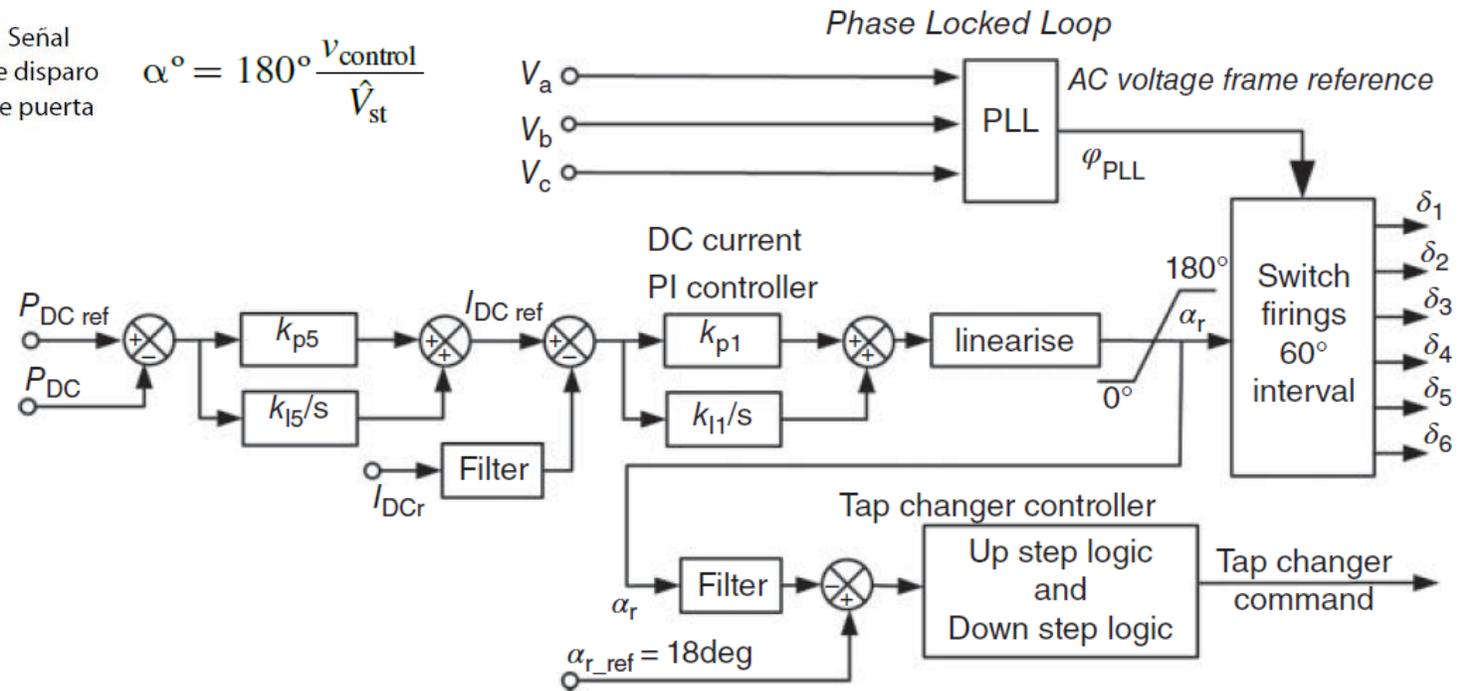
A. LCC – Line Commuted Converter

Thyristor

Controle



$$\alpha^\circ = 180^\circ \frac{v_{control}}{\hat{V}_{st}}$$



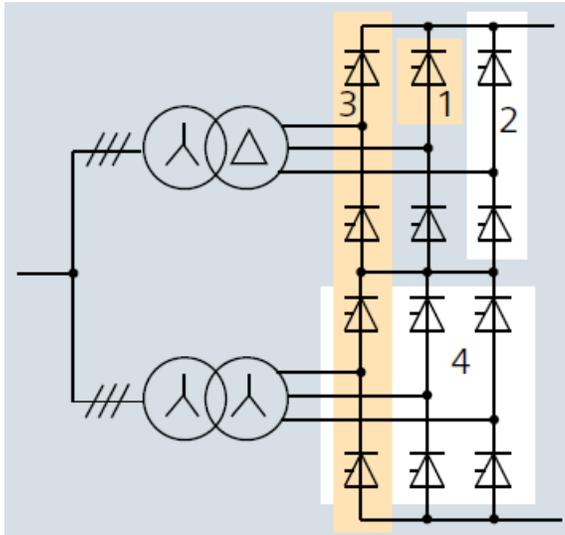


# Modelagem e Topologias HVDC

A. LCC – Line Commutated Converter

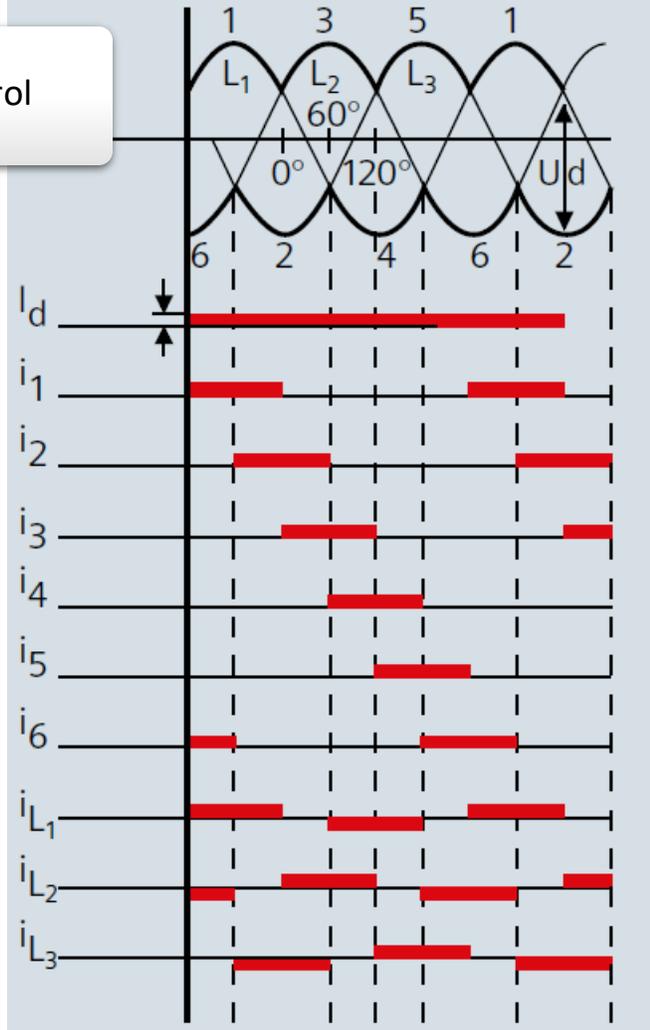
Thyristor

Control

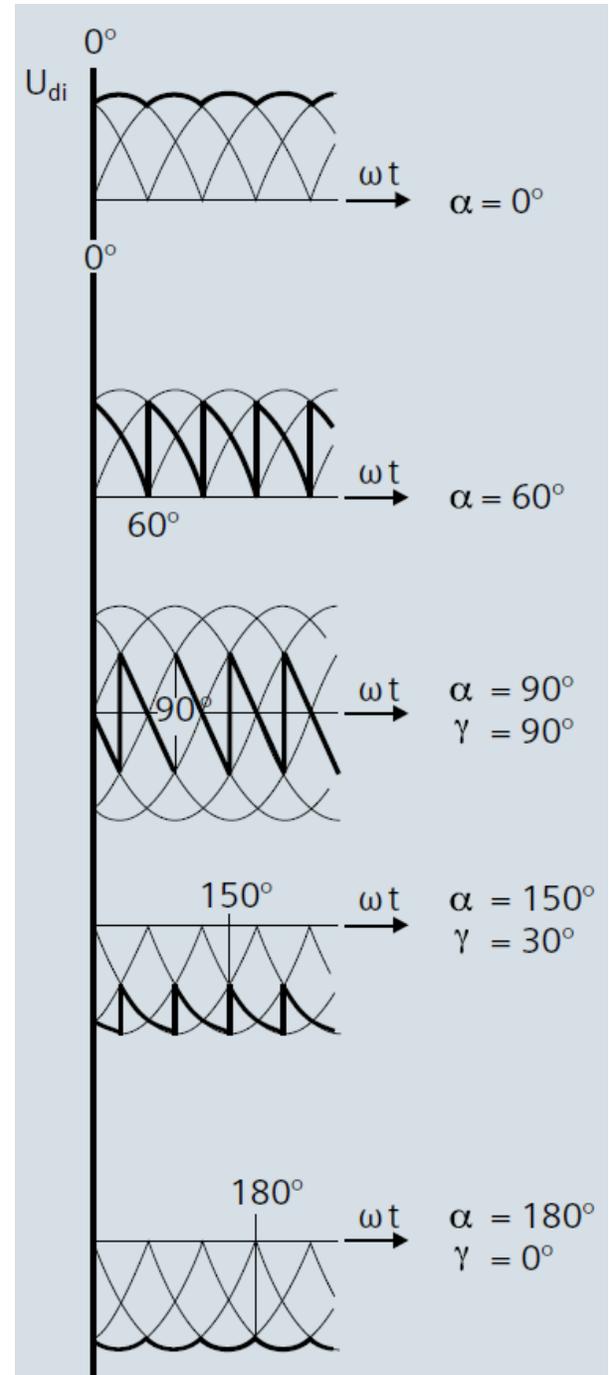


- 1 Valve Branch
- 2 Double Valve
- 3 Valve Tower
- 4 6-pulse Bridge

DC current in each valve and phase



Source: Siemens

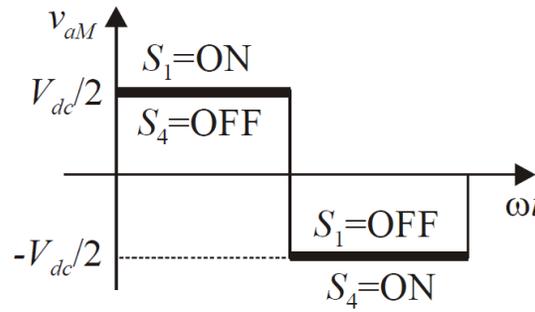
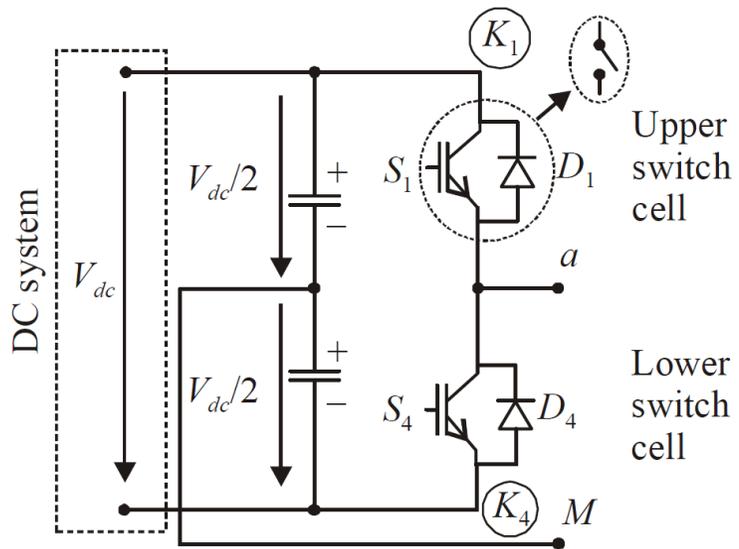




# Modelagem e Topologias HVDC

B. VSC – Voltage Source Converter

IGBT



4.5kV FZ1200R45HL3 module



| Item                           |                                        | New module       |
|--------------------------------|----------------------------------------|------------------|
|                                |                                        | CM1000HG-130XA   |
| Collector-emitter voltage      |                                        | 6.5 kV           |
| Collector current              |                                        | 1000 A           |
| Operation junction temperature |                                        | -50 °C – +150 °C |
| IGBT                           | Collector-emitter saturation voltage** | 3.6 V            |
|                                | Thermal resistance junction to case    | 11.0 K/kW        |
| Diode                          | Emitter-collector voltage**            | 3.0 V            |
|                                | Thermal resistance junction to case    | 17.0 K/kW        |

\*\* T<sub>j</sub>=125°C, I<sub>C</sub> (I<sub>E</sub>)=1000A, typical value

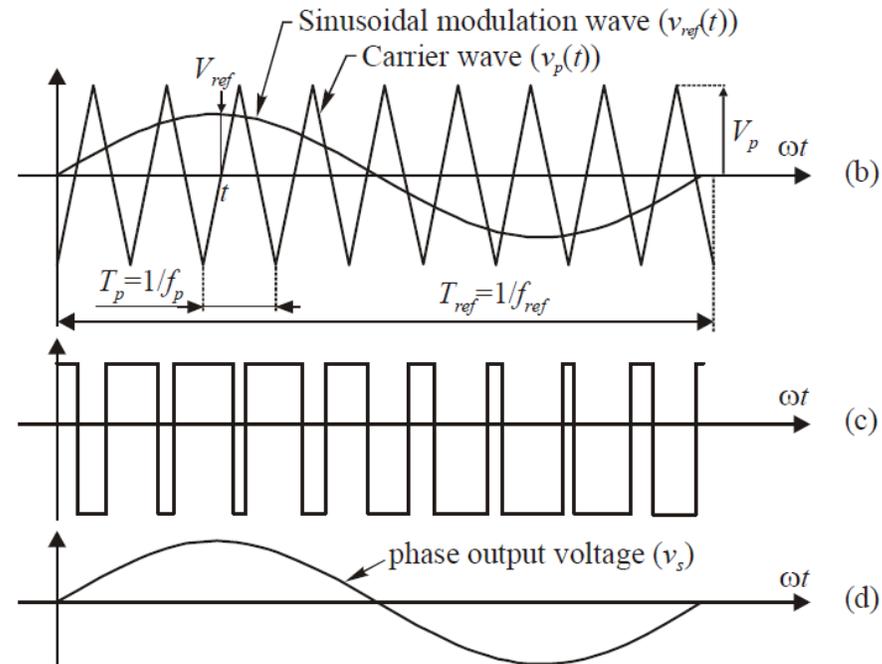
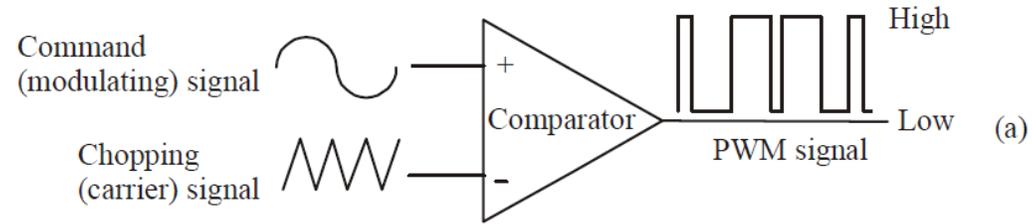
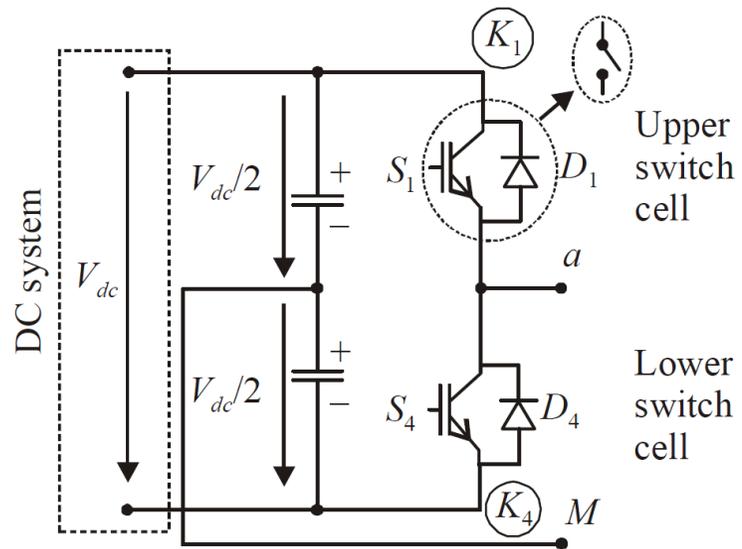


# Modelagem e Topologias HVDC

**B. VSC – Voltage Source Converter**

IGBT

Controle



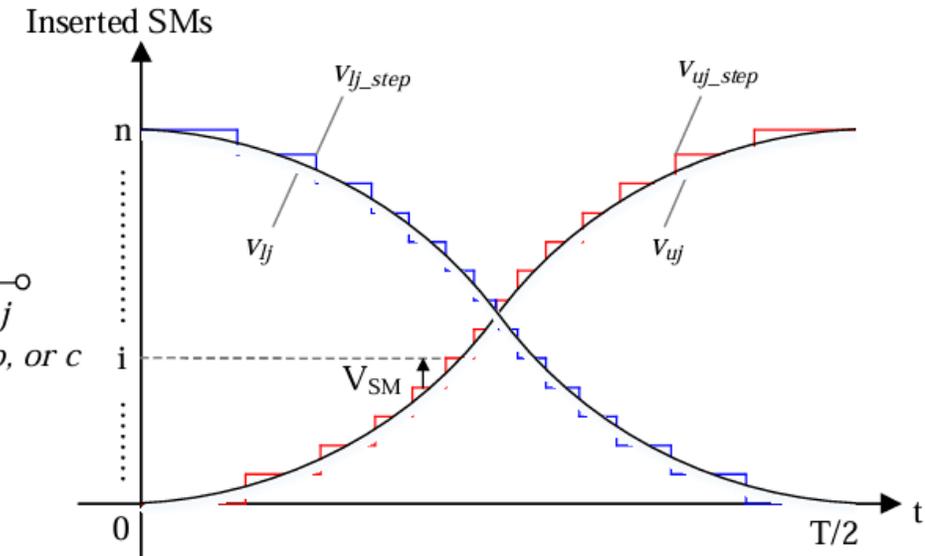
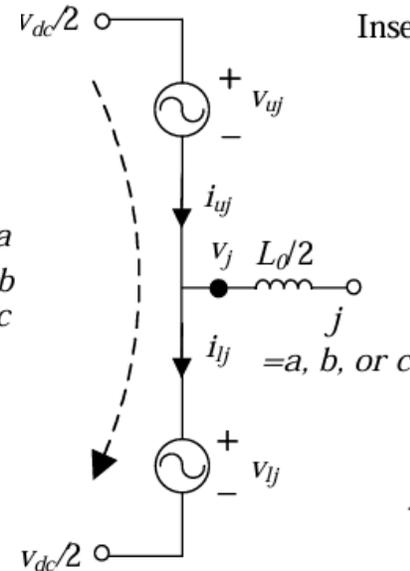
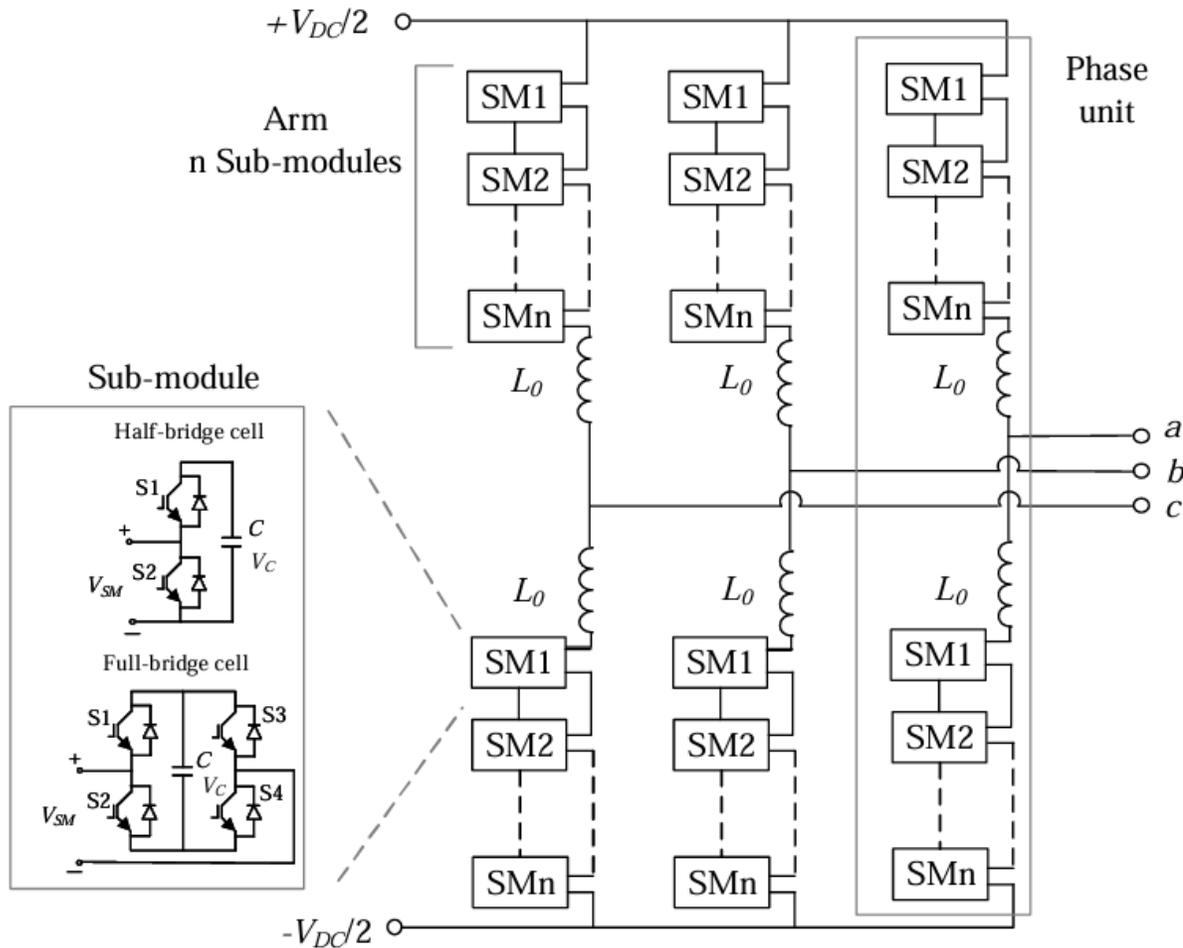


# Modelagem e Topologias HVDC

C. MMC – Modular Multinível Converter

IGBT Multinível

Controle





# Modelagem e Topologias HVDC

C. MMC – Modular Multinível Converter

IGBT Multinível

Controle

Multilevel Modulation

Low switching frequency

High switching frequency

SHE

Nearest Vector

Nearest Level

Hybrid Modulation

Multi-carrier PWM

Phase Shifted

Level Shifted

Phase Disposition

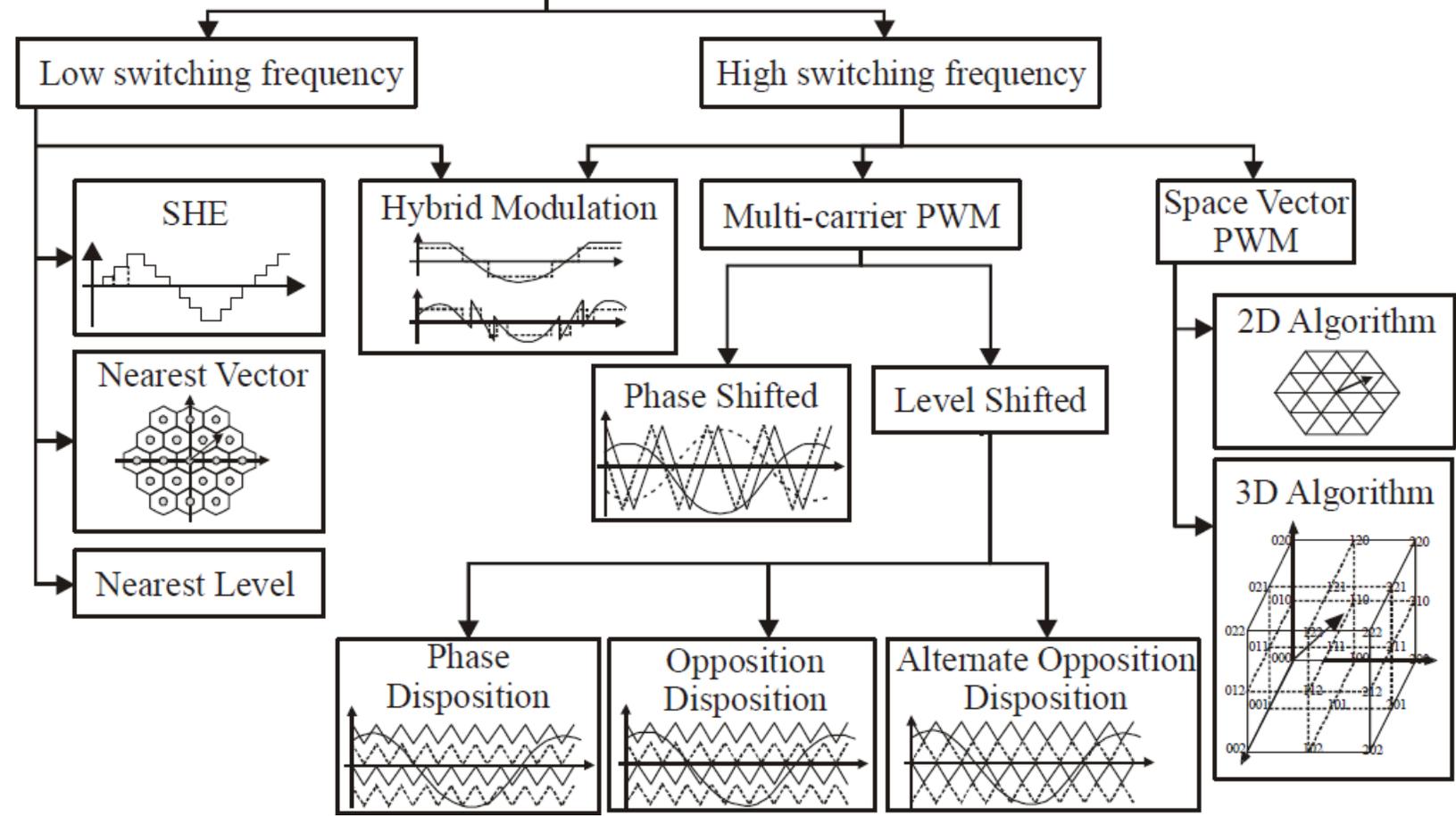
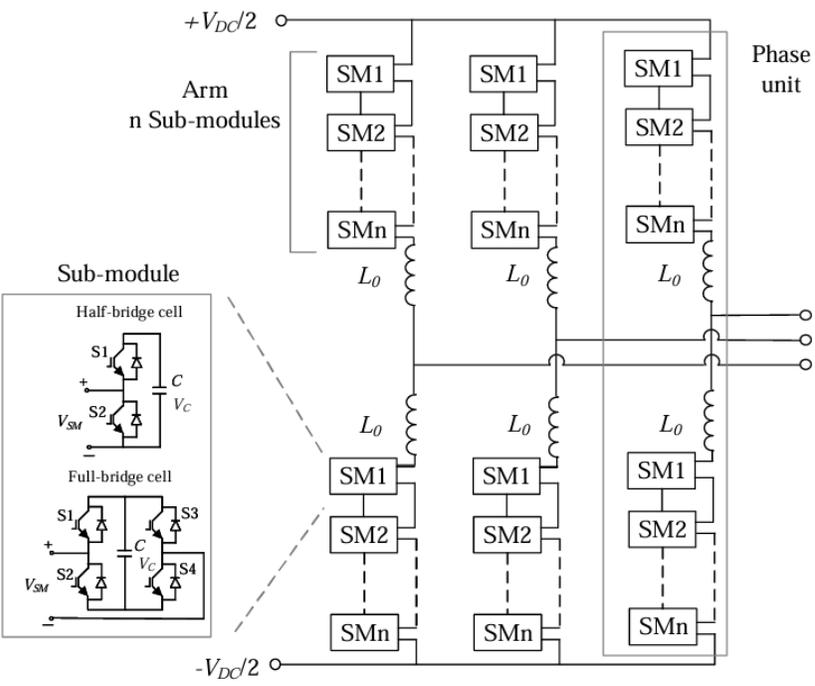
Opposition Disposition

Alternate Opposition Disposition

Space Vector PWM

2D Algorithm

3D Algorithm



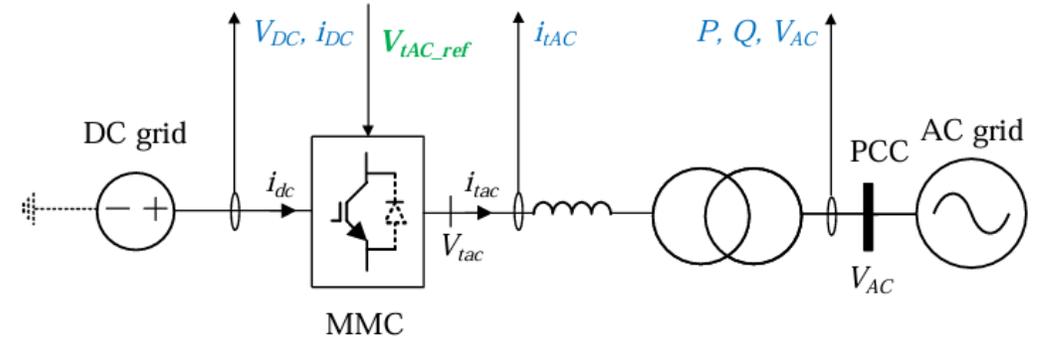
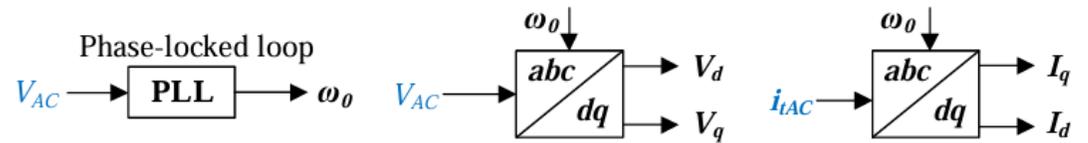
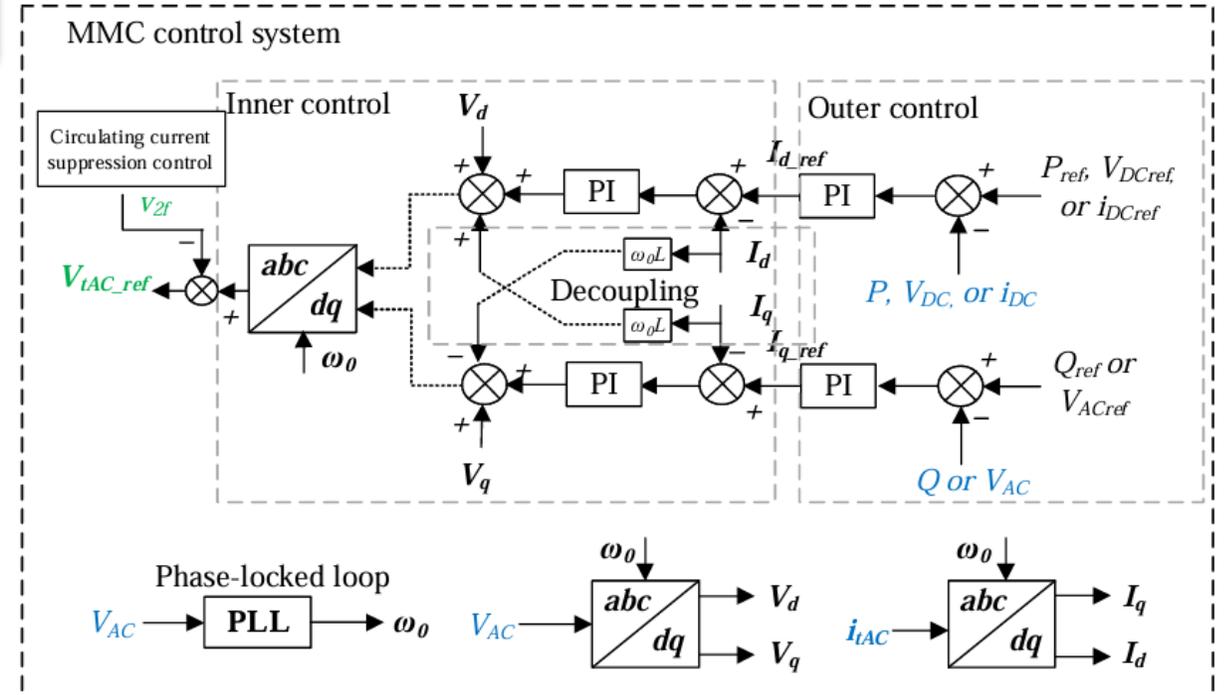


# Modelagem e Topologias HVDC

C. MMC – Modular  
Multinível  
Converter

IGBT Multinível

Controle





## Modelagem do Caso de Estudo do Sistema HVDC

### Cálculos para HVDC.

#### 1. Modelo do conversor LCC (Unidade retificadora):

- a) Modelo da válvula de thyristor
- b) Modelo do retificador de 6 pulsos
- c) Modelo do terminal retificador de 12 pulsos
- d) Circuito de *firing*.

#### 2. Modelo do conversor VSC (Unidade inversora):

- a) Modelo do IGBT
- b) Modelo do inversor IGBT
- c) Modelo do terminal inversor PWM
- d) Circuito de *modulação PWM*

#### 3. Modelo da linha

#### 4. Filtros y Compensadores AC do terminal retificador

#### 5. Filtros y Compensadores AC do terminal inversor



# Modelagem do Caso de Estudo do Sistema HVDC

$f := 50$

*Transformador\_rectifier*

$VAT1 := 345 \cdot 10^3 = 345 \cdot 10^3$

$VBT1 := 211.42 \cdot 10^3 = 211.42 \cdot 10^3$

$ST := 598 \cdot 10^6 = 598 \cdot 10^6$

$XT := 0.18$

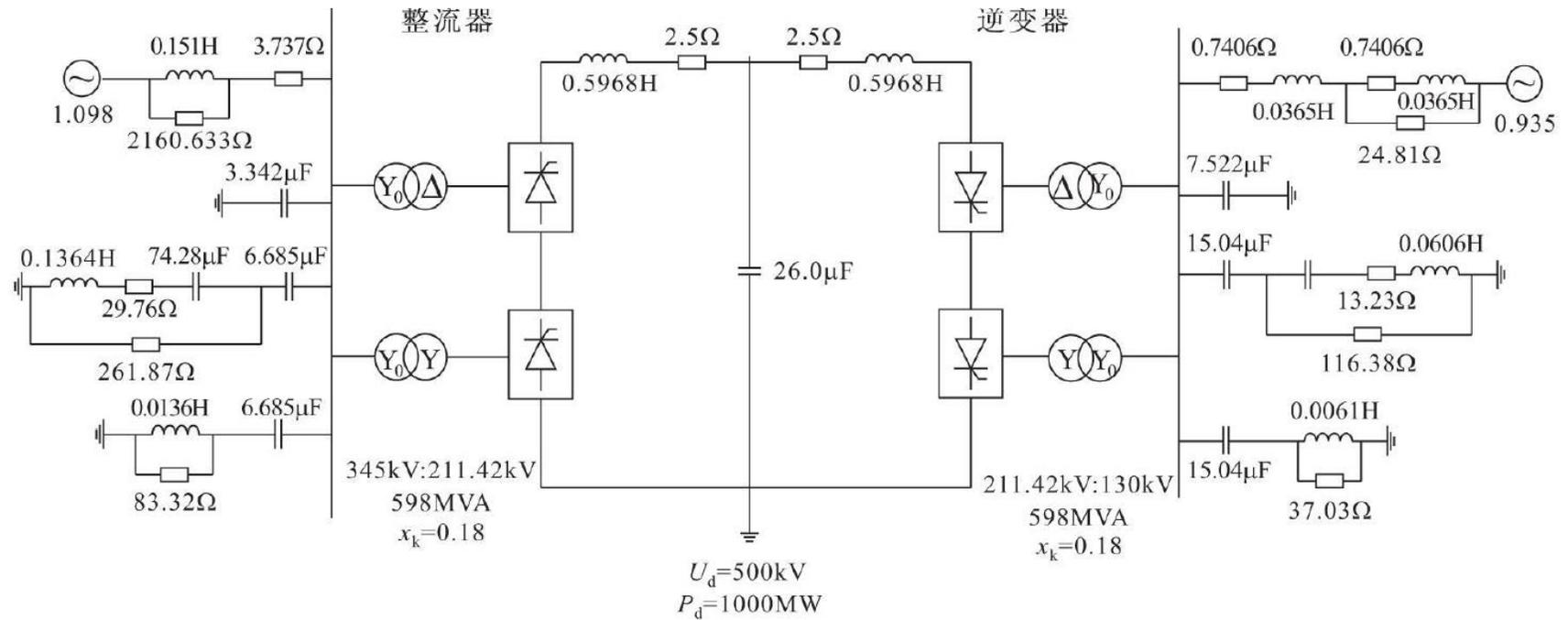
$FC := 100$

*calculo\_R\_X\_ohms*

$VB1 := VAT1 = 345 \cdot 10^3$

$VB2 := VBT1 = 211.42 \cdot 10^3$

$SB := 100 \cdot 10^6$





## Modelagem do Caso de Estudo do Sistema HVDC

$$ZB1y := \frac{\left(\frac{VB1}{\sqrt{3}}\right)^2}{SB} = 1.19 \cdot 10^3 \quad ZB2_y := \frac{\left(\frac{VB2}{\sqrt{3}}\right)^2}{SB} = 446.984 \quad ZB2_d := \frac{(VB2)^2}{3} = 1.341 \cdot 10^3$$

$$Xpu := XT \cdot \left(\frac{VAT1}{VB1}\right)^2 \cdot \frac{SB}{ST} = 30.1 \cdot 10^{-3}$$

$$X1pu := 0.5 \cdot Xpu = 15.05 \cdot 10^{-3}$$

$$X2pu_y := 0.5 \cdot Xpu = 15.05 \cdot 10^{-3}$$

$$X1 := X1pu \cdot ZB1y = 17.913$$

$$X2_y := X2pu_y \cdot ZB2_y = 6.727$$

$$L1 := \frac{X1}{2 \cdot \pi \cdot f} = 57.02 \cdot 10^{-3}$$

$$L2_y := \frac{X2_y}{2 \cdot \pi \cdot f} = 21.413 \cdot 10^{-3}$$

$$R1 := \frac{X1}{FC} = 179.135 \cdot 10^{-3}$$

$$R2_y := \frac{X2_y}{FC} = 67.272 \cdot 10^{-3}$$

$$\frac{VB2}{\sqrt{3}} = 122.063 \cdot 10^3$$

$$VB2 = 211.42 \cdot 10^3$$

$$X2pu_d := 0.5 \cdot Xpu = 15.05 \cdot 10^{-3}$$

$$X2_d := X2pu_d \cdot ZB2_d = 20.182$$

$$L2_d := \frac{X2_d}{2 \cdot \pi \cdot f} = 64.24 \cdot 10^{-3}$$

$$R2_d := \frac{X2_d}{FC} = 201.816 \cdot 10^{-3}$$

### Transformador\_inverter

$$VAT2 := 345 \cdot 10^3 = 345 \cdot 10^3$$

$$VBT2 := 211.42 \cdot 10^3 = 211.42 \cdot 10^3$$

$$ST := 598 \cdot 10^6 = 598 \cdot 10^6$$

$$XT := 0.18$$

$$FC := 100$$

calculo\_R\_X\_ohms

$$VB3 := 230 \cdot 10^3$$

$$ZB3_y := \frac{\left(\frac{VB3}{\sqrt{3}}\right)^2}{SB} = 529$$

$$ZB3_d := \frac{(VB3)^2}{3} = 1.587 \cdot 10^3$$

La\_reactancia\_x1pu\_es\_igual\_al\_sector\_2

Y\_D\_iguales\_a\_rectificador

Solo\_se\_calcula\_x3\_porque\_cambia\_la\_tensión

$$X3pu_y := 0.5 \cdot Xpu = 15.05 \cdot 10^{-3}$$

$$X3pu_d := 0.5 \cdot Xpu = 15.05 \cdot 10^{-3}$$

$$X3_y := X3pu_y \cdot ZB3_y = 7.962$$

$$X3_d := X3pu_d \cdot ZB3_d = 23.885$$

$$L3_y := \frac{X3_y}{2 \cdot \pi \cdot f} = 25.342 \cdot 10^{-3}$$

$$L3_d := \frac{X3_d}{2 \cdot \pi \cdot f} = 76.027 \cdot 10^{-3}$$

$$R3_y := \frac{X3_y}{FC} = 79.615 \cdot 10^{-3}$$

$$R3_d := \frac{X3_d}{FC} = 238.846 \cdot 10^{-3}$$



## Modelagem do Caso de Estudo do Sistema HVDC

*Tensão ideal de no-carga*

*Ideal no-load voltage*

$\alpha := 0$  degrees *punteo rectificado diodos*

$V_{LL} := VB2 = 211.42 \cdot 10^3$

$V_{dc0\_0} := \frac{3 \cdot \sqrt{2}}{\pi} \cdot V_{LL} \cdot \cos(\alpha) = 285.517 \cdot 10^3$

$V_{dc1\_0} := V_{dc0\_0} = 285.517 \cdot 10^3$

$V_{dc2\_0} := V_{dc0\_0} = 285.517 \cdot 10^3$

$V_{dc3\_0} := 2 \cdot V_{dc0\_0} = 571.035 \cdot 10^3$

*Validação do retificador*

*Considerando caída tensión en Lt*

*Lt es Ls según la literatura*

$\alpha := 15$

$L_t = 42.827 \cdot 10^{-3}$

$R_t = 134.544 \cdot 10^{-3}$

$V_{t\_LL} = 211.42 \cdot 10^3$

$I_{dc} := 2000$

$\mu := \arccos\left(\cos\left(\alpha \cdot \frac{\pi}{180}\right) - \frac{I_{dc} \cdot 2 \cdot 2 \cdot \pi \cdot f \cdot L_t}{\sqrt{2} \cdot V_{t\_LL}}\right) - \alpha \cdot \frac{\pi}{180} = 404.798 \cdot 10^{-3}$  rad

$\mu_{deg} := \mu \cdot \frac{180}{\pi} = 23.193$  degrees

$$V_{dc1\_2} := \frac{3 \sqrt{2}}{\pi} V_{t\_LL} \cdot \cos\left(\alpha \cdot \frac{\pi}{180}\right) - \frac{3}{\pi} \cdot 2 \cdot \pi \cdot f \cdot L_t \cdot I_{dc} = 250.093 \cdot 10^3$$

$$V_{dc2\_2} := \frac{3 \sqrt{2}}{\pi} V_{t\_LL} \cdot \cos\left((\alpha + 0) \cdot \frac{\pi}{180}\right) - \frac{3}{\pi} \cdot 2 \cdot \pi \cdot f \cdot L_t \cdot I_{dc} = 250.093 \cdot 10^3$$

$$V_{dc3\_2} := V_{dc1\_2} + V_{dc2\_2} = 500.185 \cdot 10^3$$

$$\frac{\frac{3}{\pi} \cdot 2 \cdot \pi \cdot f \cdot L_t \cdot I_{dc}}{V_{dc0\_0}} = 89.998 \cdot 10^{-3} \quad 2 \cdot \frac{\frac{3}{\pi} \cdot 2 \cdot \pi \cdot f \cdot L_t \cdot I_{dc}}{V_{dc0\_0}} \cdot 100 = 18$$



# Modelagem do Caso de Estudo do Sistema HVDC

*Considerando caída tensión en  $L_t + R_t$*

*Lt es Ls según la literatura*

$\alpha = 15$  *puente\_rectificado\_diodos*

$$L_t = 42.827 \cdot 10^{-3}$$

$$R_t = 134.544 \cdot 10^{-3}$$

$$U_L := VB1 = 345 \cdot 10^3$$

$K := 1$  *Numero\_unidades*

$I_d := 2000$  *I\_operación*

$U_{dioN} := 250 \cdot 10^3 = 250 \cdot 10^3$  *Tensión\_DC\_nominal\_unidad*

$I_{dN} := 2000 = 2 \cdot 10^3$  *Corrente\_DC\_nominal\_unidad*

$$U_{dio} := \frac{1}{n1} \cdot U_L \cdot \sqrt{2} \cdot \frac{3}{\pi} = 285.517 \cdot 10^3 \quad \textit{Tensión_DC_vazio_unidad}$$

$$Vdc0_0 = 285.517 \cdot 10^3 \quad \textit{Ok_cumple!}$$

$$2 \cdot U_{dio} = 571.035 \cdot 10^3$$

$$d_{xN} := \frac{3}{\pi} \cdot \frac{2 \cdot \pi \cdot f \cdot L_t \cdot I_{dN}}{U_{dioN}} \cdot 100 = 10.278 \quad \% \quad \textit{Es_significativa_debe_utilizarse}$$

$$d_{rN} := \frac{3}{\pi} \cdot \frac{R_t \cdot I_{dN}}{U_{dioN}} \cdot 100 = 102.784 \cdot 10^{-3} \quad \% \quad \textit{Es_muy_pequeña_puede_ser_despreciable}$$

$$\mu_{deg} = 23.193$$

$$\mu := \arccos \left( \cos \left( \alpha \cdot \frac{\pi}{180} \right) - 2 \cdot \frac{d_{xN}}{100} \cdot \frac{I_d}{I_{dN}} \cdot \frac{U_{dioN}}{U_{dio}} \right) - \alpha \cdot \frac{\pi}{180} = 404.798 \cdot 10^{-3}$$

$$\mu_{deg} := \mu \cdot \frac{180}{\pi} = 23.193$$

$$\Delta U_{valve} := 0$$

$$U_d := K \cdot U_{dio} \cdot \left( \cos \left( \alpha \cdot \frac{\pi}{180} \right) - \left( \frac{d_{xN}}{100} + \frac{d_{rN}}{100} \right) \cdot \frac{I_d}{I_{dN}} \cdot \frac{U_{dioN}}{U_{dio}} \right) - \Delta U_{valve} = 249.836 \cdot 10^3$$

$$Vdc3_2 = 500.185 \cdot 10^3 \quad \textit{aproximado_con_R_despreciado}$$

$$2 \cdot U_d = 499.671 \cdot 10^3 \quad 2 \cdot U_{dio} = 571.035 \cdot 10^3$$

*Restricciones\_angulos*

$\alpha_{min} := 5$  *para\_seguridad\_contra\_oscilación\_dinámica\_del\_sistema*

$\alpha_N := 15$  *el\_nominal\_está\_entre\_15-18°*



## Modelagem do Caso de Estudo do Sistema HVDC

### Potencias

$$\chi := \frac{2 \cdot \mu + \sin\left(2 \cdot \left(\alpha \cdot \frac{\pi}{180}\right)\right) - \sin\left(2 \cdot \left(\alpha \cdot \frac{\pi}{180} + \mu\right)\right)}{4 \cdot \left(\cos\left(\alpha \cdot \frac{\pi}{180}\right) - \cos\left(\alpha \cdot \frac{\pi}{180} + \mu\right)\right)} = 469.026 \cdot 10^{-3}$$

$$\varphi := \text{atan}\left(\frac{2 \cdot \mu + \sin\left(2 \cdot \left(\alpha \cdot \frac{\pi}{180}\right)\right) - \sin\left(2 \cdot \left(\alpha \cdot \frac{\pi}{180} + \mu\right)\right)}{\left(\cos\left(2 \cdot \alpha \cdot \frac{\pi}{180}\right) - \cos\left(2 \cdot \left(\alpha \cdot \frac{\pi}{180} + \mu\right)\right)\right)}\right) = 491.613 \cdot 10^{-3}$$

$$\phi_{deg} := \varphi \cdot \frac{180}{\pi} = 28.167$$

$$P_L := U_d \cdot I_d + I_d \cdot \left(d_{rN} \cdot \frac{I_d}{I_{dN}} \cdot U_{dioN} + \Delta U_{valve}\right) = 551.063 \cdot 10^6 \quad \text{por\_polo}$$

$$Q_L := K \cdot \chi \cdot U_{dio} \cdot I_d = 267.83 \cdot 10^6 \quad \text{por\_polo}$$

### o\_tambien

$$Q_L := P_L \cdot \tan(\varphi) = 295.073 \cdot 10^6 \quad \text{por\_polo}$$

### Calculo\_compensador

$$P_{tot} := 2 \cdot P_L = 1.102 \cdot 10^9$$

$$Q_{tot} := 2 \cdot Q_L = 590.147 \cdot 10^6$$

$$Q_f := \frac{Q_{tot}}{3} = 196.716 \cdot 10^6$$

$$V_f := \frac{VB3}{\sqrt{3}} = 132.791 \cdot 10^3$$

$$X_{comp} := \frac{V_f^2}{Q_f} = 89.639$$

$$C_{comp} := \frac{1}{X_{comp} \cdot 2 \cdot \pi \cdot f} = 35.51 \cdot 10^{-6}$$



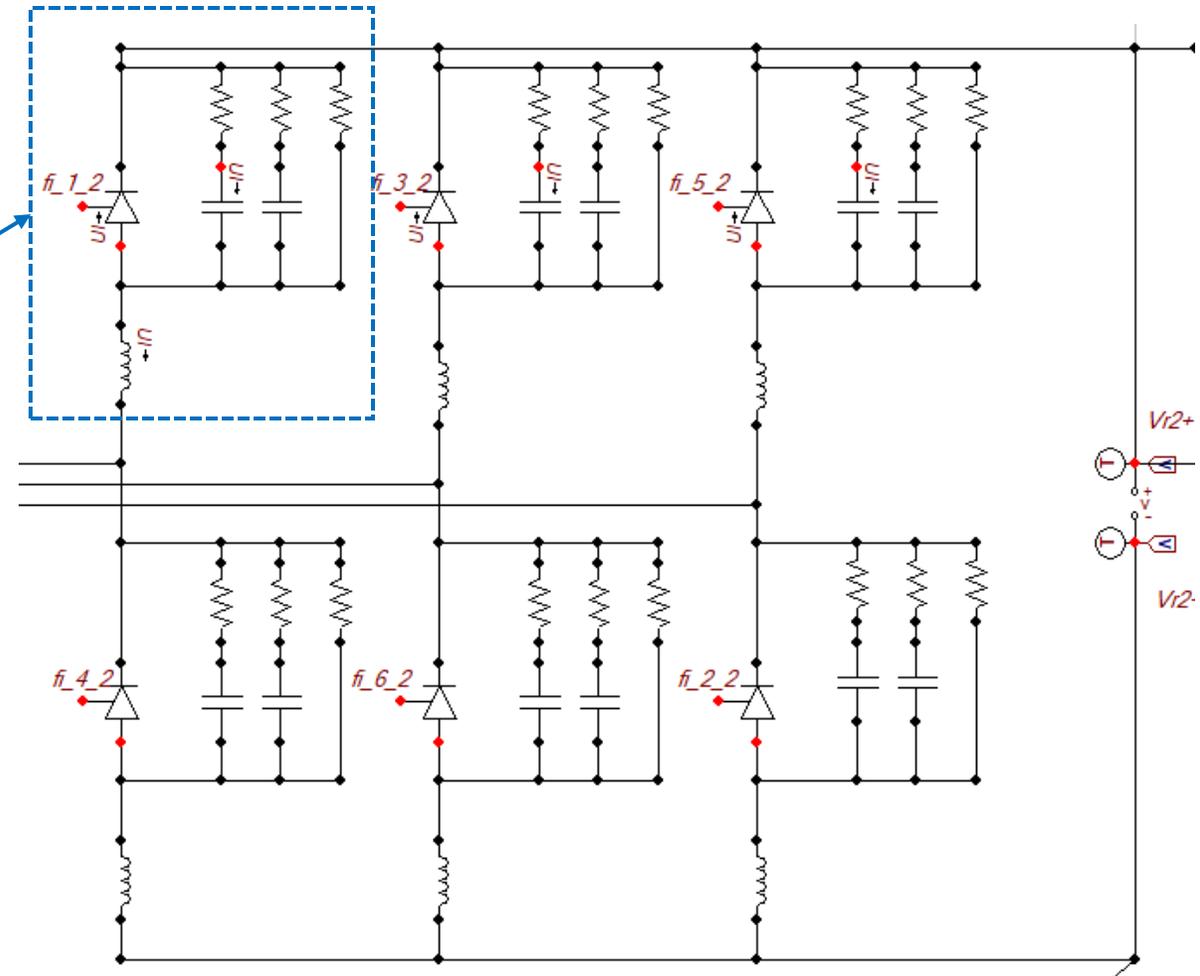
# Modelagem do Caso de Estudo do Sistema HVDC

## 1. Modelo do retificador LCC:

- a) Modelo da válvula de thyristor
- b) Modelo do retificador de 6 pulsos
- c) Modelo do terminal retificador de 12 pulsos
- d) Circuito de *firing*.

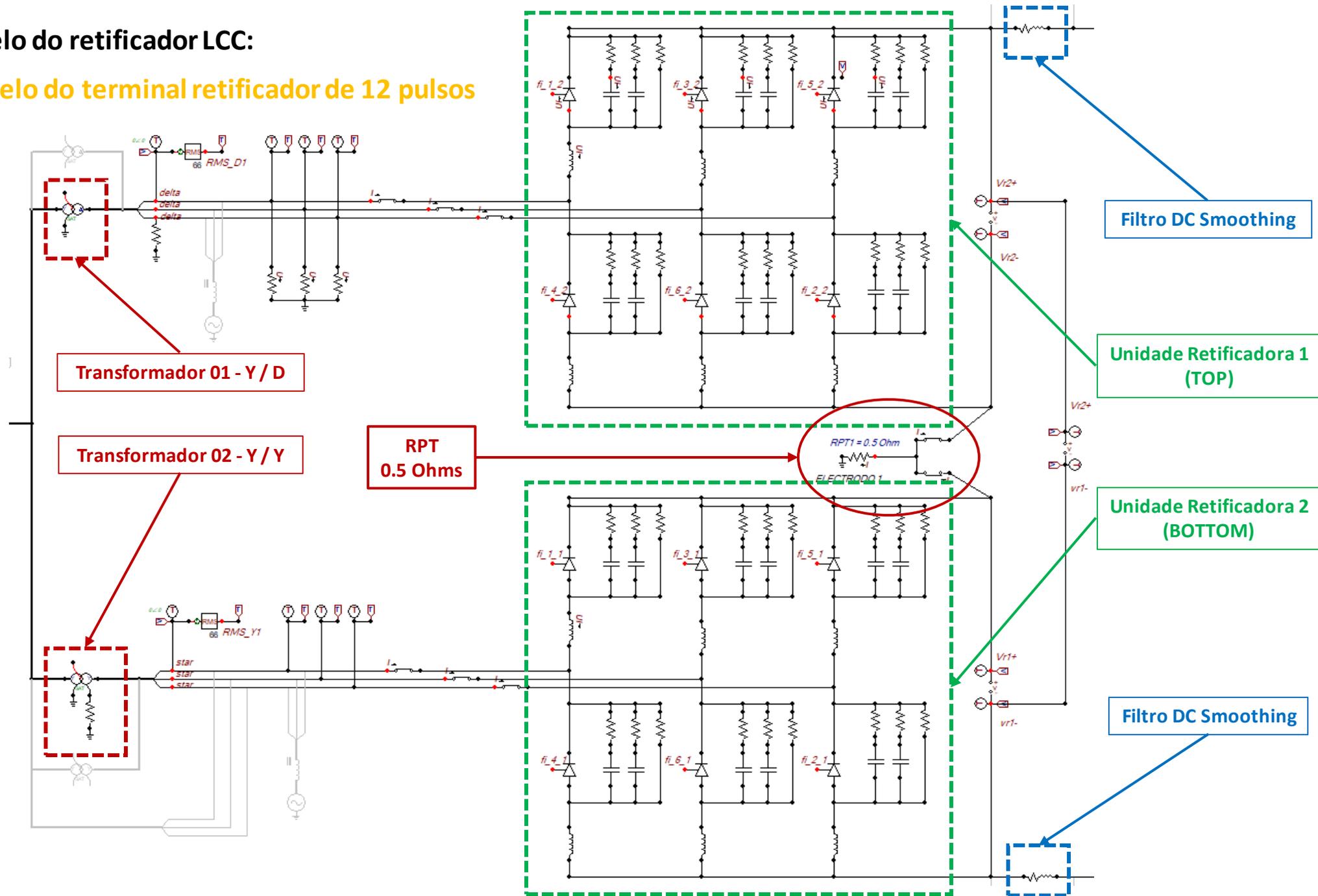
a) Circuito Snubber  
Válvula Thyristores

b) Retificador de 6 pulsos



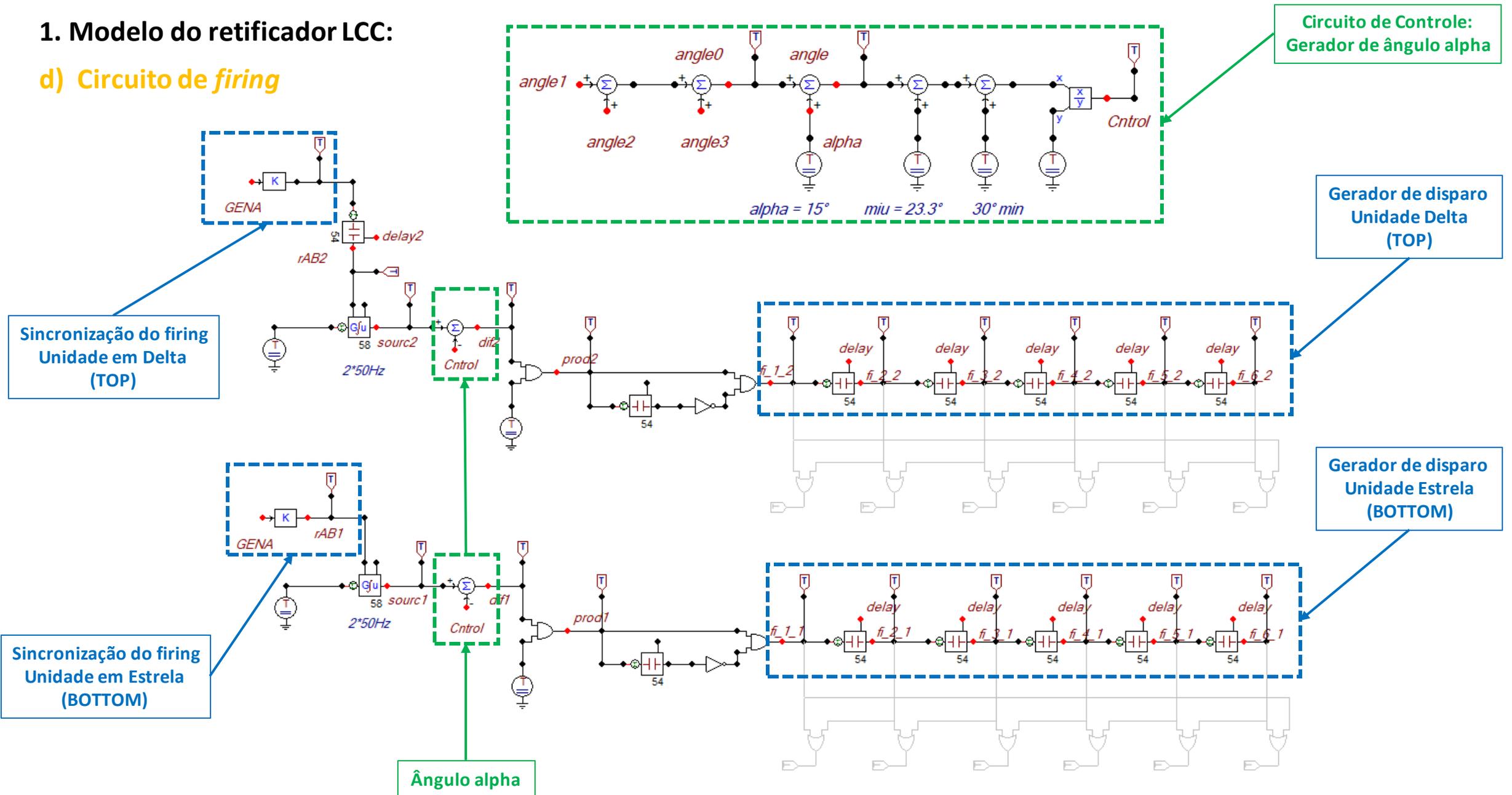
# 1. Modelo do retificador LCC:

## c) Modelo do terminal retificador de 12 pulsos



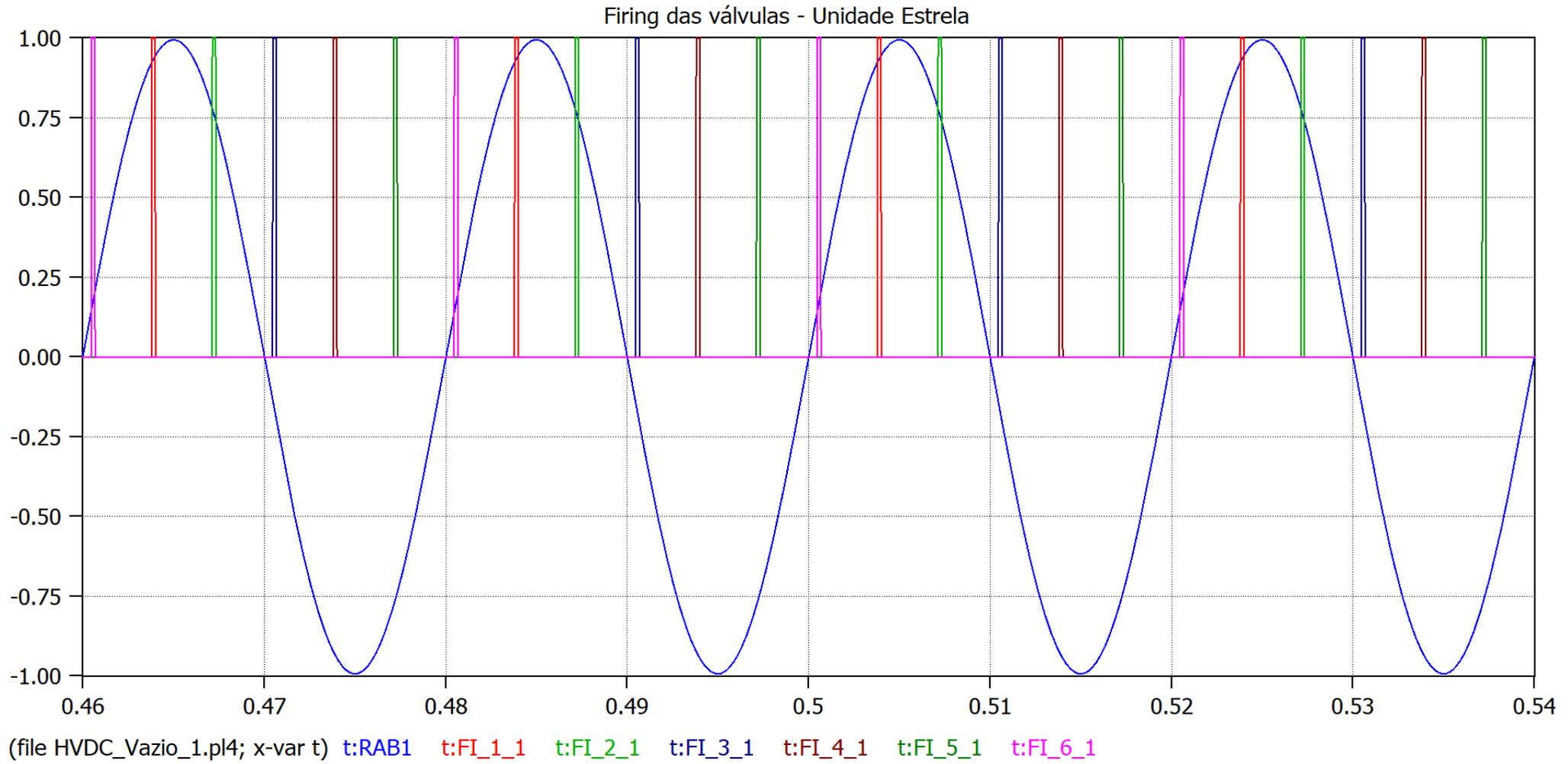
# 1. Modelo do retificador LCC:

## d) Circuito de firing



# 1. Modelo do retificador LCC:

## d) Circuito de firing



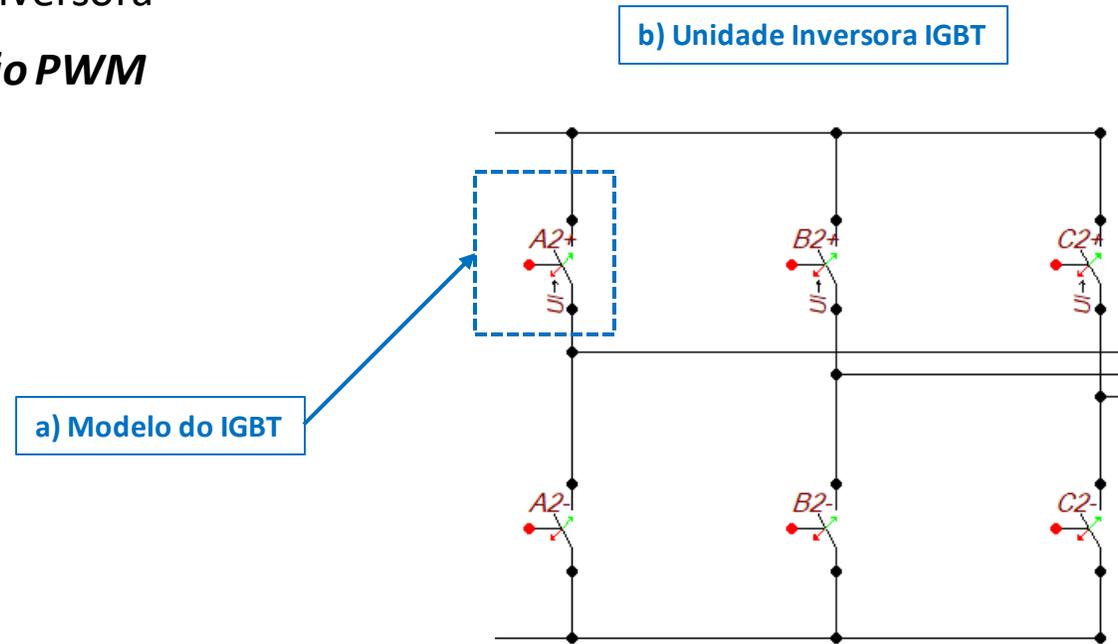
## 2. Modelo do Inversor VSC:

a) Modelo do IGBT

b) Modelo do inversor IGBT

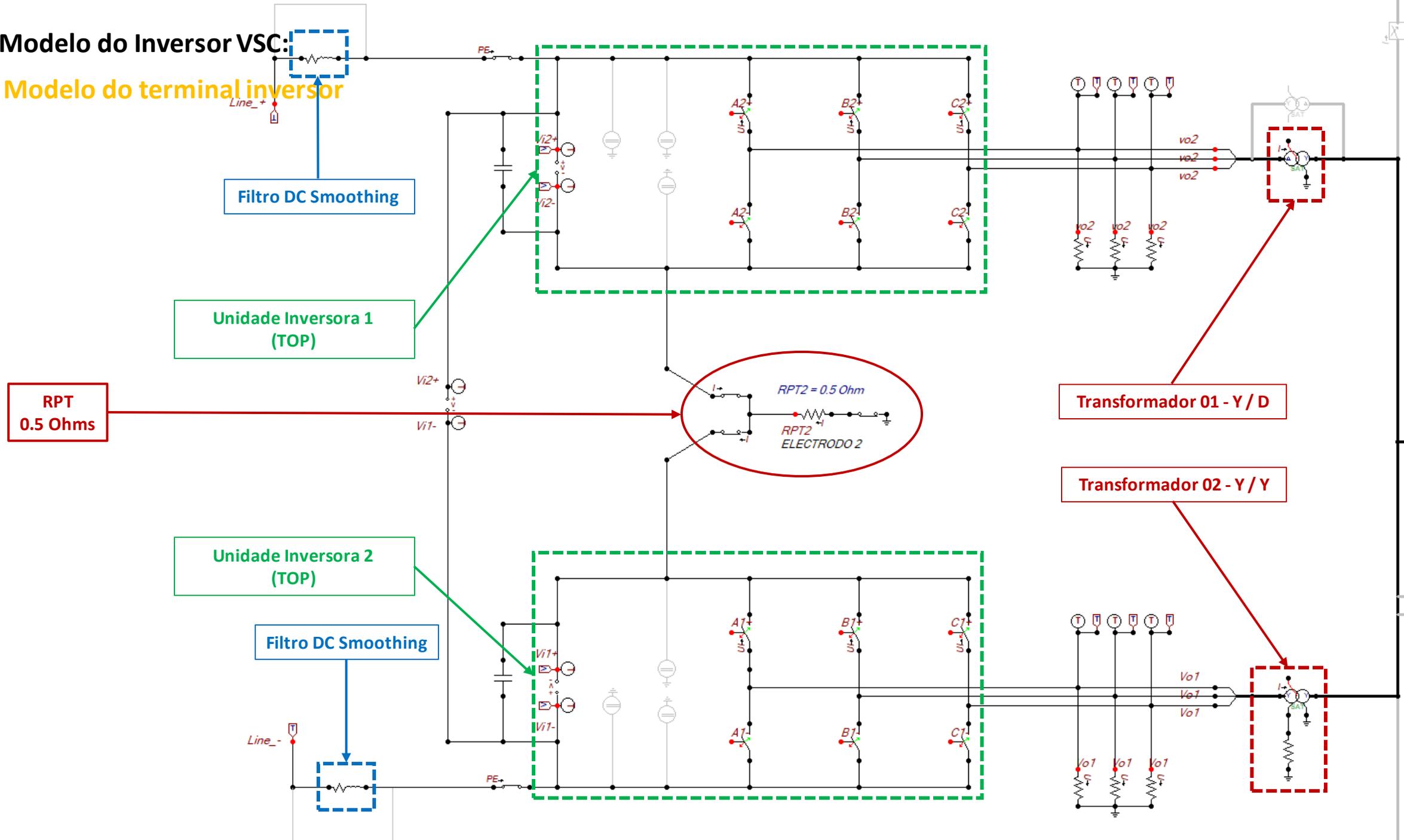
c) Modelo da unidade inversora

d) Circuito de *modulação PWM*



## 2. Modelo do Inversor VSC:

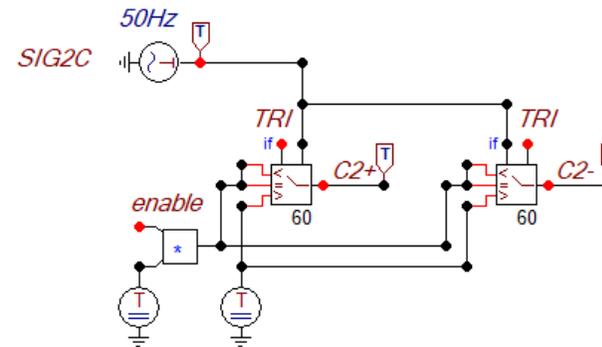
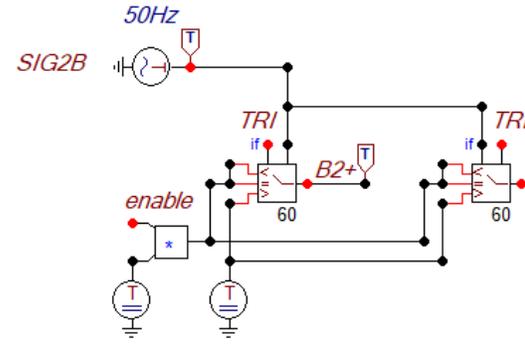
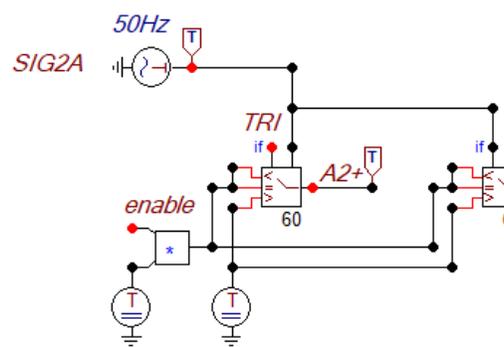
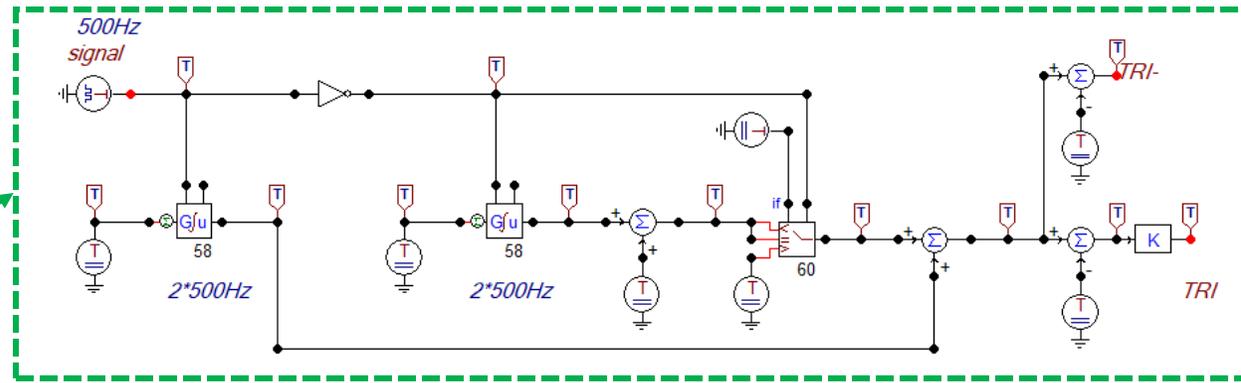
### c) Modelo do terminal inversor



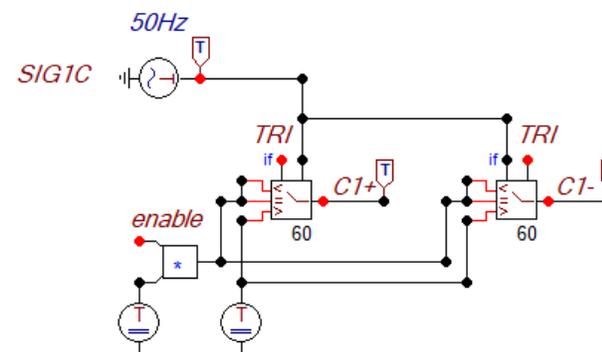
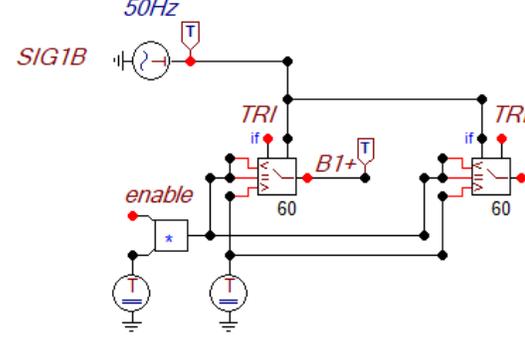
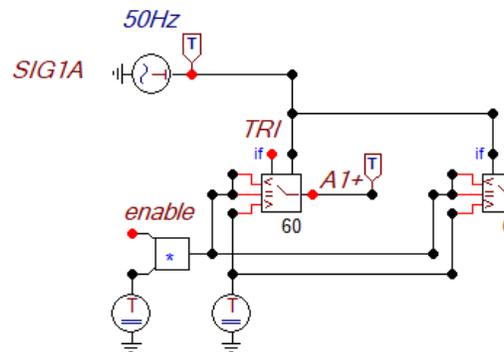
## 2. Modelo do Inversor VSC:

### d) Circuito de modulação PWM

Circuito de Controle:  
Gerador da portadora Triangular



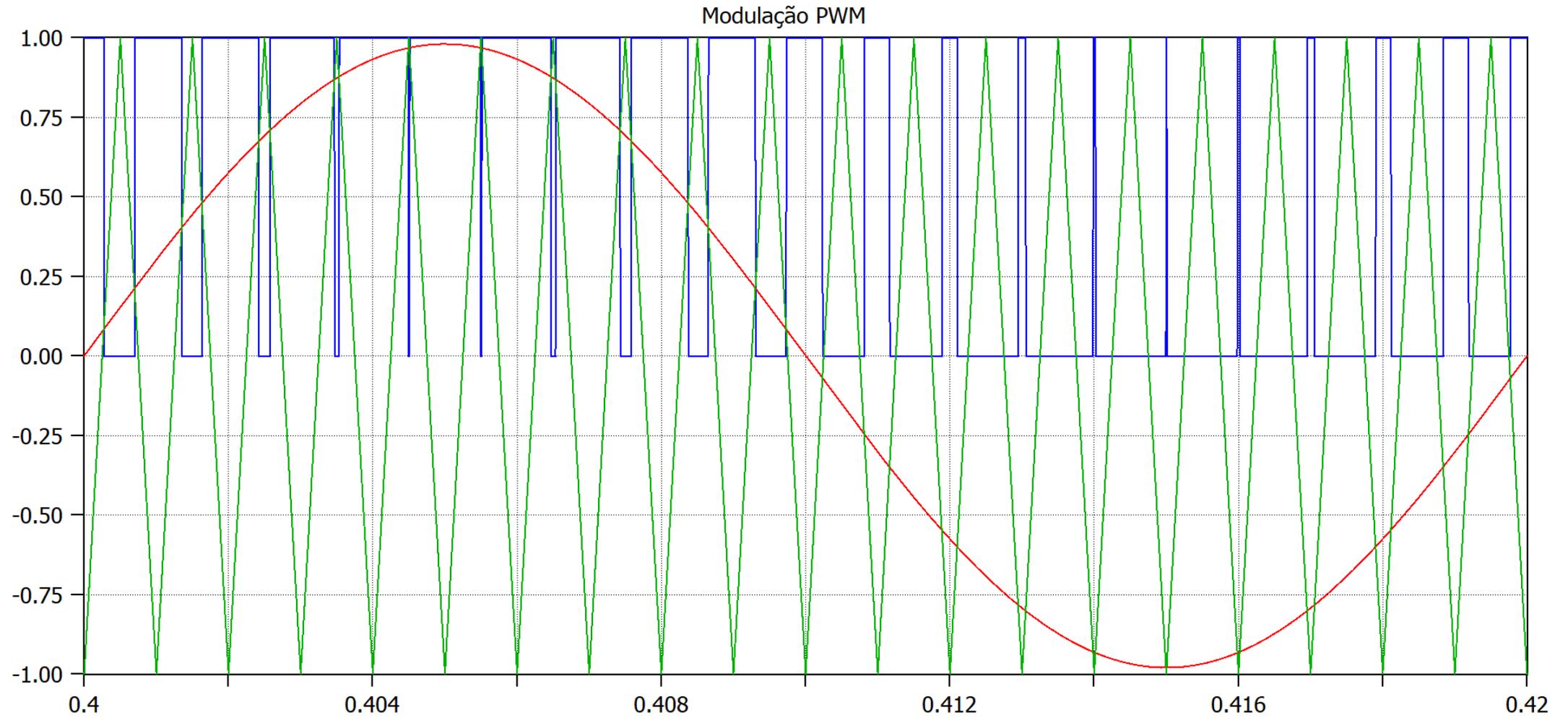
Gerador de disparo  
Unidade Delta  
(TOP)



Gerador de disparo  
Unidade Estrela  
(TOP)

## 2. Modelo do Inversor VSC:

### c) Modelo do terminal inversor

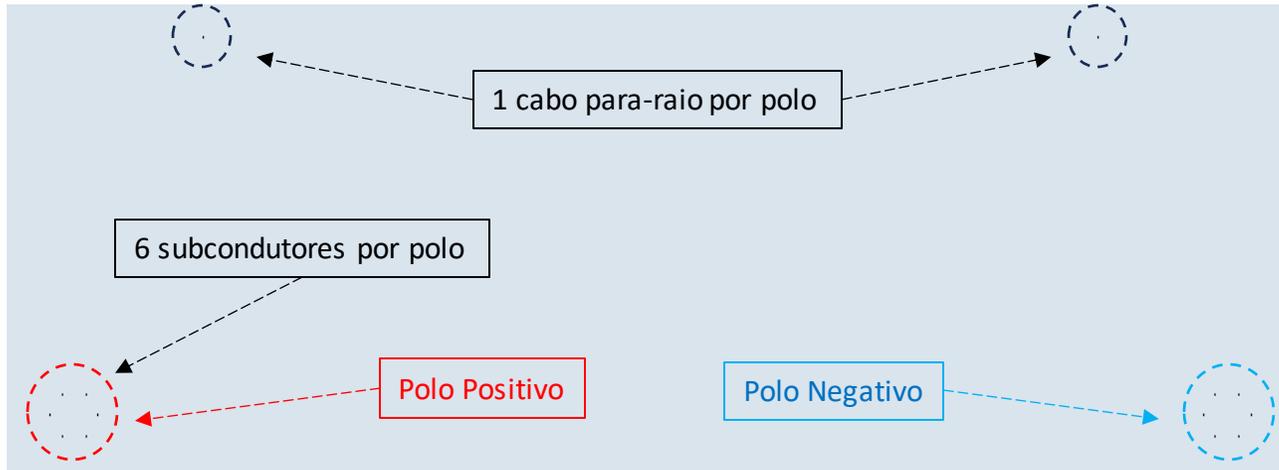


(file HVDC\_Vazio\_1.pl4; x-var t) t:A1+ t:SIG1A t:TRI

### 3. Modelo da linha:

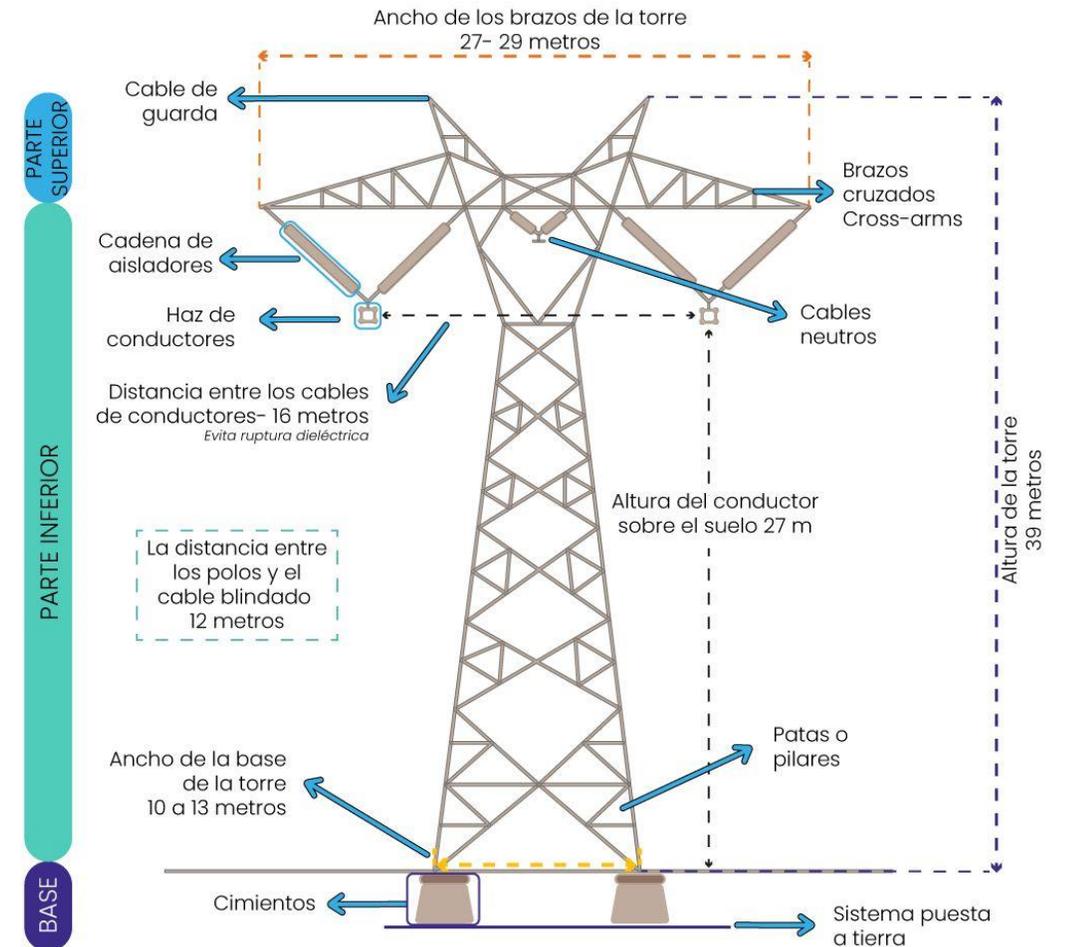
#### Geometría y dimensiones DE LA TORRE HVDC

Ejemplo para torres típicas de  $\pm 500$  kV y  $\pm 600$  kV



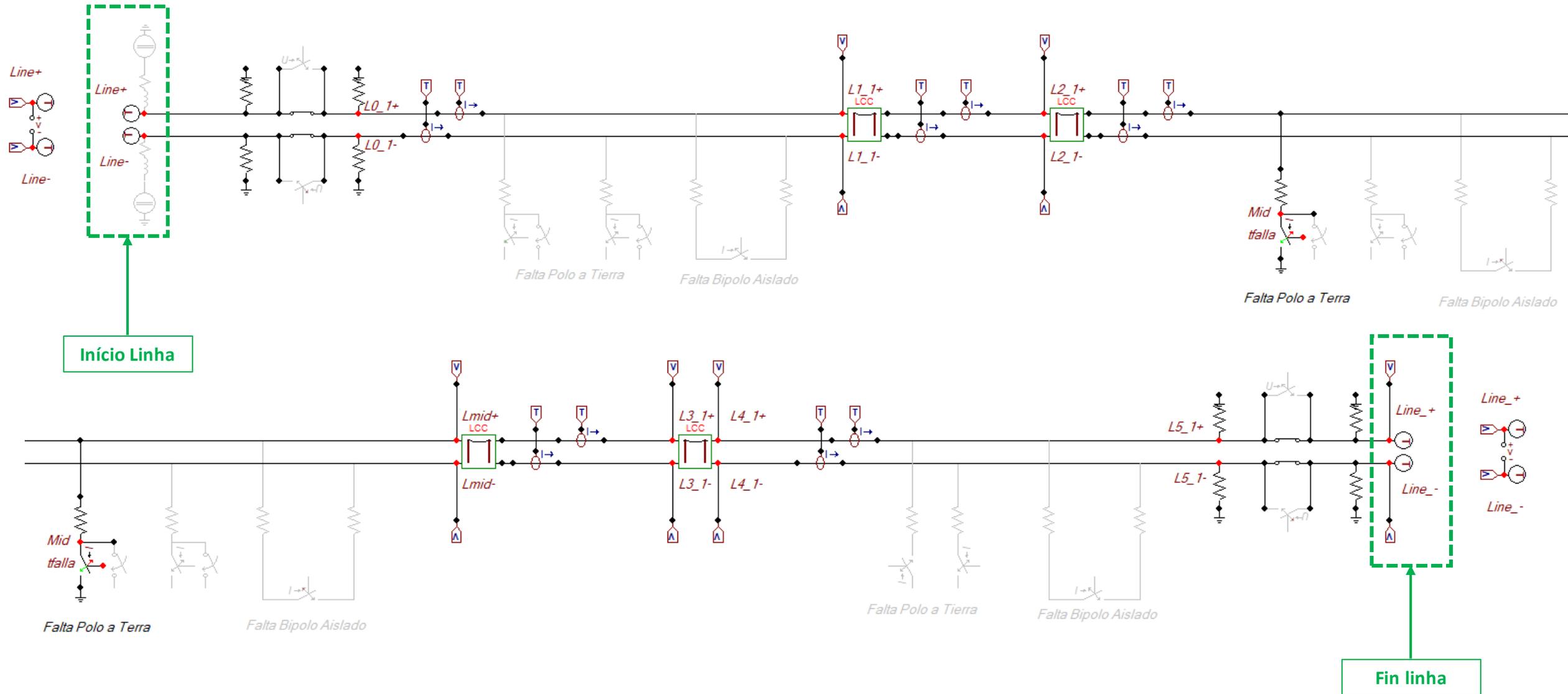
| # | Ph.no. | Rin [cm] | Rout [cm] | Resis [ohm/km DC] | Horiz [m] | Vtower [m] | Vmid [m] | Separ [cm] | Alpha [deg] | NB |
|---|--------|----------|-----------|-------------------|-----------|------------|----------|------------|-------------|----|
| 1 | 1      | 0.4775   | 1.9075    | 0.03991           | 10.95     | 35.72      | 17.3     | 45.72      | 0           | 6  |
| 2 | 2      | 0.4775   | 1.9075    | 0.03991           | -10.95    | 35.72      | 17.3     | 45.72      | 0           | 6  |
| 3 | 0      | 0        | 0.457     | 4.1889            | 8.5       | 42.85      | 24.43    | 0          | 0           | 1  |
| 4 | 0      | 0        | 0.457     | 4.1889            | -8.5      | 42.85      | 24.43    | 0          | 0           | 1  |

Dados dos subconductores para um linha HVDC de 6GW,  $\pm 800$  kV, China.



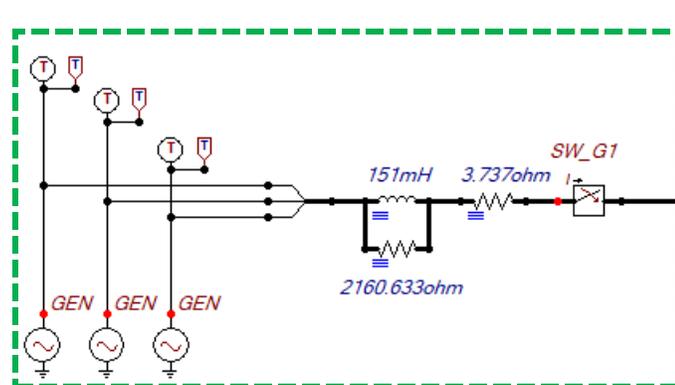
Fuente: Inel, Perú.

### 3. Modelo da linha:

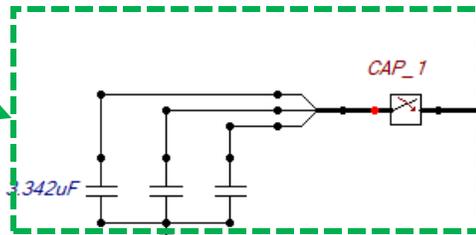


#### 4. Filtros y Compensadores AC do terminal retificador

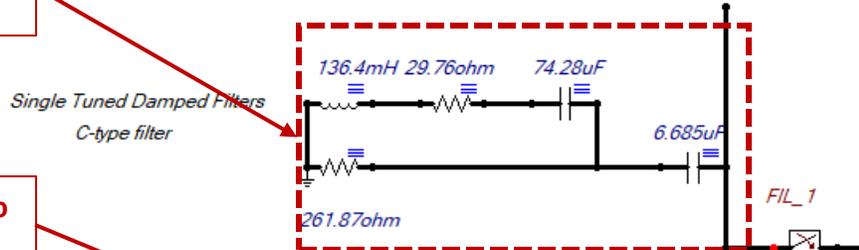
Compensador Potência Reativa



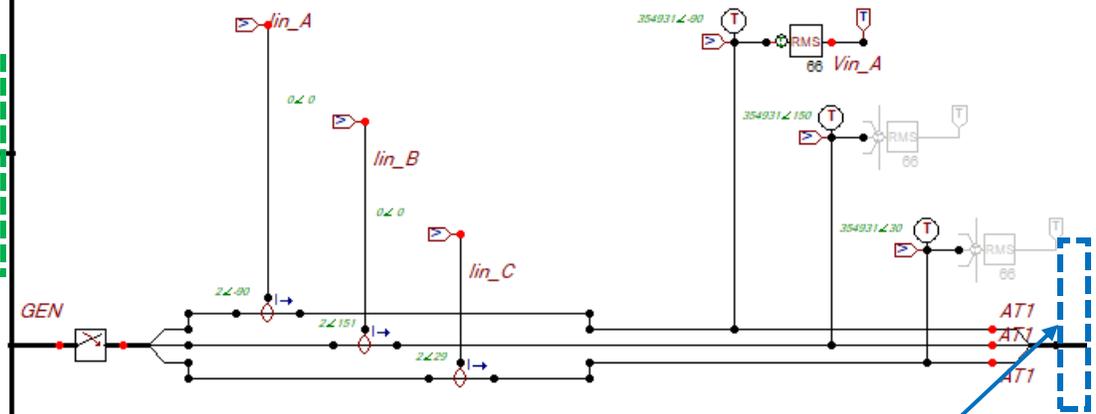
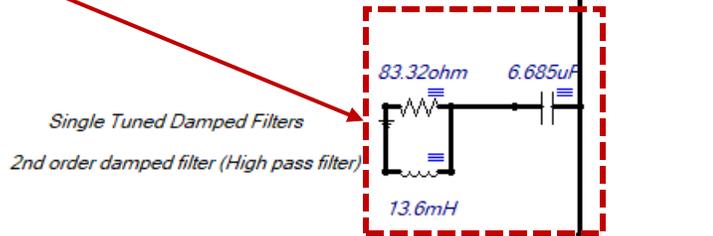
Equivalente do Sistema AC  
 $I_{FALLA}^{3\phi} = 7.447 [kA]$



Filtro passa altos C-Type

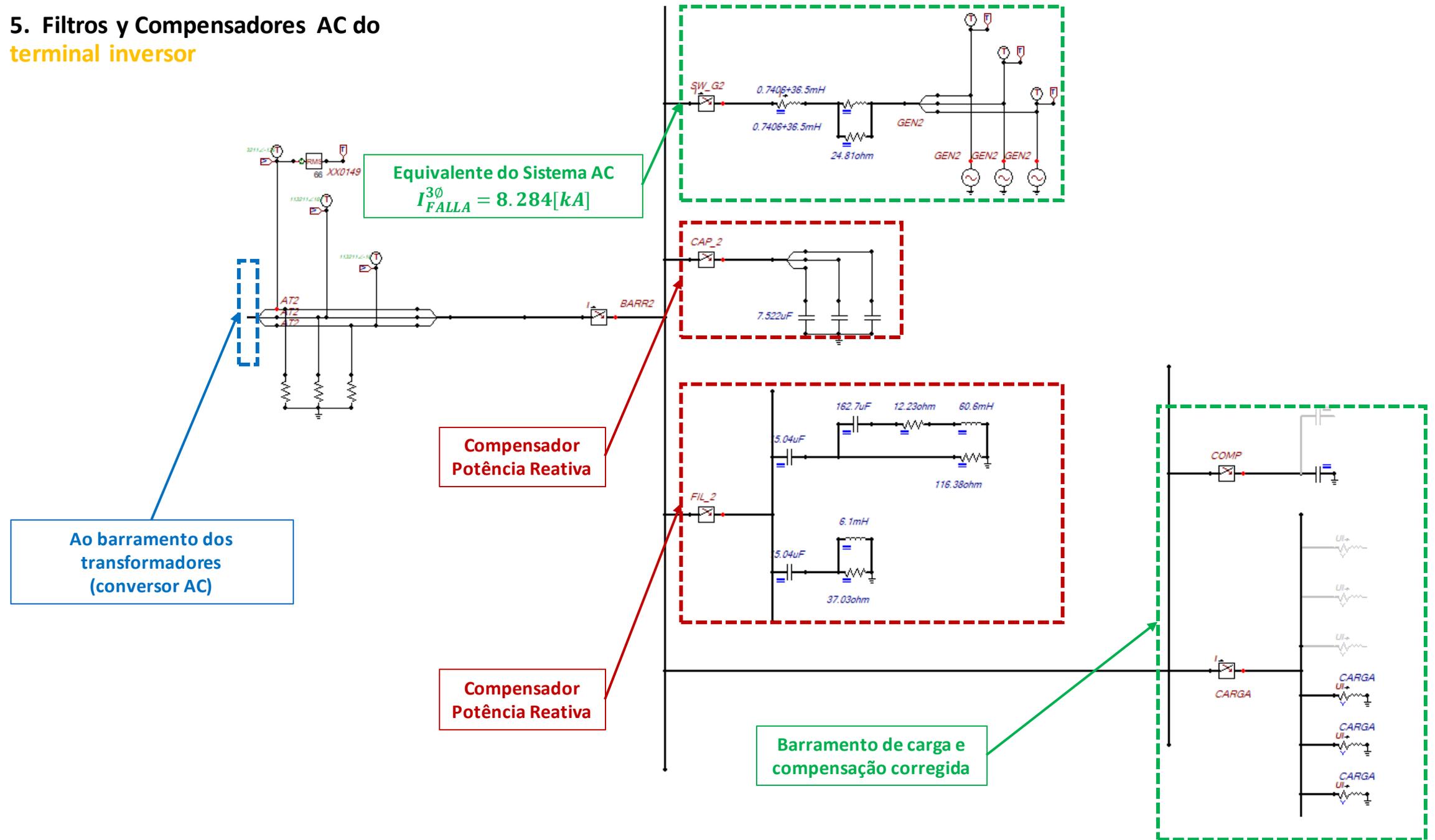


Filtro passa alto 2do ordem

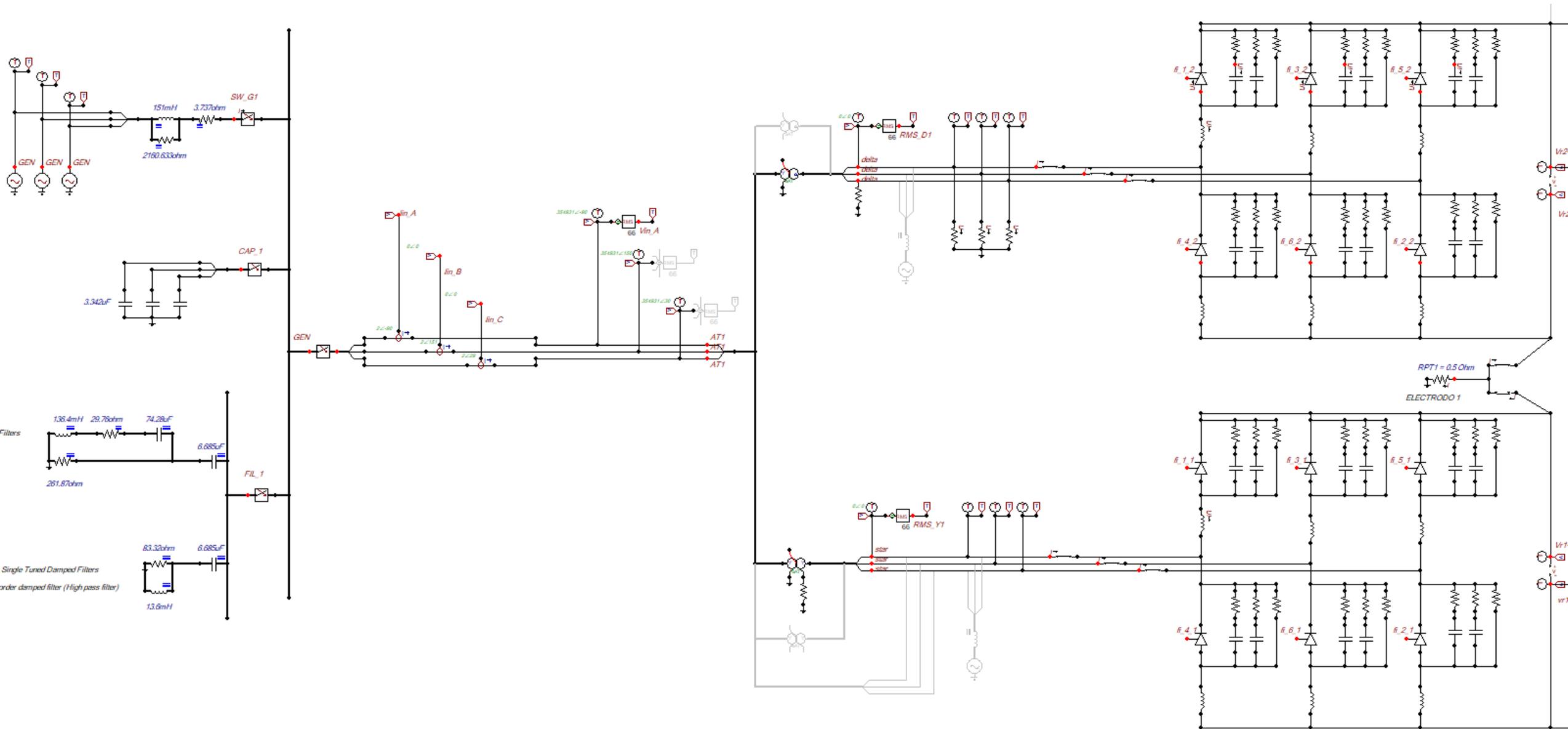


Ao barramento dos transformadores (conversor LCC)

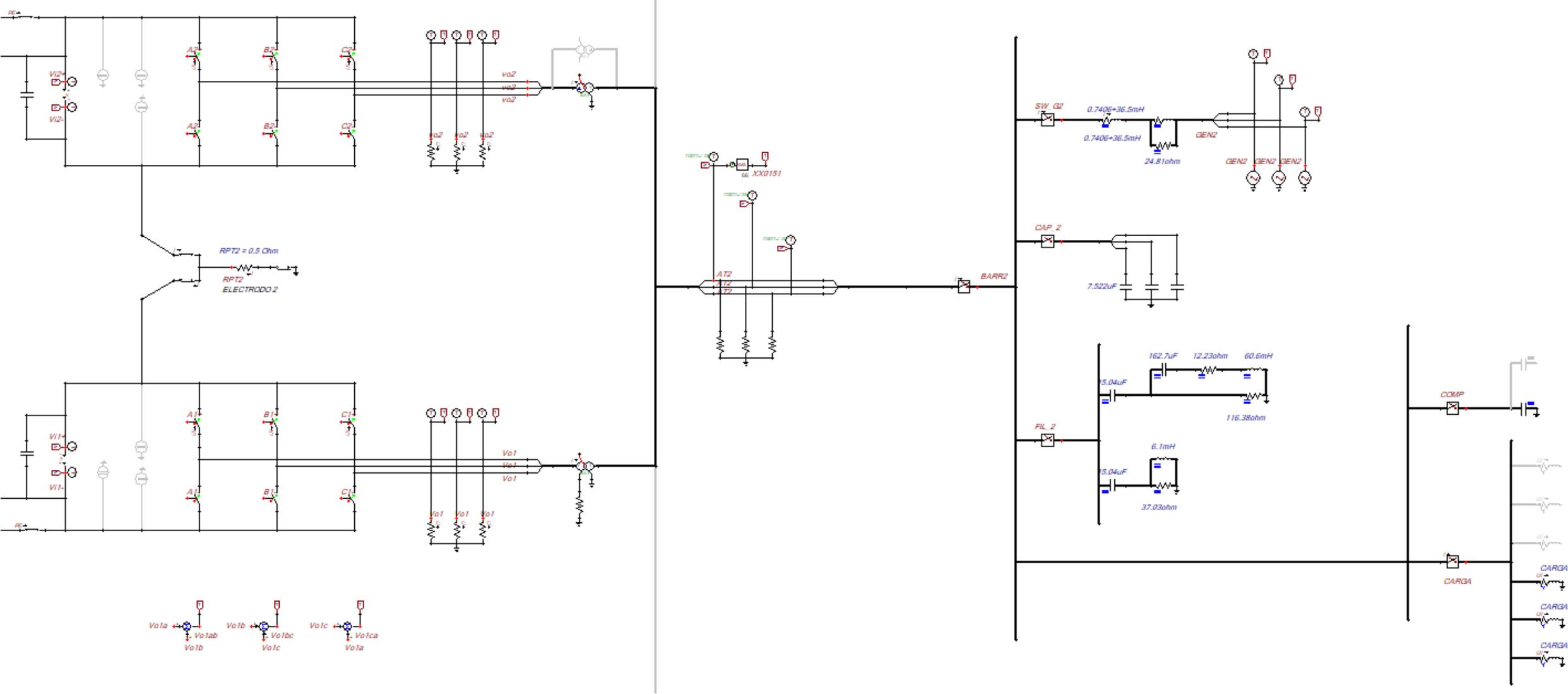
## 5. Filtros y Compensadores AC do terminal inversor



# Conversor (Retificador) LCC:



# Conversor (inversor) VSC:





## Casos de estudo HVDC

### A. Energização da linha

- Com e sem controle de  $\alpha$

### B. Falhas no ELO DC no início y meio da linha:

#### 1. *Início da linha $L = 0$ [km]:*

a) Falta polo positivo terra

#### 2. *Meio da linha $L = 1000$ [km]:*

a) Falta polo positivo terra

#### 3. *Se realizará medições de tensões e correntes:*

a) No início, meio e final da linha:

$L1 = 0$  [km],  $L2 = 500$  [km],  
 $L3 = 1500$  [km] y  $L4 = 2000$  [km]

a) No barramento AC antes do transformador retificador

b) No barramento AC após do transformador inversor

c) Entre outros

#### 4. *Os pontos 1 ao 3 serão feitos sem e com controle de $\alpha$ , e seguido de um religamento da linha.*



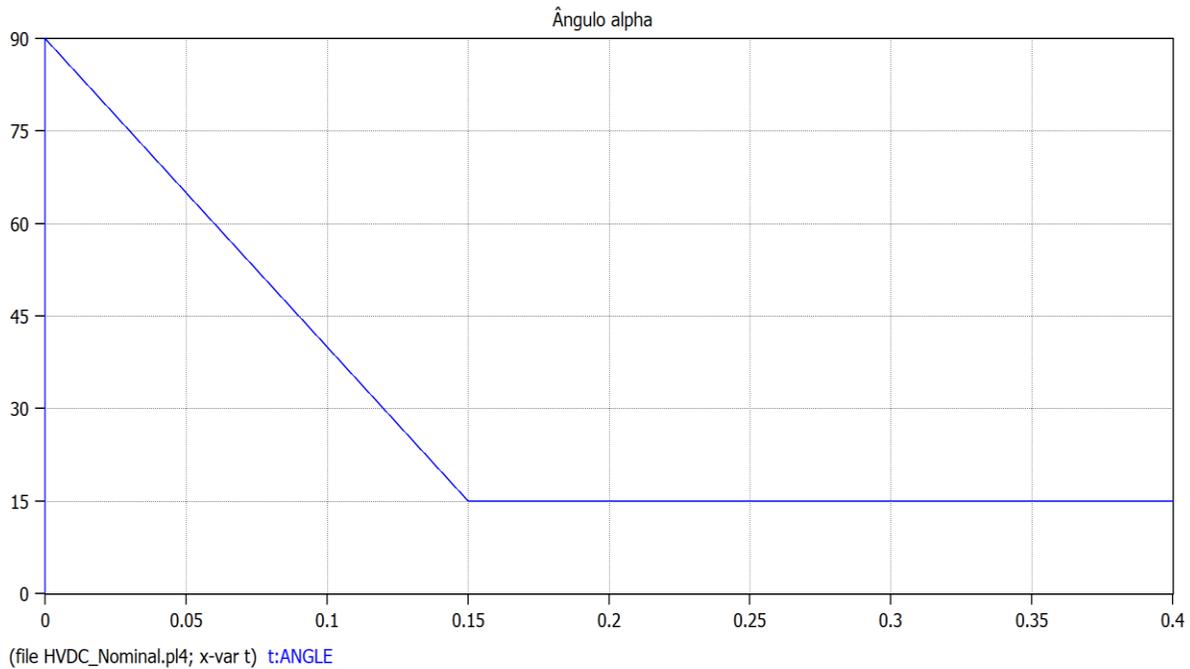


## Resultados

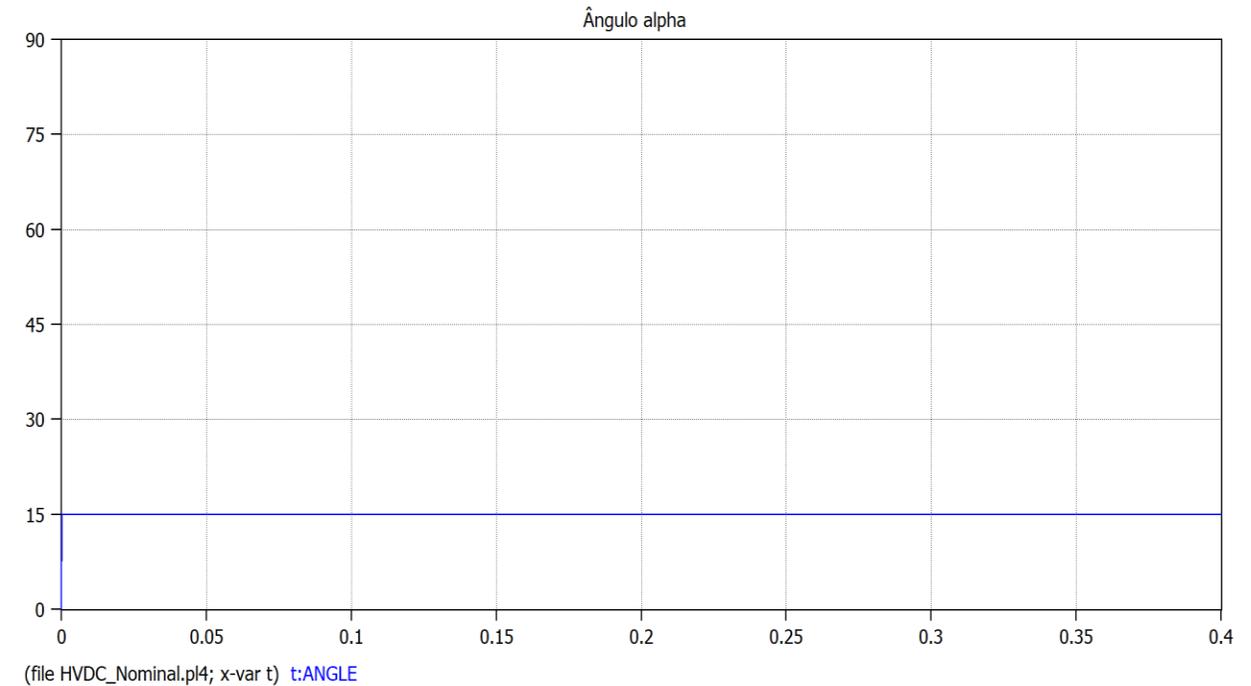
### A. Se realizará energização da linha:

- A energização é precisa para chegar ao regime permanente na condição de pre-falla.

#### A.1. Caso energização com controle de alpha:

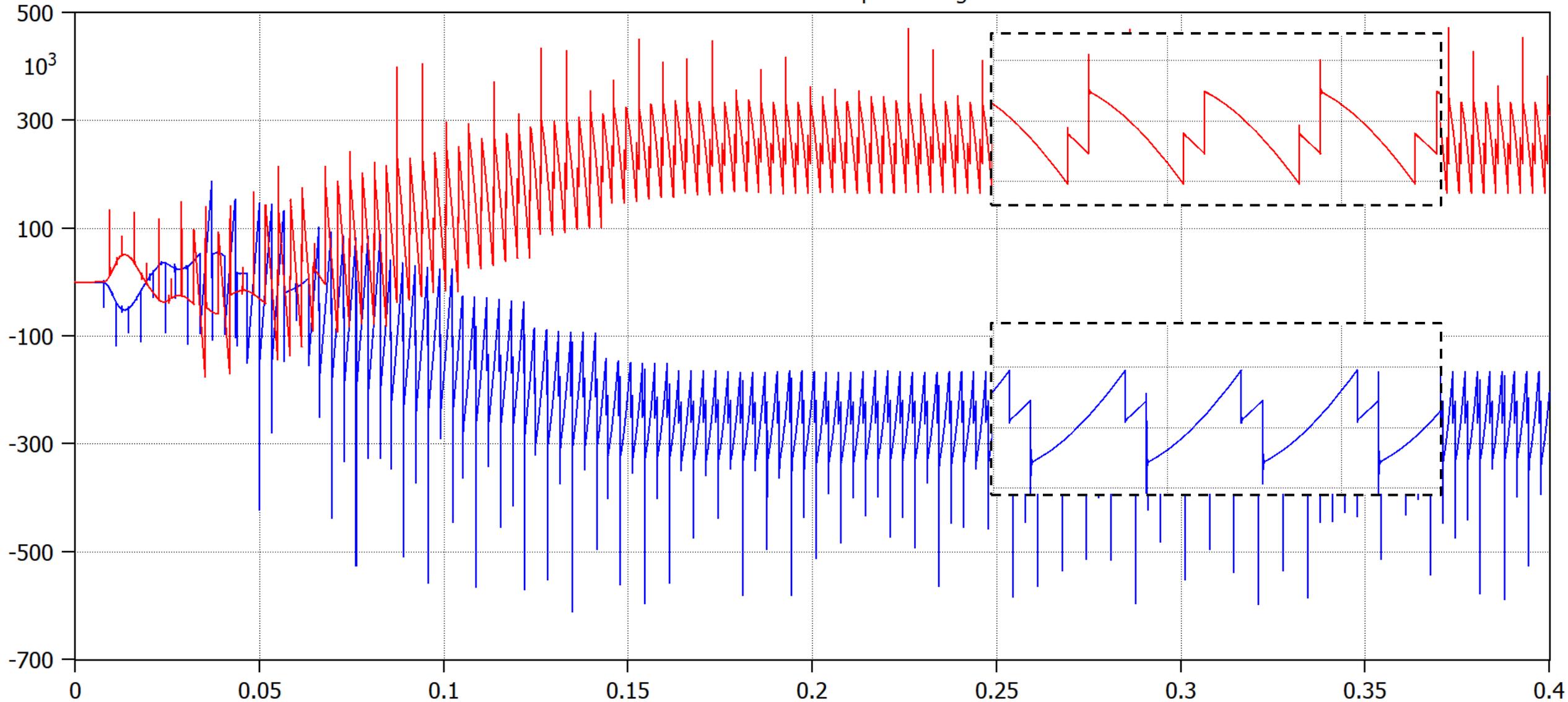


#### A.2. Caso energização sem controle de alpha:



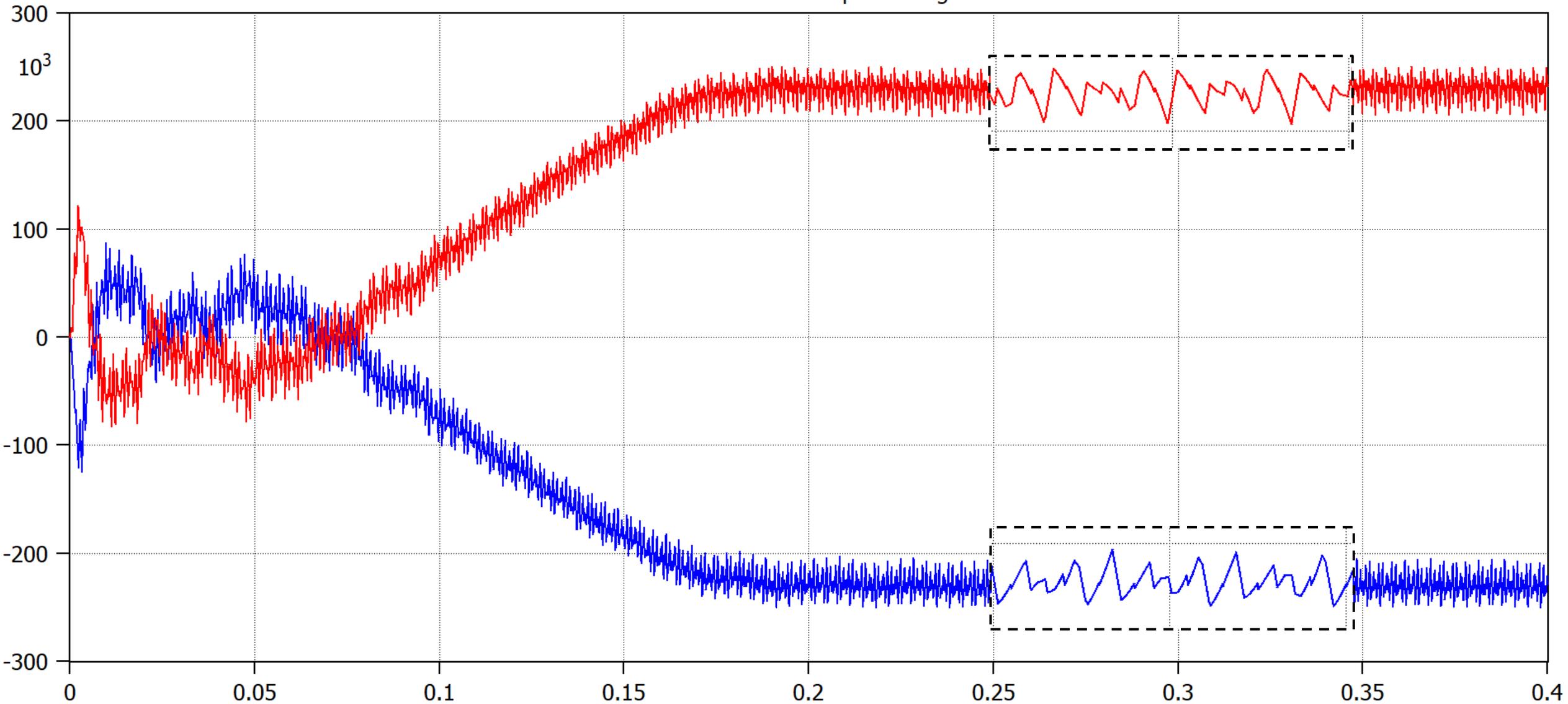


Tensão no rectificador a plena carga



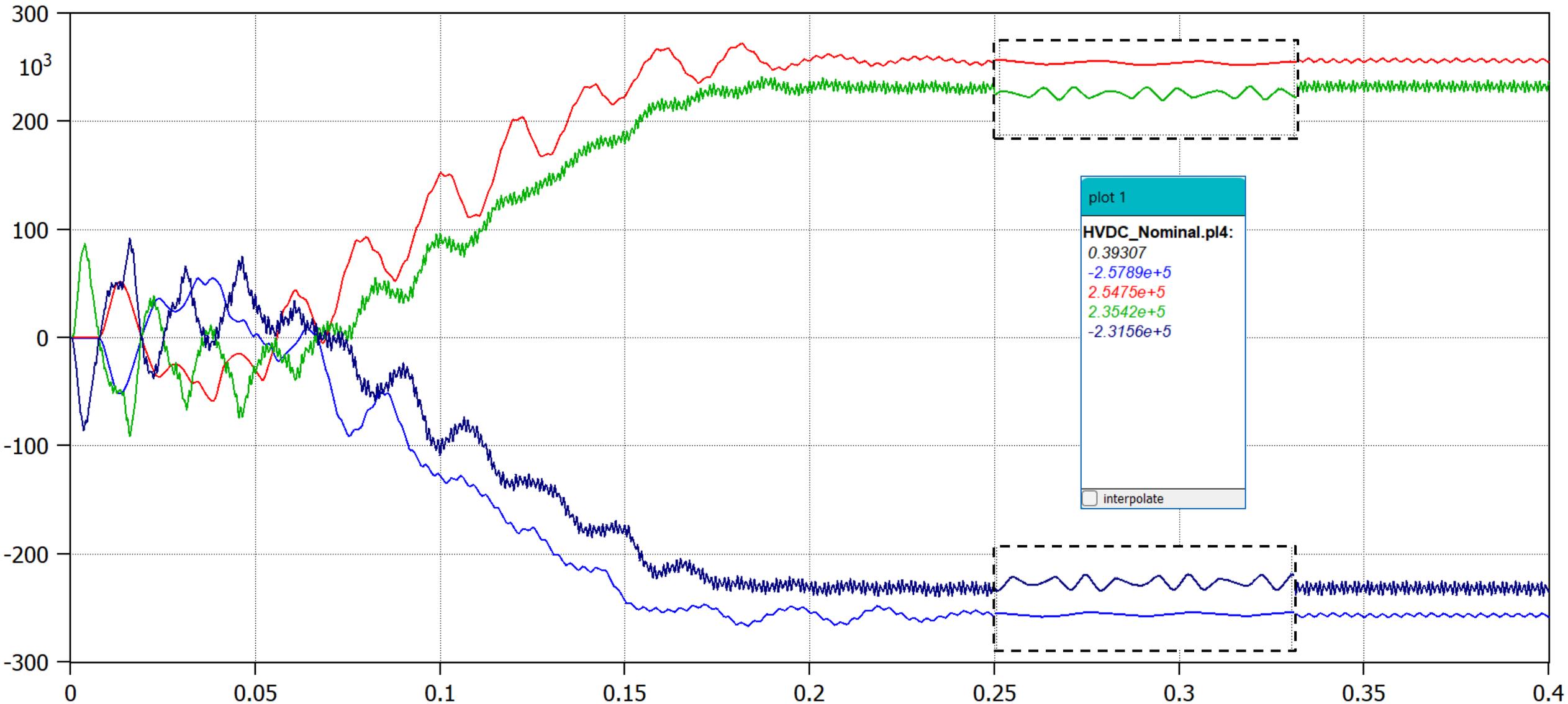


Tensão no inversor a plena carga



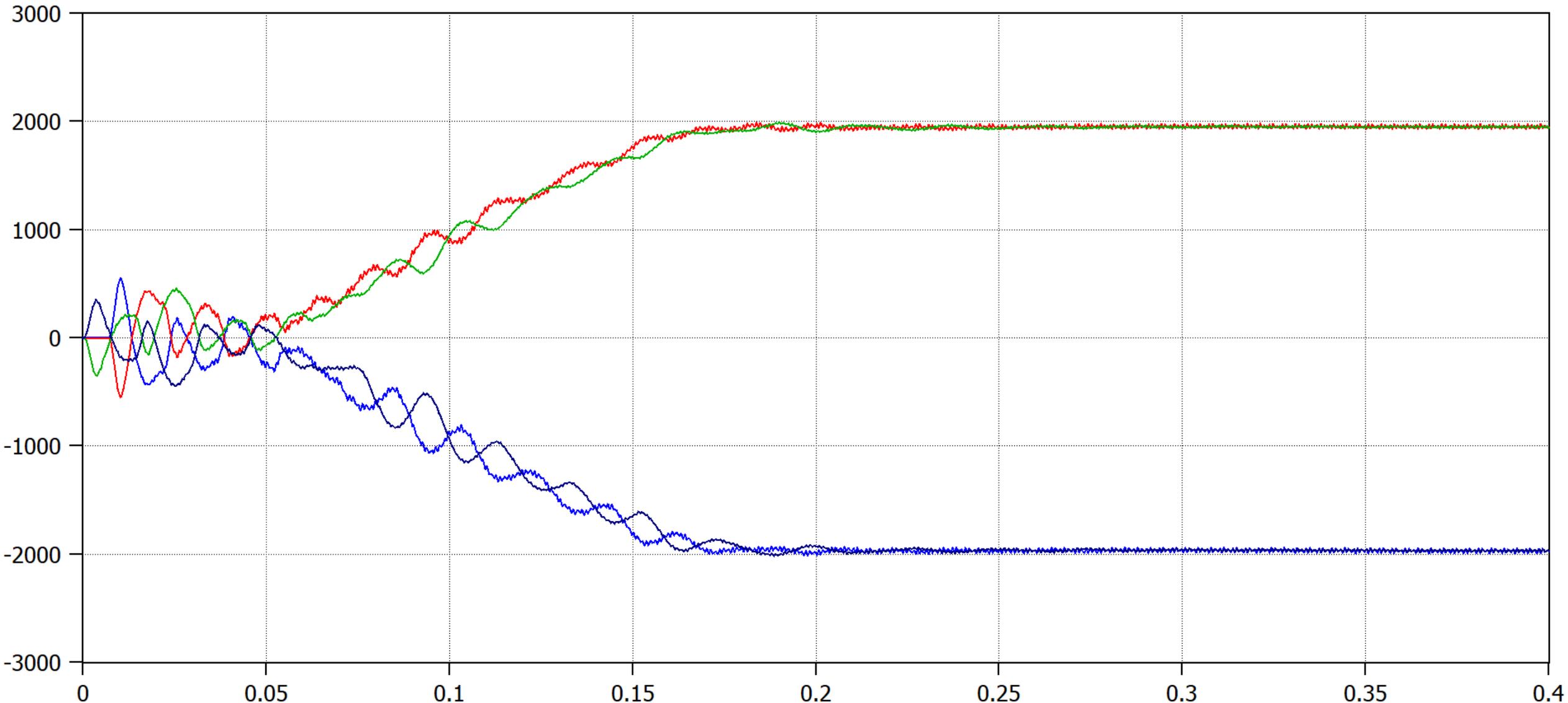


Tensão no início e final da linha



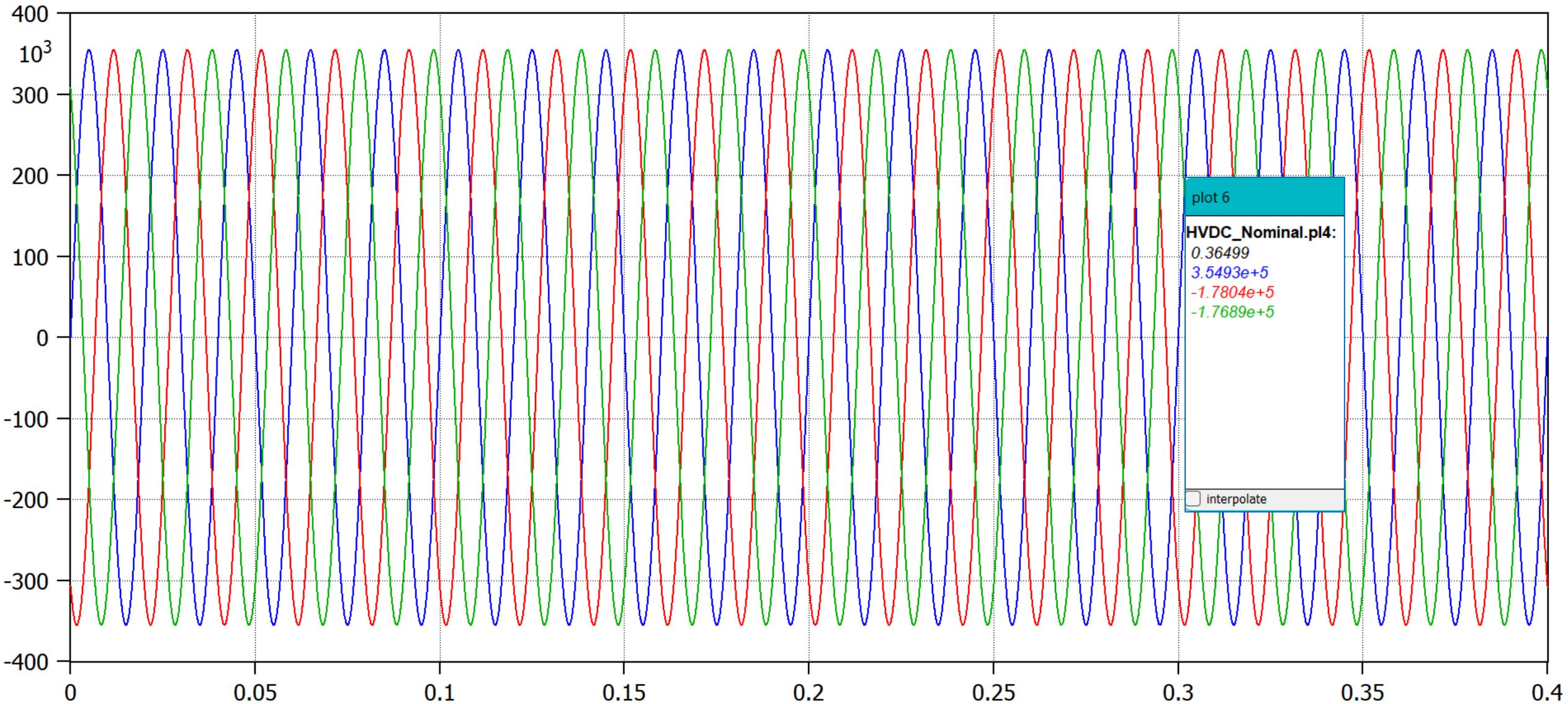


Corrente no início e final da linha



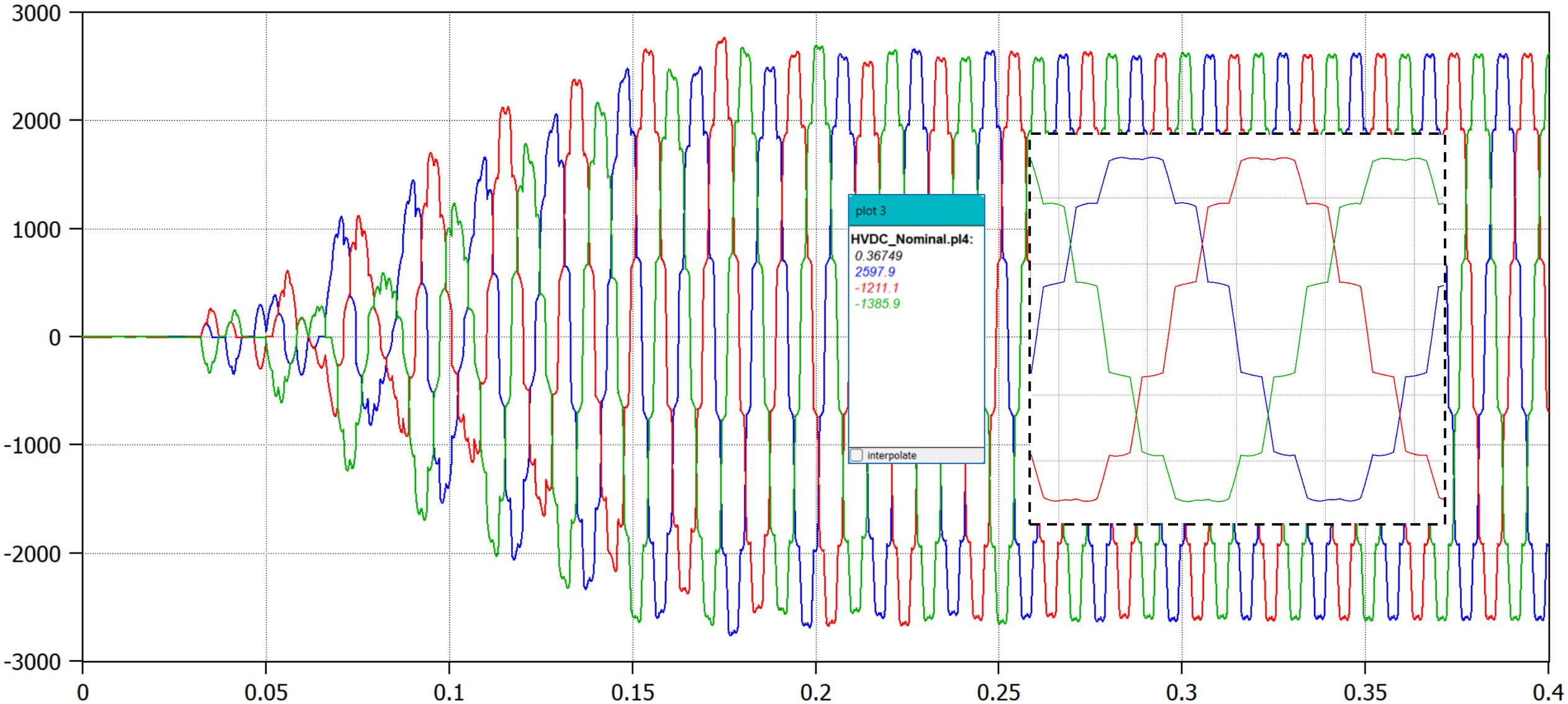


Tensão AC no retificador antes do trafo



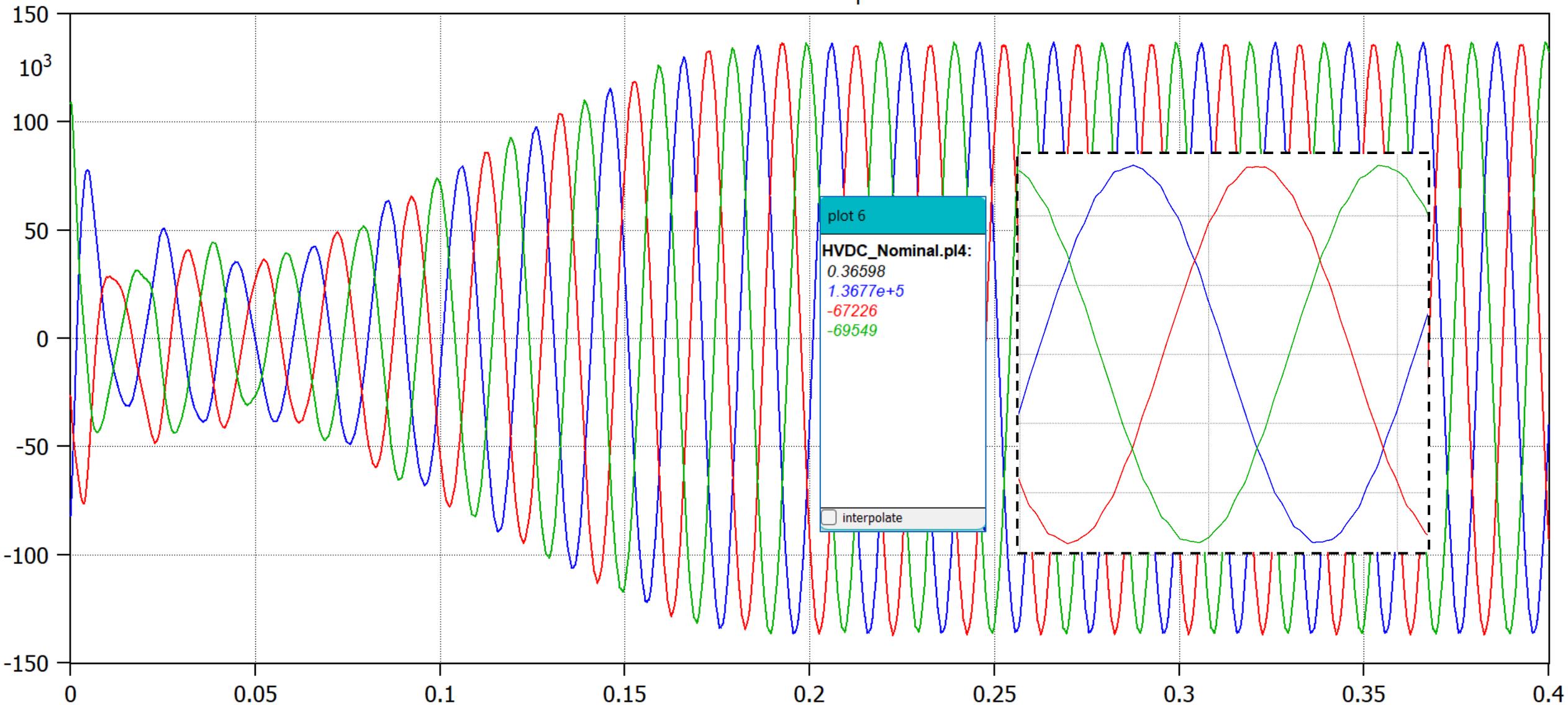


Corrente AC no retificador antes do trafo



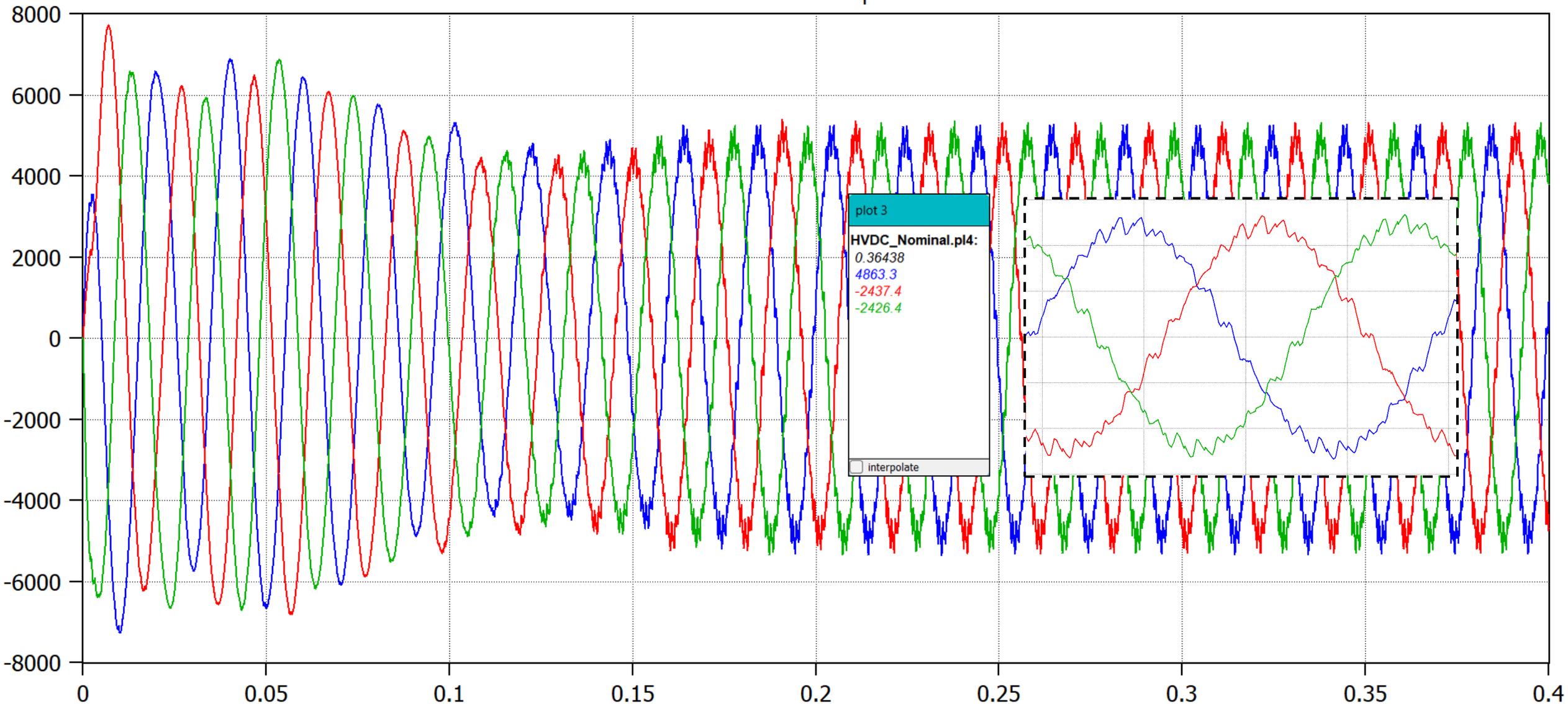


Tensão AC no inversor após do trafo





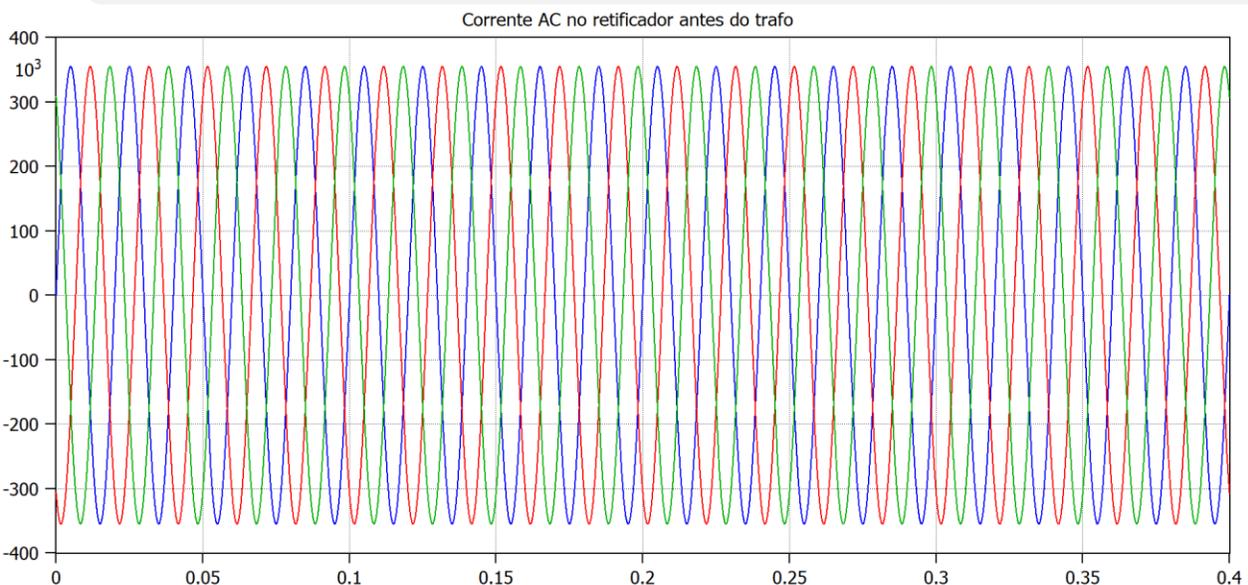
Corrente AC no inversor após do trafo



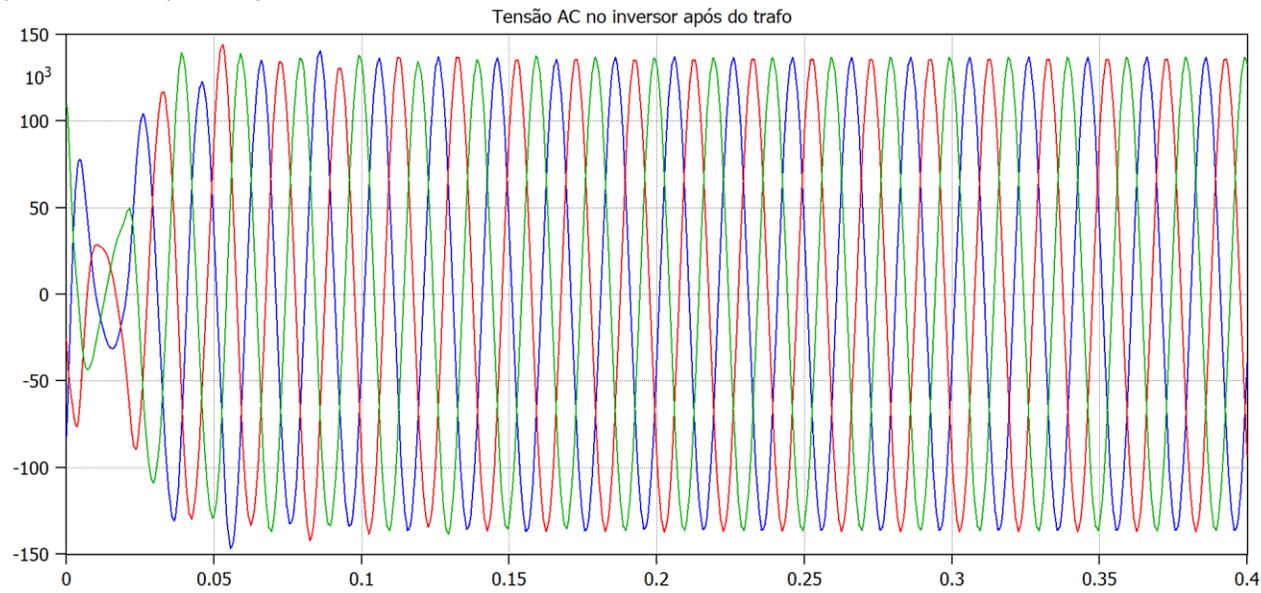


# Resultados

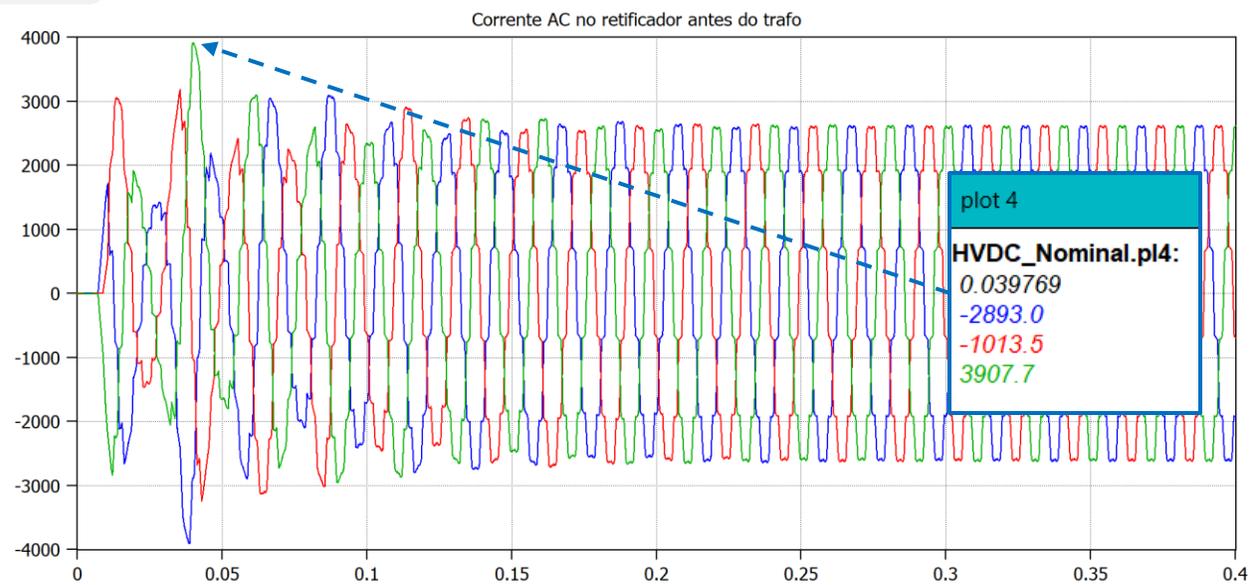
## A.2. Caso energização sem controle de alpha:



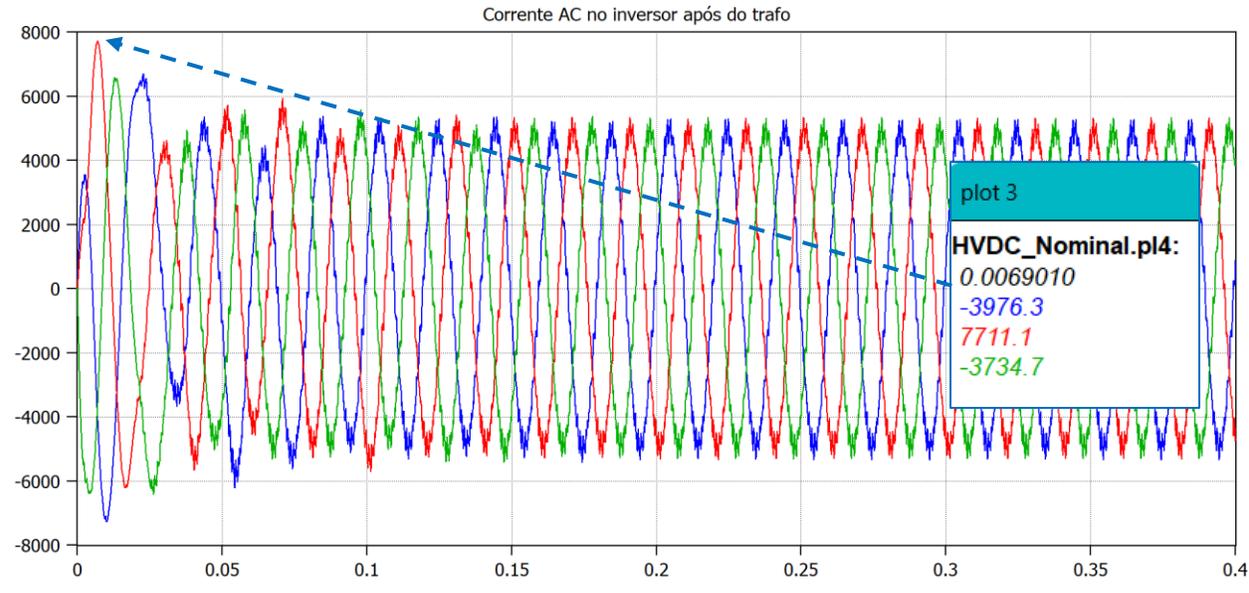
(file HVDC\_Nominal.pl4; x-var t) v:AT1A v:AT1B v:AT1C



(file HVDC\_Nominal.pl4; x-var t) v:AT2A v:AT2B v:AT2C



(file HVDC\_Nominal.pl4; x-var t) c:X0001A-AT1A c:X0001B-AT1B c:X0001C-AT1C



(file HVDC\_Nominal.pl4; x-var t) c:AT2A -BARR2A c:AT2B -BARR2B c:AT2C -BARR2C

plot 4  
 HVDC\_Nominal.pl4:  
 0.039769  
 -2893.0  
 -1013.5  
 3907.7

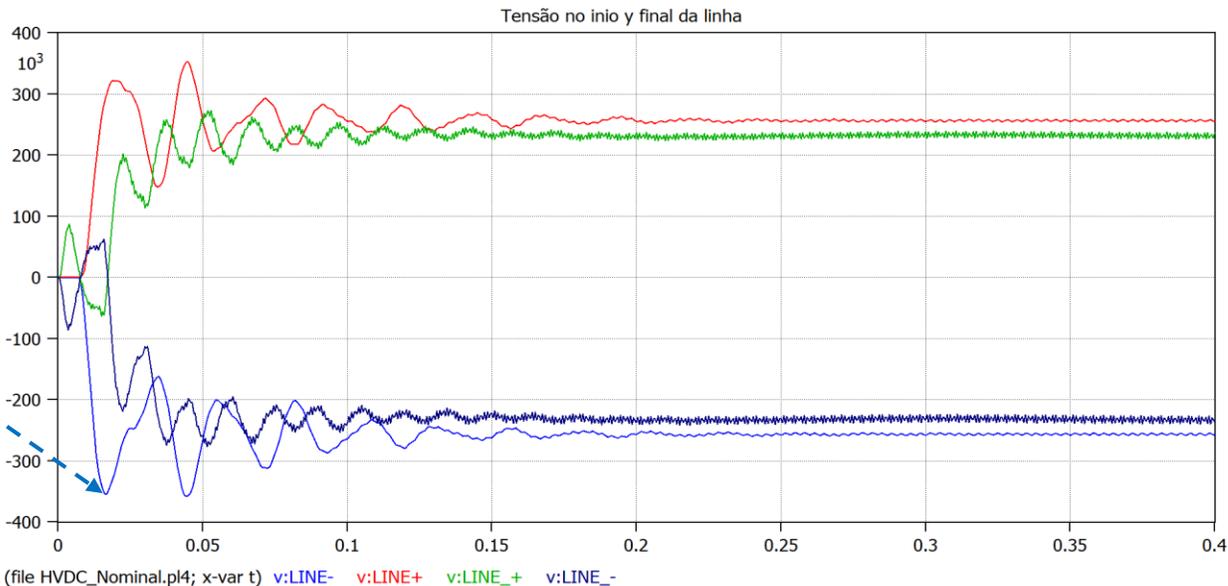
plot 3  
 HVDC\_Nominal.pl4:  
 0.0069010  
 -3976.3  
 7711.1  
 -3734.7



# Resultados

## A.2. Caso energização sem controle de alpha:

Aparecem sobretensões



plot 1

HVDC\_Nominal.pl4:

0.044749

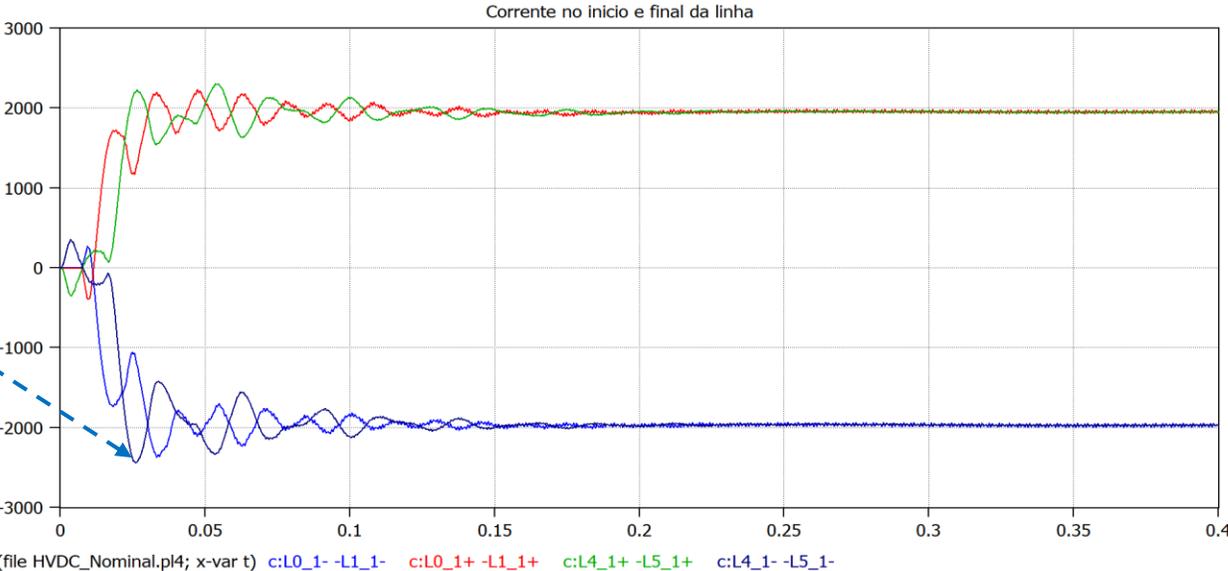
-3.5751e+5

3.5261e+5

1.8710e+5

interpolate

As correntes tem oscilações



plot 2

HVDC\_Nominal.pl4:

0.026141

-1175.3

1263.7

2202.2

-2440.2

interpolate

As energizações dos ELOS HVDC devem ser feitos com controle de ângulo em HVDC



#### B. Falhas no ELO DC no início y meio da linha:

##### 1. *Início da linha L = 0 [km]:*

- Falta polo positivo terra

##### 2. *Meio da linha L = 1000 [km]:*

- Falta polo positivo terra

##### 3. *Se realizará medições de tensões e correntes:*

- No início, meio e final da linha:  
 $L1 = 0 [km], L2 = 500 [km],$   
 $L3 = 1500 [km] y L4 = 2000 [km]$
- No barramento AC antes do transformador retificador
- No barramento AC após do transformador inversor
- Entre outros

##### 4. *Os pontos 1 ao 3 serão feitos sem e com controle de alpha, e seguido de um religamento da linha.*

#### ✓ Condições de operação:

$$\alpha_N = 15^\circ, \mu = 23.3^\circ, m_a = 0.98, m_f = 20$$

#### ✓ Medições:

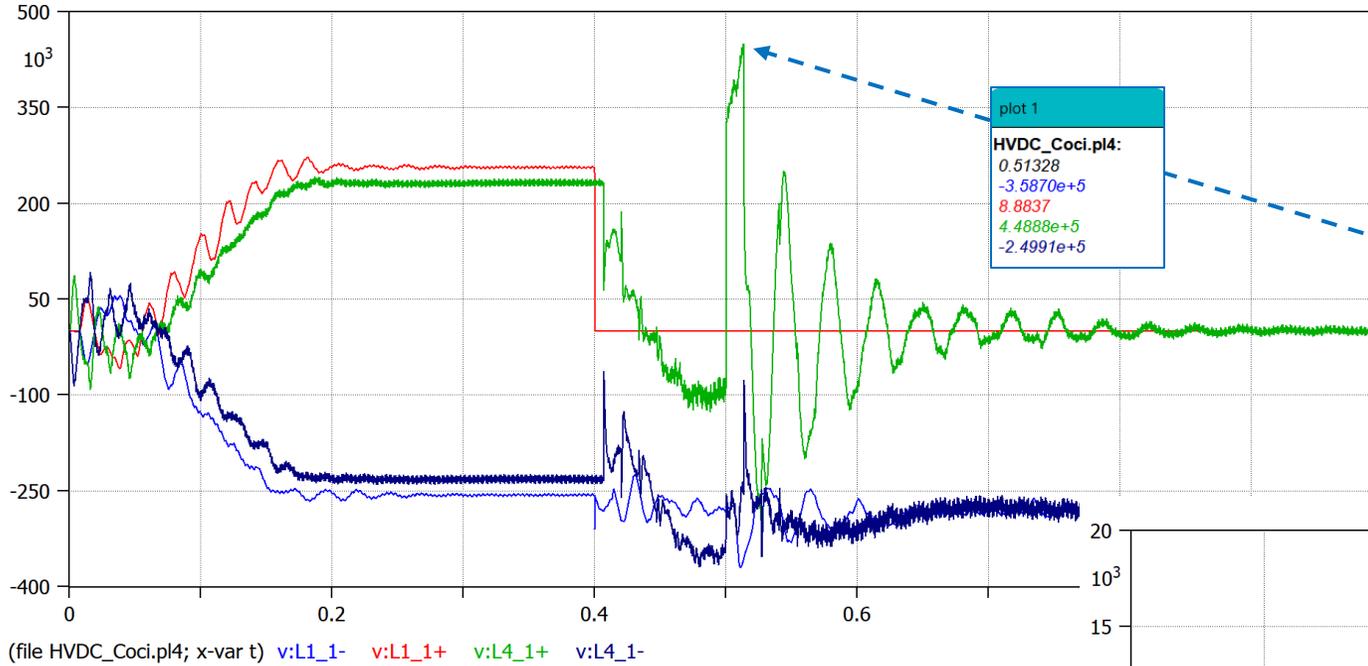
- Tensão DC na entrada e saída da linha*
- Corrente DC na entrada e saída da linha*
- Tensão e Corrente AC no retificador antes do transformador*
- Tensão em Corrente AC no inversor depois do transformador*



# Resultados

## B.1. Falta PT sem controle de alpha, $l = 0$ [km]:

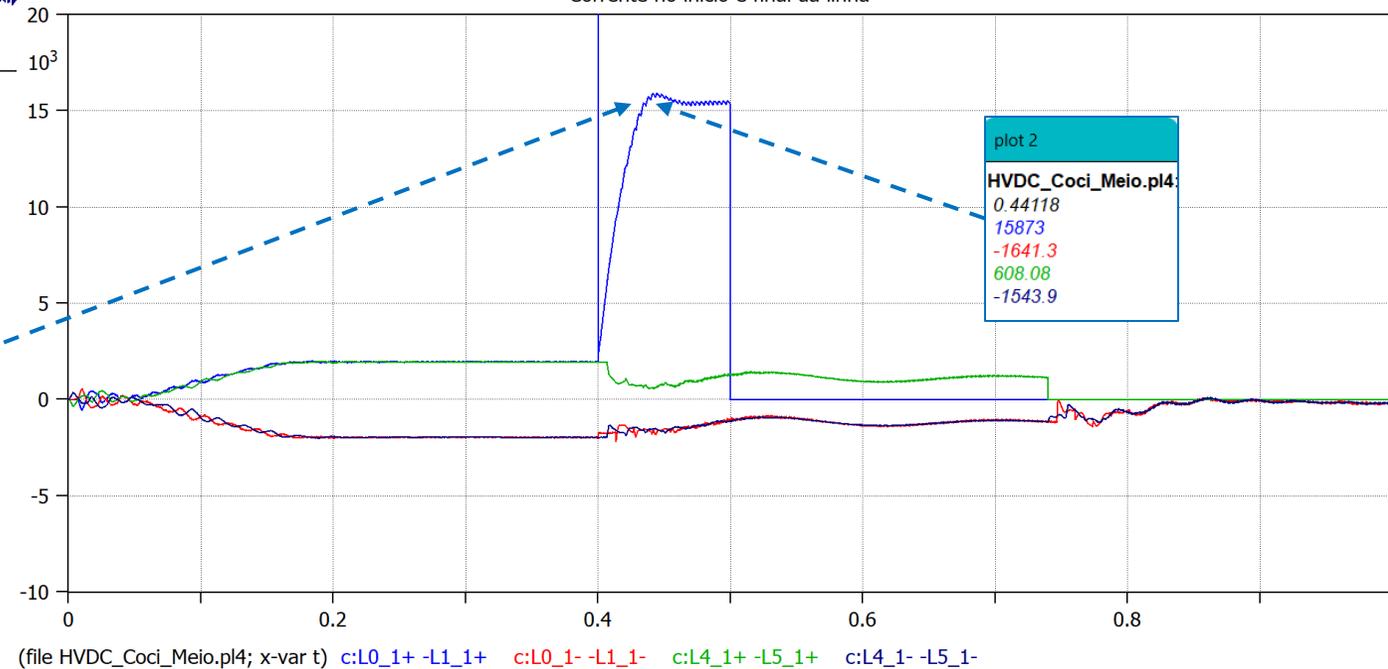
Temsoes no inicio e final da linha



Sobretensão muito forte após a abertura da linha

Sobrecorrentes que os Thyristores não podem suportar durante a falta

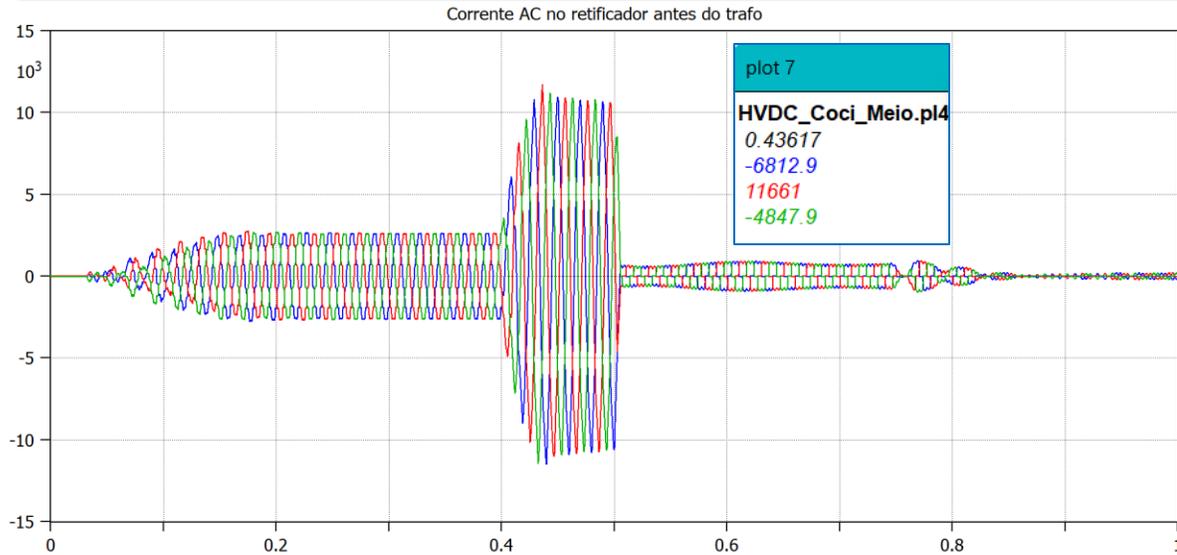
Corrente no inicio e final da linha



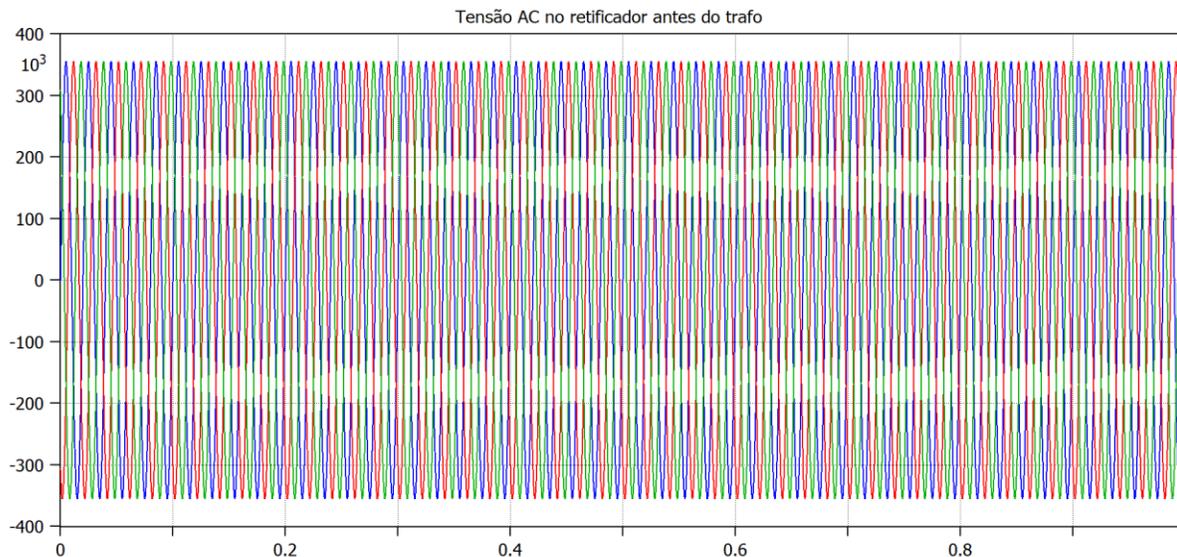


# Resultados

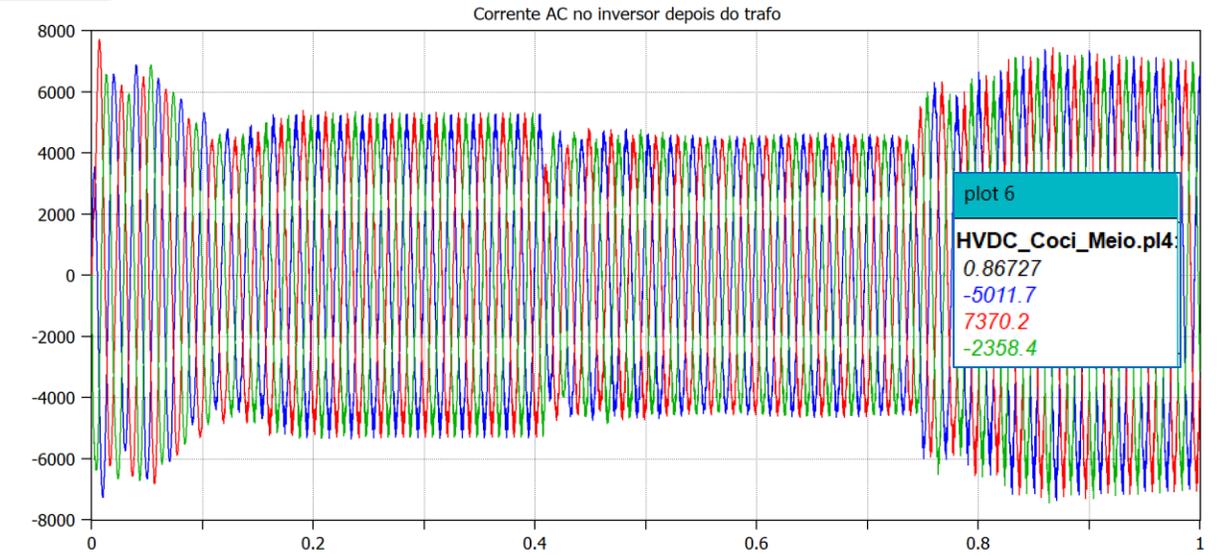
## B.1. Falta PT sem controle de alpha $l = 0$ [km]:



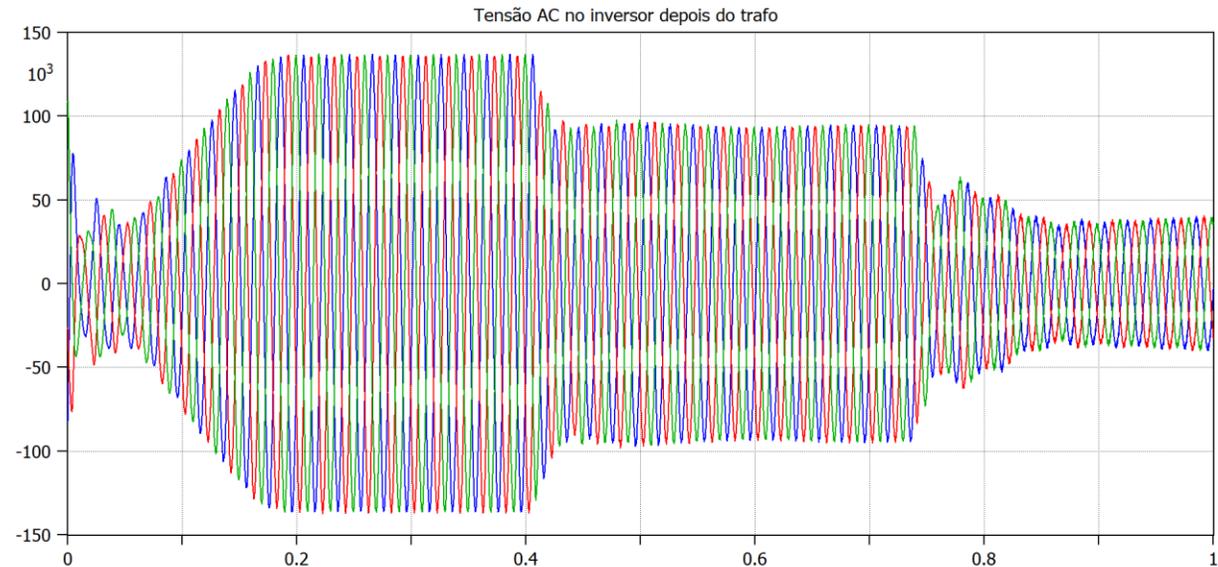
(file HVDC\_Coci\_Meio.pl4; x-var t) c:X0001A-AT1A c:X0001B-AT1B c:X0001C-AT1C



(file HVDC\_Coci\_Meio.pl4; x-var t) v:AT1A v:AT1B v:AT1C



(file HVDC\_Coci\_Meio.pl4; x-var t) c:AT2A -BARR2A c:AT2B -BARR2B c:AT2C -BARR2C



(file HVDC\_Coci\_Meio.pl4; x-var t) v:AT2A v:AT2B v:AT2C

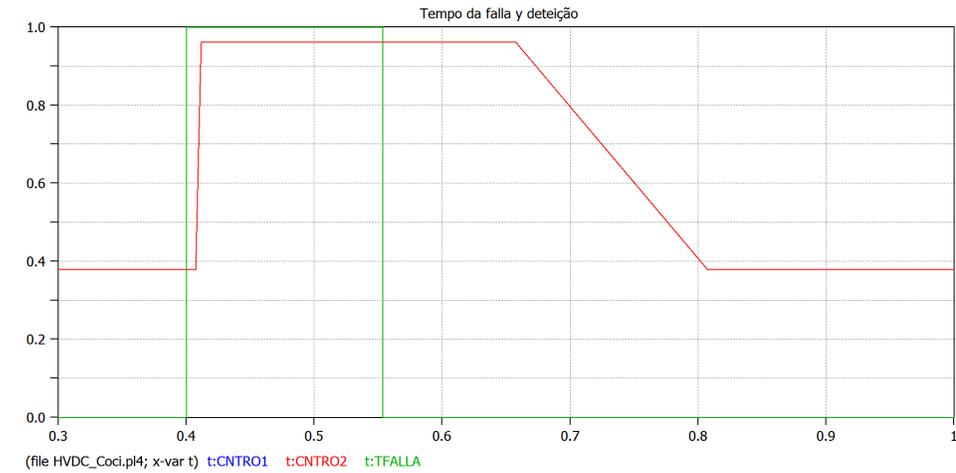
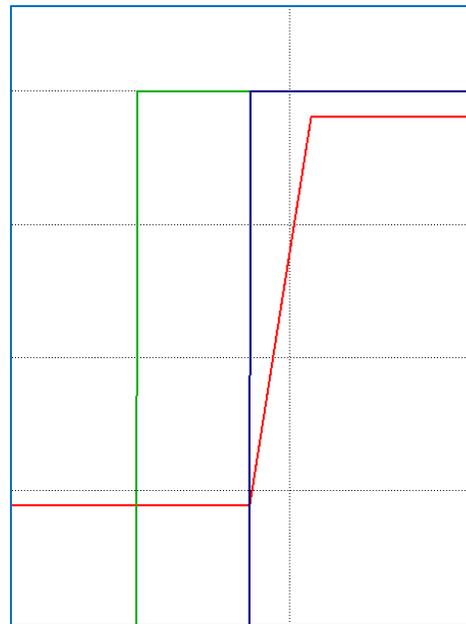
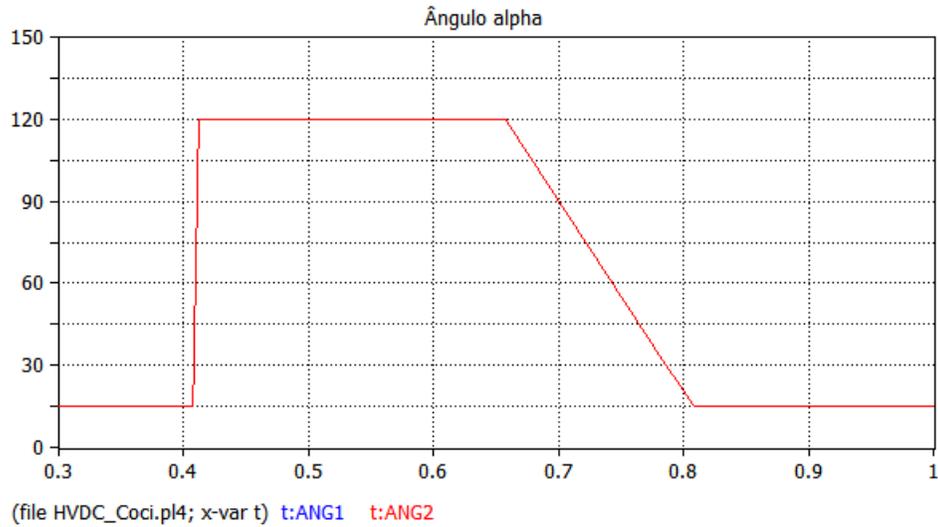


## Resultados

## B.2. Falta PT com controle de alpha $l = 0$ [km]:

✓ Condições de operação:

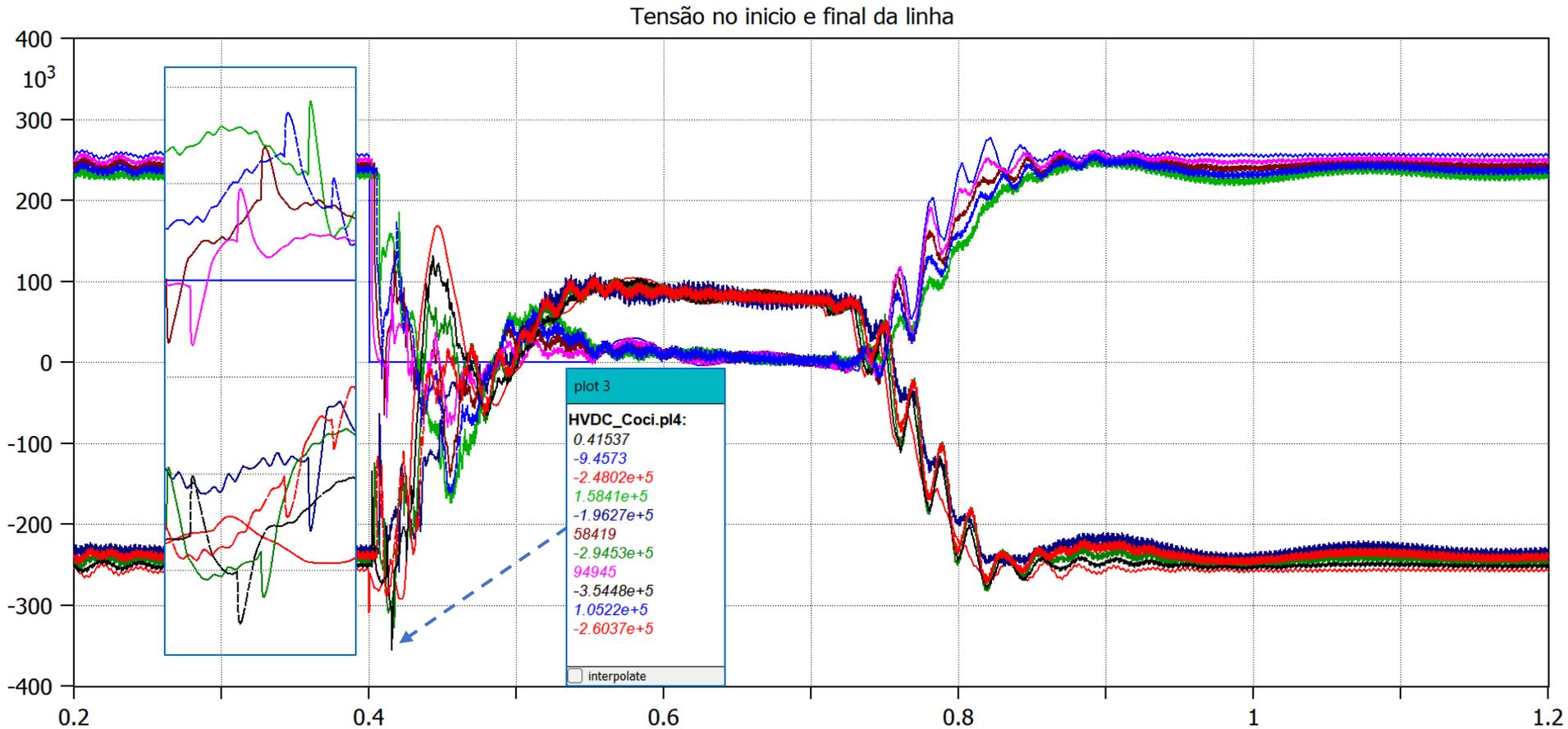
$$t_{falta} = 400[ms], t_{trafego} = 0[ms], t_{deteção} = 4[ms], t_{atuação} = 4[ms]$$





# Resultados

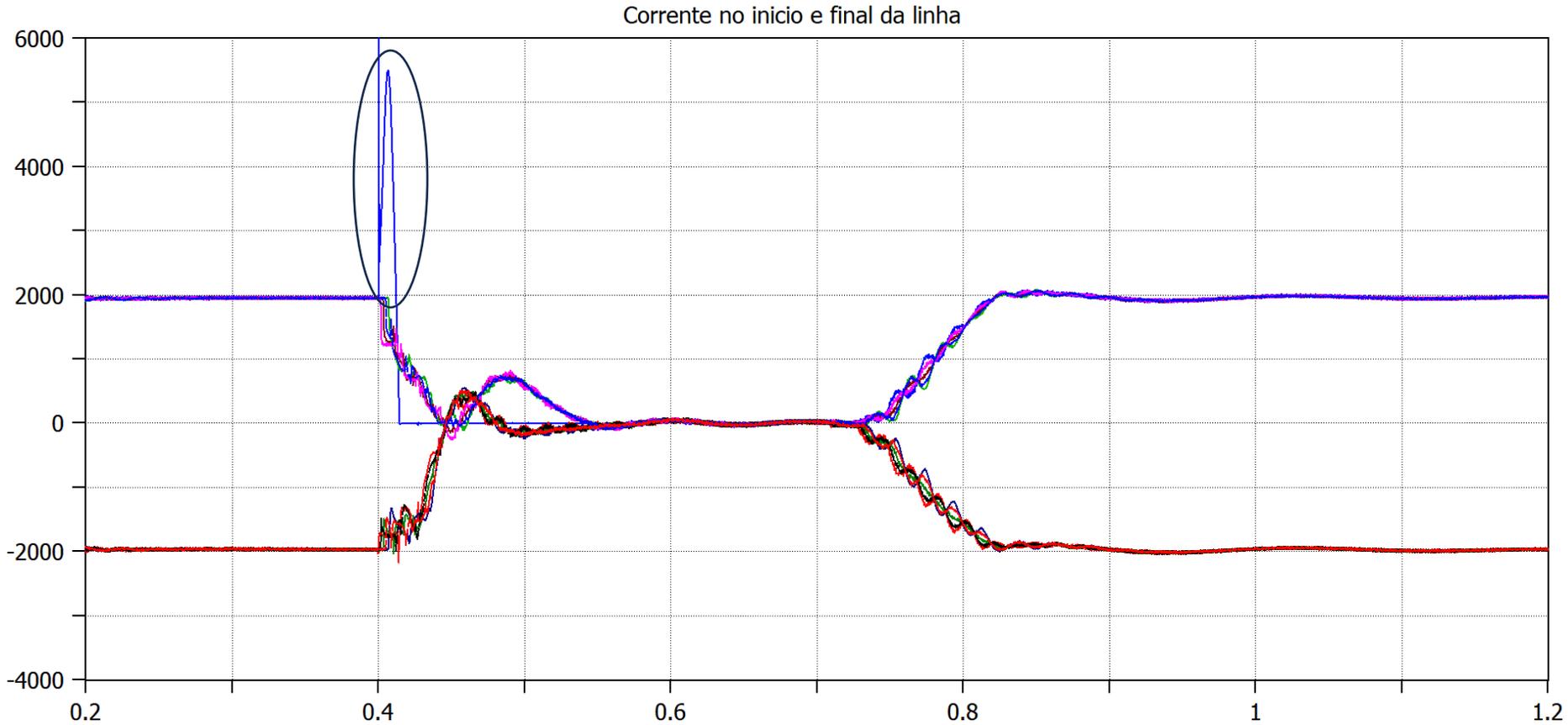
## B.2. Falta PT com controle de alpha $l = 0$ [km]:



A controle de alpha nas unidas retificadores reduz as sobretensões.

As sobretensões encontram-se controladas no trecho da linha

(file HVDC\_Coci.pl4; x-var t) v:LINE+ v:LINE- v:LINE\_+ v:LINE\_- v:LMID+ v:LMID- v:L2\_1+ v:L2\_1- v:L3\_1+ v:L3\_1-



A rápida atuação do conversor LCC vai reduzir as sobrecorrentes da falta

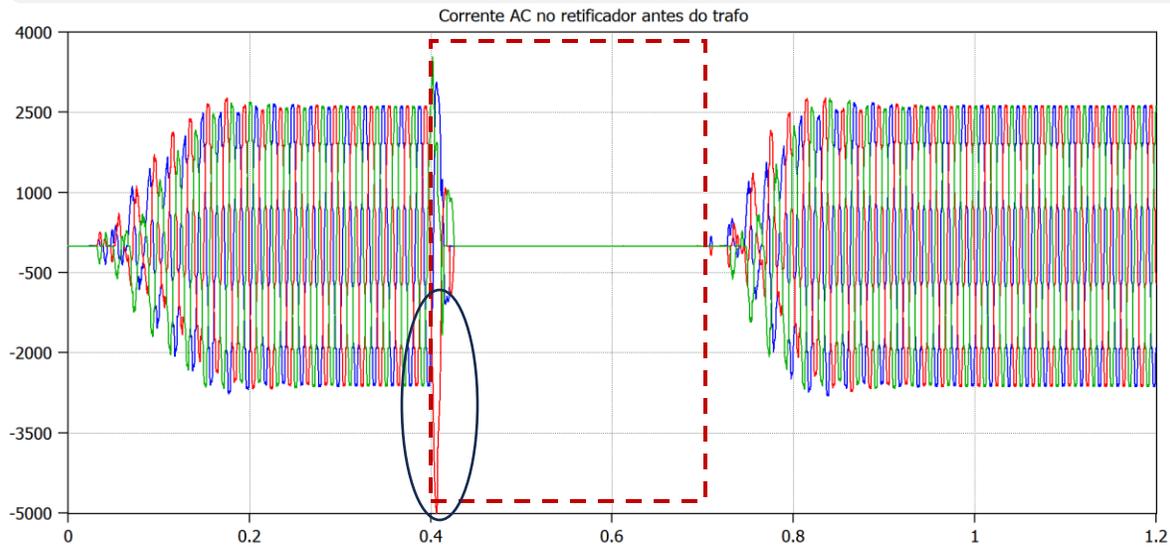
As sobrecorrentes são reduzidas para qualquer trecho da linha

(file HVDC\_Coci.pl4; x-var t) c:L0\_1+ -L1\_1+ c:L0\_1- -L1\_1- c:L4\_1+ -L5\_1+ c:L4\_1- -L5\_1- c:XX0177-LMID+ c:XX0176-LMID-  
c:XX0141-L2\_1+ c:XX0140-L2\_1- c:XX0180-L3\_1+ c:XX0179-L3\_1-

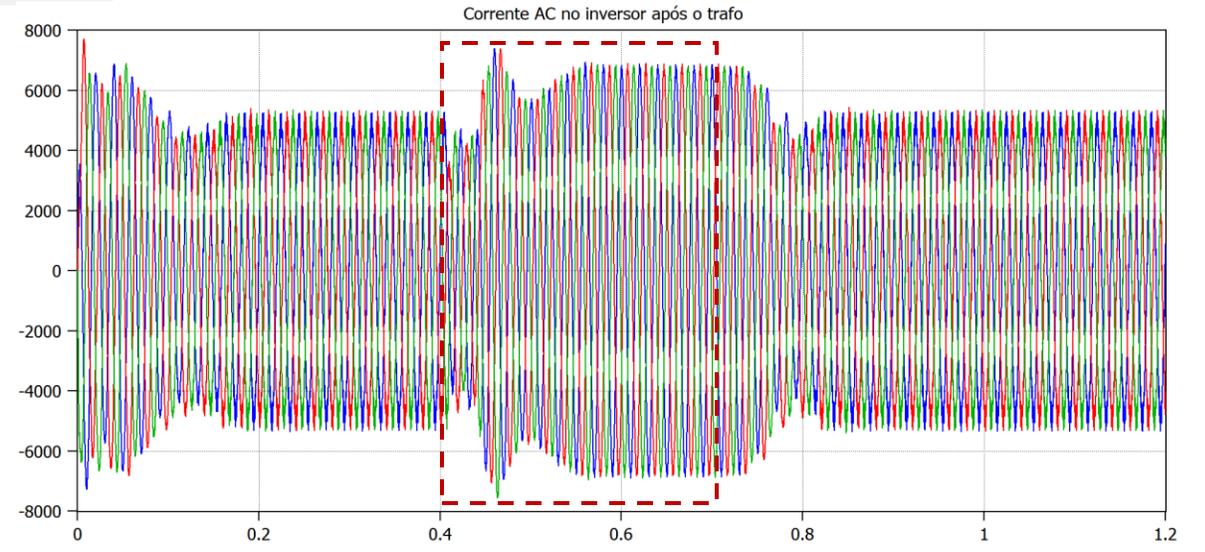


# Resultados

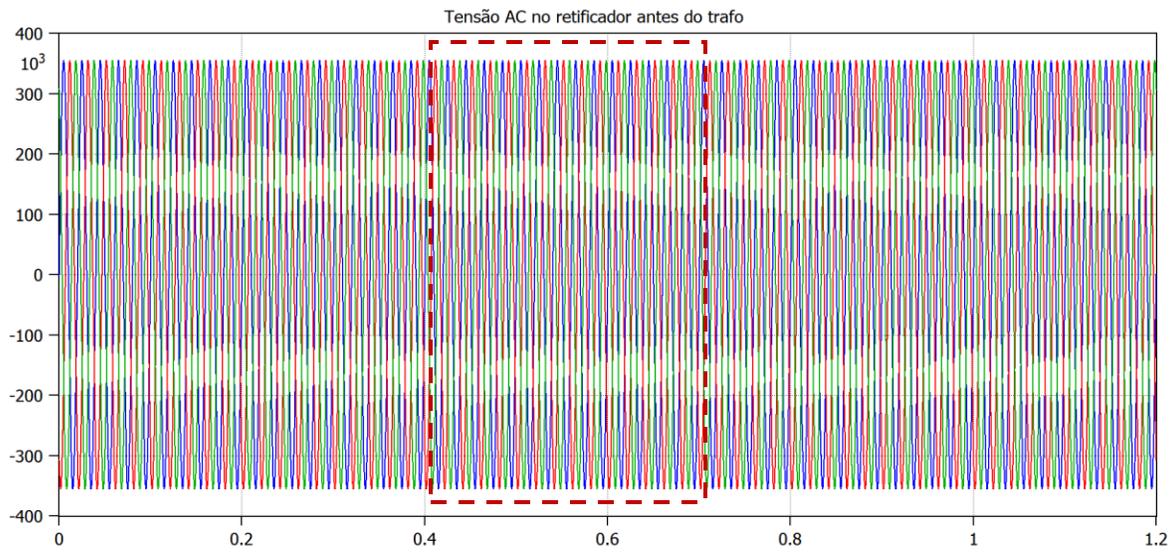
## B.2. Falta PT com controle de alpha $l = 0$ [km]:



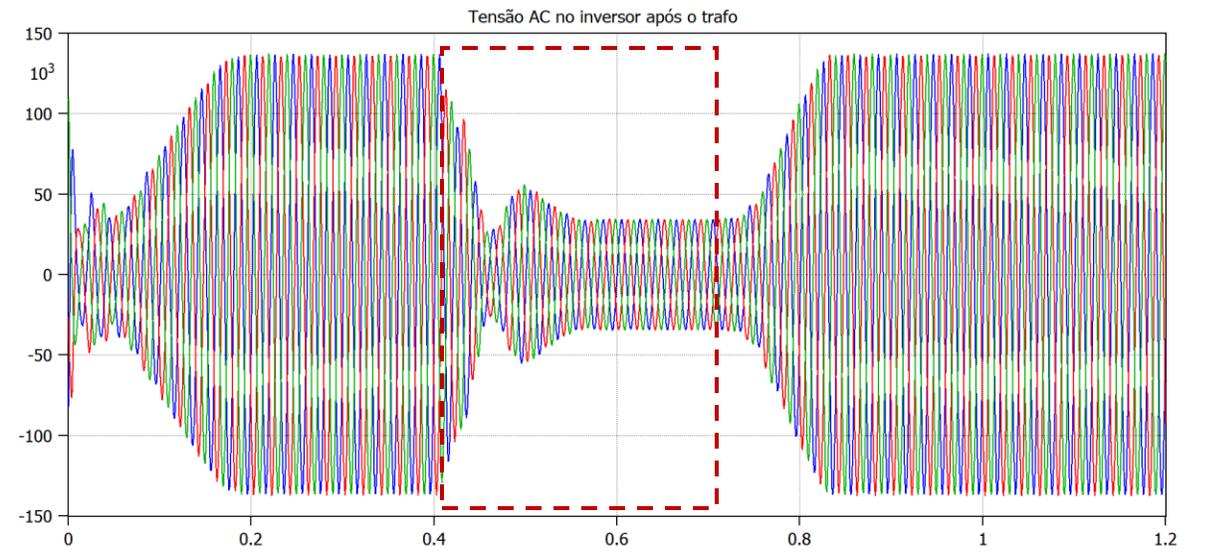
(file HVDC\_Coci.pl4; x-var t) c:X0001A-AT1A c:X0001B-AT1B c:X0001C-AT1C



(file HVDC\_Coci.pl4; x-var t) c:AT2A -BARR2A c:AT2B -BARR2B c:AT2C -BARR2C



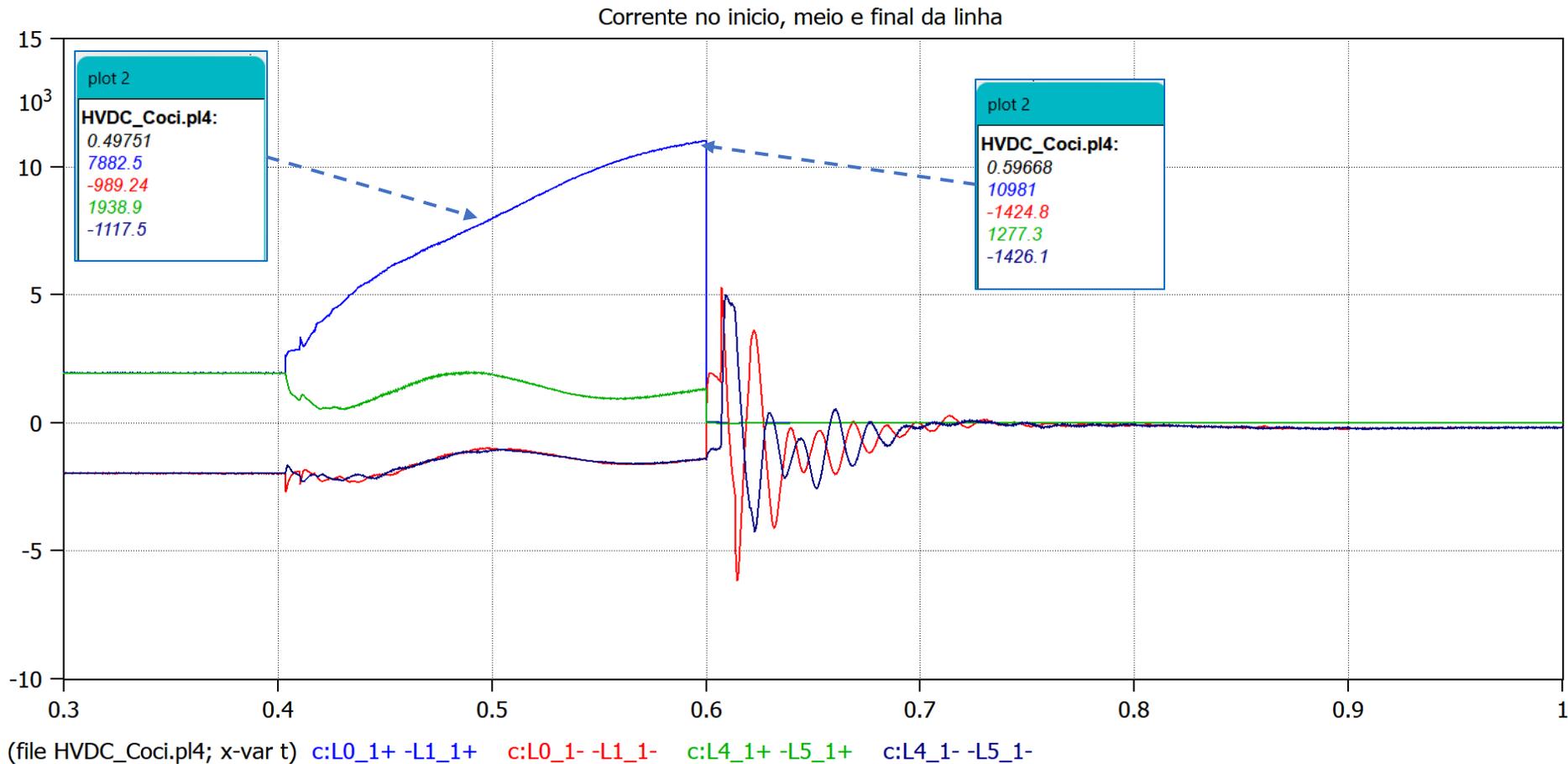
(file HVDC\_Coci.pl4; x-var t) v:AT1A v:AT1B v:AT1C



(file HVDC\_Coci.pl4; x-var t) v:AT2A v:AT2B v:AT2C



✓ **Condições de operação:**  
 $t_{falta} = 400[ms], t_{abertura} = 600 [ms]$

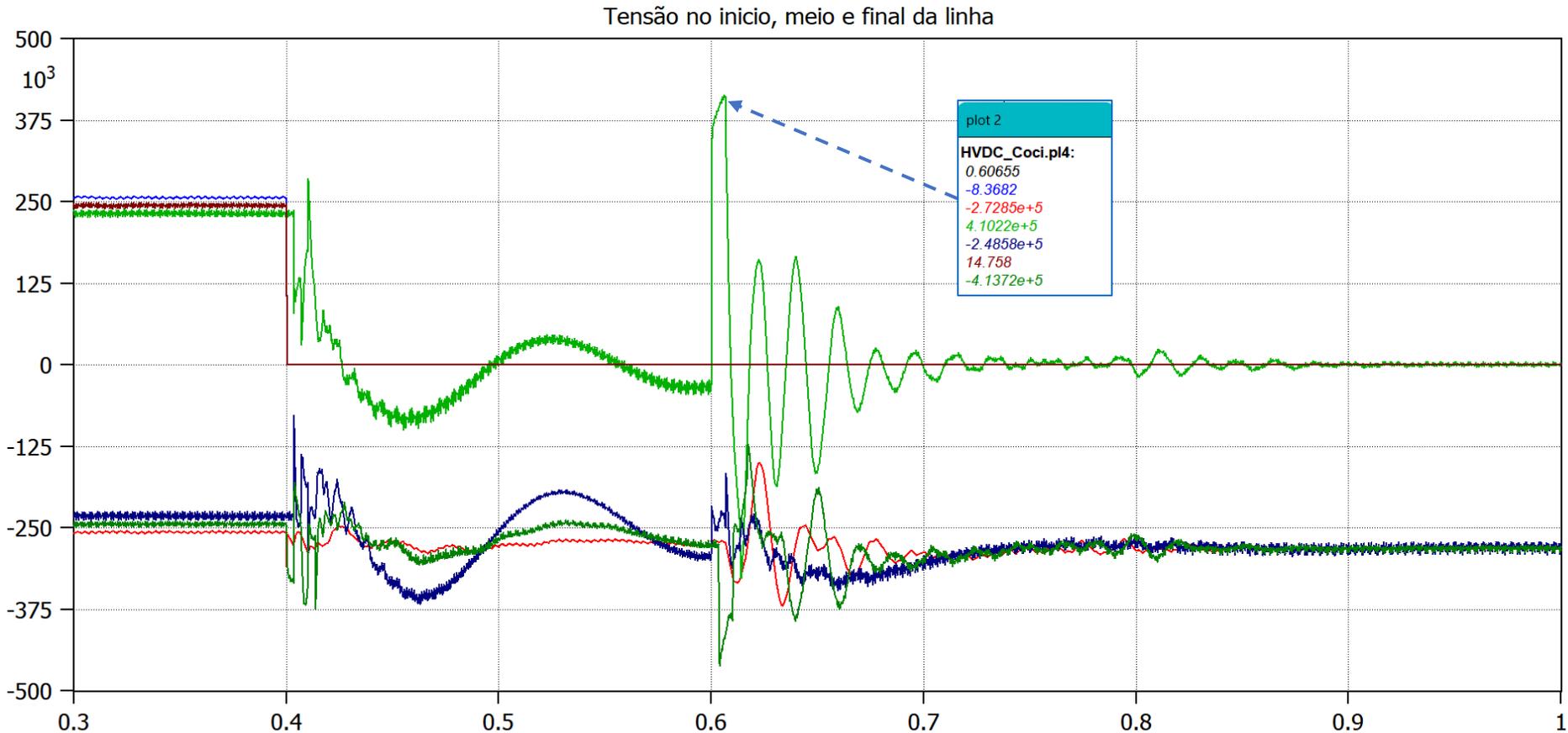


As correntes produzidas por faltas não podem permanecer longo tempo no sistema



✓ Condições de operação:

$$t_{falta} = 400[ms], t_{abertura} = 600 [ms]$$



(file HVDC\_Coci.pl4; x-var t) v:L1\_1+ v:L1\_1- v:L4\_1+ v:L4\_1- v:LMID+ v:LMID-

Si usar disjuntores para tirar o defeito vão produzir sobretensões muito fortes.

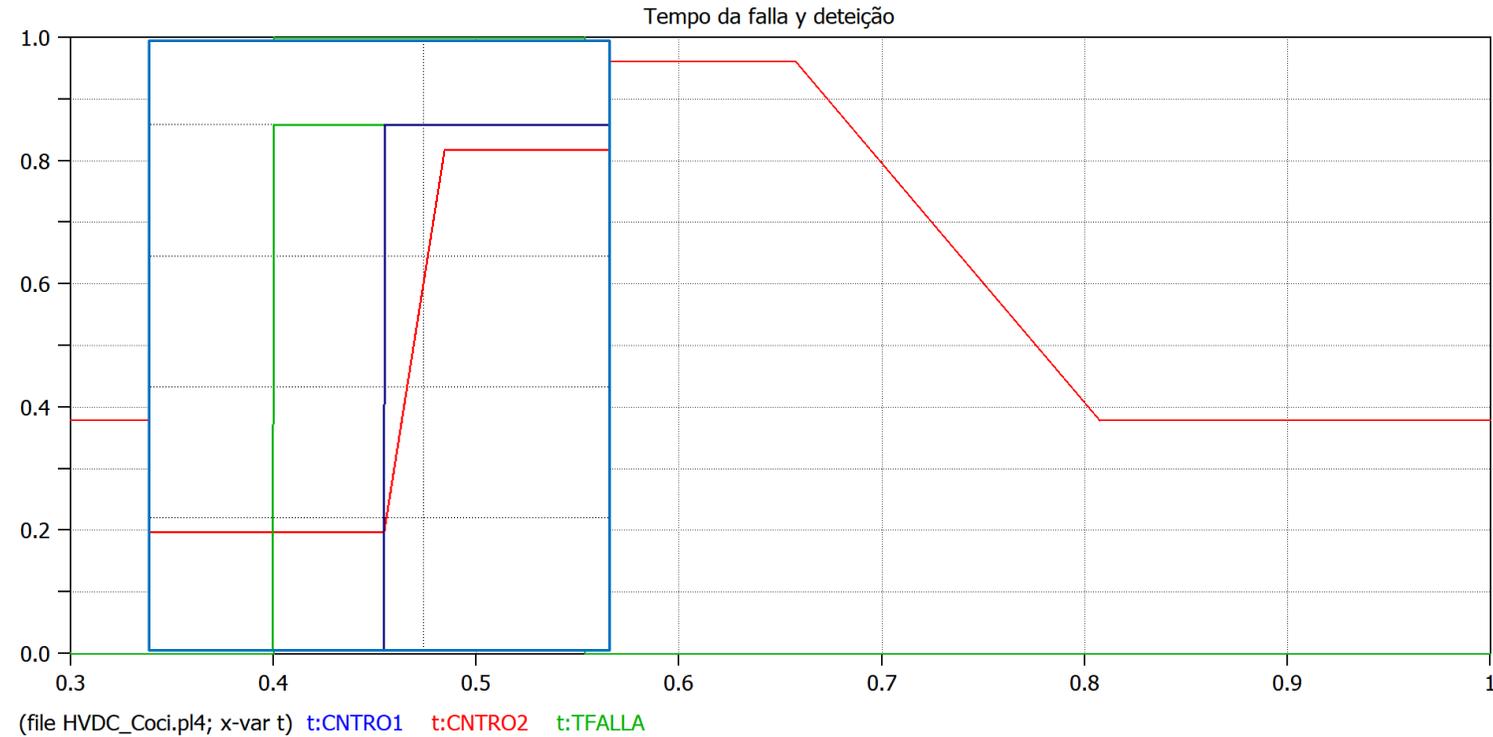
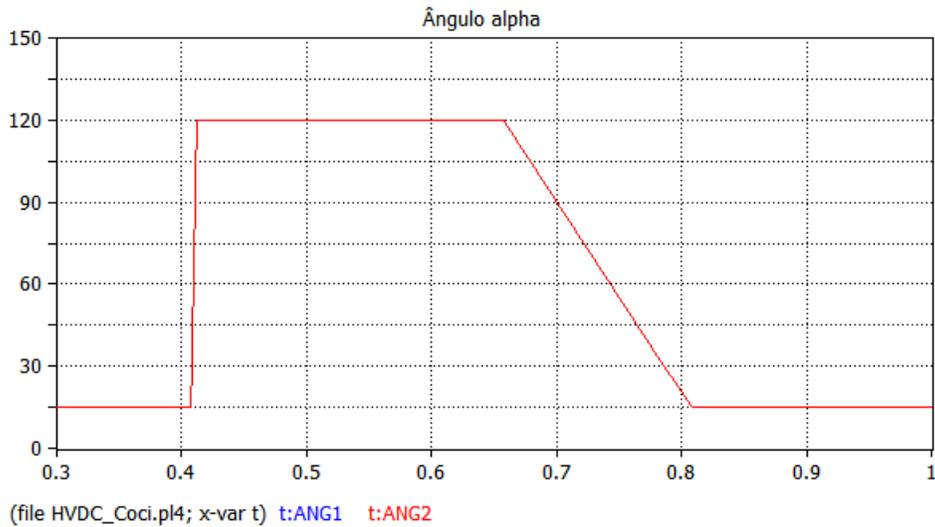


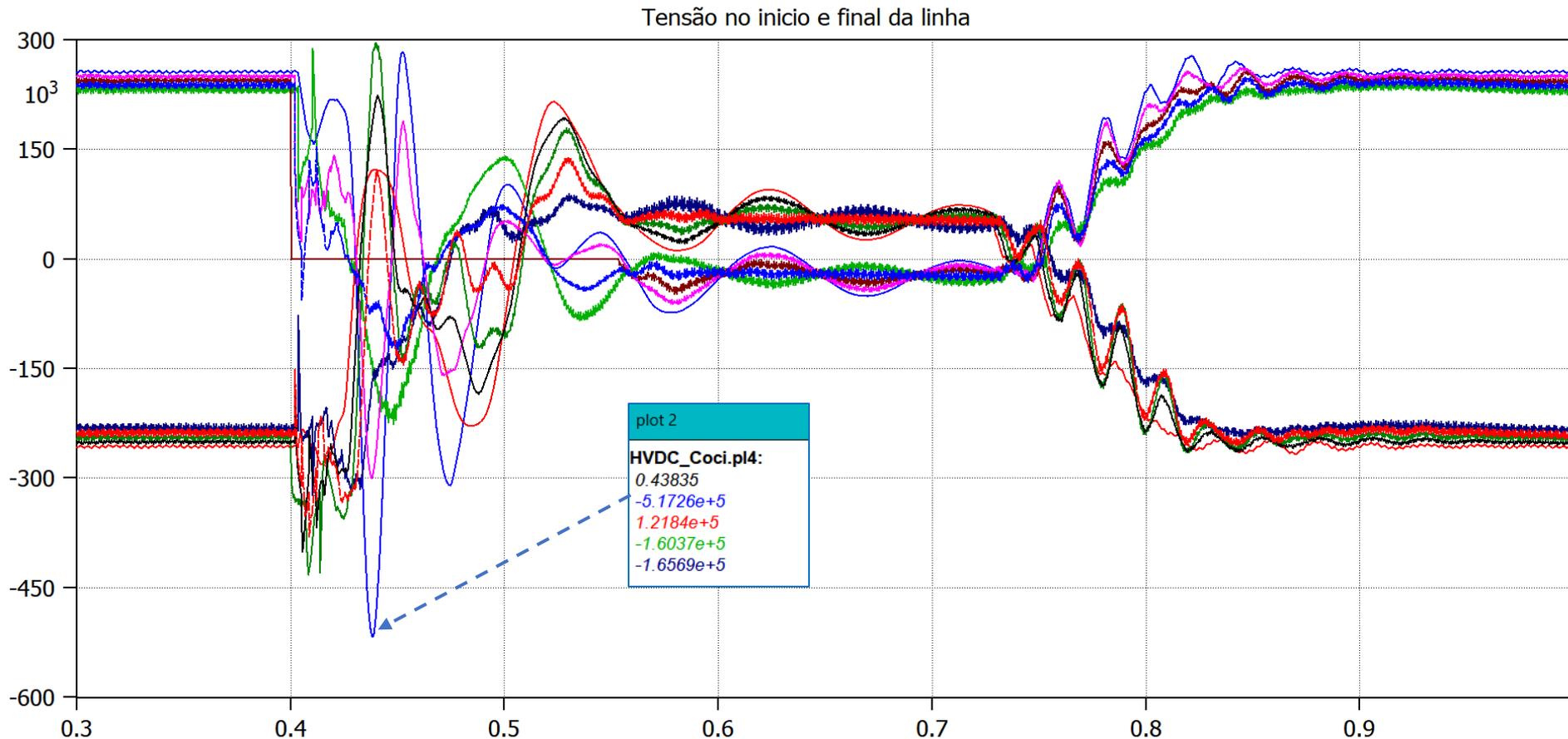
## Resultados

## B.4. Falta PT com controle de alpha $l = 1000$ [km]:

### ✓ Condições de operação:

$$t_{falta} = 400[ms], t_{trafego} = 3.374[ms], t_{deteção} = 4 [ms], t_{atuacao} = 7.374[ms]$$

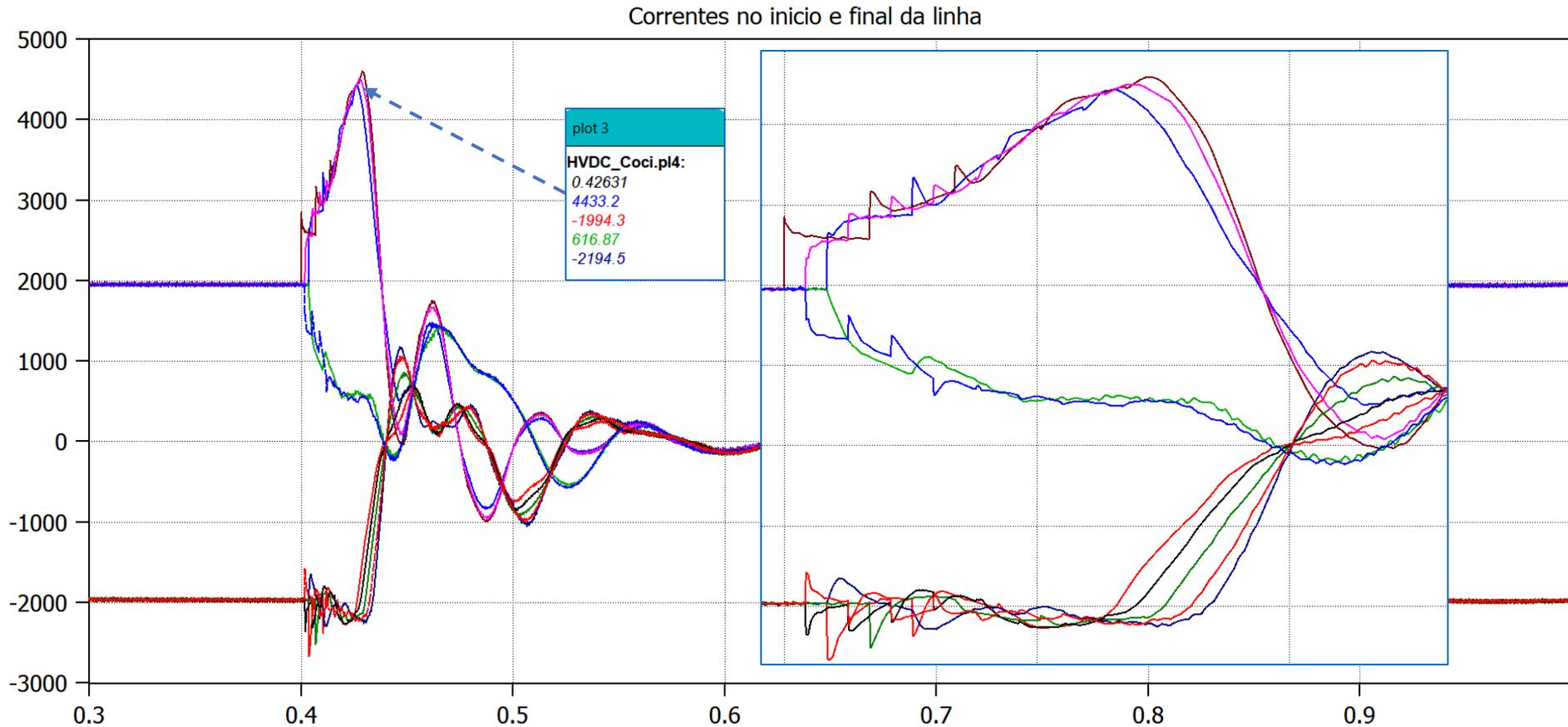




A rápida atuação do convertidor LCC vai reduzir as sobretensões.

As sobretensões são reduzidas para qualquer trecho da linha

(file HVDC\_Coci.pl4; x-var t) v:LINE+ v:LINE- v:LINE\_+ v:LINE\_- v:LMID+ v:LMID- v:L2\_1+ v:L2\_1- v:L3\_1+ v:L3\_1-



A rápida atuação do conversor LCC vai reduzir as sobrecorrentes da falta

As sobrecorrentes são reduzidas para qualquer trecho da linha

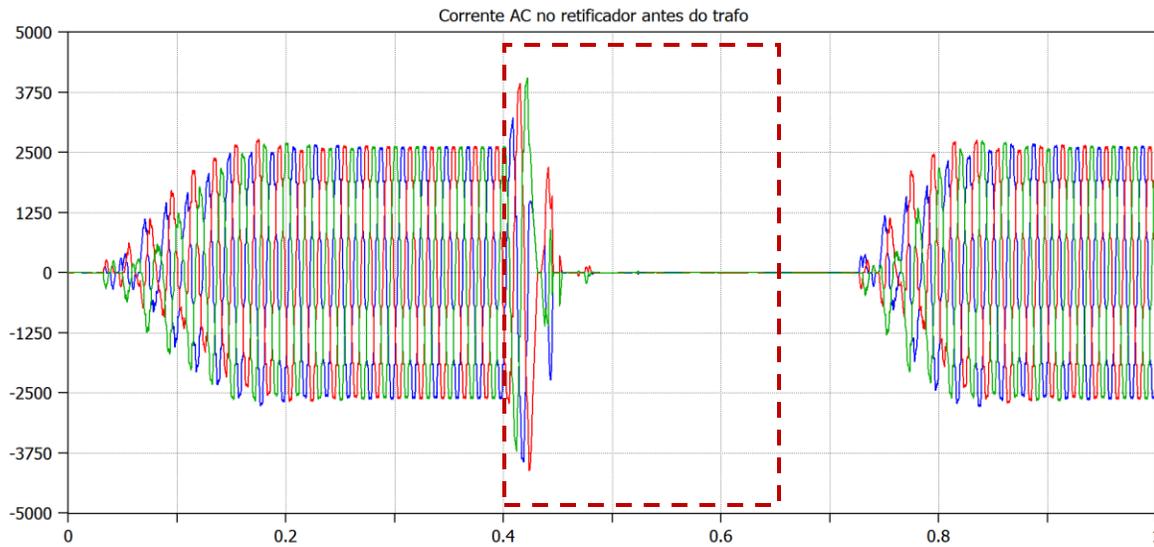
Ocorrem propagações e reflexões

(file HVDC\_Coci.pl4; x-var t) c:L0\_1+ -L1\_1+ c:L0\_1- -L1\_1- c:L4\_1+ -L5\_1+ c:L4\_1- -L5\_1- c:XX0178-LMID+ c:XX0177-LMID- c:XX0142-L2\_1+ c:XX0141-L2\_1- c:XX0181-L3\_1+ c:XX0180-L3\_1-

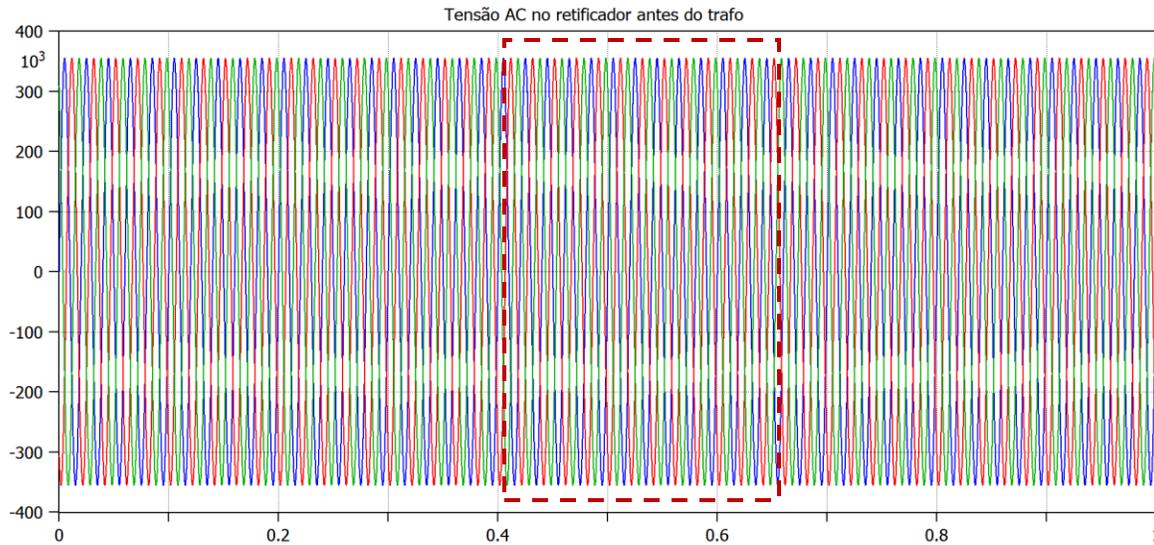


# Resultados

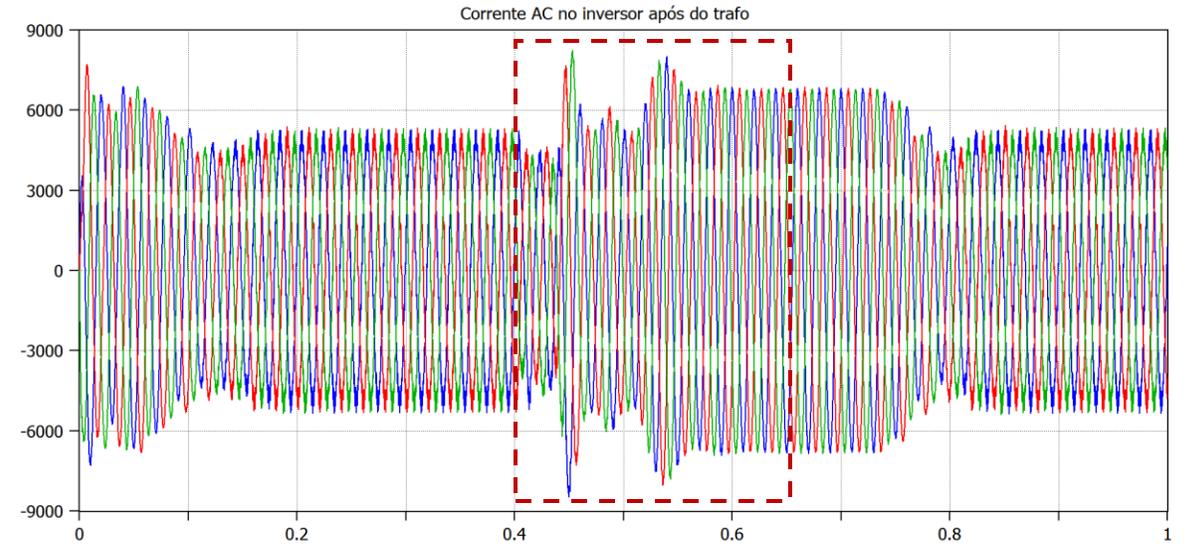
## B.4. Falta PT com controle de $\alpha$ $l = 1000$ [km]:



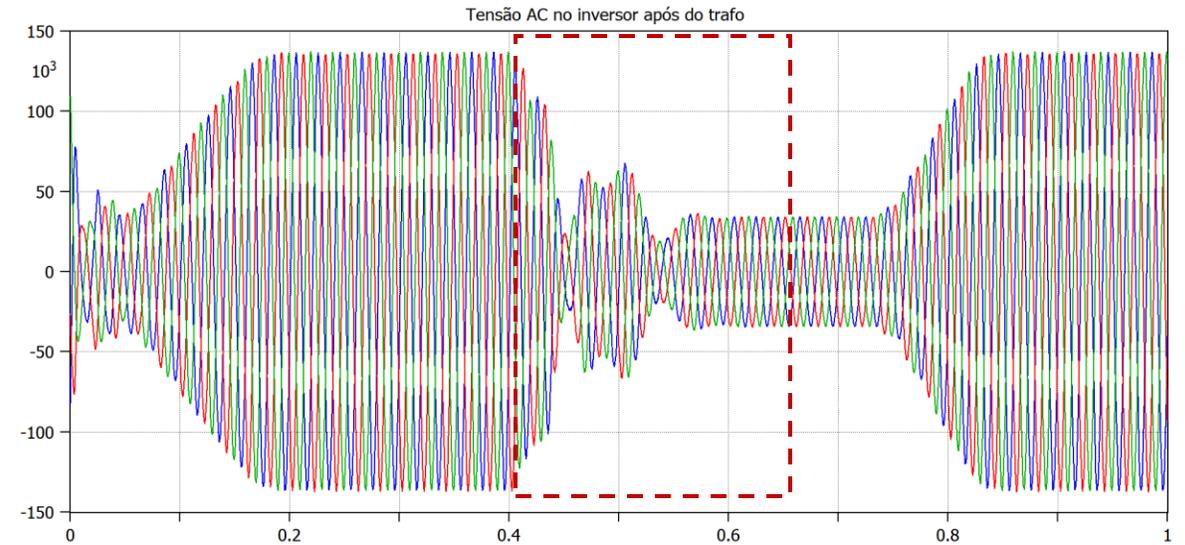
(file HVDC\_Coci.pl4; x-var t) c:X0001A-AT1A c:X0001B-AT1B c:X0001C-AT1C



(file HVDC\_Coci.pl4; x-var t) v:AT1A v:AT1B v:AT1C



(file HVDC\_Coci.pl4; x-var t) c:AT2A -BARR2A c:AT2B -BARR2B c:AT2C -BARR2C



(file HVDC\_Coci.pl4; x-var t) v:AT2A v:AT2B v:AT2C



## Conclusões

1. As faltas polo terra incrementam muito as correntes DC ao invés do AC que a componente DC diminui com o tempo.
2. O uso indiscriminado de disjuntores para aberturas de falta polo terra em topologia LCC-VSC irão a produzir sobretensões muito fortes.
3. Um jeito de reduzir sobretensões e sobrecorrentes originados pelos defeitos nos polos é por meio do controle do ângulo de disparo (**firing**). Isso também aplica na energização do ELO DC.
4. Deve-se procurar um jeito de reduzir ainda mais as correntes (até **5 [kA]**) para faltas no barramento da linha ou faltas quilométricas, por ser essas as mais severas para os **Thyristores**. O controle do ângulo alpha no terminal LCC não é suficiente.
5. Pode ser considerado o uso de disjuntores DC (eletromecânicos, estado sólido ou híbridos) ou **surge arresters** nos extremos da linha.
6. Para a topologia híbrida LCC – VSC, o LCC deve ser melhorado o controle por meio de: PLLs, dq0, transformada de Clarke, Park, etc. Em tanto, o VSC pode ser melhorado fazendo uso do complexo controle multinível.



## REFERÊNCIAS



- [1] D. Jovcic, *High voltage direct current transmission: converters, systems and DC grids*, Second edition. Hoboken, NJ: Wiley, 2019.
- [2] G. S. EPRI Project Manager, 'HVDC Ground Electrode Overview', *Electr. POWER Res. Inst.*, Nov. 2010.
- [3] 'C2-2007 National Electrical Safety Code'.
- [4] '\_ATP-EMTPCIGREHVDC.pdf'.

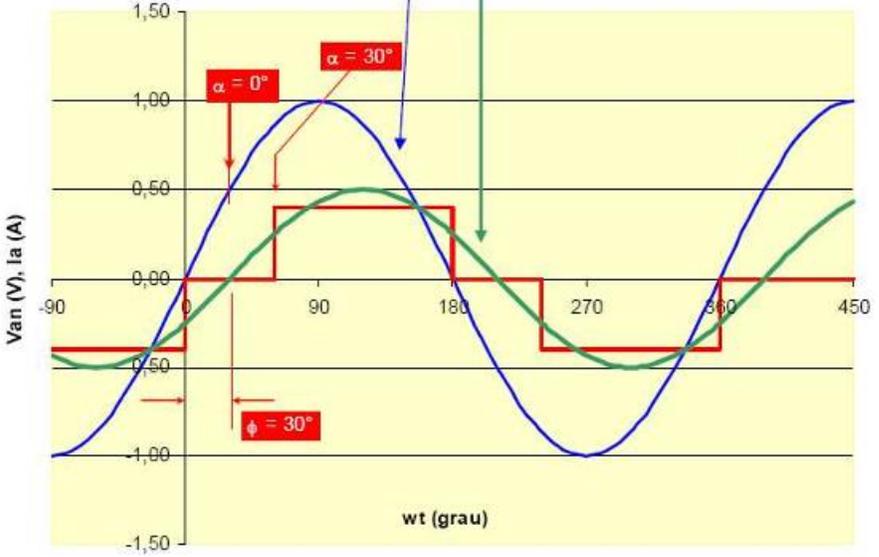
# MUITO OBRIGADO!

| Matriz de aplicabilidad                       |                |     |                                                     |
|-----------------------------------------------|----------------|-----|-----------------------------------------------------|
| Aplicación                                    | LCC            | VSC | Comentario                                          |
| Back to Back                                  | Sí             | Sí  | Aplica a LCC y VSC                                  |
| Transmisión de larga distancia                | Sí             | Sí  | LCC es más eficiente                                |
| Conexión de sistemas aislados                 | Sí             | Sí  | VSC mejor para sistemas aislados débiles            |
| Conexión de energía eléctrica <i>offshore</i> | Menos adecuado | Sí  | VSC más implementado                                |
| Cambiador de frecuencia                       | Sí             | Sí  | VSC es menos susceptible a fallas en la conmutación |
| Líneas aéreas                                 | Sí             | Sí  | VSC requiere módulos FB y CB                        |
| Líneas subterráneas                           | Sí             | Sí  | Aplica a ambas tecnologías                          |
| Operación multi-terminal                      | Sí             | Sí  | Más difícil con LCC                                 |
| Muy alta potencia                             | Sí             | No  | VSC en desarrollo                                   |
| Servicios de recuperación del sistema         | No             | Sí  | Black start                                         |

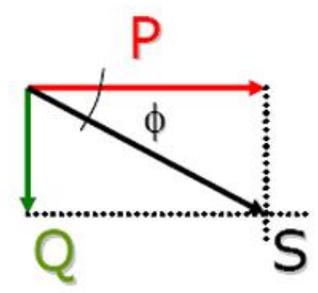
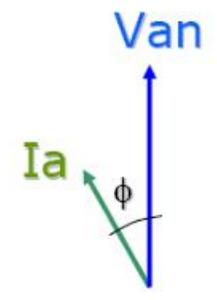
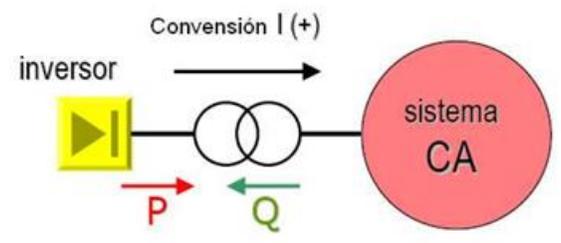
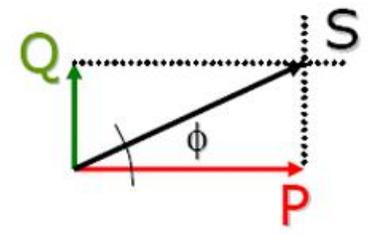
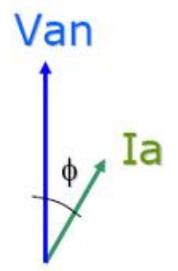
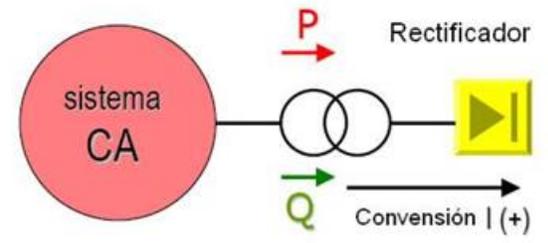
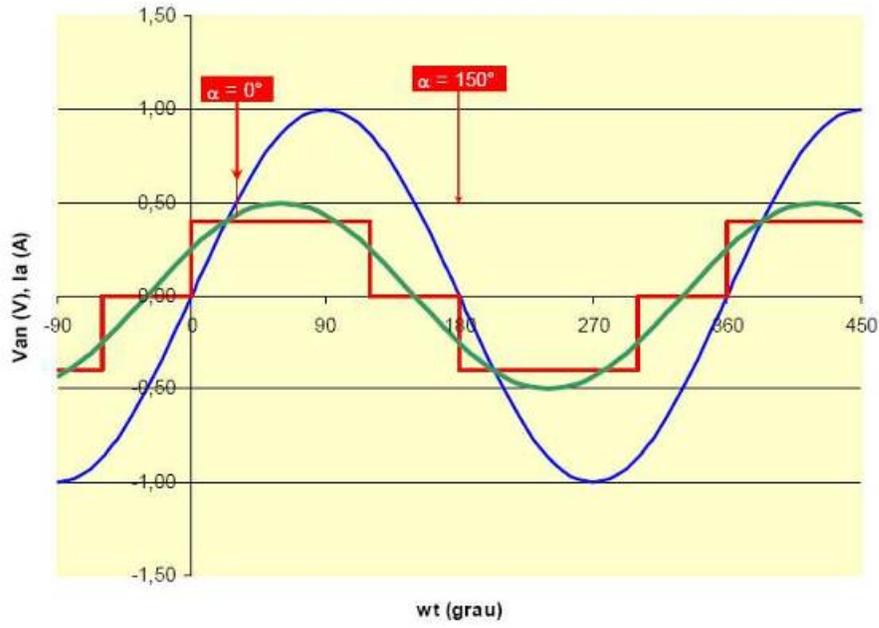
# PERGUNTAS?

| <b>Matriz de aplicabilidad</b>                |                |            |                                                     |
|-----------------------------------------------|----------------|------------|-----------------------------------------------------|
| <b>Aplicación</b>                             | <b>LCC</b>     | <b>VSC</b> | <b>Comentario</b>                                   |
| Back to Back                                  | Sí             | Sí         | Aplica a LCC y VSC                                  |
| Transmisión de larga distancia                | Sí             | Sí         | LCC es más eficiente                                |
| Conexión de sistemas aislados                 | Sí             | Sí         | VSC mejor para sistemas aislados débiles            |
| Conexión de energía eléctrica <i>offshore</i> | Menos adecuado | Sí         | VSC más implementado                                |
| Cambiador de frecuencia                       | Sí             | Sí         | VSC es menos susceptible a fallas en la conmutación |
| Líneas aéreas                                 | Sí             | Sí         | VSC requiere módulos FB y CB                        |
| Líneas subterráneas                           | Sí             | Sí         | Aplica a ambas tecnologías                          |
| Operación multi-terminal                      | Sí             | Sí         | Más difícil con LCC                                 |
| Muy alta potencia                             | Sí             | No         | VSC en desarrollo                                   |
| Servicios de recuperación del sistema         | No             | Sí         | Black start                                         |

Van x Ia



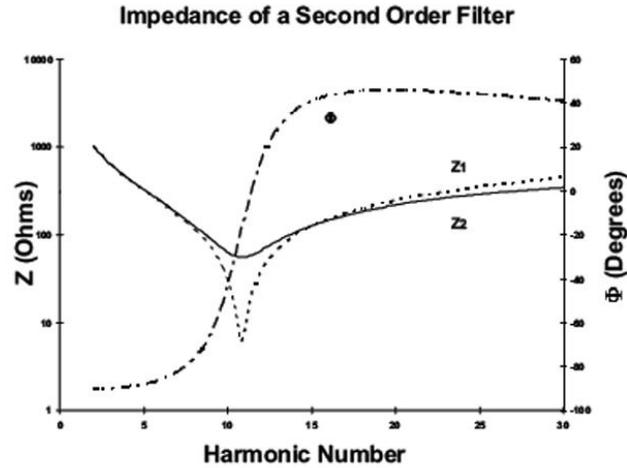
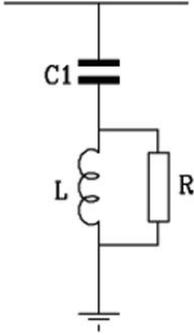
Van x Ia



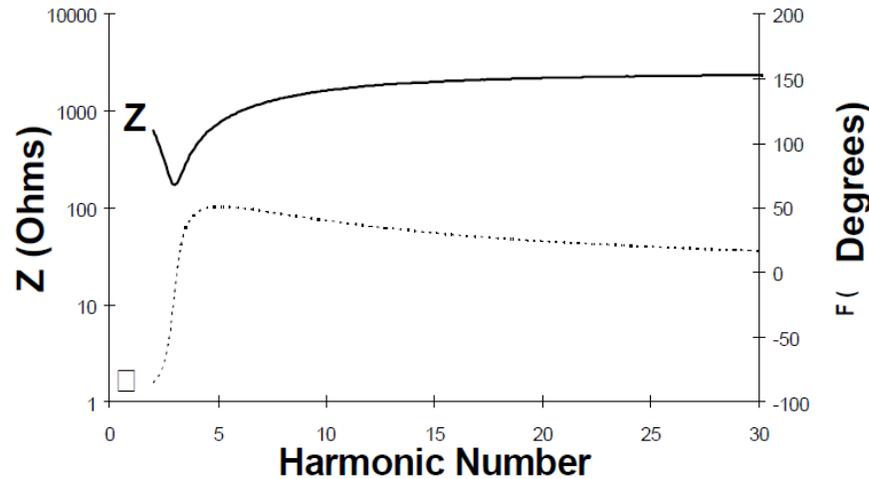
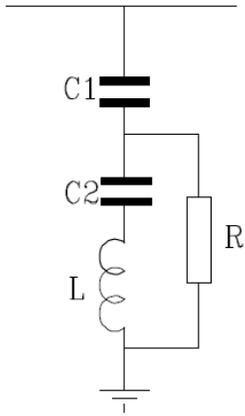
La conclusión final es que cada una de las estaciones convertidoras consume potencia reactiva durante su operación como rectificador y como inversor

## Tipos de filtros utilizados en HVDC:

1. Filtros amortiguados o pasa altos:
2. a) Filtro pasa altos de 2° orden



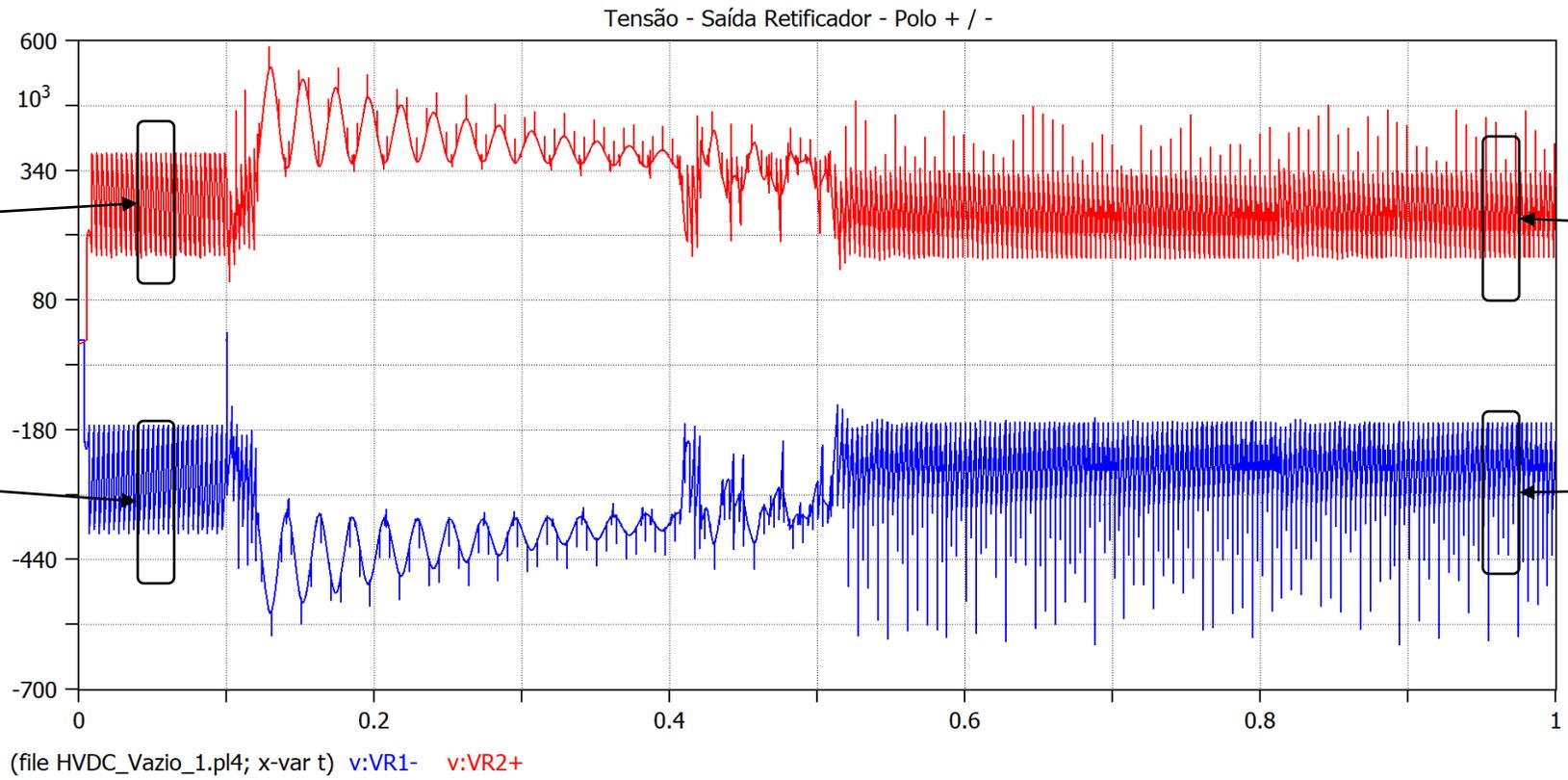
Impedance of a C Type Filter



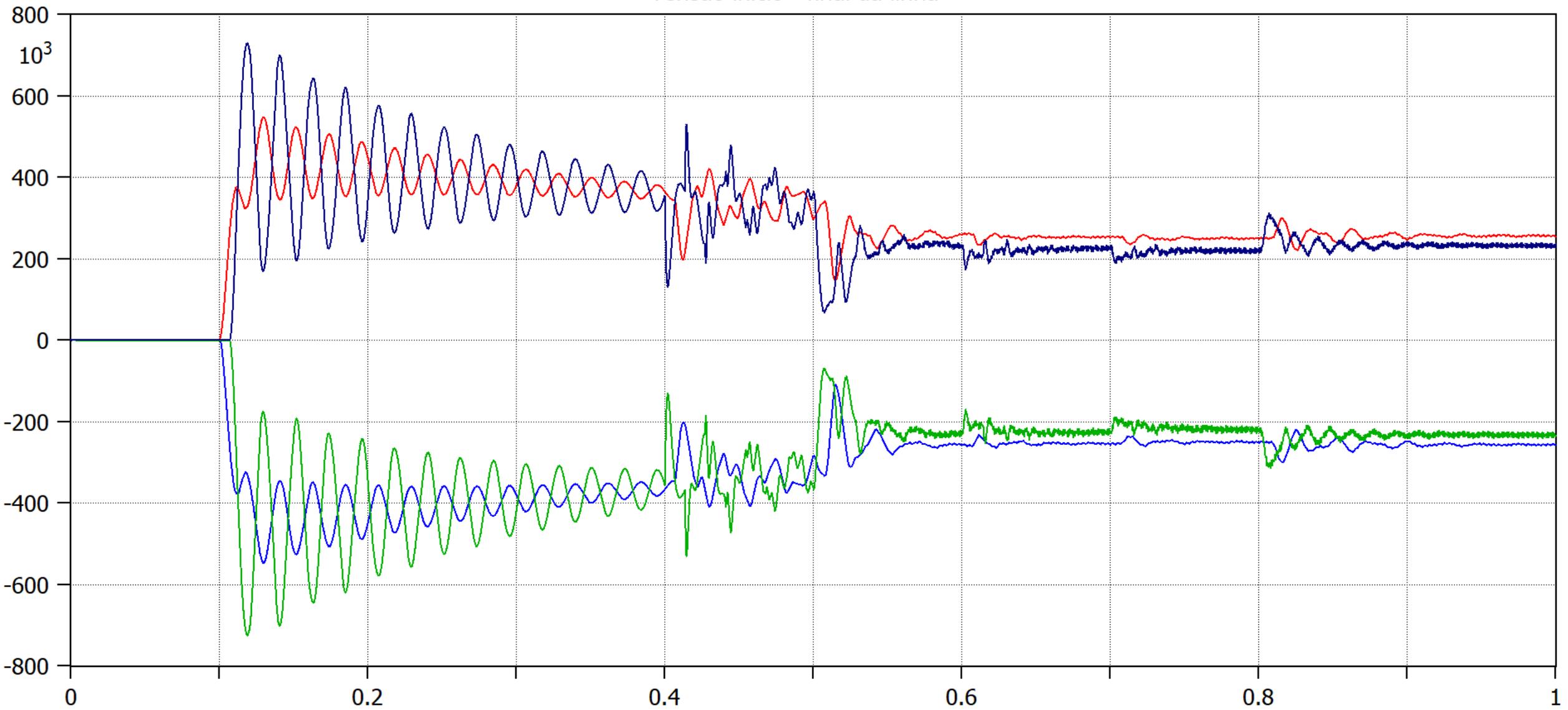
Este tipo de filtros son ampliamente utilizados en sistemas HVDC para atenuar pares de armónicas como por ejemplo 11°/13°. El resumen de ventajas y desventajas se presenta a continuación

La Figura 2.29 presenta la configuración típica y la respuesta en frecuencia de un filtro para la armónica 3ra

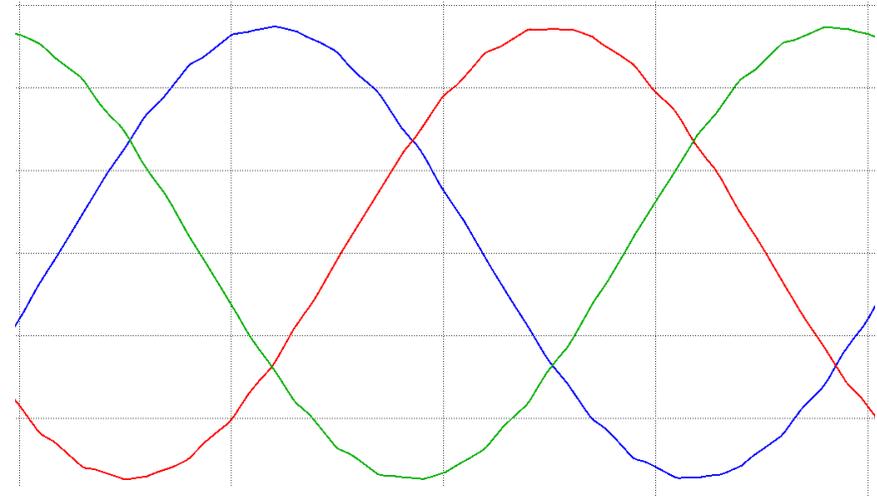
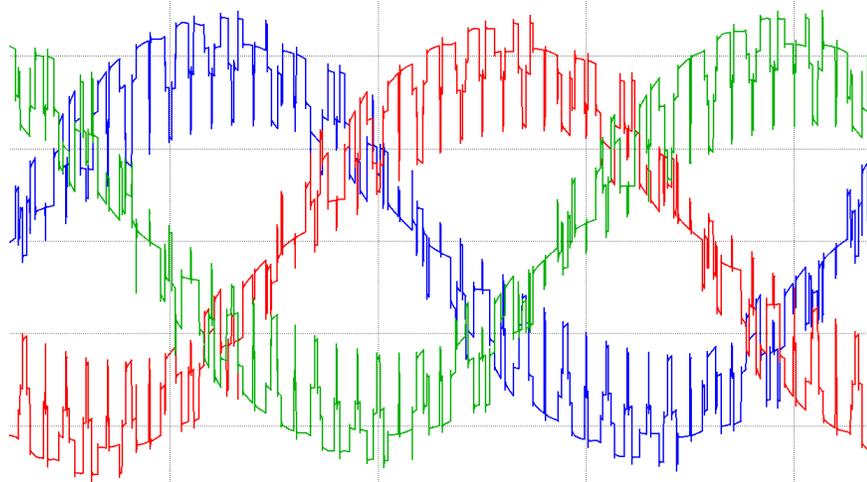
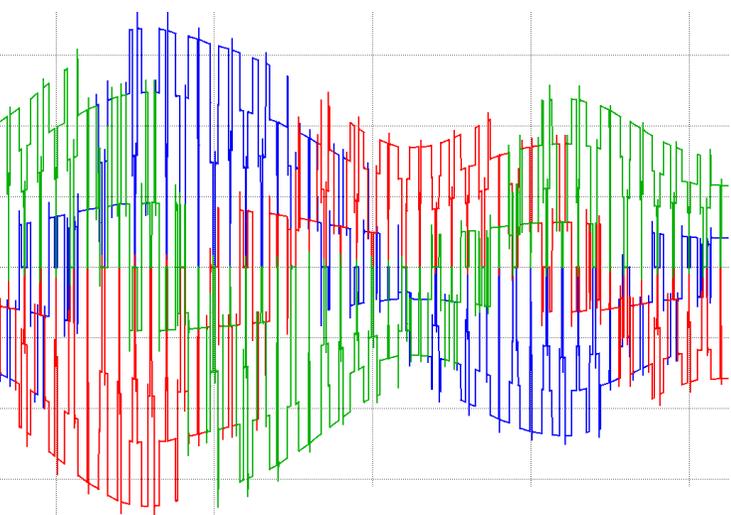




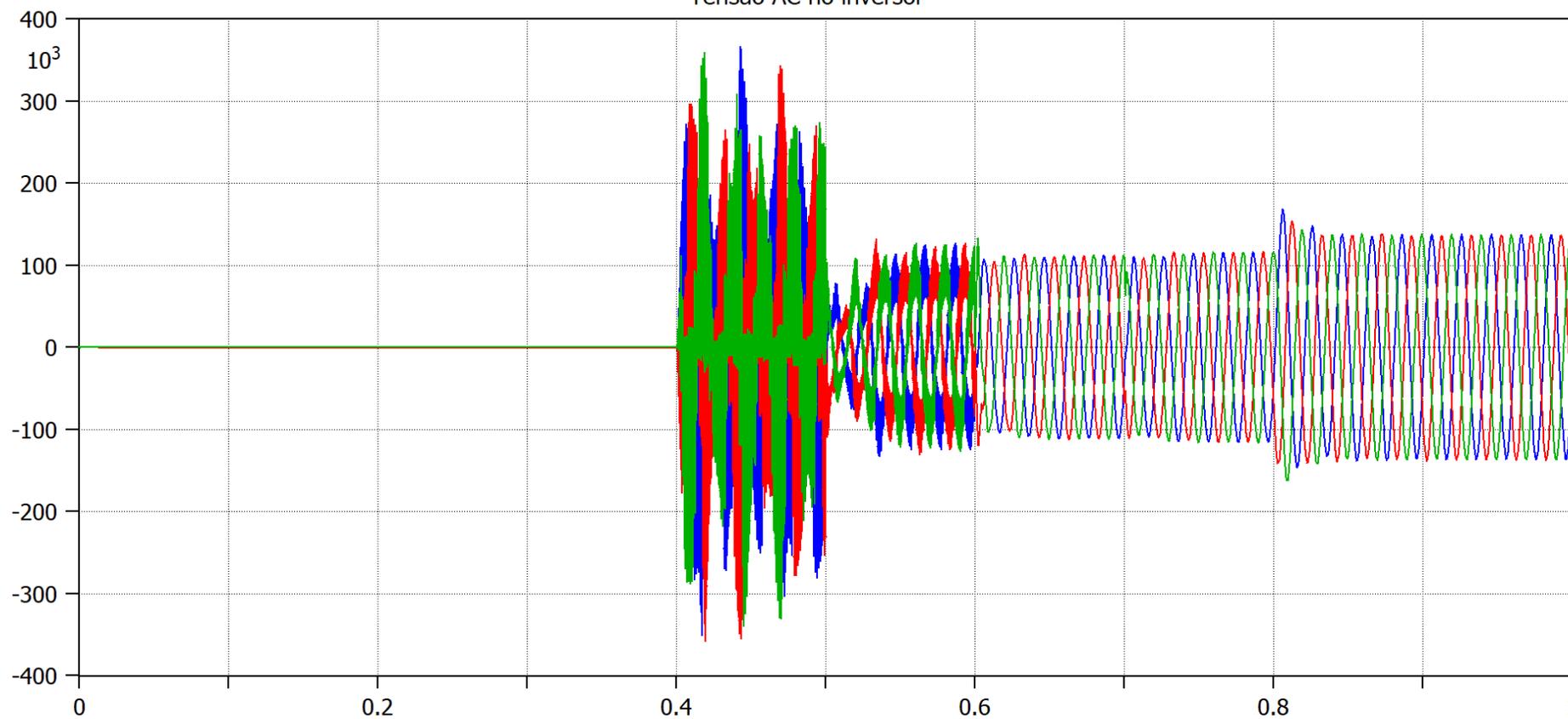
Tensão início - final da linha



(file HVDC\_Vazio\_1.pl4; x-var t) v:LINE- v:LINE+ v:LINE\_- v:LINE\_+

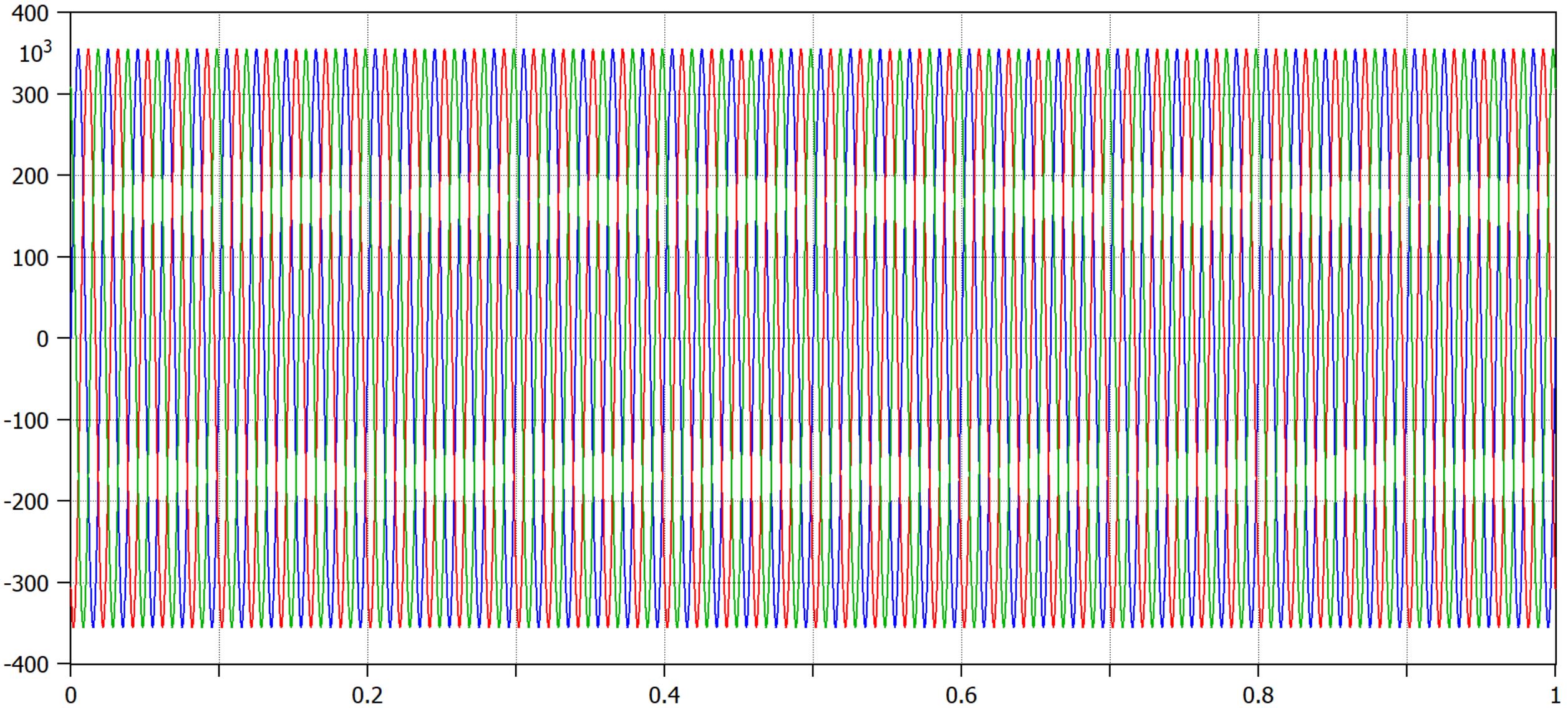


Tensão AC no inversor

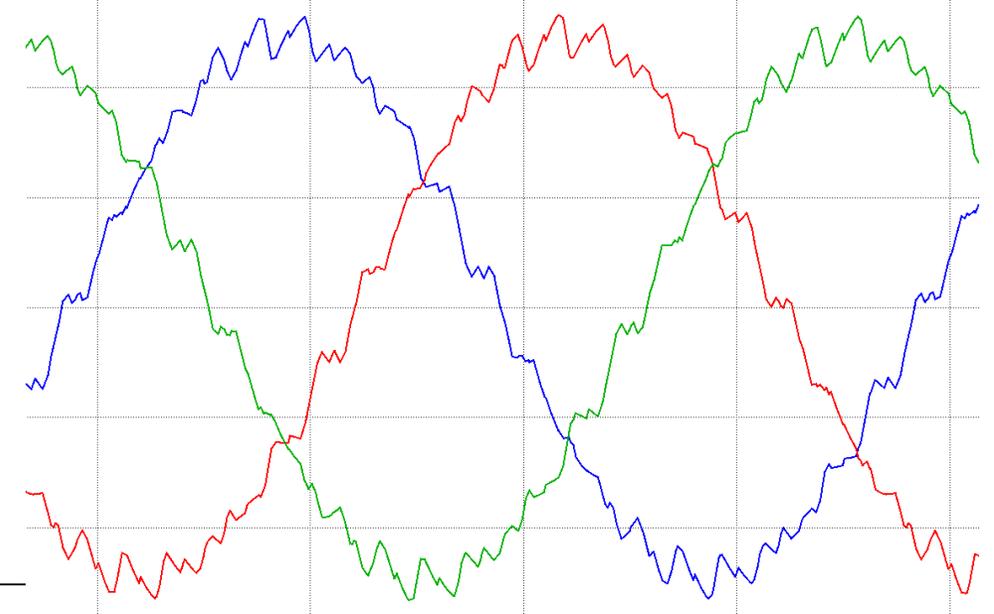
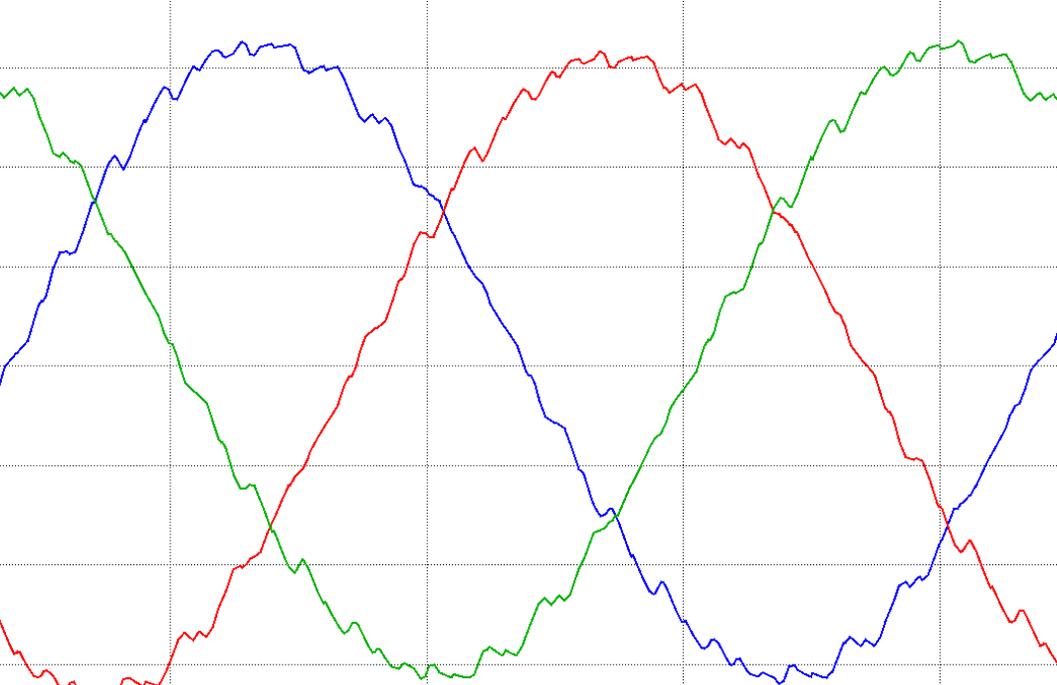


(file HVDC\_Vazio\_1.pl4; x-var t) v:AT2A v:AT2B v:AT2C

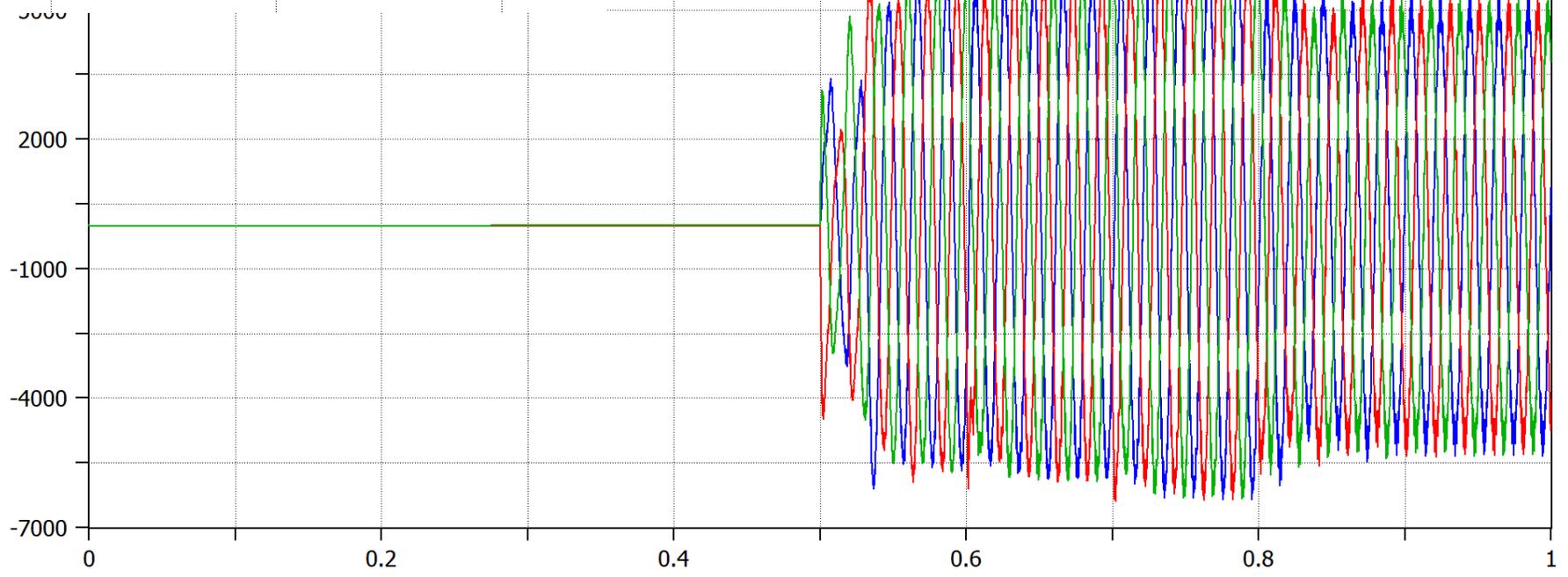
Tensão AC no retificador



(file HVDC\_Vazio\_1.pl4; x-var t) v:AT1A v:AT1B v:AT1C

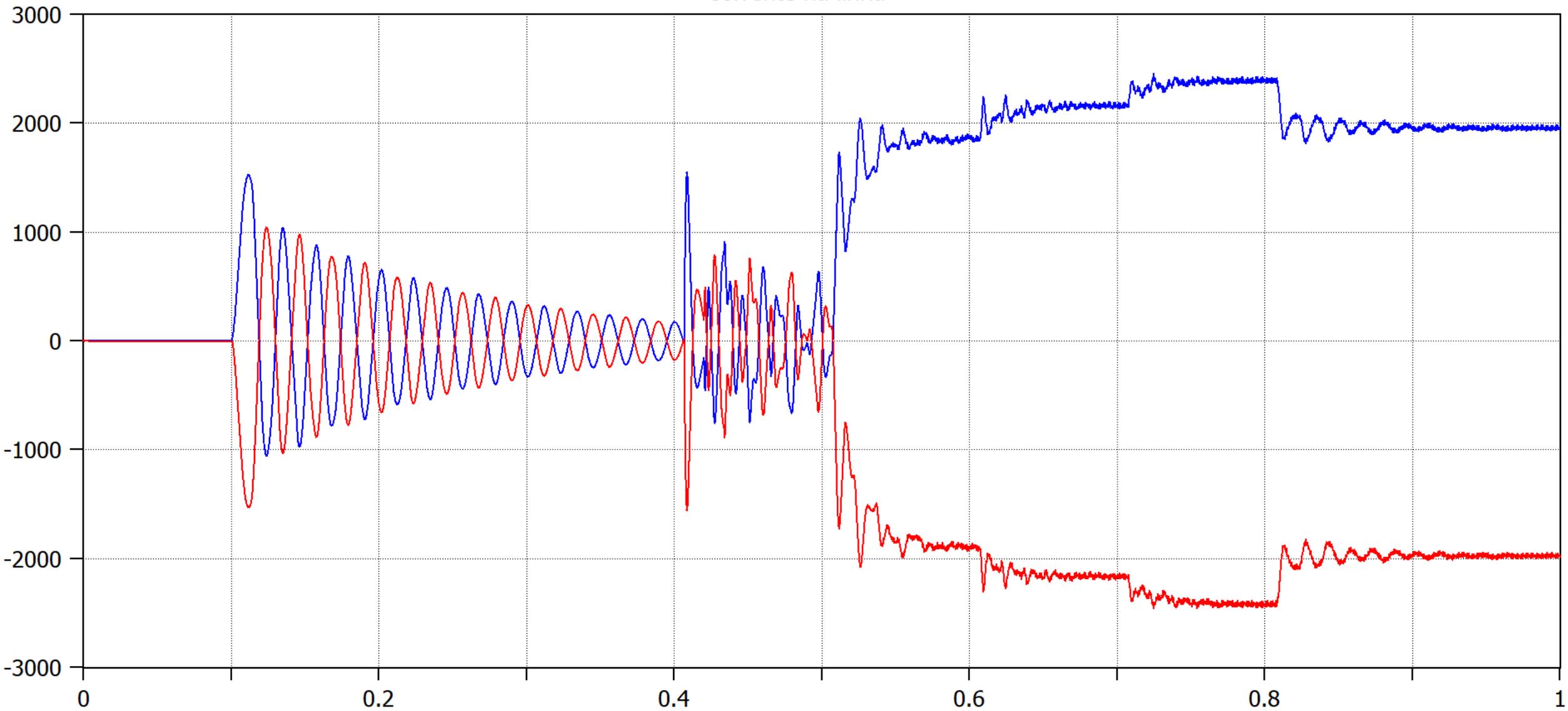


Corrente AC no inversor - depois do trafo

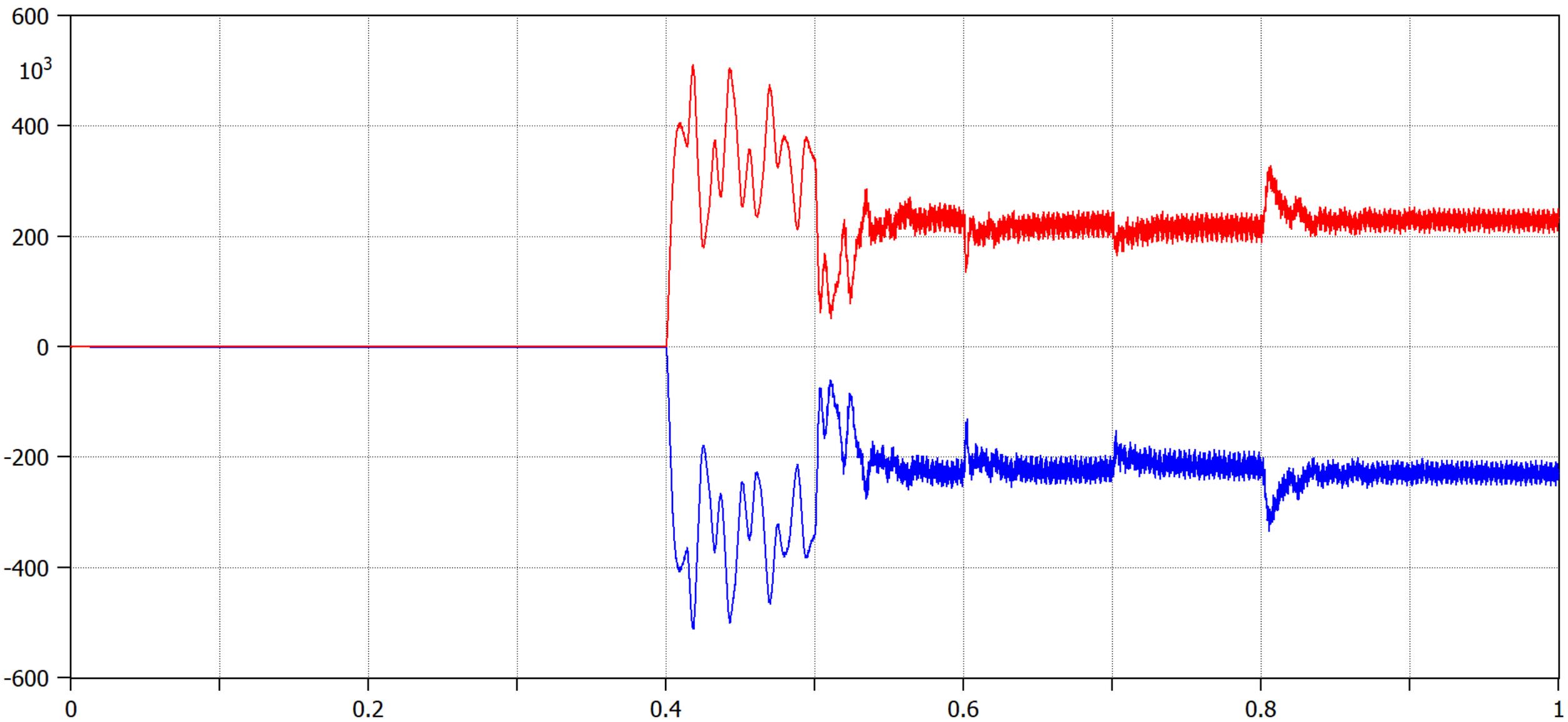


(file HVDC\_Vazio\_1.pl4; x-var t) c:AT2A -BARR2A c:AT2B -BARR2B c:AT2C -BARR2C

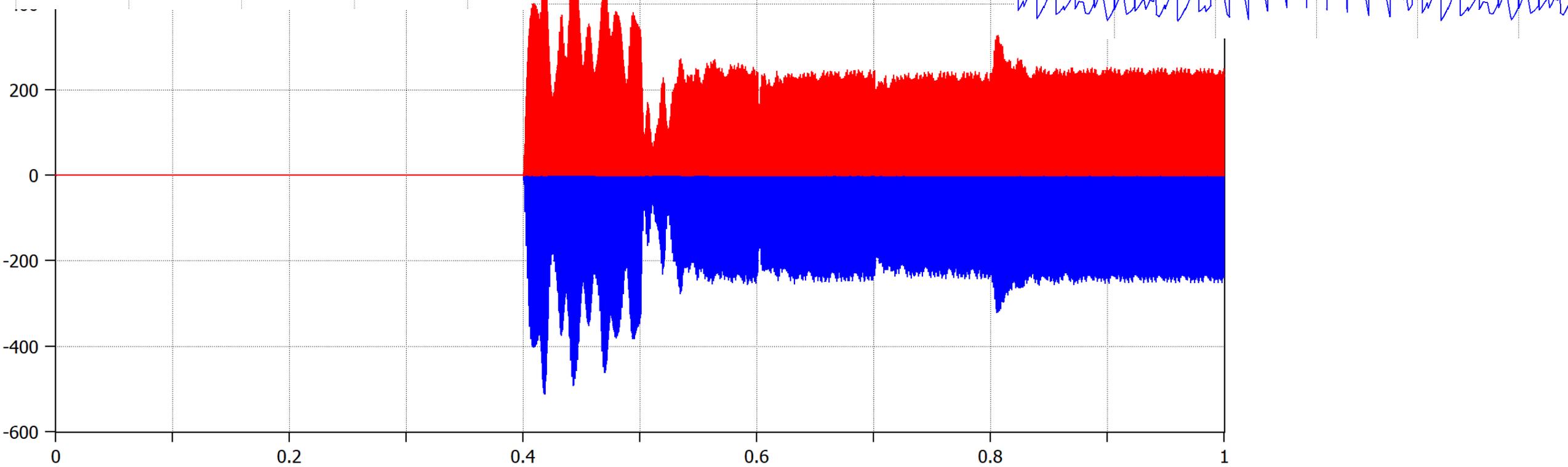
Corrente na linha



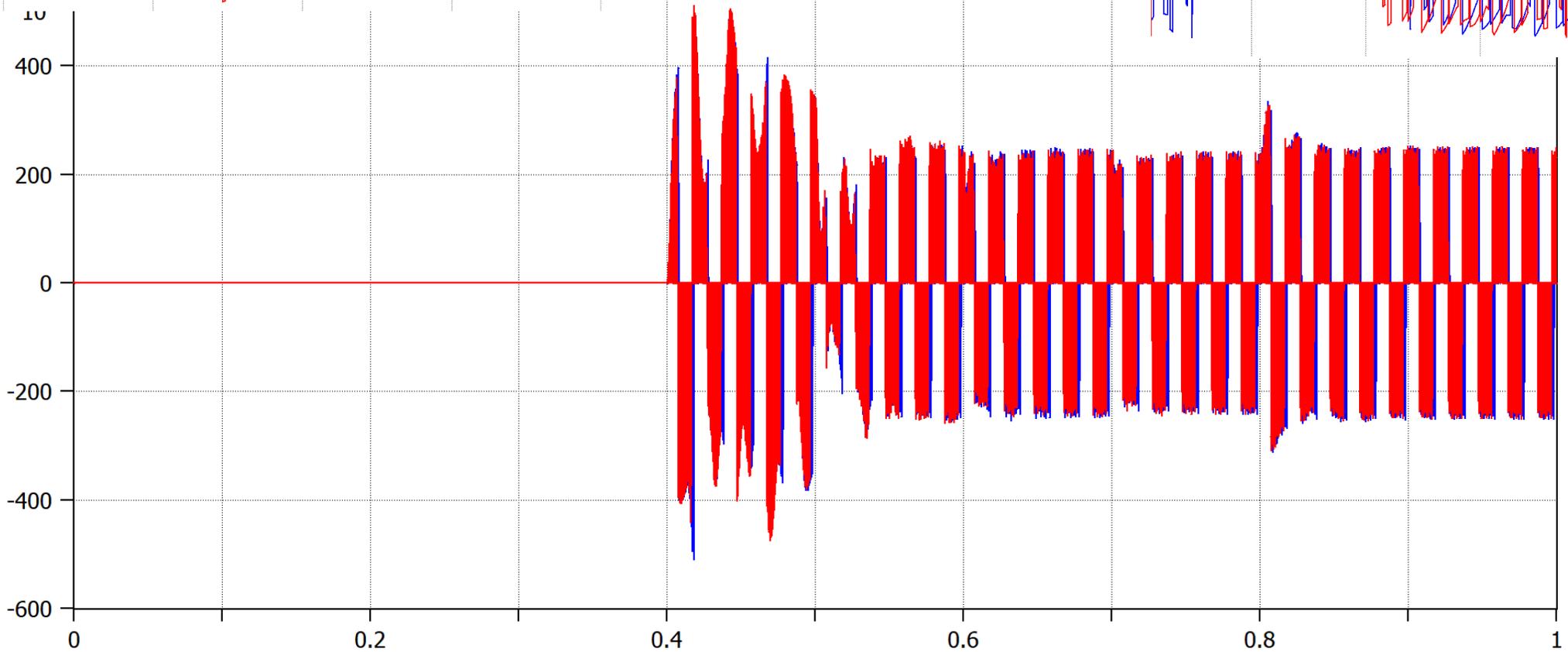
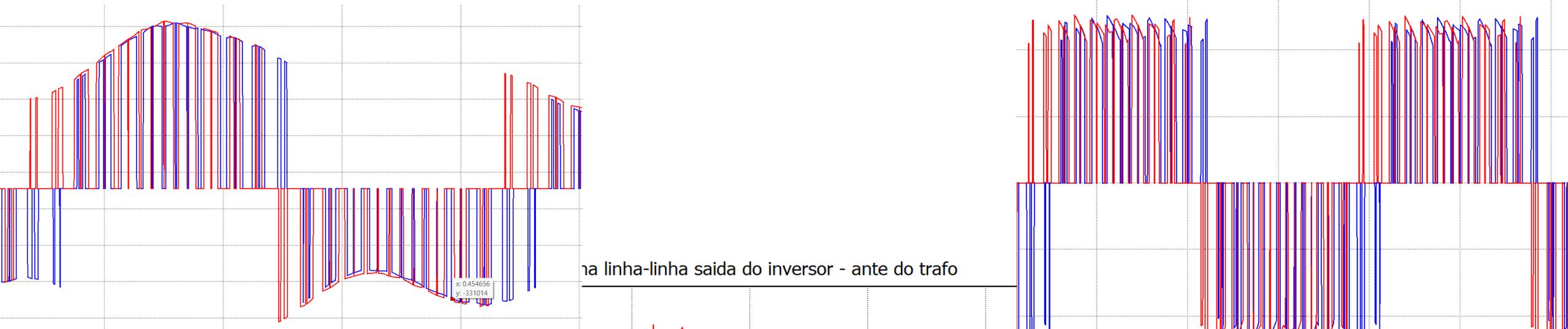
(file HVDC\_Vazio\_1.pl4; x-var t) c:L0\_1+ -L1\_1+ c:L0\_1- -L1\_1-



(file HVDC\_Vazio\_1.pl4; x-var t)  $v:VI1-$   $v:VI2+$



(file HVDC\_Vazio\_1.pl4; x-var t) t:VO1A t:VO2A



(file HVDC\_Vazio\_1.pl4; x-var t) t:VO1AB t:VO2AB