EPI Universidad de Oviedo

Energy Storage Seminars

Seminars presented in:

National Cheng Kung University

Dr Manuel Rico-Secades (University of Oviedo)

Seminar 7: *An introduction to energy storage applications (March 21)*
Seminar 8: *Bidirectional converters for energy storage and recovery (March 22)*
Seminar 9: *Cell voltage measurements, protection circuits modules (PCM) and balancing strategies (March 23)*

21, 22 and 23 March, 2016

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GOBIERNO DE ESPAÑA

GOBIERNO DEL PRINCIPADO DE ASTURIAS

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- *ENE2013-41491-R (LITCITY Project)*
- *GRUPIN14-076*

EPI Universidad de Oviedo

Energy Storage Seminar

with batteries and ultra-capacitors

TOPICS:

Seminar 7.- An introduction to energy storage applications

Seminar 8.- Bidirectional converters for energy storage and recovery

Charge (energy storage) and discharge (energy recovery) circuits

- Control strategies
- One-Leg converter
- DAB converter

Seminar 9.- Cell voltage measurements, protection circuits modules (PCM) and balancing strategies

- Protection circuits (PCM)
- Balanced circuits
  - Active with switched capacitor
  - Active with additional current

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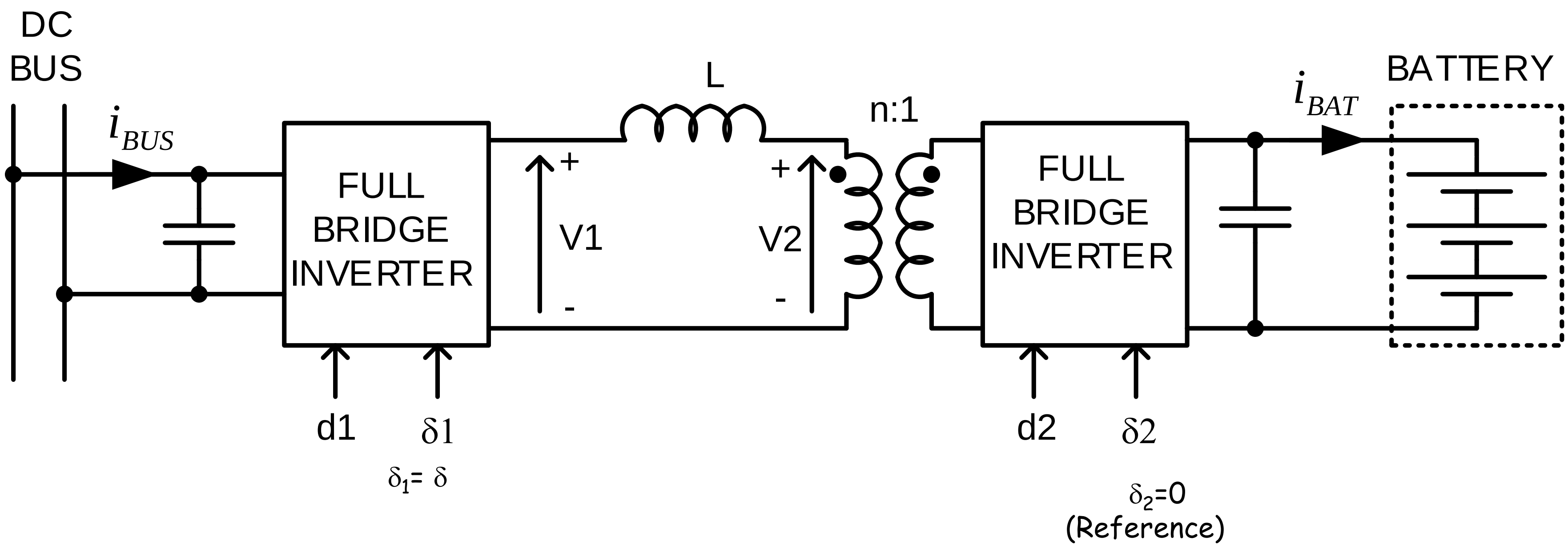
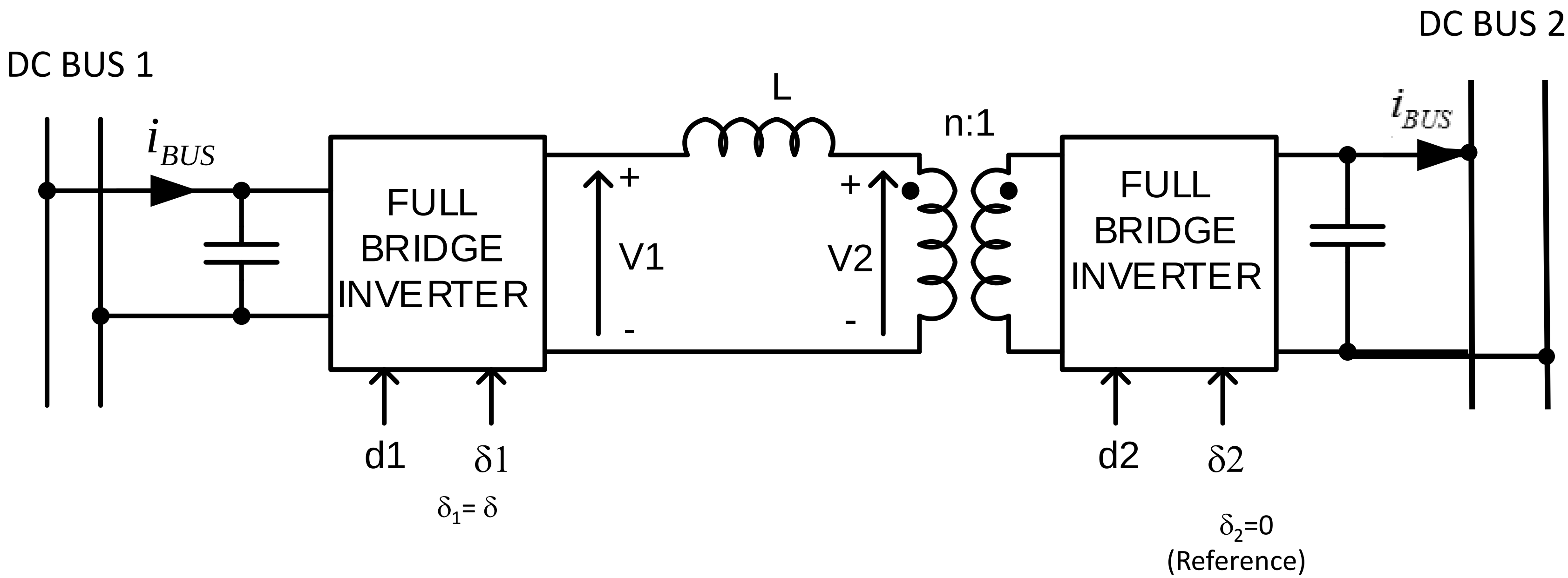
Dual-Active Bridge (DAB) Converter for Energy Storage/Recovery Systems



DC-link using DAB Converter



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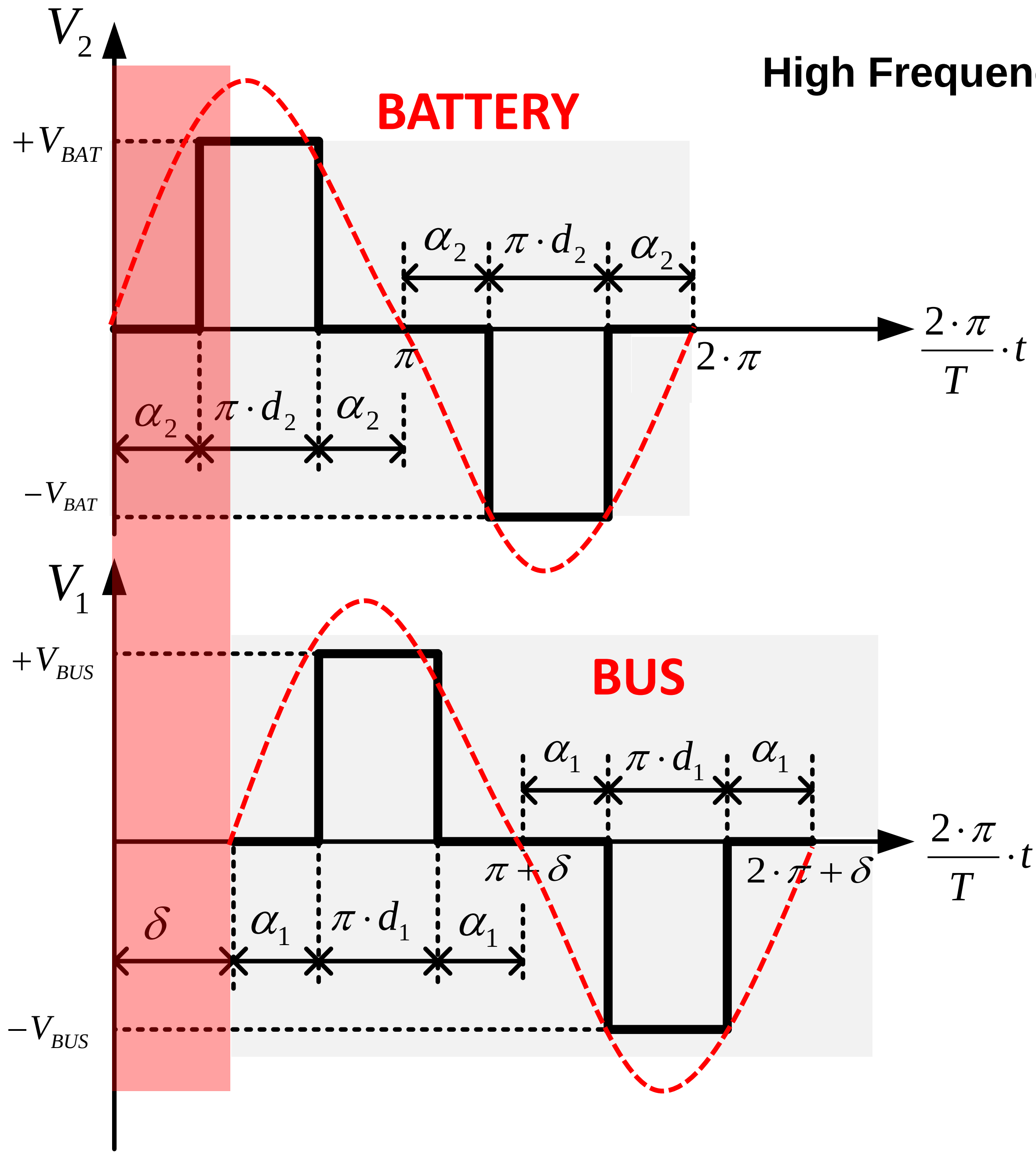
High Frequency Square waves



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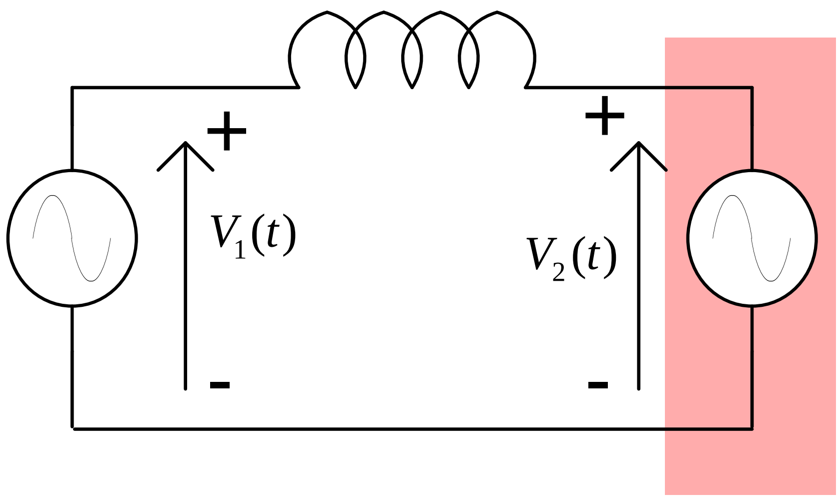
Fourier development of V1 (battery voltage)

$$V_2(t)=\frac{4\cdot n\cdot V_{BAT}}{\pi}\cdot\sum_{i=0}^{\infty}\frac{1}{2\cdot i+1}\cdot\cos\left(\frac{\pi}{2}\cdot(1-d_2)\cdot(2\cdot i+1)\right)\cdot\sin\left(\frac{2\cdot\pi}{T}\cdot(2\cdot i+1)\cdot t\right)$$

First harmonic

$$V_{2\_F}(t)=\frac{4\cdot n\cdot V_{BAT}}{\pi}\cdot\cos\left(\frac{\pi}{2}\cdot(1-d_2)\right)\cdot\sin\left(\frac{2\cdot\pi}{T}\cdot t\right)$$



BATTERY INVERTER

Turn ratio (n) of the isolation transformer included

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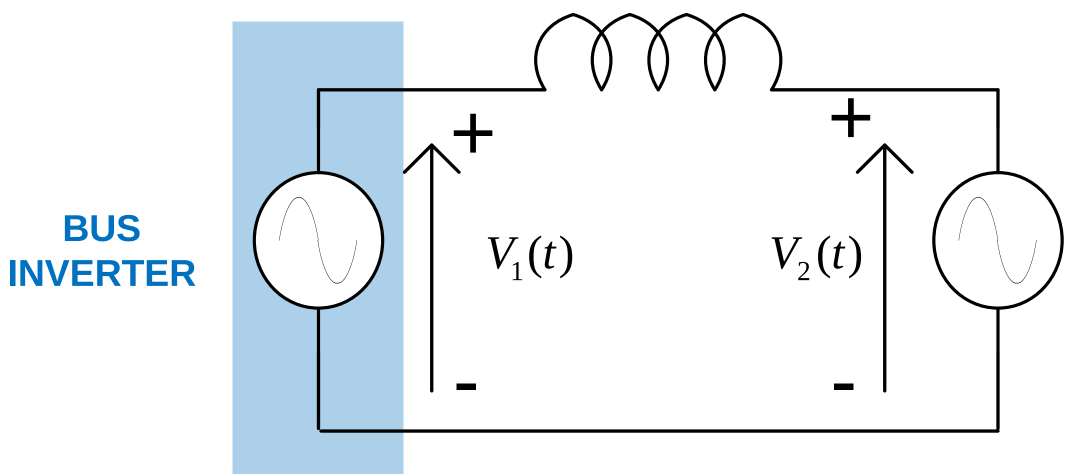
Fourier development of V1 (bus voltage)

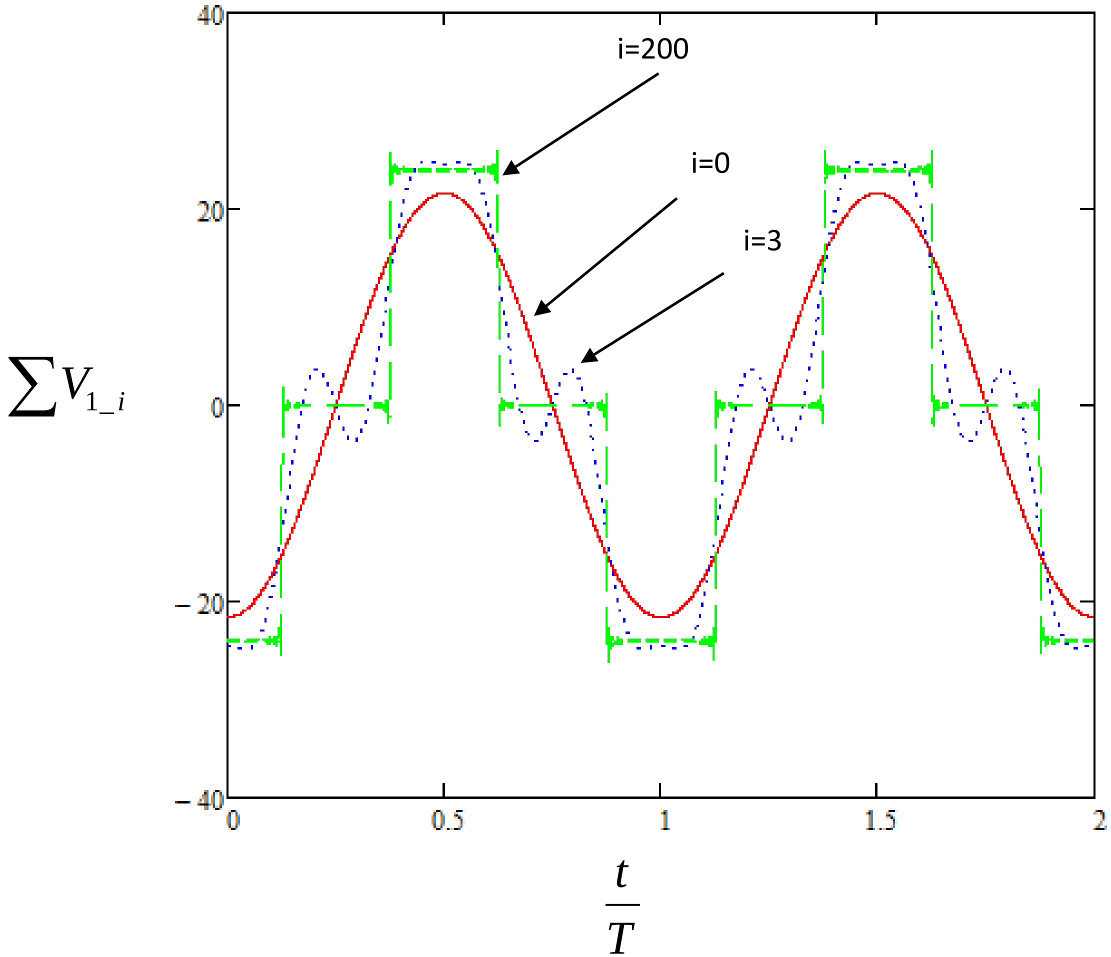
$$V_1(t)=\frac{4\cdot V_{BUS}}{\pi}\cdot\sum_{i=0}^{\infty}\frac{1}{2\cdot i+1}\cdot\cos\left(\frac{\pi}{2}\cdot(1-d_1)\cdot(2\cdot i+1)\right)\cdot\sin\left(\frac{2\cdot\pi}{T}\cdot(2\cdot i+1)\cdot t+\delta\cdot\frac{\pi}{180}\right)$$

First harmonic

$$V_{1\_F}(t)=\frac{4\cdot V_{BUS}}{\pi}\cdot\cos\left(\frac{\pi}{2}\cdot(1-d_1)\right)\cdot\sin\left(\frac{2\cdot\pi}{T}\cdot t+\delta\cdot\frac{\pi}{180}\right)$$



Verification using a mathematical program



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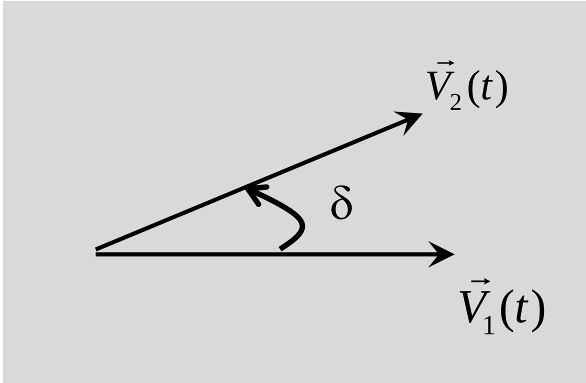
Complex representation of V1 (battery voltage)

$$\vec{V}_{1\_i} = \frac{4 \cdot n \cdot V_{BAT}}{\pi \cdot (2 \cdot i + 1)} \cdot \cos\left(\frac{\pi}{2} \cdot (1 - d_1) \cdot (2 \cdot i + 1)\right)$$

All Harmonics

$$\vec{V}_1 = \frac{4 \cdot n \cdot V_{BAT}}{\pi} \cdot \cos\left(\frac{\pi}{2} \cdot (1 - d_1)\right)$$



Complex representation of V2 (bus voltage)

$$\vec{V}_{2\_i} = \frac{4 \cdot V_{BUS}}{\pi \cdot (2 \cdot i + 1)} \cdot \cos\left(\frac{\pi}{2} \cdot (1 - d_2) \cdot (2 \cdot i + 1)\right) \cdot \left[\cos\left(\delta \cdot \frac{\pi}{180}\right) + j \cdot \sin\left(\delta \cdot \frac{\pi}{180}\right)\right]$$

All Harmonics

$$\vec{V}_2 = \frac{4 \cdot V_{BUS}}{\pi} \cdot \cos\left(\frac{\pi}{2} \cdot (1 - d_2)\right) \cdot \left[\cos\left(\delta \cdot \frac{\pi}{180}\right) + j \cdot \sin\left(\delta \cdot \frac{\pi}{180}\right)\right]$$

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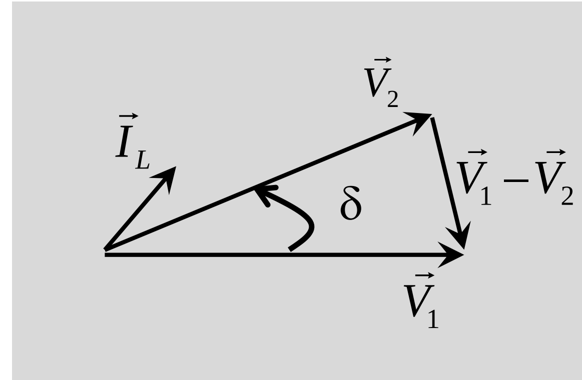
Complex representation of Inductor Current (IL)

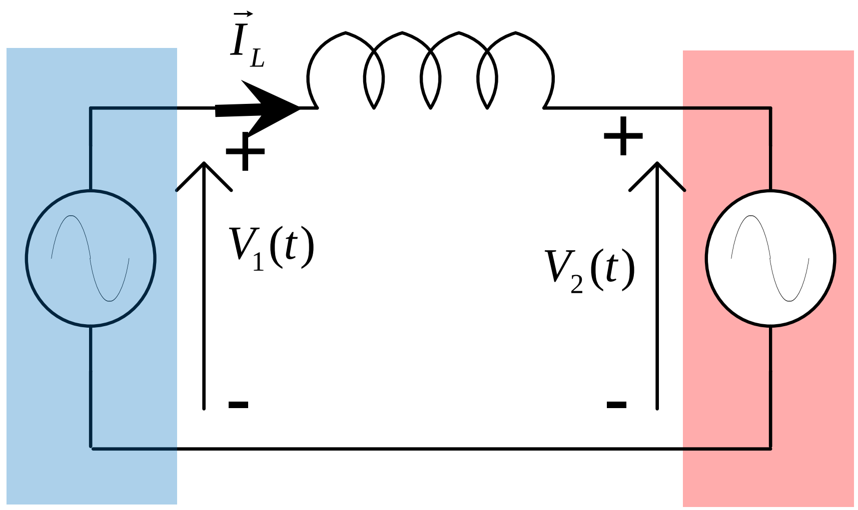
$$\vec{I}_{L\_i} = \frac{\vec{V}_{1\_i} - \vec{V}_{2\_i}}{R + j \cdot 2 \cdot \pi \cdot f \cdot (2 \cdot i + 1) \cdot L}$$

All Harmonics

$$\vec{I}_{L} = \frac{\vec{V}_{1} - \vec{V}_{2}}{R + j \cdot 2 \cdot \pi \cdot f \cdot L}$$



BUS INVERTER



BATTERY INVERTER

Turn ratio (n) of the isolation transformer included

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Power evaluation (Active and reactive) using Complex representation (in the battery)

$$\vec{S}_i = \frac{\vec{V}_{2\_i} \cdot \vec{I}_{L\_i}}{2} = P_i + j \cdot Q_i$$

All Harmonics

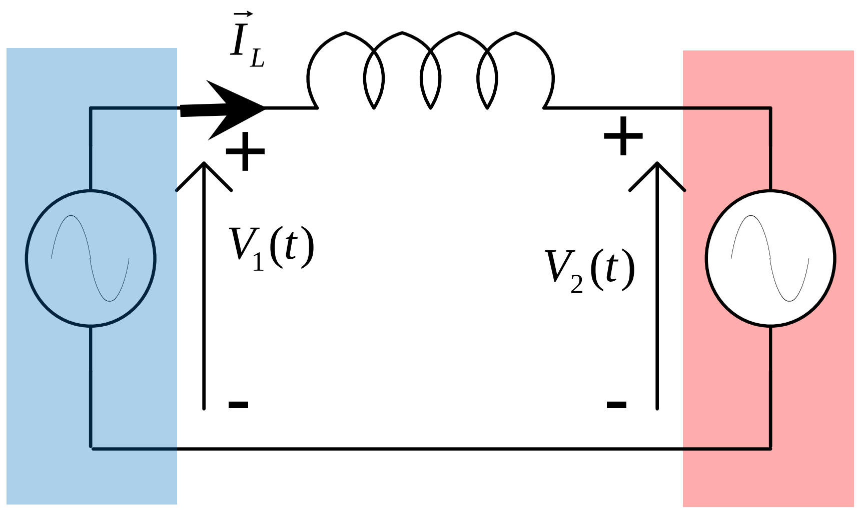
$$P = \sum_{i=0}^{\infty} P_i$$

ACTIVE POWER

$$Q = \sum_{i=0}^{\infty} Q_i$$

POWER HANDLING (REACTIVE POWER)

BUS INVERTER



BATTERY INVERTER

Turn ratio (n) of the isolation transformer included

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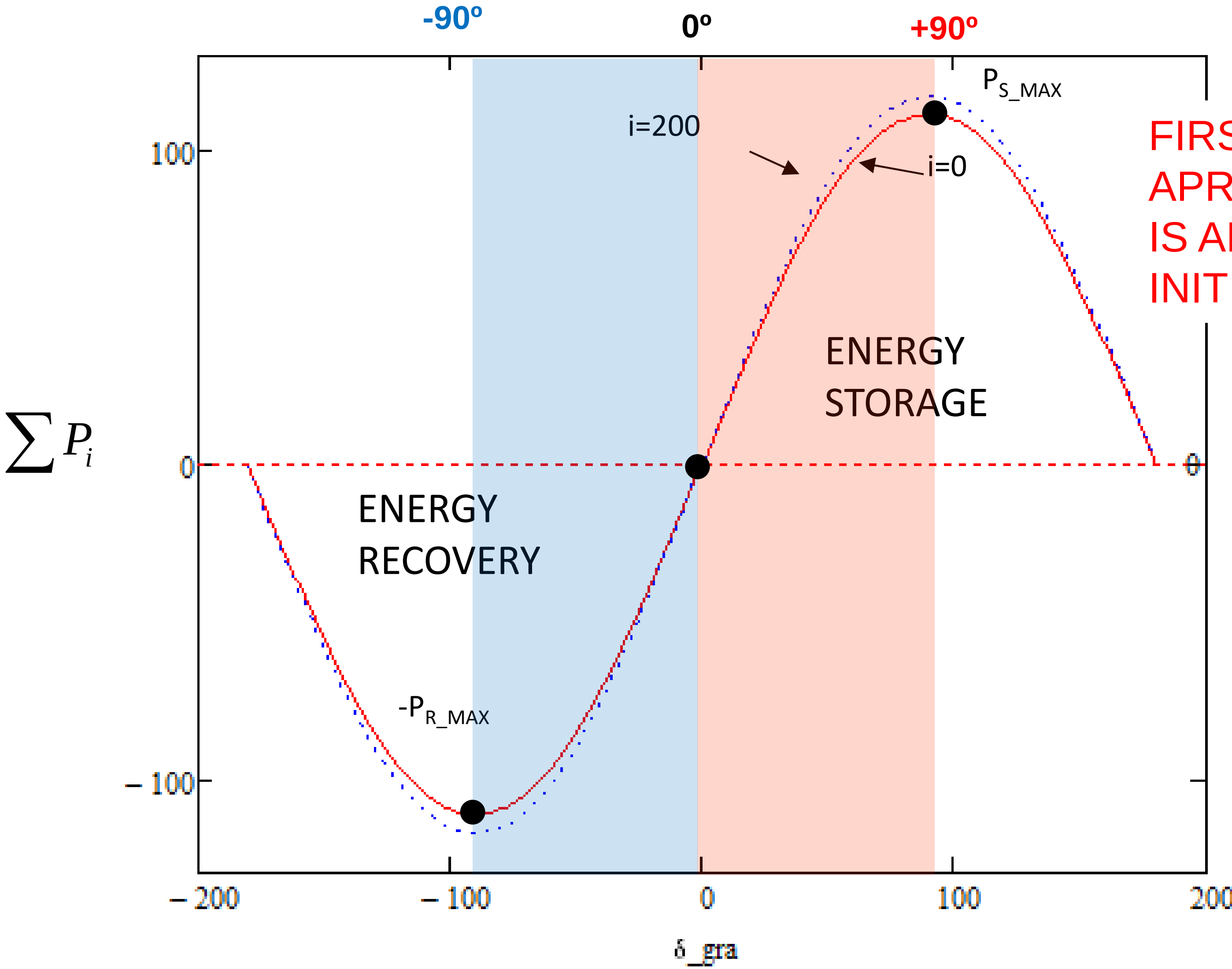

FIRST HARMONIC APROACH DESIGN IS AN EXCELLENT INITIAL DESIGN

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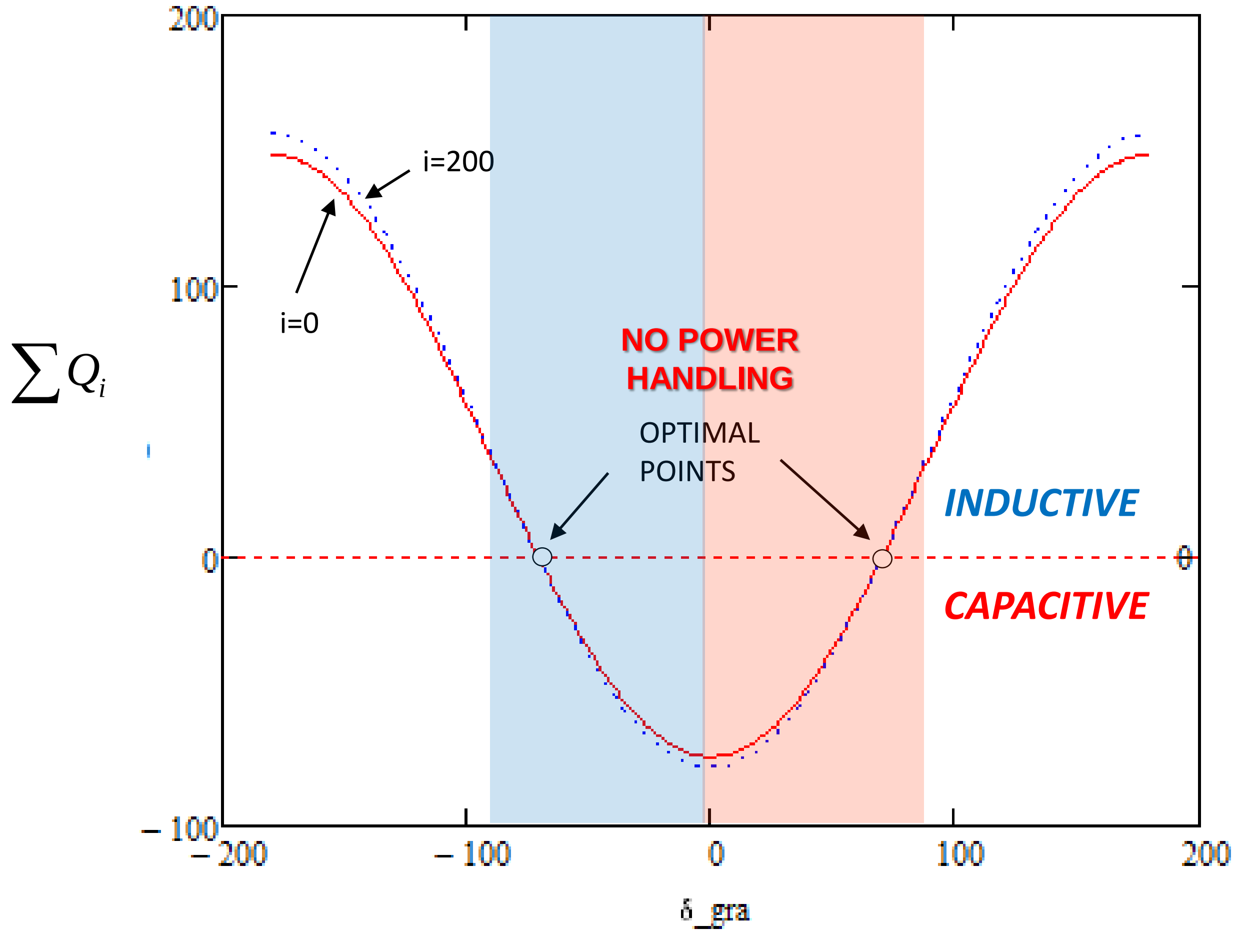

Reactive Power handled by the converter ($\sum Q_i$) using only fundamental (i=0) and 200 Harmonics.
(V_{BUS} = 24 V, V_{BAT} = 12 V, f = 50 KHz n = 1, L = 10 µH and R = 1 mΩ)

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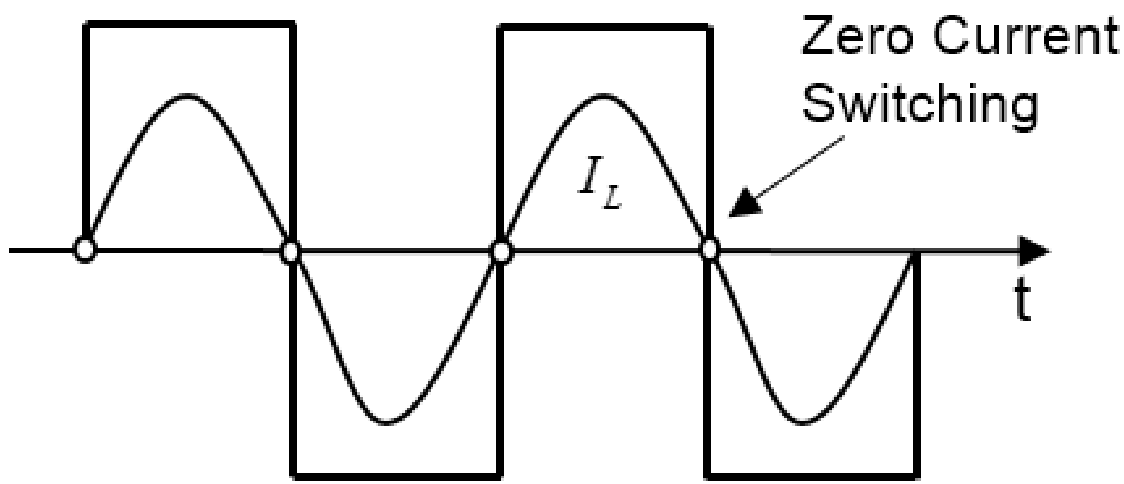
DAB operation over Q=0 line
Zero Current Switching (ZCS)



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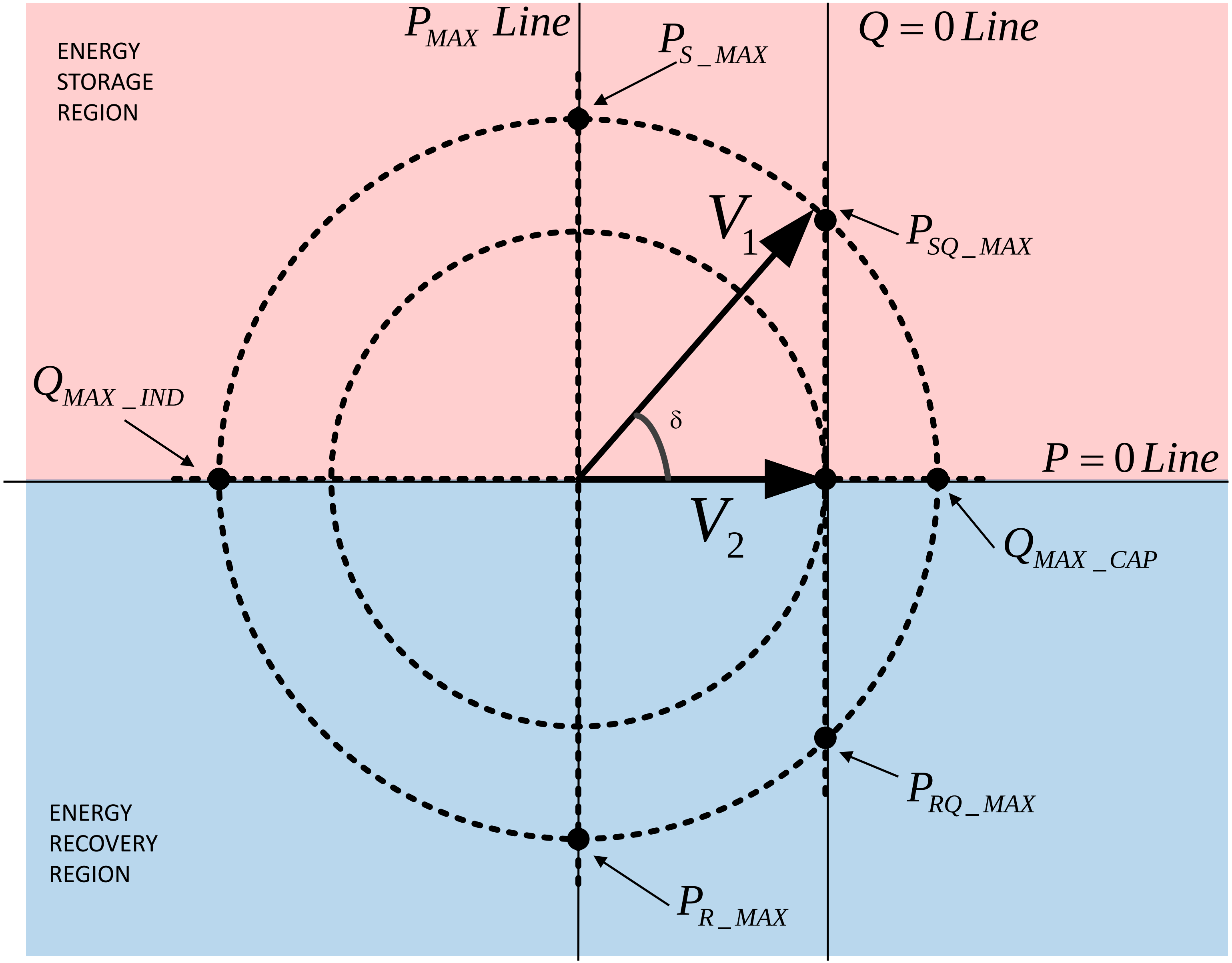

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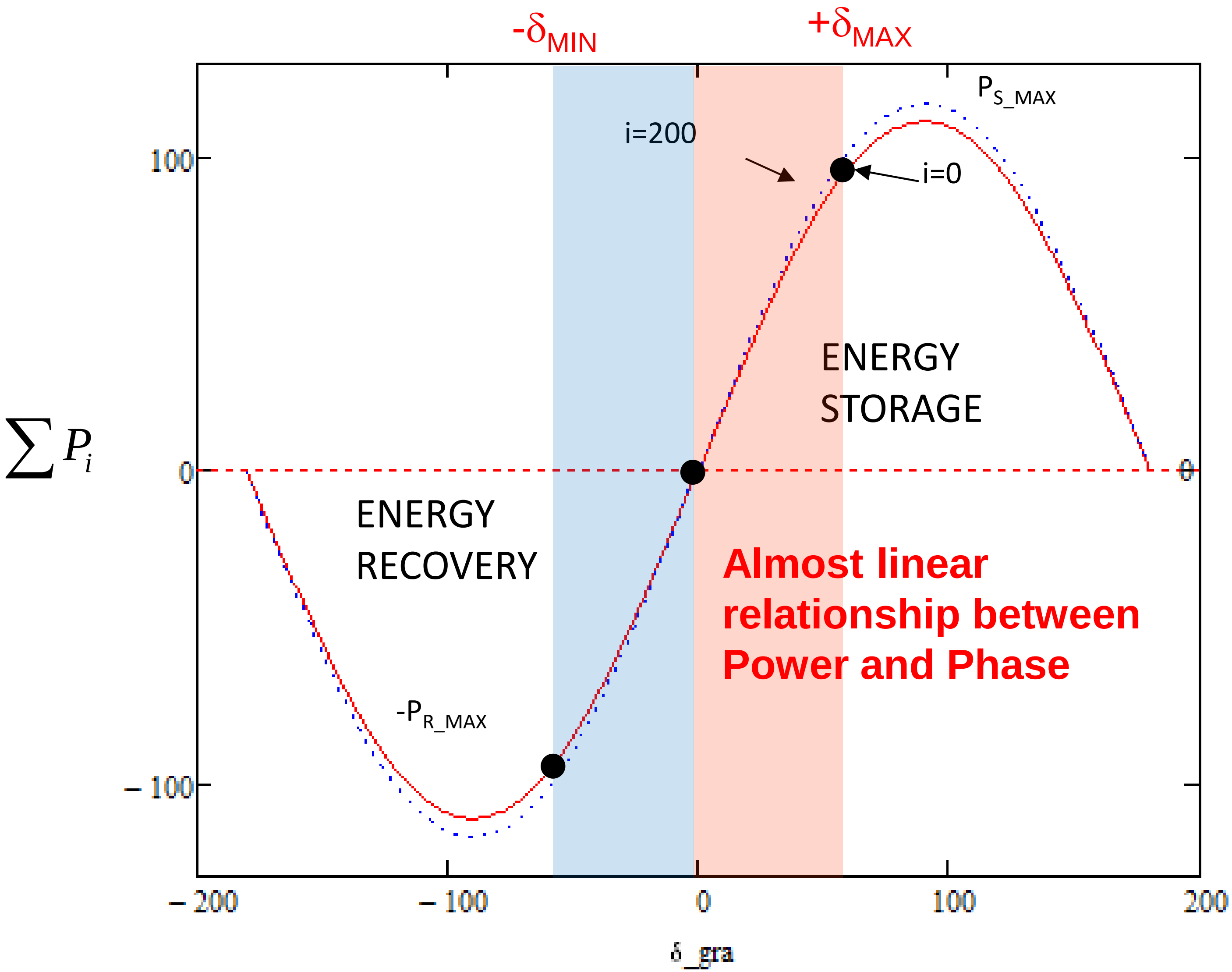

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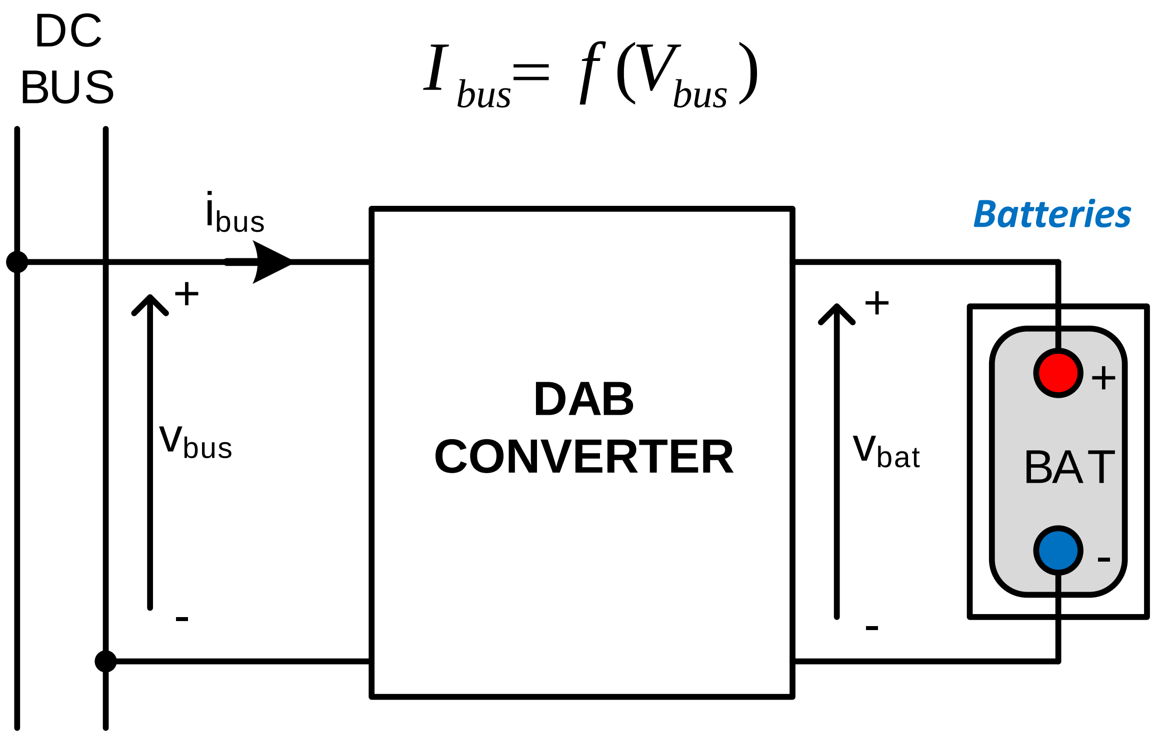
Classical solution: Linear Droop Control (LDC)

$$I_{bus} = f(V_{bus})$$



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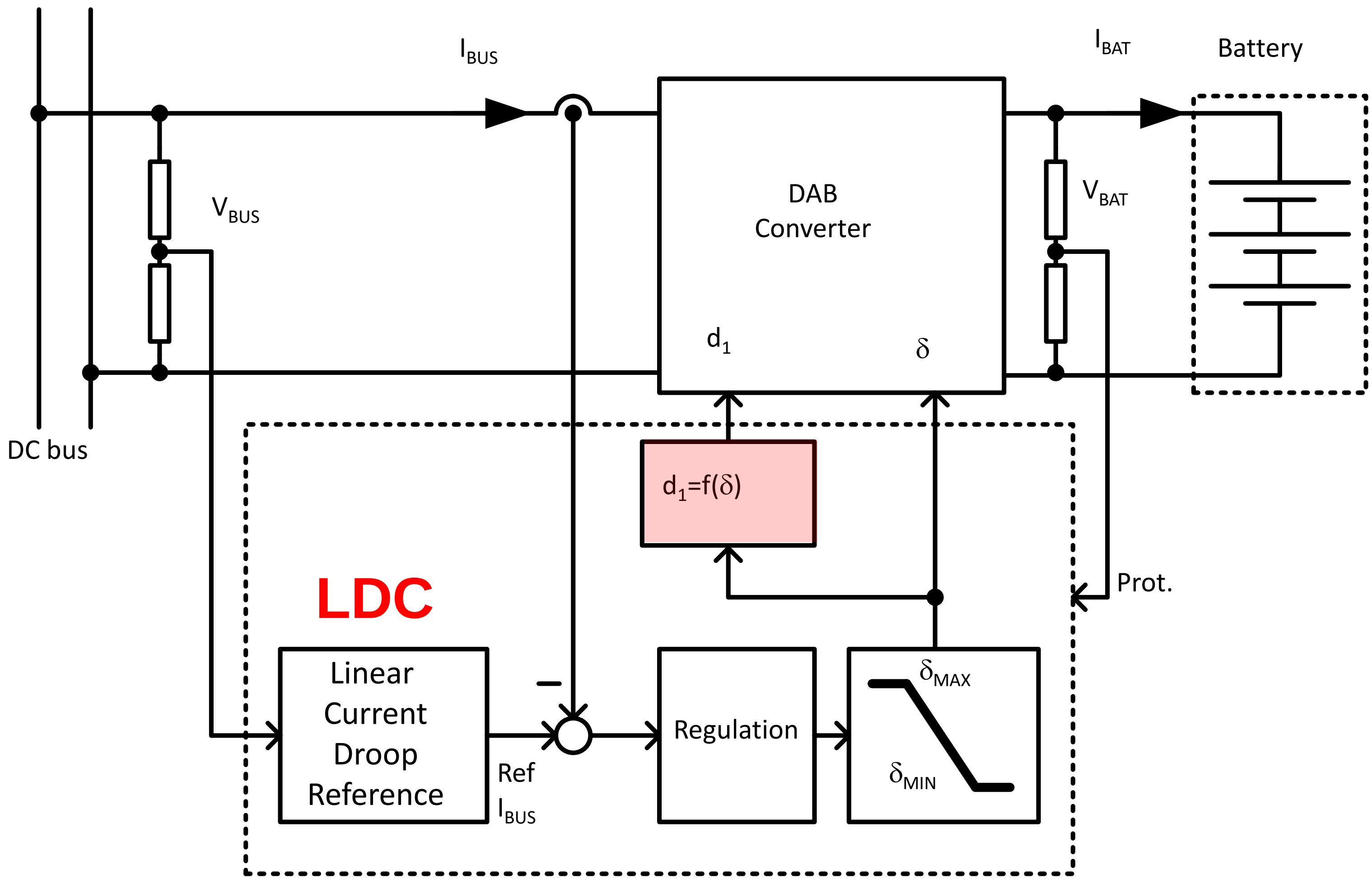

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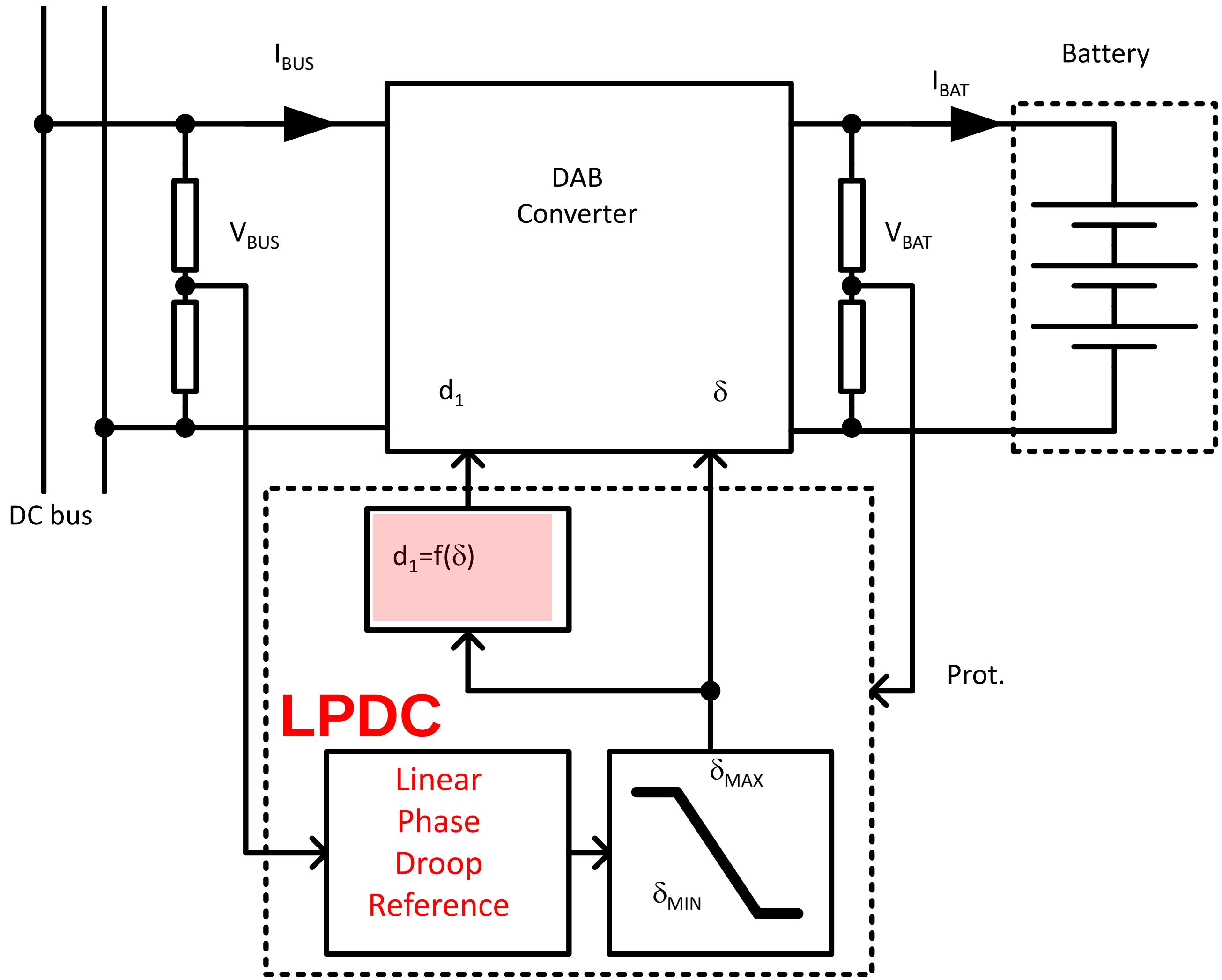
ALTERNATIVE: Linear Phase Droop Control (LPDC)



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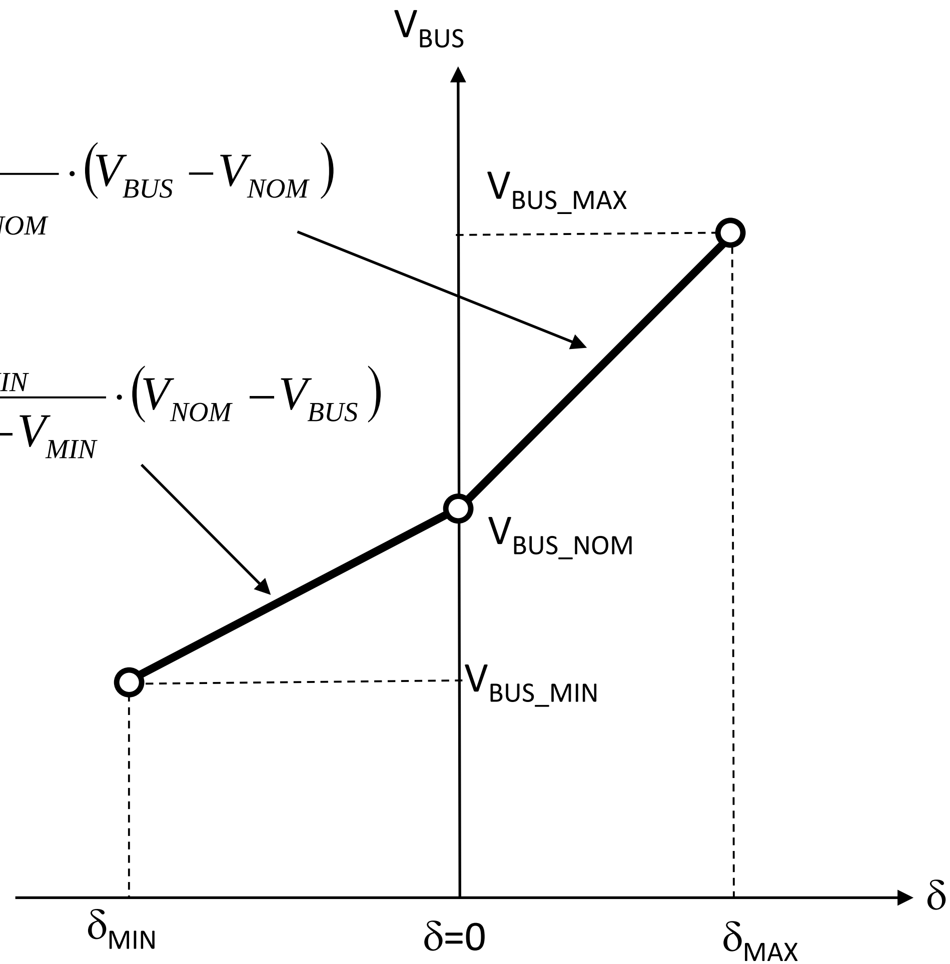
ALTERNATIVE: Linear Phase Droop Control (LPDC)

$$\delta = \frac{\delta_{MAX}}{V_{MAX} - V_{NOM}} \cdot \left(V_{BUS} - V_{NOM}\right)$$

$$\delta = \frac{\delta_{MIN}}{V_{NOM} - V_{MIN}} \cdot \left(V_{NOM} - V_{BUS}\right)$$



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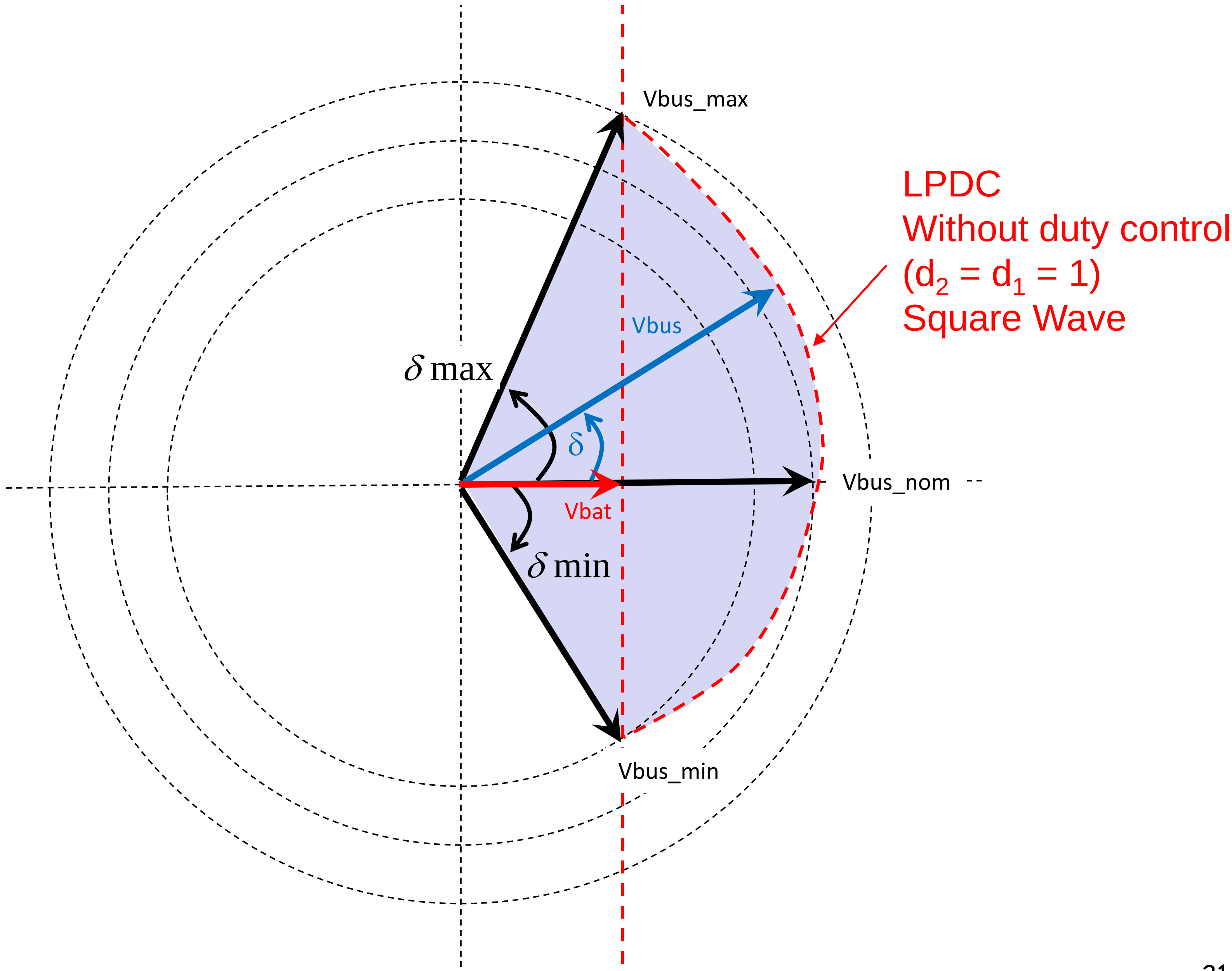
ALTERNATIVE: Linear Phase Droop Control



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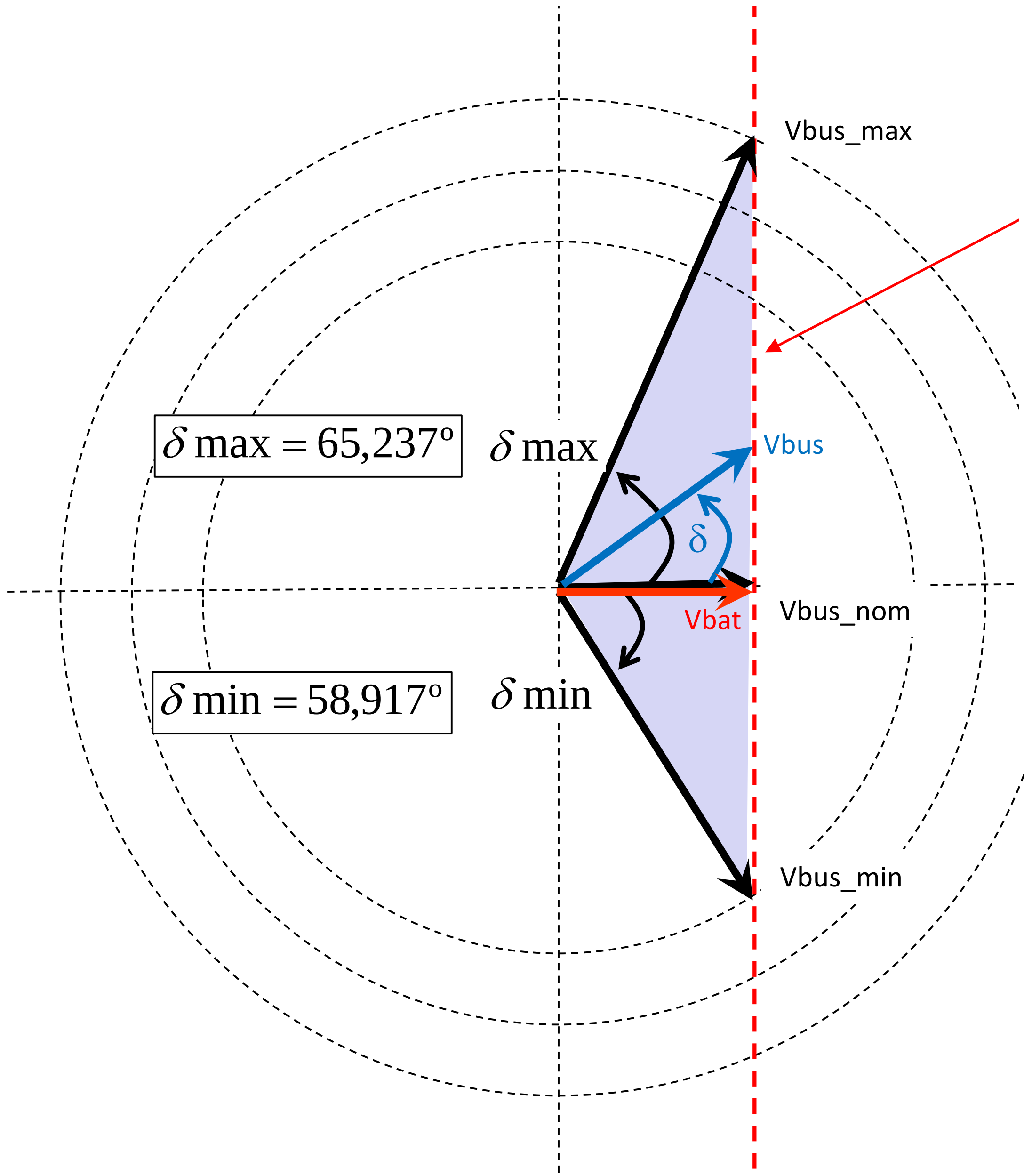
ALTERNATIVE: Linear Phase Droop Control (LPDC)



LPDC
With duty control
no power handling
in the battery inverter

NOTE: No power handling in the bus inverter is also possible

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ALTERNATIVE: Linear Phase Droop Control (LPDC)

$$\left|\vec{V}_1\right| \cdot \cos(\delta) = \left|\vec{V}_2\right|$$

$$\frac{4 \cdot V_{BUS}}{\pi} \cdot \cos\left[\frac{\pi}{2} \cdot (1 - d_1)\right] \cdot \cos\left(\delta \cdot \frac{\pi}{180}\right) = \frac{4 \cdot n \cdot V_{BAT}}{\pi}$$

$$\cos\left[\frac{\pi}{2} \cdot (1 - d_1)\right] = \frac{n \cdot V_{BAT}}{V_{BUS} \cdot \cos\left(\delta \cdot \frac{\pi}{180}\right)}$$

LPDC
With duty control for no power handling in the battery inverter

$$d_1(\delta) = 1 - \frac{2}{\pi} \cdot a\cos\left(\frac{n \cdot V_{BAT}}{V_{BUS}(\delta) \cdot \cos\left(\delta \cdot \frac{\pi}{180}\right)}\right)$$

OVER OPTIMAL LINE (ZVS OPERATION

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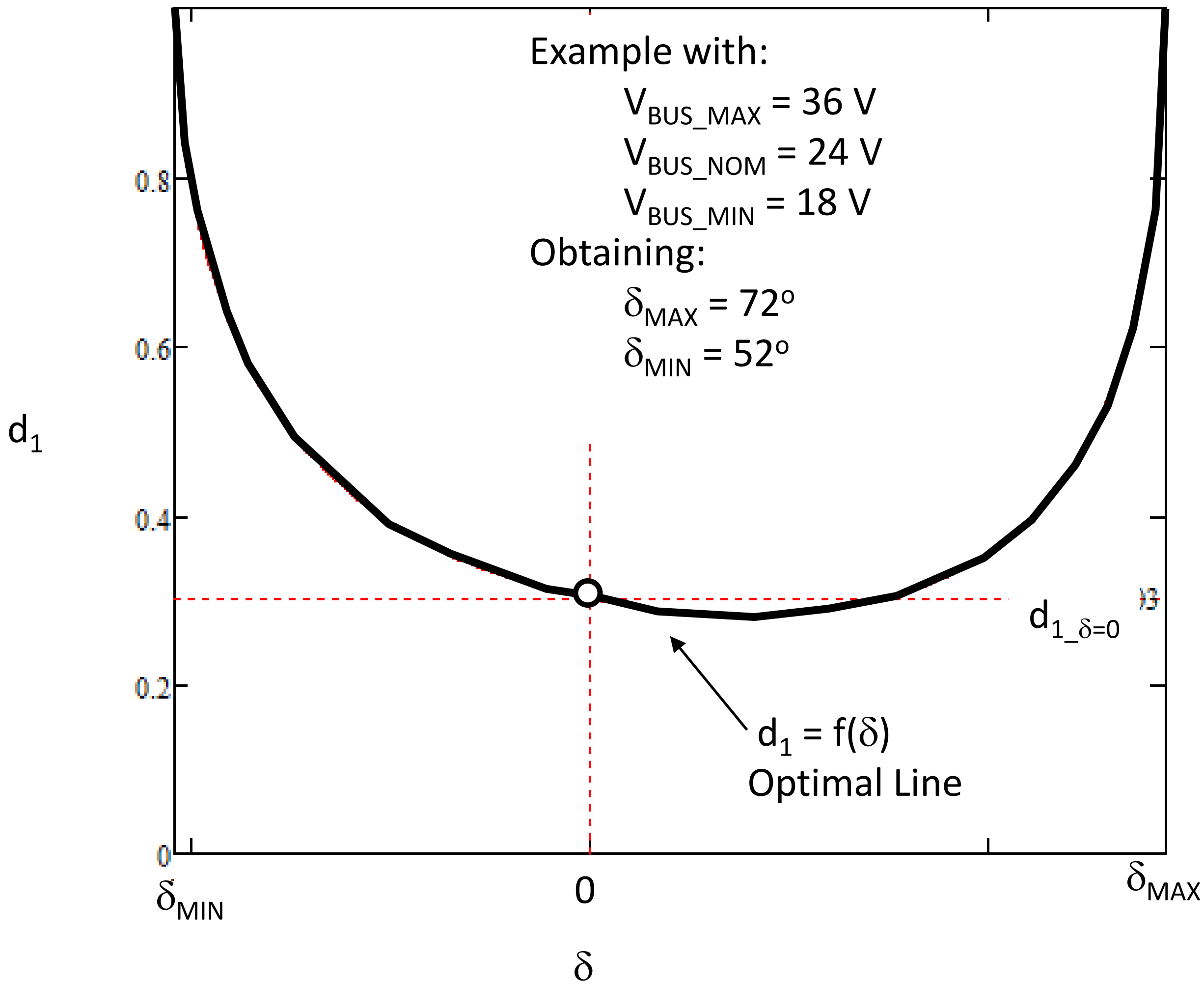
ATTERNATIVE: Linear Phase Droop Control (LPDC)



LPDC
With duty control for no power handling in the battery inverter

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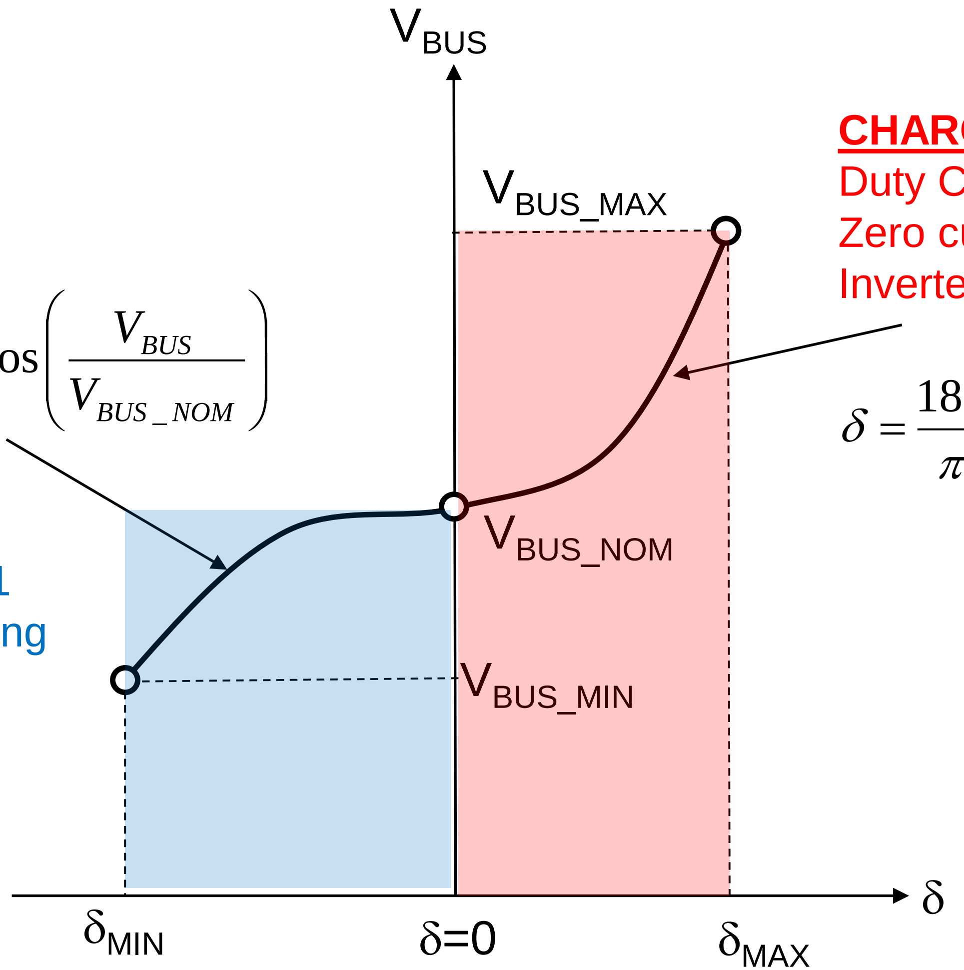
NEW PROPOSAL: Cosine Phase Droop Control (CPDC)

$$\delta = -\frac{180}{\pi} \cdot a\cos\left(\frac{V_{BUS}}{V_{BUS\_NOM}}\right)$$

RECOVERY:
Duty Cycle always 1
Zero current switching
Inverter bus side



CHARGE:
Duty Cycle always 1
Zero current switching
Inverter battery side

$$\delta = \frac{180}{\pi} \cdot a\cos\left(\frac{V_{BUS\_NOM}}{V_{BUS}}\right)$$

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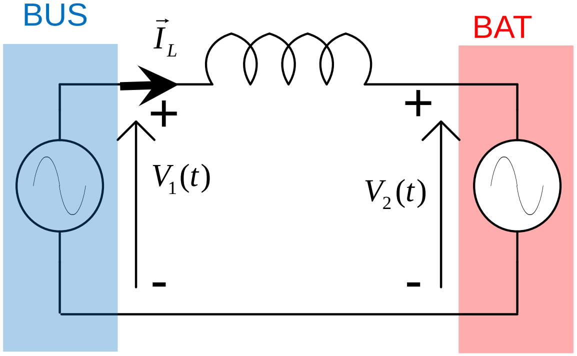
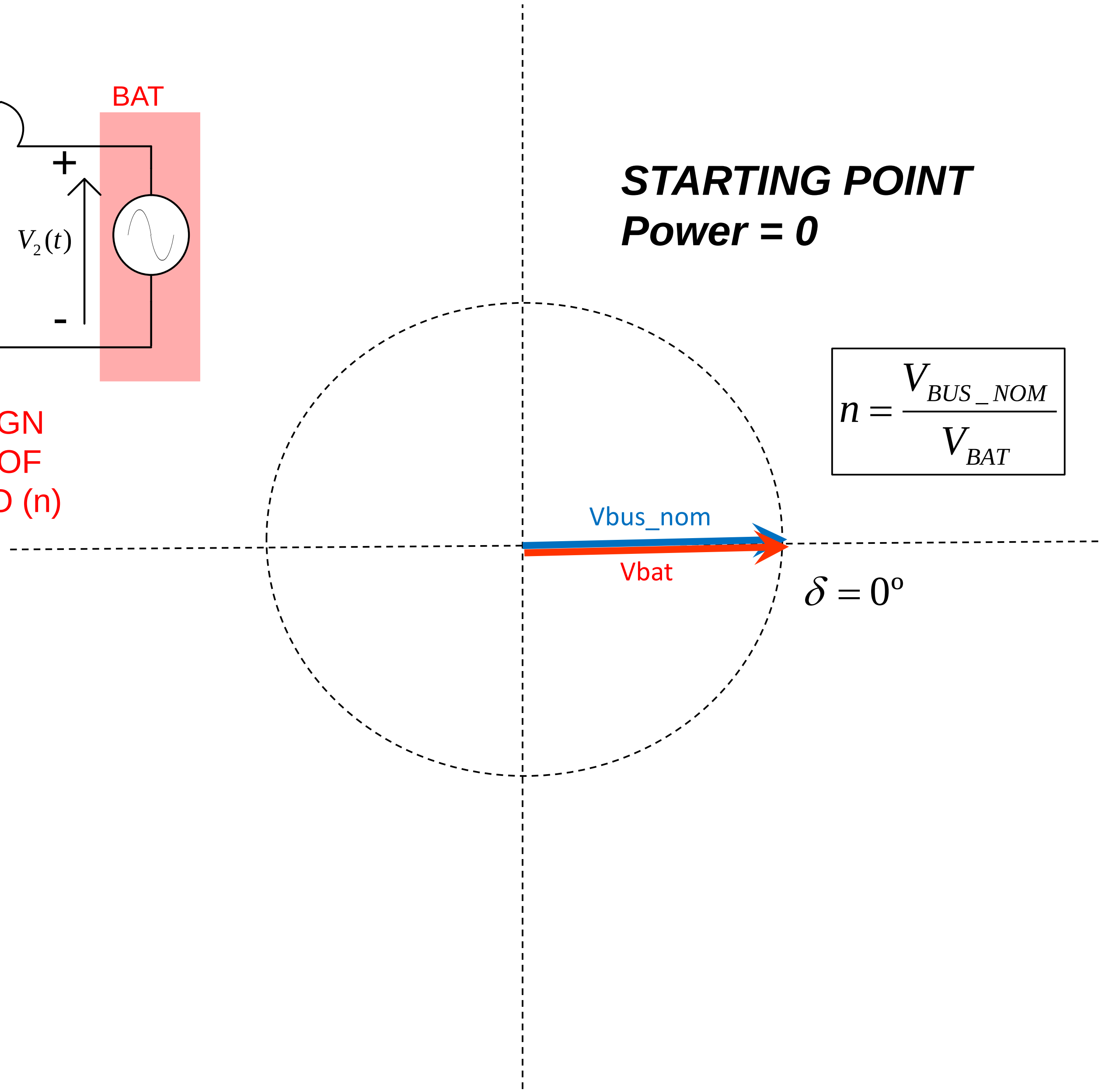
NEW PROPOSAL: Cosine Phase Droop Control (CPDC)



NEW DESIGN CRITERIA OF TURN RATIO (n)

STARTING POINT
Power = 0

$$n = \frac{V_{BUS\_NOM}}{V_{BAT}}$$



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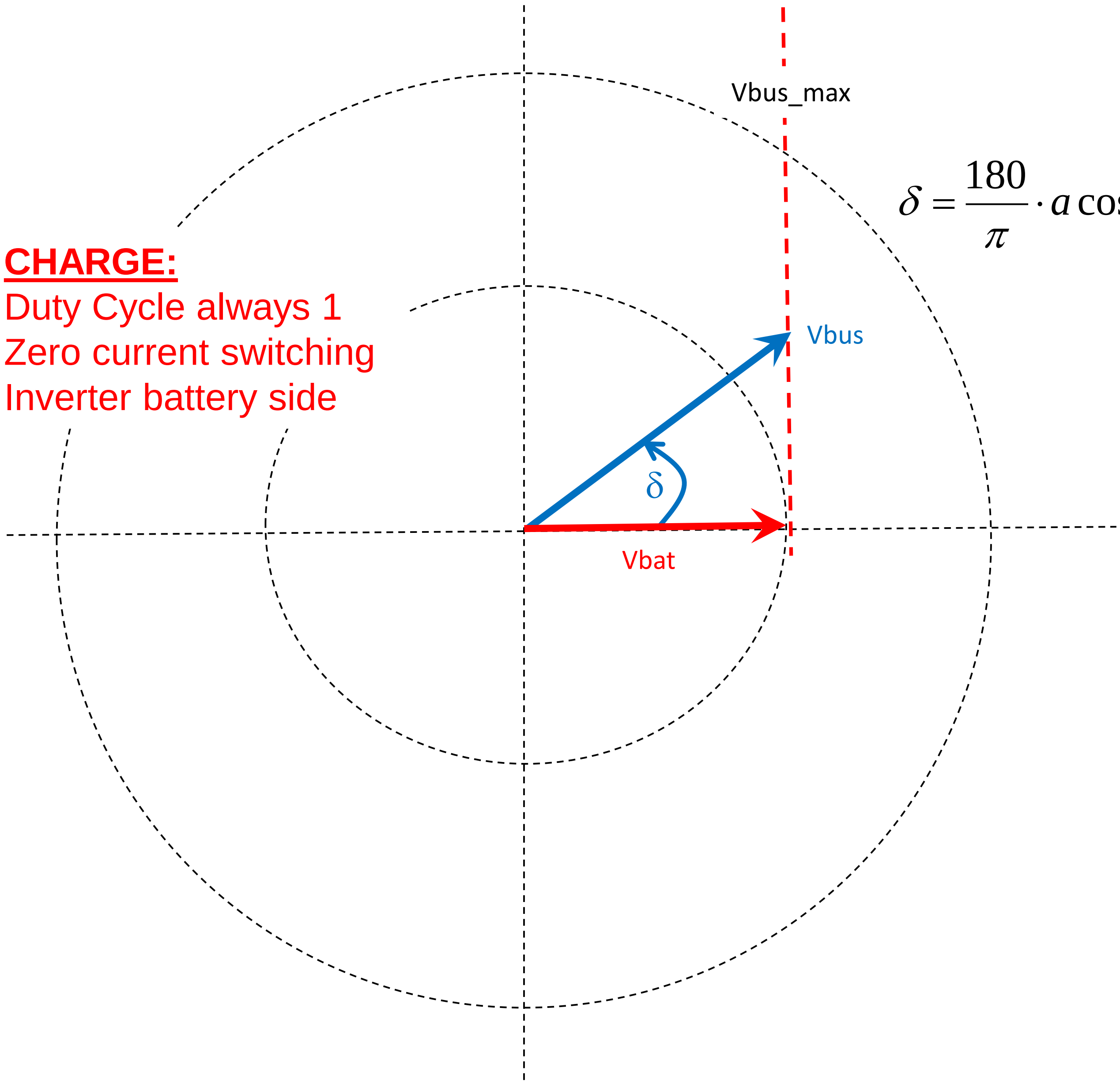
NEW PROPOSAL: Cosine Phase Droop Control (CPDC)

CHARGE:

Duty Cycle always 1

Zero current switching

Inverter battery side



$$\delta = \frac{180}{\pi} \cdot a\cos\left(\frac{V_{BUS\_NOM}}{V_{BUS}}\right)$$

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NEW PROPOSAL: Cosine Phase Droop Control (CPDC)

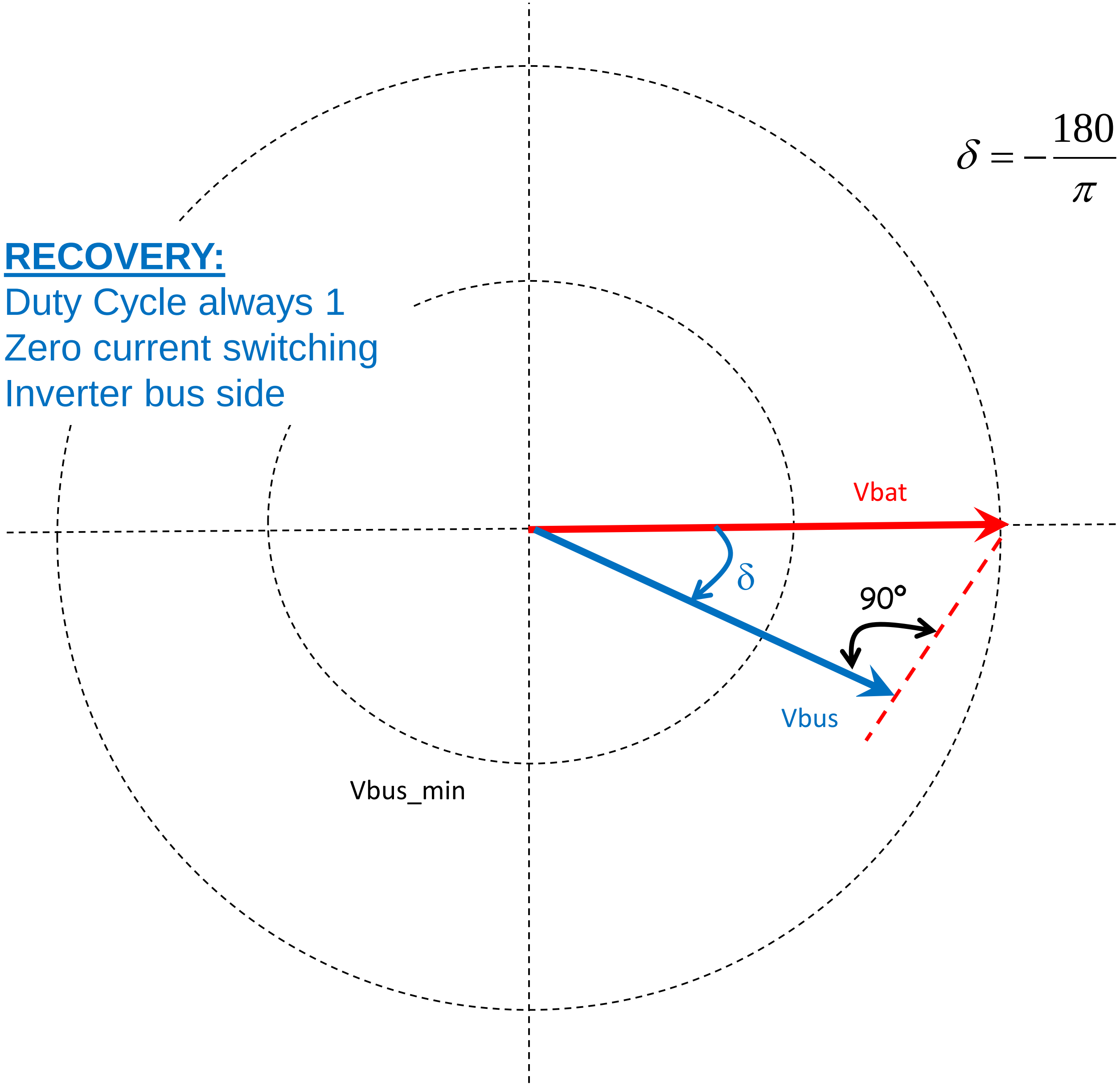
$$\delta = -\frac{180}{\pi} \cdot a\cos\left(\frac{V_{BUS}}{V_{BUS\_NOM}}\right)$$

RECOVERY:

Duty Cycle always 1

Zero current switching

Inverter bus side



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NEW PROPOSAL: Cosine Phase Droop Control (CPDC)

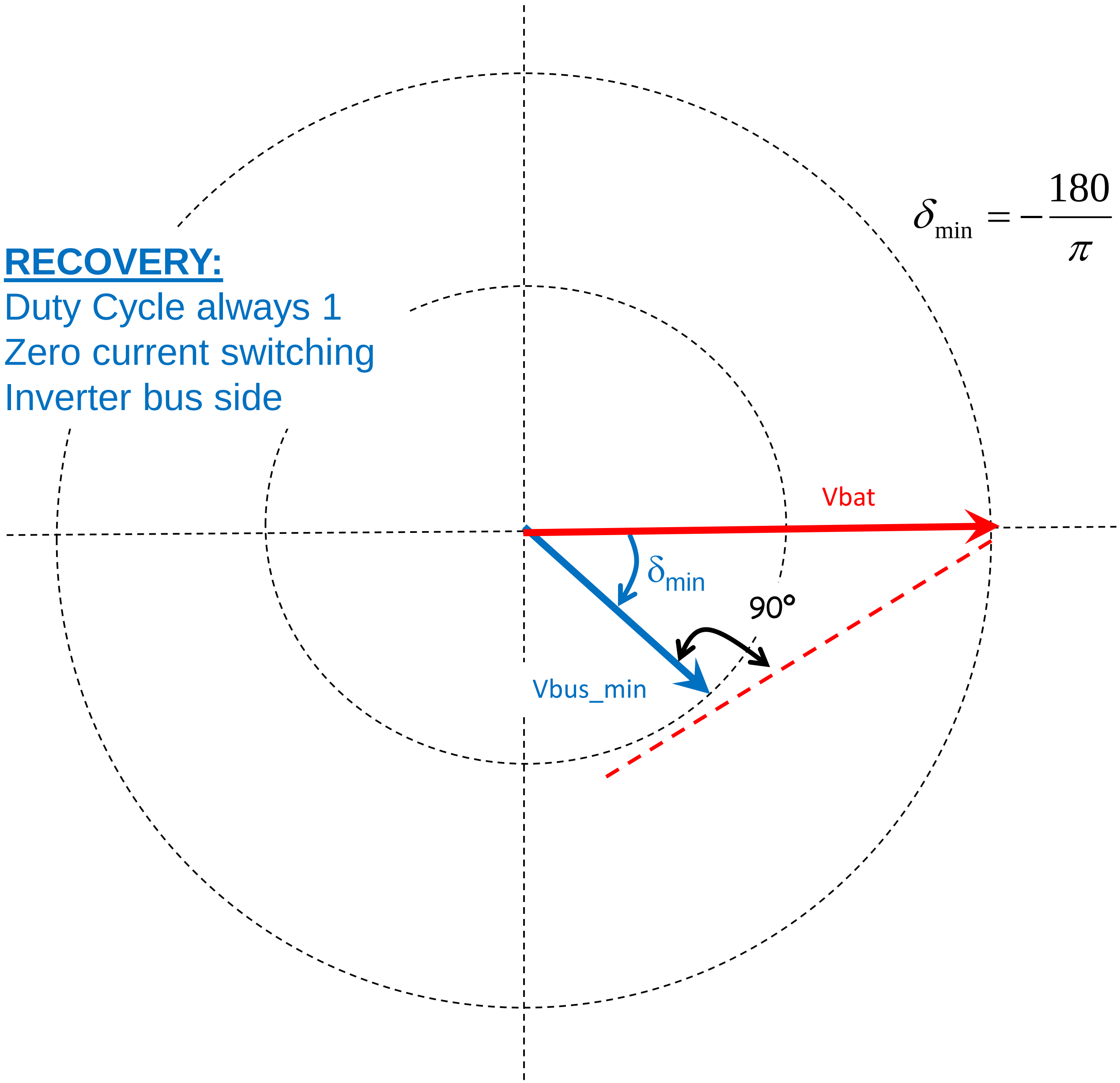
$$\delta_{\min} = -\frac{180}{\pi} \cdot a\cos\left(\frac{V_{BUS\_MIN}}{V_{BUS\_NOM}}\right)$$

RECOVERY:

Duty Cycle always 1

Zero current switching

Inverter bus side



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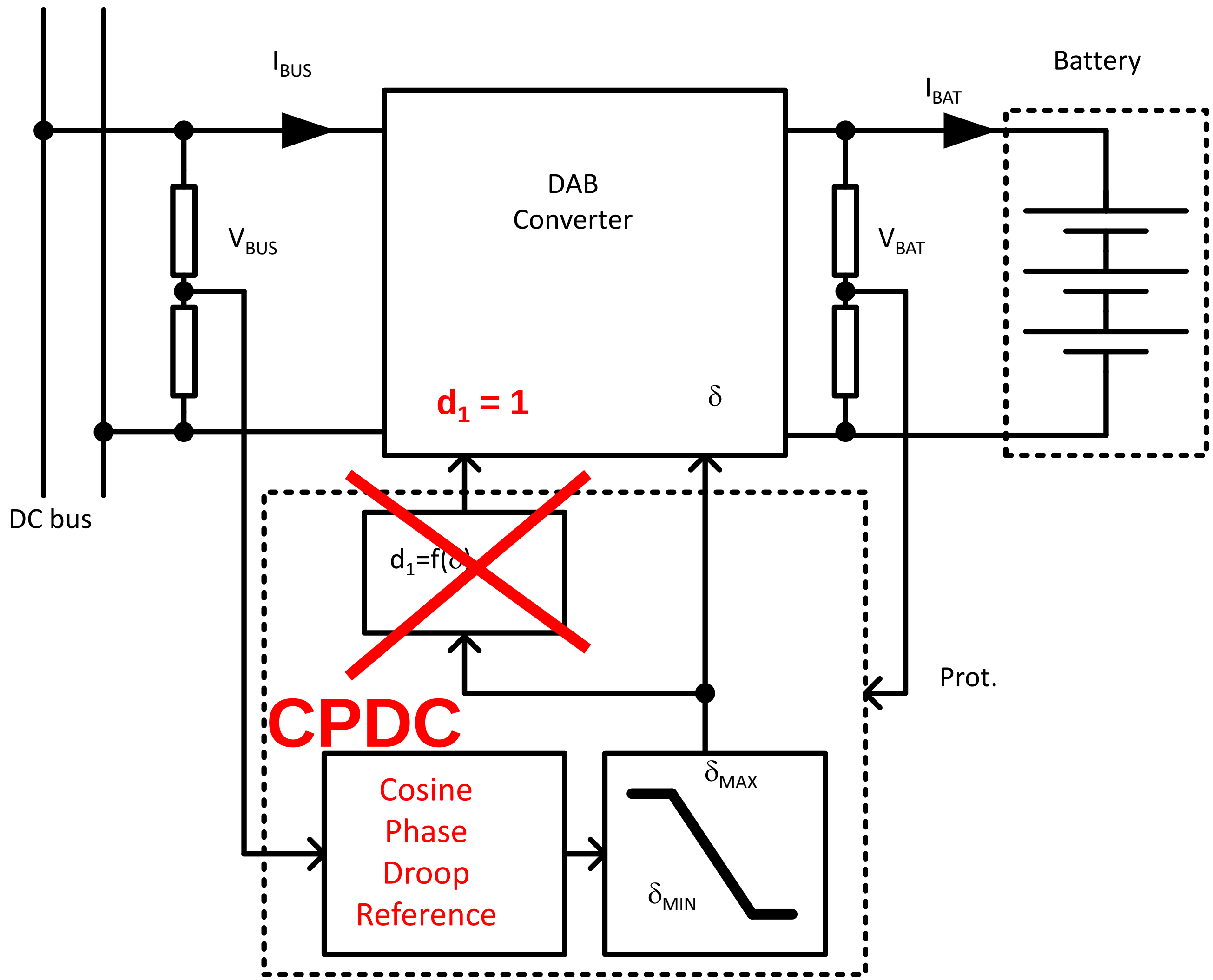
NEW PROPOSAL: Cosine Phase Droop Control (CPDC)



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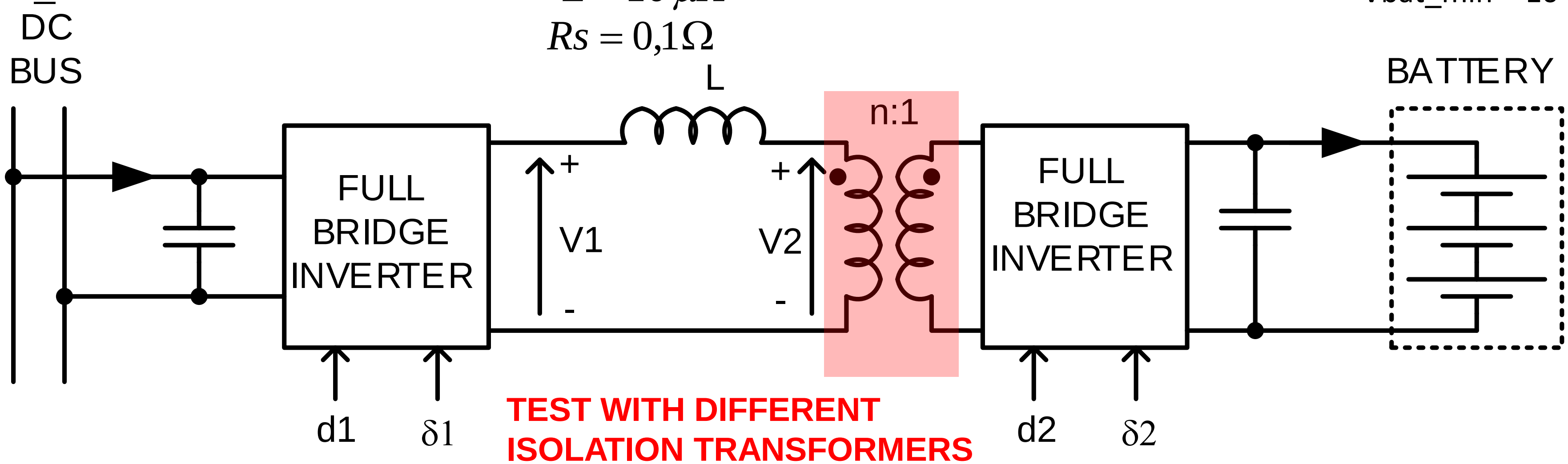
PSIM SIMULATIONS

$$Vbus\_\max = 36\,V$$
$$Vbus\_nom = 24\,V$$
$$Vbus\_\min = 18\,V$$

Vbat_max = 14 V
Vbat_nom = 12 V
Vbat_min = 10 V

$$L = 10\,\mu H$$
$$Rs = 0{,}1\Omega$$



TEST WITH DIFFERENT ISOLATION TRANSFORMERS

$$d2 = 1$$
$$\delta 2 = 0\,(reference)$$

$$Fs = 50\,kHz$$
$$Ts = 20\,\mu S$$

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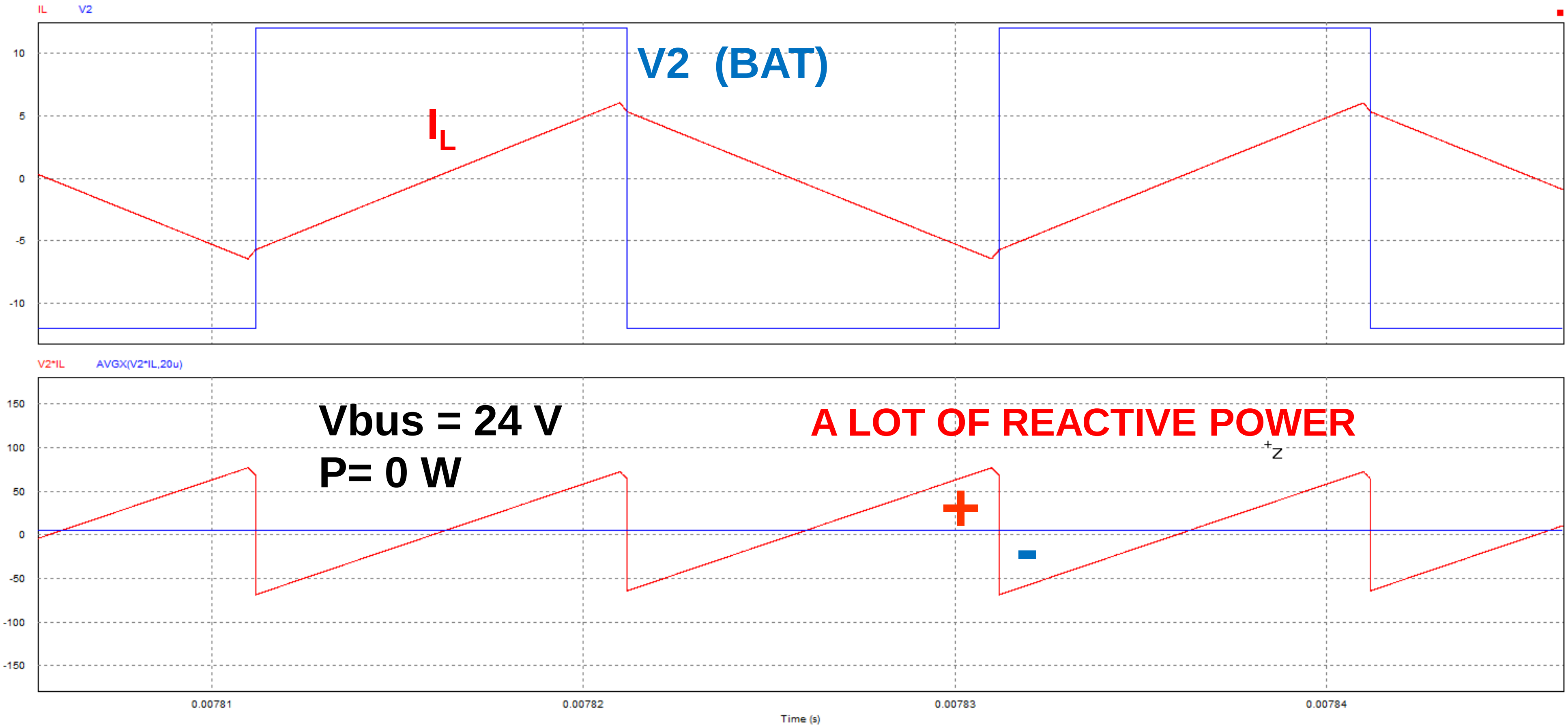
TRAFO 1:1 (LPDC)

BUS WITH NOMINAL VOLTAGE



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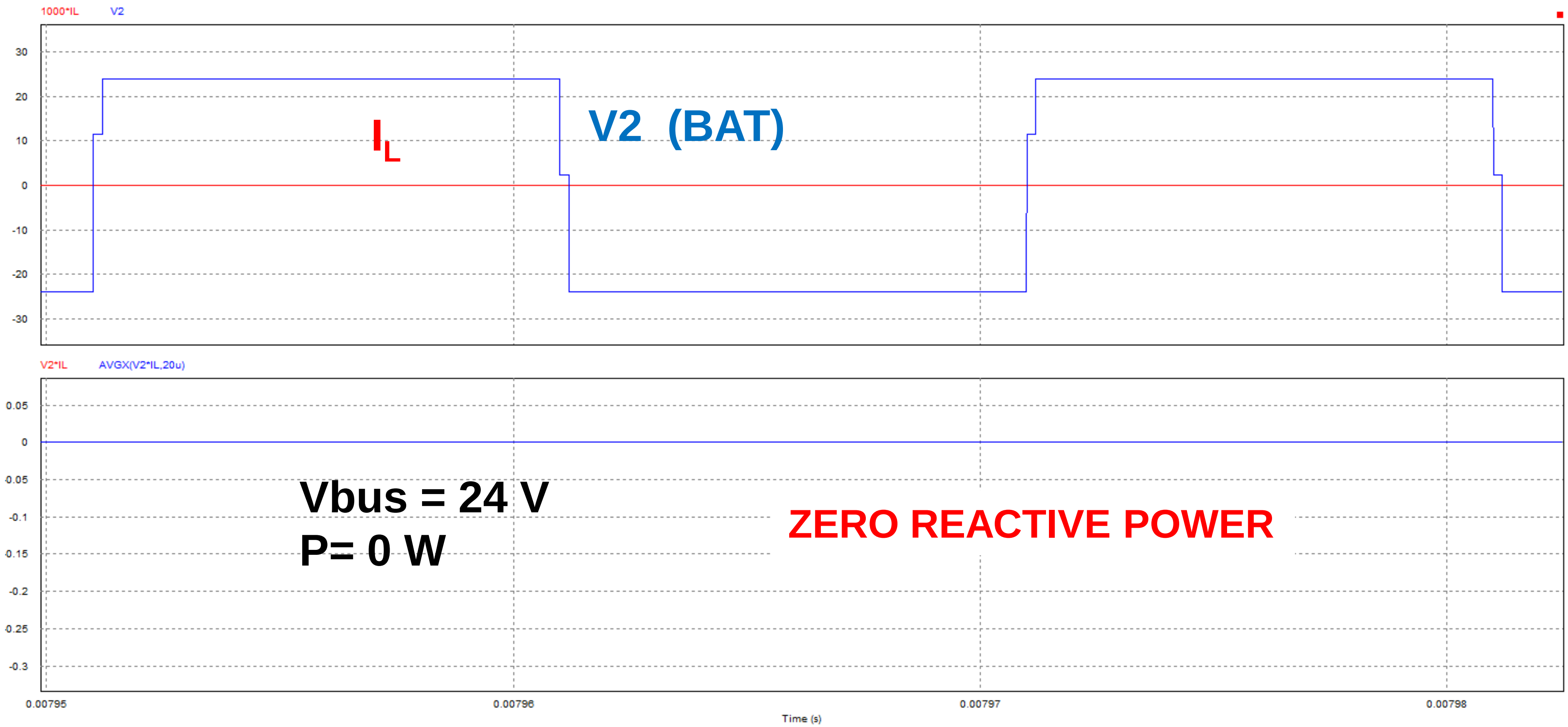
TRAFO 2:1 (CPDC)

$$n = \frac{V_{BUS\_NOM}}{V_{BAT}}$$

BUS WITH NOMINAL VOLTAGE



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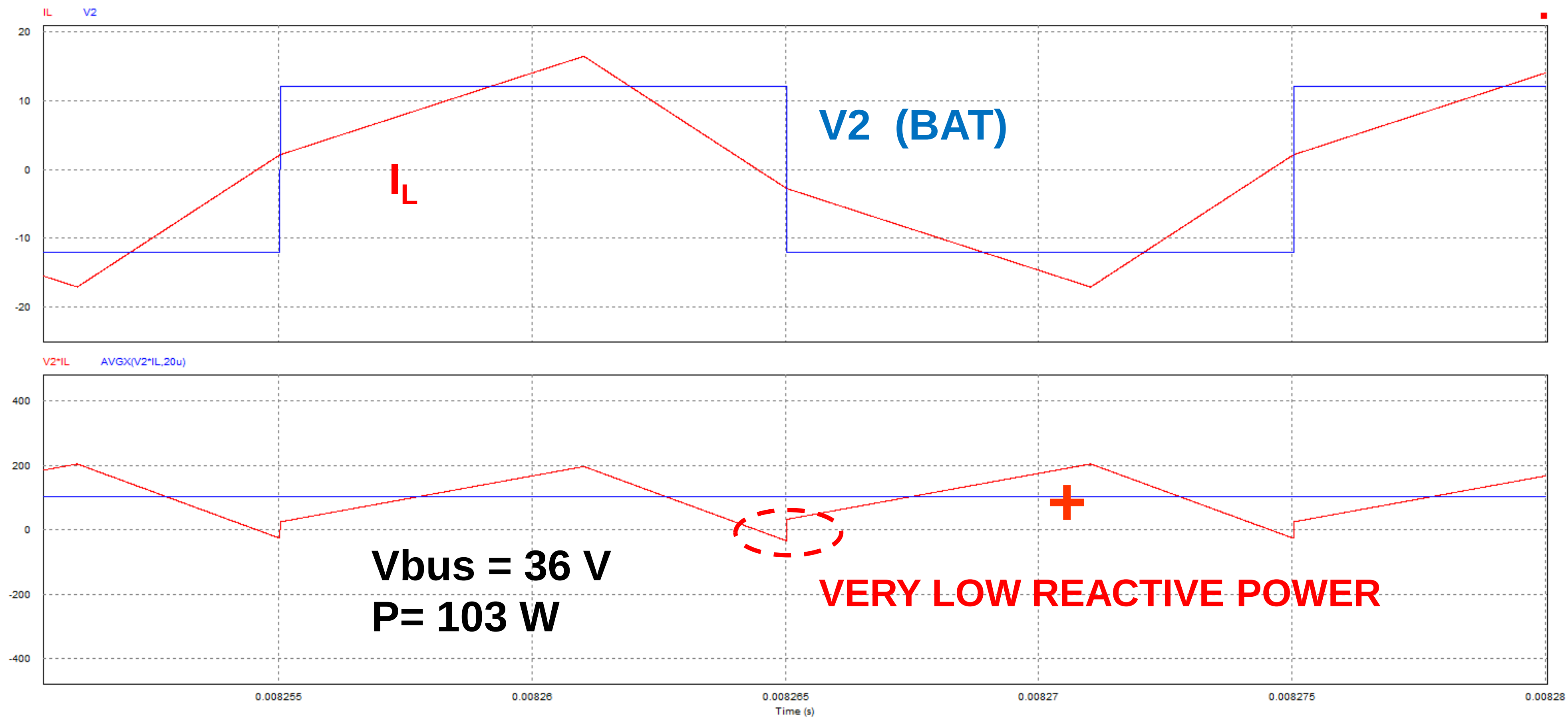
TRAFO 1:1 (LPDC)

BUS WITH MAX VOLTAGE



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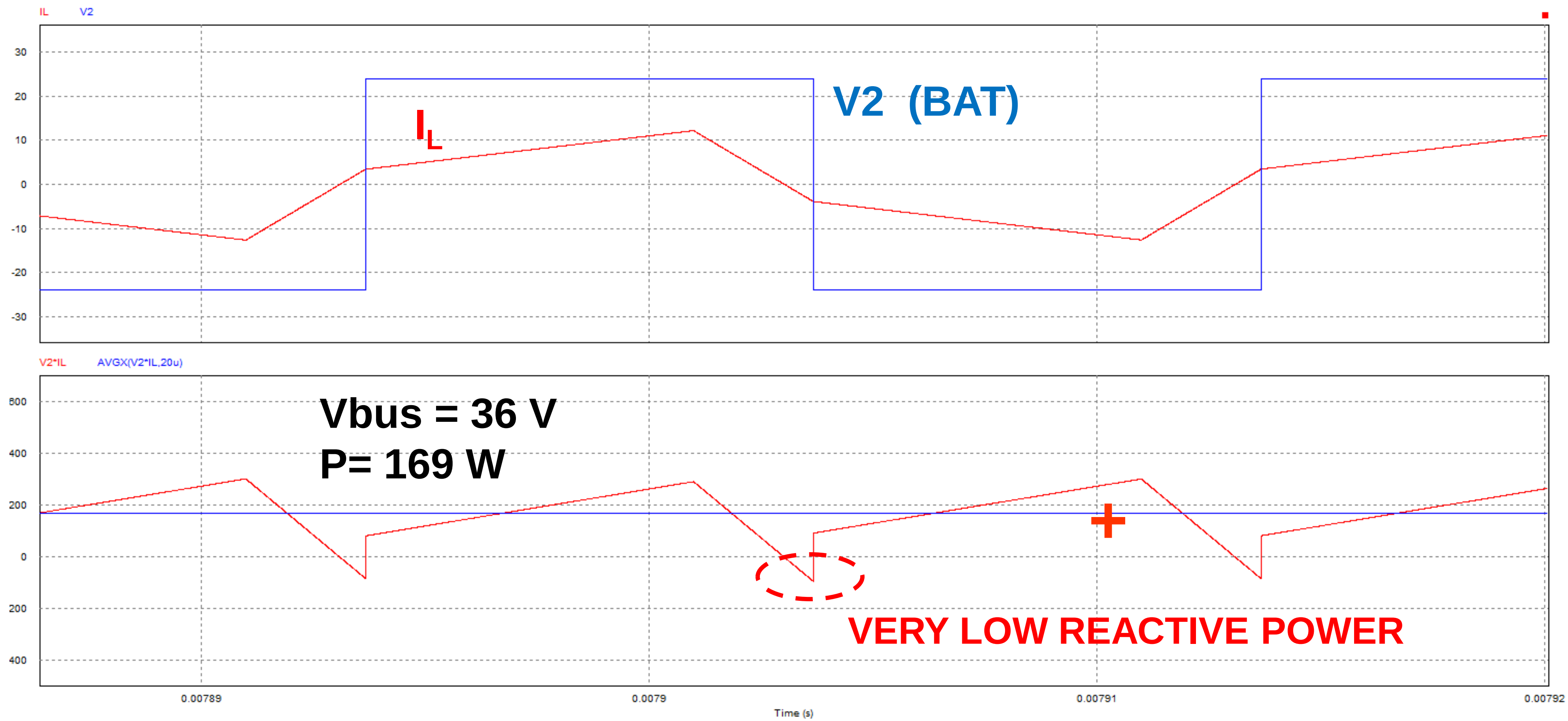
TRAFO 2:1 (CPDC)

$$n = \frac{V_{BUS\_NOM}}{V_{BAT}}$$

BUS WITH MAX VOLTAGE



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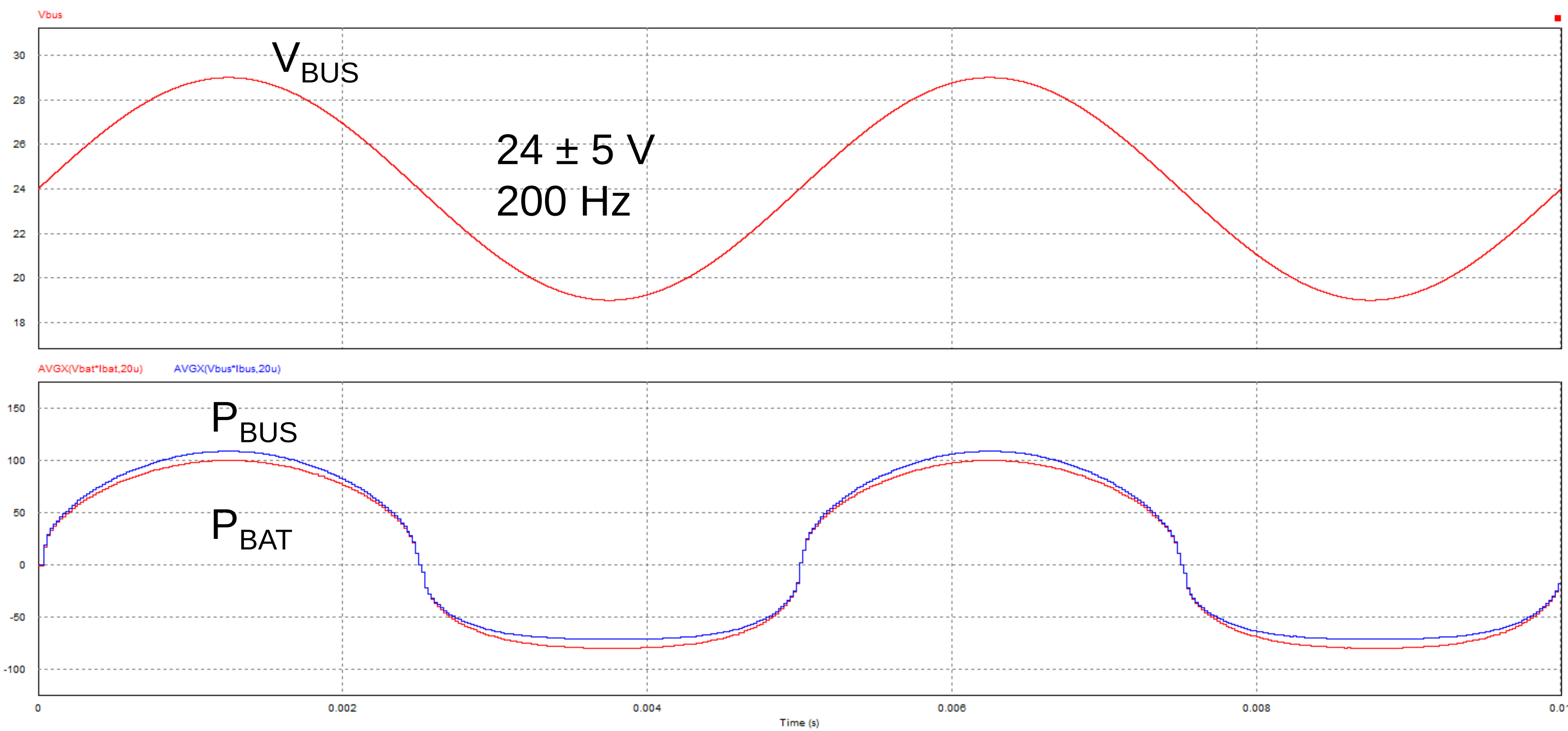
TRAFO 2:1 (CPDC)

$$n = \frac{V_{BUS\_NOM}}{V_{BAT}}$$

BUS VOLTAGE FLUCTUATION



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