FUTURE ELECTRONICS

Introduction to Three-Phase Power Factor Correction

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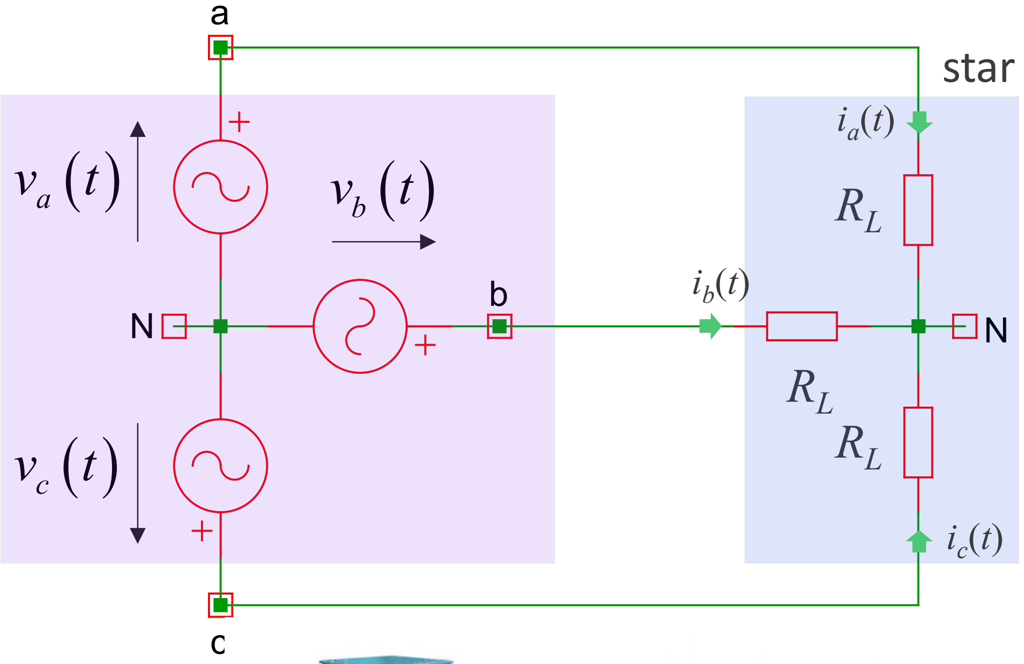
Agenda

- Tri-Phase Rectification Basics
- Single-Switch Active Power Factor Correction
- Six-Switch Implementation
- Three-Level Converters
- The Vienna Rectifier

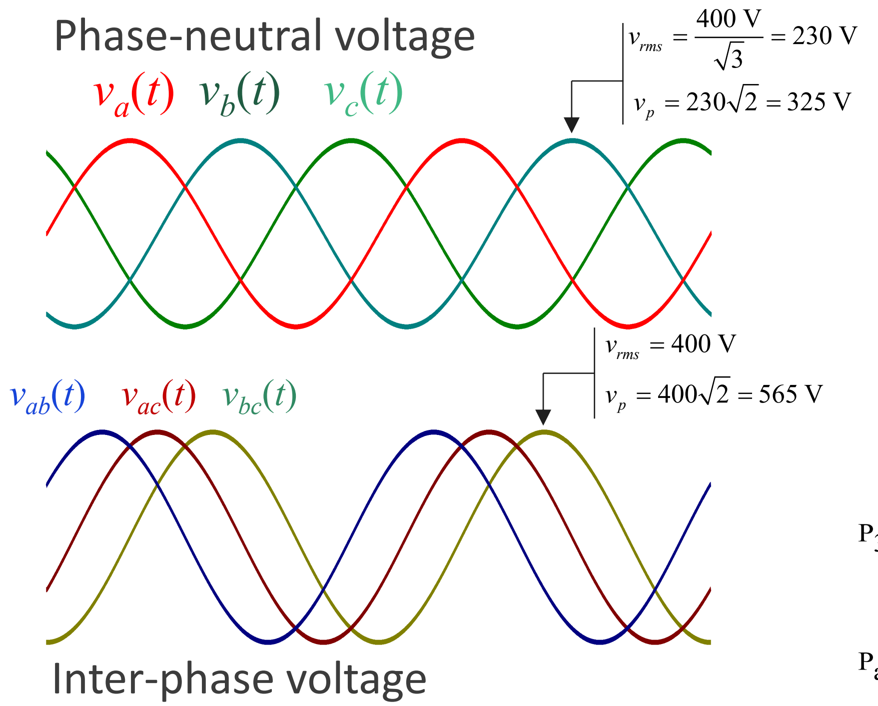
Operating Waveforms in a 3-Phase Circuit

- A power plant delivers 3 voltages out of phase by 120° and referenced to a neutral point
- For a given wire gauge, more power is conveyed in 3-phase than in 1-phase network
- In a balanced system, there is no current flowing in the neutral wire



Power plant

3-phase load



$R_L := 50\Omega$

$P_L := \frac{V_{AC}^2}{R_L} = 1.058\text{kW}$

Total power is 3 times the power per phase

$P_{3tot}(t) := \frac{v_a(t)^2}{R_L} + \frac{v_b(t)^2}{R_L} + \frac{v_c(t)^2}{R_L}$

$P_{avg} := F_{line} \cdot \int_0^{T_{line}} P_{3tot}(t)\,dt = 3.174\text{kW}$

$v_a(t) = V_{AC} \cdot \sqrt{2} \cdot \sin(\omega \cdot t + \varphi_1) \qquad \varphi_1 = 0°$

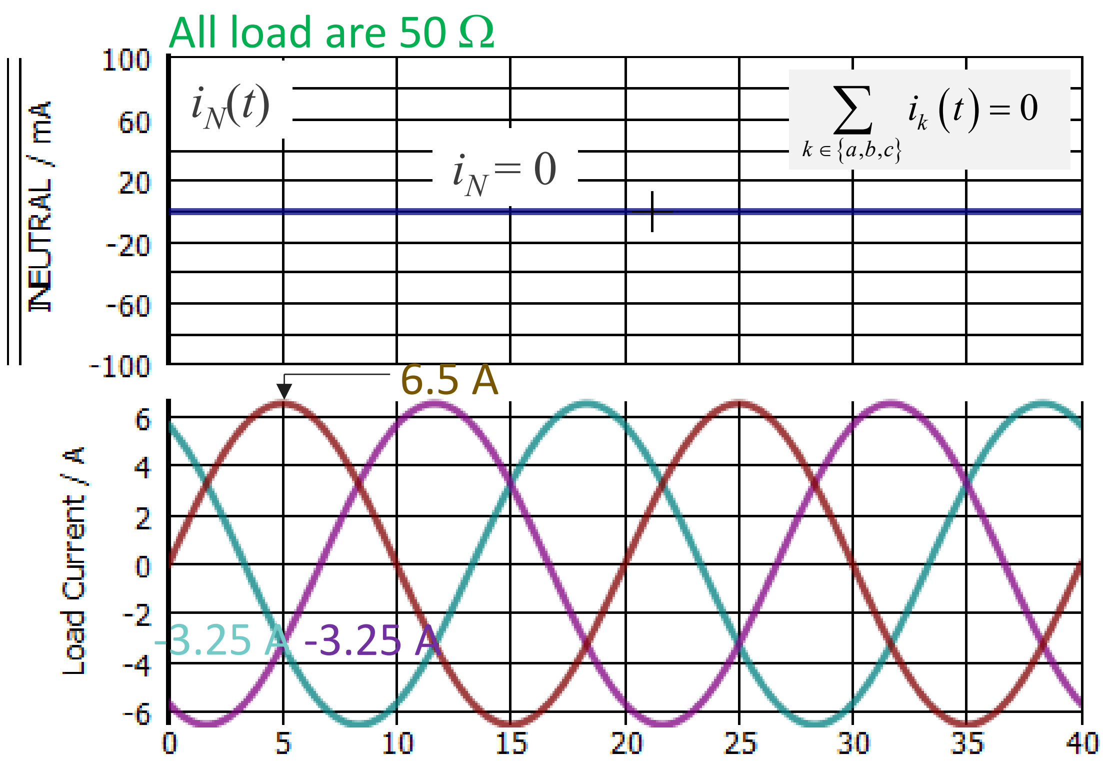
$v_b(t) = V_{AC} \cdot \sqrt{2} \cdot \sin(\omega \cdot t + \varphi_2) \qquad \varphi_2 = -120°$

$v_c(t) = V_{AC} \cdot \sqrt{2} \cdot \sin(\omega \cdot t + \varphi_3) \qquad \varphi_3 = -240°$

$$\sum_{k \in \{a,b,c\}} v_k(t) = 0 \quad \text{and} \quad \sum_{k \in \{a,b,c\}} i_k(t) = 0$$

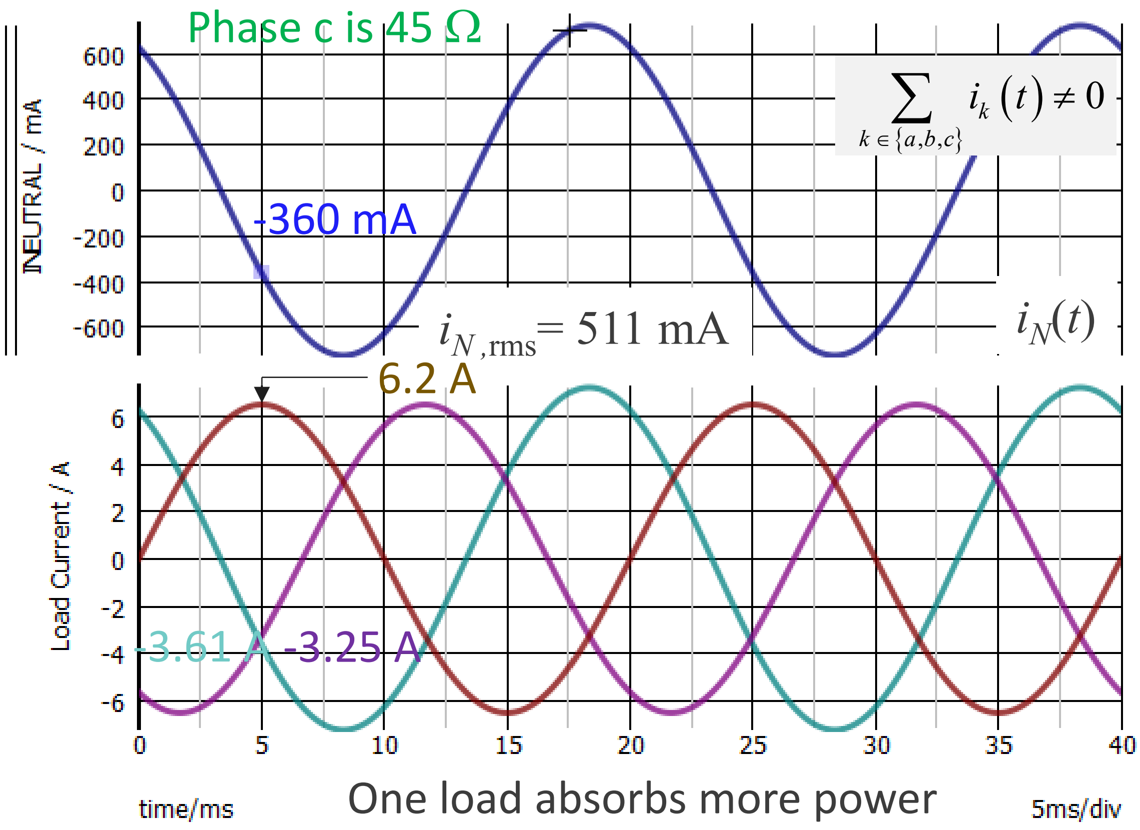
No Current in the Neutral Wire

- With perfectly-balanced loads, the current in the wire is equal to zero
- Should a load absorb different power or is nonlinear, current may flow in the neutral
- ❖ Overheating the neutral because of unbalanced consumption is a major cause of hazard



All loads absorb the same power

6.5 + (-3.25) + (-3.25) = 0 A

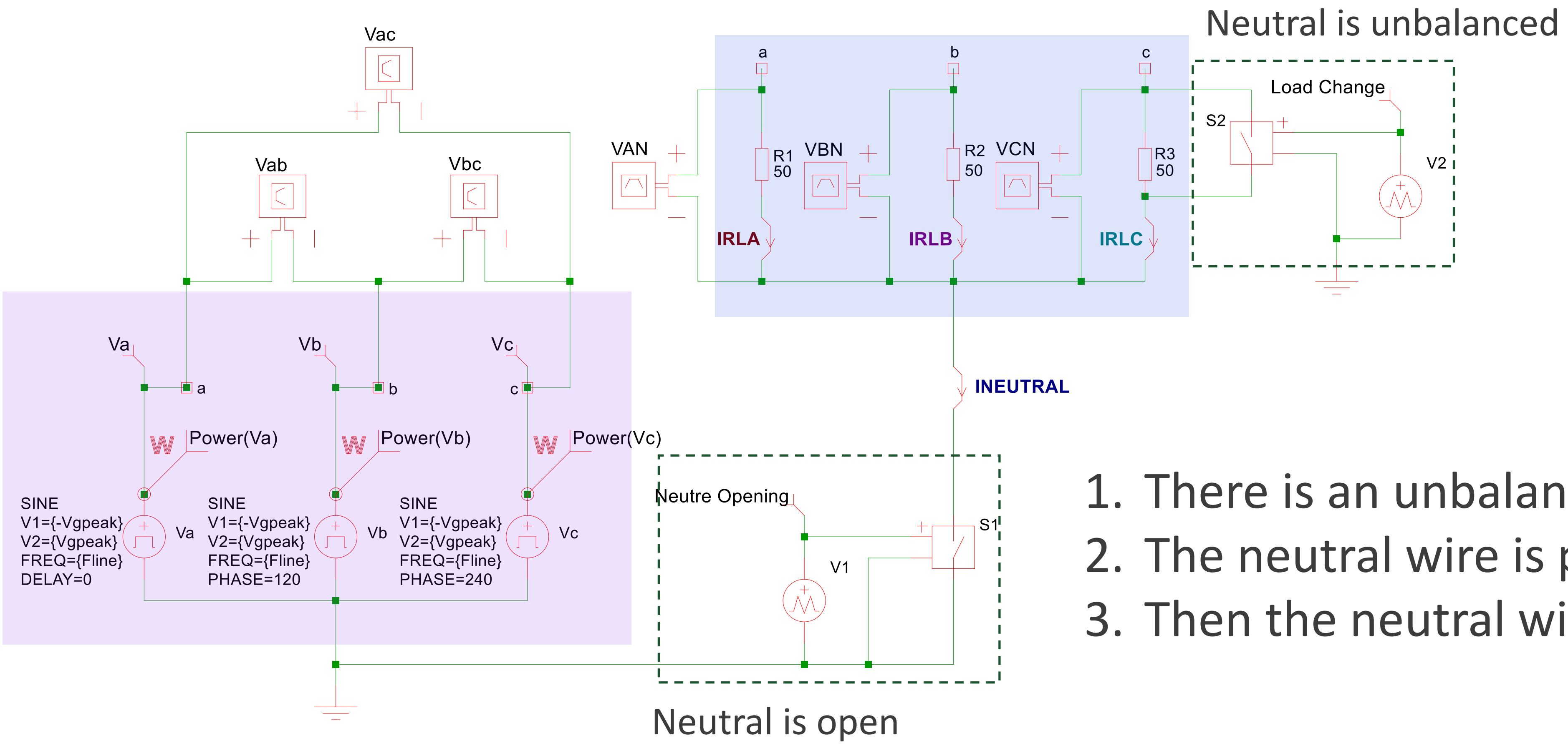


One load absorbs more power

6.5 + (-3.25) + (-3.61) = -0.36 A

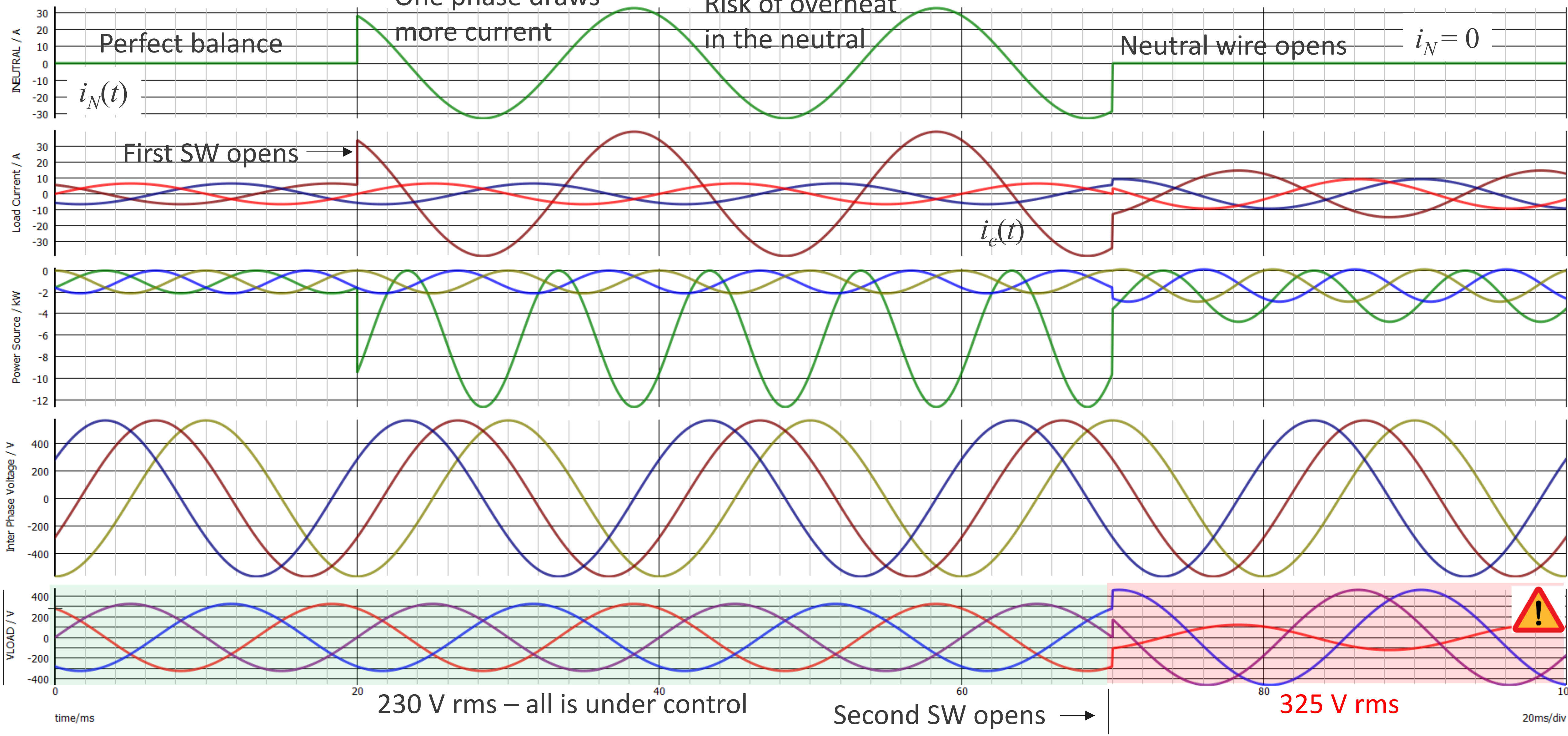
Opening the Neutral

- The neutral wire is distributed in a house for a tri- or single-phase usage
- It can be inadvertently opened during a maintenance phase by the utility company
  - The voltage between phases dangerously increases



1. There is an unbalance in one phase
2. The neutral wire is present
3. Then the neutral wire is open

Load Voltages run out of Control



When the Neutral Brakes at the Substation

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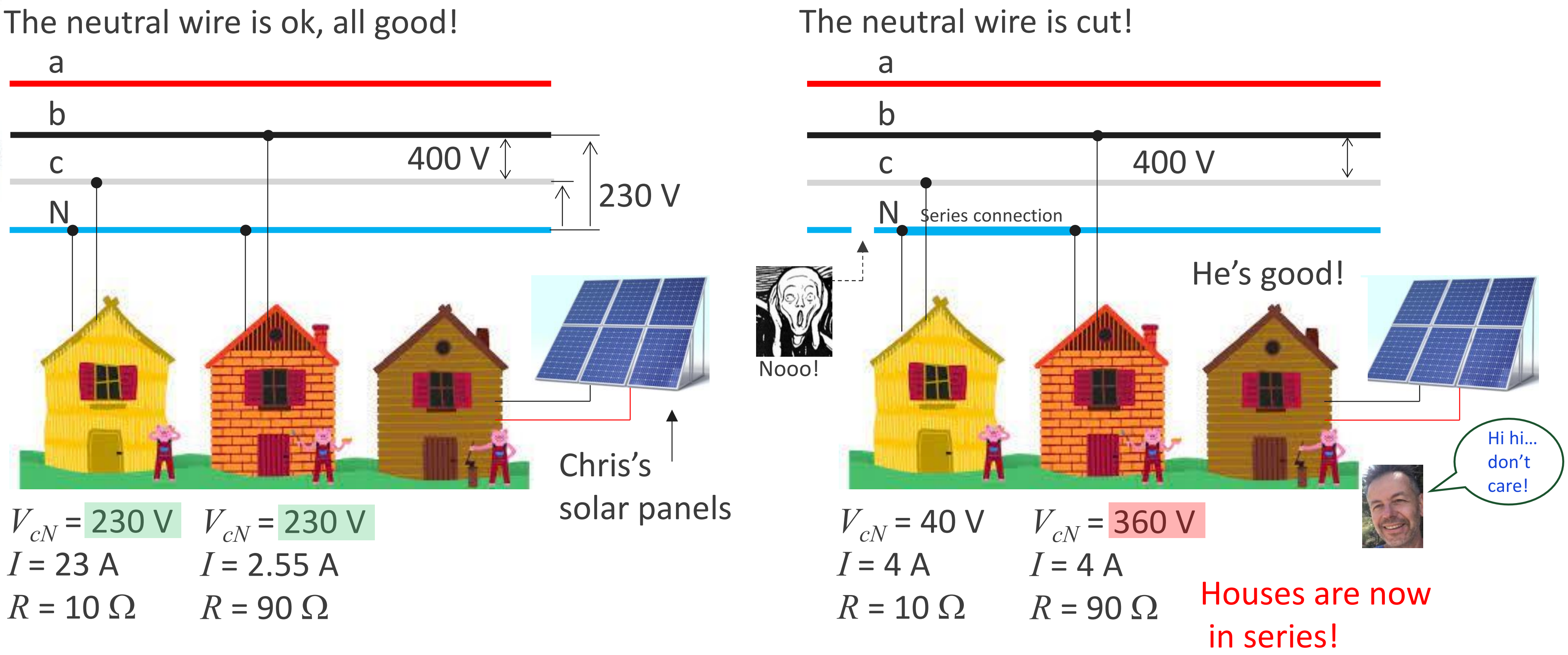
- Utility companies often power houses with single-phase distribution schemes
- Equilibrium is ensured when distributing phases in a neighborhood
- If for any reason the neutral is open at the substation, some appliances may fry!



More Power by Wire in a 3-Phase Network

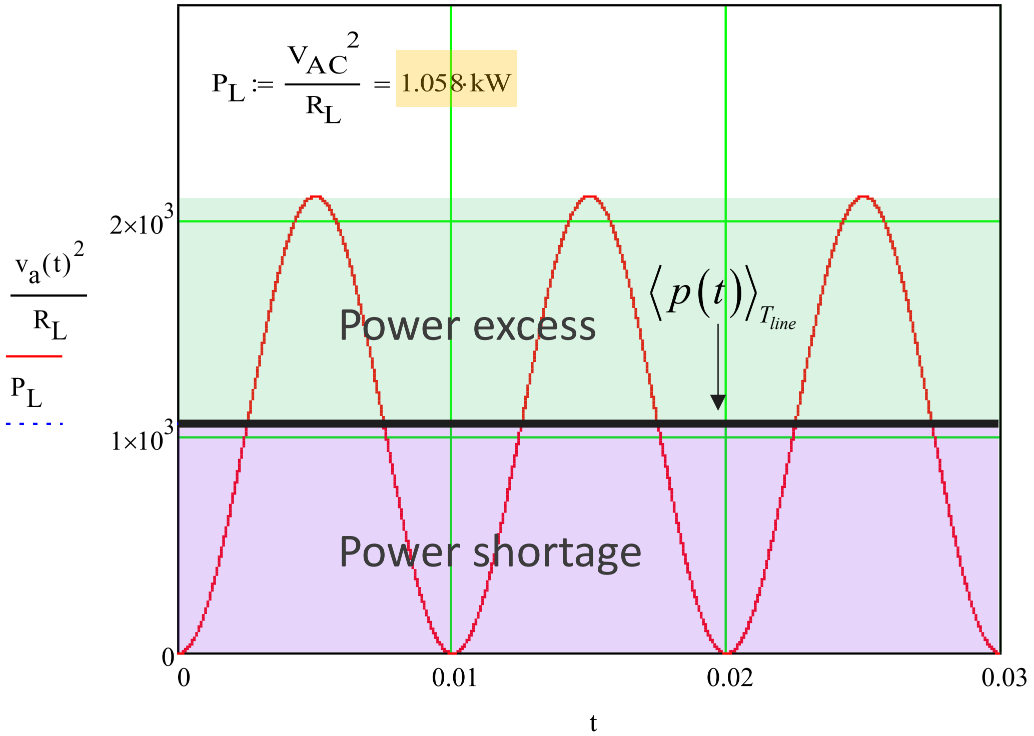
- Instantaneous power $p(t)$ fluctuates around the average value in a single-phase grid
- Average power in a 3-phase system is *constant* to 3 times the single-phase power

$$p(t) = \frac{\left[V_p \sin(\omega t)\right]^2}{R_L}$$

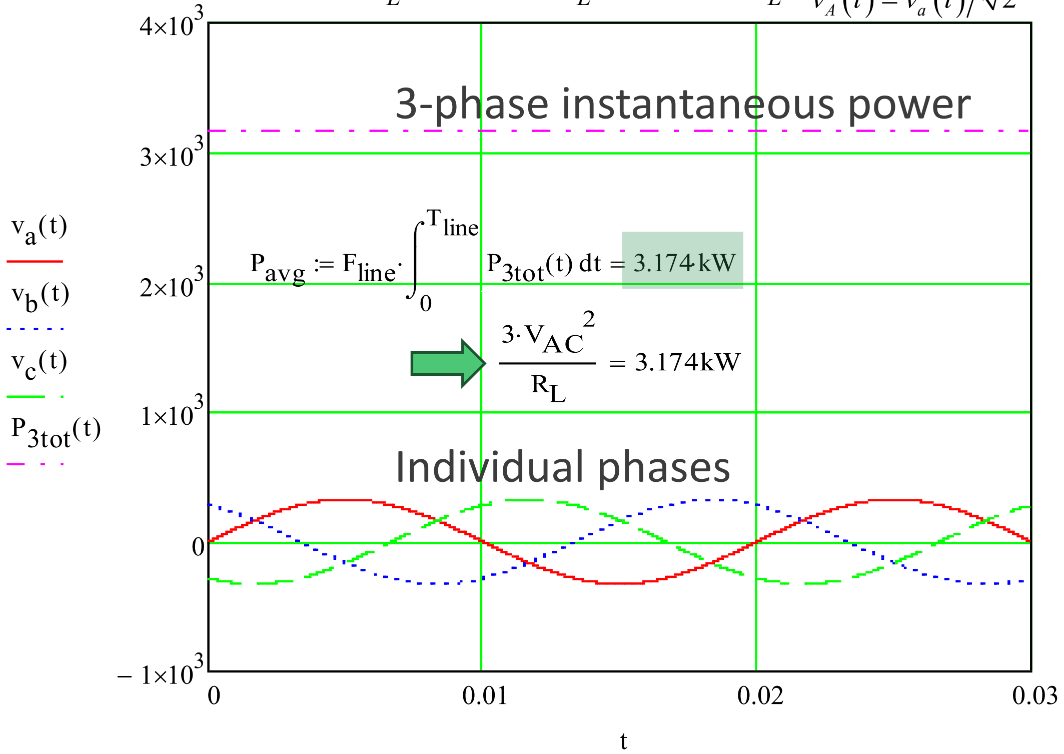
1 phase ⟵ 4.6 A rms per phase
50 m of 1.5 mm² ⟶ 3 phases

$$p(t) = \frac{\left[v_A(t)\right]^2}{R_L} + \frac{\left[v_B(t)\right]^2}{R_L} + \frac{\left[v_C(t)\right]^2}{R_L}$$

$v_A(t) = v_a(t)/\sqrt{2}$



Instantaneous power in a single-phase application

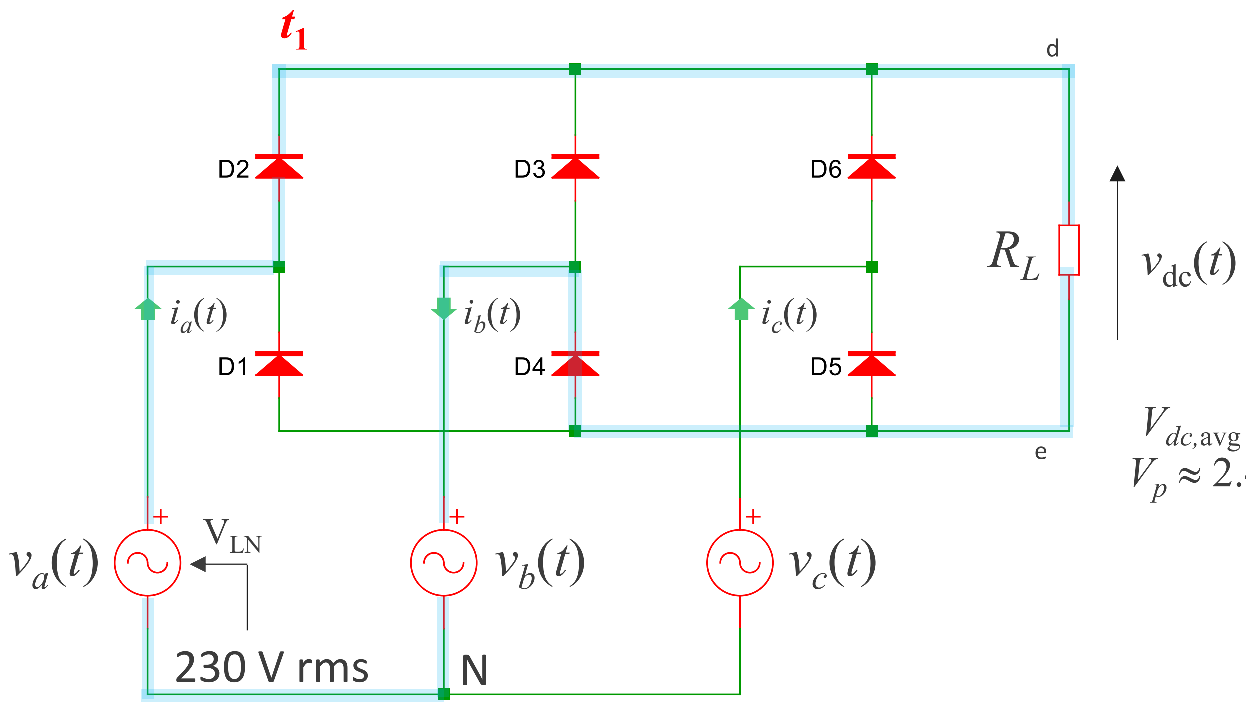


Instantaneous power in a 3-phase application

D. Balocco, Demystifying 3-Phase PFC Technology, How2Power, Feb. 2021

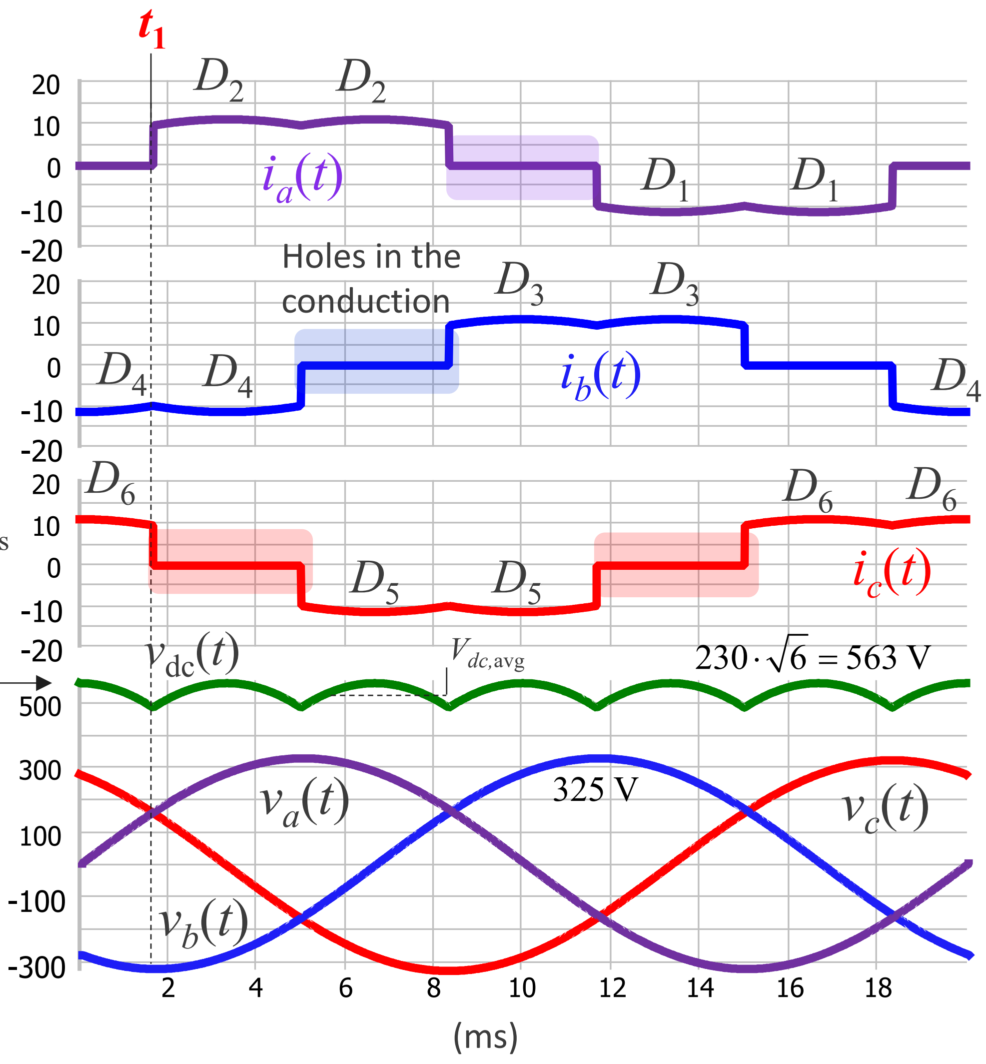
Rectification with a 3-Phase Diodes Bridge – I

- The most positive voltage source takes the lead
- ✓ The current returns by the most negative source



$V_{dc,avg} \approx 2.34 \cdot V_{LN,rms}$

$V_p \approx 2.45 \cdot V_{LN,rms}$



$V_{pp} \approx 75$ V

$V_{dc,avg} = 538$ V

$V_p = 563$ V

F = 300 Hz

$$v_a(t) = V_p \sin(\omega t)$$

$$v_b(t) = V_p \sin\left(\omega t + \frac{2\pi}{3}\right)$$

$$v_c(t) = V_p \sin\left(\omega t - \frac{2\pi}{3}\right)$$

t_1 event:

v_a is the most positive

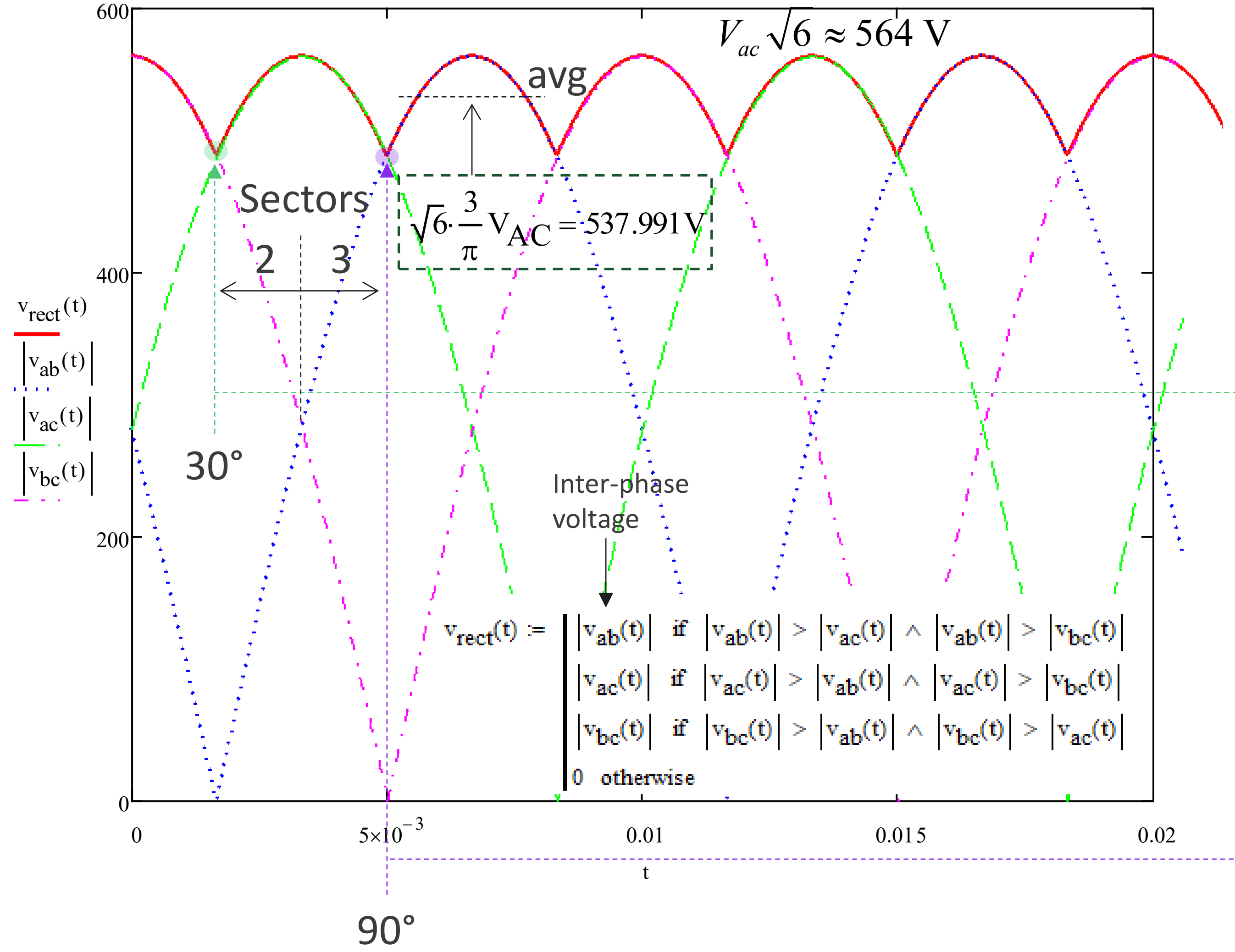
v_b is the most negative

v_c is the least positive/negative

Katherine Kim, 3-Phase Full-Wave Rectifier Operation, YouTube, katkimshow channel

Rectification with a 3-Phase Diodes Bridge – II

- Plotting the absolute value of the inter-phase voltage leads to the rectified voltage



$$V_{AC}\cdot\sqrt{2}\cdot\sin(\omega\cdot t_1) = V_{AC}\cdot\sqrt{2}\cdot\sin\left(\omega\cdot t_1 + \frac{2\cdot\pi}{3}\right)$$

$$\omega\cdot t_1 = \pi - \left(\omega\cdot t_1 + \frac{2\cdot\pi}{3}\right)$$ solve ---> $t_1 := \frac{\pi}{6\cdot\omega} = 1.667\cdot ms$

$$\theta_1 := \frac{t_1}{T_{line}}\cdot 360° = 30\cdot°$$ corresponding angle with respect to line frequency

$v_{ac}(t_1) = 487.904V$ $v_{bc}(t_1) = 487.904V$

$$V_{AC}\cdot\sqrt{2}\cdot\sin\left(\omega\cdot t_2 + \frac{2\cdot\pi}{3}\right) = V_{AC}\cdot\sqrt{2}\cdot\sin\left(\omega\cdot t_2 - \frac{2\cdot\pi}{3}\right)$$

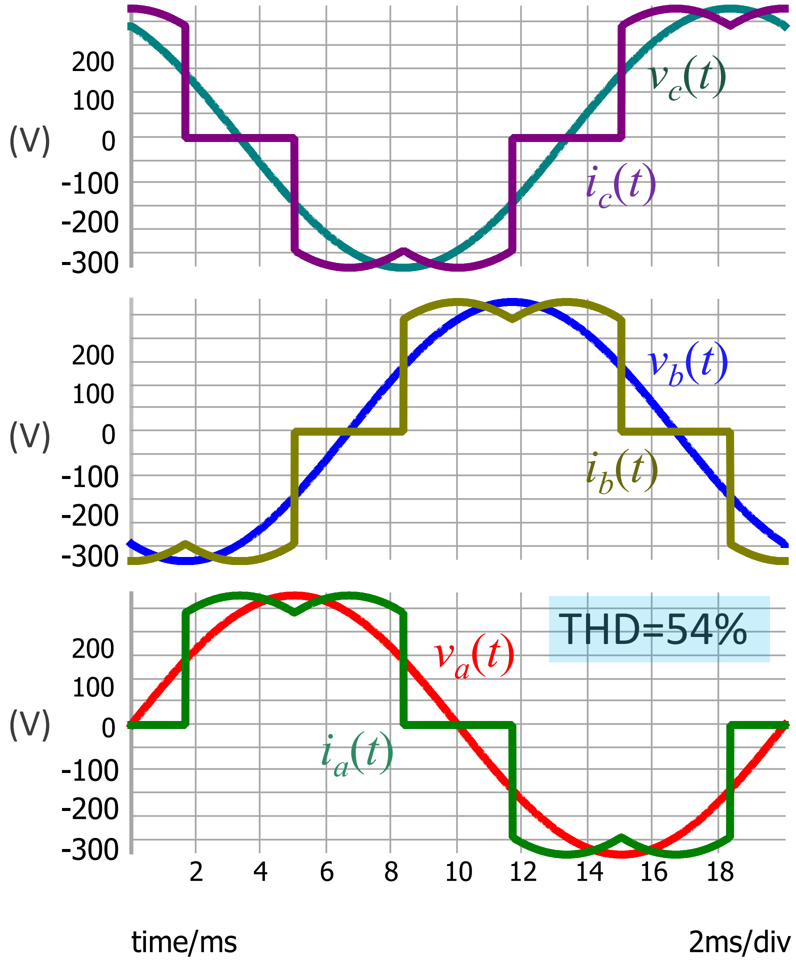
$$\omega\cdot t_2 + \frac{2\cdot\pi}{3} = \pi - \left(\omega\cdot t_2 - \frac{2\cdot\pi}{3}\right)$$ solve ---> $t_2 := \frac{\pi}{2\cdot\omega} = 5\cdot ms$

$$\theta_2 := \frac{t_2}{T_{line}}\cdot 360° = 90\cdot°$$ corresponding angle with respect to line frequency

$v_{ab}(t_2) = 487.904V$ $v_{ac}(t_2) = 487.904V$

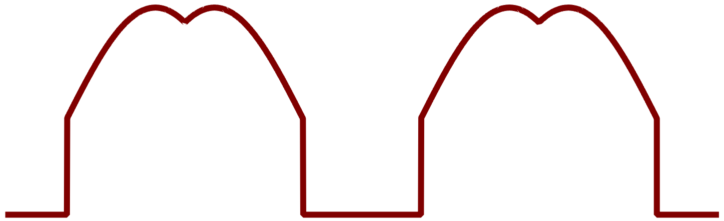
Power Factor of the 3-Phase Rectifier – No Bulk Cap.

- The total power of a 3-phase system is the sum of the three power sources
- The power factor is obtained by computing the total apparent and active powers



$$S_{tot} = \sum_{k\{a,b,c\}} V_{k,rms} I_{k,rms} \quad [\mathrm{VA}]$$

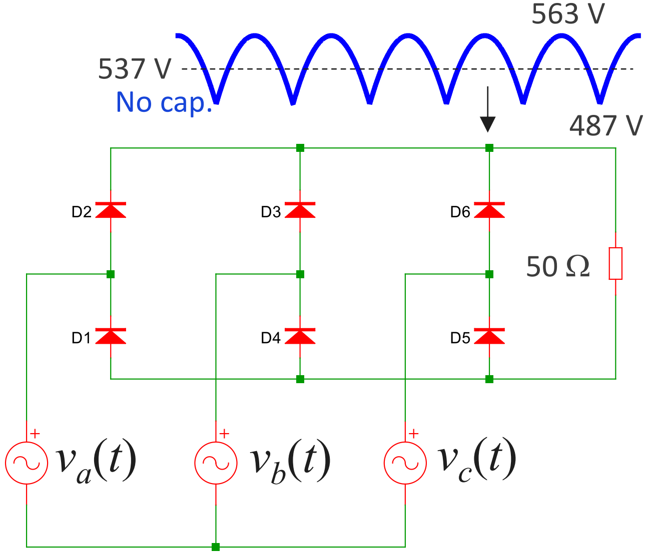
$$S_{tot} = 2.02 \times 3 = 6.07\ \mathrm{kVA}$$



$$p_k(t) = v_k(t)\, i_k(t)$$

$$P_{tot} = \sum_{k\{a,b,c\}} \left\langle v_k(t)\, i_k(t) \right\rangle_{T_{line}} \quad [\mathrm{W}]$$

$$P_{tot} = 1.94 \times 3 = 5.82\ \mathrm{kW}$$

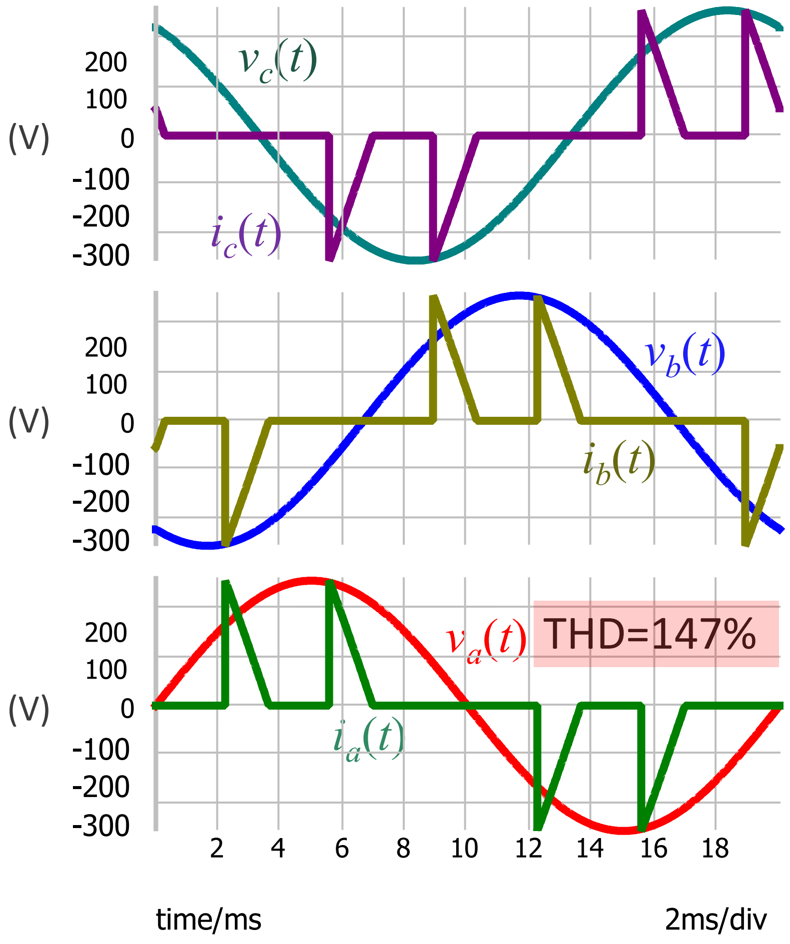


- Input sources are 230 V rms
- Load resistance is 50 Ω
- No output capacitance
- V_{dc} = 537 V, V_{pp} = 75 V

$$PF = \frac{P_{tot}}{S_{tot}} = \frac{5.82k}{6.07k} = 0.958$$

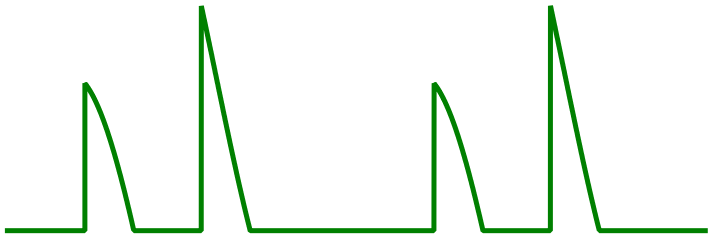
Power Factor of the 3-Phase Rectifier – Bulk Cap.

- An *oversized* 680-µF bulk capacitor is installed to smooth the output ripple
- The total harmonic distortion increases to a very large value



$$S_{tot} = \sum_{k\{a,b,c\}} V_{k,rms} I_{k,rms} \quad [\mathrm{VA}]$$

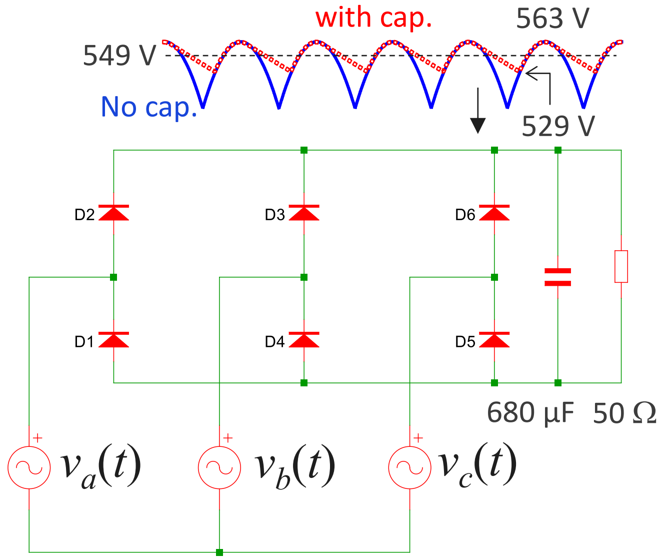
$$S_{tot} = (230 \times 15.95) \times 3 = 11\,\mathrm{kVA}$$



$$p_a(t) = v_a(t) i_a(t)$$

$$P_{tot} = \sum_{k\{a,b,c\}} \langle v_k(t) i_k(t) \rangle_{T_{line}} \quad [\mathrm{W}]$$

$$P_{tot} = 2.015 \times 3 = 6.045\,\mathrm{kW}$$



- Input sources are 230 V rms
- Load resistance is 50 Ω
- 680-µF capacitance
- V_{dc} = 549 V, V_{pp} = 33 V

$$PF = \frac{P_{tot}}{S_{tot}} = \frac{6.045k}{11k} = 0.549$$

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- Single-Switch Active Power Factor Correction
- Six-Switch Implementation
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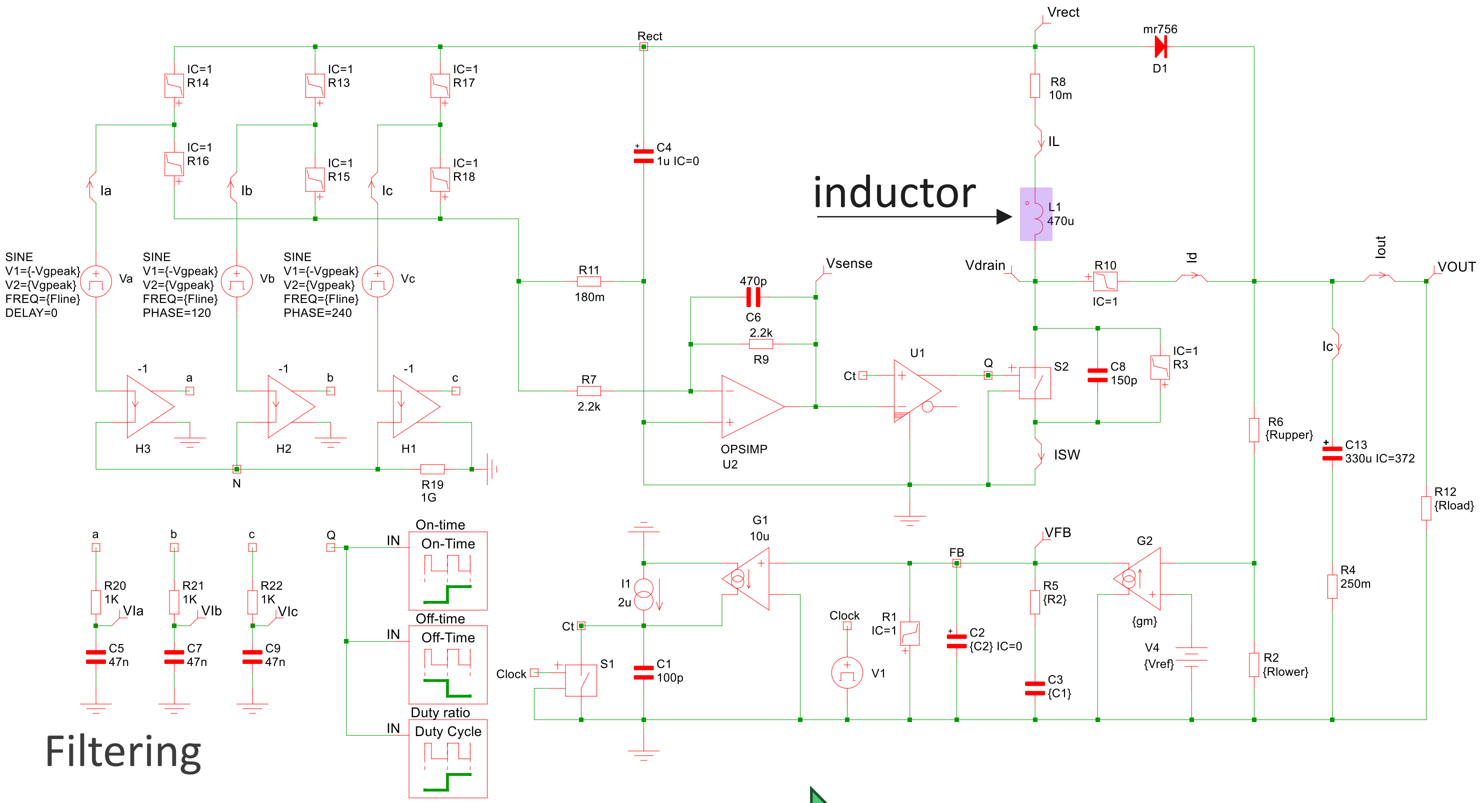
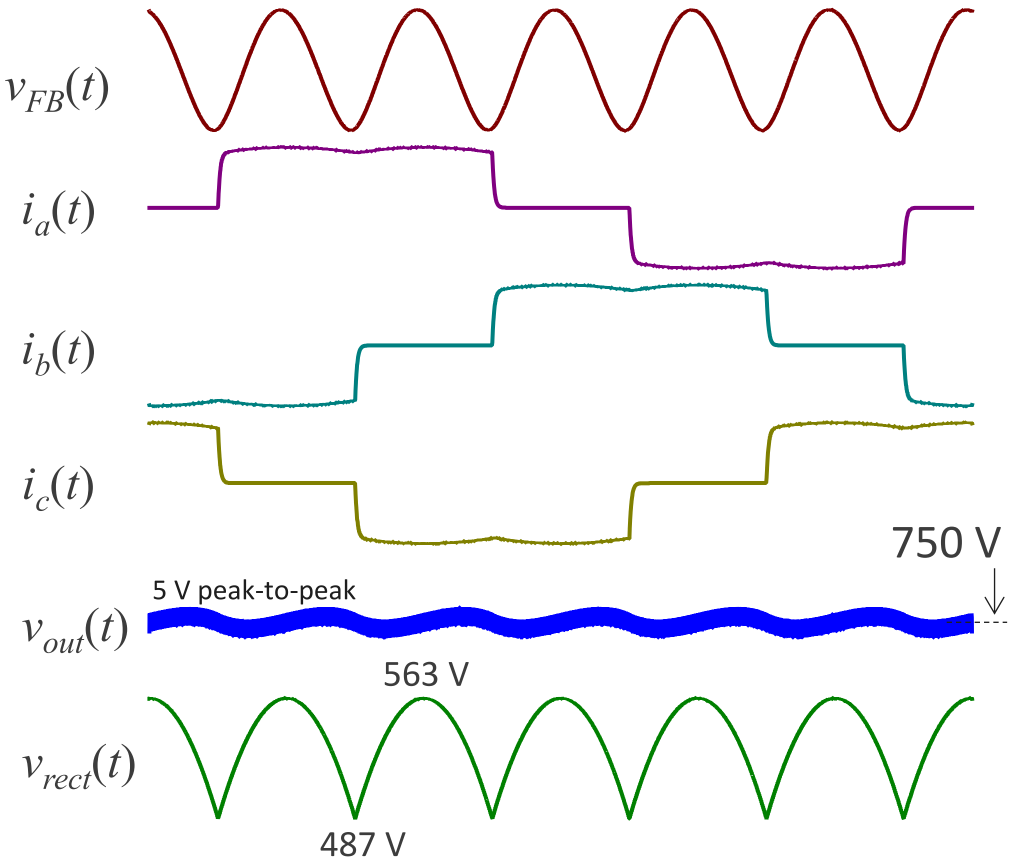
Single-Switch Active Power Factor Correction

- The classical boost structure does not lend itself for low-distortion current absorption
  - The input current is distorted considering the “hole” in input diodes conduction time
  - The high-voltage bus is typically regulated at 800 V dc for a 380/480-V ac input

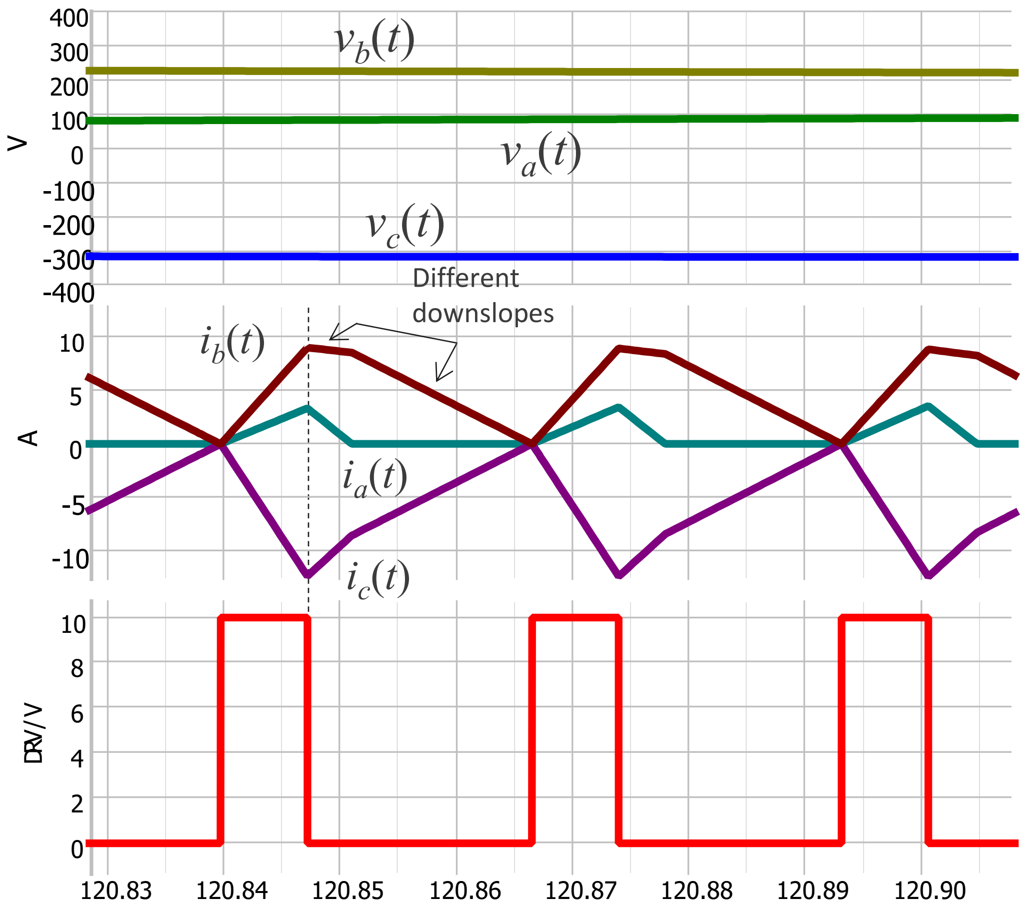


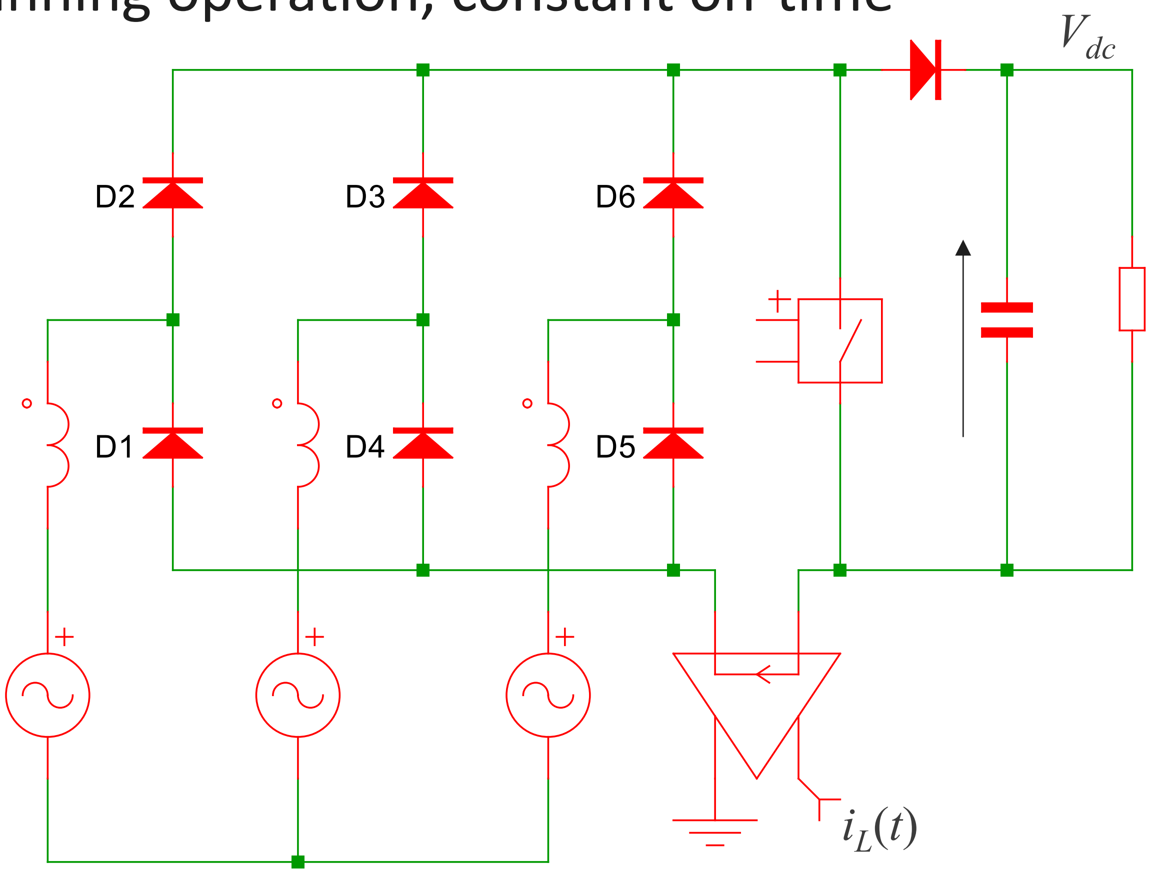
Input current THD ≈ 35%



Single-Switch Borderline Operation

- Rather than using fixed-frequency operation, the PFC operates in borderline operation
- The total inductive current is sensed, ensuring no inductor will operated in CCM
- ✓ No particular control law, classical free-running operation, constant on-time

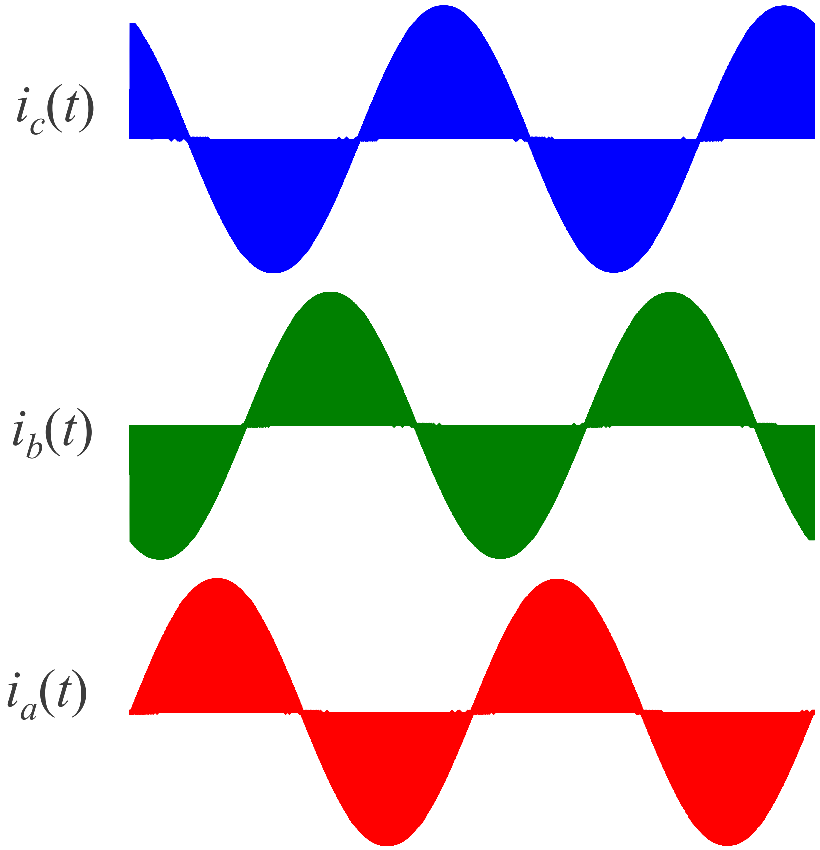




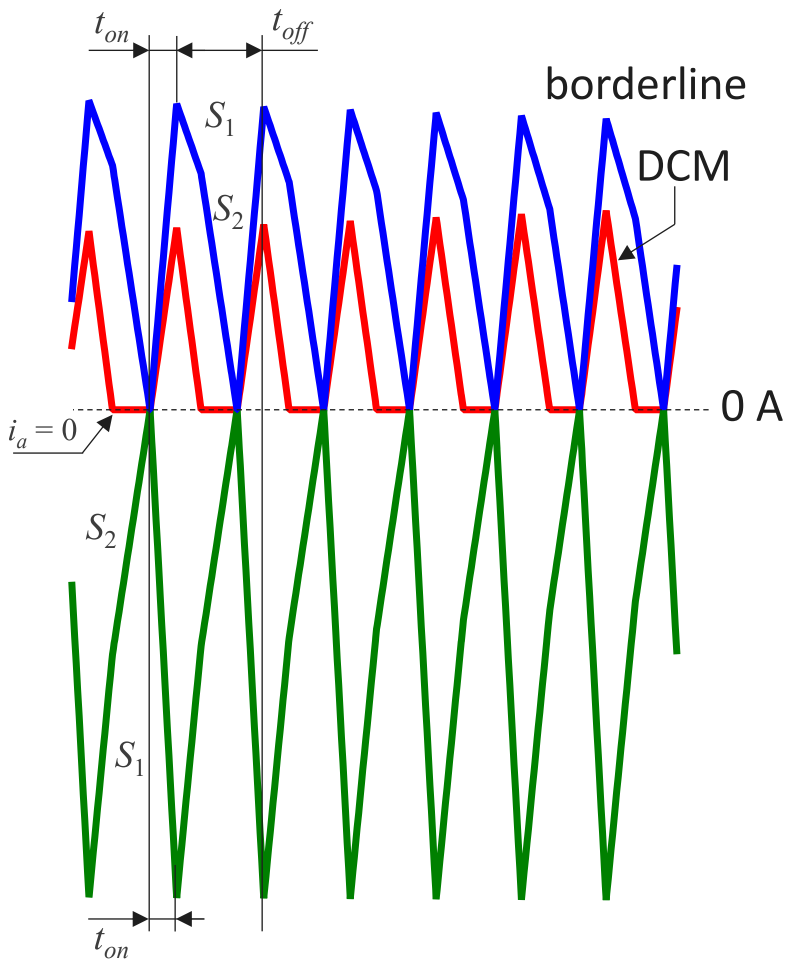
D. S. L. Simonetti, J. Sebastian and J. Uceda, [Single-switch three-phase power factor preregulator under variable switching frequency and discontinuous input current], *Proceedings of IEEE Power Electronics Specialist Conference - PESC '93*

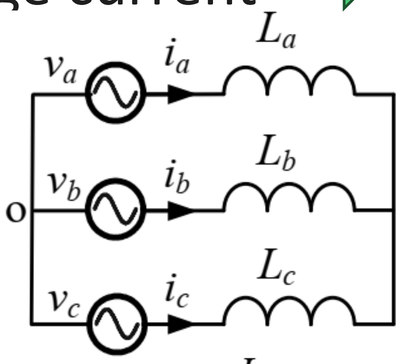
A Distorted Waveform

- The inductor currents go through different downslopes at the switch turn-off
- The input current envelope is sinusoidal but not the average current ➡ $\langle i_L(t)\rangle_{T_{sw}} \neq \frac{I_{L,peak}}{2}$

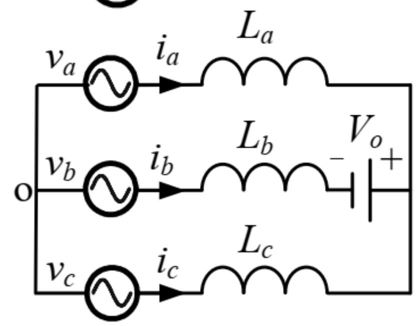


$$i_a(t)+i_b(t)+i_c(t)=0$$

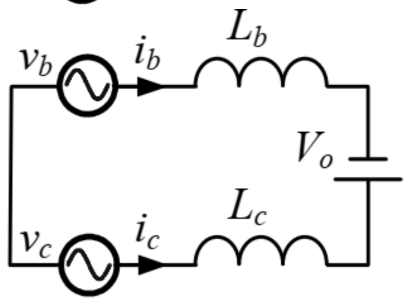




Mains switch is turned on: $S_k = \frac{V_k}{L_k}$



Mains switch is turned off, diode D_b conducts

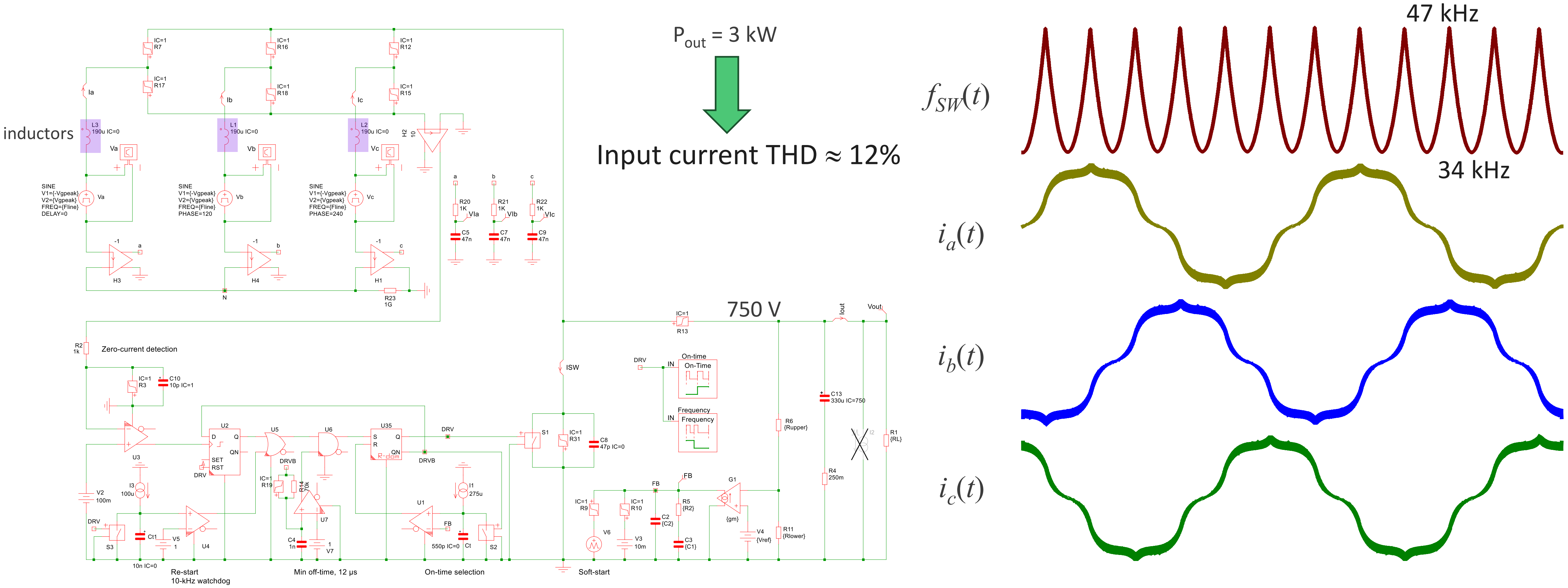


Mains switch is turned off, $i_a = 0$

K. Yao et al., *A Novel Control Scheme of Three-Phase Single-Switch Quasi-CRM Boost Rectifier*, *IEEE Transactions on Power Electronics*, vol. 32, no. 8, August 2017

Simulations of the BCM 3-Phase Single-Switch PFC

- You can implement a BCM circuit where the inductive current is always discontinuous
- ✓ No CCM operation hence lower switching losses at turn-on
- ❖ Requires a high-voltage output to minimize input current distortion



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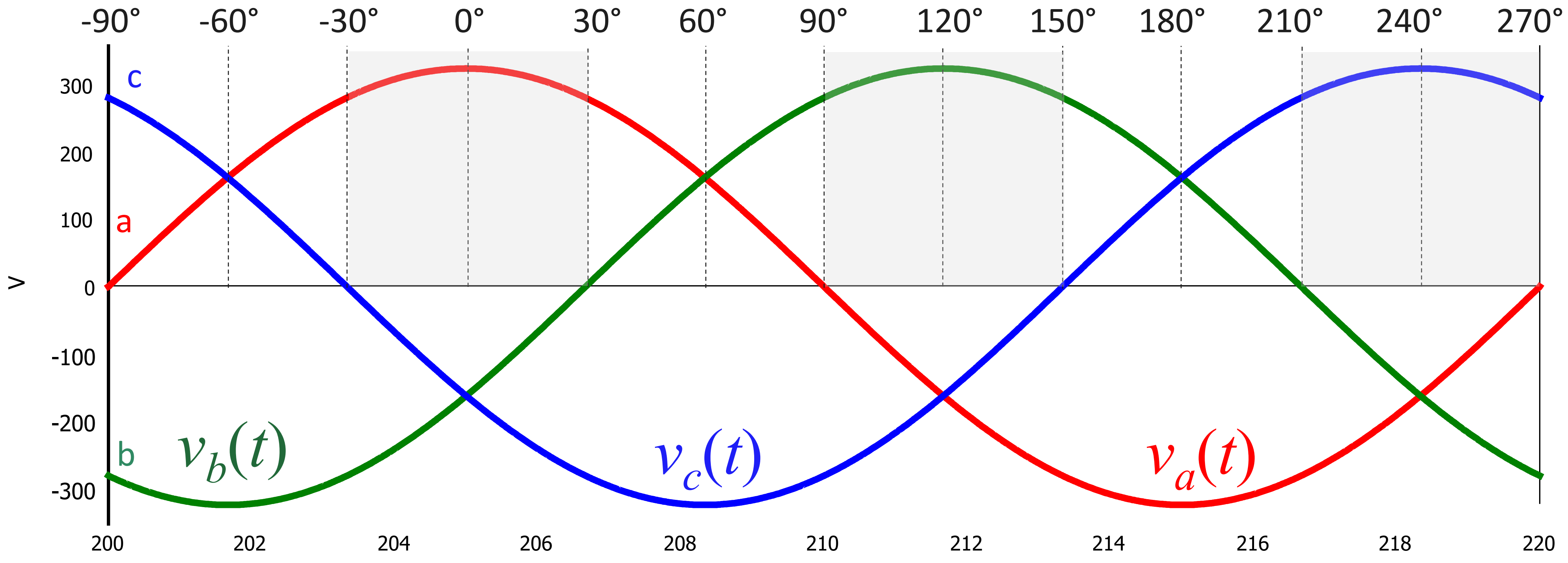
Dividing a Cycle into Sectors

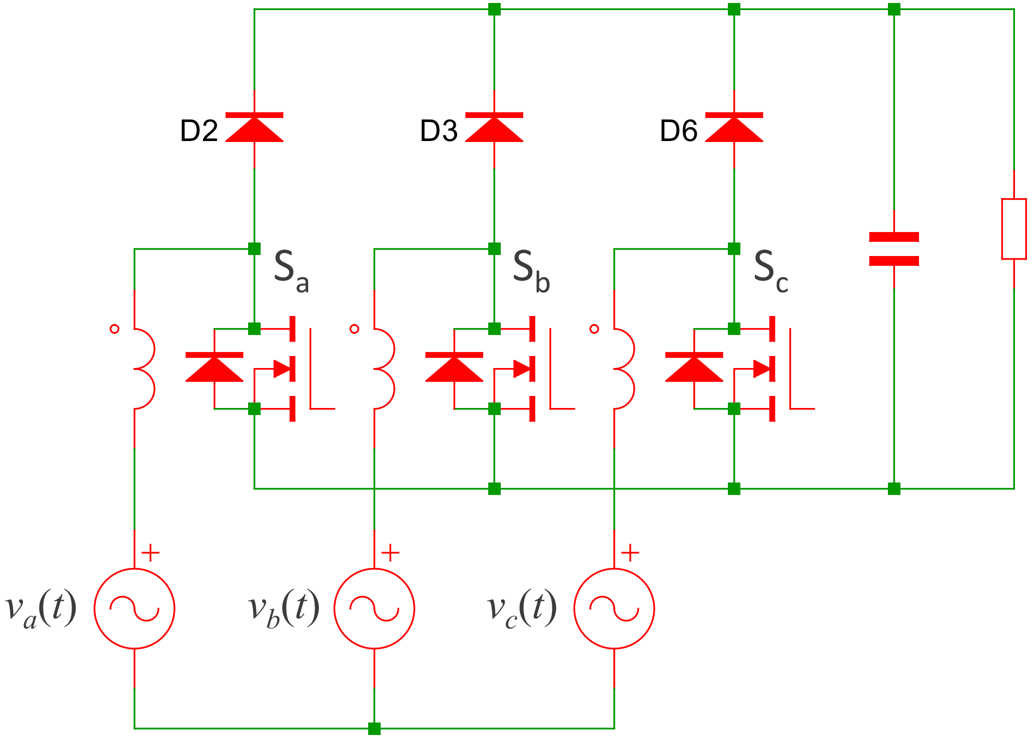
- A power factor correction algorithm needs the sinusoidal angle for proper operation
- ✓ The period is divided into 6 sectors of 60° (π/3) width with each specific phase sign

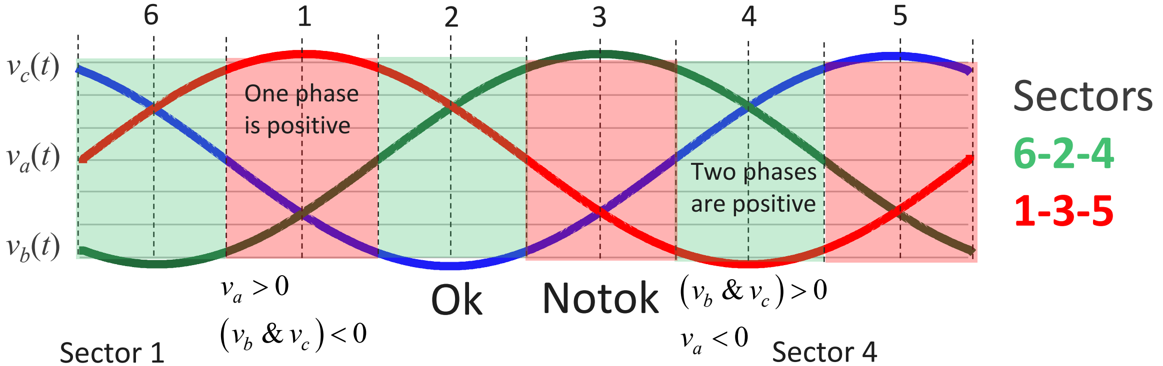


60° sectors	6	1	2	3	4	5
Phase polarity (v_a v_b v_c)	p n p	p n n	p p n	n p n	n p p	n n p

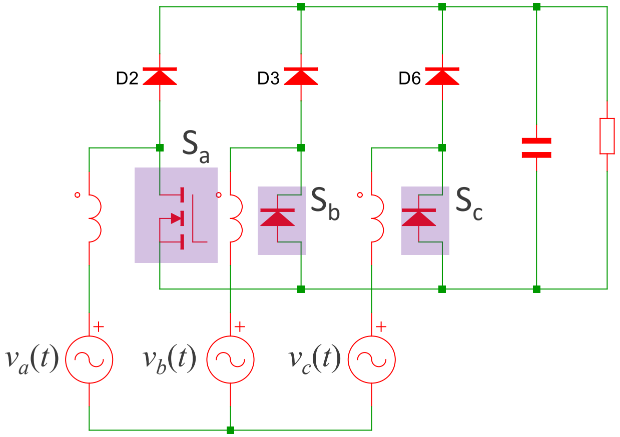
Three-Switch Power Factor Correction

- This hybrid half-controlled 3-switch PFC cannot achieve a sinusoidal input current
- ✓ You can only impress a sinusoidal shape if at least *two* phases are controlled
- The equation $i_a(t) + i_b(t) + i_c(t) = 0$ could lead to a sinusoidal input only in a few sectors

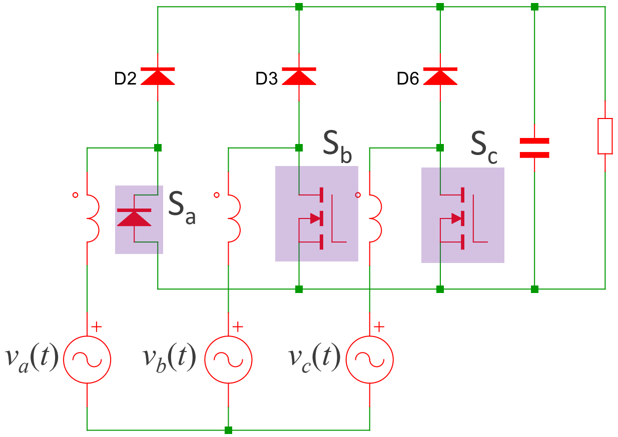




Sector 1



Sector 4



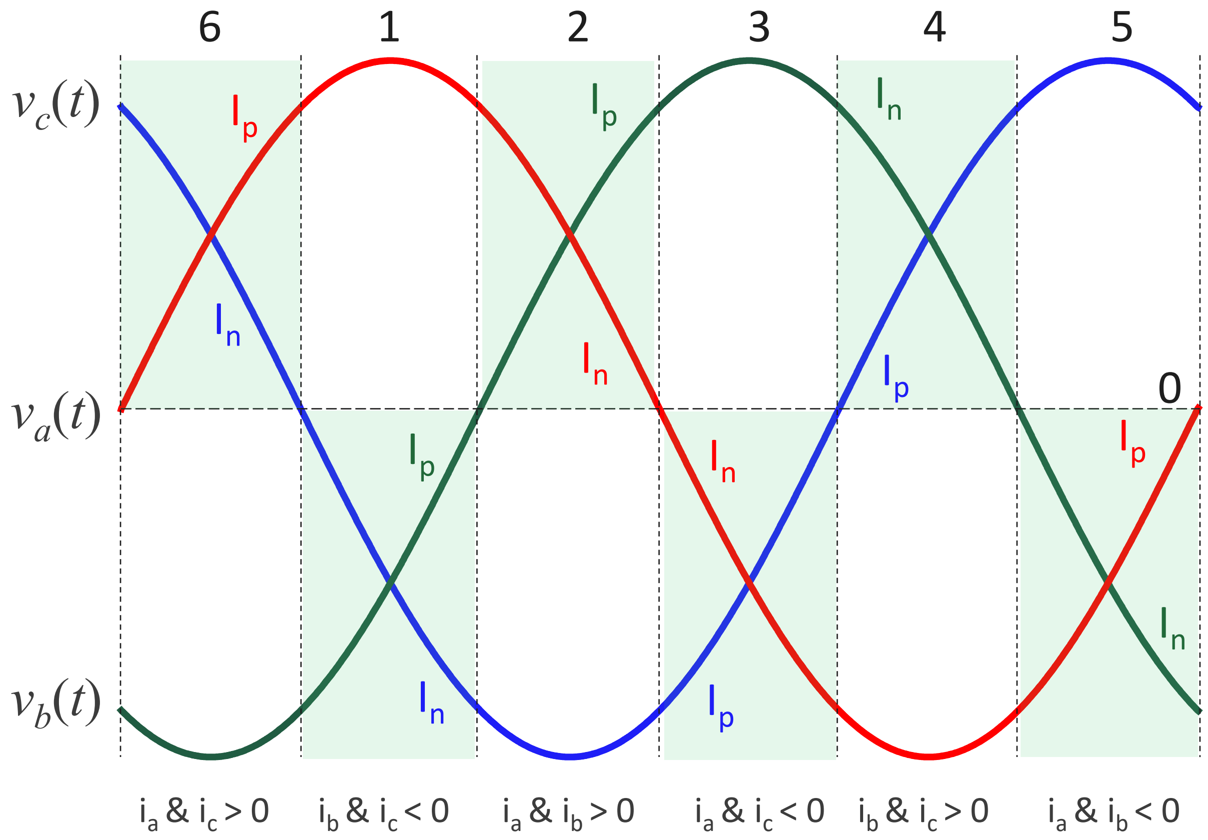
S_b and S_c switches have no effect as body diodes conduct

S_b and S_c are driven, S_a body conducts: $i_a = -(i_b + i_c)$

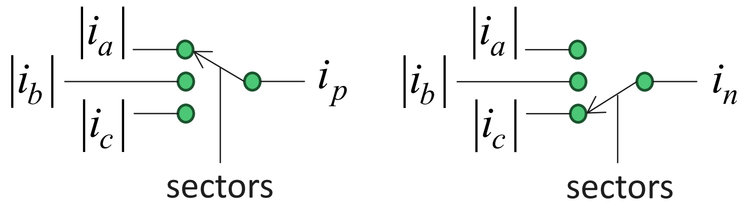
J. W. Kolar and T. Friedli, *The Essence of Three-Phase PFC Rectifier Systems—Part I*, *IEEE Transactions on Power Electronics*, vol. 28, no. 1, Jan. 2013

Six-Switch Power Factor Correction

- This is the configuration of choice for this B6 power factor correction circuit
- One-cycle control or OCC represents a possible solution for simple control
- ✓ All-analogue solution, no complicated calculations!



- ✓ Decode sectors to identify where *two* phases are positive or negative
- ✓ In the sector, identify rising or decreasing sine waves then multiplex I_p and I_n variables



Resistive input

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R_e \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Control law for 3-phase OCC

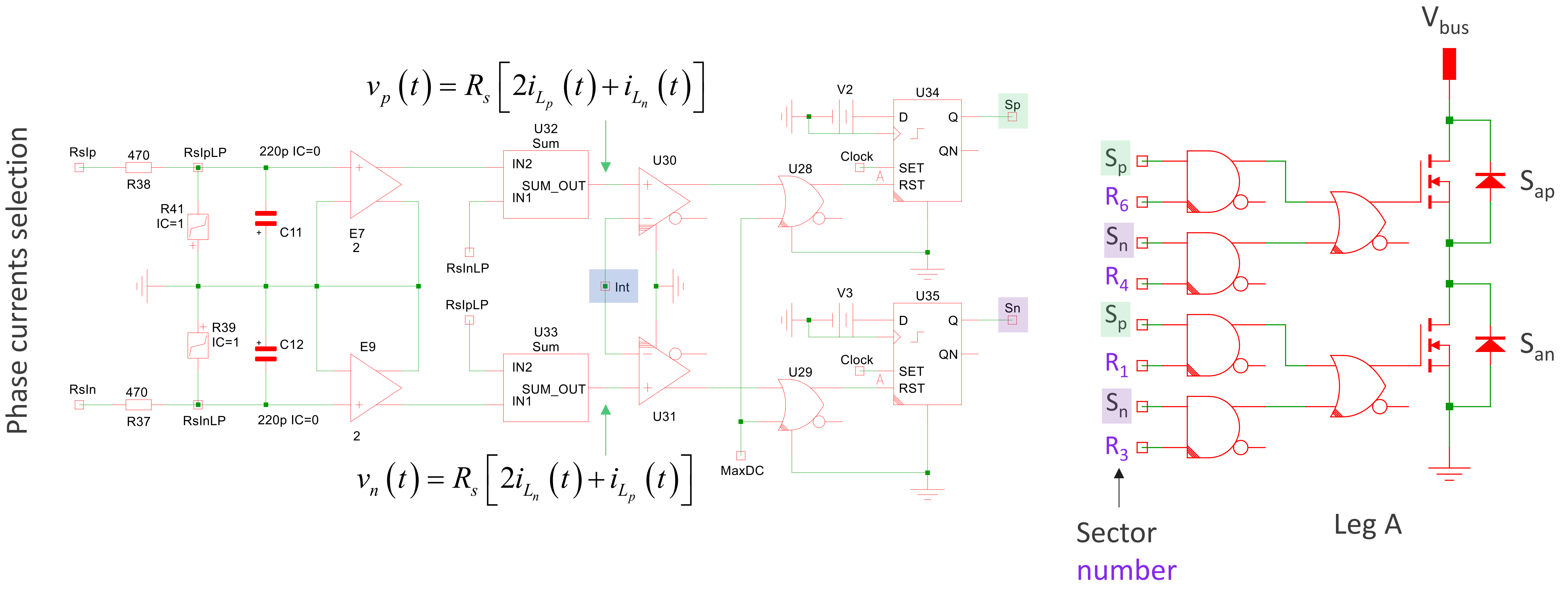
$$V_m \cdot \begin{bmatrix} 1-d_p \\ 1-d_n \end{bmatrix} = R_s \cdot \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} \langle i_{L_p}(t) \rangle \\ \langle i_{L_n}(t) \rangle \end{bmatrix}$$

↑ Error voltage

US patent 6,297,980 B1, Unified Constant-Frequency Integration Control of 3-Phase Power Correct Rectifiers, *K. Smedley, C. Qiao, 2001*

Implementing the Control Law

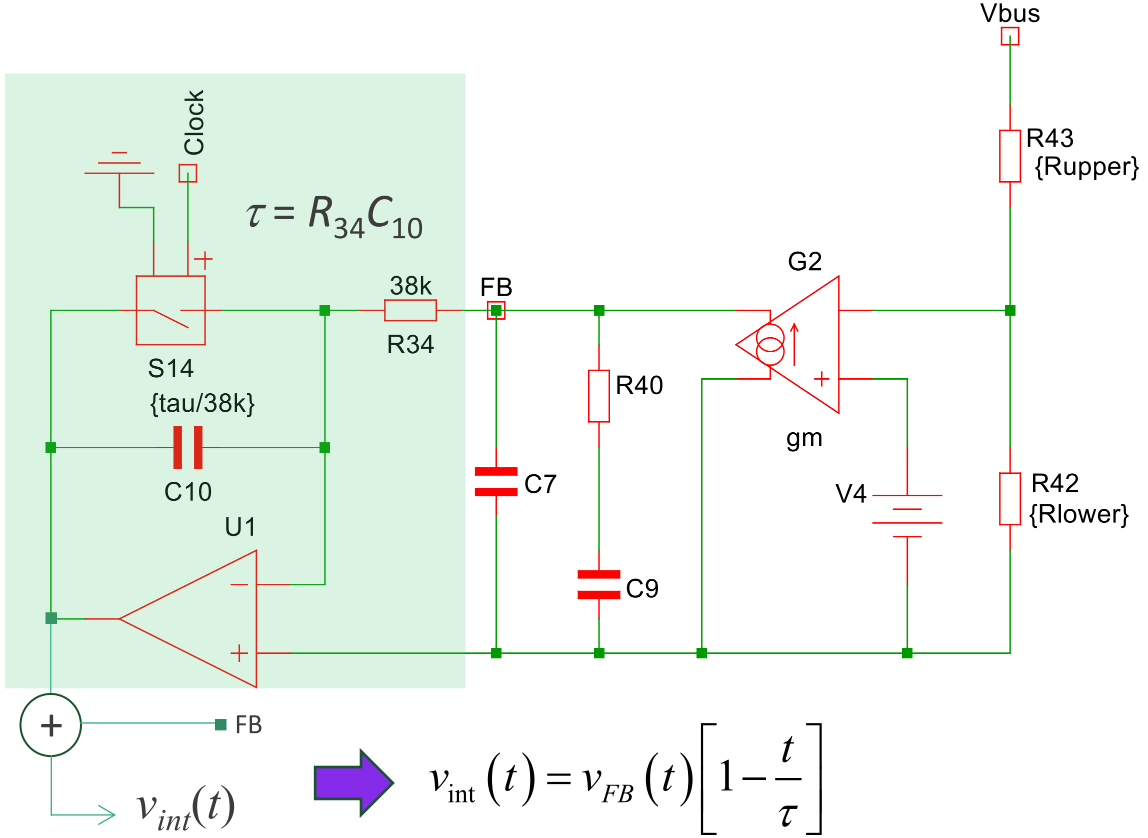
- The duty ratio is modulated by comparing a sawtooth with the current information
- Square waves S_p and S_n are generated and drive a leg depending on the active sector



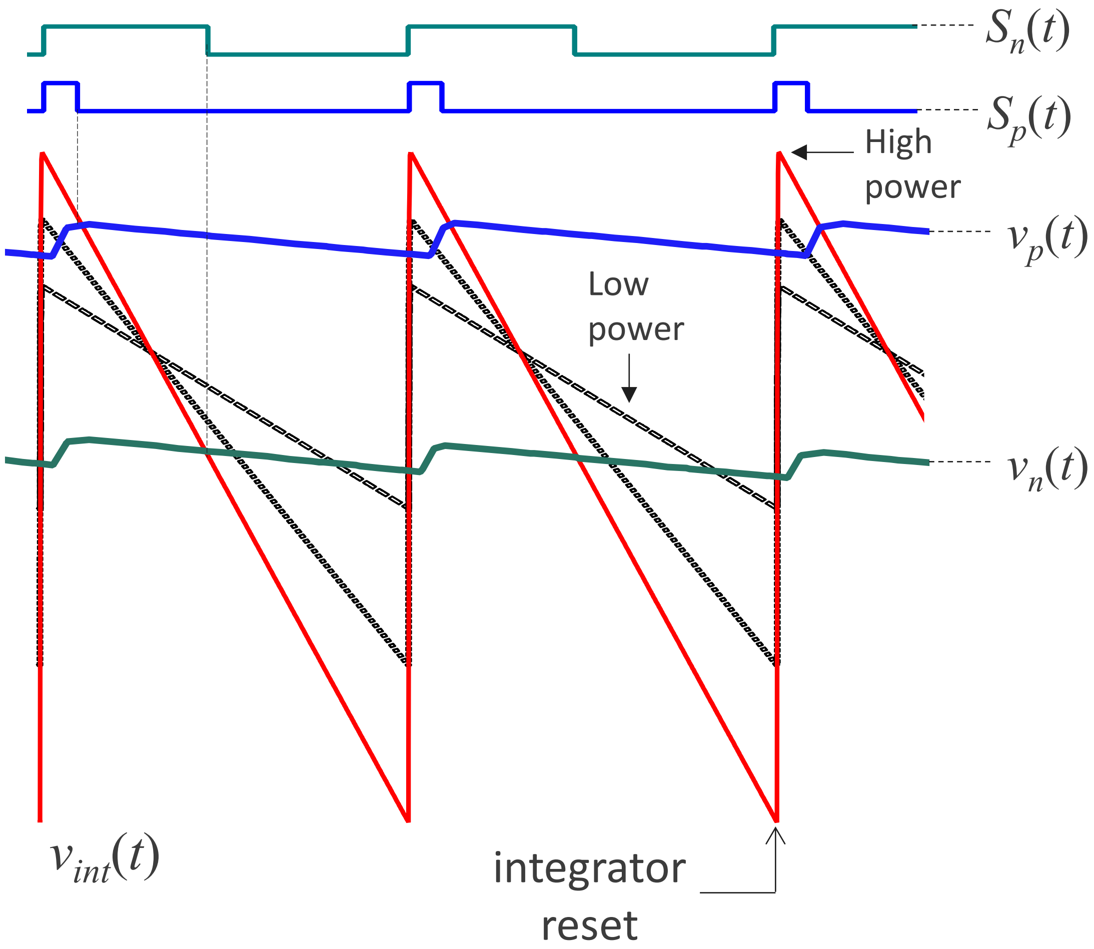
Zhen, Q. & Di, Q, Soft-Switching Technology of Three-Phase Six-Switch PFC Rectifier, *Energies* **2020**, *13*, 5130.

An Analogue Integrator

- The duty ratio is modulated by comparing a sawtooth with the current information
- Square waves S_p and S_n are generated and drive a leg depending on the active sector



$$v_{\text{int}}(t) = v_{FB}(t)\left[1 - \frac{t}{\tau}\right]$$

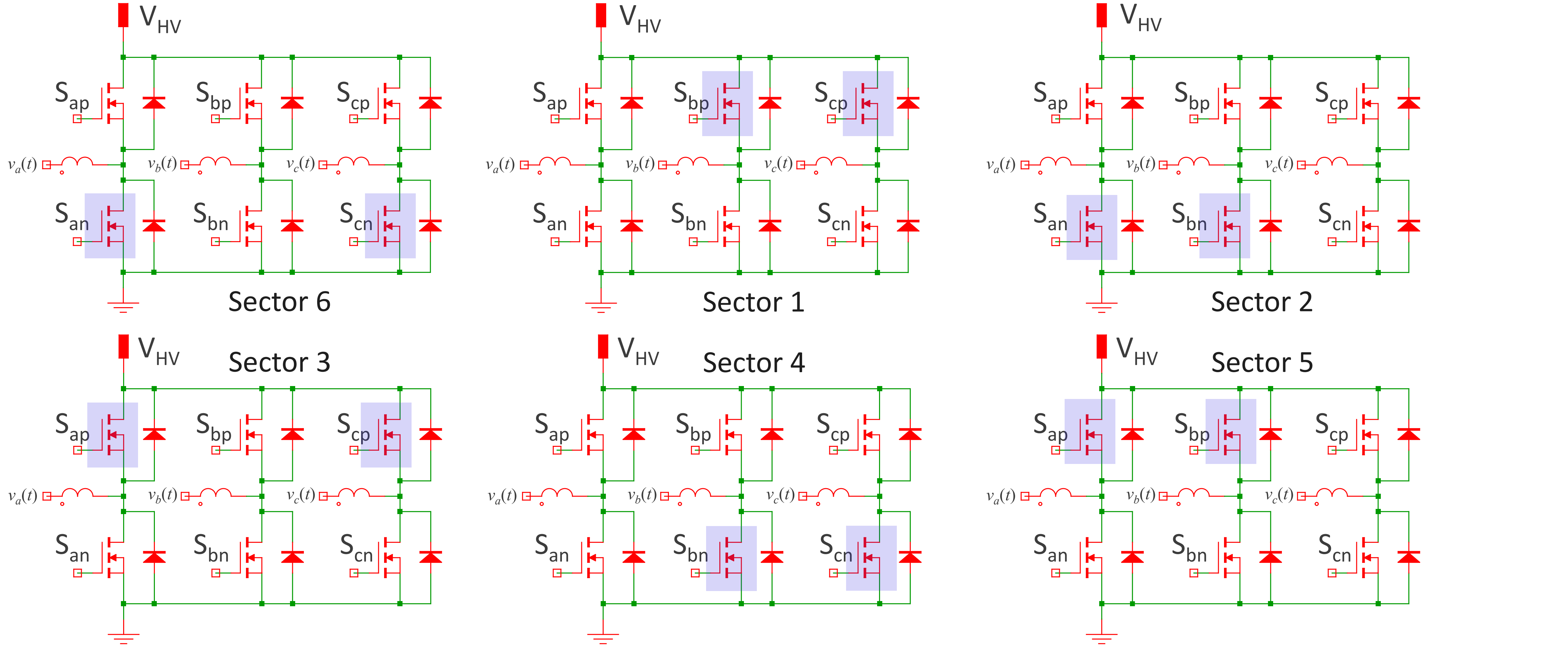


C. Qiao, K. Smedley, *A general three-phase PFC controller for rectifiers with a parallel-connected dual boost topology*, IEEE Transactions on Power Electronics, vol. 17, no. 6, pp. 925-934, Nov. 2002

Switching in the Right Region

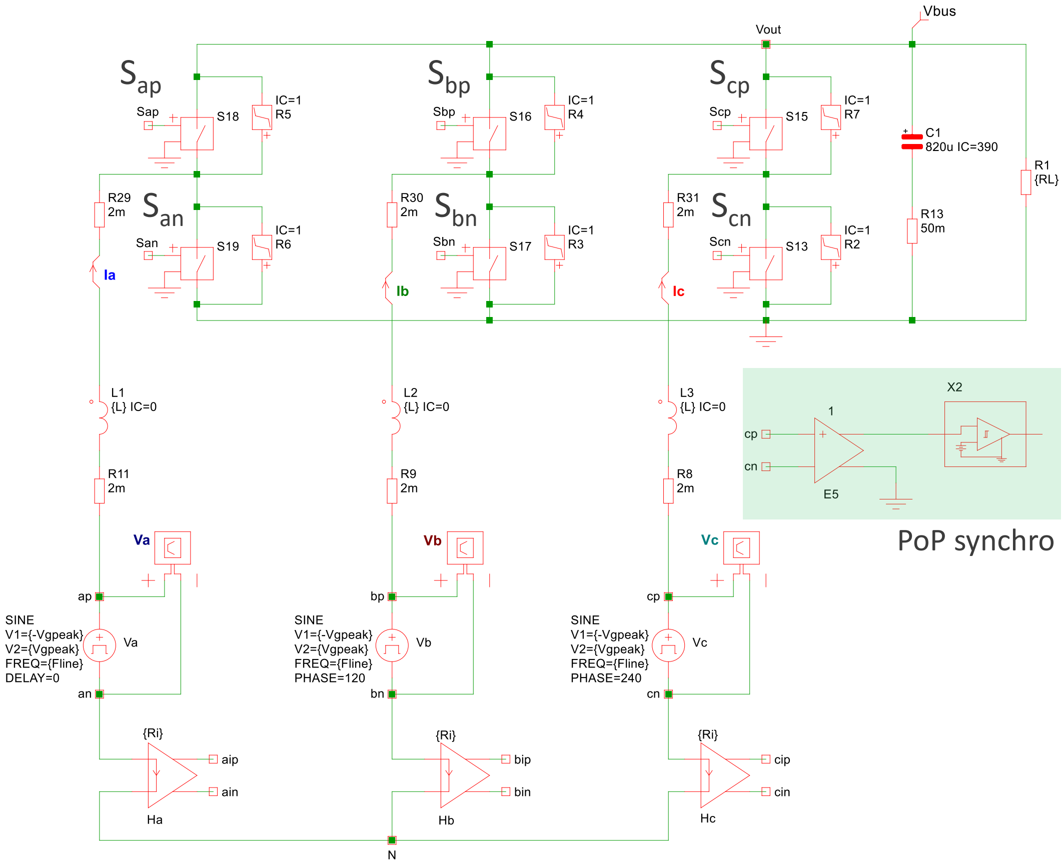
- A decoder is necessary to select the switching transistors in the active region

✓ No deadtime needed considering the switching patterns



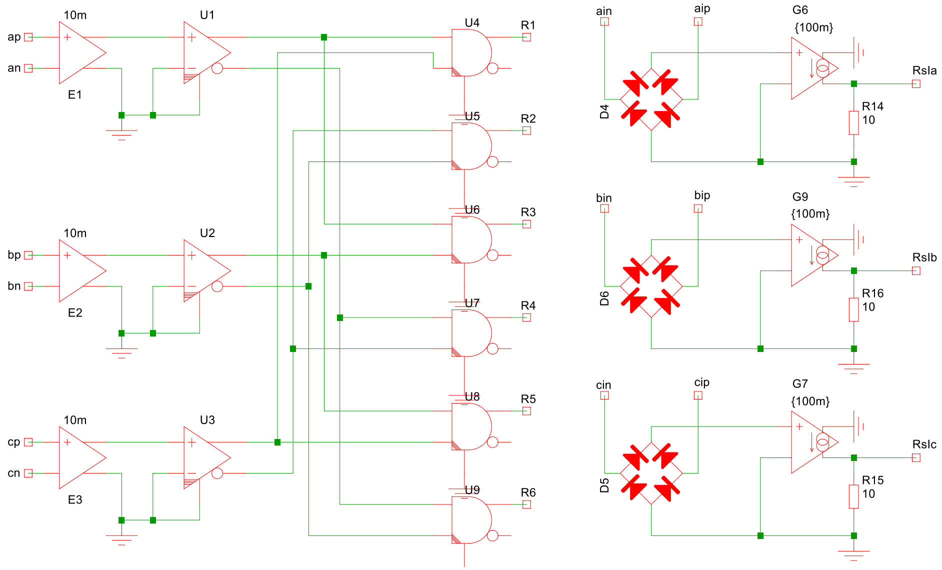
The Complete Simulation Circuit

- The entire circuit can be simulated in SIMPLIS
- The POP finds the operating point in a one minute
- ✓ Transient and ac analyses for loop control are easy!

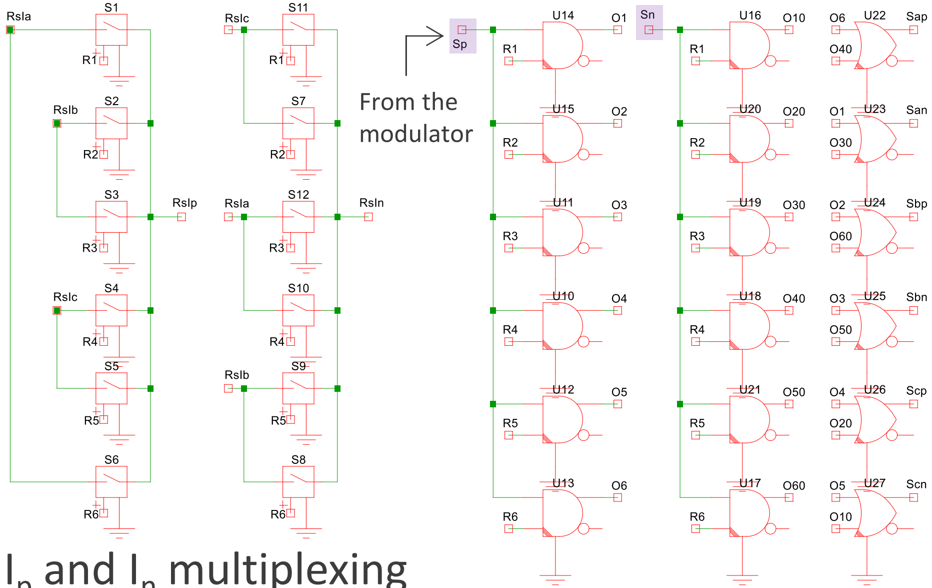


PoP synchro

Sector determination



Phase current rectification



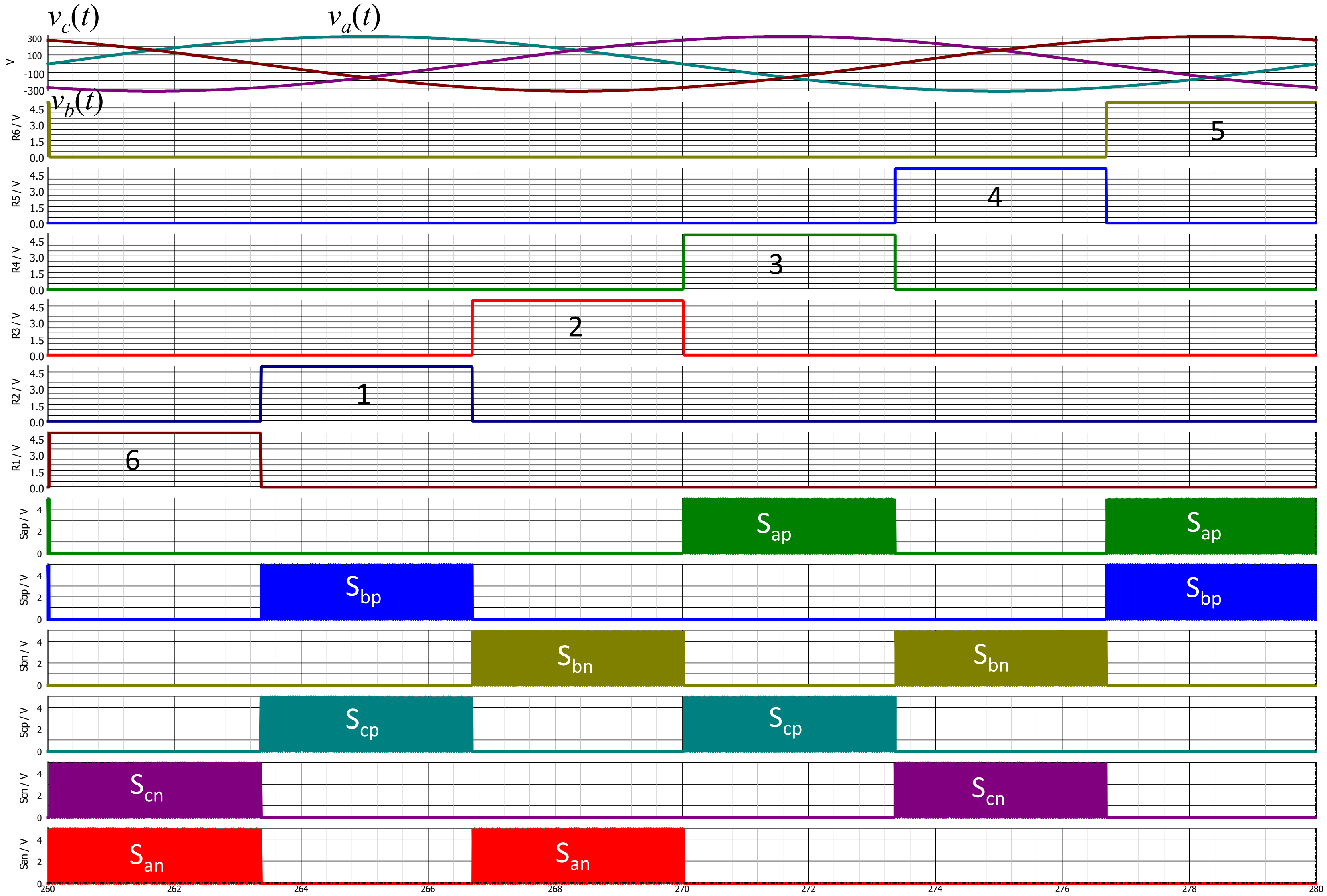
From the modulator

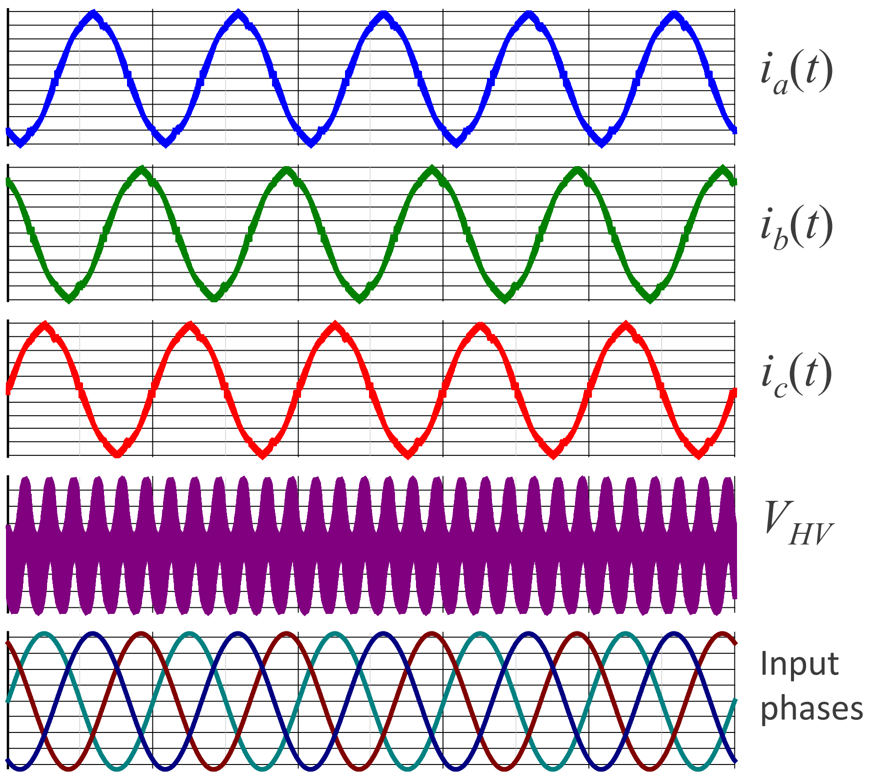
Control routing

I_p and I_n multiplexing

Switching Patterns and Sector Selection

- Resulting waveform for this 400-V/3-kW PFC supplied from a 150-V rms source

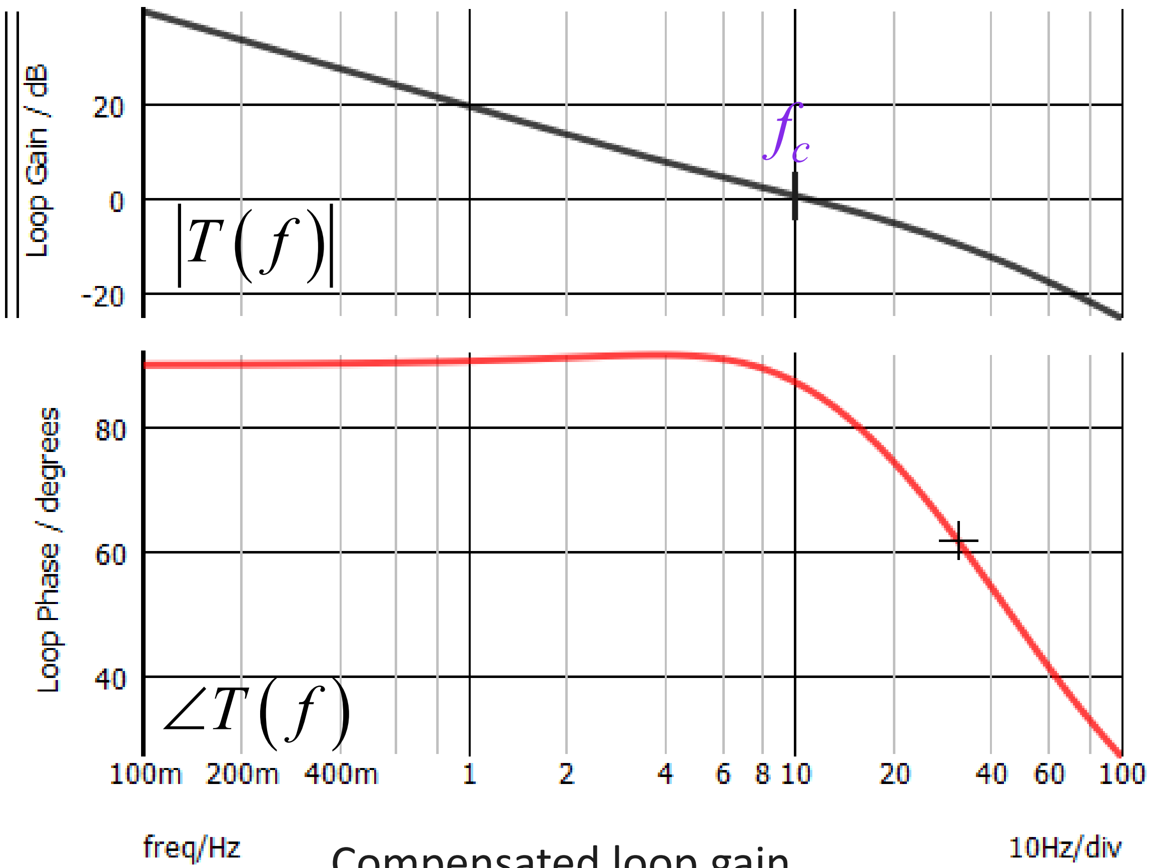




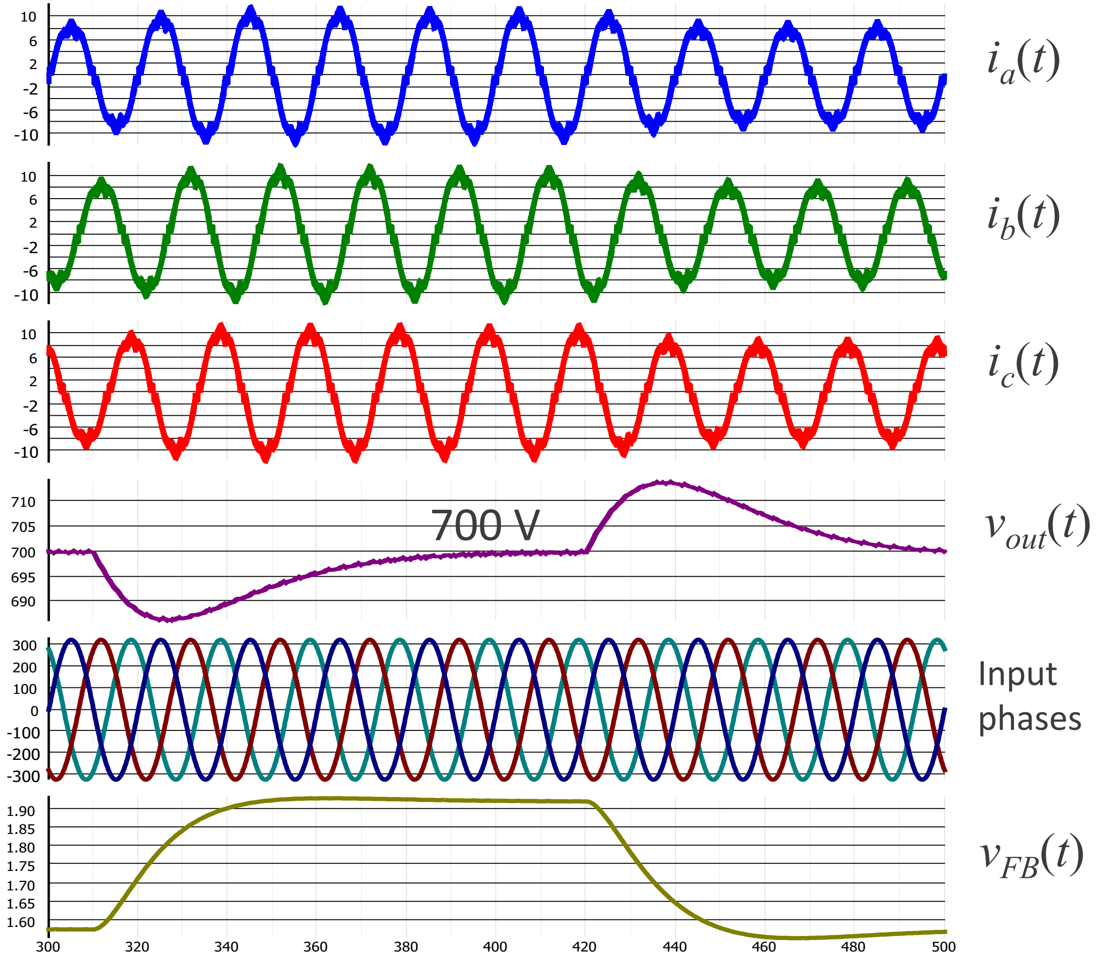
Curve label	Name	Value
Ia (simplis_pop5)	Distortion	4.70704%
Ib (simplis_pop5)	Distortion	4.73216%
Ic (simplis_pop5)	Distortion	4.72033%

Stability Analysis

- A stable periodic operating point lets the engine ac-sweep the converter
- ✓ A 10-Hz crossover frequency is adopted with a comfortable margin



Compensated loop gain

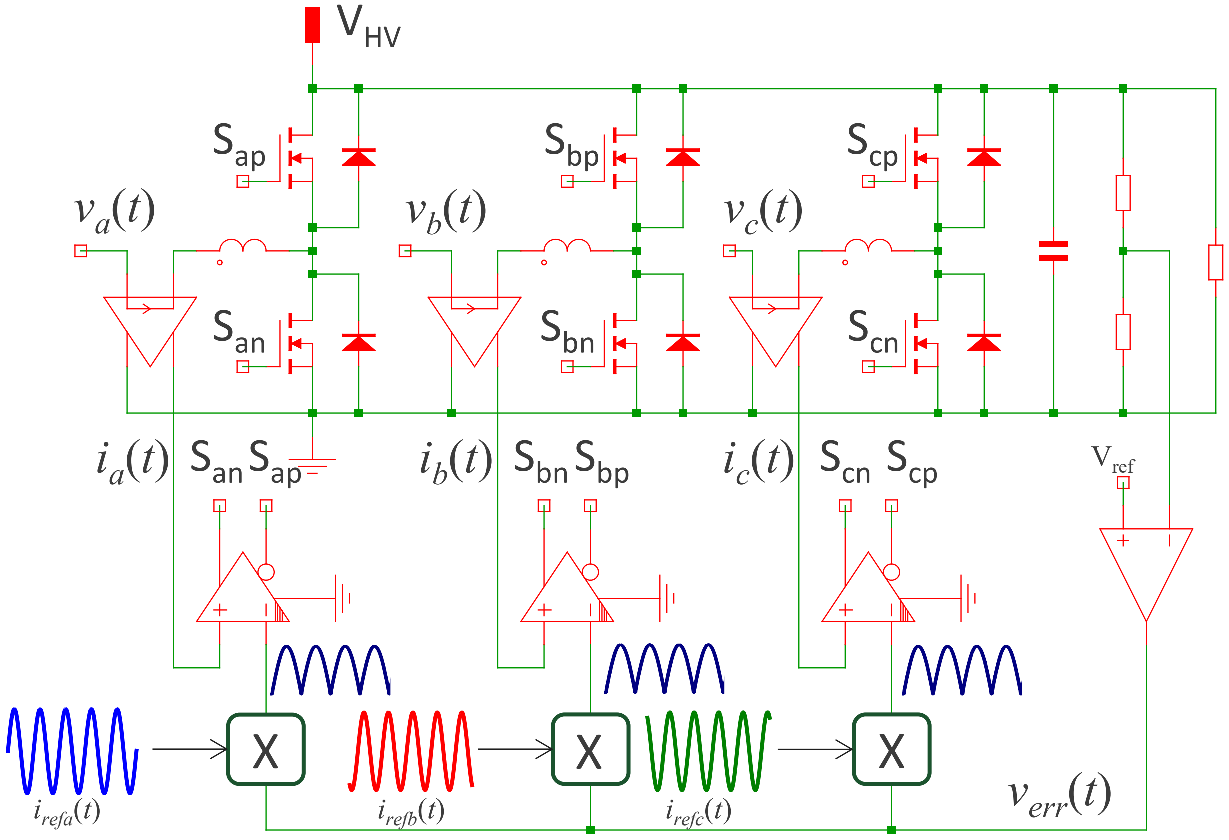


V_{in} = 230 V rms, P_{out} 4 to 5 kW

Individual Current Loops

- The classical approach based on multiplier also represents a possibility
- Three current loops are designed and controlled by a common error amplifier

✓ All-analogue solution requiring three multipliers plus PLL-synchronized references



✓ Deadtime is needed in each branch to limit shoot-through currents

✓ Reverse-recovery losses of the body diode is an issue

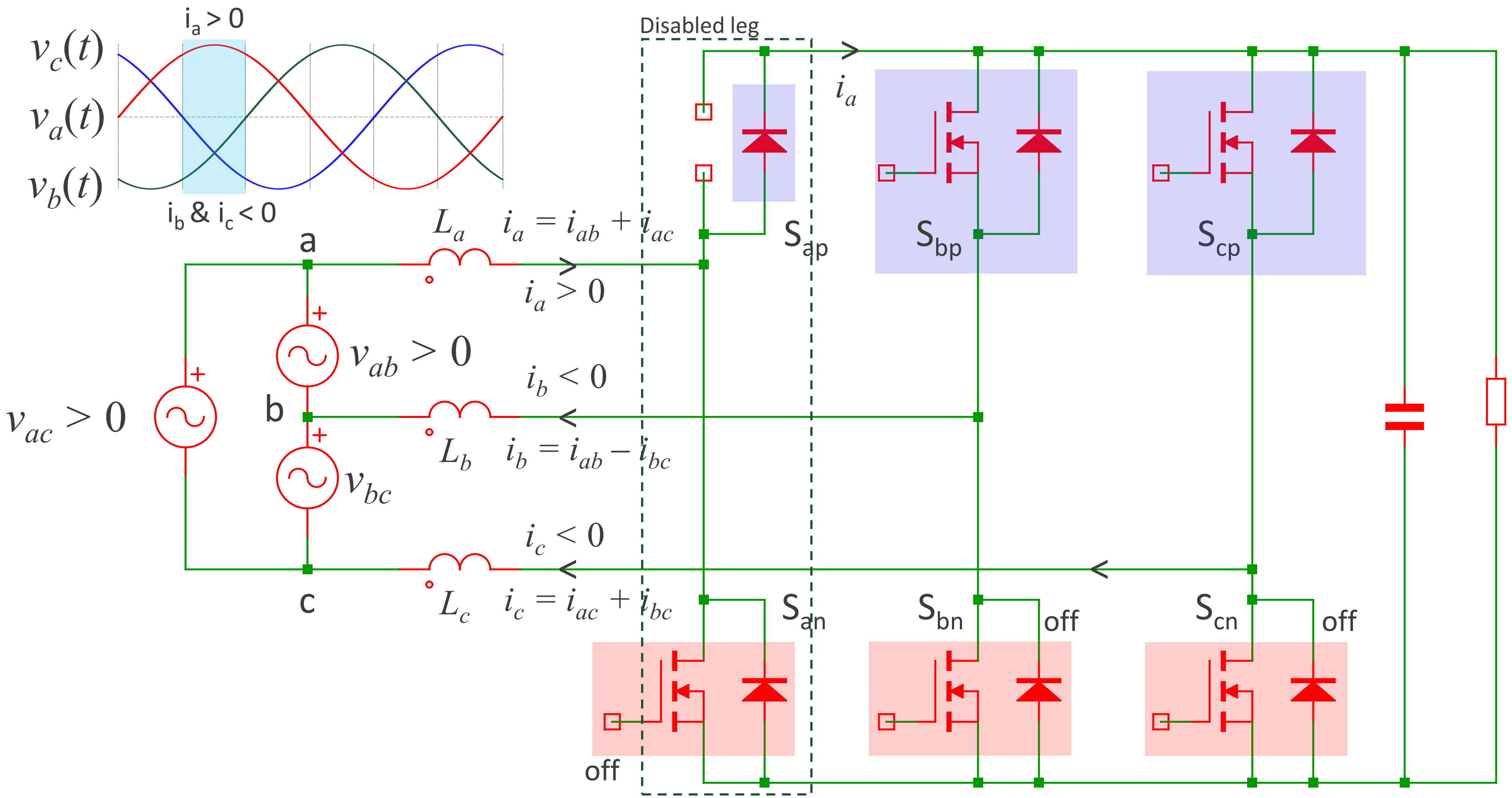
❖ It is thus difficult to increase the switching frequency

Implement 6-step sectorized operation

Y. Jiang, H. Mao, F. C. Lee and D. Borojevic, *Simple high performance three-phase boost rectifiers*, *Proceedings of 1994 Power Electronics Specialist Conference - PESC'94*, Taipei, Taiwan, 1994

6-Step Operation and Sectors

- In this 6-step operation, two switches are active while another reverse-conducts

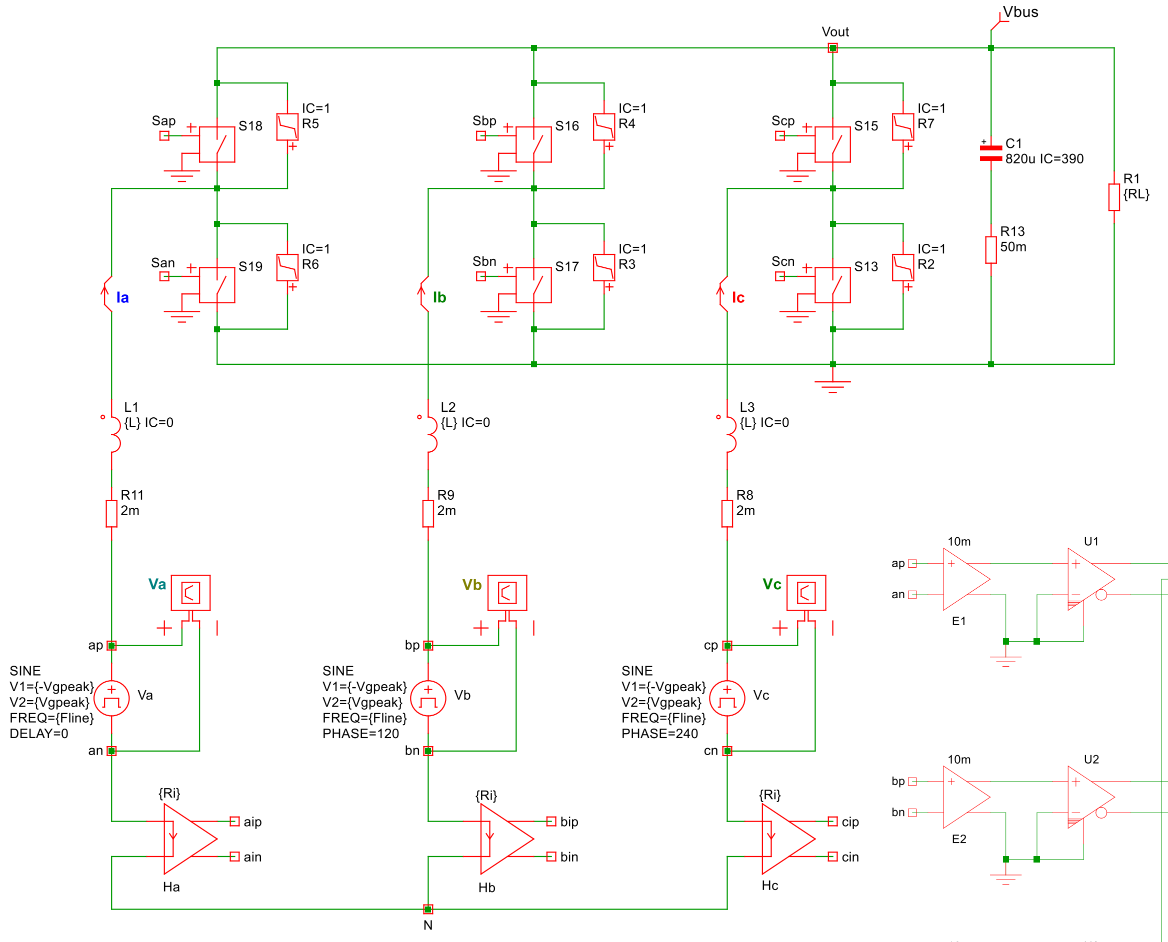


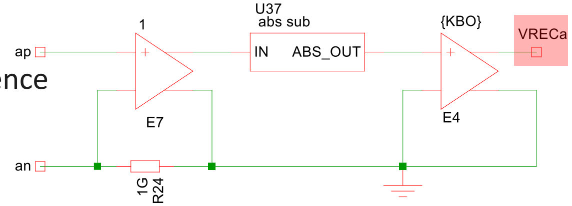
- ✓ The circuit requires a simple logic decoder to determine the active sector
- ✓ It can work with individual CCM PFC controllers
- ✓ Distortion figures are good at nominal power

L. Huber, M. Kumar and M. M. Jovanović, *Performance comparison of three-step and six-step PWM in average-current-controlled three-phase six-switch boost PFC rectifier*, *2015 Applied Power Electronics Conference and Exposition (APEC)*, Charlotte, NC, USA, 2015, pp. 1861-1868

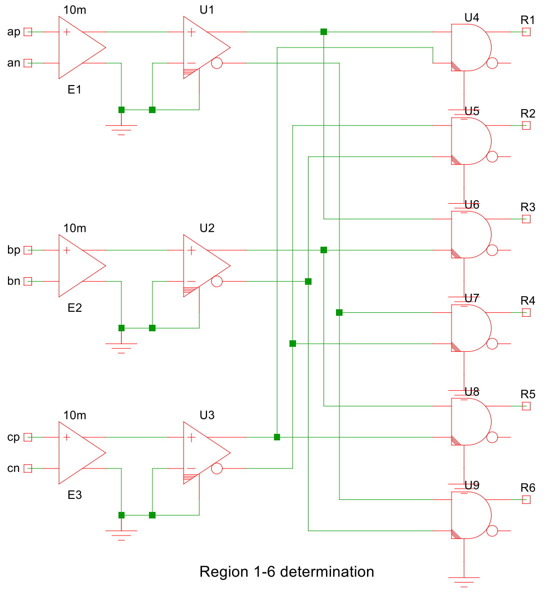
Simulation Setup with SIMPLIS

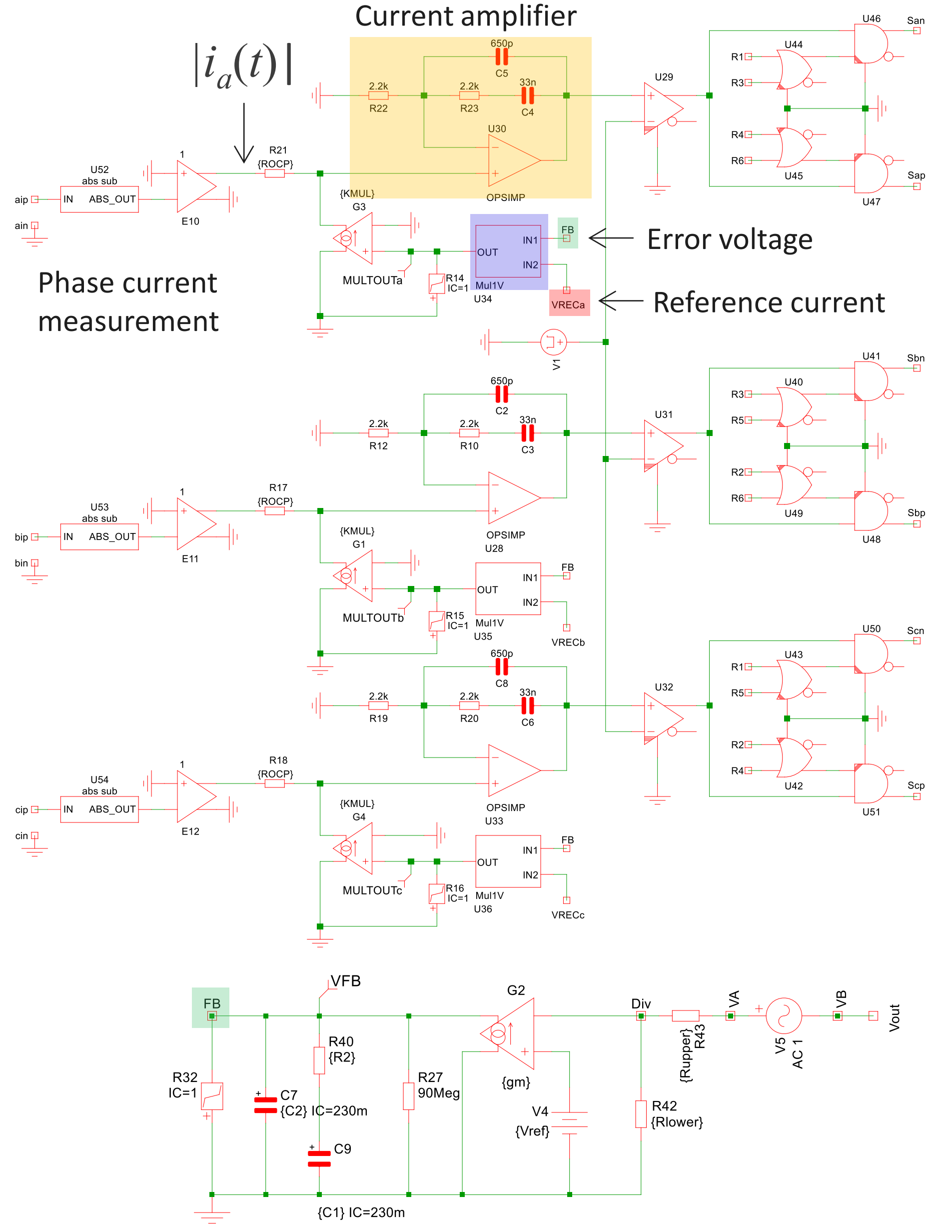
- The circuit simulates fast: 30 s to PoP!
- Ac response 1 mn later





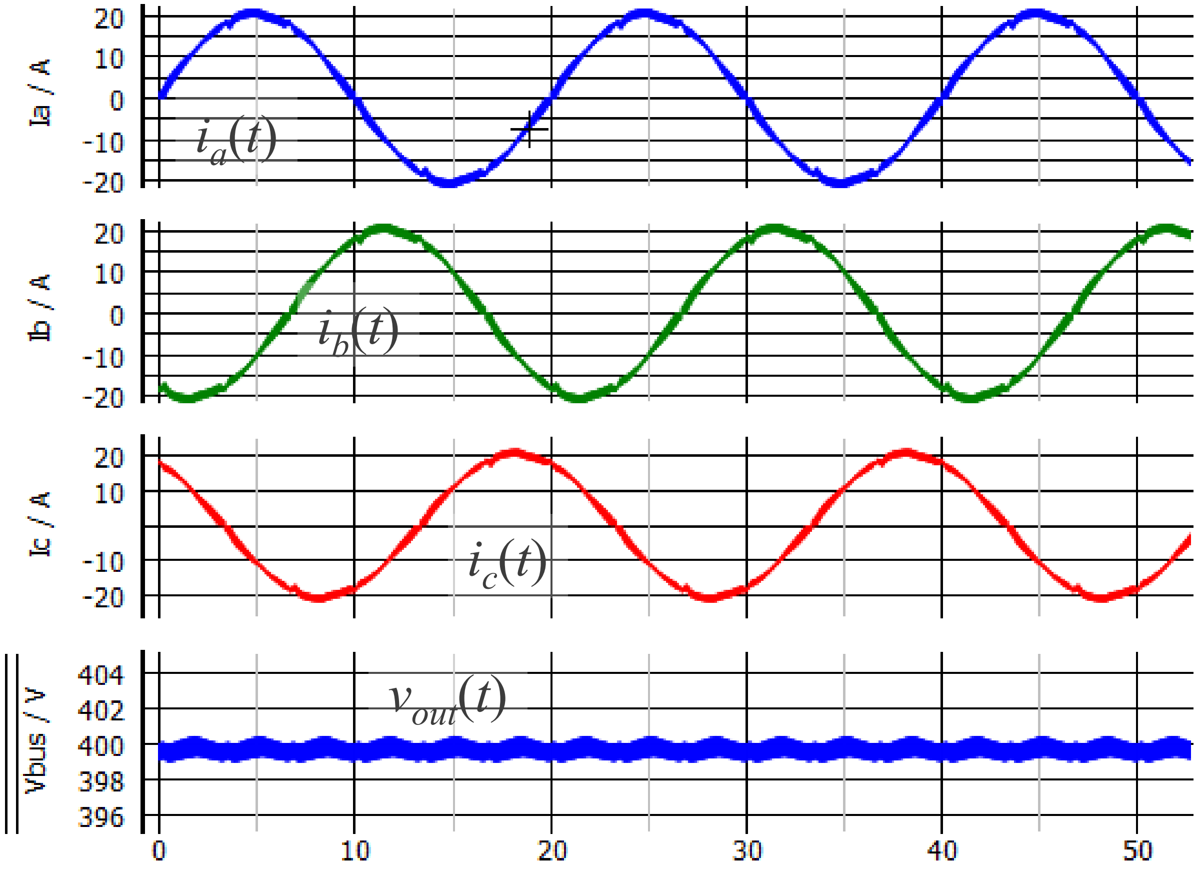
Synced reference currents

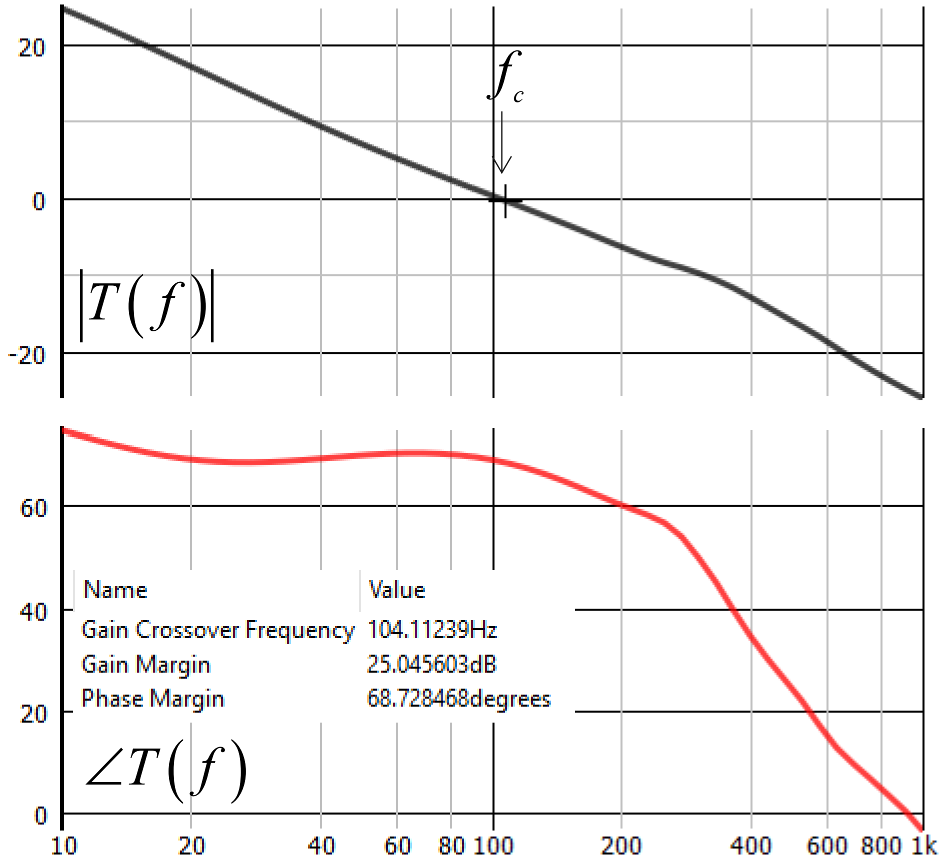




Good Distortion Figures

- Total distortion at a 150-V input voltage is 4% for an output power of 6.5 kW





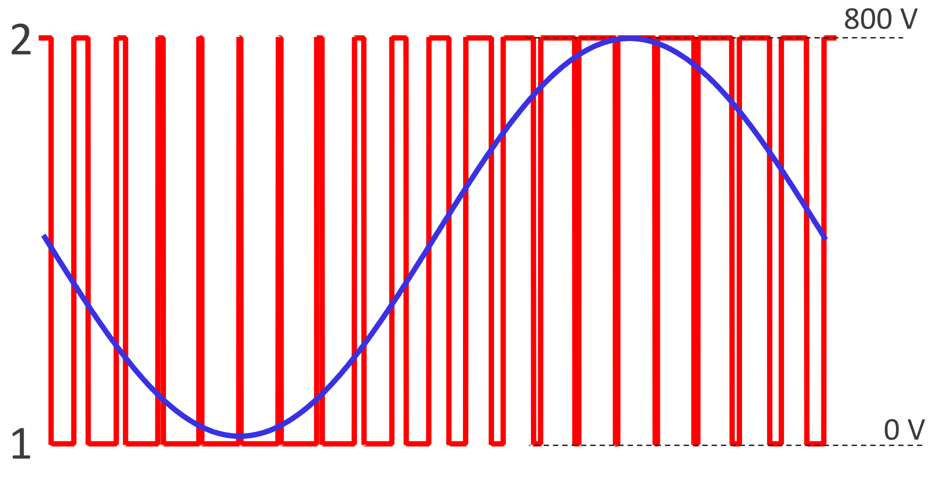
- The converter is compensated for a 100-Hz crossover frequency with good margin

Agenda

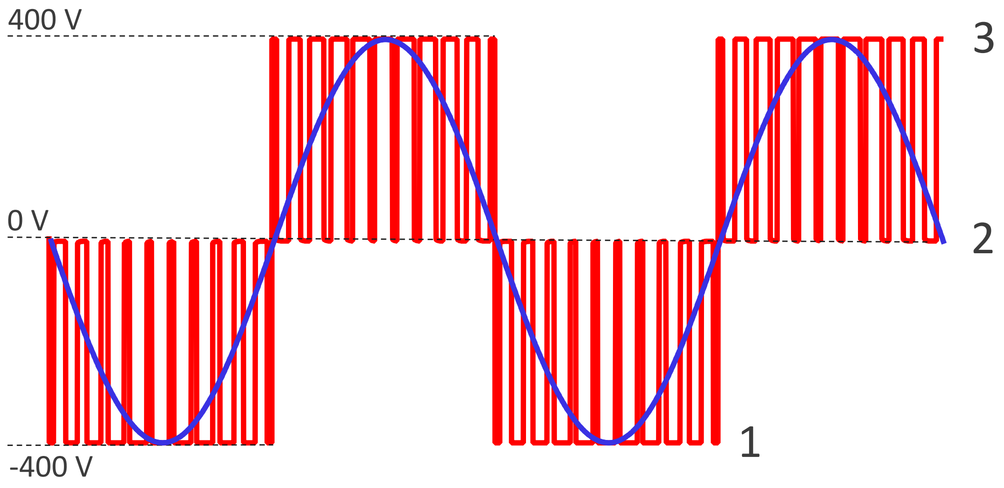
- Tri-Phase Rectification Basics
- Single-Switch Active Power Factor Correction
- Six-Switch Implementation
- Three-Level Converters
- The Vienna Rectifier

Three-Level Power Conversion

- The classical boost structure delivers a single output voltage of 800 V
- ✓ It is called a *two-level* inverter, meaning the switching pattern is unipolar
- An intermediate 0-V level can be added to form a *three-level* inverter
- ✓ The switching pattern becomes bipolar and transitions via a 0-V state



2-level switching pattern

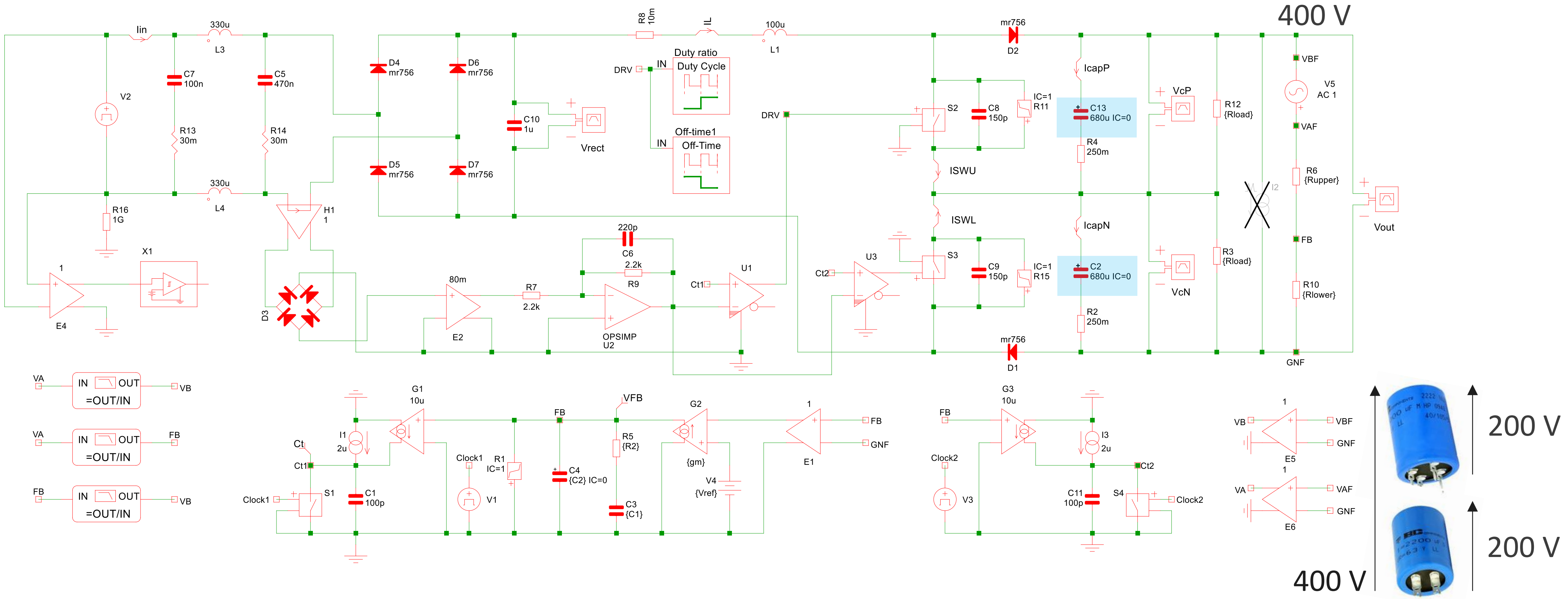


3-level switching pattern

Stack converters supplied by 400-V rails and reduce semiconductors stress

Single-Phase 3-Level PFC

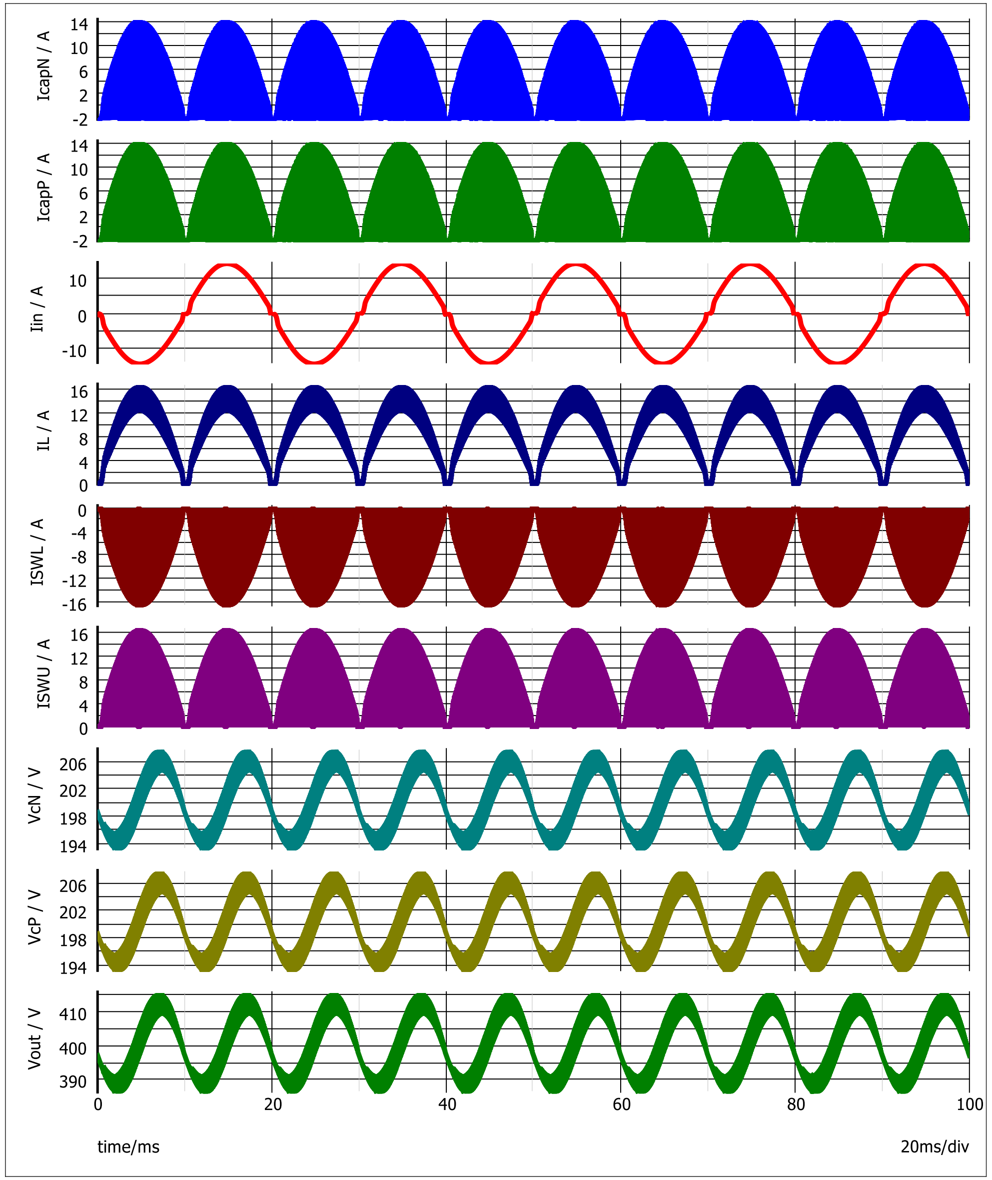
- The boost converter splits the high-voltage rail into two-stacked dc values
- These intermediate values let you use semiconductors of lower breakdown voltages



✓ Steady-state simulations as well as ac response are obtained in a snapshot with SIMPLIS

M. T. Zhang et al., Single-phase three-level boost power factor correction converter, *IEEE Applied Power Electronics Conference and Exposition - APEC'95*, Dallas

Operating Point and Ac Response

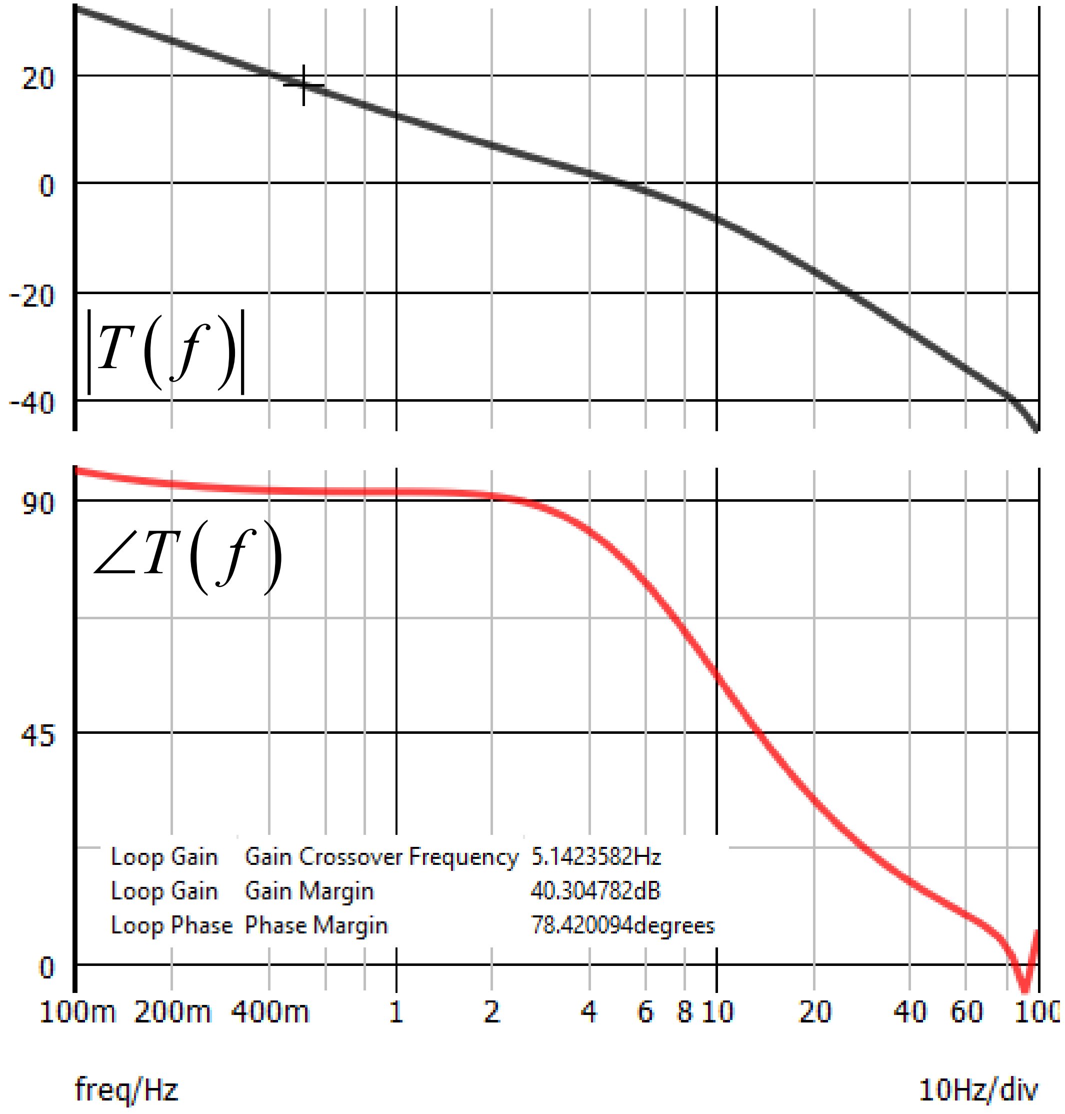


- It is to stabilize the loop for a 5-Hz crossover.
- The phase margin at 78° is very comfortable and ensures stability.
- THD = 3.6%

High-side output

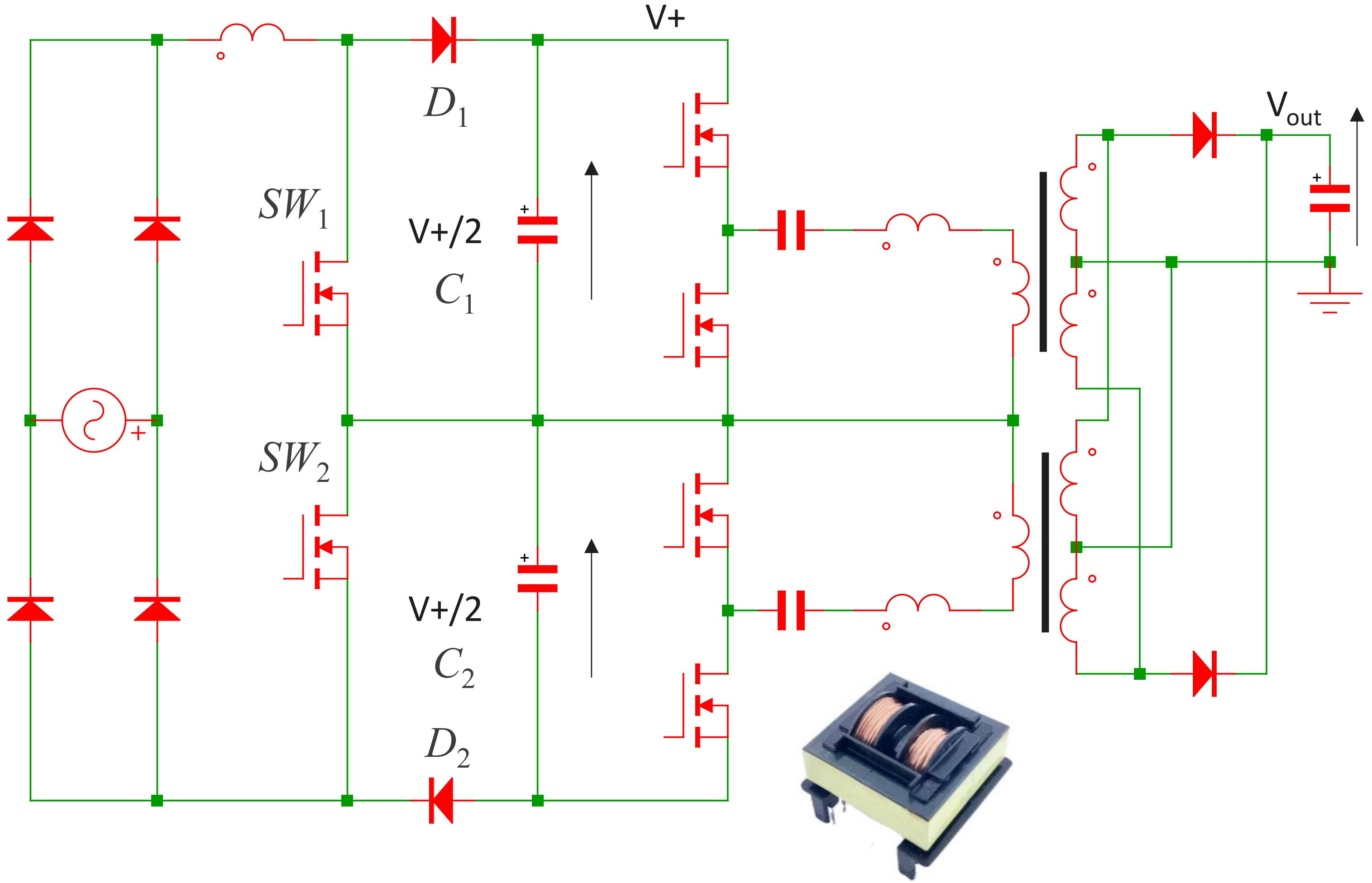
Low-side output

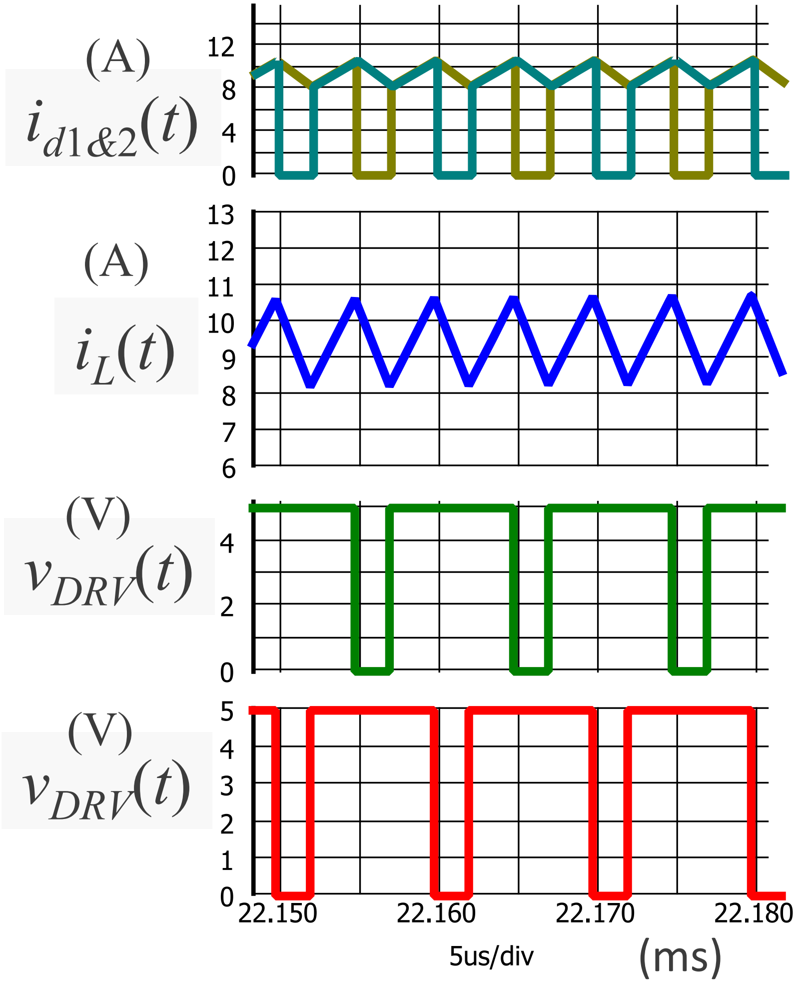
Total output



Stacking High-Power Converters

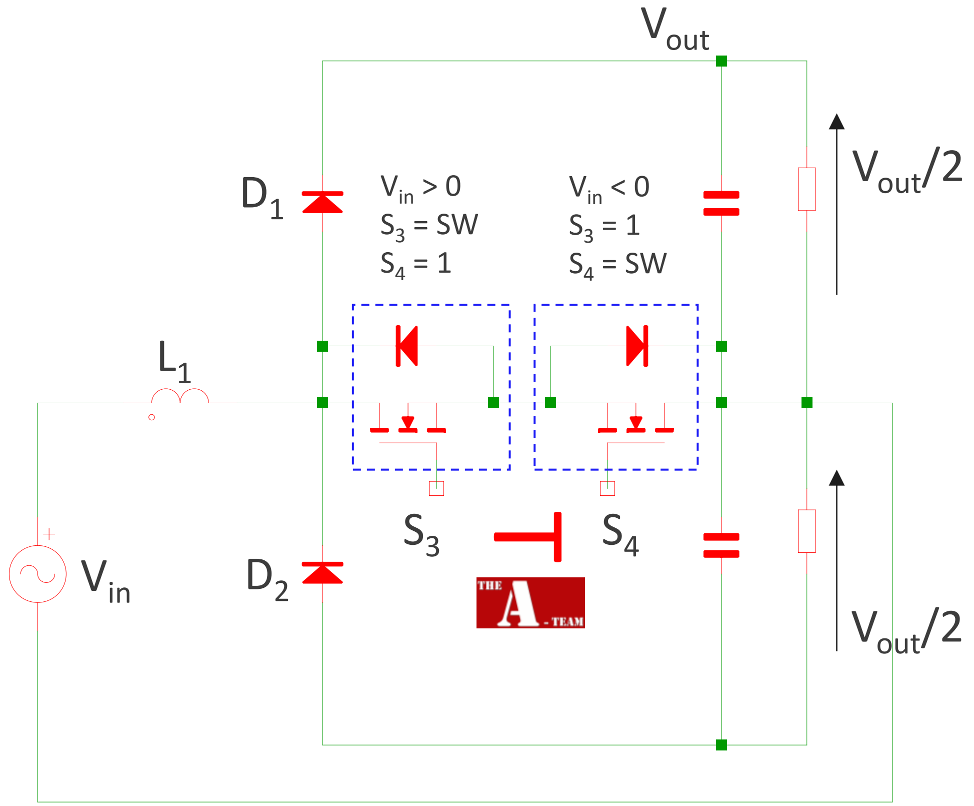
- The two dc rails of equal values let you use semiconductors of lower voltage
- The output transformers can then be serialized or paralleled for more power

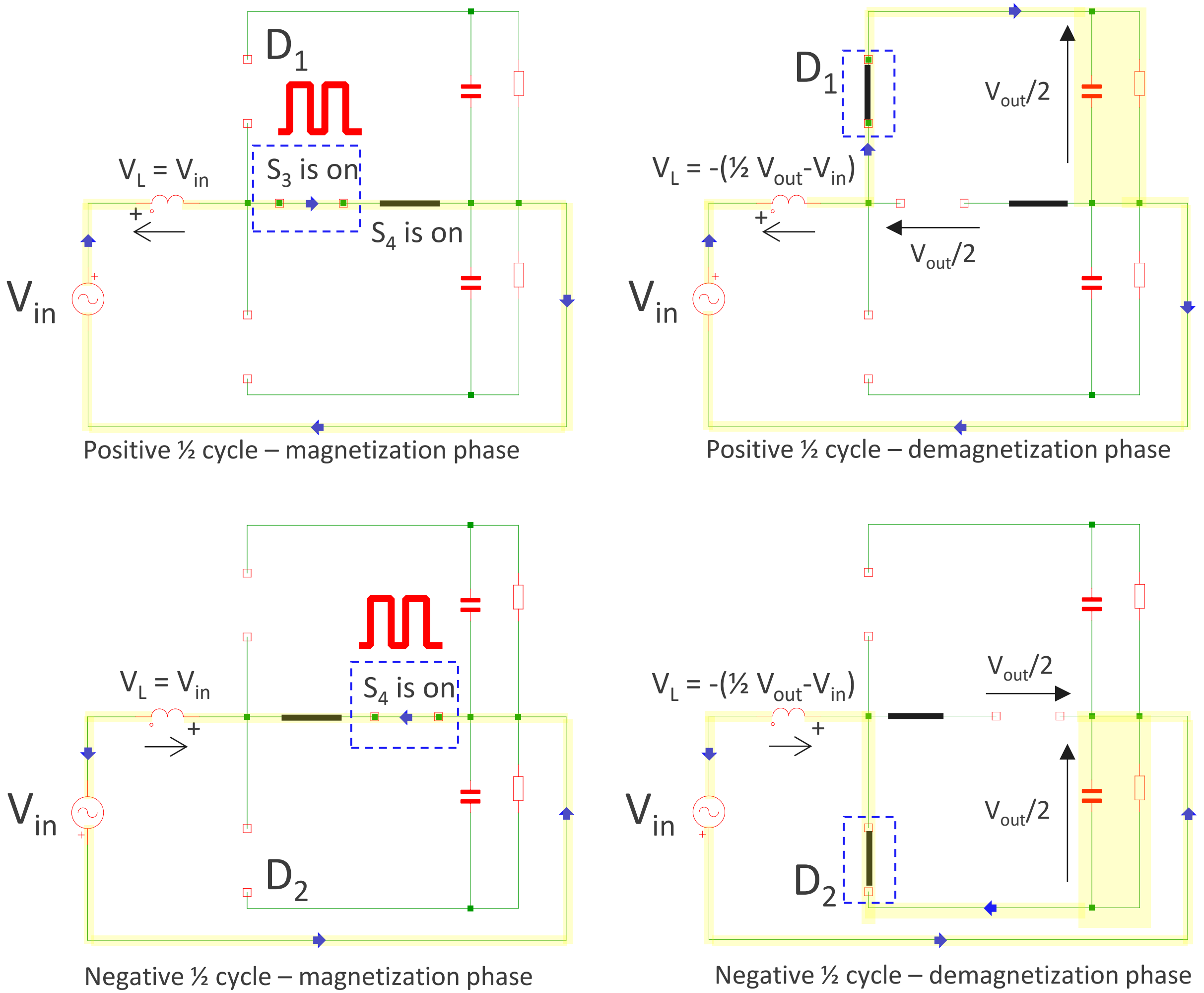




Three-Level T-Type TPPFC

- A simple totem-pole PFC can be implemented by adding a bidirectional switch
- The two T switches operate at high frequency and block $V_{out}/2$



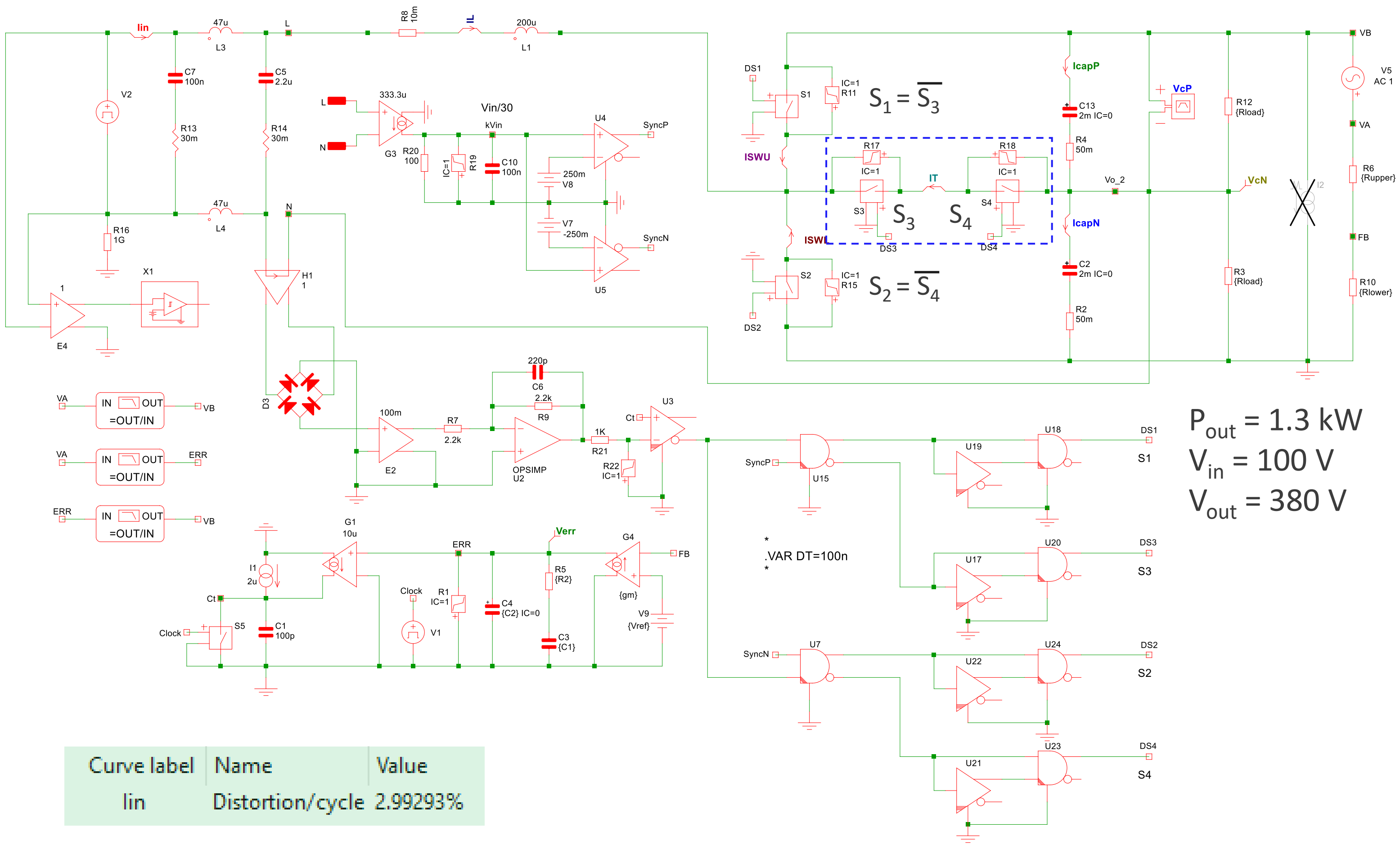


- The off-time voltage is half of a 400-V PFC

✓ Design with a smaller inductor for same ripple

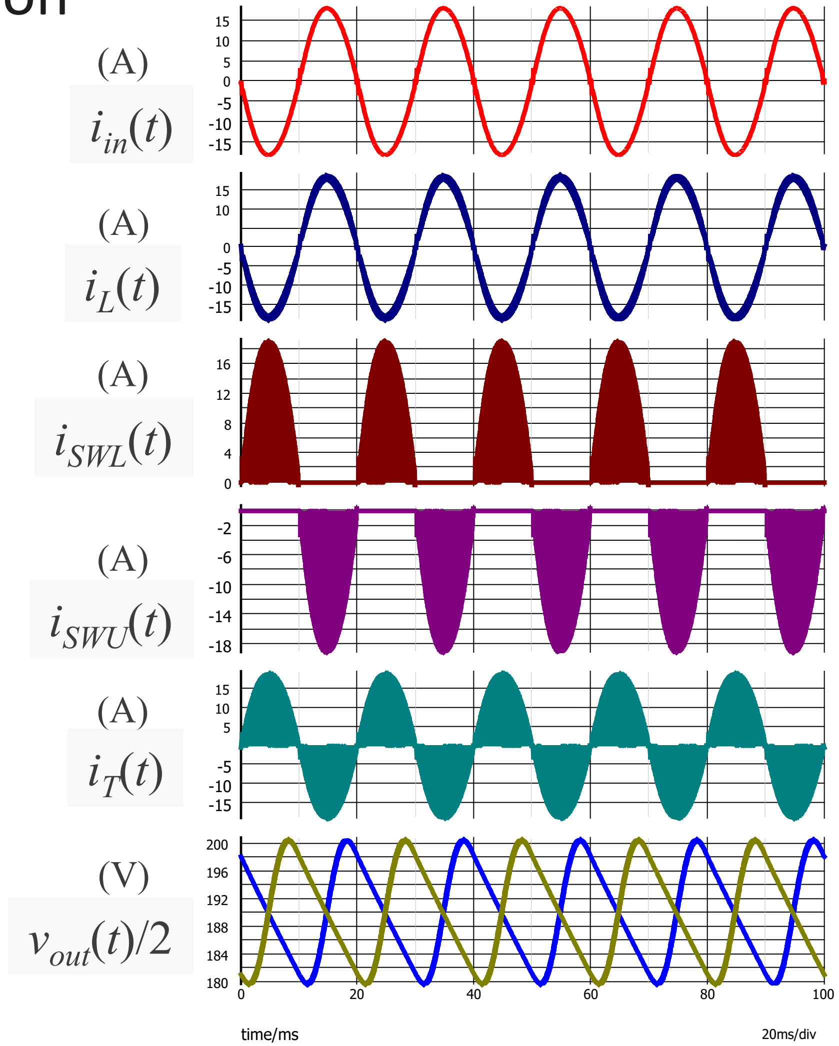
A Voltage Doubler

- The structure doubles the input voltage implying $V_{in} < V_{out}/2$ or 800-V bus for 265 V_{rms}
- Deadtime needs to be inserted for synchronous rectification



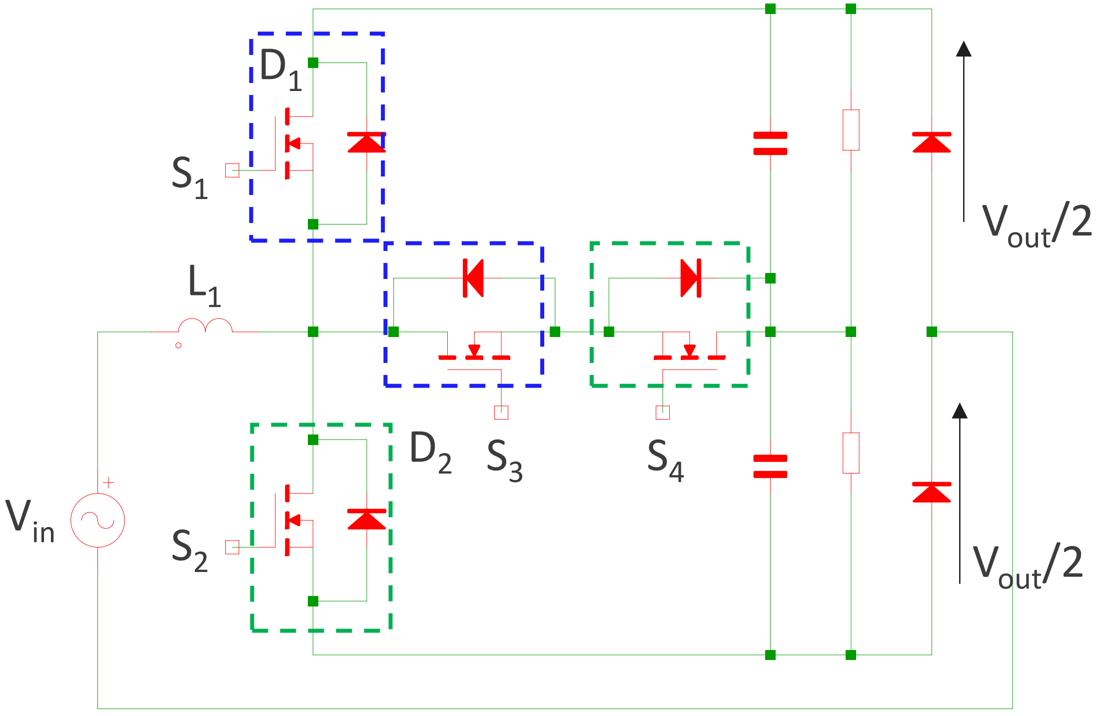
Curve label	Name	Value
Iin	Distortion/cycle	2.99293%

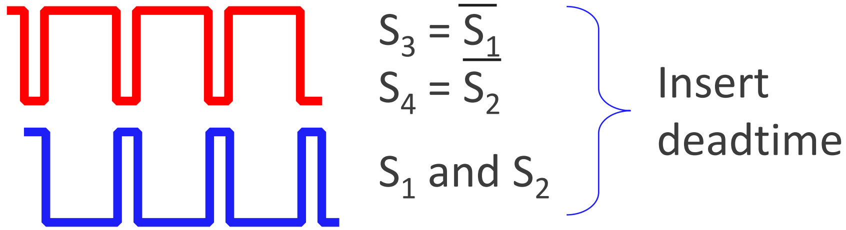
P_{out} = 1.3 kW
V_{in} = 100 V
V_{out} = 380 V

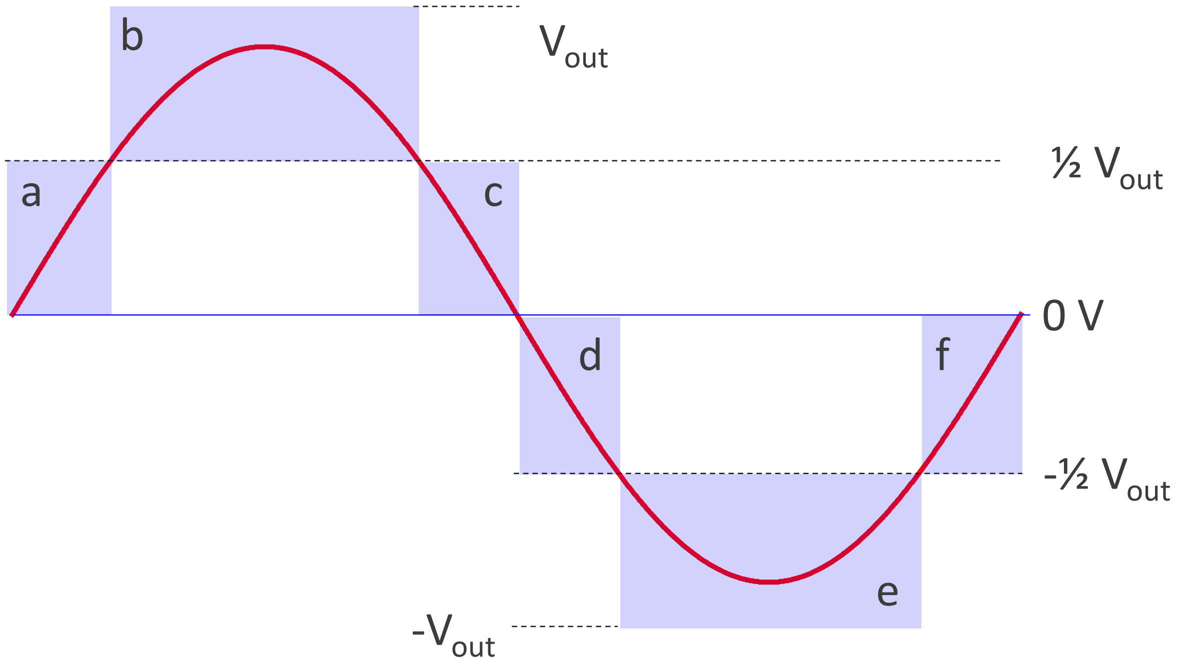


Single-Phase T-Type Power Factor Correction

- A TPPFC is implemented with slow and fast legs as in the classical approach
- Sectorization is necessary for ensuring wide-mains operation







Positive section

- Sector a: $V_{in} < ½ V_{out}$
- Sector b: $V_{in} > ½ V_{out}$
- Sector c: $V_{in} < ½ V_{out}$

Negative section

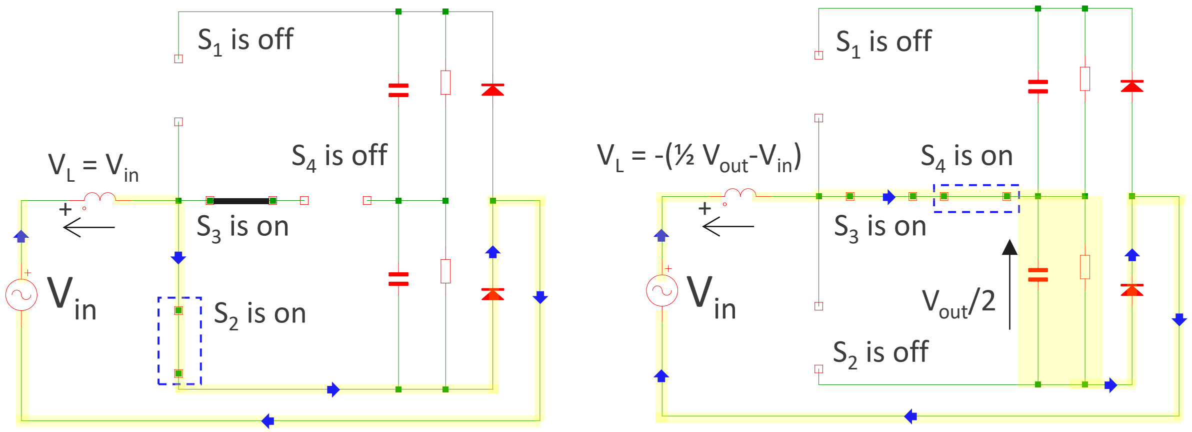
- Sector d: $|V_{in}| < ½ V_{out}$
- Sector e: $|V_{in}| > ½ V_{out}$
- Sector f: $|V_{in}| < ½ V_{out}$

1.6-kW T-Type 3-Level PFC Power Supply – Design Guide RD172 – Toshiba

Sectorization of the Transitions

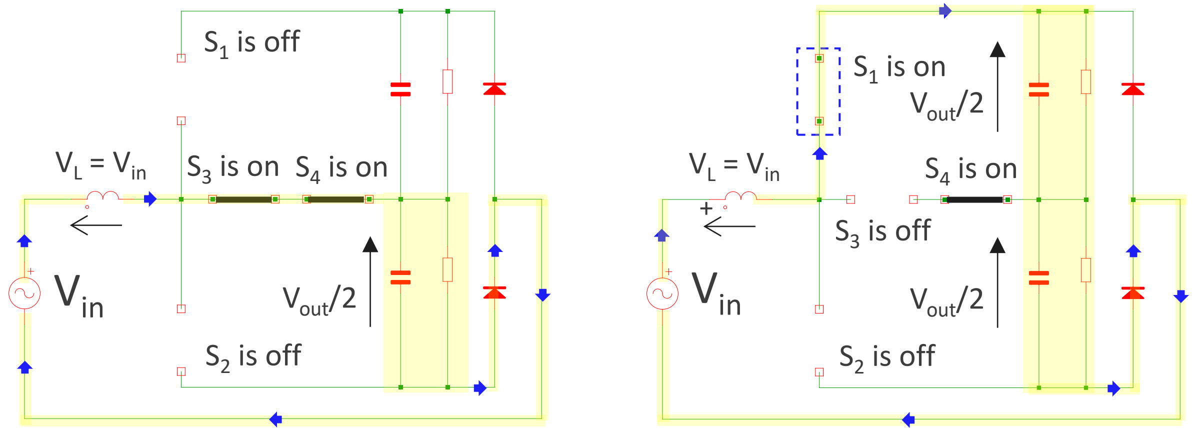
- Dedicated switching sequences are selected depending on the input line

Section a/c: $V_{in} > 0$ & $V_{in} < ½ V_{out}$



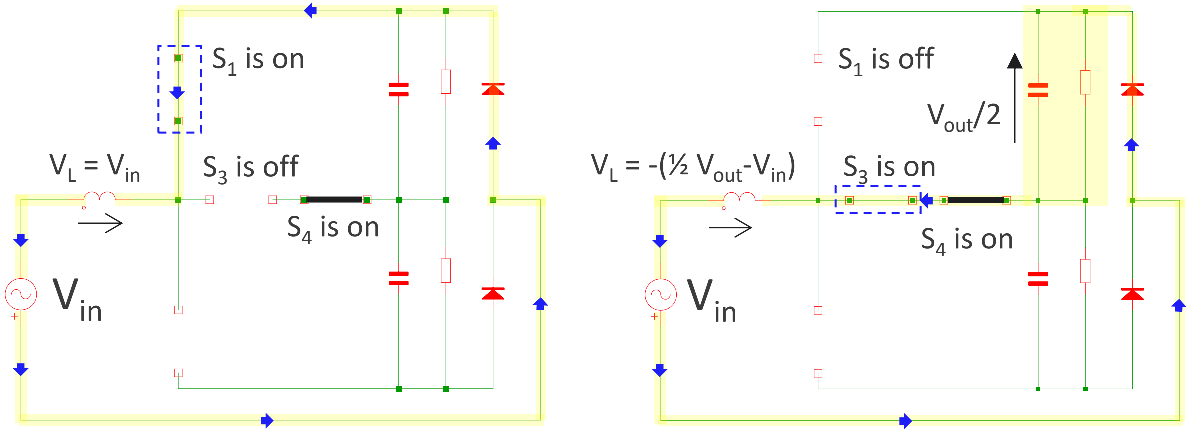
Magnetization phase   Demagnetization phase

Section b: $V_{in} > 0$ & $V_{in} > ½ V_{out}$



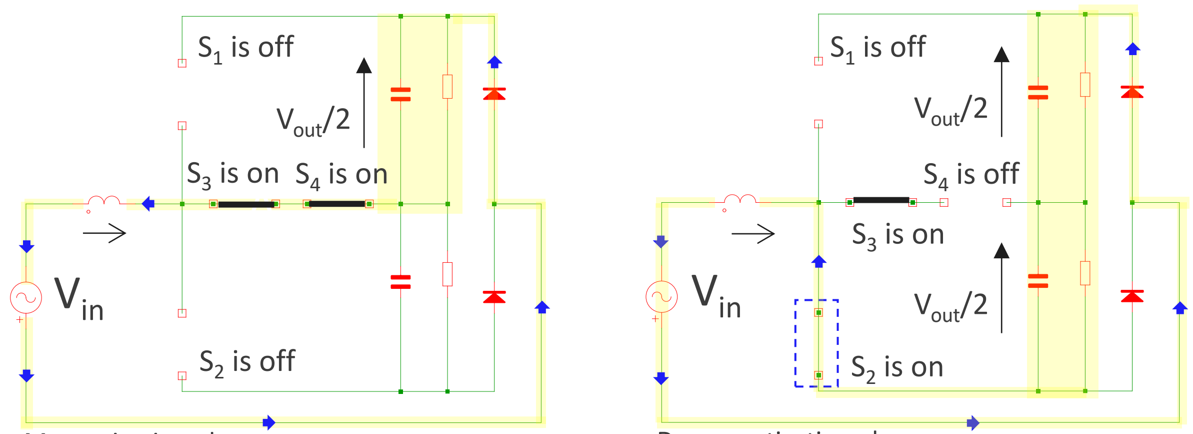
Magnetization phase   Demagnetization phase

Section d/f: $V_{in} < 0$ & $|V_{in}| < ½ V_{out}$



Magnetization phase   Demagnetization phase

Section e: $V_{in} < 0$ & $|V_{in}| > ½ V_{out}$

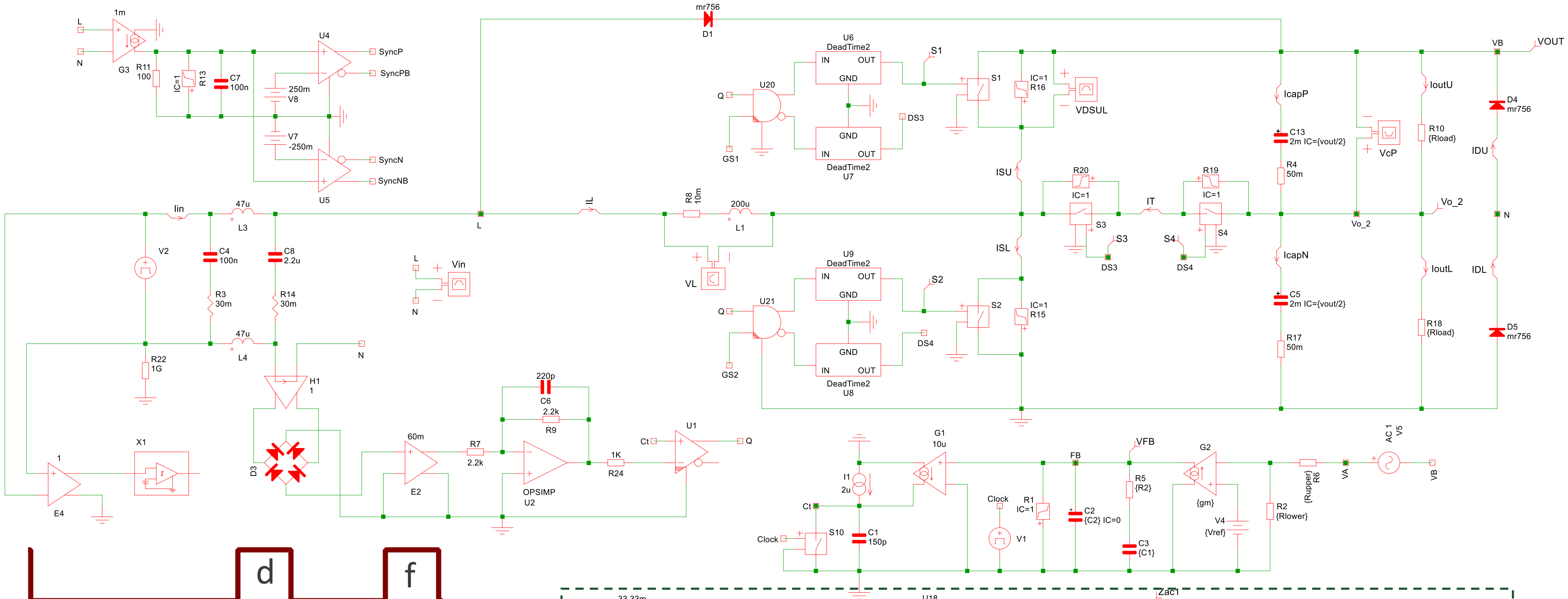


Magnetization phase   Demagnetization phase

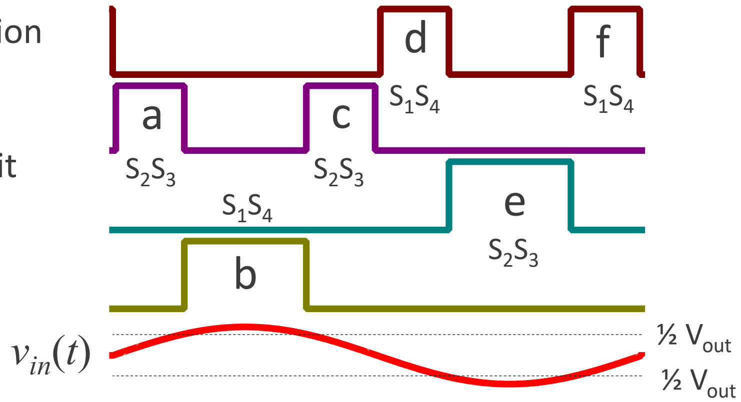
FUTURE ELECTRONICS

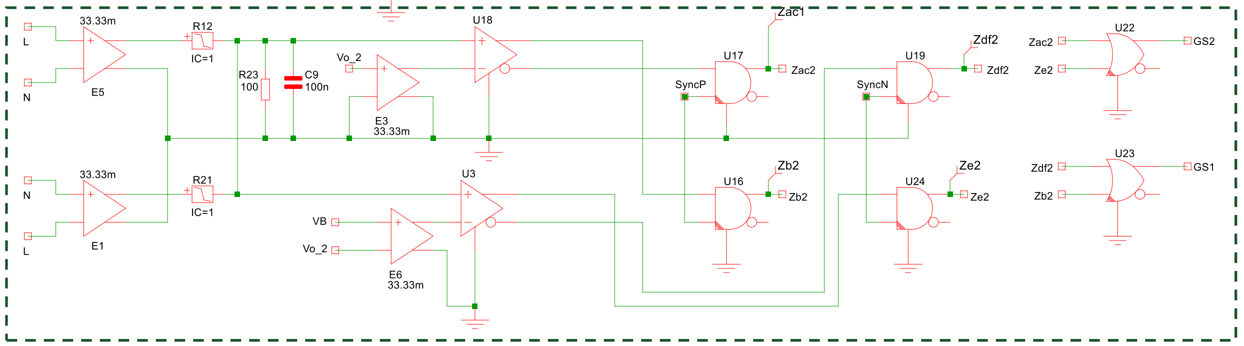
Simulating the T-Type with SIMPLIS

- The operating circuit gains in complexity, especially considering the sectorization



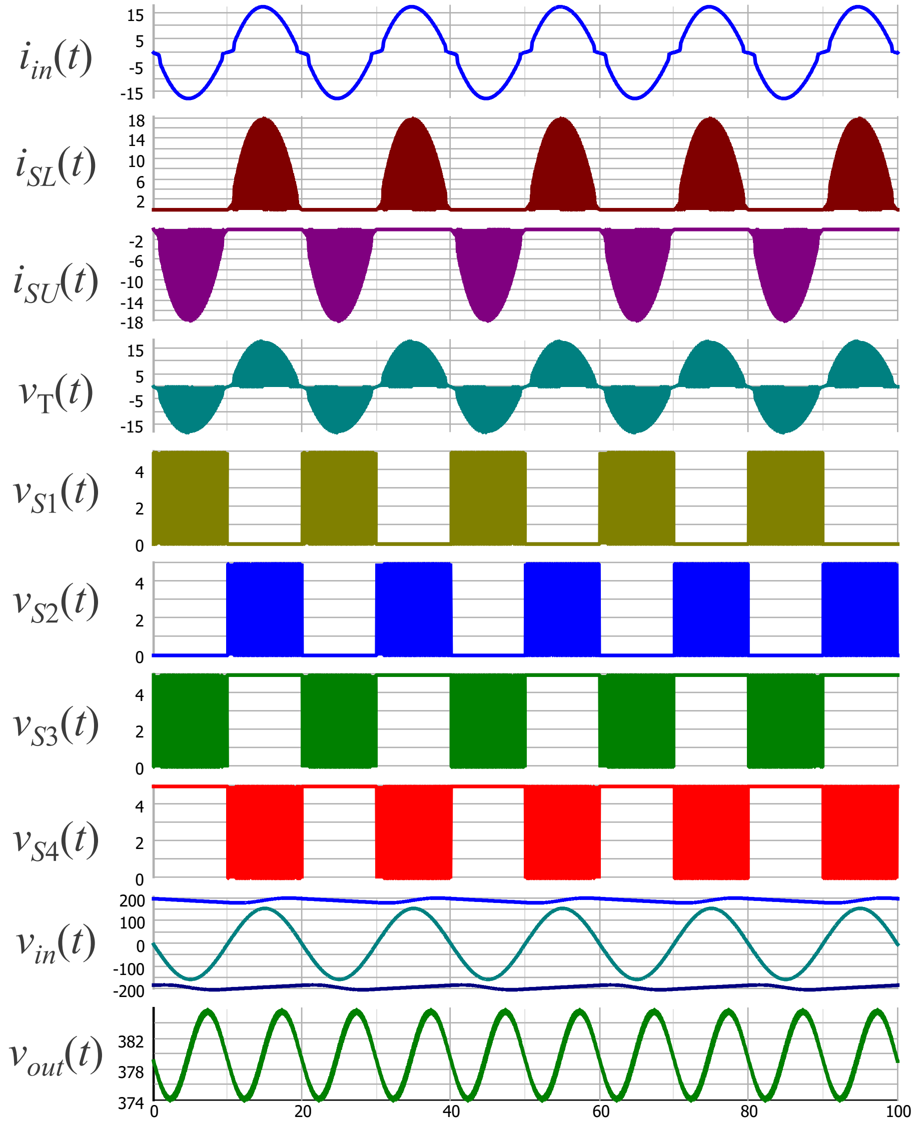
- Sectorization requires a dedicated logic circuit

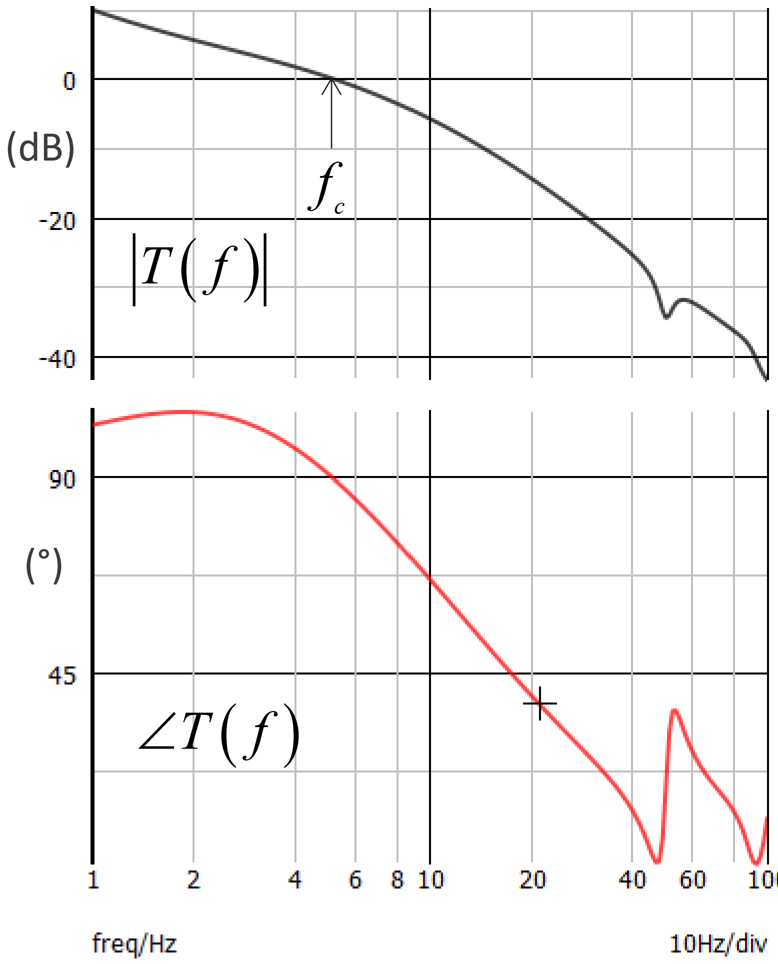




T-Type Simulation Results

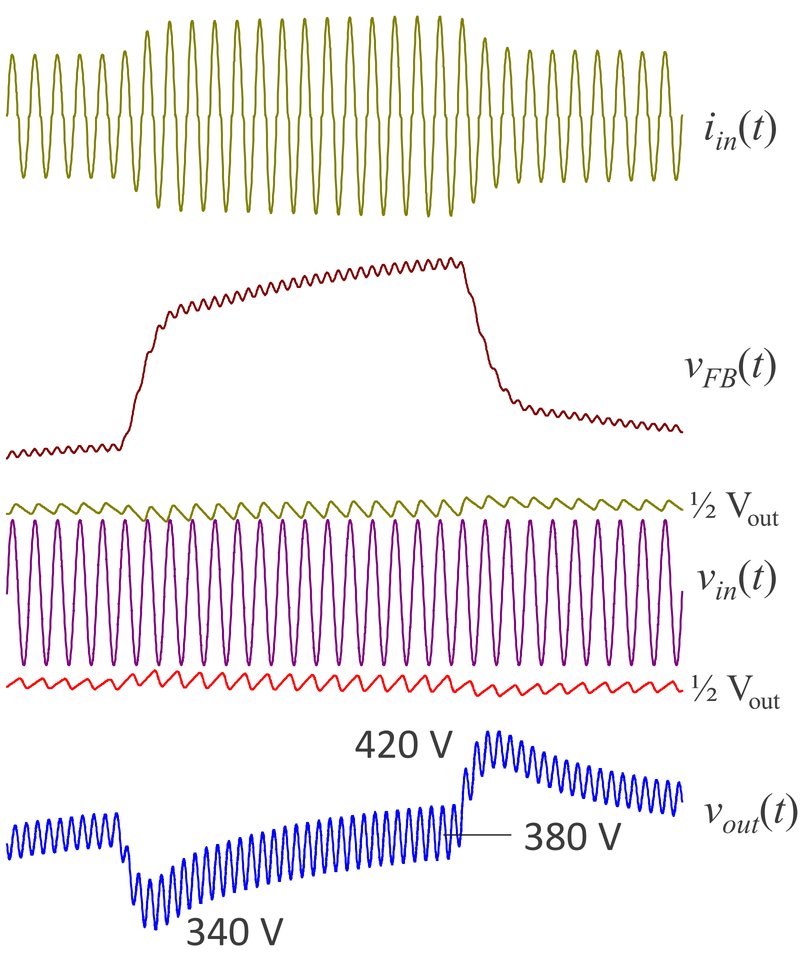
- It is possible to run an ac analysis once the operating point is determined – low line





Loop Gain	Gain Crossover Frequency	5.2780167Hz
Loop Gain	Gain Margin	***ERROR***
Loop Phase	Phase Margin	89.287725degrees

2-A step-load with a 1-A/µs slope



Agenda

- Tri-Phase Rectification Basics
- Single-Switch Active Power Factor Correction
- Six-Switch Implementation
- Three-Level Converters
- The Vienna Rectifier

The Vienna Rectifier

FUTURE ELECTRONICS

- The Vienna rectifier patent was granted on December 23rd 1993
- The inventor is Johann Kolar and assignee was IXYS Semiconductor (now Littelfuse)

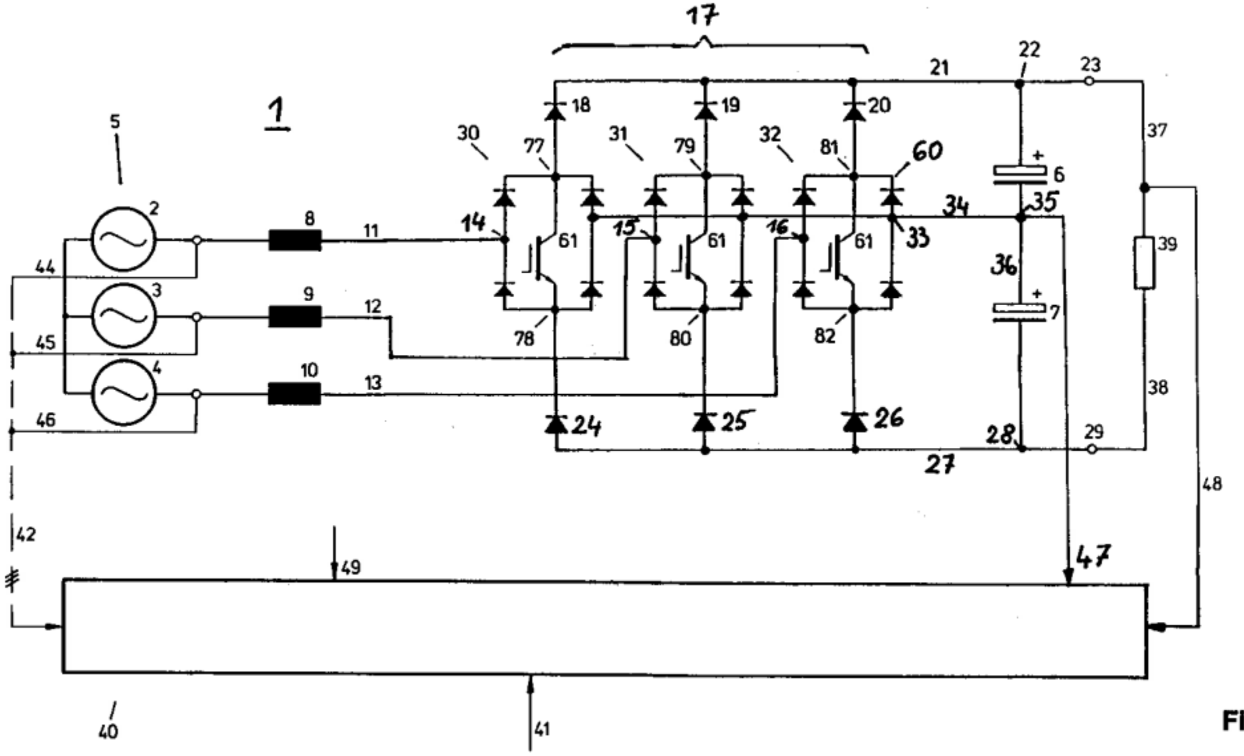


Fig. 1

0 660 498 A2

✓ Three controlled switches versus six
✓ 600-V-rated diodes and switches
✓ Smaller inductance than in 6-switch
✓ 3-level power converter
✓ High reliability in case of failure

❖ Unidirectional
❖ Complex control like SVPM

3-level Vienna rectifier 1993
Johann Kolar
EP0660498A2

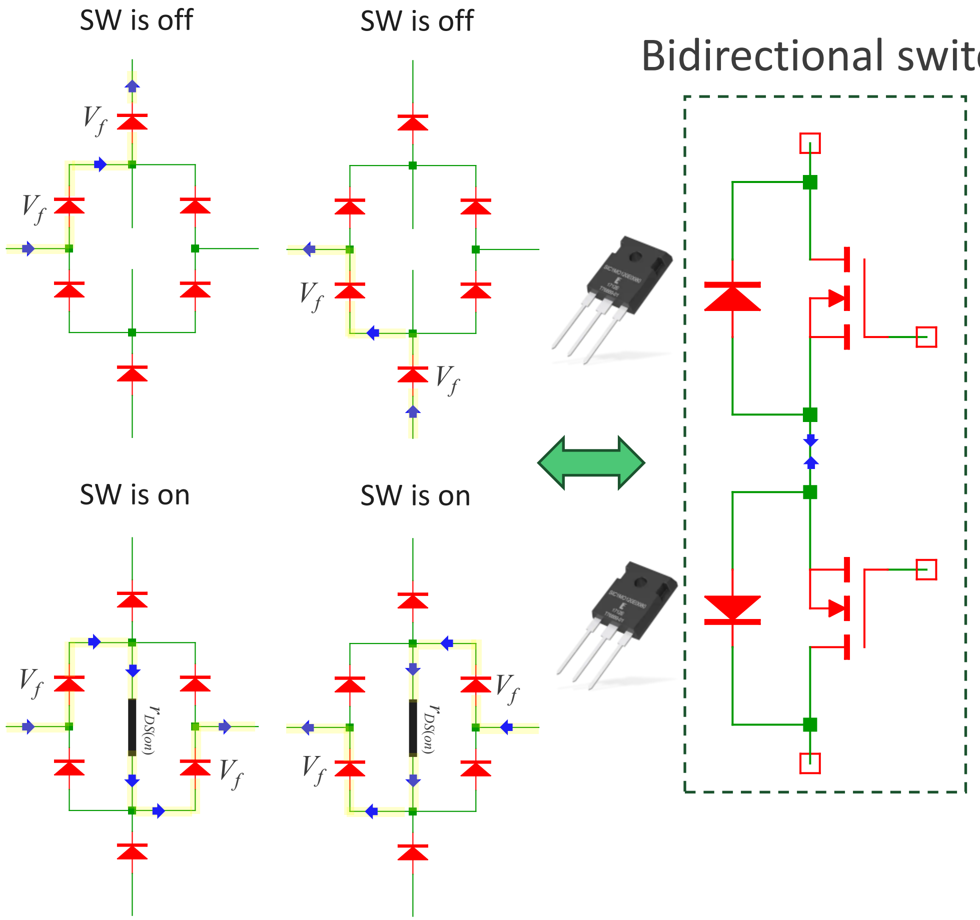
2-level Warsaw rectifier 1992
Włodzimierz Koczara
Wikipedia – 3-phase boost

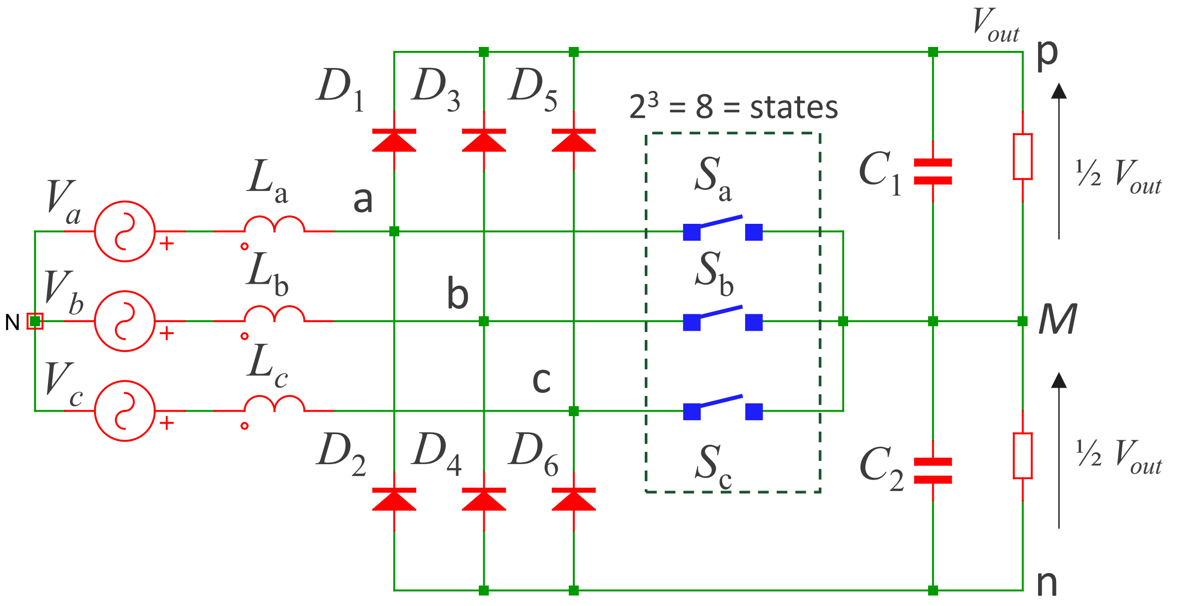
30 kW

Vienna 3-Phase PFC Reference Design, Microchip

Bidirectional Power Switches

- The arrangement featuring a transistor and diodes represents a bidirectional switch
- Two transistors back-to-back help reduce forward losses





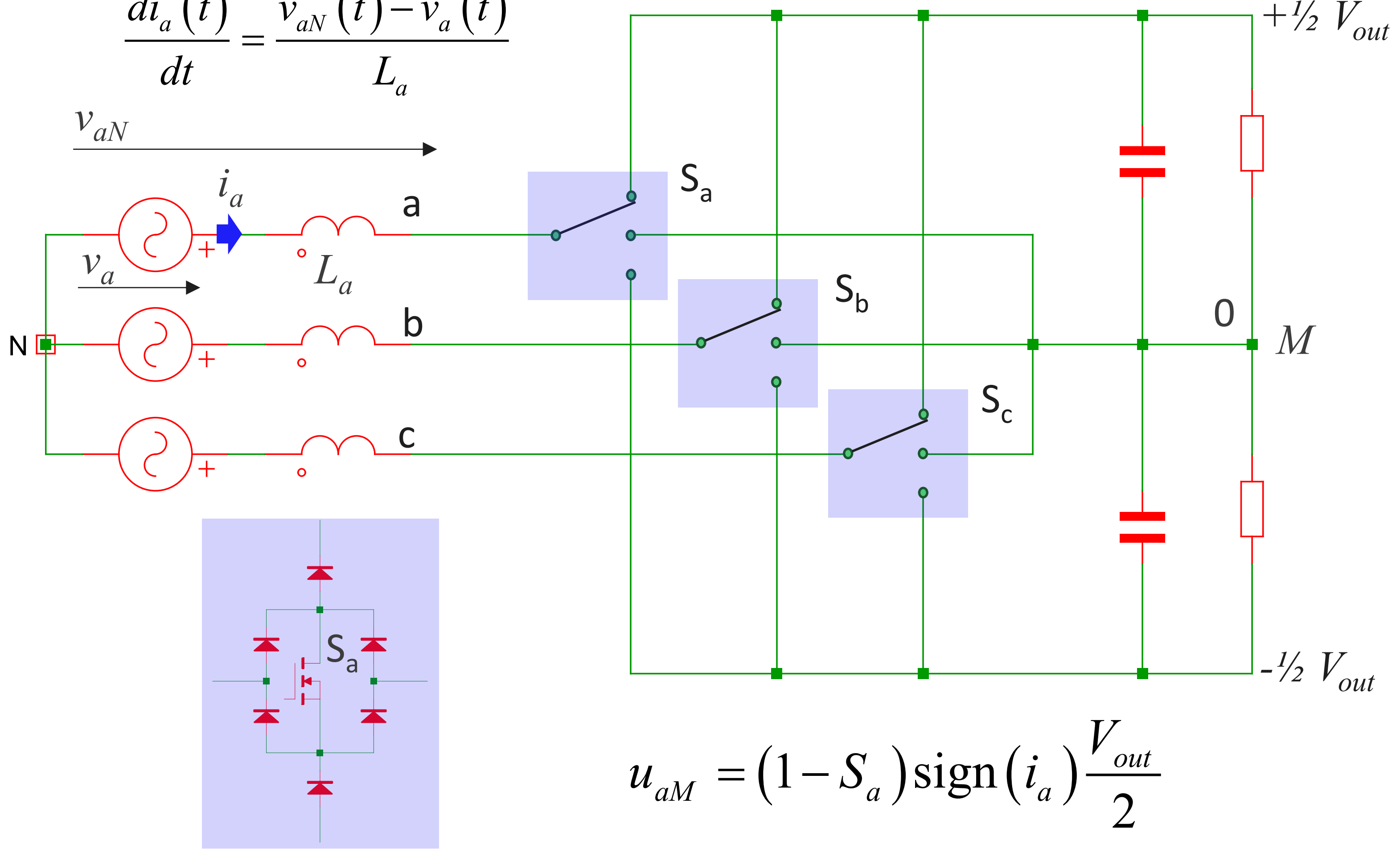
- The blocking voltage of the T-type switch is half the dc bus
- Inductor magnetization occurs when SW is turned on

Controlling the Vienna Rectifier Using a Simplified SVP, Ali Sunbul, MSEE thesis, Ontario, Canada, 2019

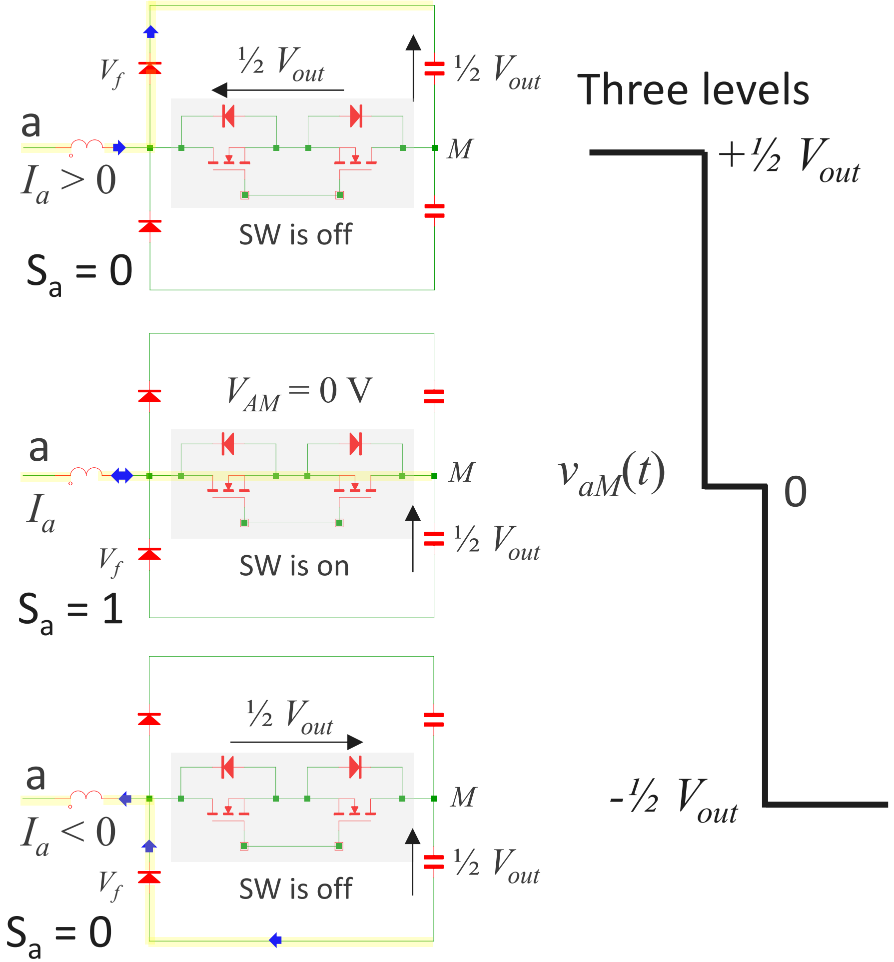
A Simplified View

- The Vienna rectifier can be visualized with three single-pole triple-throw switches
- The voltage at nodes a, b and c swings between ½ V_{out}, 0 V or - ½ V_{out}

$$\frac{di_a(t)}{dt} = \frac{v_{aN}(t) - v_a(t)}{L_a}$$



$$u_{aM} = (1 - S_a)\,\mathrm{sign}(i_a)\,\frac{V_{out}}{2}$$



Different Current and Voltage States

- There are six sectors in a mains cycle and eight switches combinations
- ✓ Three switches – each being either open or closed – lead to 8 different combinations

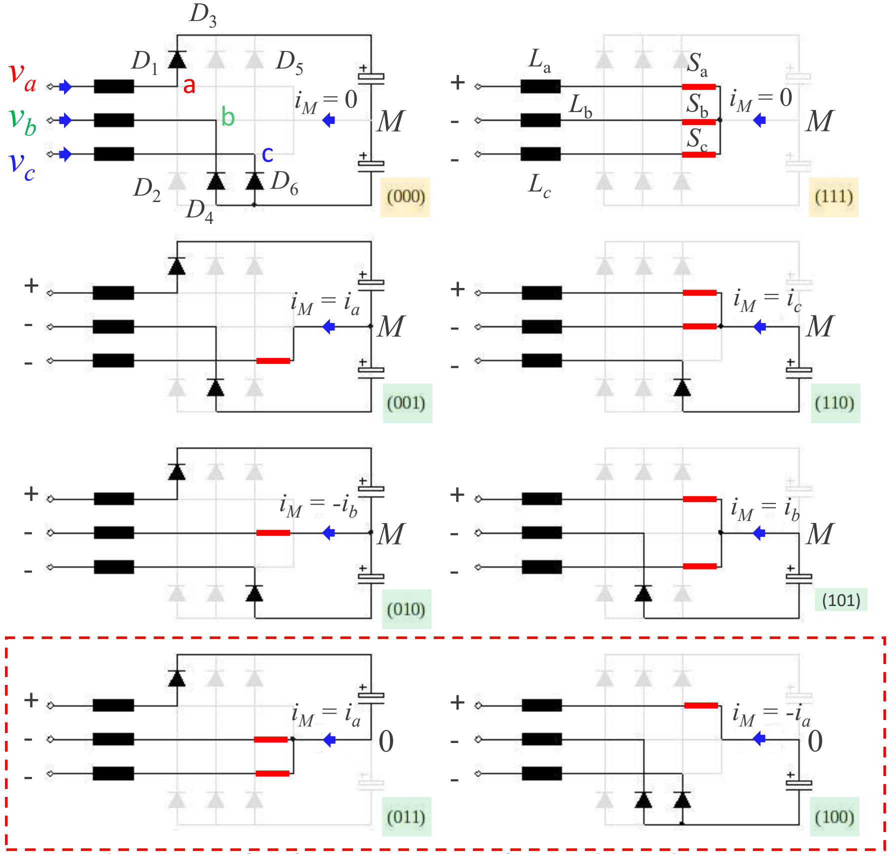
8 *space vectors*

	States	S_a	S_b	S_c
null	0 0 0	off	off	off
	1 0 0	on	off	off
	0 0 1	off	off	on
	1 0 1	on	off	on
	0 1 0	off	on	off
	1 1 0	on	on	off
	0 1 1	off	on	on
null	1 1 1	on	on	on

Operations in sector 1

$i_a > 0$ i_b & $i_c < 0$

p n n or + - -



Mid-point balancing with redundant states

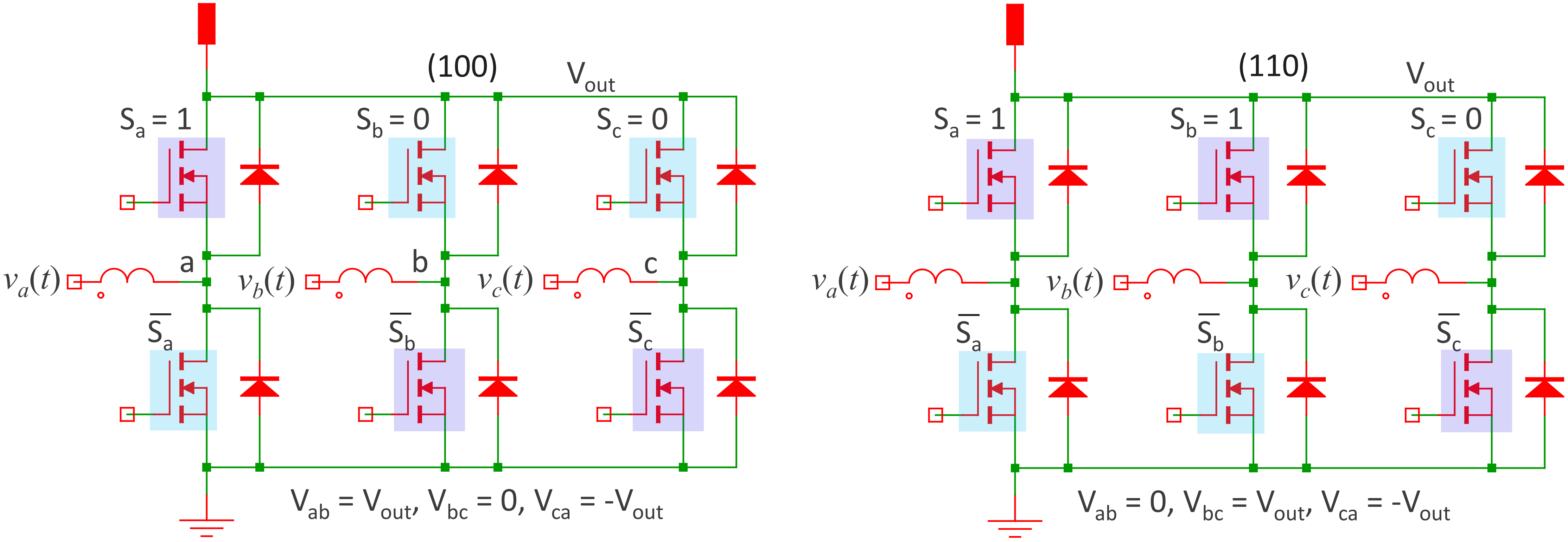
Voltage levels produced in each state

Sector	States	V_{a0}	V_{b0}	V_{c0}
Sector 1	0 0 0	$V_{out}/2$	$-V_{out}/2$	$-V_{out}/2$
	1 0 0	0	$-V_{out}/2$	$-V_{out}/2$
	0 0 1	$V_{out}/2$	$-V_{out}/2$	0
	1 0 1	0	$-V_{out}/2$	0
	0 1 0	$V_{out}/2$	0	$-V_{out}/2$
	1 1 0	0	0	$-V_{out}/2$
	0 1 1	$V_{out}/2$	0	0
	1 1 1	0	0	0

J. Kolar et al., Three-Phase PFC Rectifier and Ac-Ac Converter Systems, APEC 2018 Seminar.

Similar Truth Table for a 6-Pack PFC

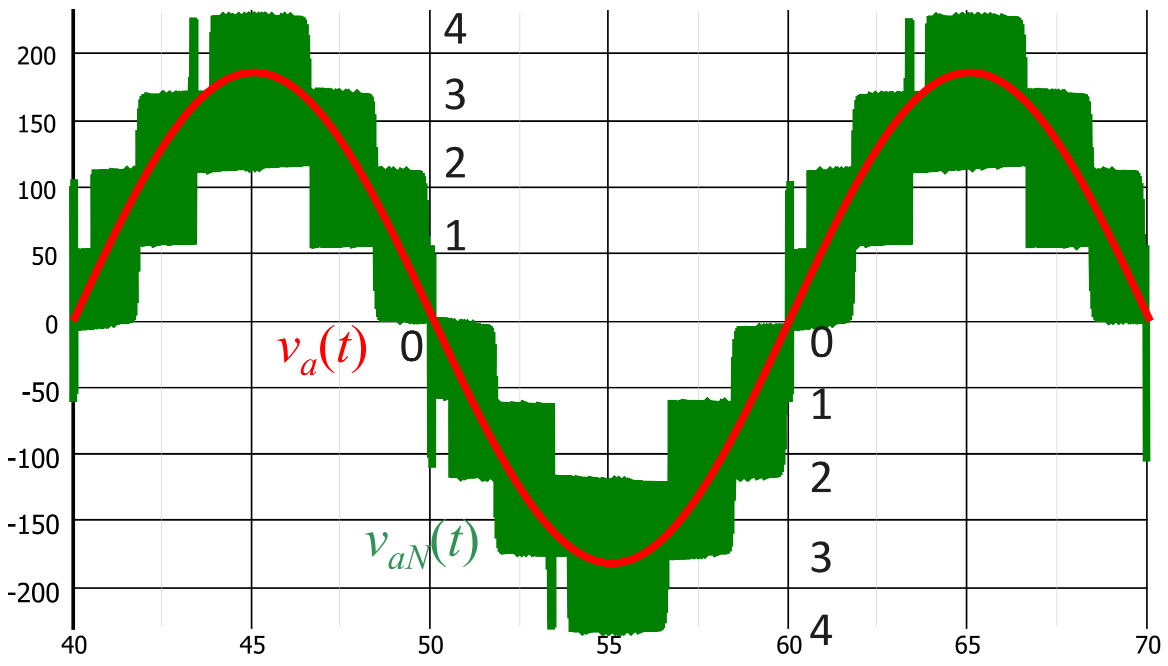
- The same concept of switching states is applied to a 6-switch converter
- Three controlled switches lead to 8 different combinations from 000 to 111



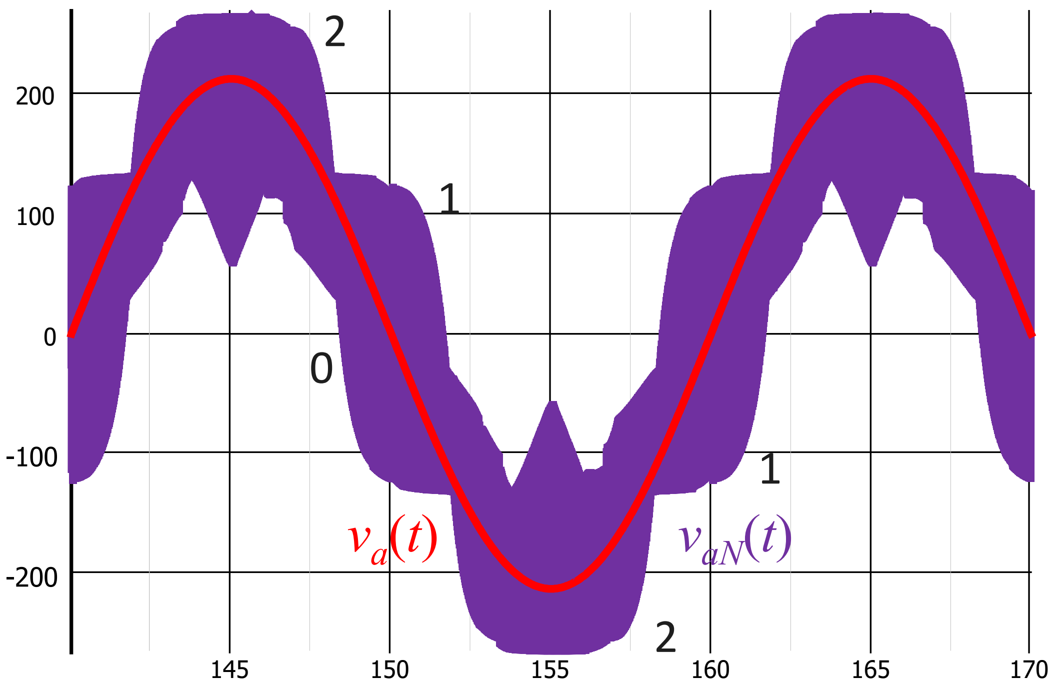
- ✓ The idea is to synthetize voltages by alternating the combinations
- ✓ Adjusting the time during which a combination is set, *averages* intermediate values

Three-Phase Three-Level Converter

- The number of levels defines how many voltage steps form the envelope
- A three-level PFC overs a better granularity than a two-level version



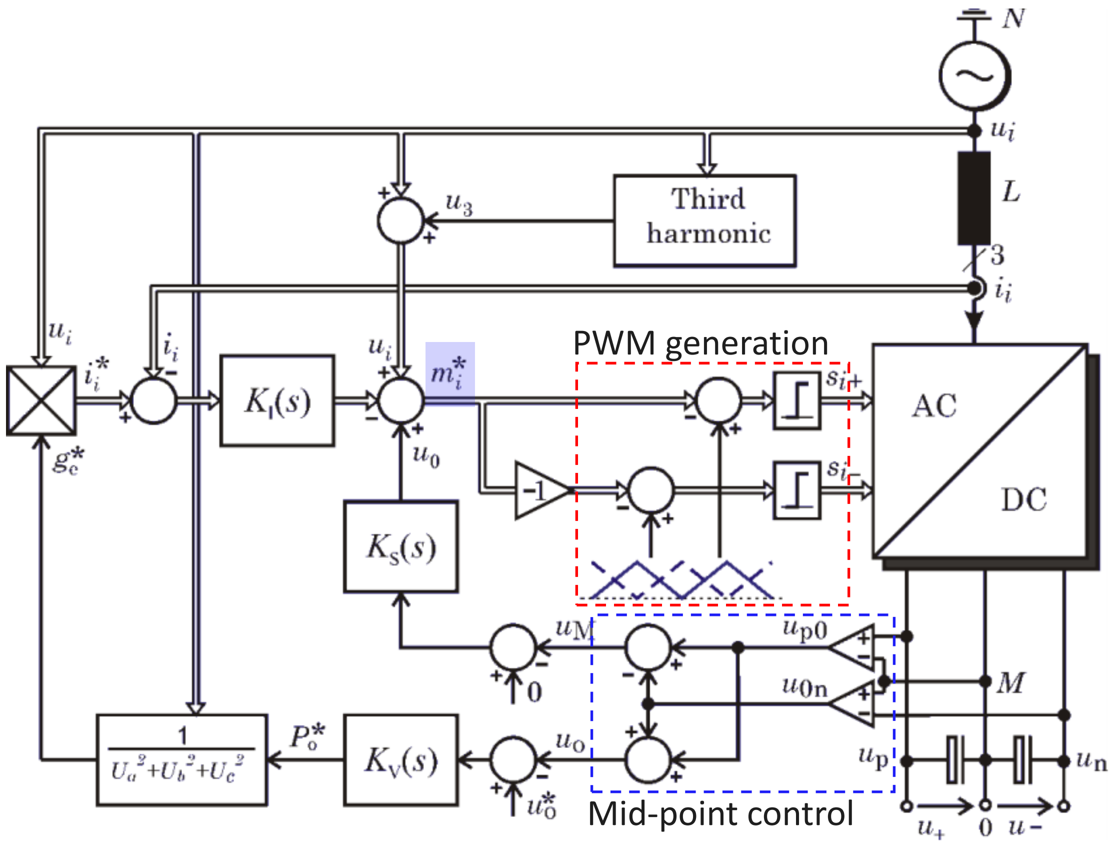
There are 9 different possible voltages with a 3-level PFC
Vienna, individual phase control, THD = 2.8%

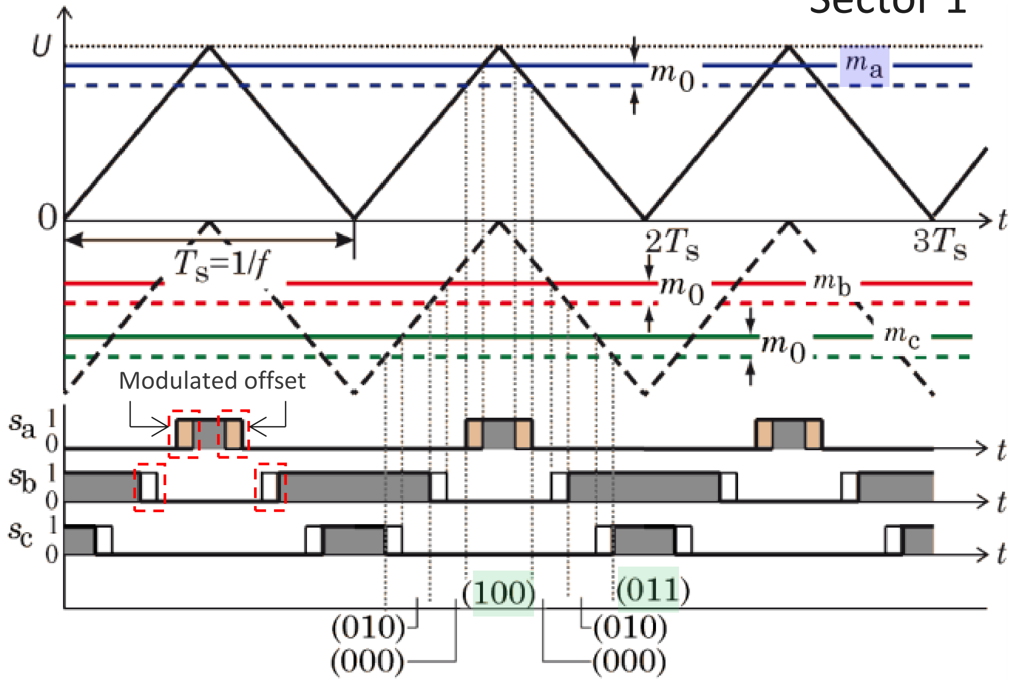


5 different possible voltages with a 2-level PFC
6-pack type – THD = 4.7%

Control of the Vienna Rectifier

- There are many options to control a Vienna rectifier
- Space vector modulation (SVPWM) is one of them with OCC or individual phase control





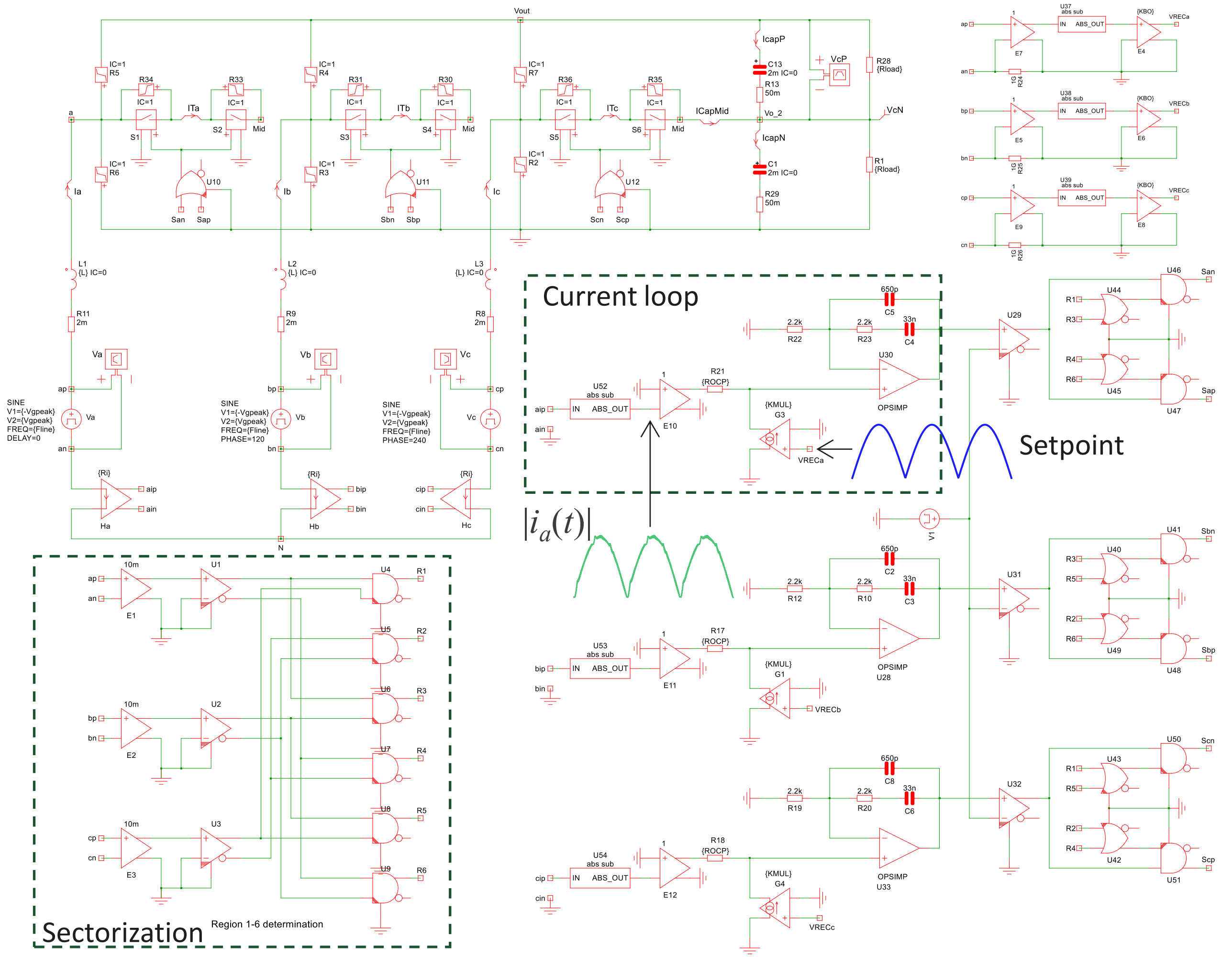
- Typical space vector realization with a triangular carrier and setpoints m_a, m_b and m_c.
- An offset m_0 is added to control the mid-point through redundant vectors 100 and 011.

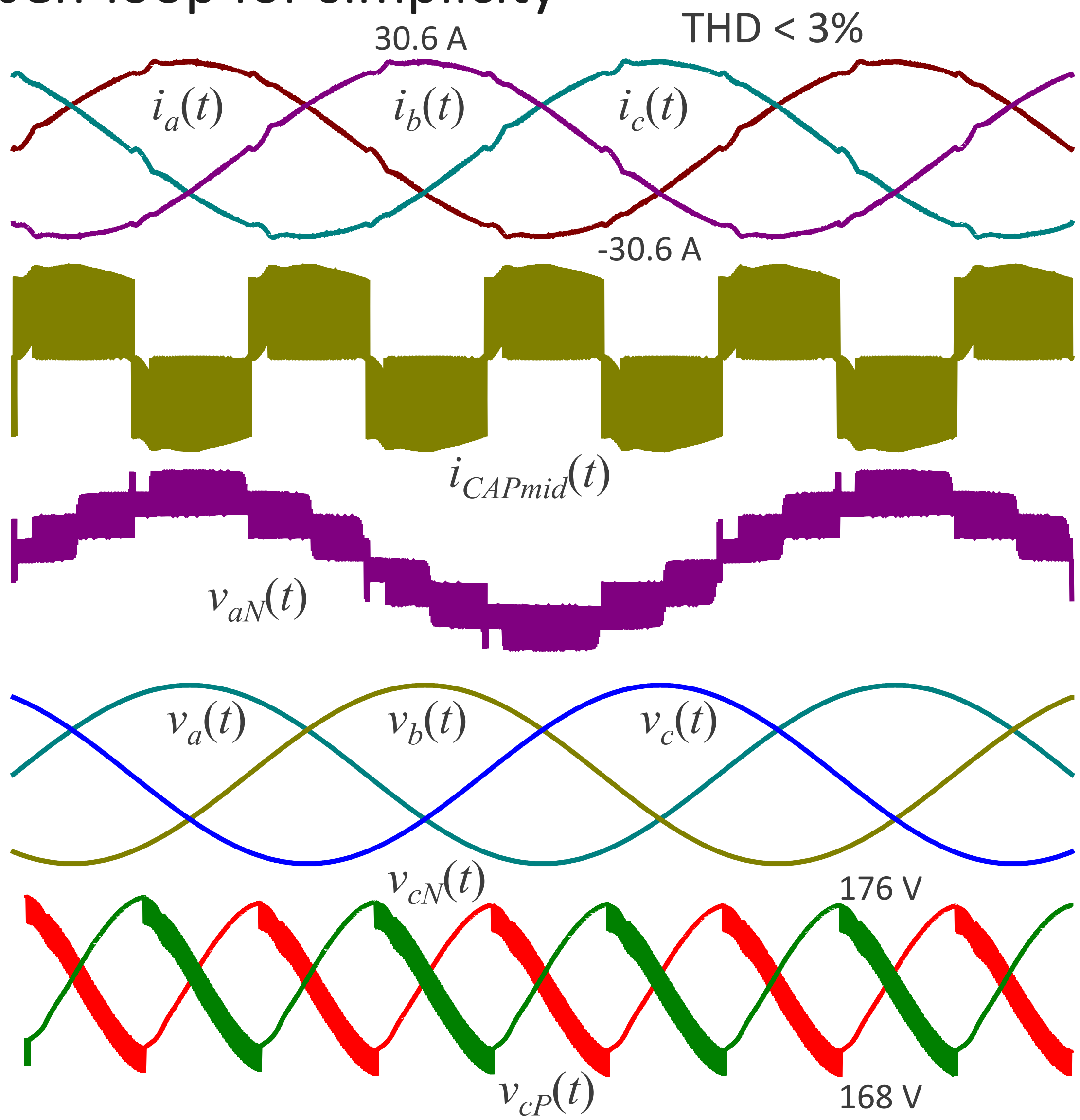
Three-Phase PFC Rectifier and Ac-Ac Converter Systems, J.W. Kolar, M. Hartmann and T. Friedli, Professional Seminar, APEC 2011, fort Worth

FUTURE ELECTRONICS

Simulating a Vienna Rectifier

- This is a 3-loop switching system operated in open-loop for simplicity
- Output power is 8 kW from a 130-V ac source





Conclusion

- Diode bridge in tri-phase rectification brings 60° holes in the phase currents
- Power factor correction is necessary to reduce the harmonic content
- Single-switch PFC do not lead to acceptable results
- Two-level rectifiers feature a high-voltage rail and bring stress on semis
- Three-level types are more complex but improve distortion and reduce stress
- The Vienna rectifier can be implemented with an analogue or digital solution