VFD Installations and Applications

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Chicago IEEE Chapter

Agenda

Part 1:

- Harmonic Mitigation
  - Methods to reduce Ithd, Vthd
  - Line reactors and DC link chokes
- Active Rectifier Applications
  - Downhill conveyors
  - Centrifuges
  - Fans
  - Dynamometers
  - Fibers
  - Paper mills
  - Cranes
- Active Rectifier Operation
- What about Power Factor?

Part 2:

- Motor speed vs max load / cooling, use of motor RTDs
- Overspeed with fans / pumps and increase in torque and power
- Min speed with pumps
- SCCR for drives
- HRG vs solid ground
- Shaft grounding brushes / bearing currents
- Load reactors on the output
- Wiring on input / output
  - Insulation types
  - Conduit, tray
  - Type (VFD, individual wires)
  - Control wiring management

Part 1

Harmonic Mitigation

Harmonics — What can be done?

Solutions typically used

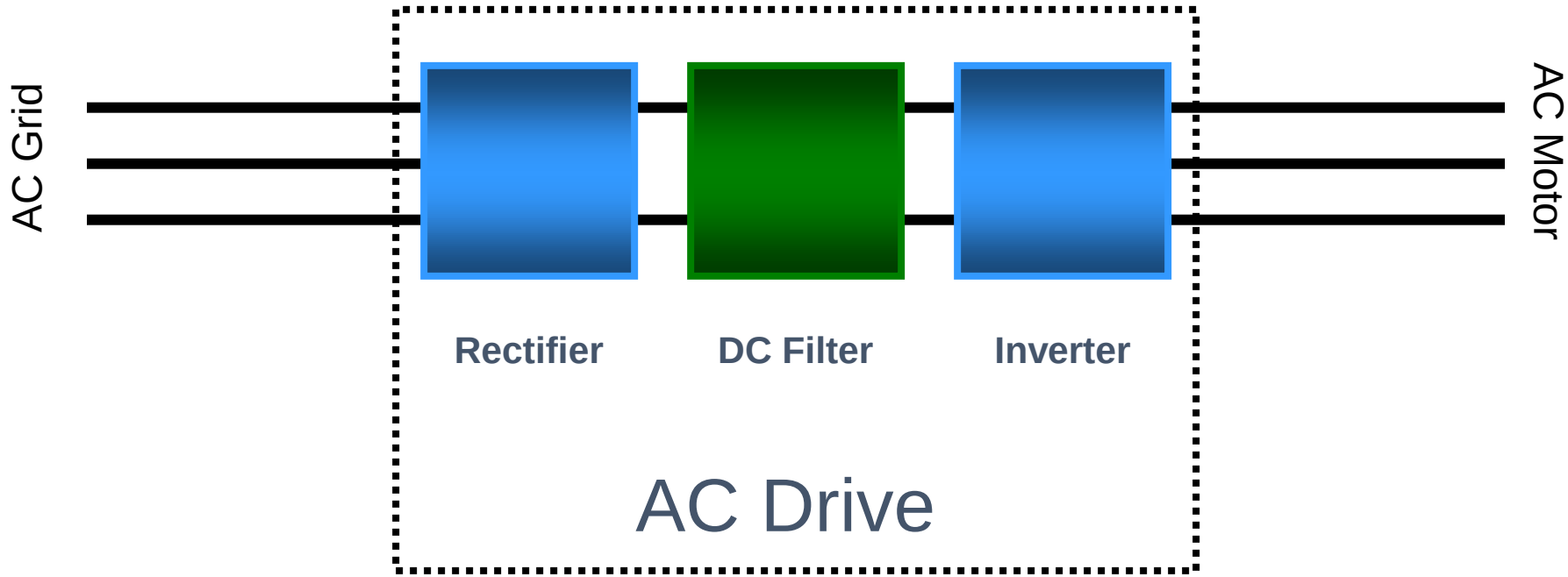
LV Drives

- Line Reactors or isolation transformers
- DC Link Chokes
- Passive Harmonic Filters
- Active Harmonic Filters
- Multi-Pulse (parallel bridges)
- 12P, 18P
- AFE (ULH)

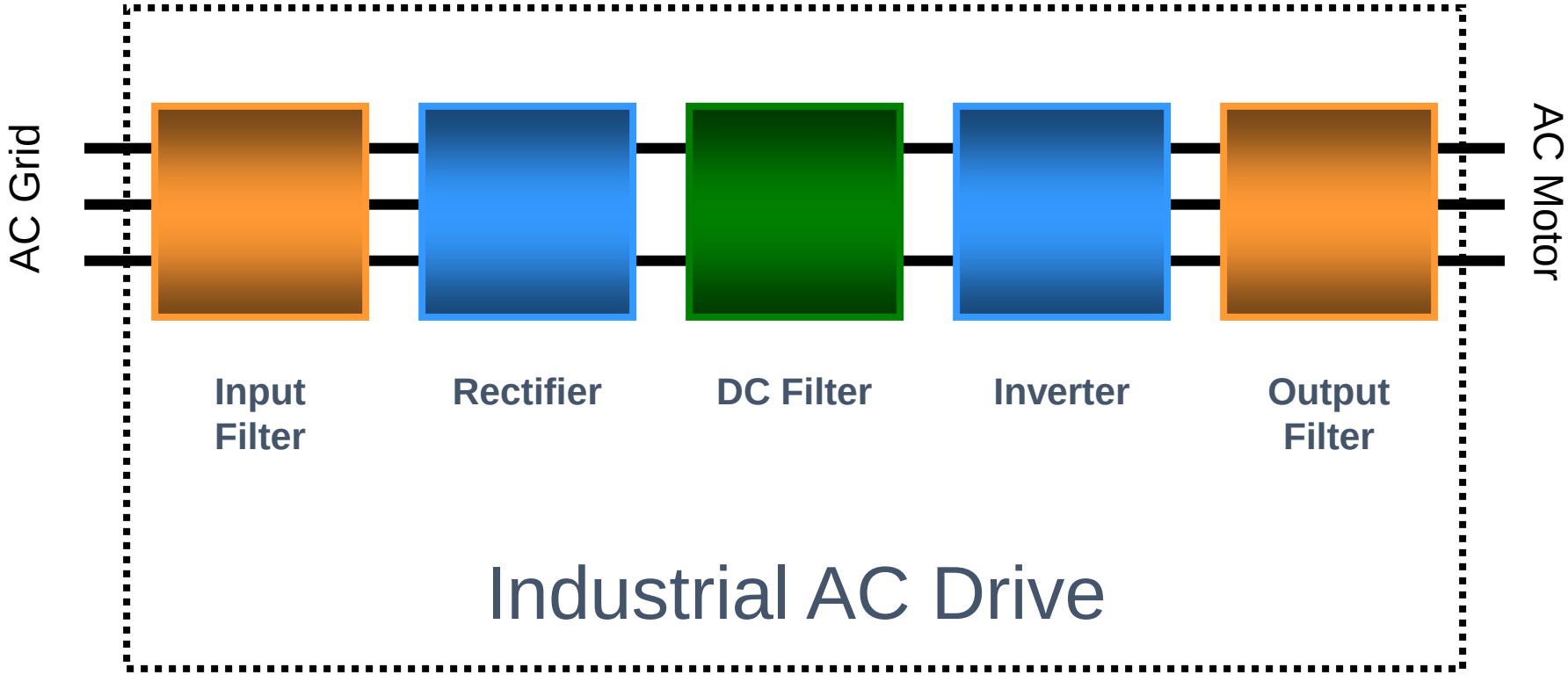
MV Drives

- Multi-Pulse (series or series/parallel bridges)
- 12P, 18P, 24P, 36P, 72P
- AFE (ULH)

General Block Diagram of an AC Drive

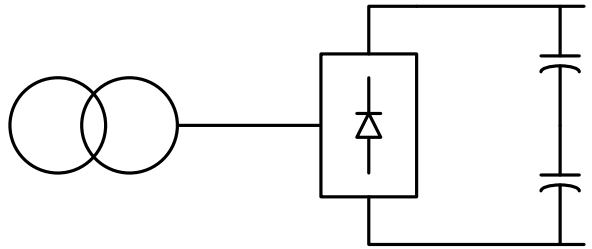


General Block Diagram of an Industrial AC Drive

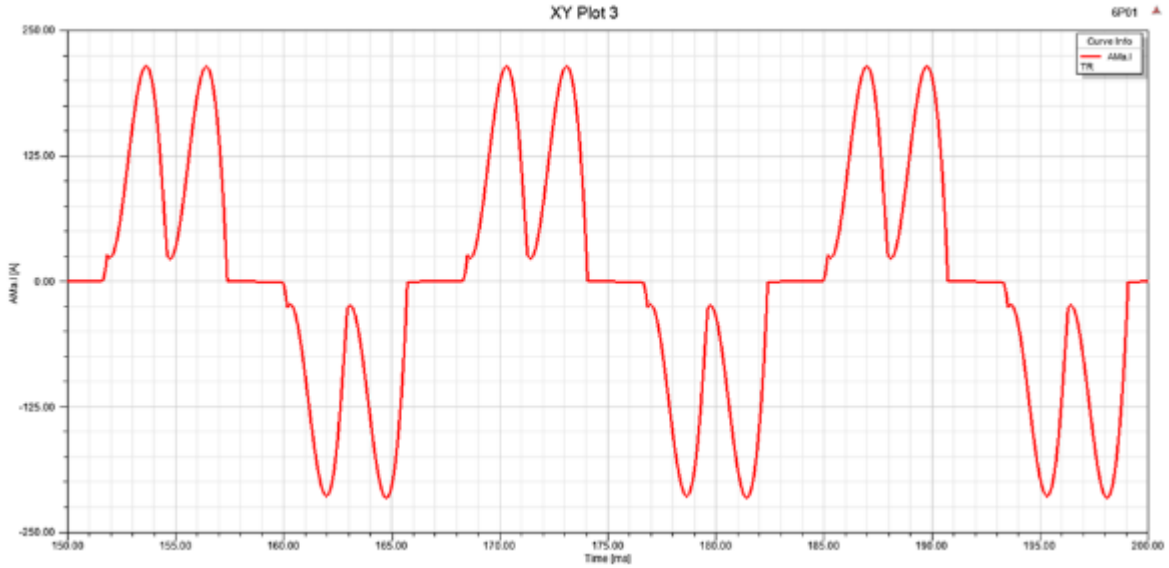


6-Pulse Drive, no mitigation

80-120% Ithd

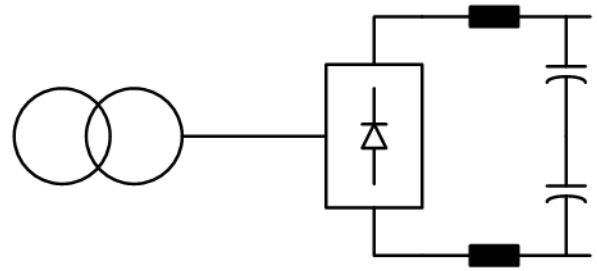


Basic Converter

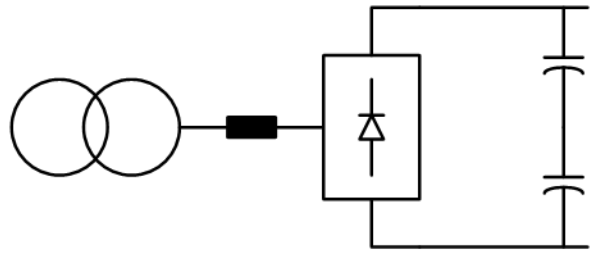


6-Pulse Drive with Line Reactor and/or Link Choke

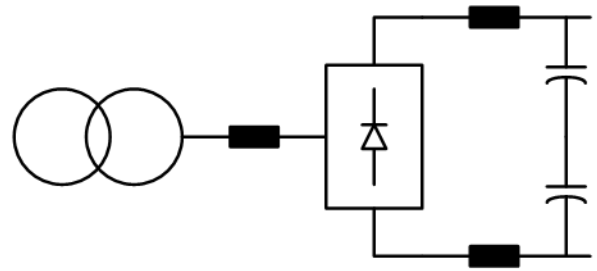
30-40% Ithd



DC Link Chokes

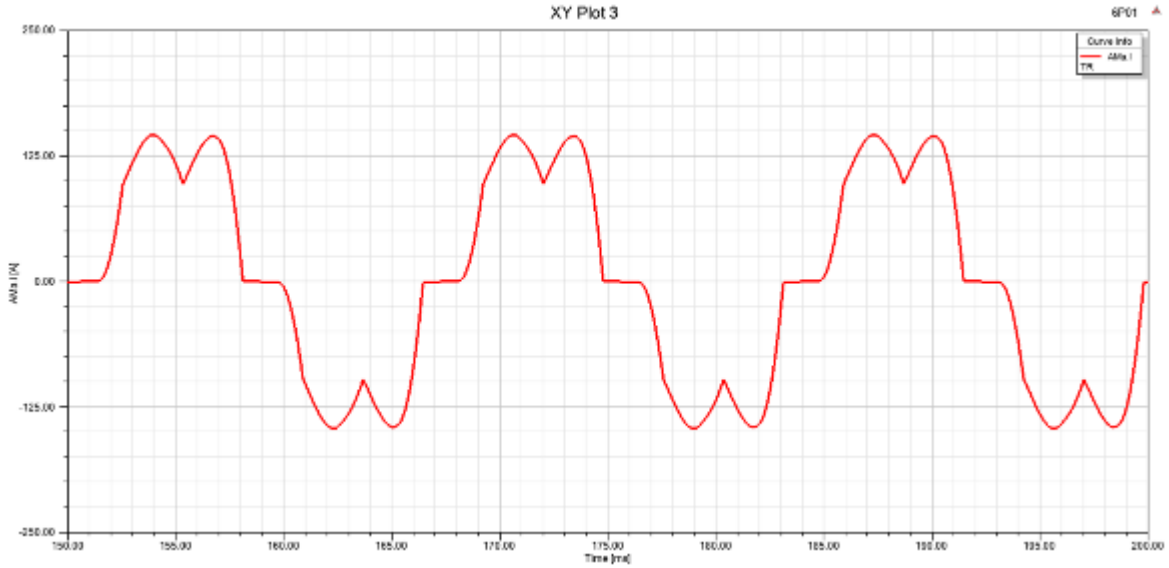


AC Line Reactor



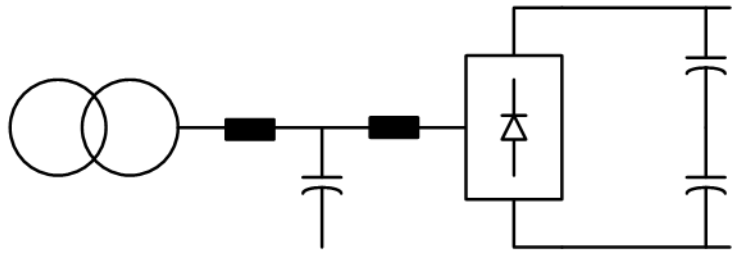
Link Choke and Reactor

(reduces harmonics)

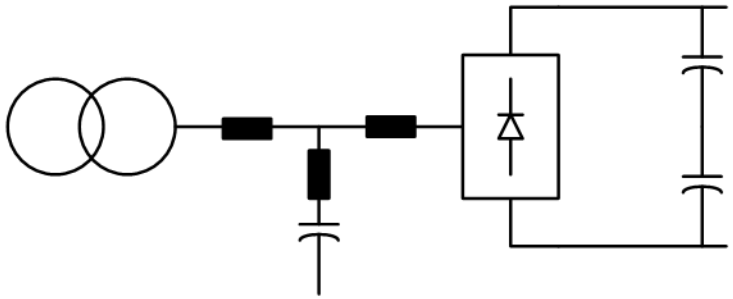


6-Pulse Drive with Passive Harmonic Filter

5-10% Ithd

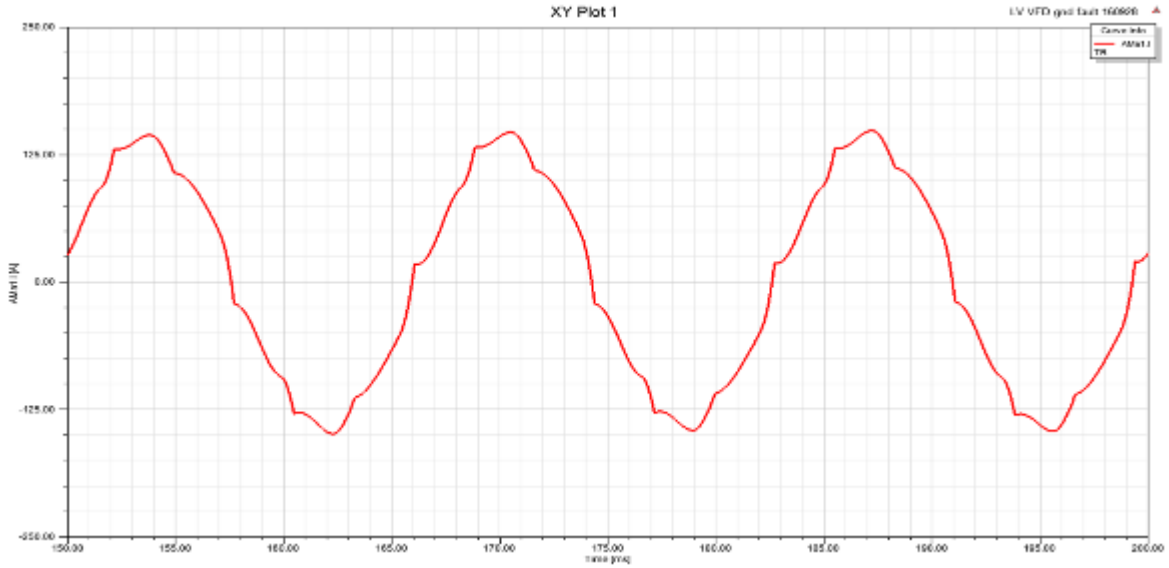


Passive Harmonic Filter



Passive Notch Filter

(supplies harmonics)

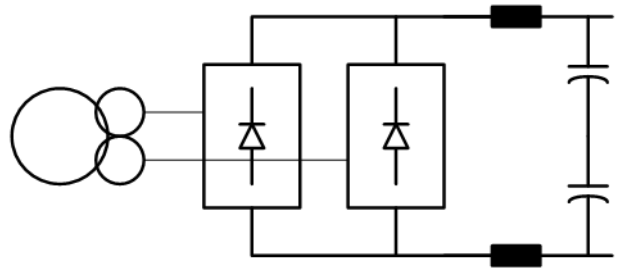


How is Multi-Pulse accomplished?

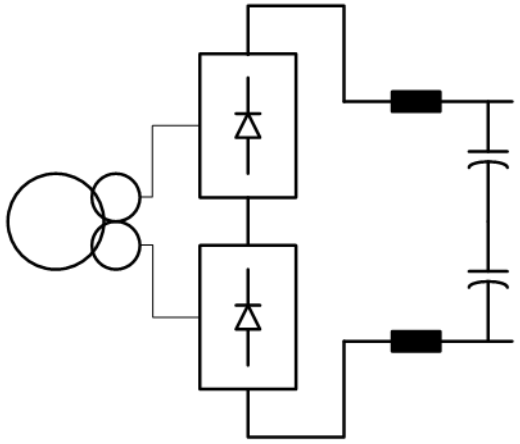
Input Current Pulses / Cycle	Number of 6-Pulse Bridges (secondaries)	Number of Phases (wires)	Phase Shift Between Bridges	Harmonic Pairs
6	1	3	--	$6k \pm 1$
12	2	6	30	$12k \pm 1$
18	3	9	20	$18k \pm 1$
24	4	12	15	$24k \pm 1$
36	6	18	10	$36k \pm 1$
48	8	24	7.5	$48k \pm 1$
72	12	36	5	$72k \pm 1$
= multiple of 6	= Pulses / 6	= Pulses / 2	= 360 / Pulses	k = 1,2,3,…

12-Pulse Drive: Series or Parallel Bridges

10-15% Ithd

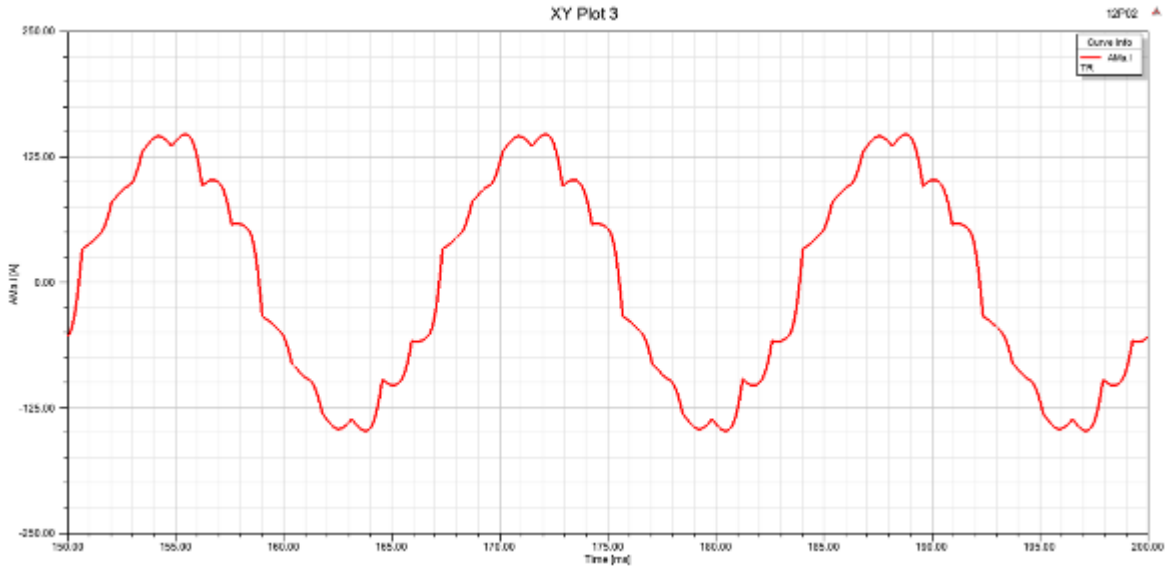


Parallel Bridges



*Series Bridges

(cancels harmonics)

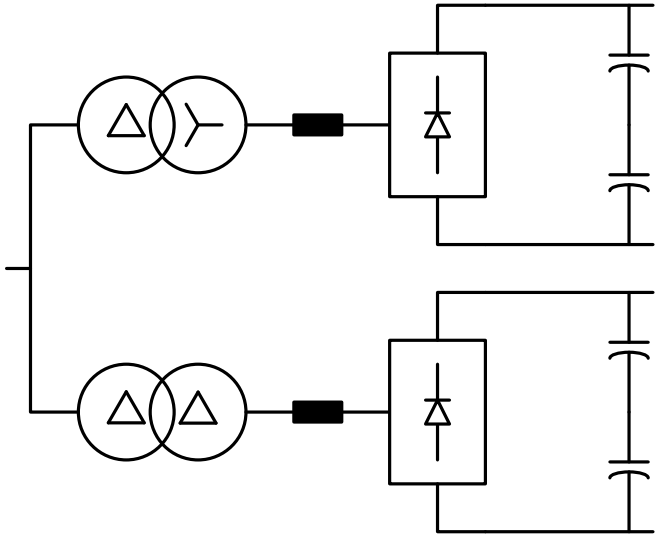


* used for MV drives

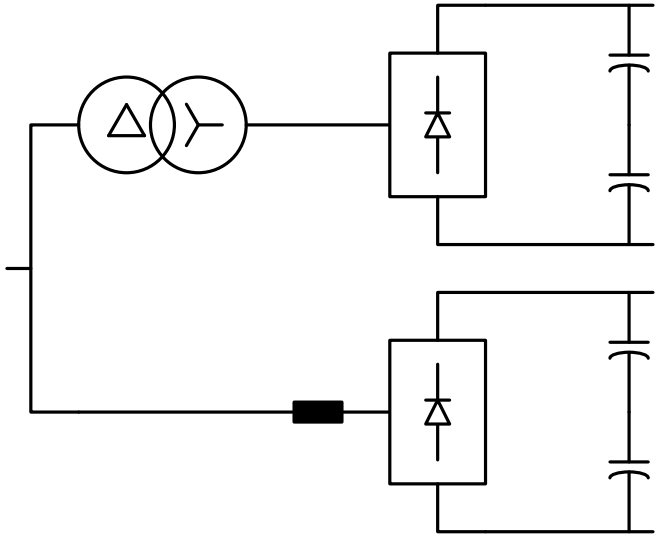
12-Pulse Drive: Pseudo 12-Pulse

10-15% Ithd

Split the drive load into two, somewhat equal parts.



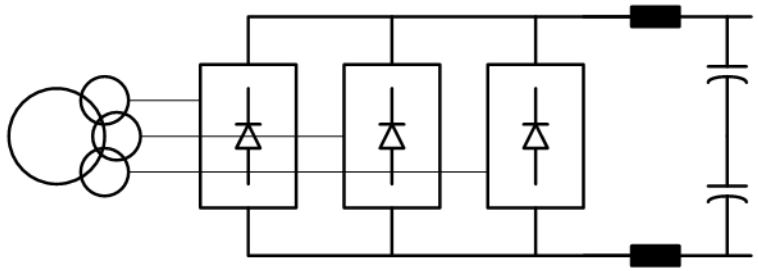
Or use two zig-zag transformers:
One zigs +15º, the other zags -15º
One spare can be used either way.



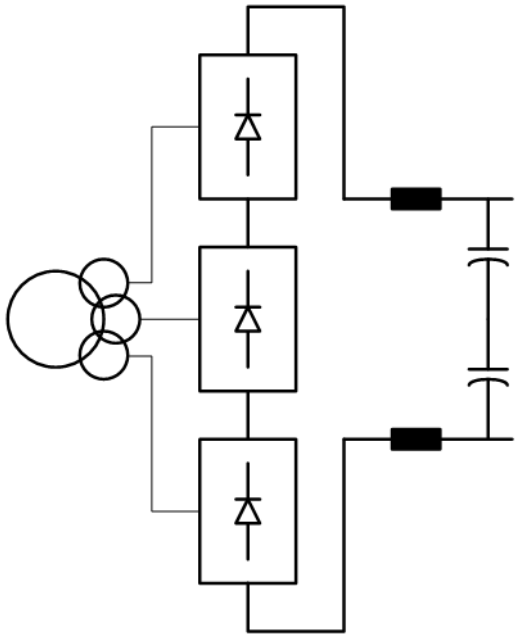
Or use one Dy transformer
and a line reactor.
Match the impedances.

18-Pulse Drive: Series or Parallel Bridges

5-6% Ithd

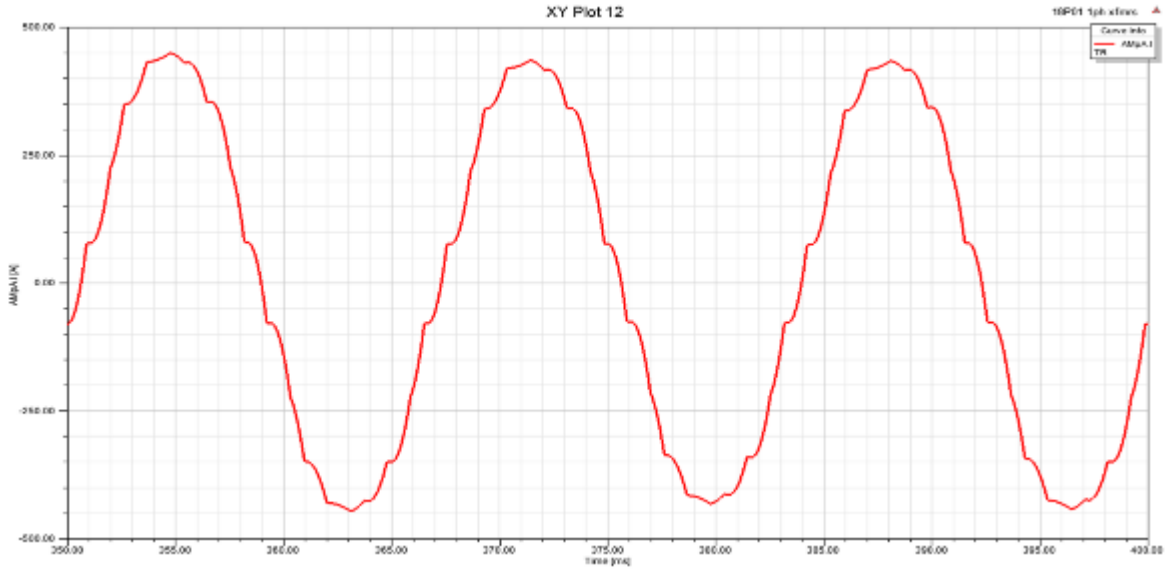


Parallel Bridges



*Series Bridges

(cancels harmonics)

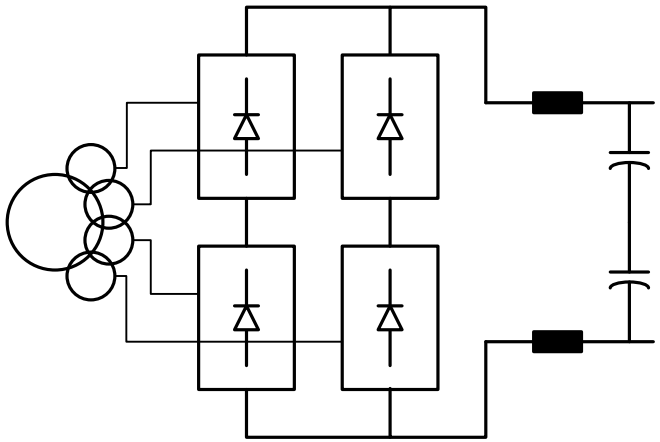


* used for MV drives

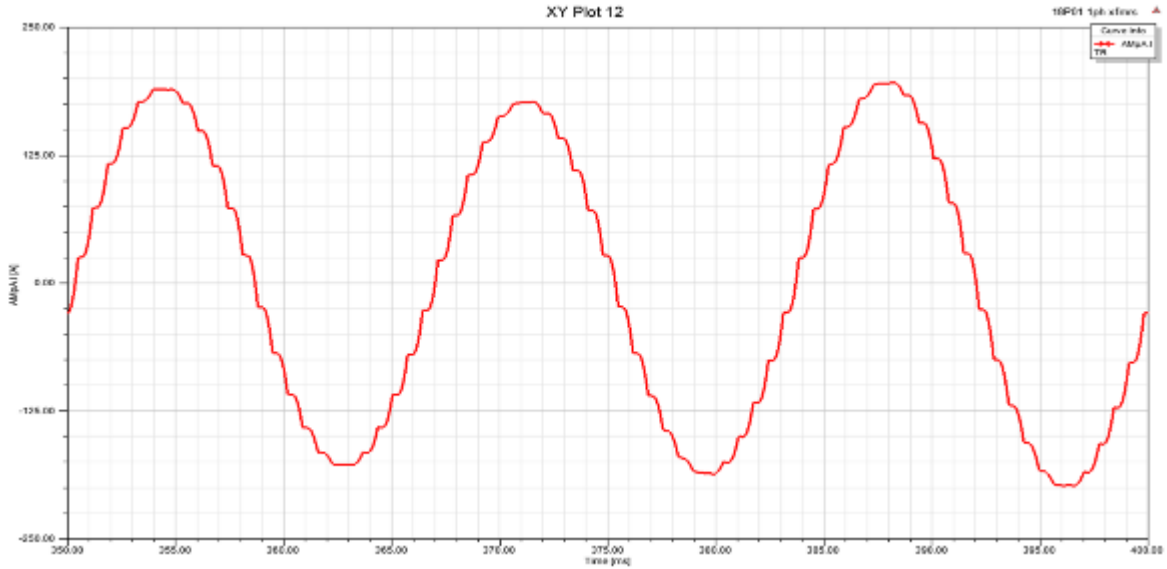
24-Pulse Drive: Series / Parallel Bridges

4-5% Ithd

(cancels harmonics)



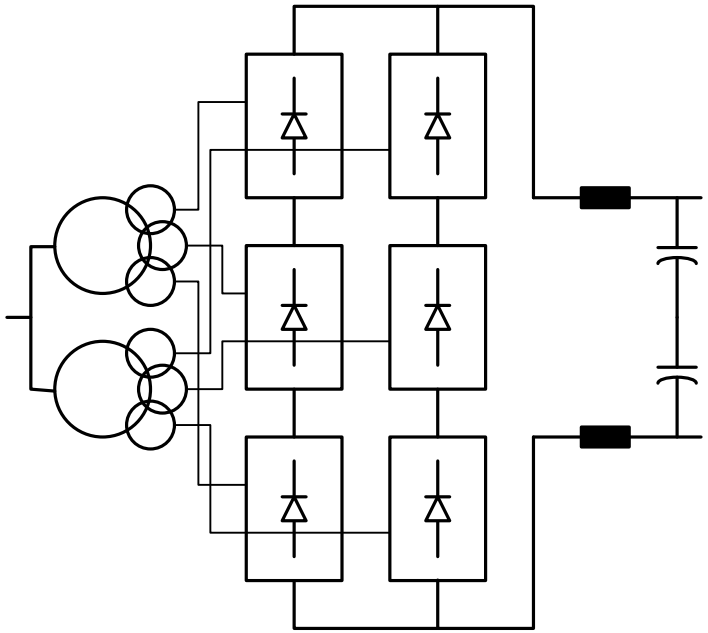
*Series / Parallel Bridges, 24P



* used for MV drives

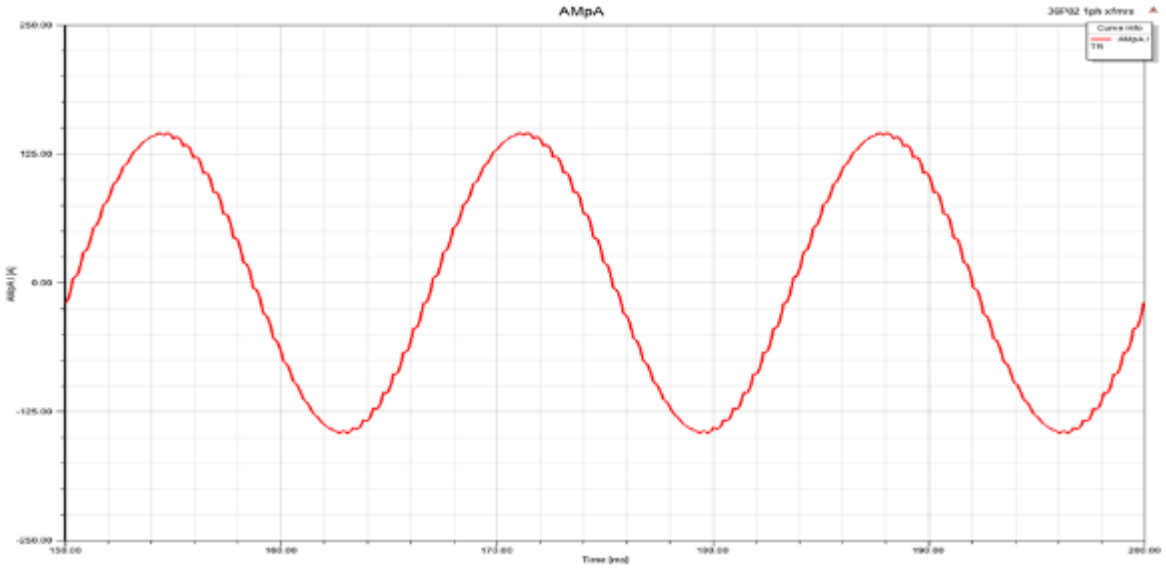
36-Pulse Drive: Series / Parallel Bridges

3-4% Ithd



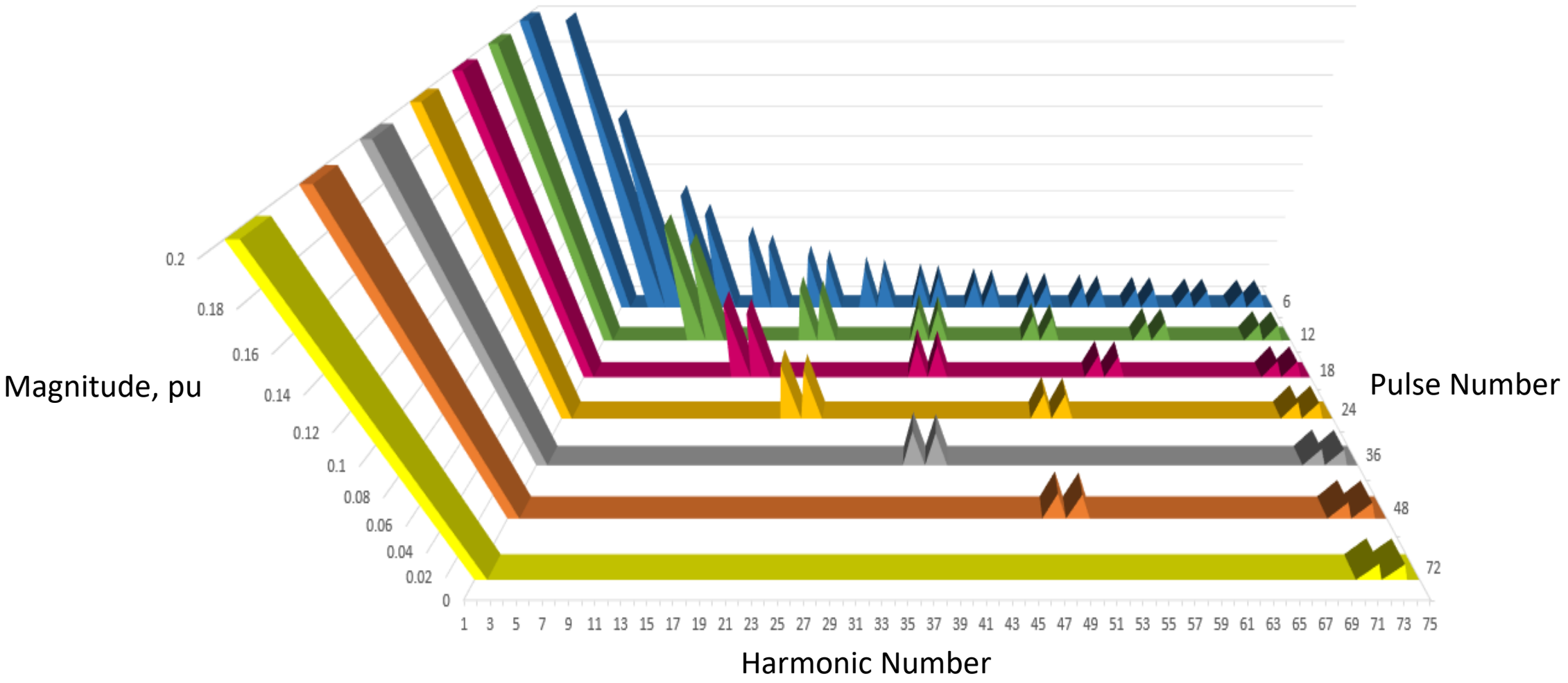
*Series / Parallel Bridges, 36P

(cancels harmonics)



* used for MV drives

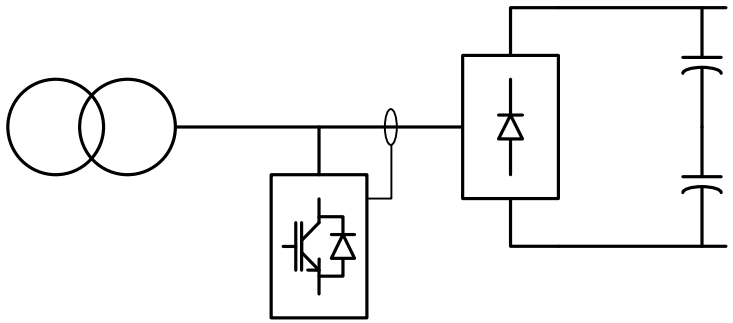
How does it help?



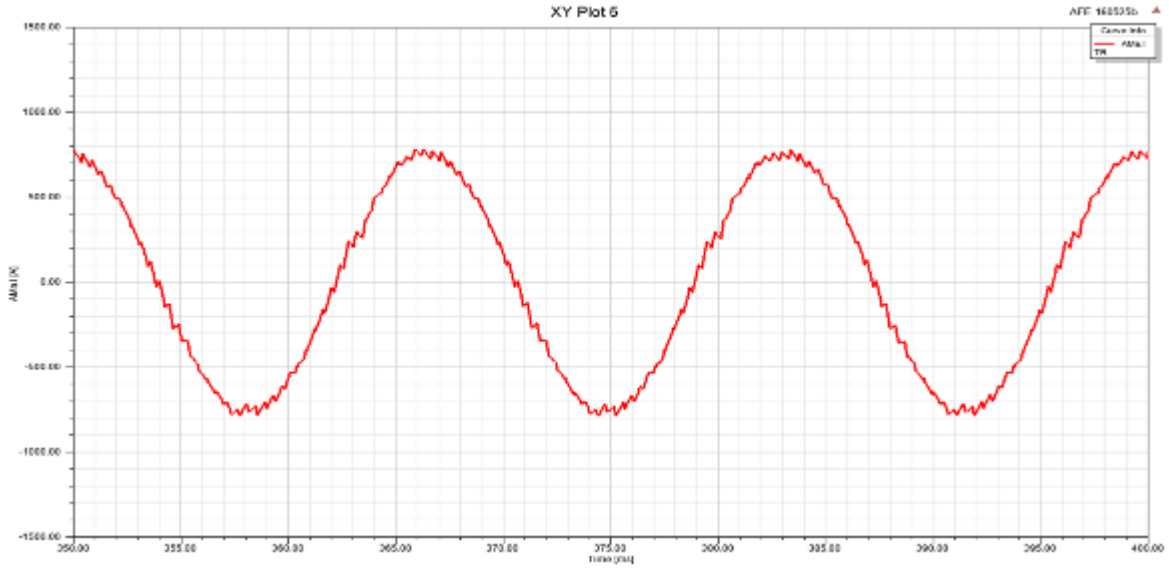
6-Pulse with Active Harmonic Filter

3-5% Ithd

(supplies harmonics)

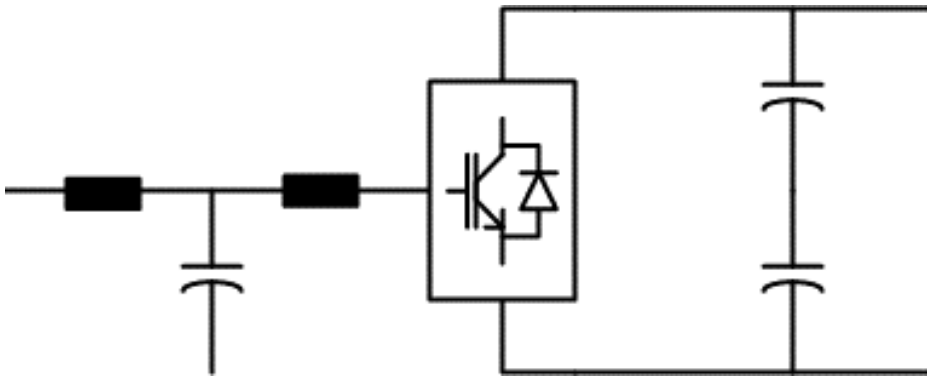


Active Harmonic Filter



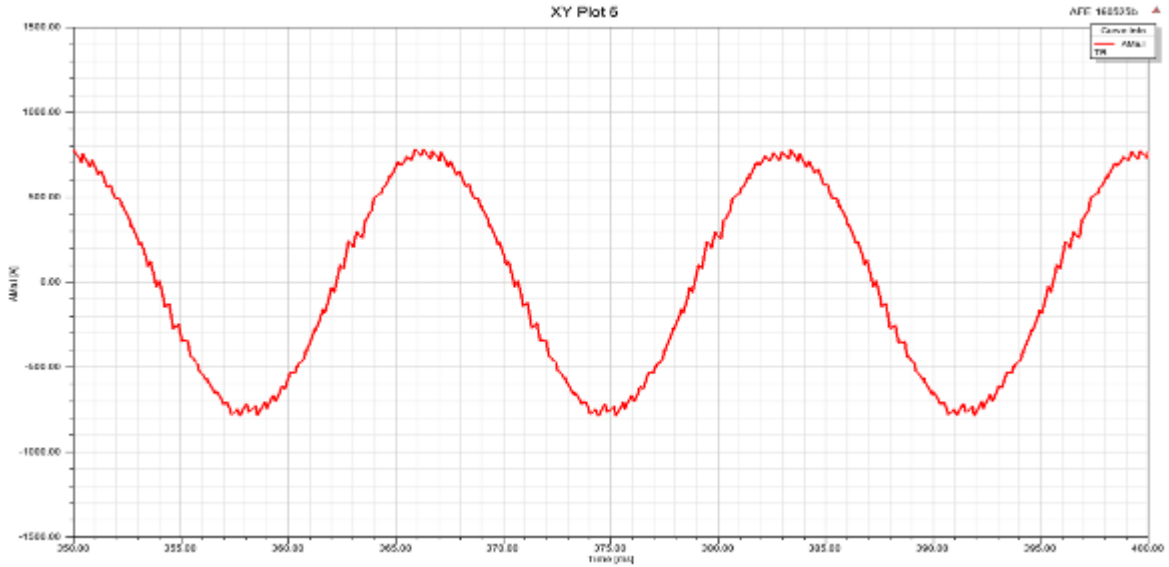
3-Phase Drive with Active Front End

4-5% Ithd



*AFE with LCL Filter

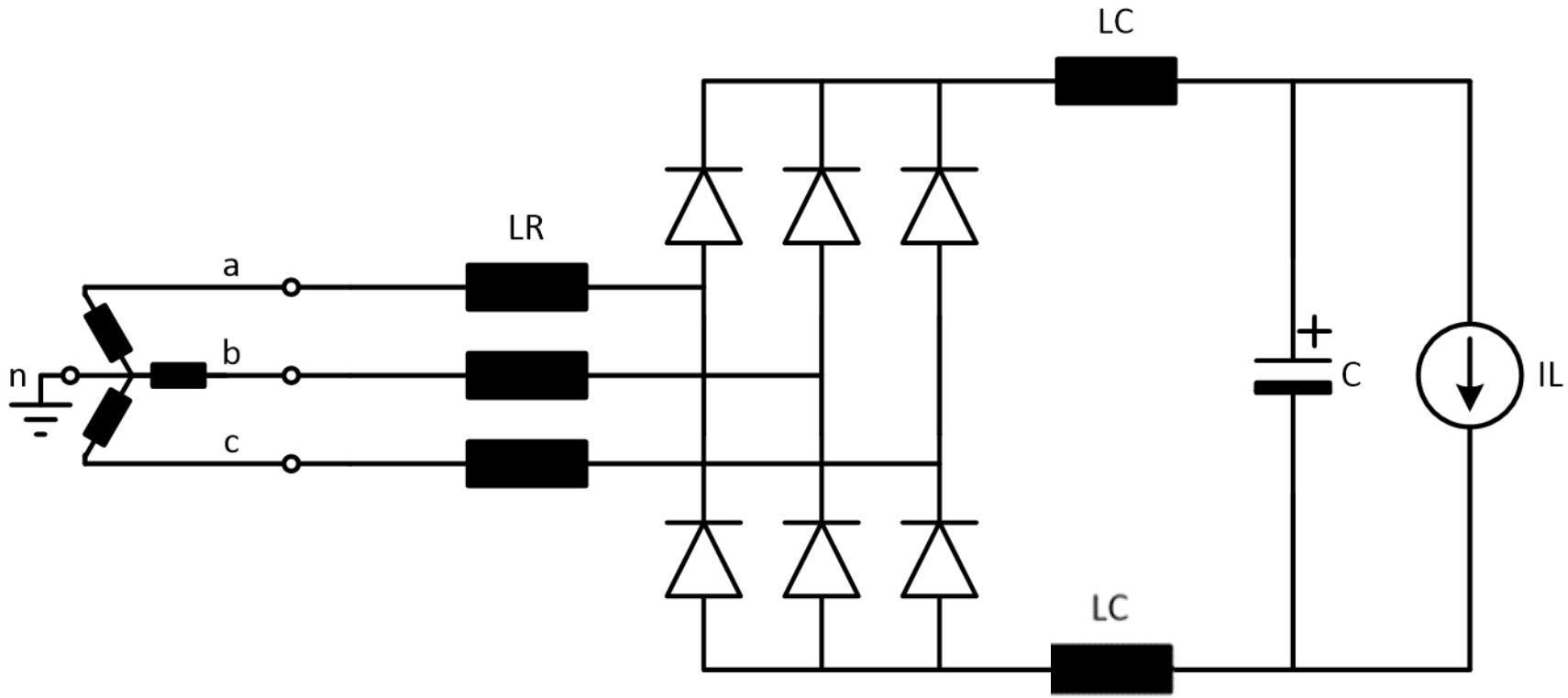
(does not produce harmonics)



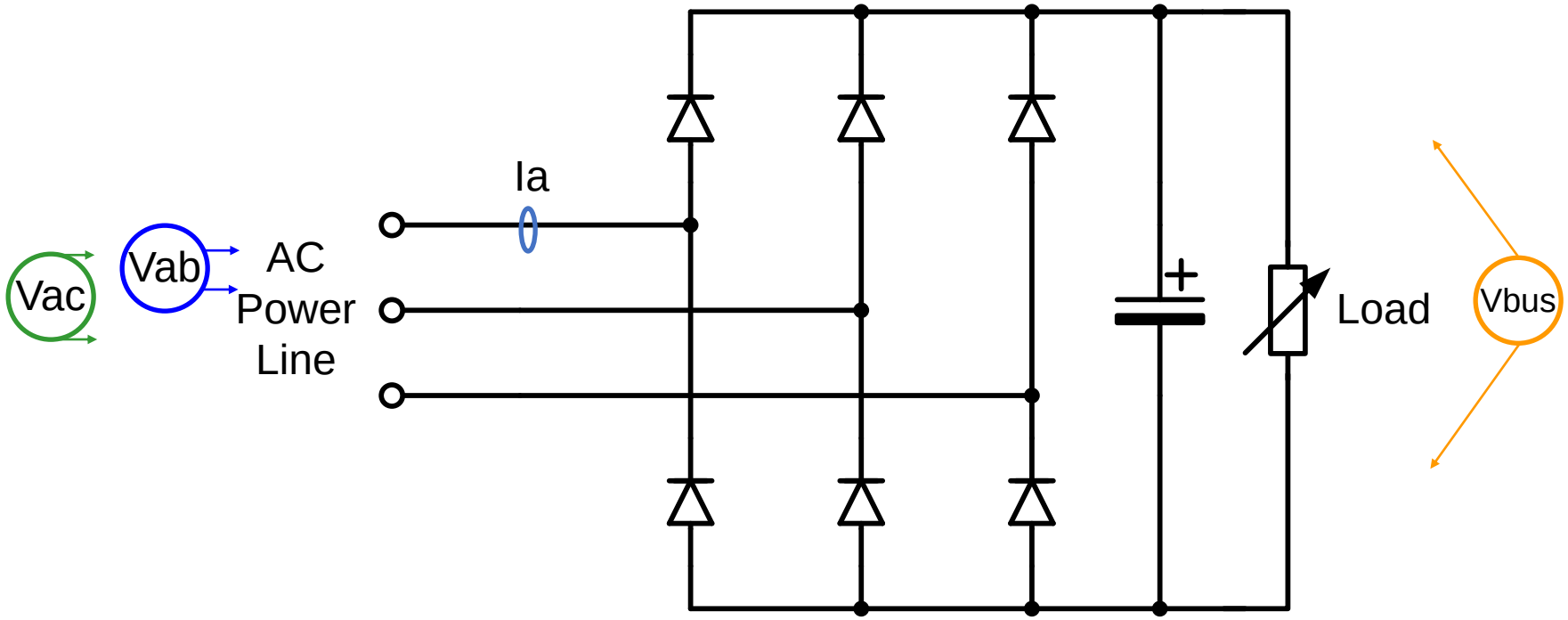
* used for MV drives

Line Reactors and DC Link Chokes

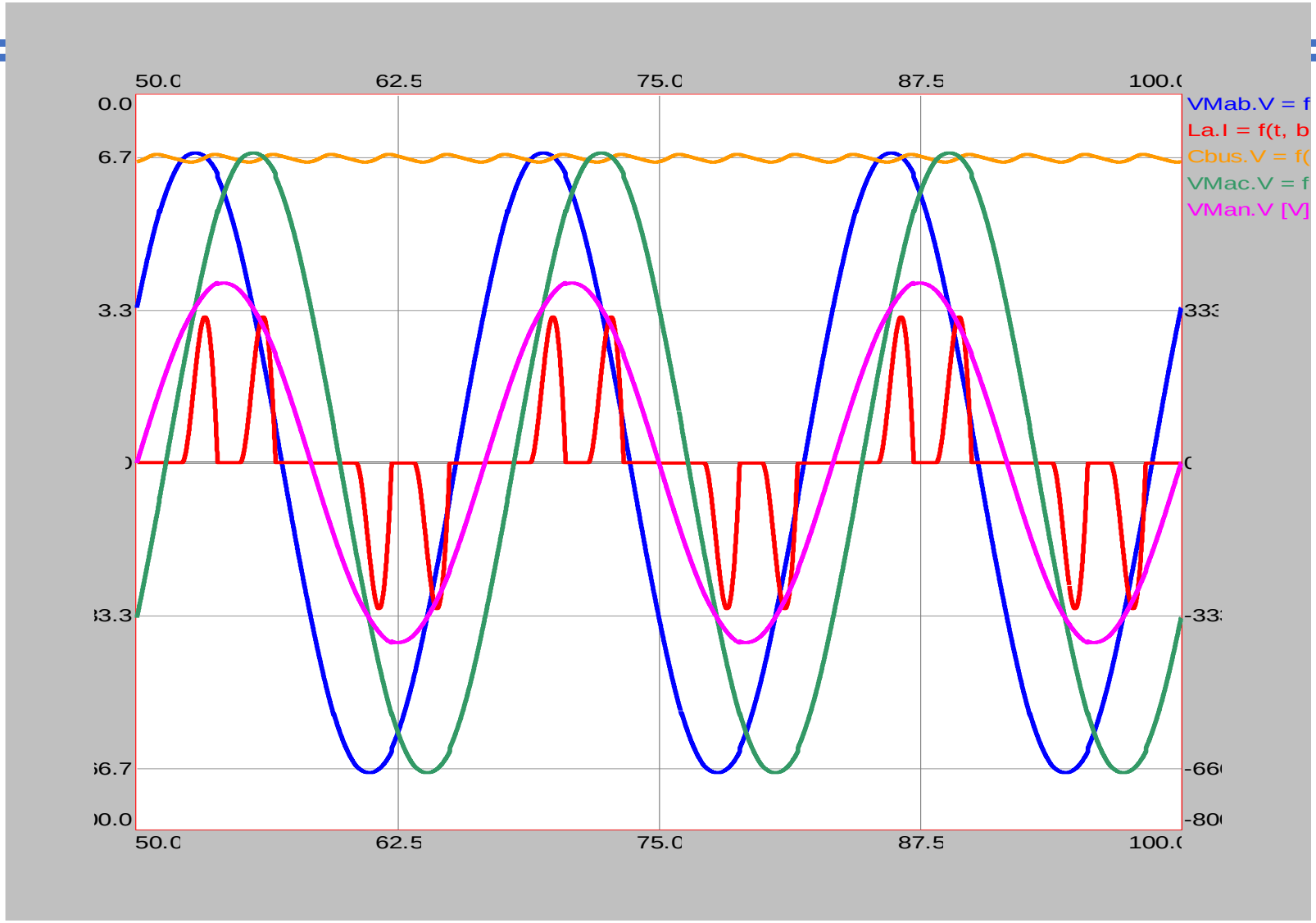
Line Reactors on the Input to a Drive



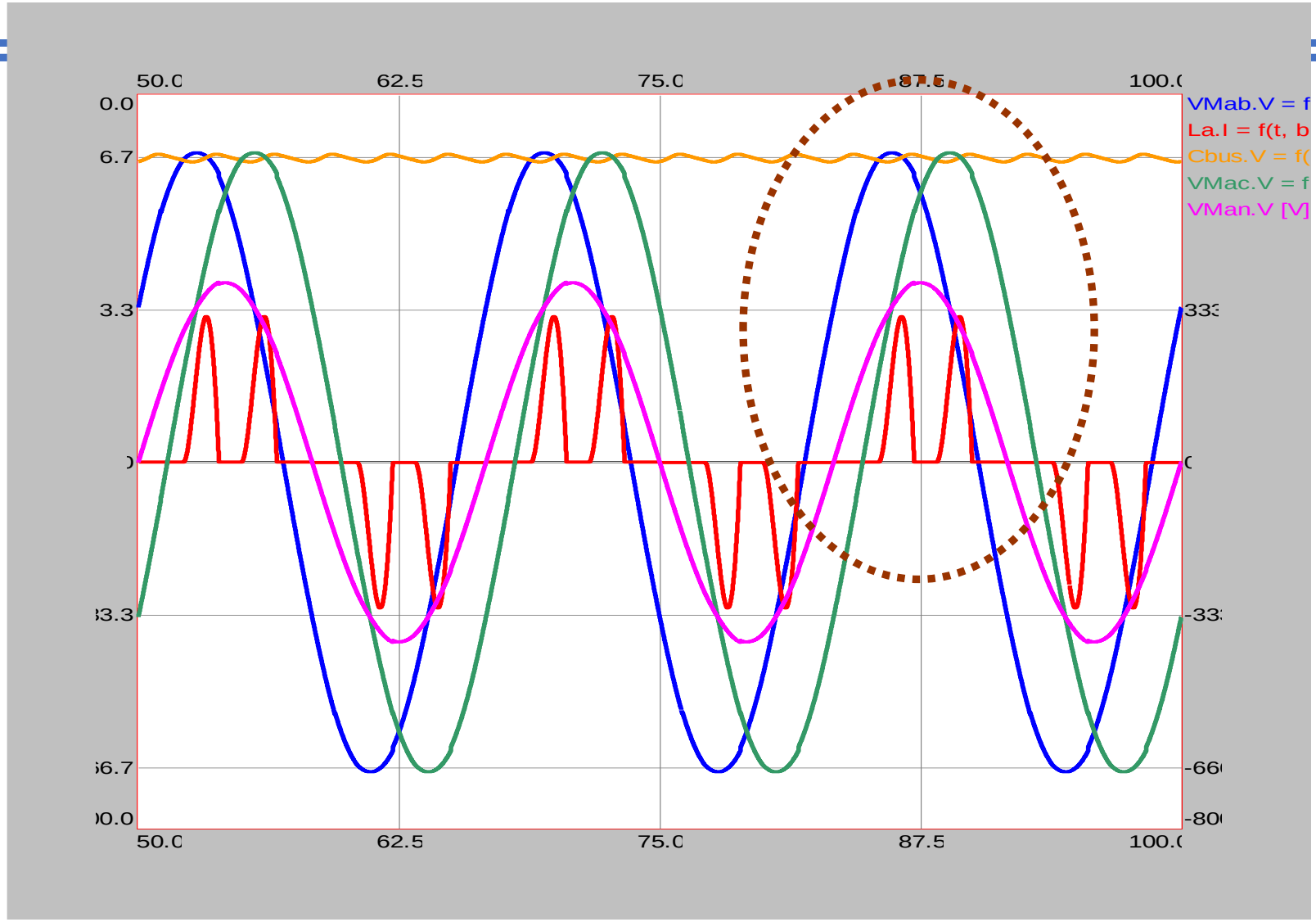
Let’s look at some voltages and current.



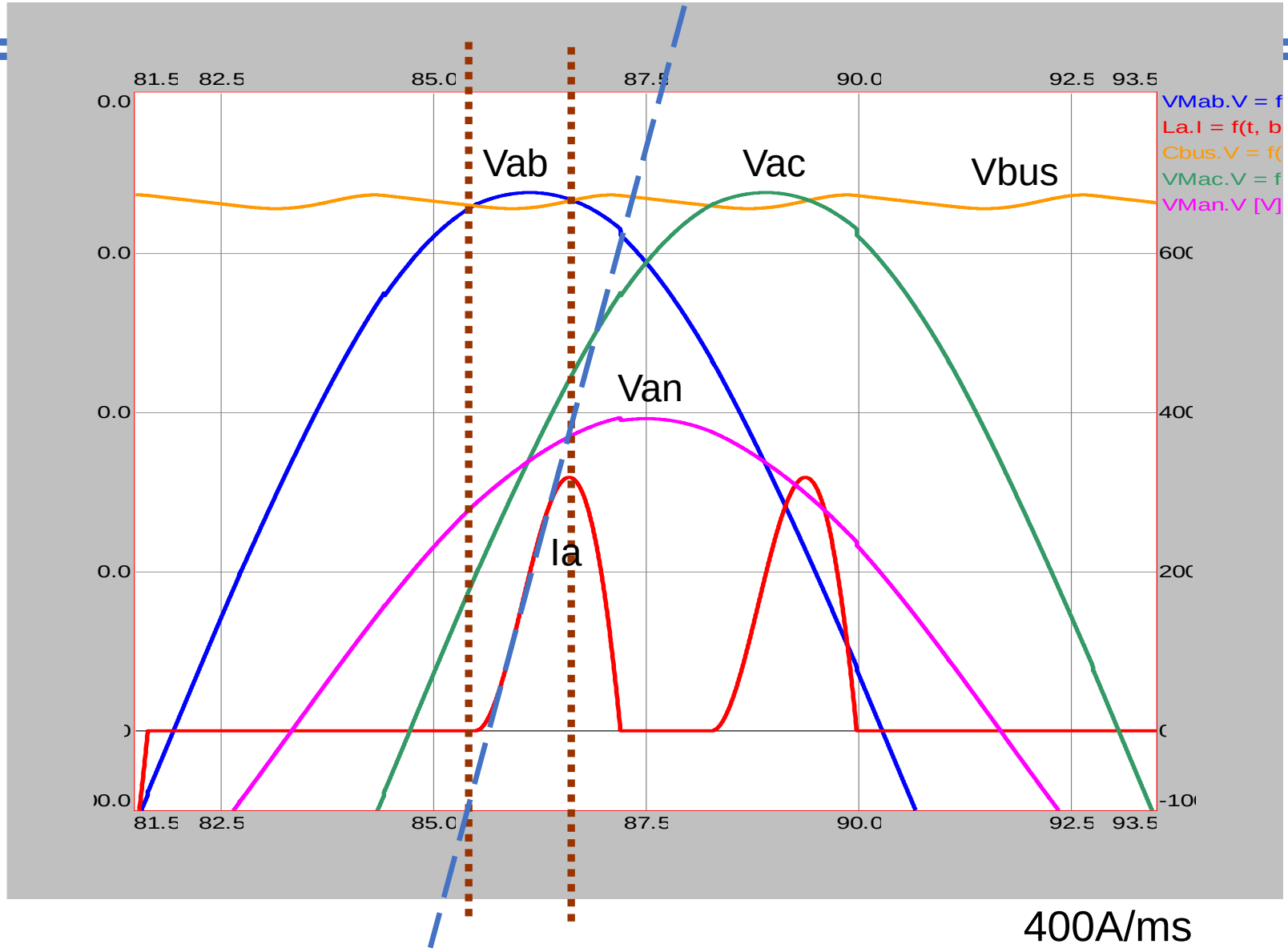
Rectifier w/o DC Link Choke



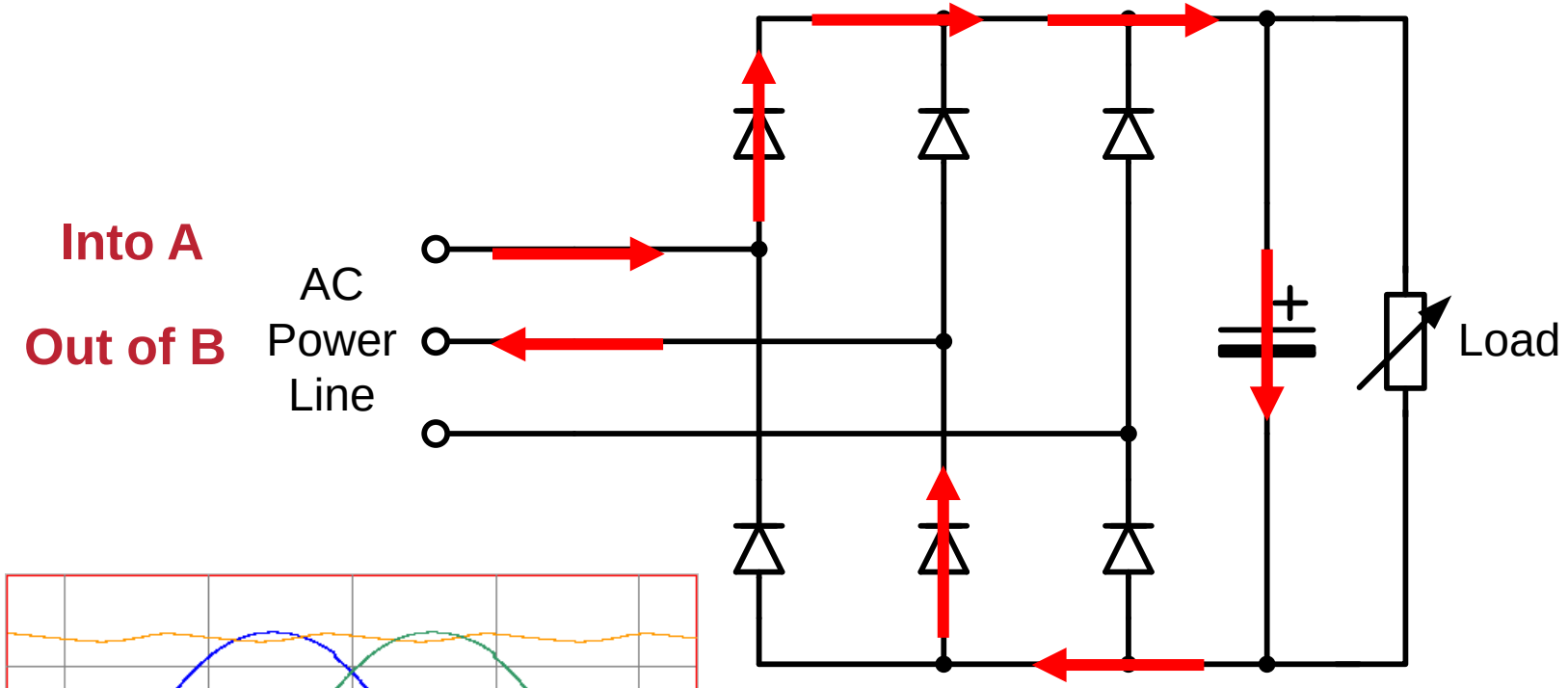
Rectifier w/o DC Link Choke

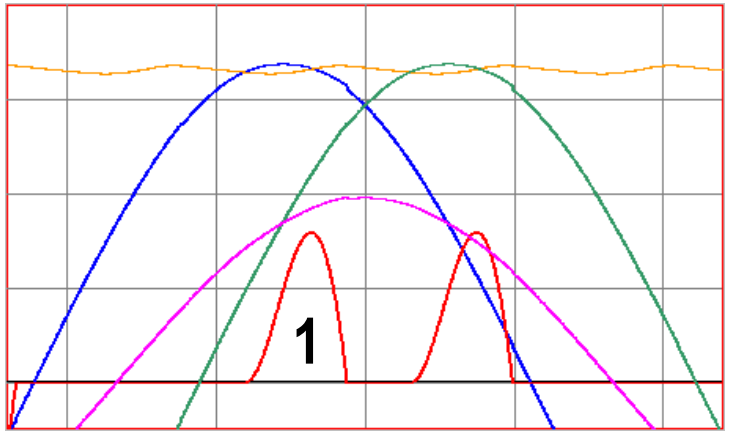


Rectifier w/o DC Link Choke

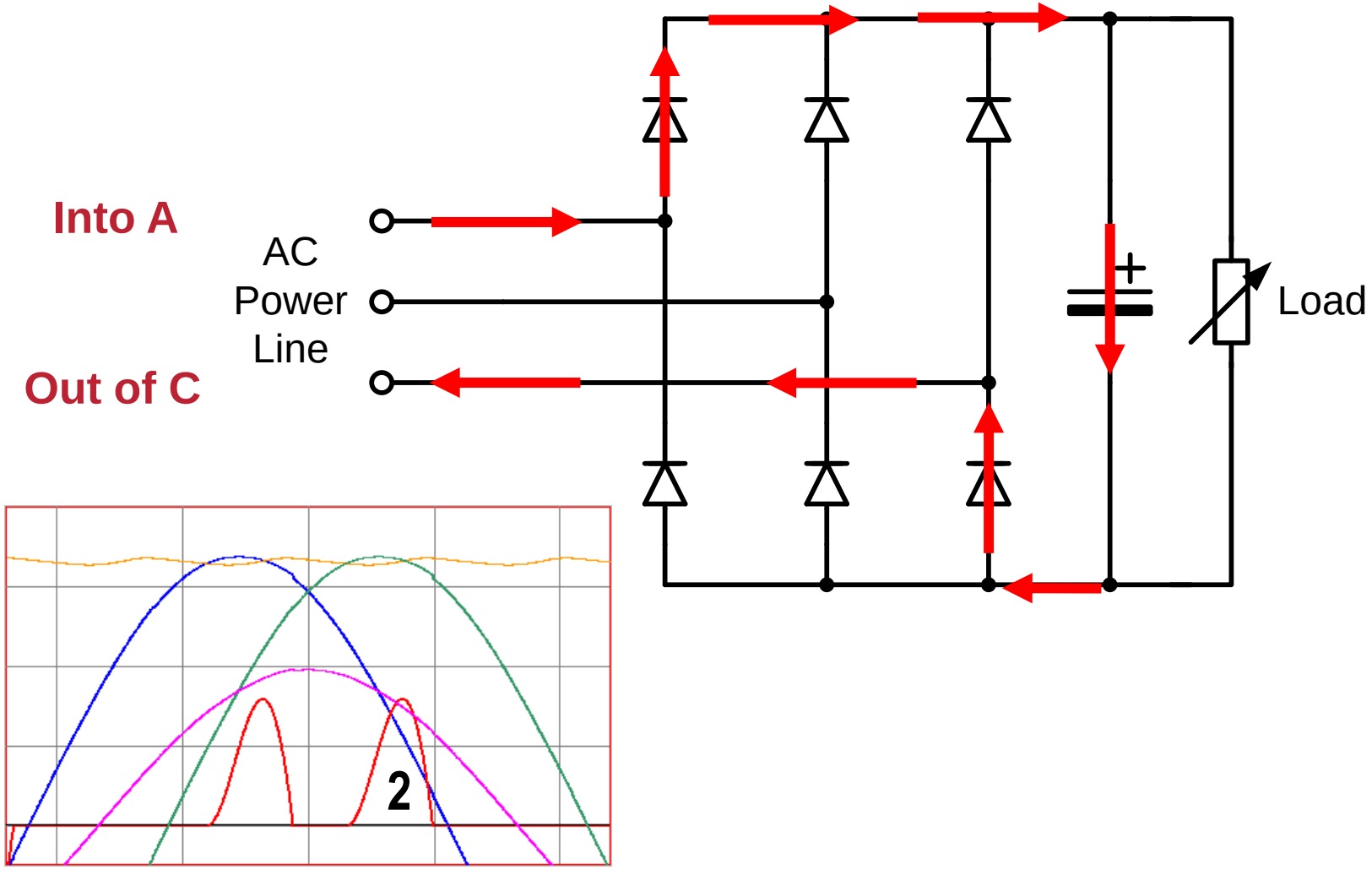


First Current Pulse

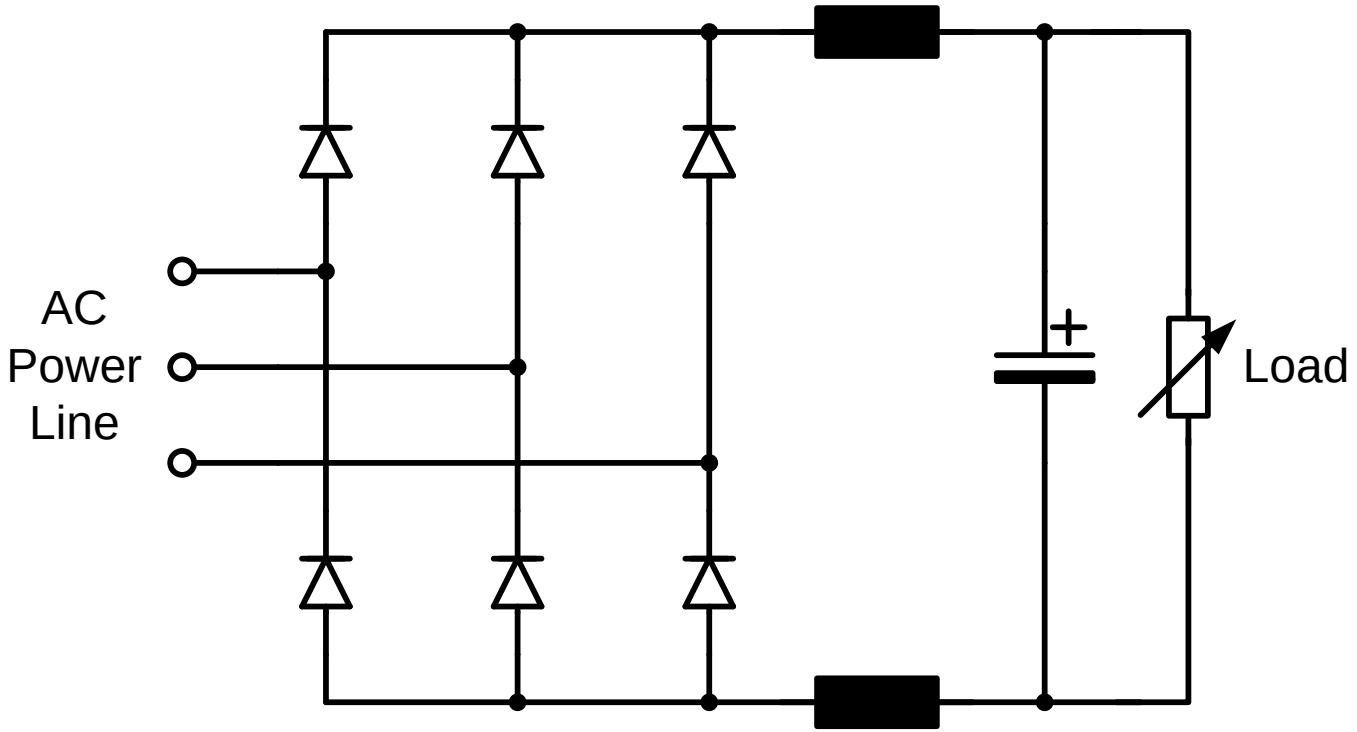




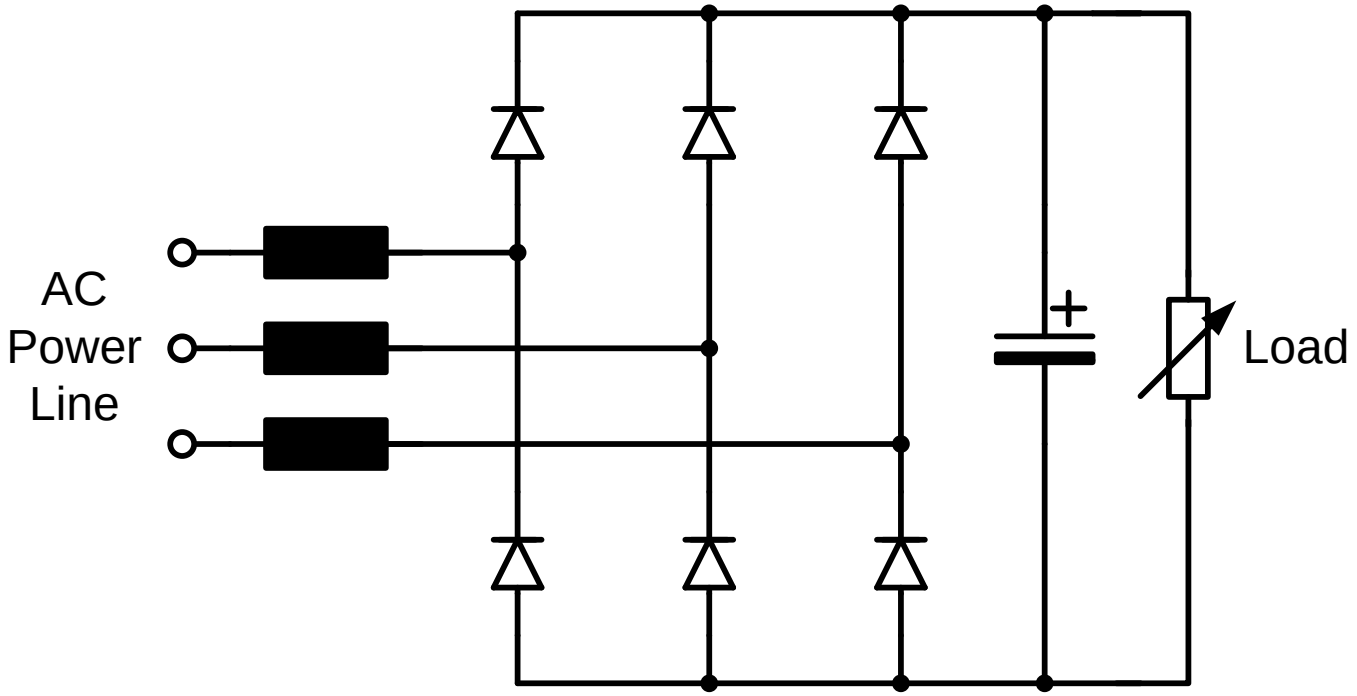
Second Current Pulse



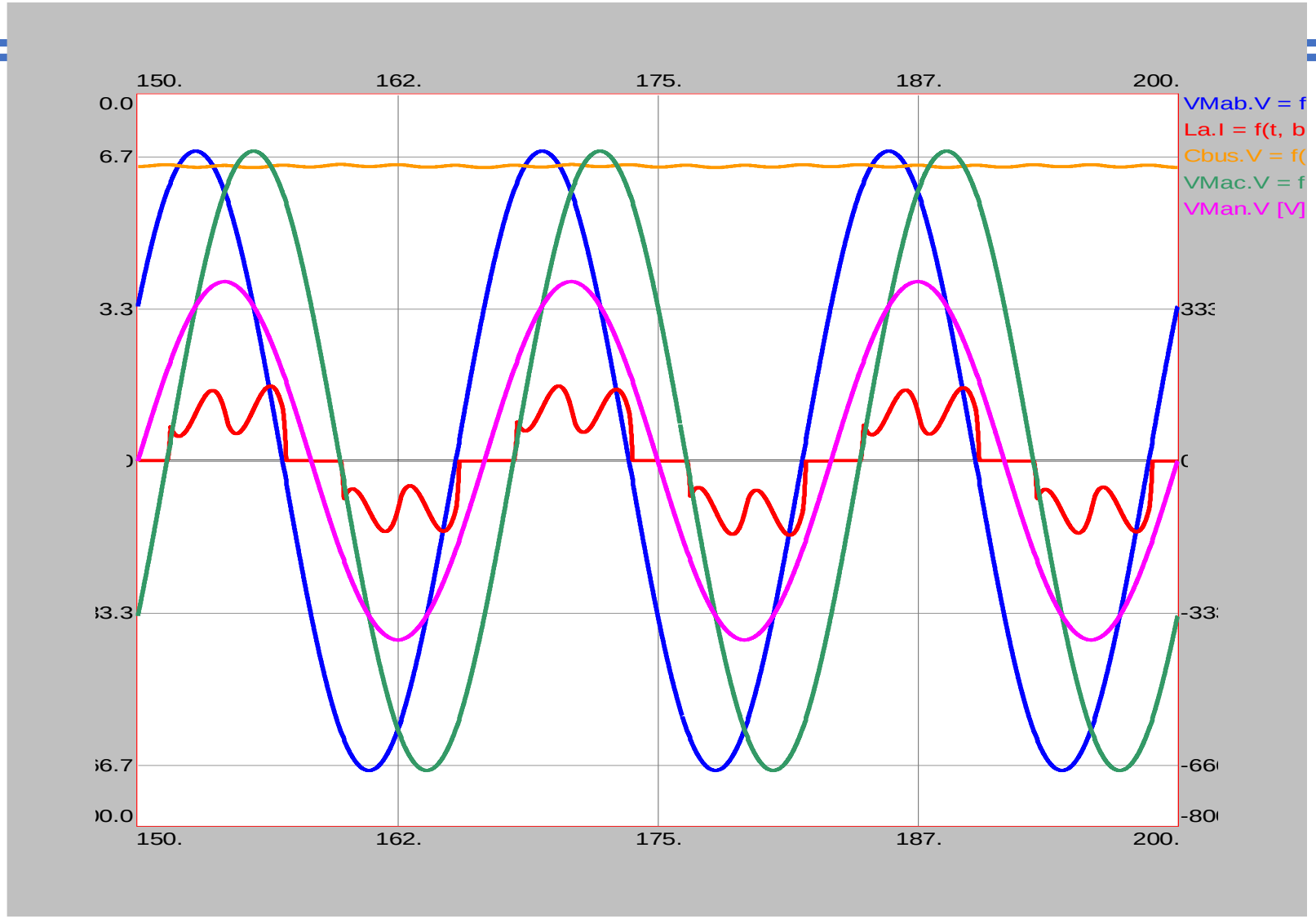
Addition of DC Link Choke



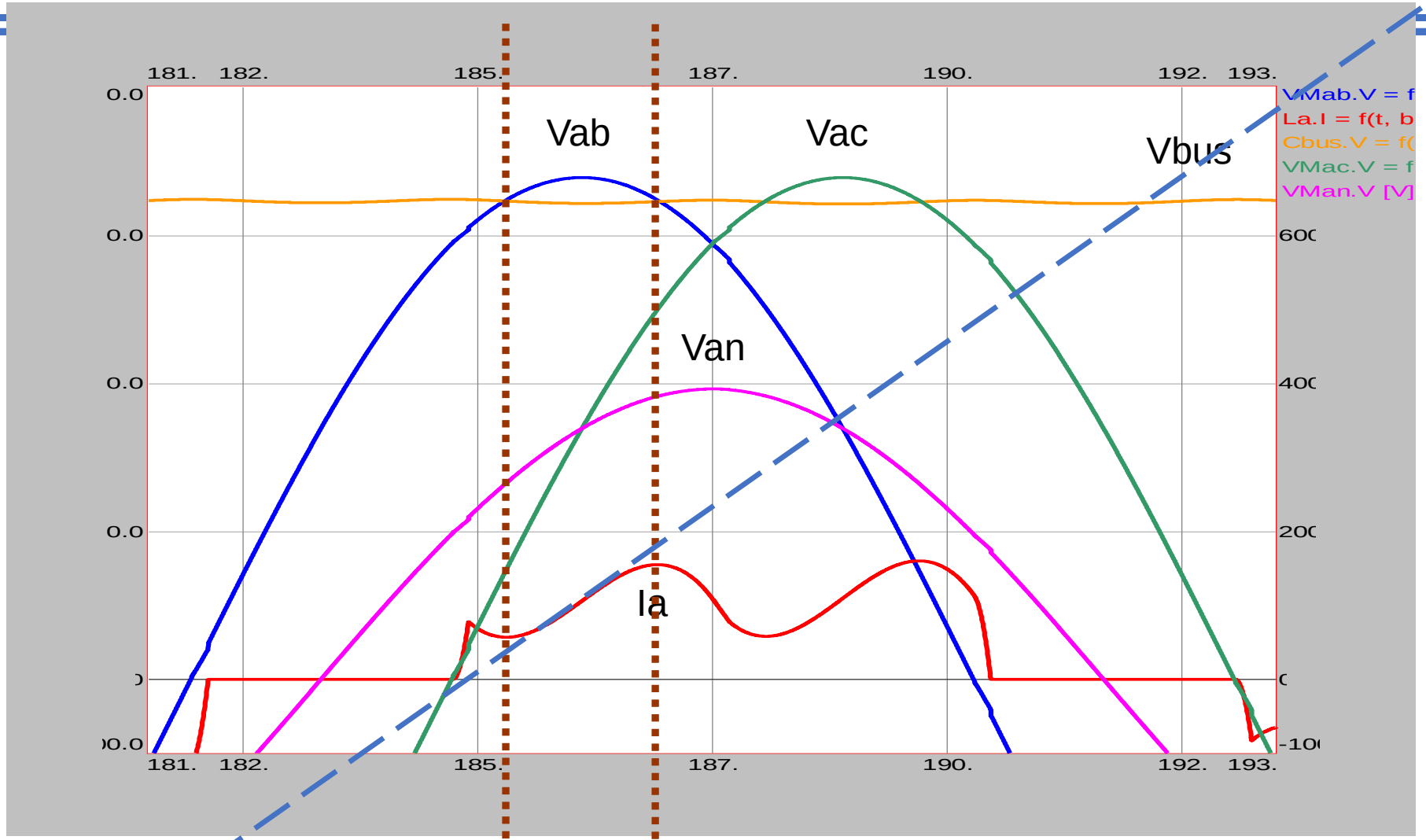
-or- an Addition of AC Line Reactor



Rectifier with DC Link Choke

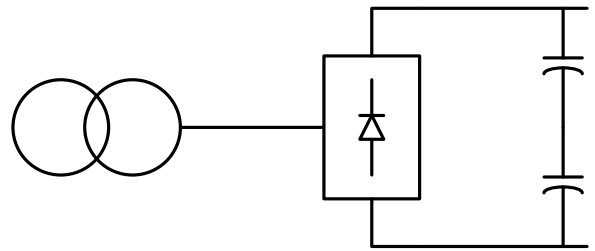


Rectifier with DC Link Choke

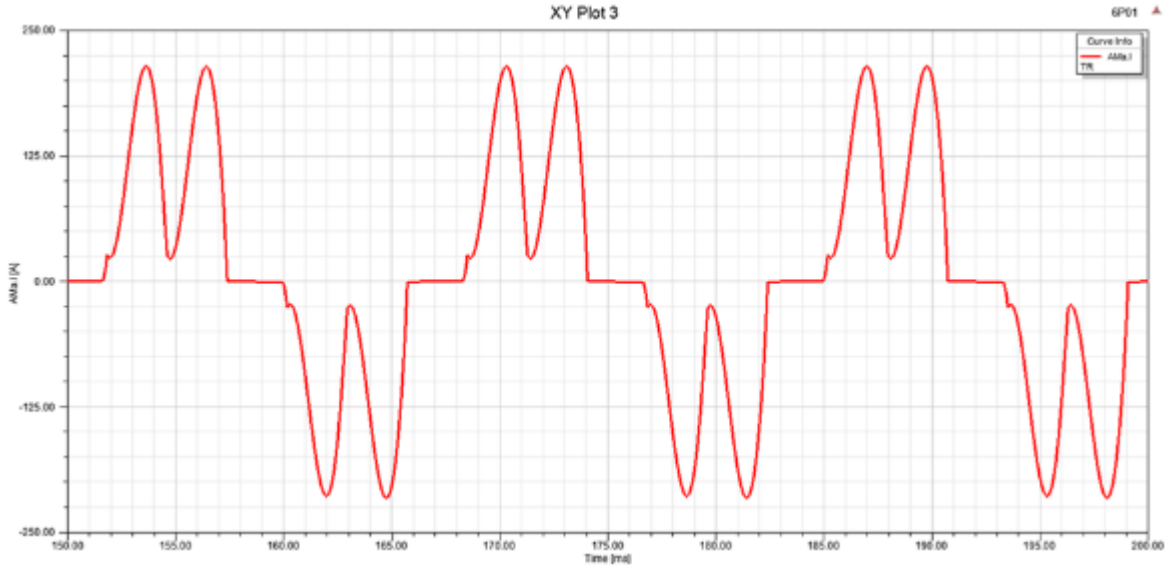


6-Pulse Drive, no mitigation

80-120% Ithd

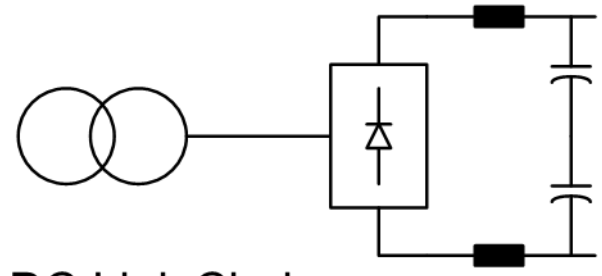


Basic Converter

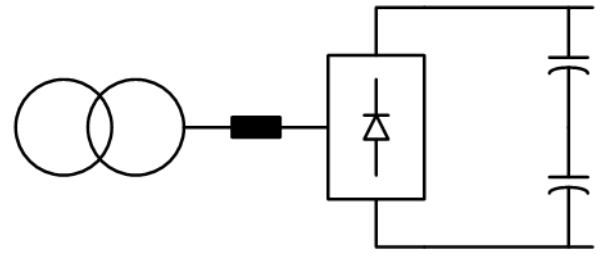


6-Pulse Drive with Line Reactor and/or Link Choke

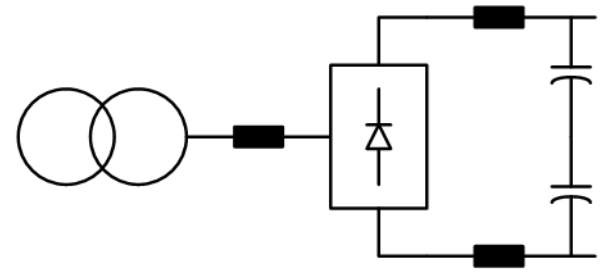
30-40% Ithd



DC Link Chokes

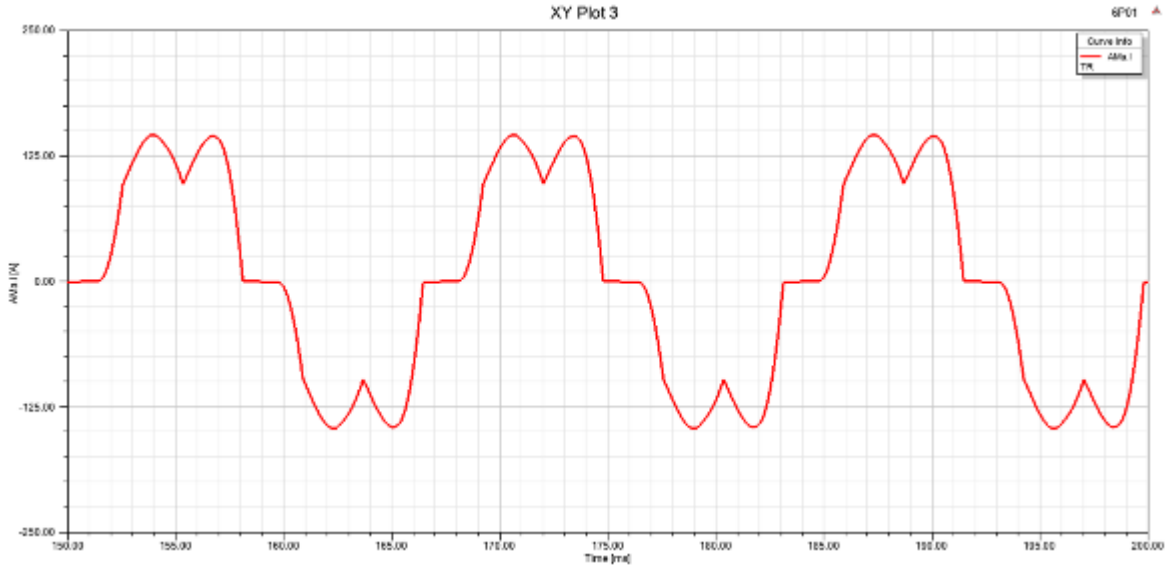


AC Line Reactor



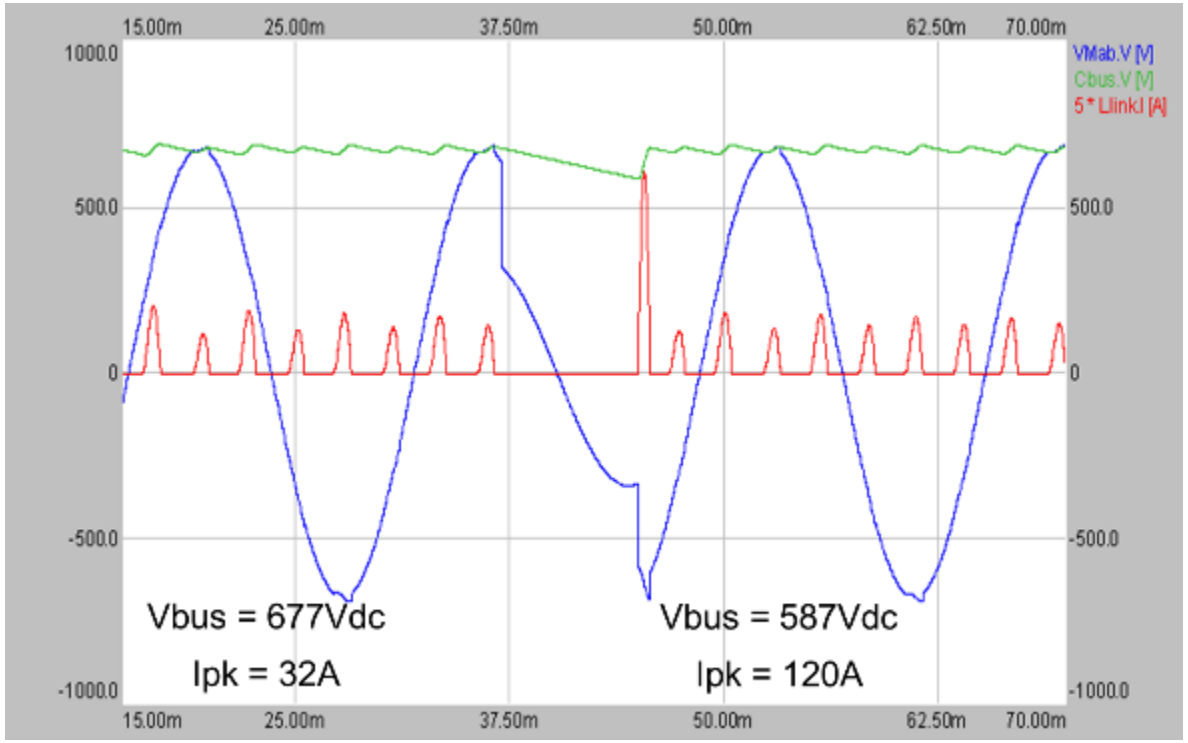
Link Choke and Reactor

(reduces harmonics)

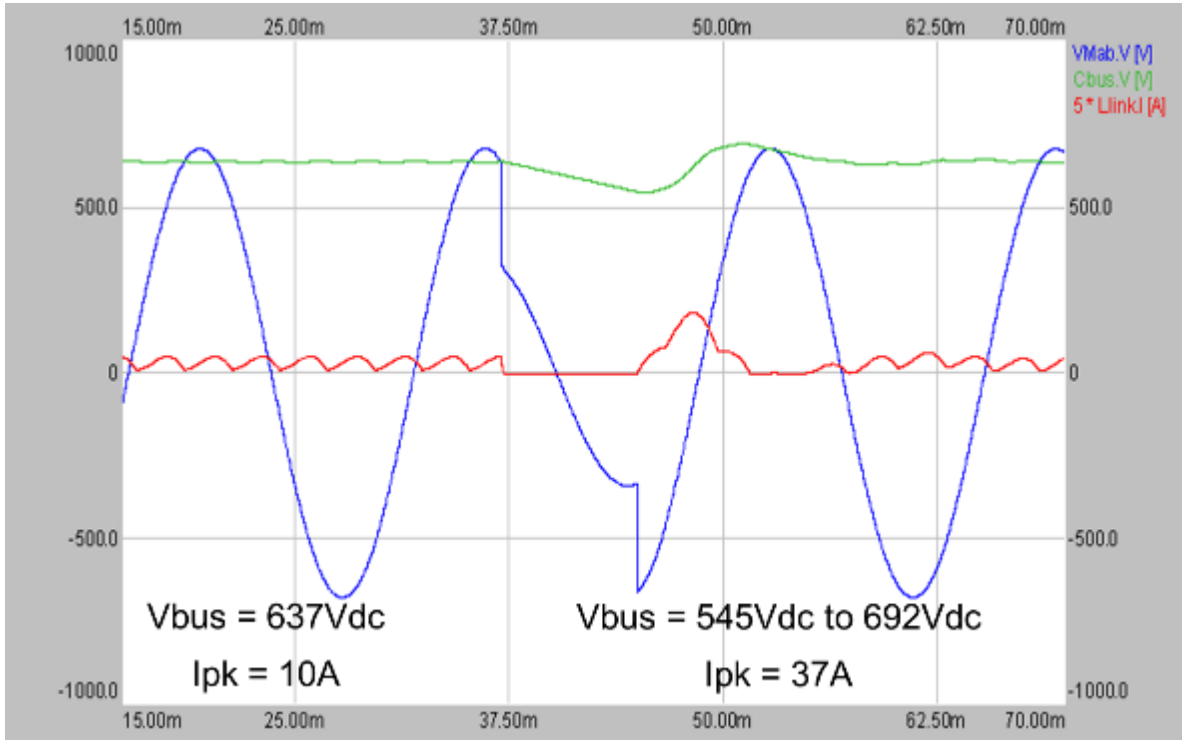


How else does a line reactor help?

Recovery from a sag or interruption

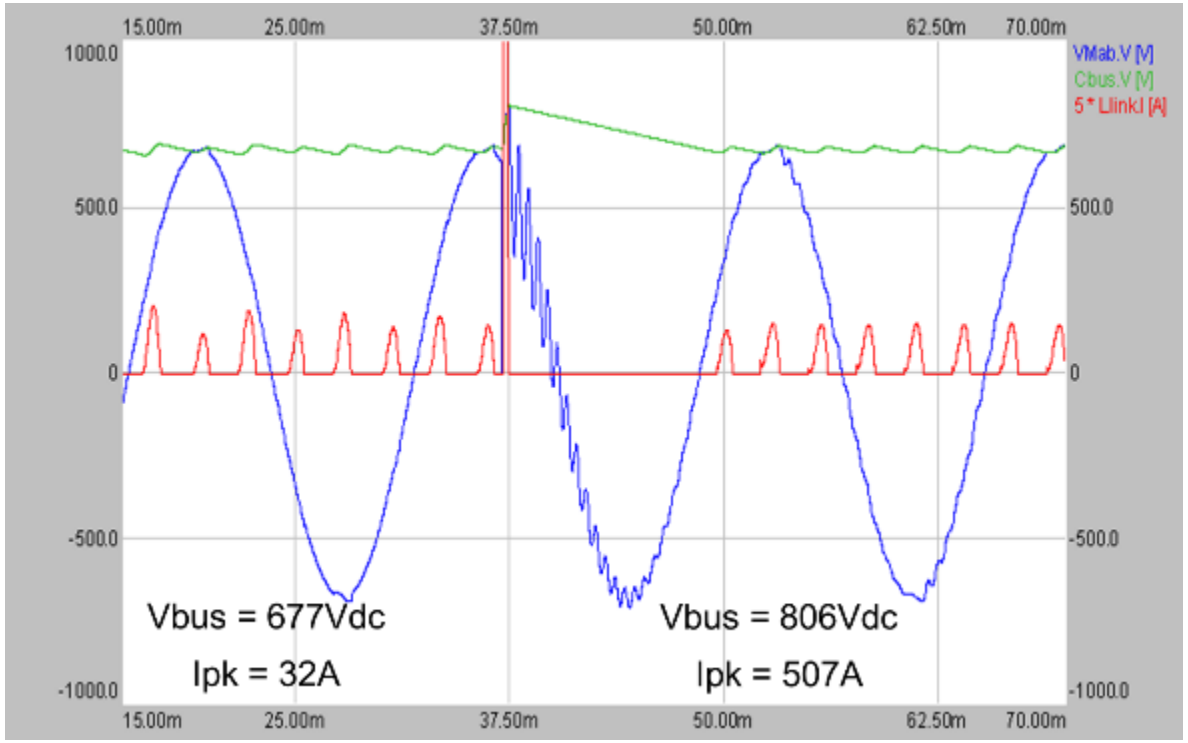


Less likely to blow a fuse or trip a CB.

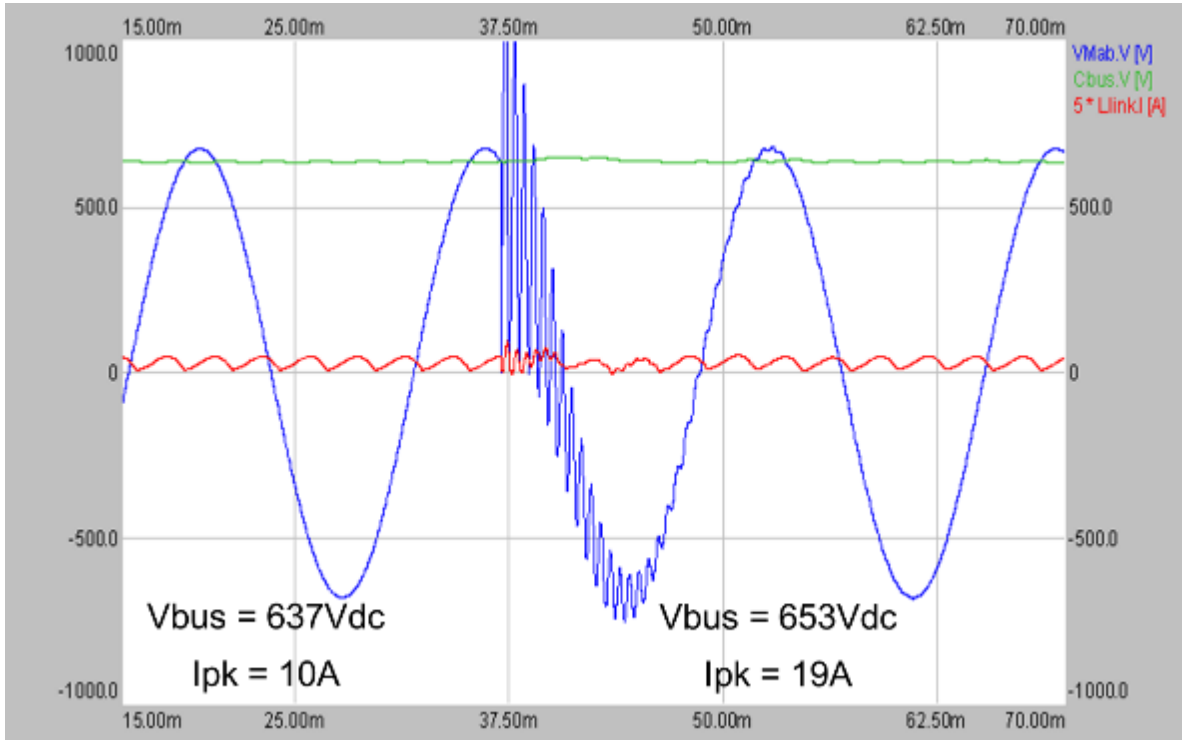


How else does a line reactor help?

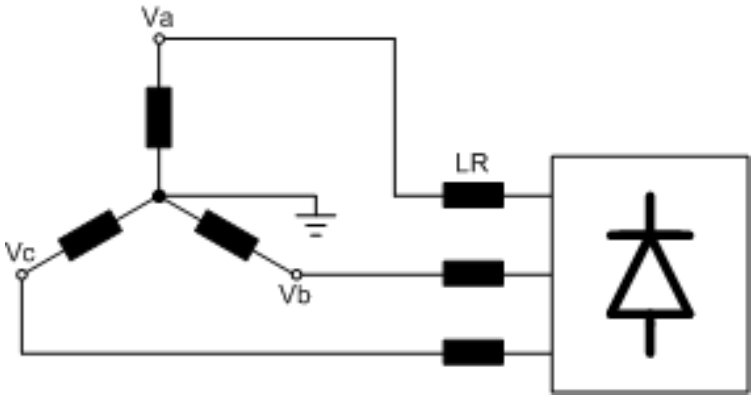
PFCC energization

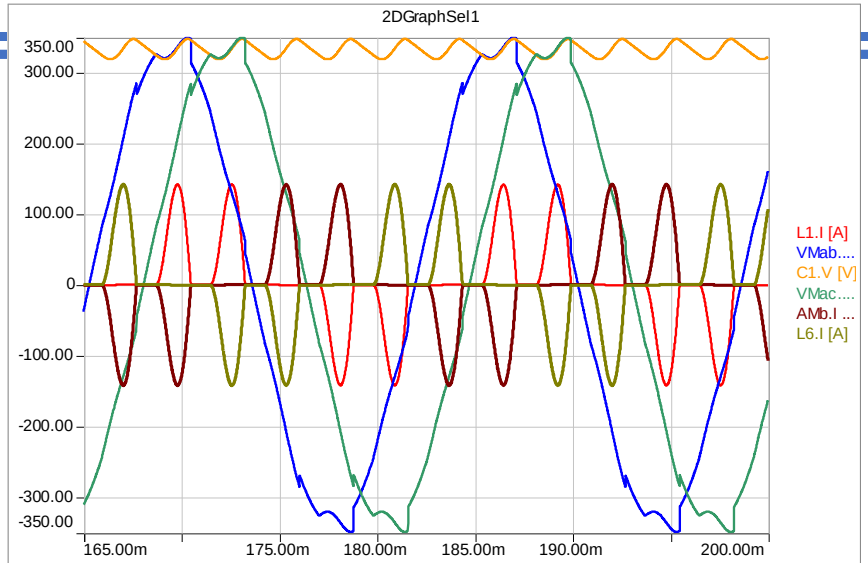


Less likely to blow a fuse or trip a CB or trip on OV.



Low Impedance Source (a very big transformer)

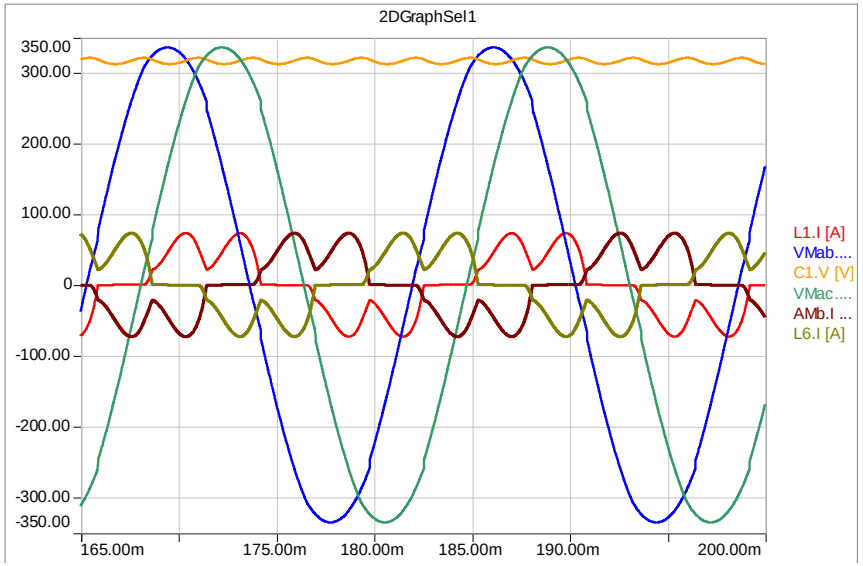




No LR or LC

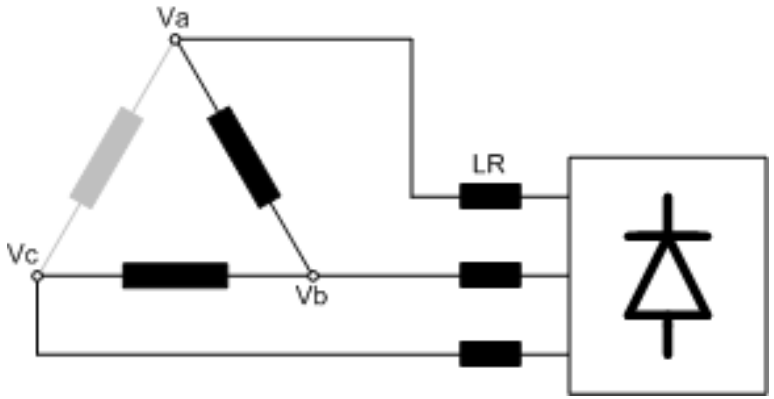
Less stress on diode bridge – longer life.
Less bus ripple – longer cap life.
Less likely to trip on excessive bus ripple.

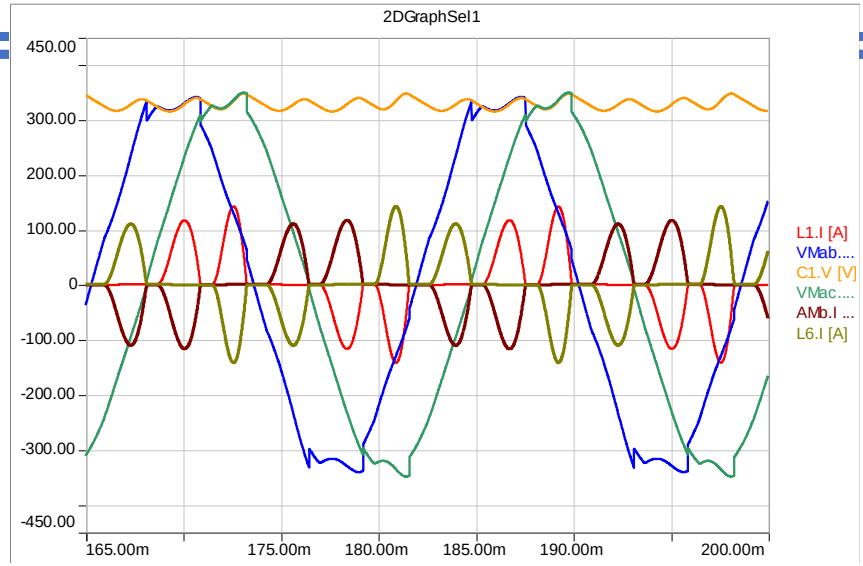
Rule of thumb: if xfmr is > 20x kVA rating of drive,
add a line reactor!



With LR and LC

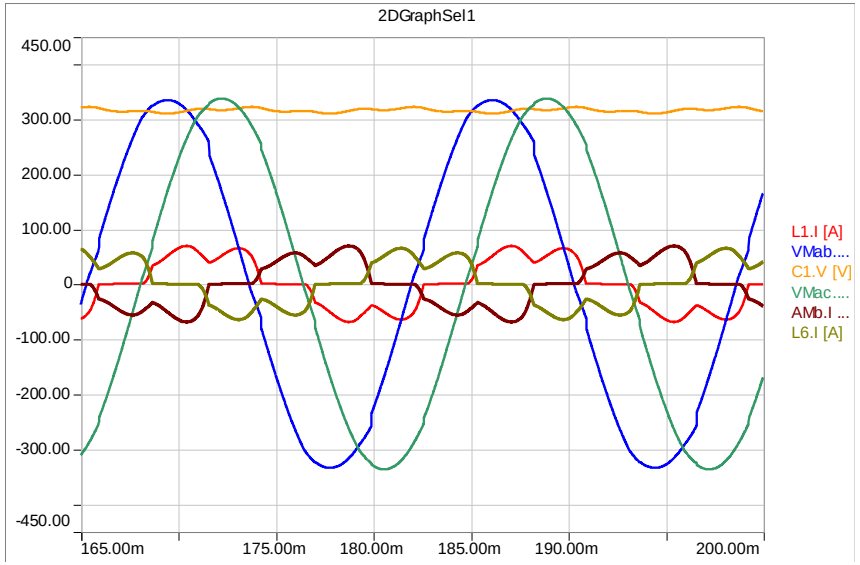
Open Delta Source – Unbalanced Impedances





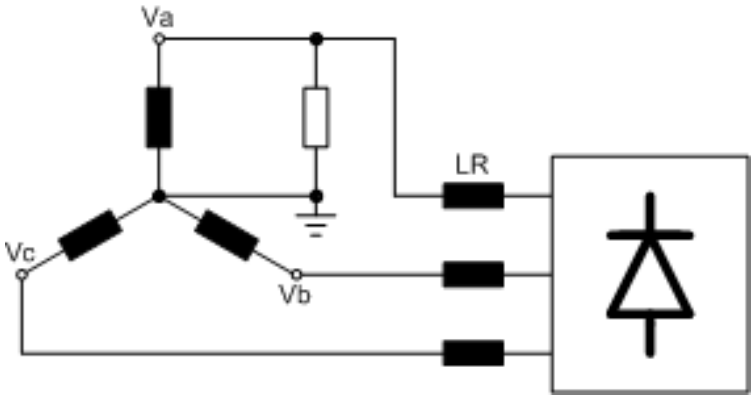
No LR or LC

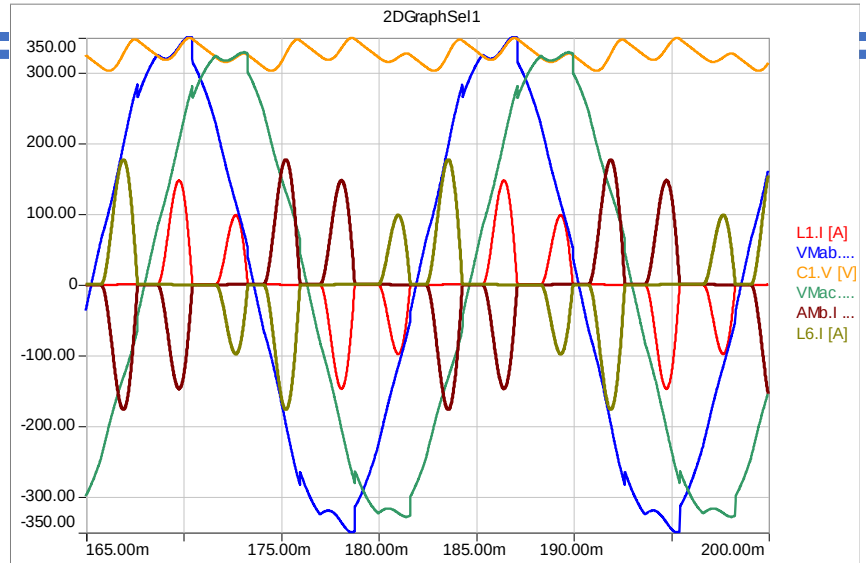
Less stress on diode bridge – longer life.
Less bus ripple – longer cap life.
Less likely to trip on excessive bus ripple.



With LR and LC

Unbalanced Line Voltages





No LR or LC

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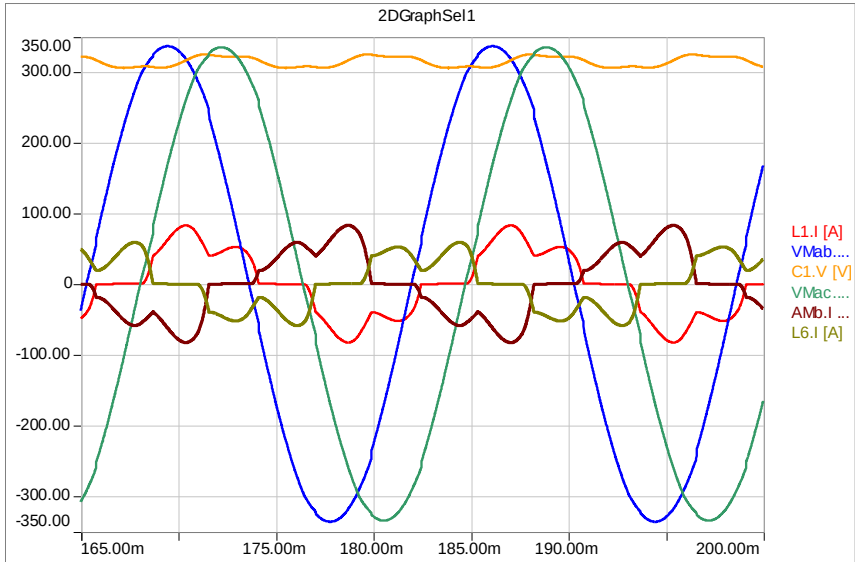
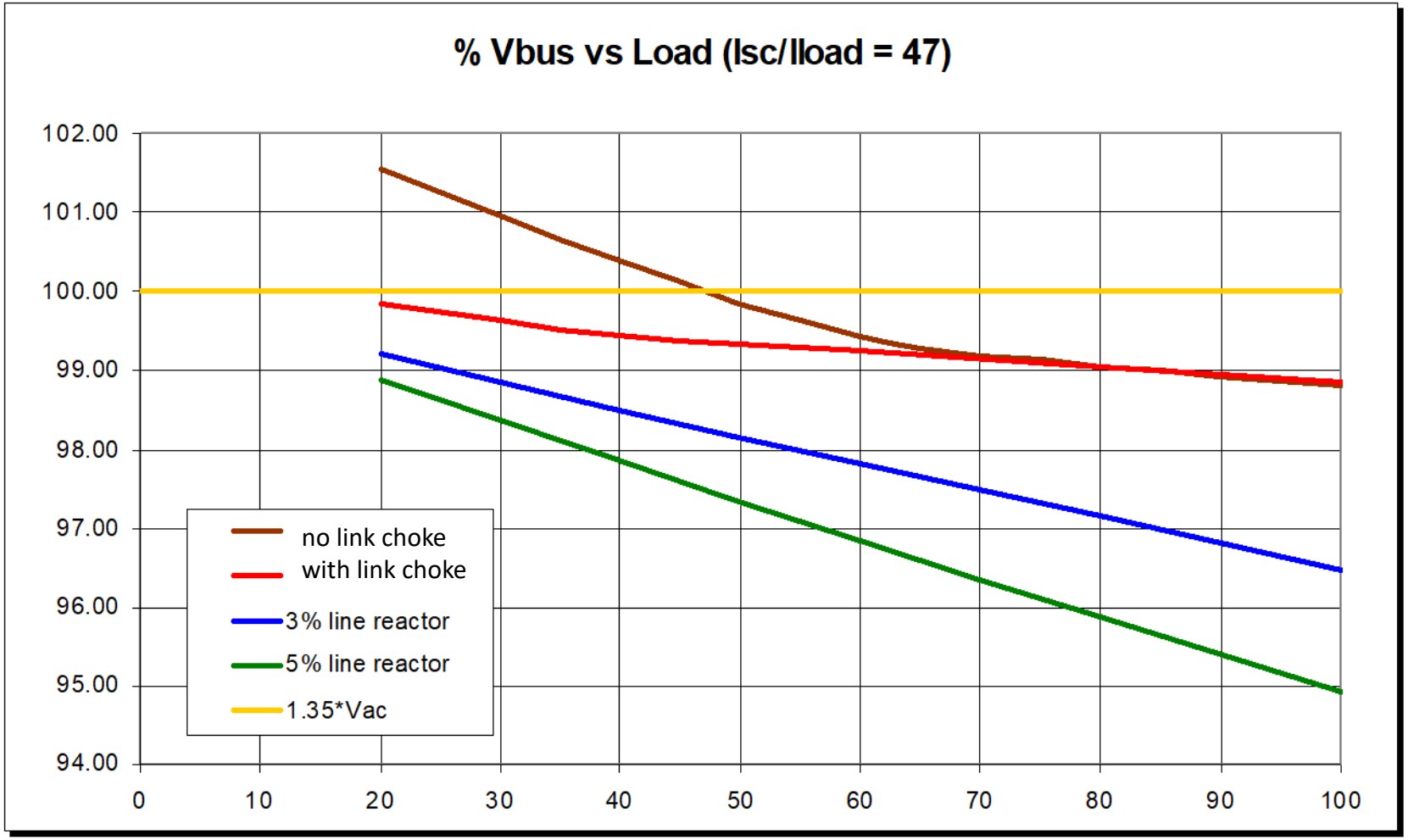


With LR and LC

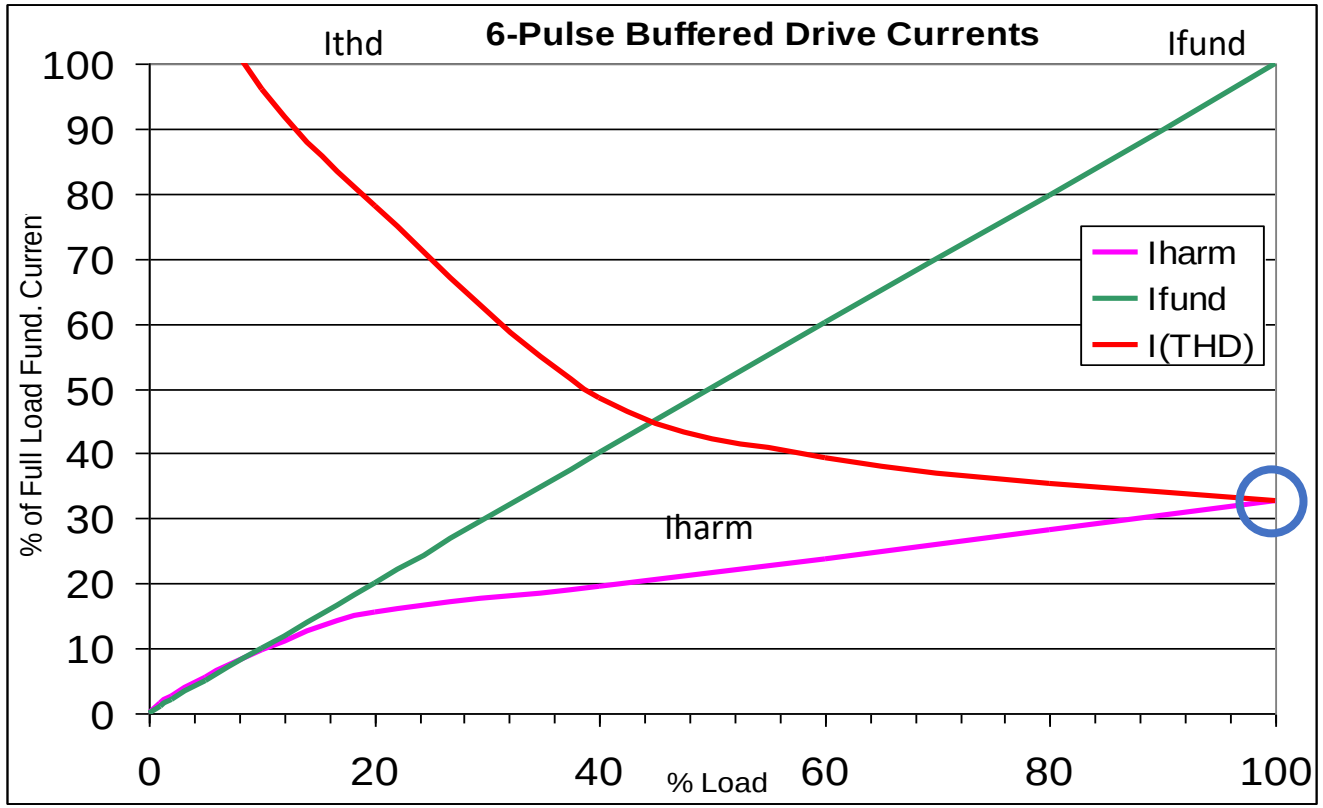
Problem with too much Line Reactor % (max = 5%)

Low DC bus voltage means:

Low motor voltage (at max speed)
Higher motor current
More heating
Shorter life



How does motor load affect I(THD)?



At what % load is worst case?

I(TDD)

NOTES:

I(THD) = Iharm / Ifund

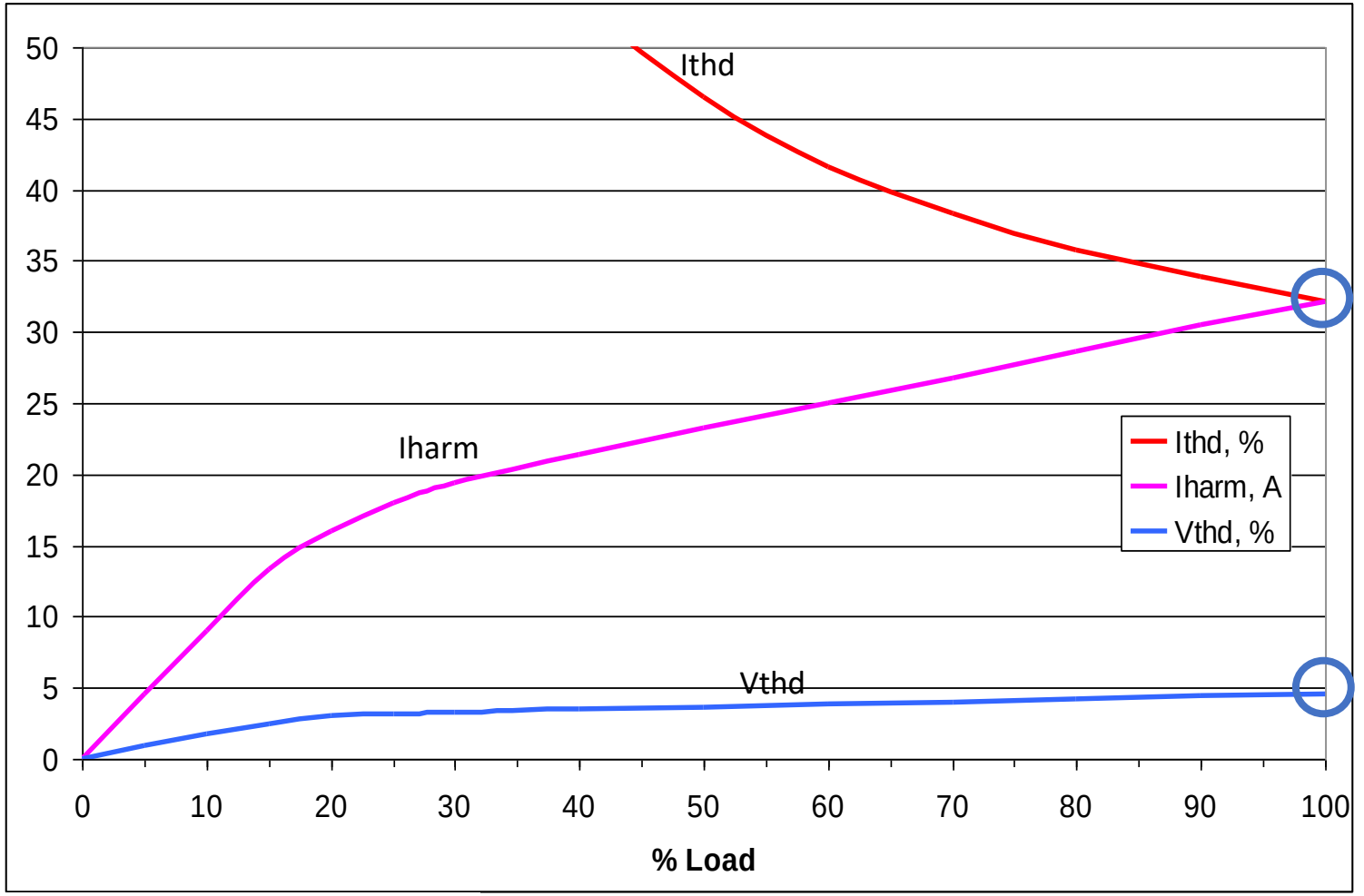
I(THD) **increases** as load decreases

Ifund **decreases** as load decreases

Iharm **decreases** as load decreases

(drive is at full speed)

Vthd vs Load – Zoomed In



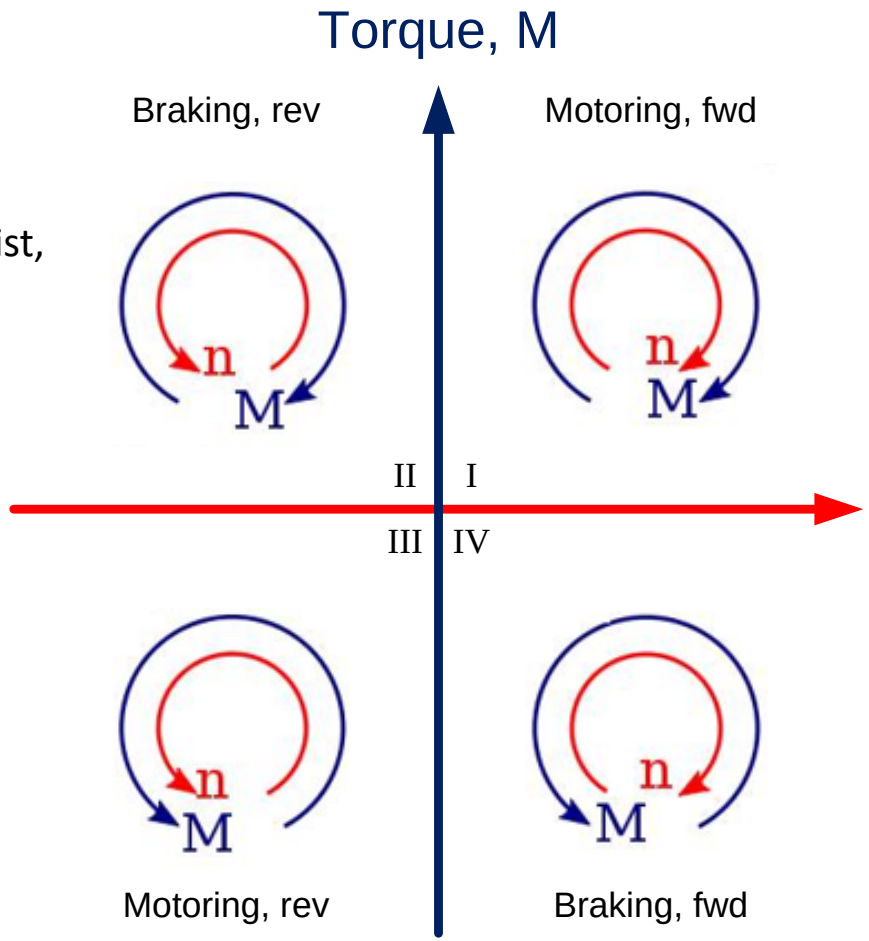
I(TDD)

Max Vthd

100hp drive on 250kVA xfmr, 6%

Active Rectifier Applications

Quadrants of Operation



Braking in reverse direction: stopping, plugging, lowering hoist, generator action

Normal motoring in forward direction: raising hoist, running conveyor, pump, fan

Normal motoring in reverse direction

Braking in forward direction: stopping, downhill conveyor, generator action

Special applications that require regeneration

- Downhill conveyors
- Centrifuges
- Cooling and ID fans
- Dynamometers
- Fabrics - Kevlar
- Paper mills
- Cranes

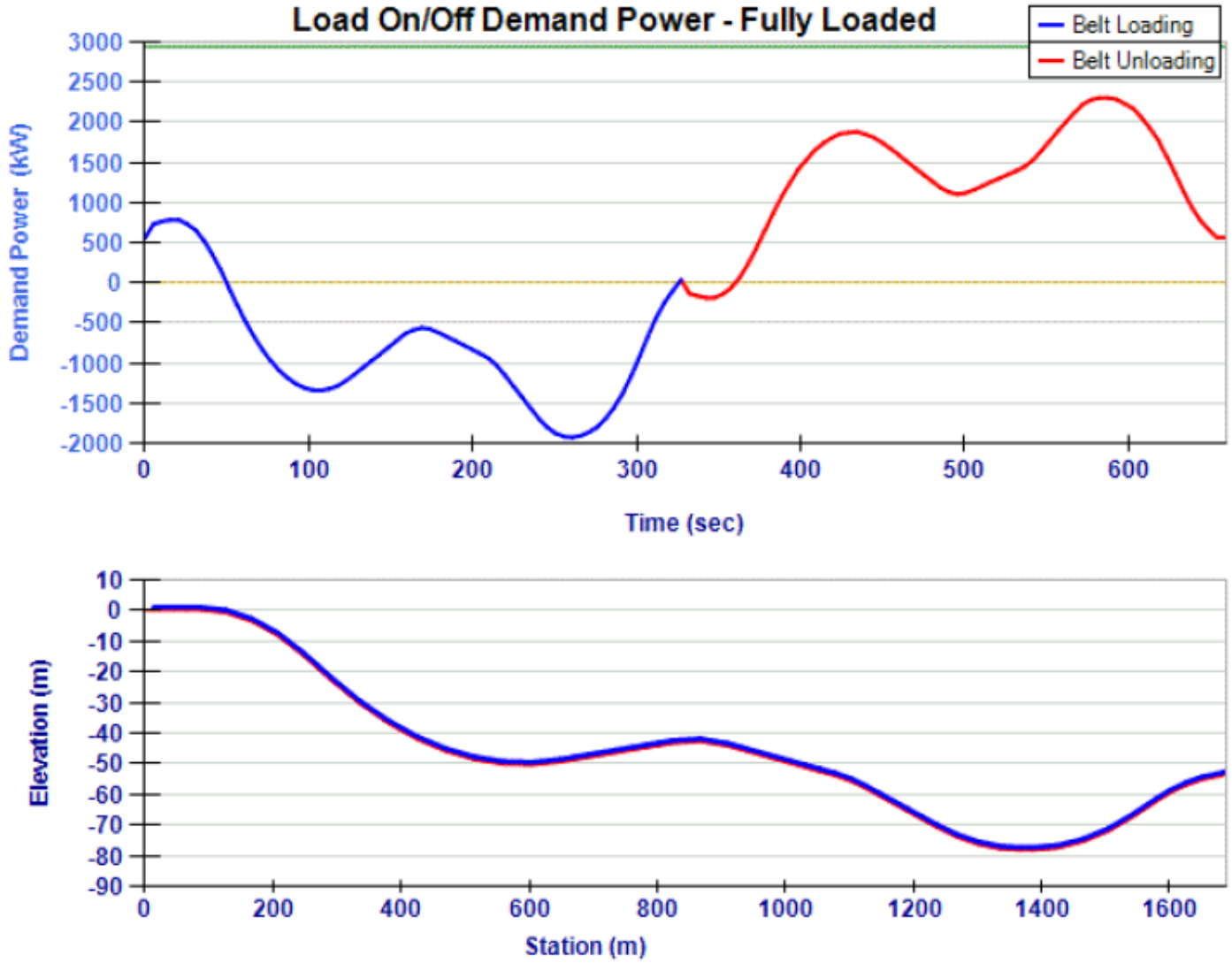
- Reasons:
  - Continually braking (reverse torque)
  - Braking or slowing down high inertia loads
  - Emergency stopping for safety

  - Dynamic braking dissipates the energy as heat in a resistor
  - Regenerative braking sends the energy back into the power lines for other loads to use
  - Constant braking torque throughout the speed range

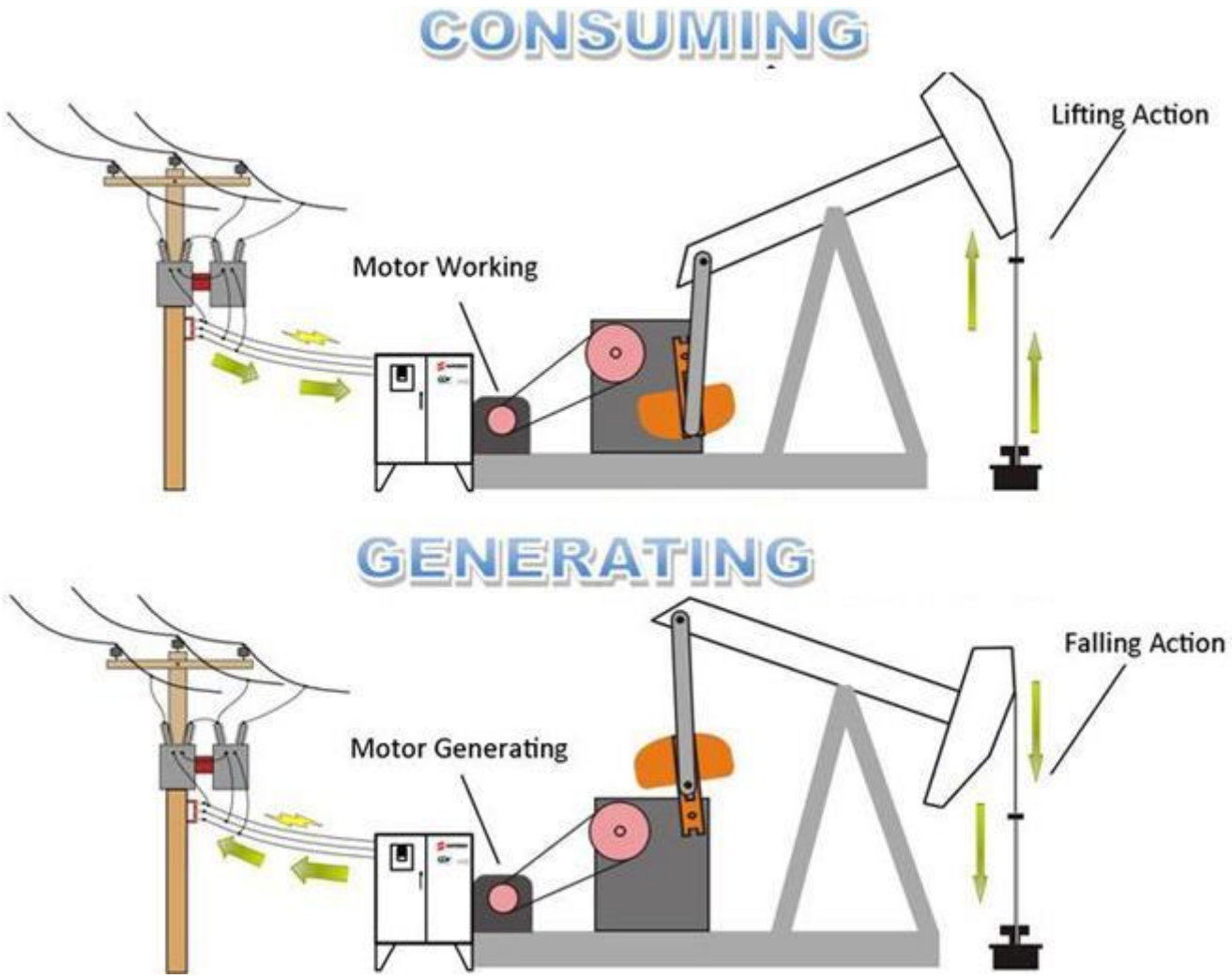
Shipyard Cranes

Cooling Fans

Downhill Conveyor

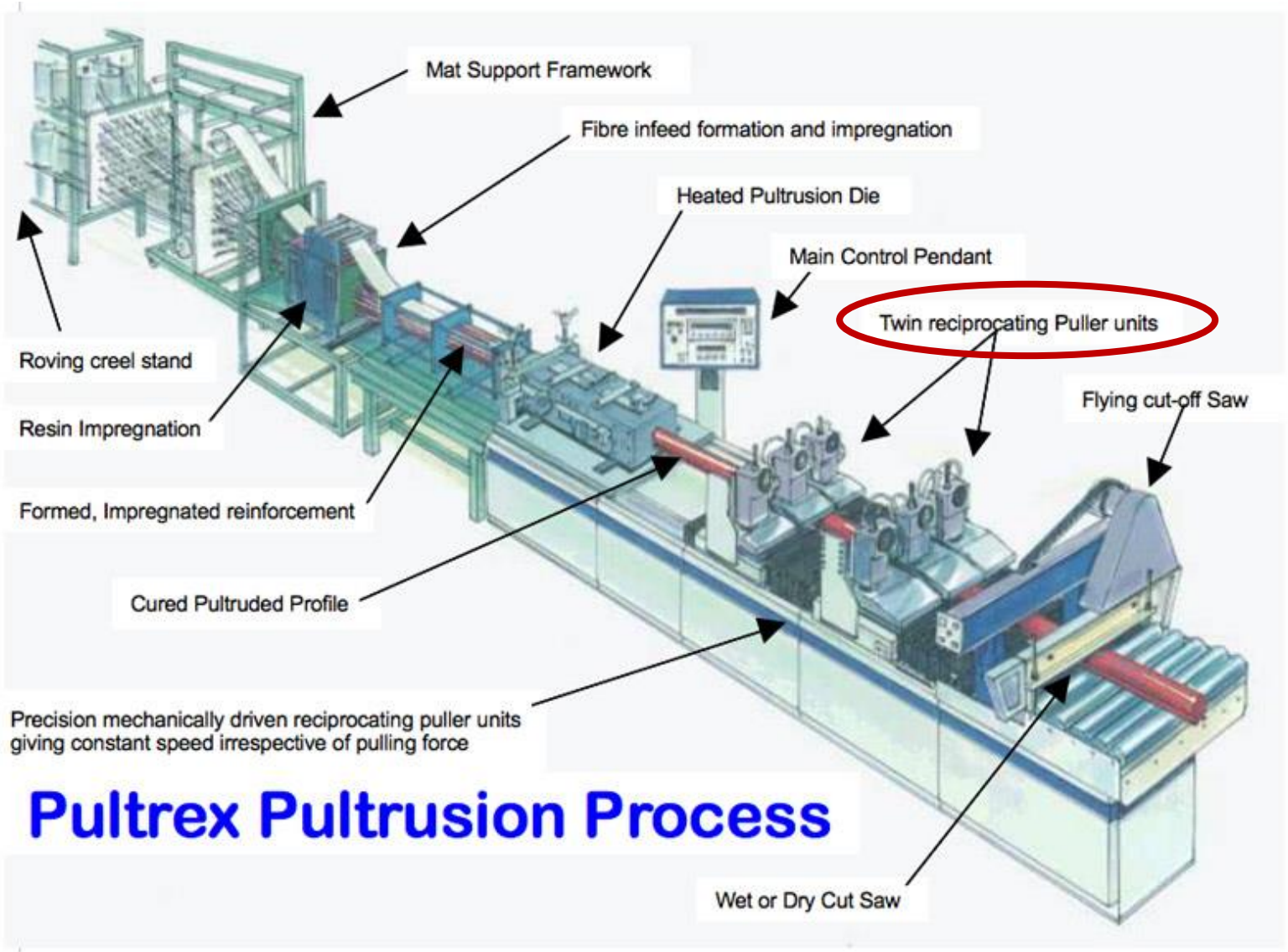


Pump Jack


CONSUMING
Lifting Action
Motor Working
GENERATING
Falling Action
Motor Generating

Paper Mill

Fibers such as Kevlar

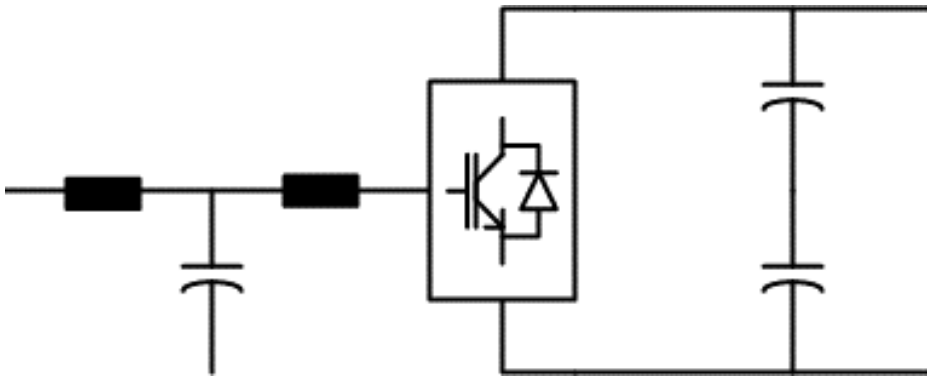


Active Rectifier Operation

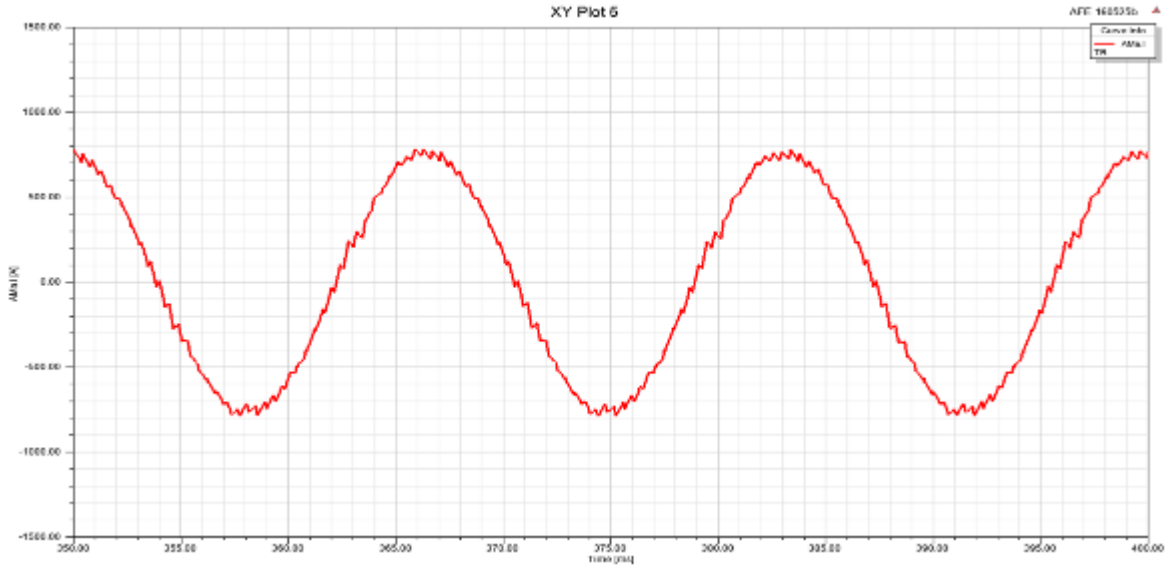
3-Phase Drive with Active Front End

4-5% Ithd

(does not produce harmonics)



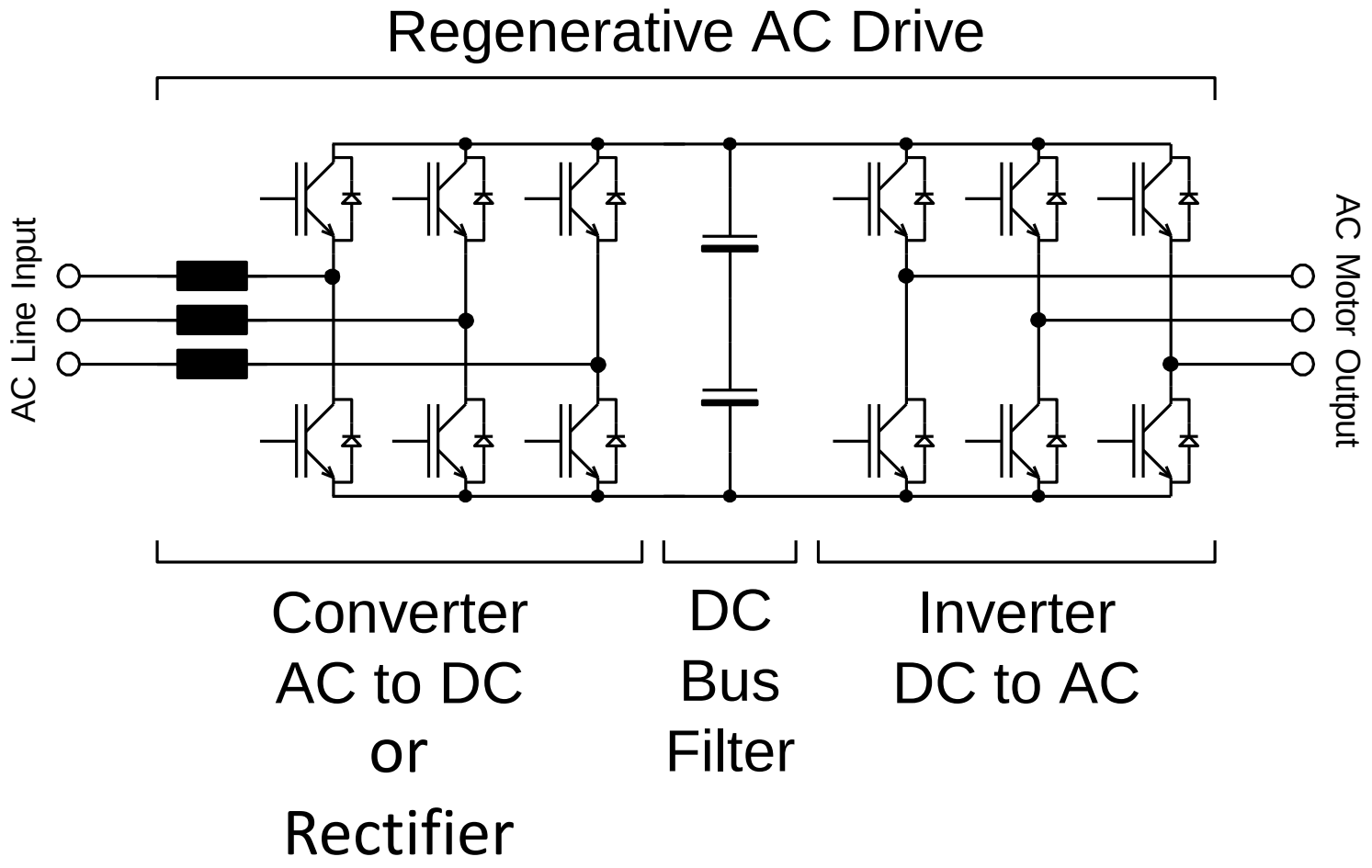
*AFE with LCL Filter



* used for LV and MV drives

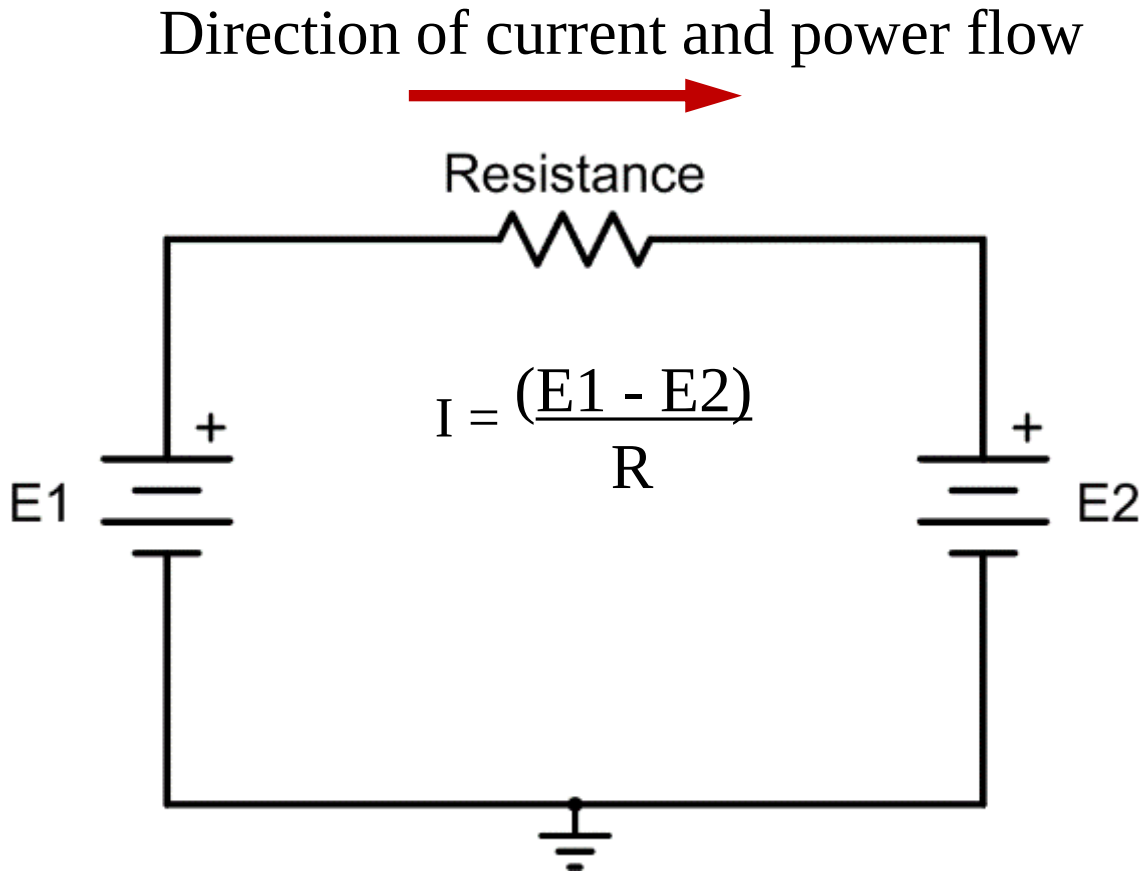
Active Rectifier (AFE, ULH) AC Drive

Active Rectifier
Synchronous Rectifier
Synchronous Converter
Active Front End, AFE
Regenerative Unit, RGU
Ultra-Low Harmonic, ULH
IGBT Supply Unit, ISU



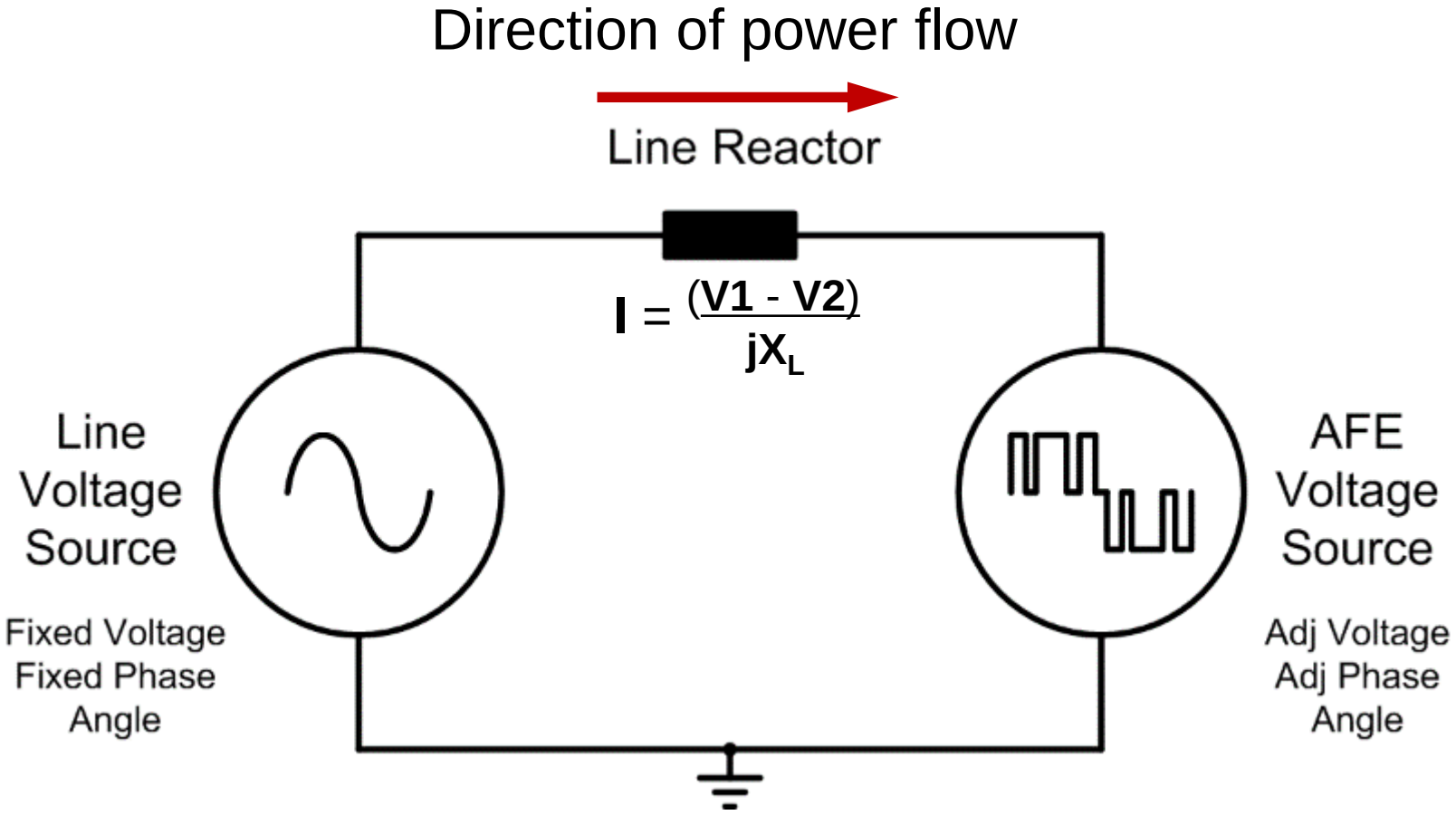
Just Like Two DC Voltage Sources

(jump starting your car)



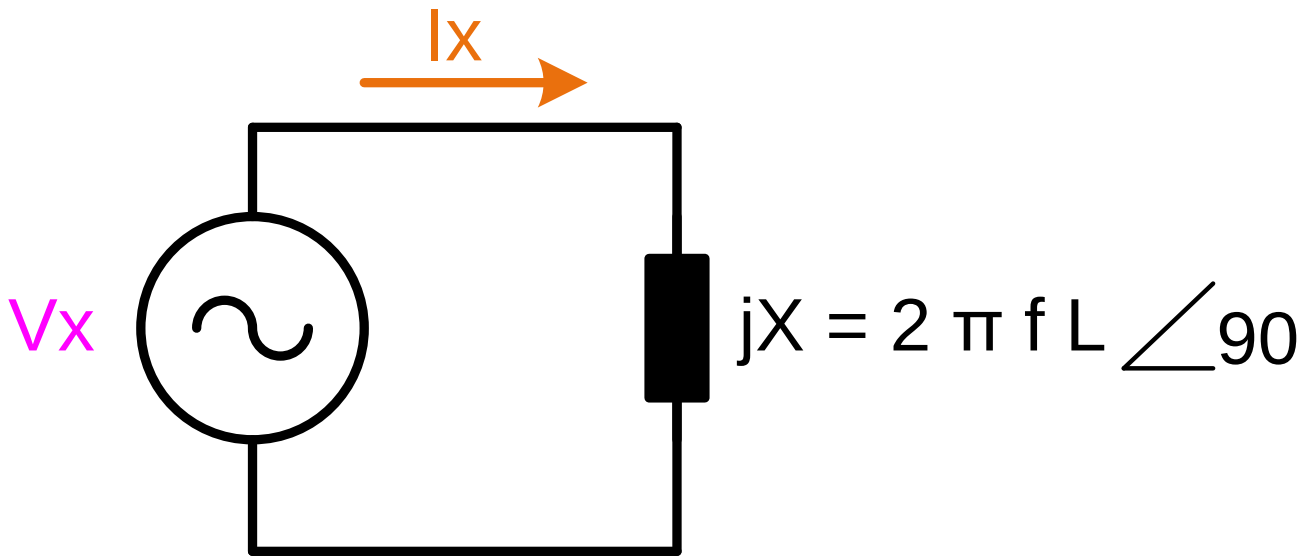
Relative voltage magnitudes and resistance determine current magnitude and direction of power flow

Two AC Voltage Sources

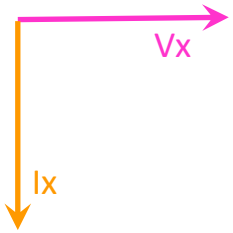


Relative voltage magnitudes and phase angles determine current magnitude, PF, and direction of power flow

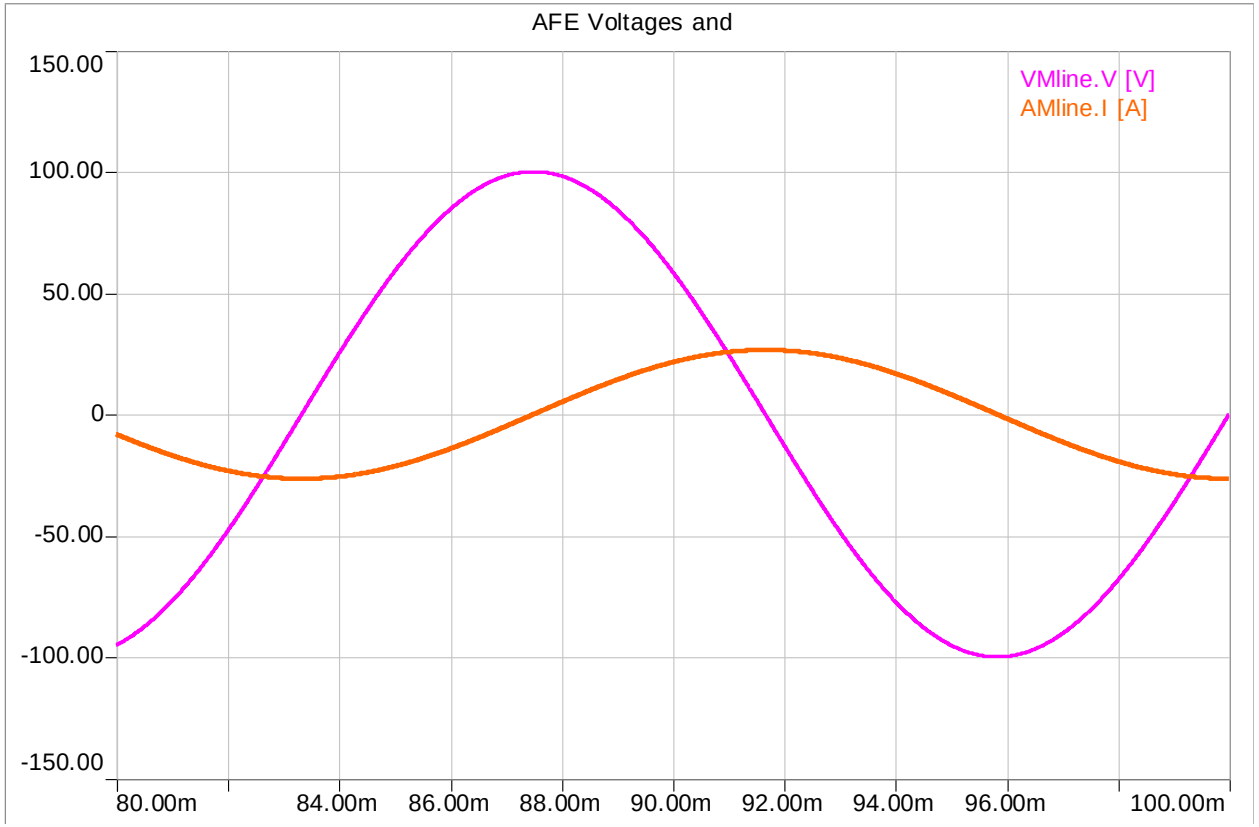
Current and Power Flow with an Inductor

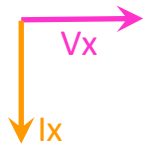


$$\overline{Ix} = \frac{\overline{Vx}}{\overline{jX}} = \frac{Vx}{2\,\pi\,f\,L} \angle -90$$



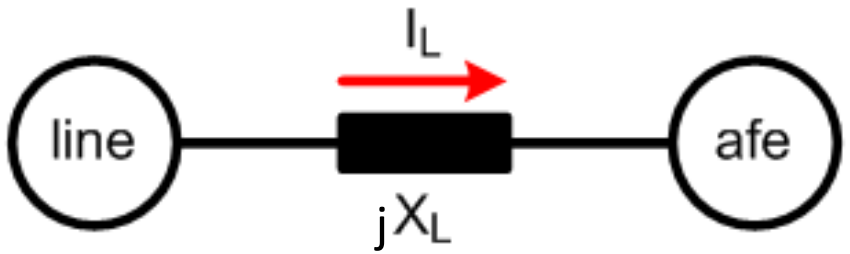
Θ = 0°, Vafe = 100 Vpk, Current lags by 90°





Current and Power Flow with AFE

By adjusting V_a and θ, you can control I_L and β.



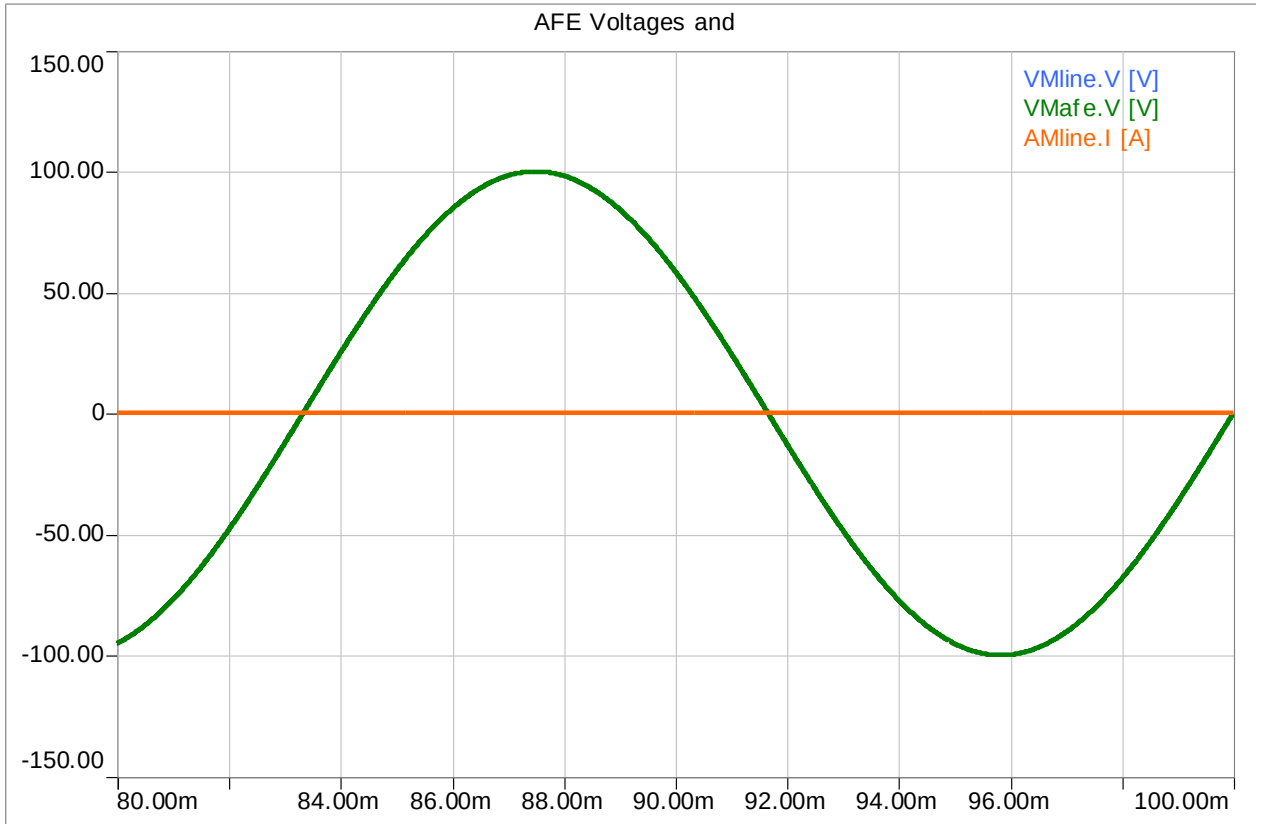
$V_L \angle 0^\circ$ $V_a \angle \theta^\circ$

Fixed Voltage and Angle

Adjustable Voltage and Angle

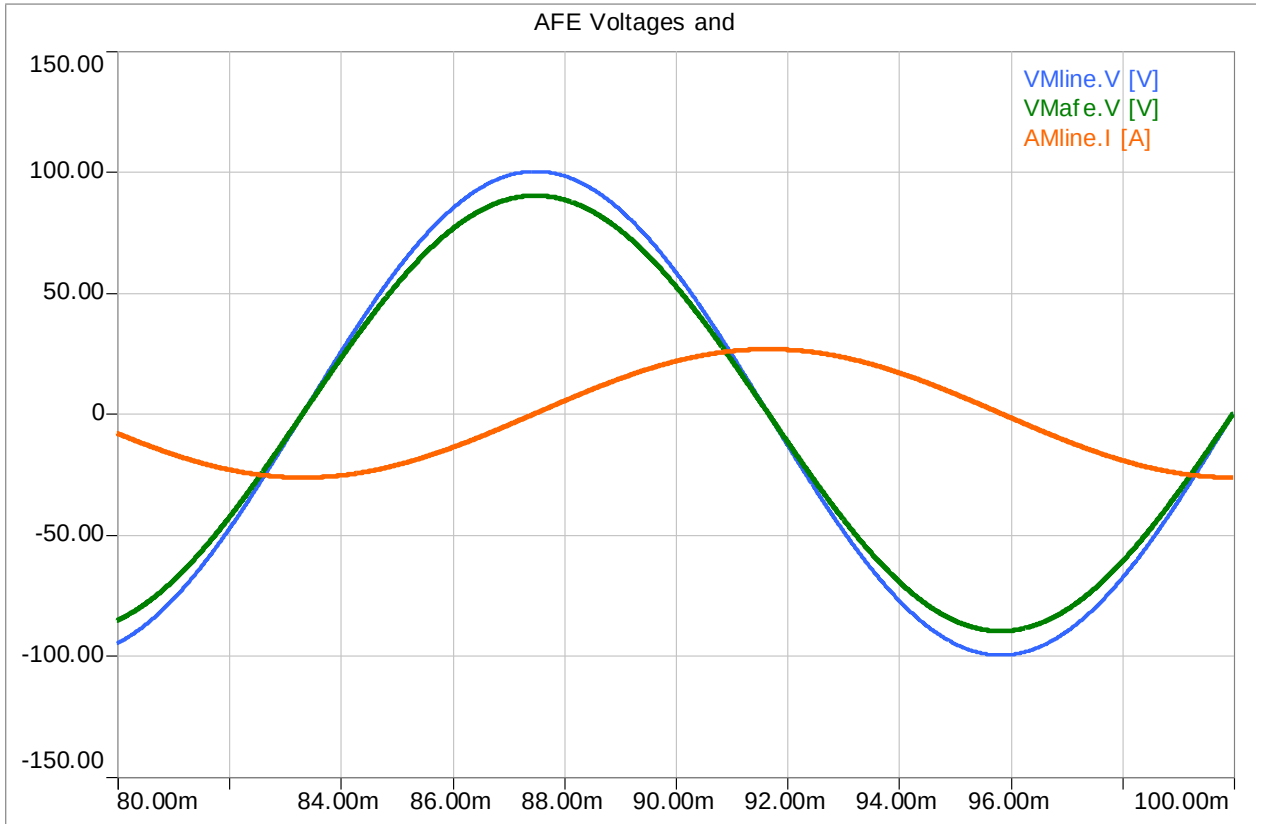
$$I_L \angle \beta^\circ = \frac{(V_L \angle 0^\circ - V_a \angle \theta^\circ)}{X_L \angle 90^\circ}$$

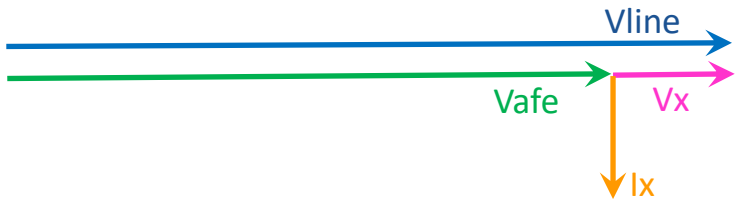
θ = 0°, Vafe = 100, Vline = 100



Zero Current
Zero Watts

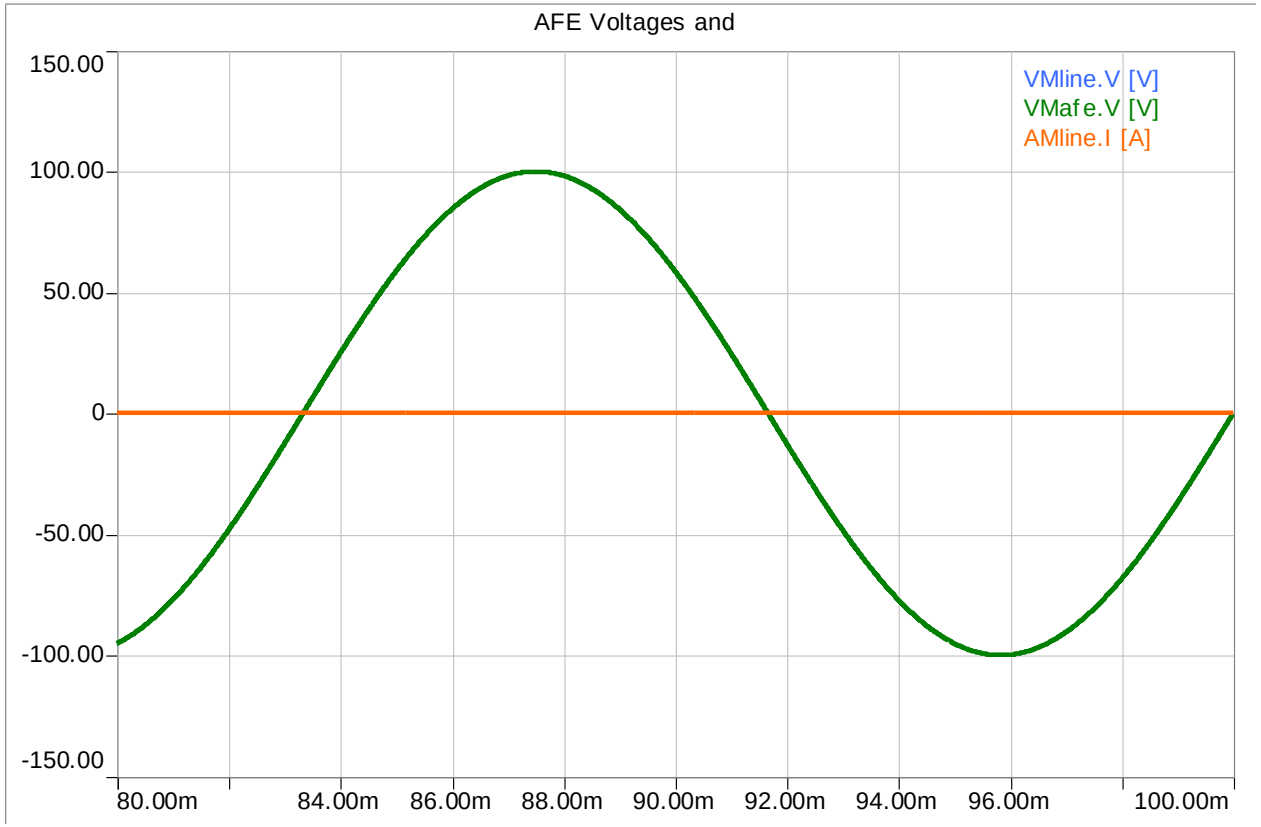
θ = 0°, Vafe = 90





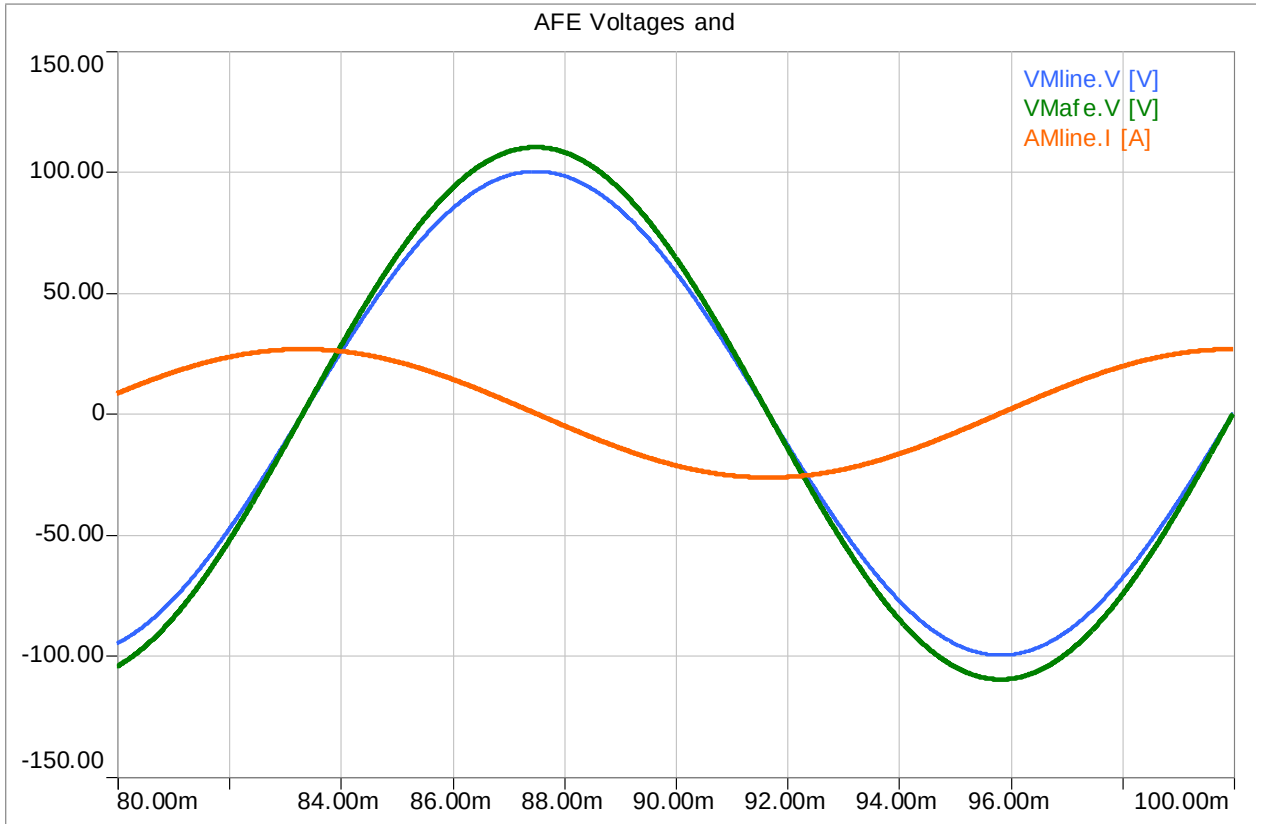
Lagging Current
Zero Watts

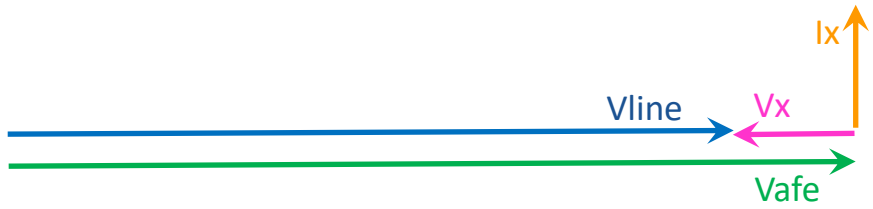
θ = 0°, Vafe = 100



Zero Current
Zero Watts

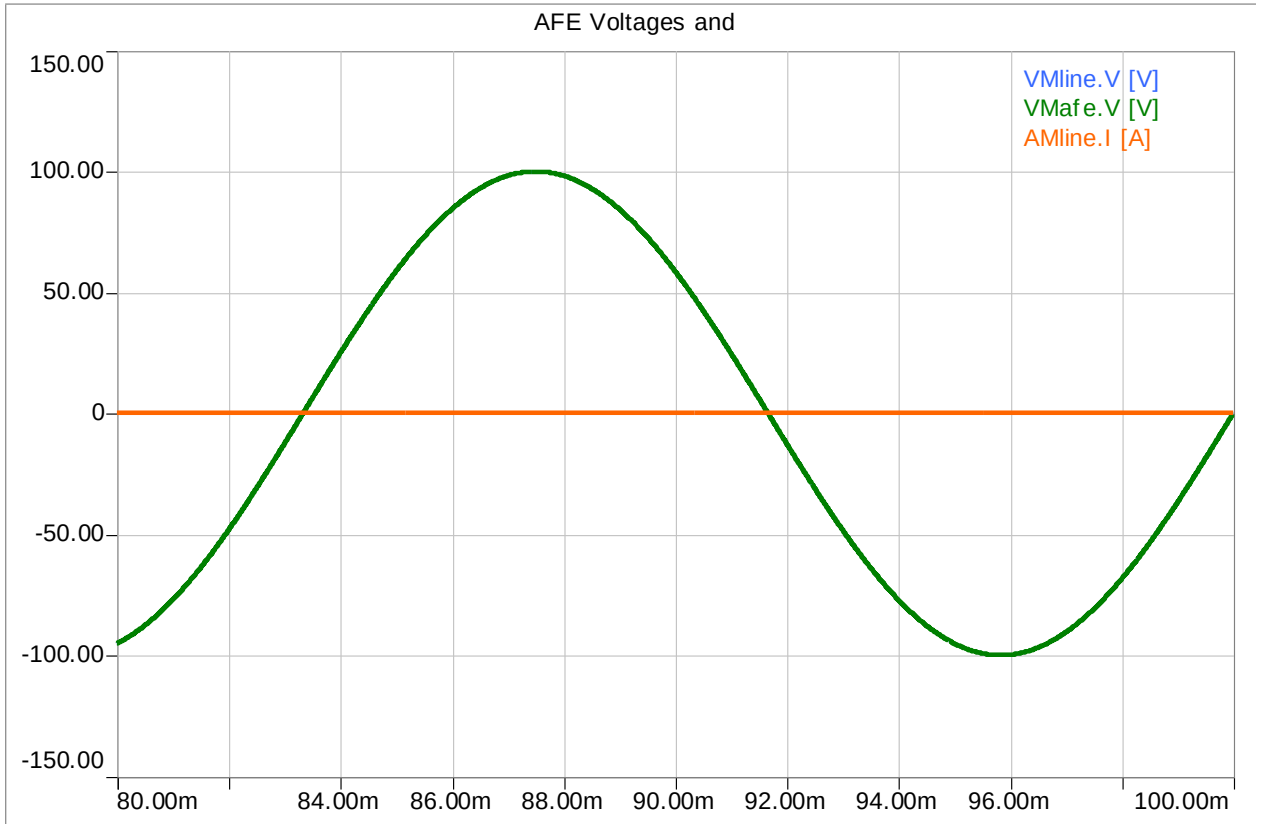
θ = 0°, Vafe = 110





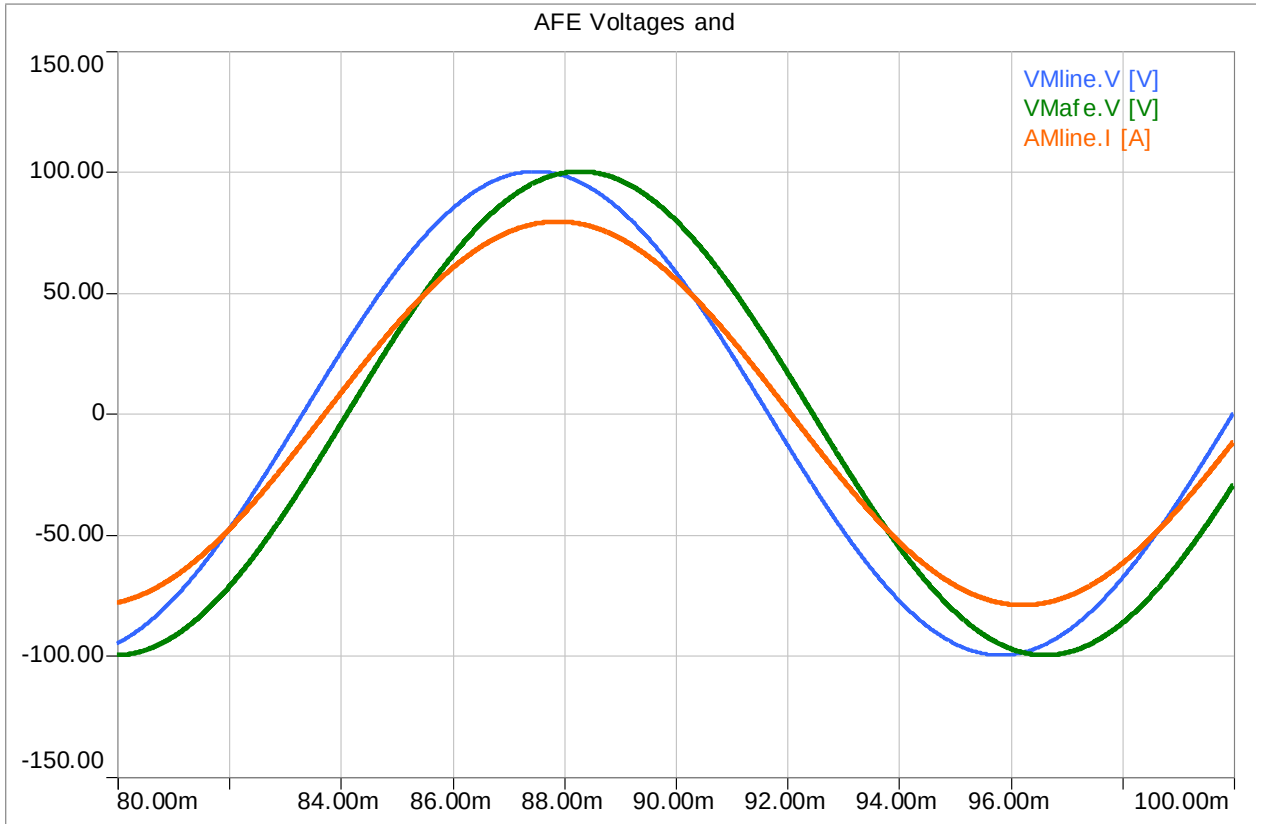
Leading Current
Zero Watts

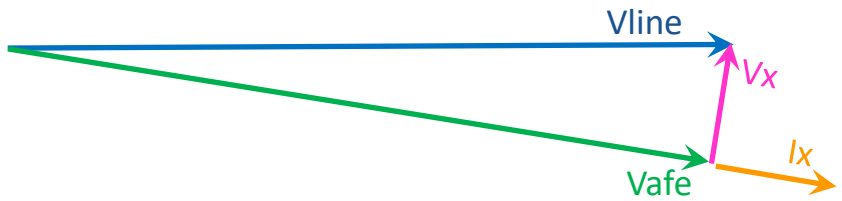
θ = 0°, Vafe = 100



Zero Current
Zero Watts

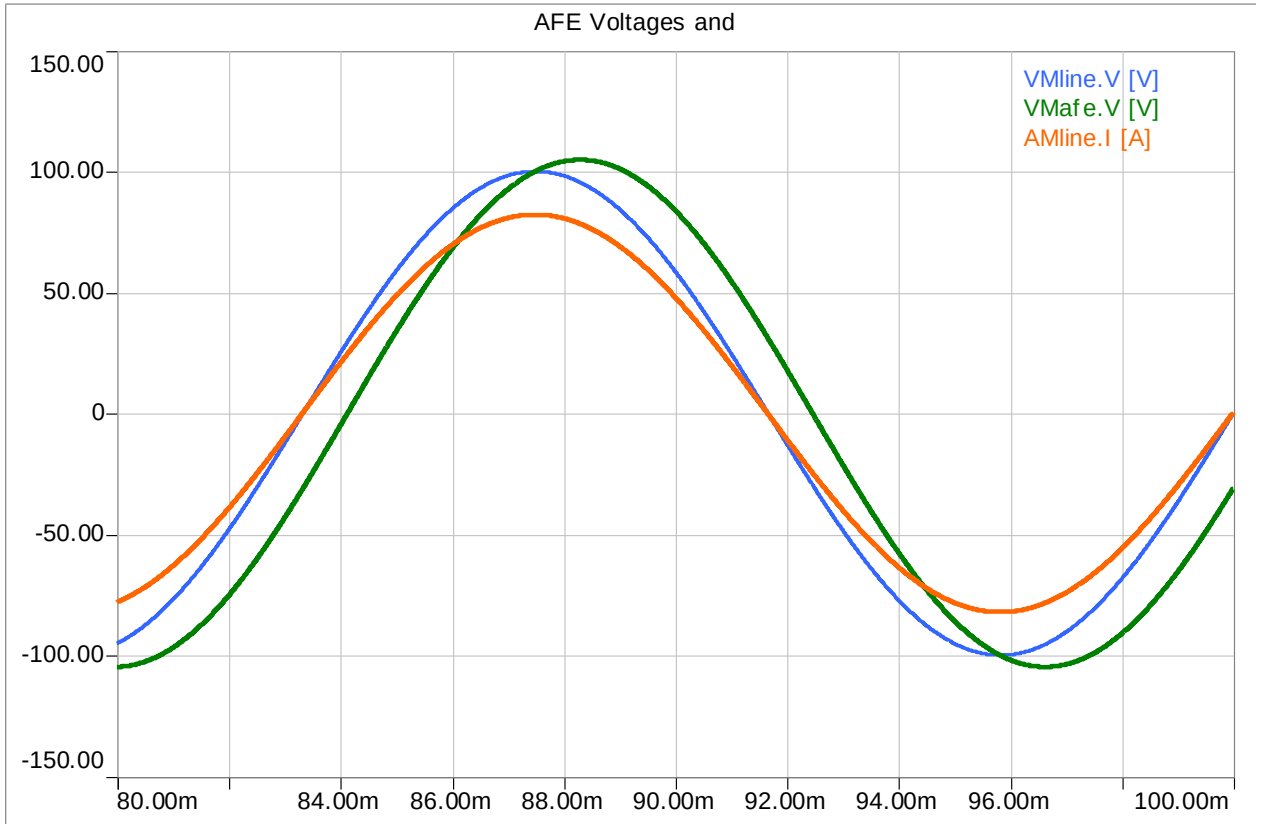
θ = -17°, Vafe = 100



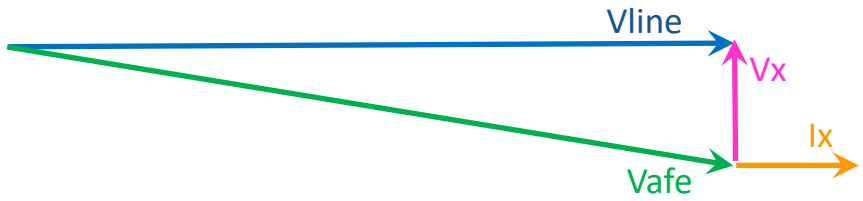


Lagging Current
> 0 Watts

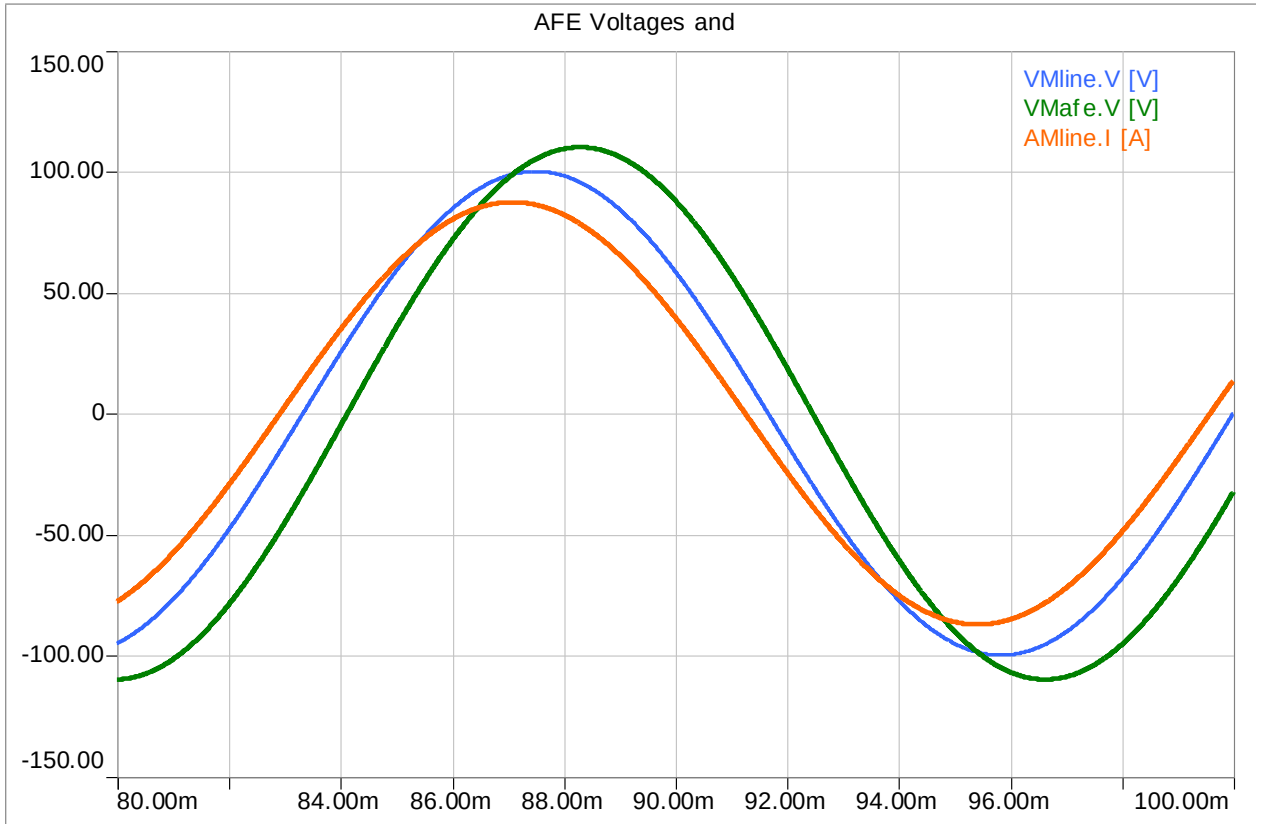
θ = -17°, Vafe = 105

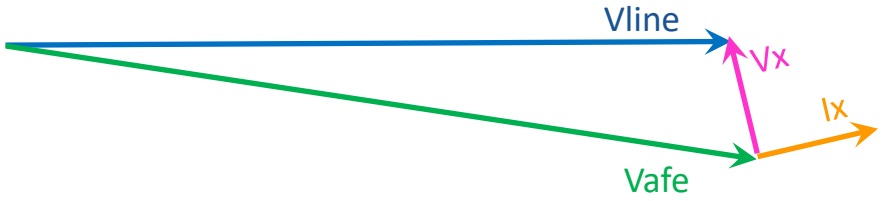


Unity PF Current
> 0 Watts



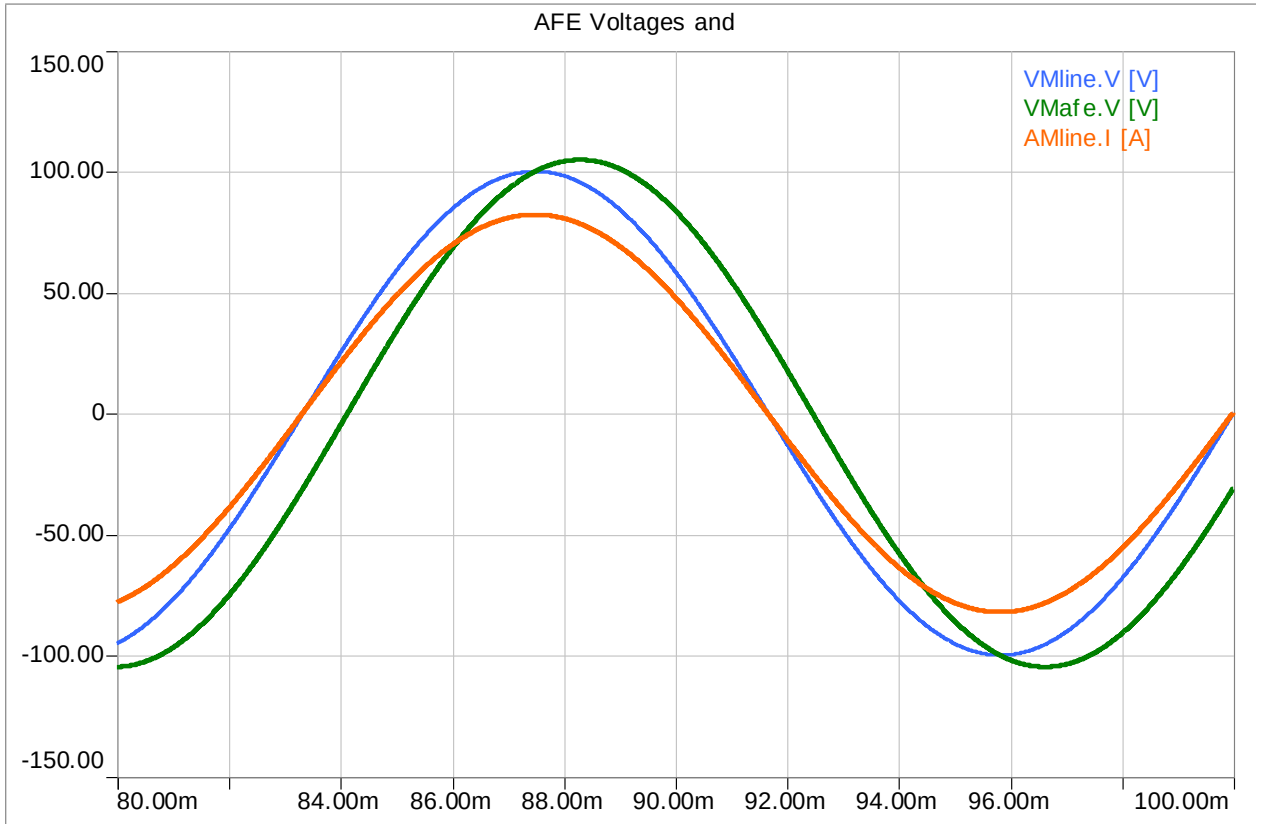
θ = -17°, Vafe = 110

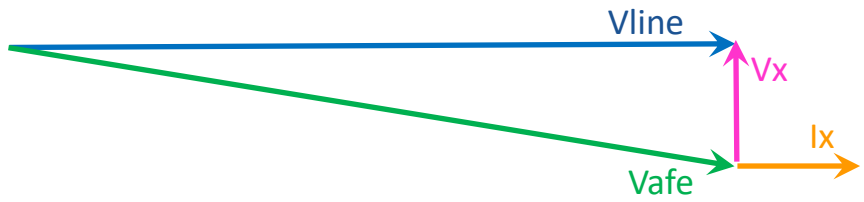




Leading Current
> 0 Watts

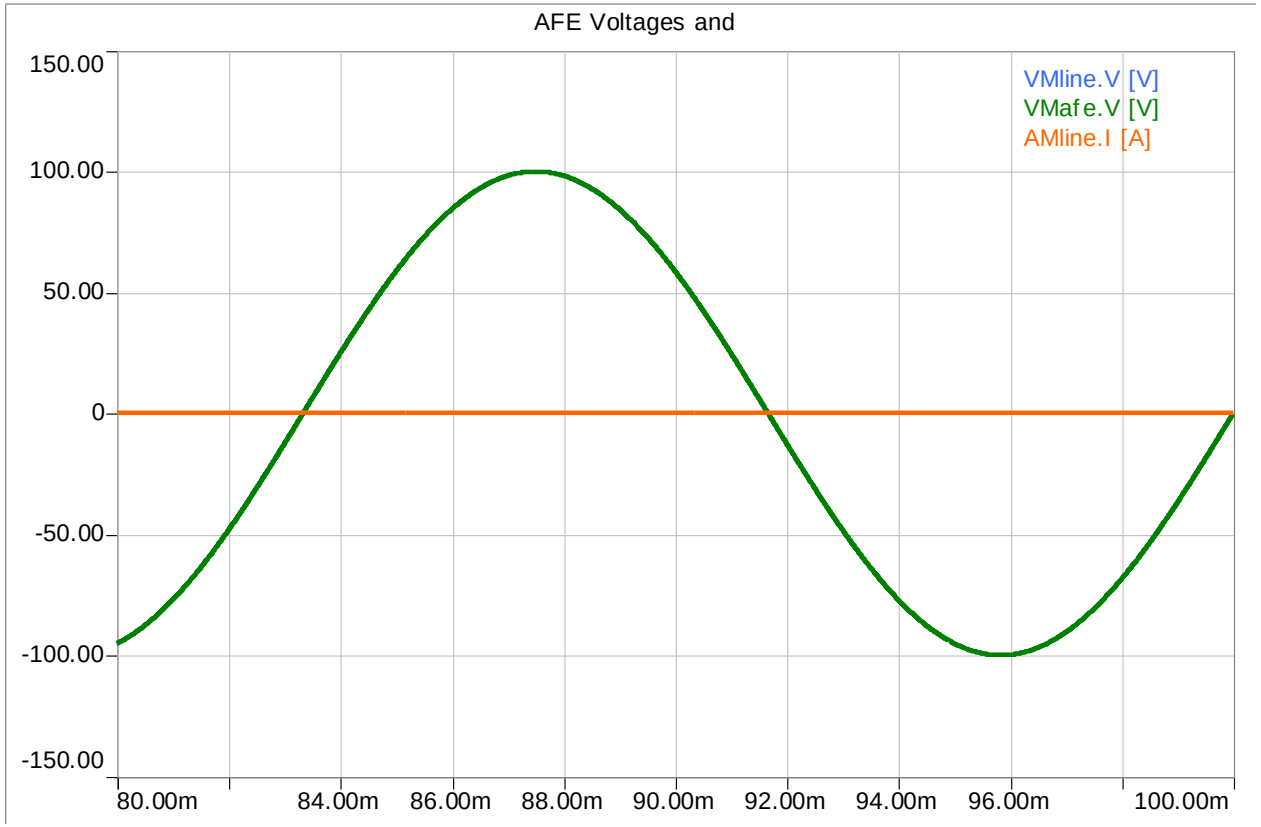
θ = -17°, Vafe = 105





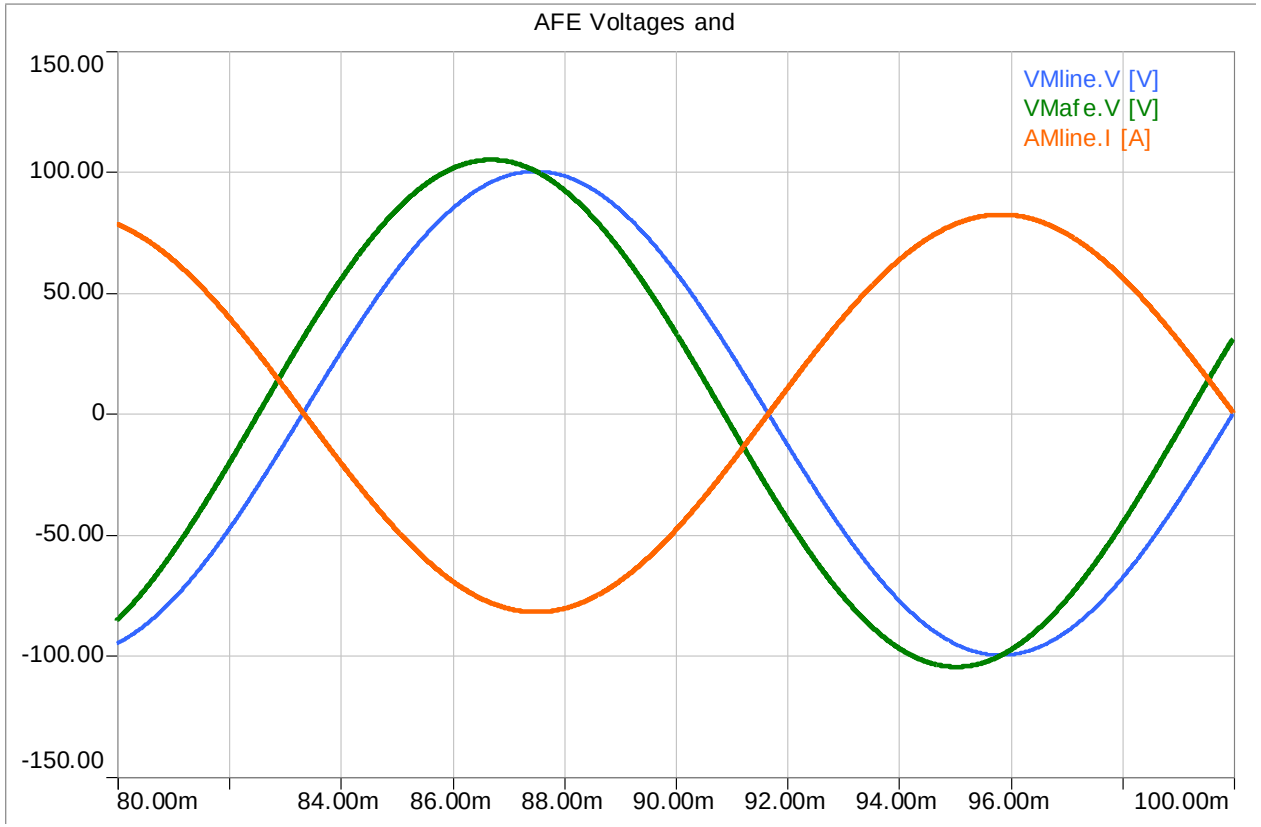
Unity PF Current
> 0 Watts

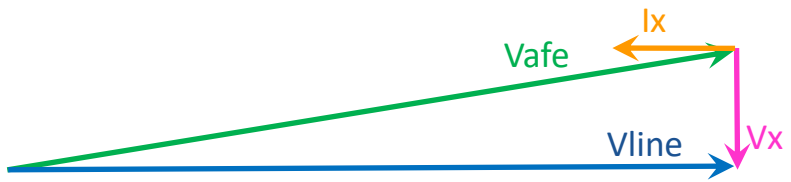
θ = 0°, Vafe = 100



Zero Current
Zero Watts

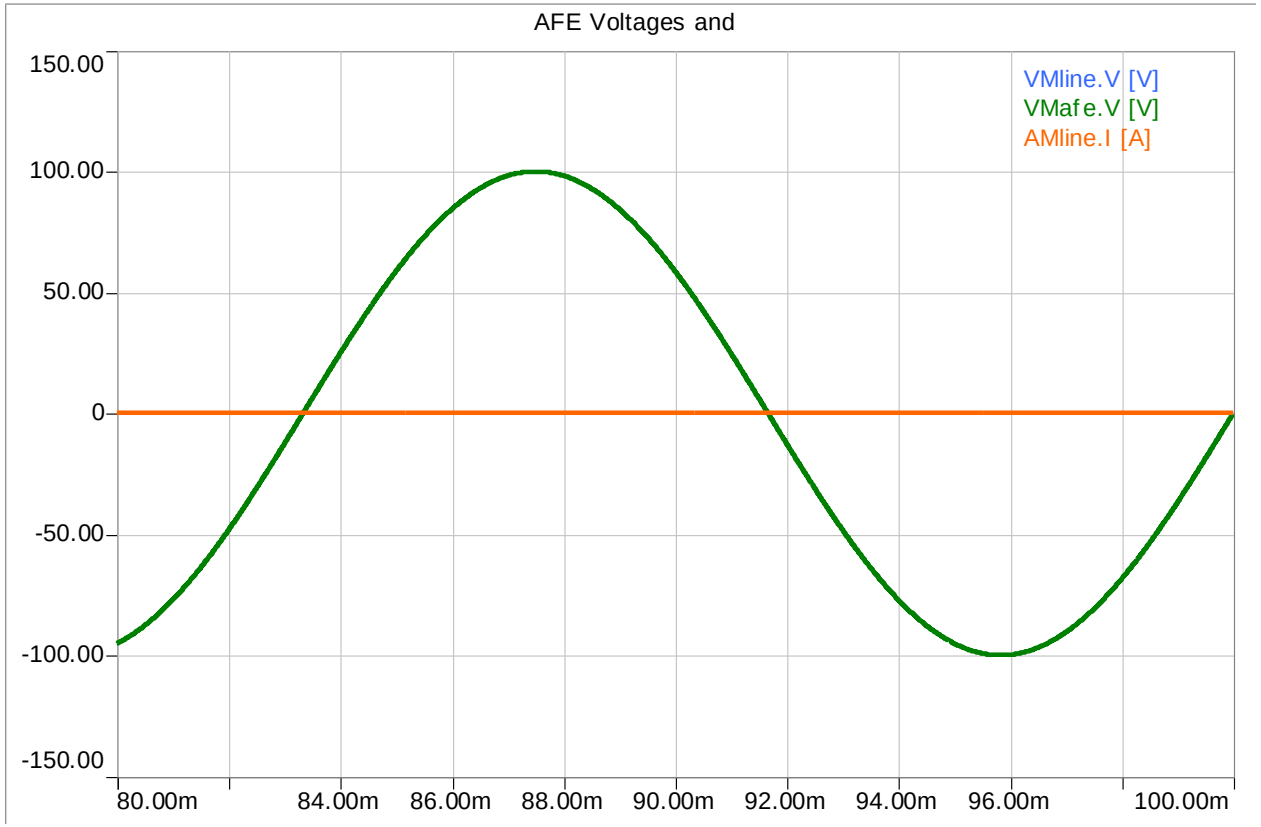
θ = +17°, Vafe = 105





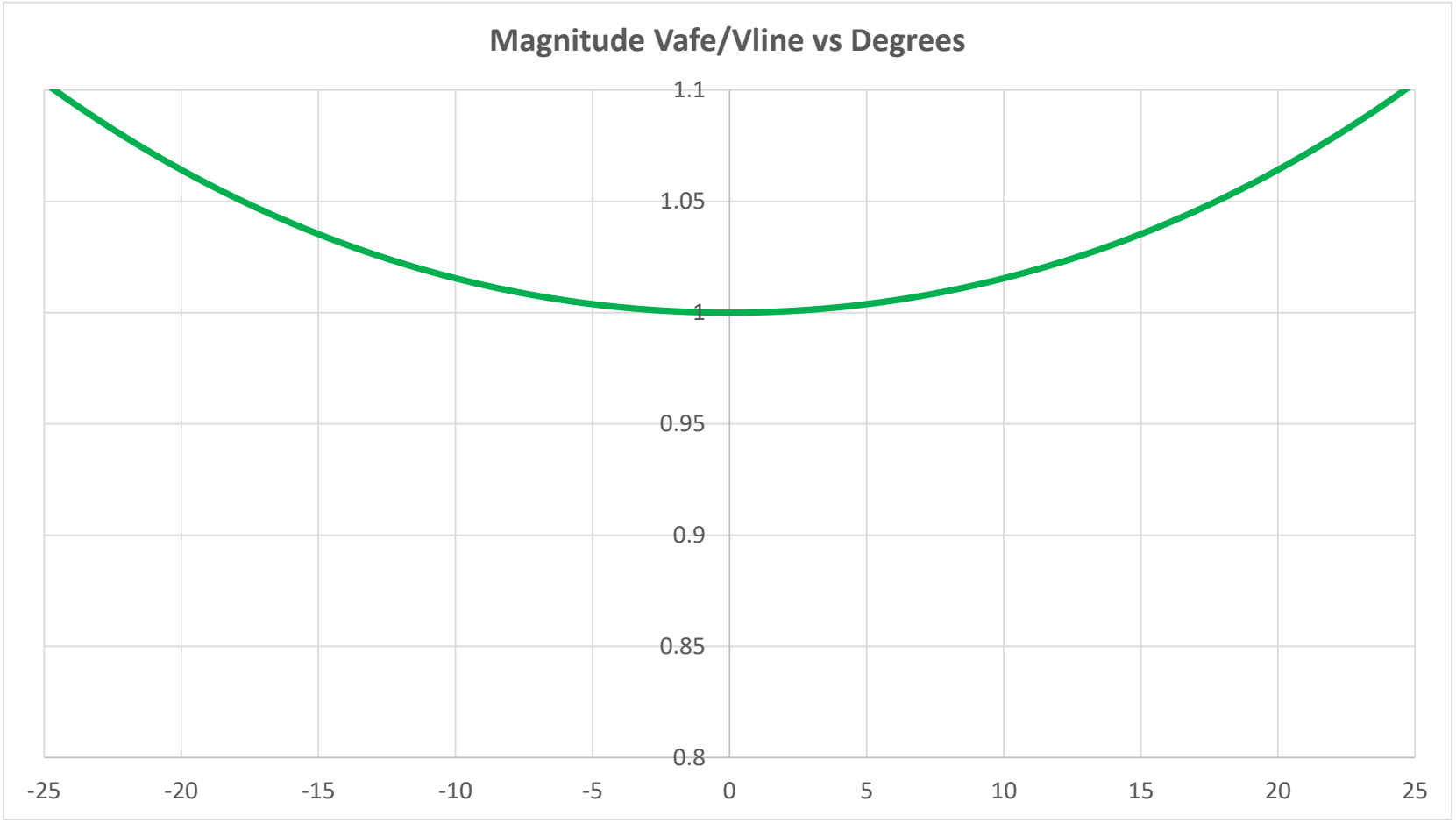
Unity PF Current
< 0 Watts

θ = 0°, Vafe = 100



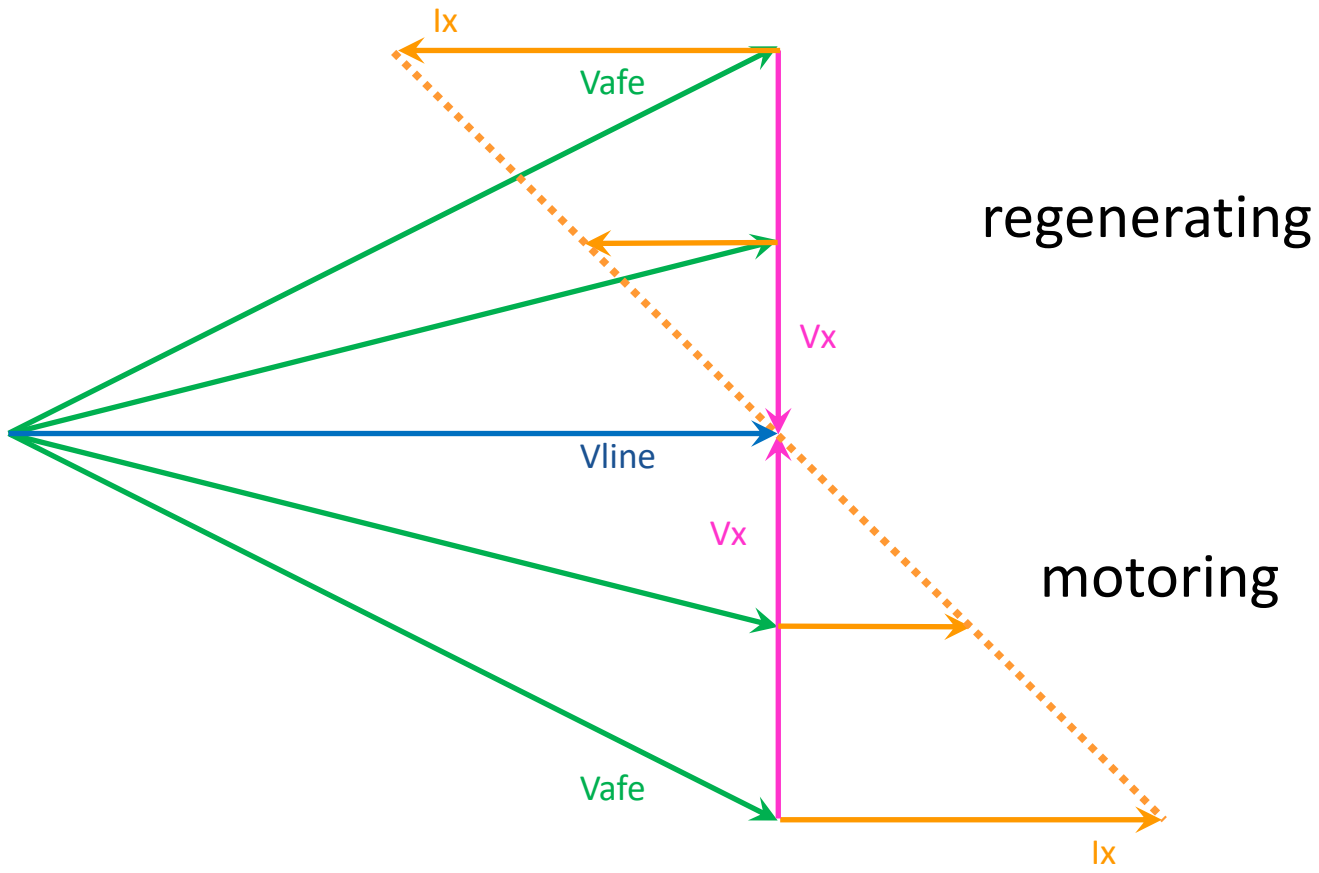
Zero Current
Zero Watts

Ratio of Vafe to Vline vs Degrees



$$\text{Ratio} = 1/\cos(\theta)$$

Vector Loci for Unity PF



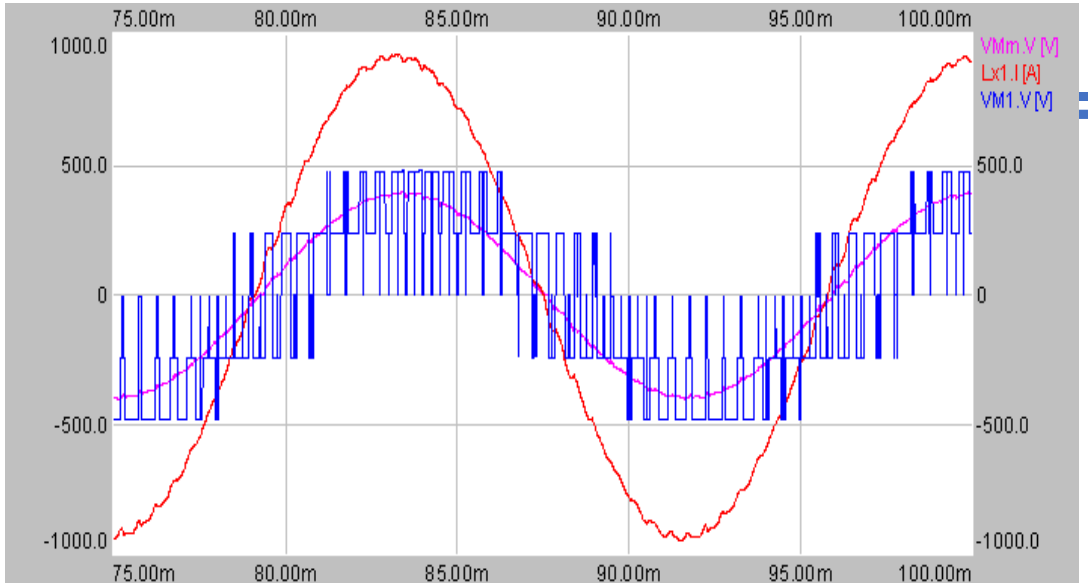
Vafe = Vline/cos(θ)

AFE Converter

Motoring

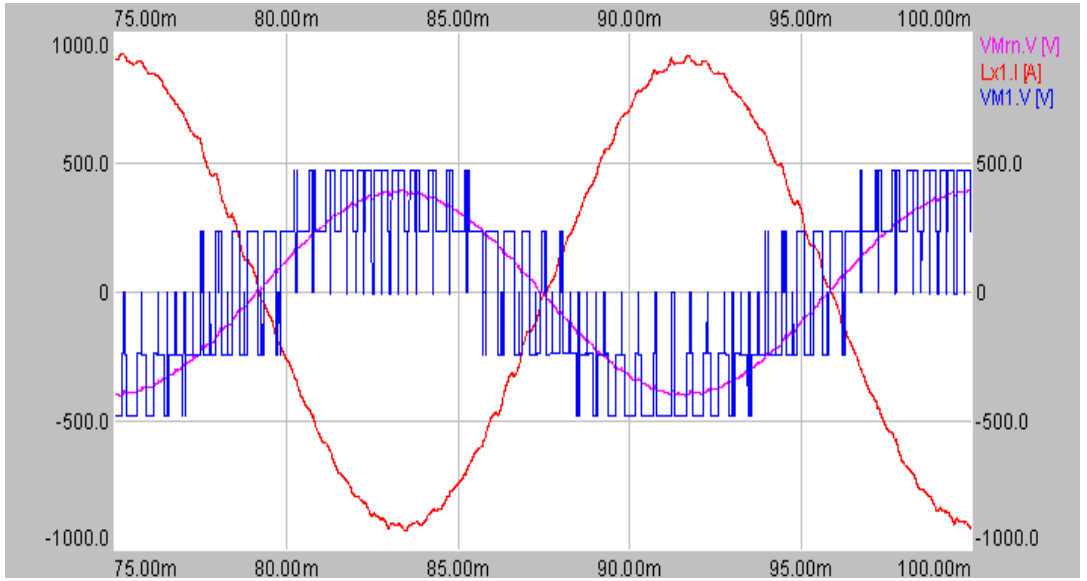
- unity power factor
- I and V in-phase
- I(THD) = 3.6%

Iline Vline Vafe



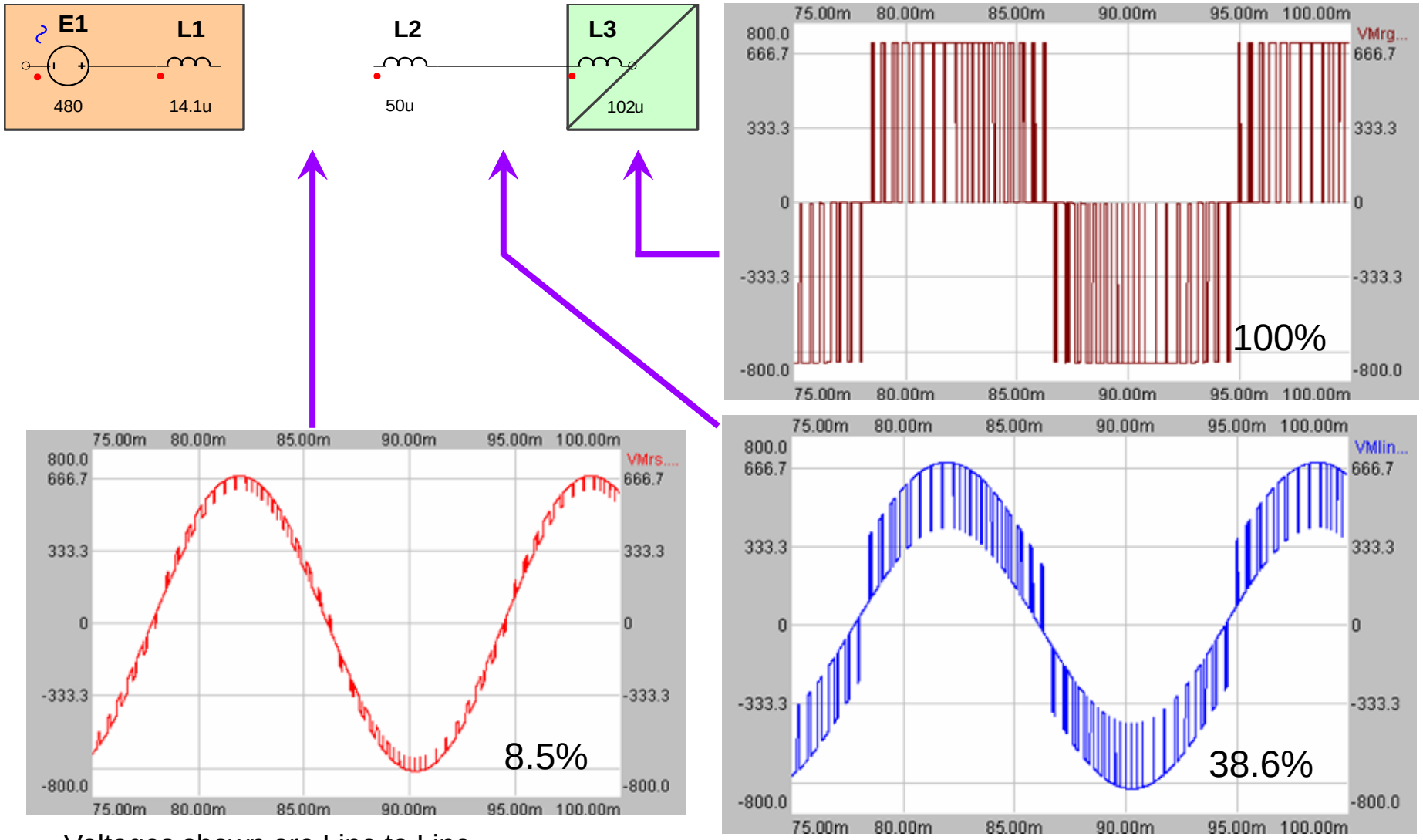
Regenerating

- unity power factor
- I and V 180 deg out-of-phase
- I(THD) = 3.6%



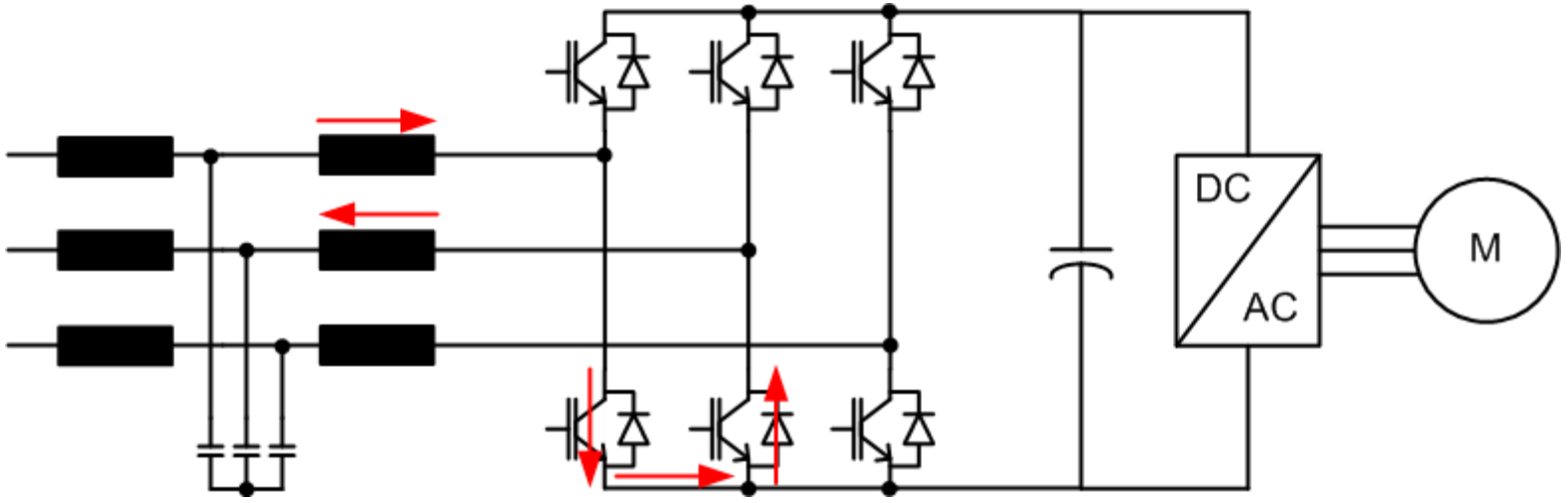
Voltages shown are Line to Neutral

AFE Line Notches without LCL Filter



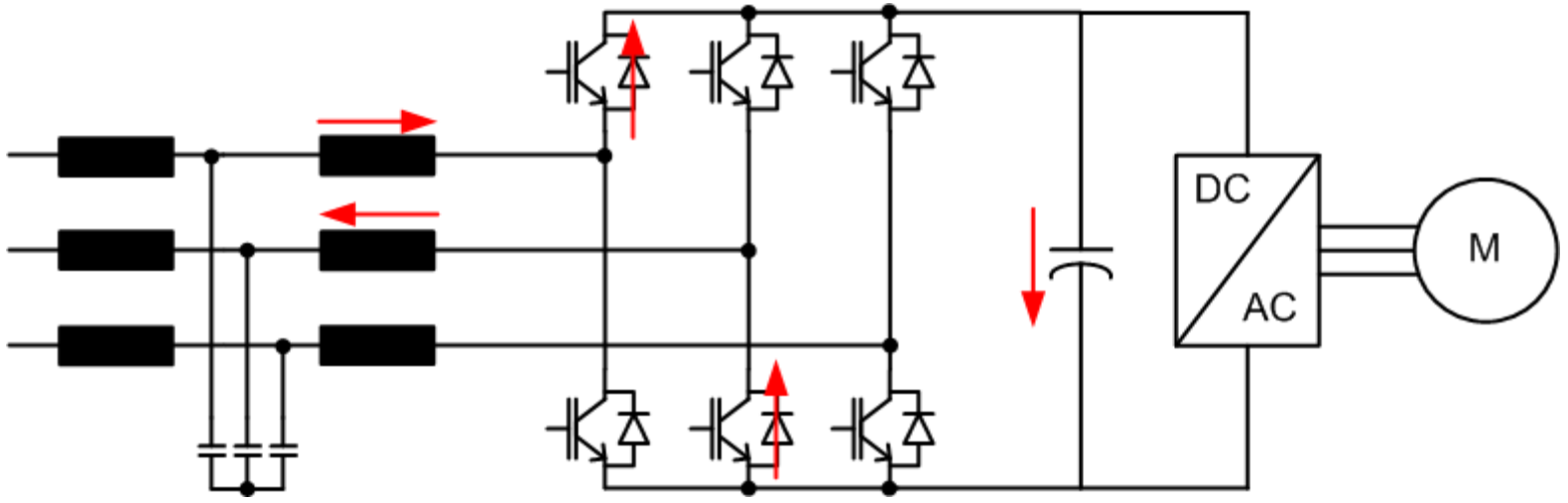
Voltages shown are Line to Line

Line Notching



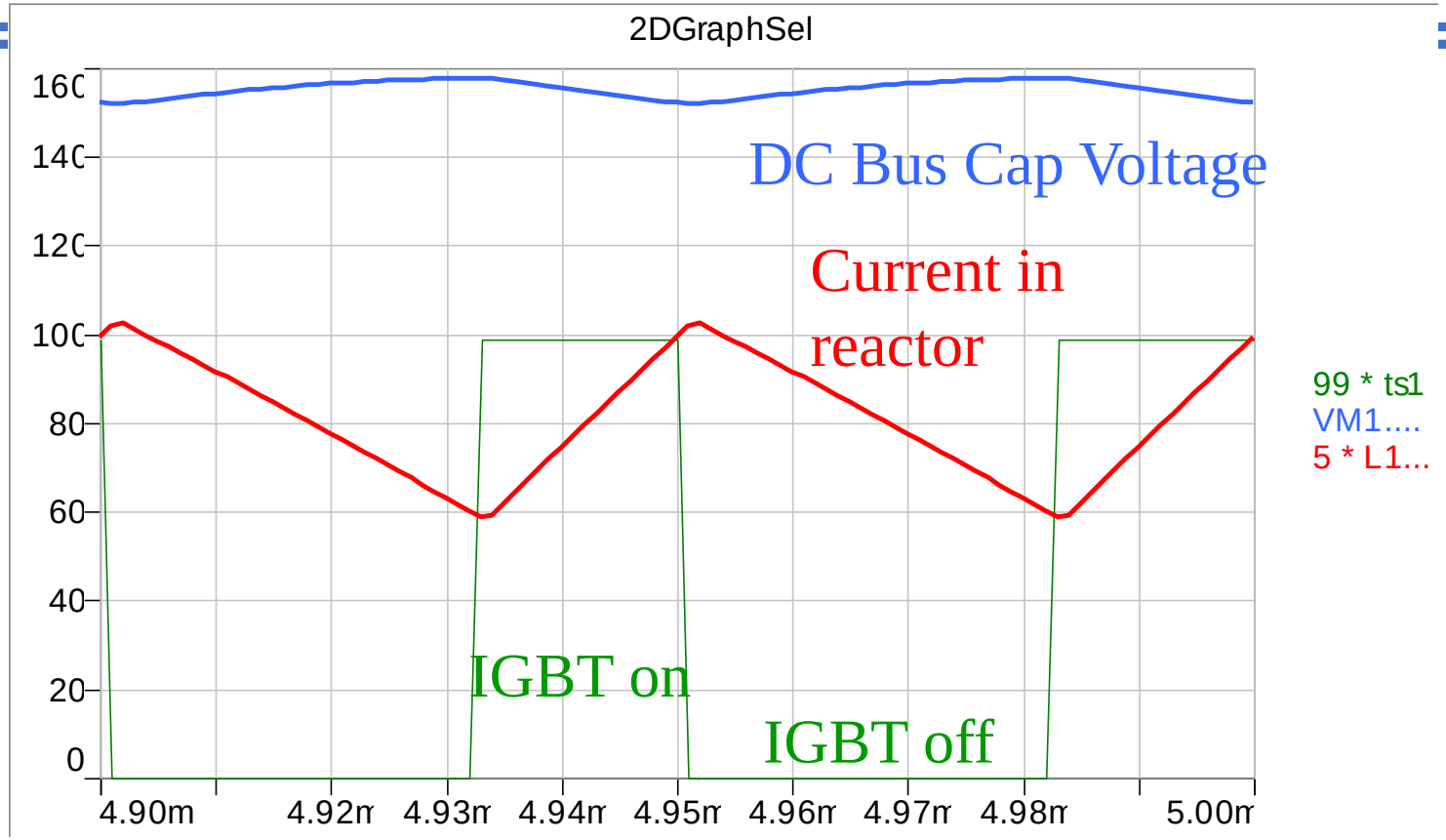
IGBT is on, creating line-to-line short circuit
Current in line reactor is increasing, storing energy in the reactors
Load is discharging the DC bus cap

Line Notching



IGBT is off
Current in line reactor is charging the DC bus cap
Reactor energy is transferred to DC bus cap

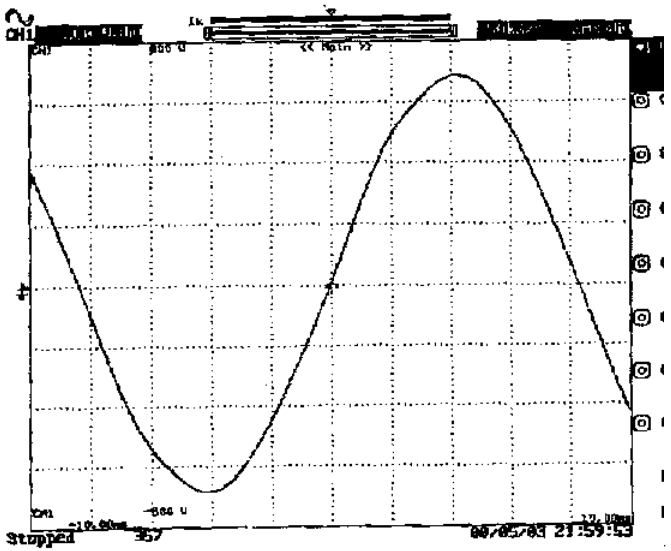
Line Notching



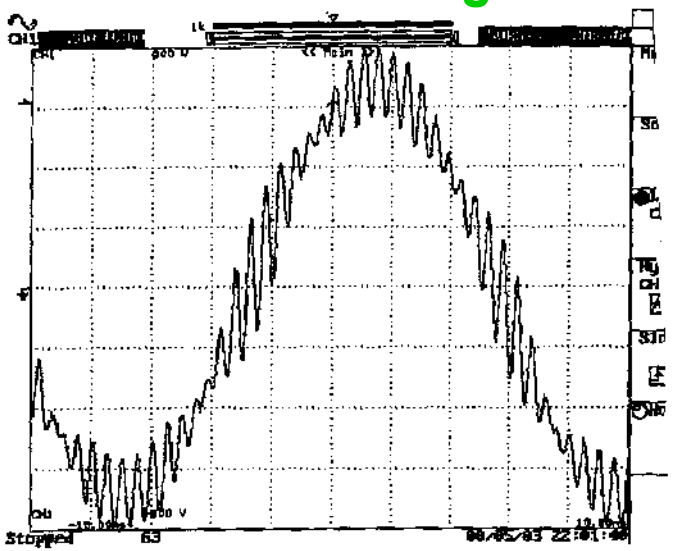
Blue = DC bus cap voltage
Red = Current in line reactor
Green = IGBT on/off signal

Customer’s 120V supply for office area

Without LCL Filter, AFE stopped

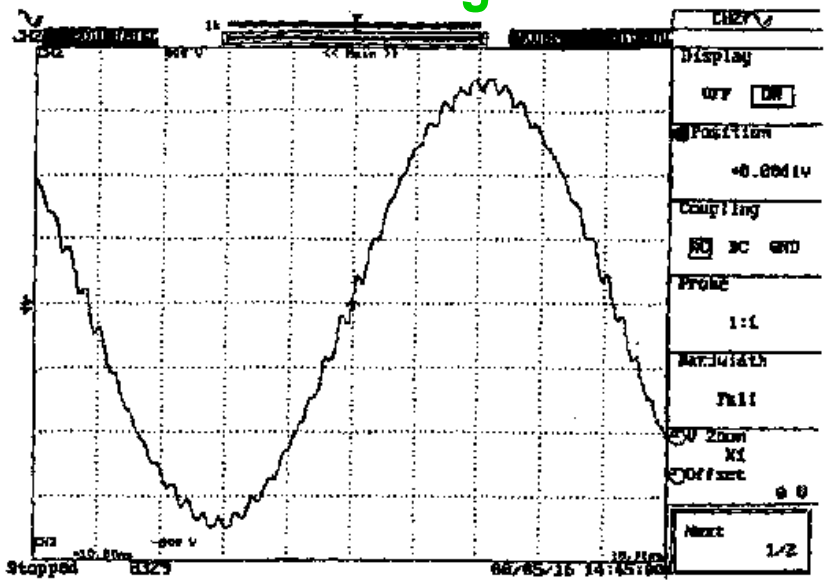


Without LCL Filter, AFE running



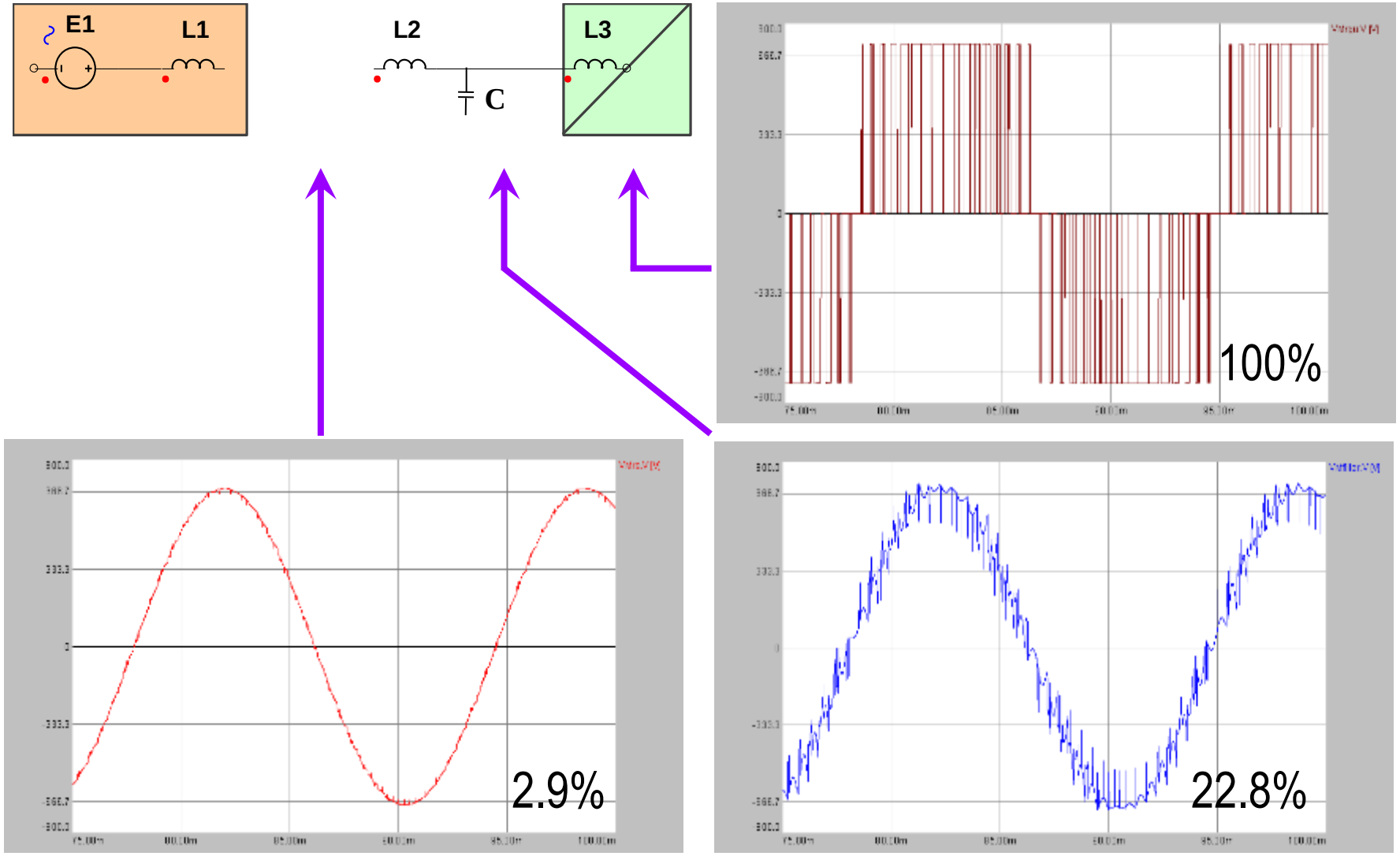
Input to 550 KVA

With LCL Filter, AFE running



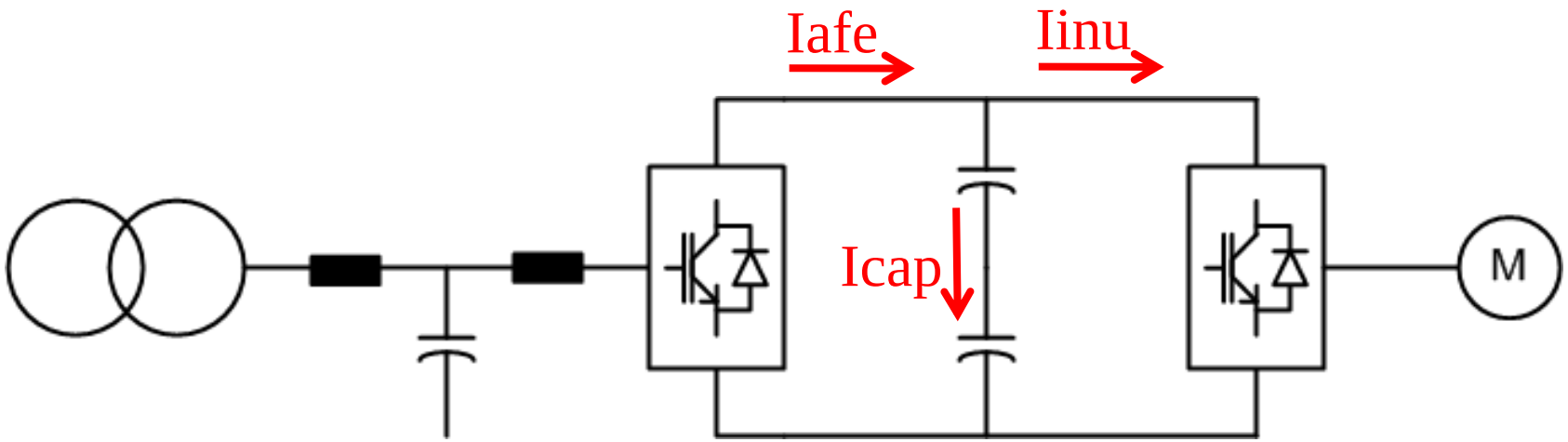
460VAC with filter on with 40 µf capacitors installed

AFE Line Notches Reduced with LCL Filter



Voltages shown are Line to Line

Control of Vdc bus



Note the following:

The average current in the DC Bus Caps, Icap = Iafe – Iinu

Normally Icap = 0, so Iinu = Iafe

If the load increases:

Vcap decreases, and control increases Iafe to bring Vcap back to normal

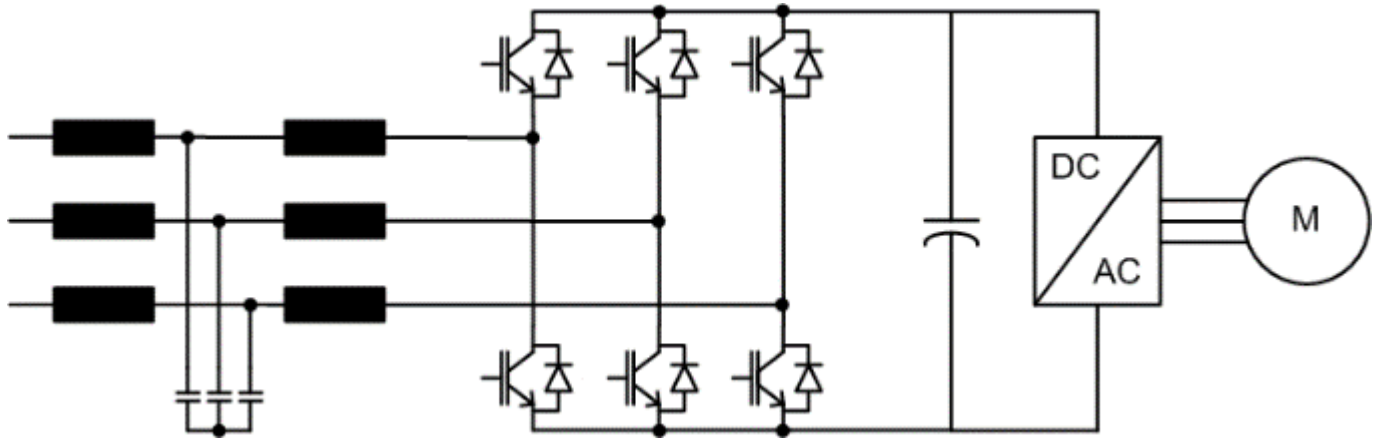
If the load decreases or reverses:

Vcap increases, and control decreases or reverses Iafe to maintain Vcap

AFE Rectifier with LCL Filter

Advantages:

- Very low line harmonics, 3-4% Ithd
- Unity PF
- Can operate with leading PF
- Sags will not affect motor voltage
- Possible to compensate for voltage drop along long leads
- Full power regeneration continually
- Constant torque braking at all speeds
- Fast stopping
- All in a small package without extra hardware!



Active Converter removes low frequencies by not creating them < 1kHz

LCL filter (passive filter) removes high frequencies >1.2 kHz
(current and voltage)

Power factor adjustable from 0.85 (leading or lagging) to 1.0

Full output voltage is available with 80% input voltage
(400VIn = 480VOut) (3300VIn = 4160VOut)

Full regenerative capability

No phase shifting transformer required

Less affected by line imbalance

IEEE 519-2014, Annex C

Table C-1—Recommended limits on commutation notches

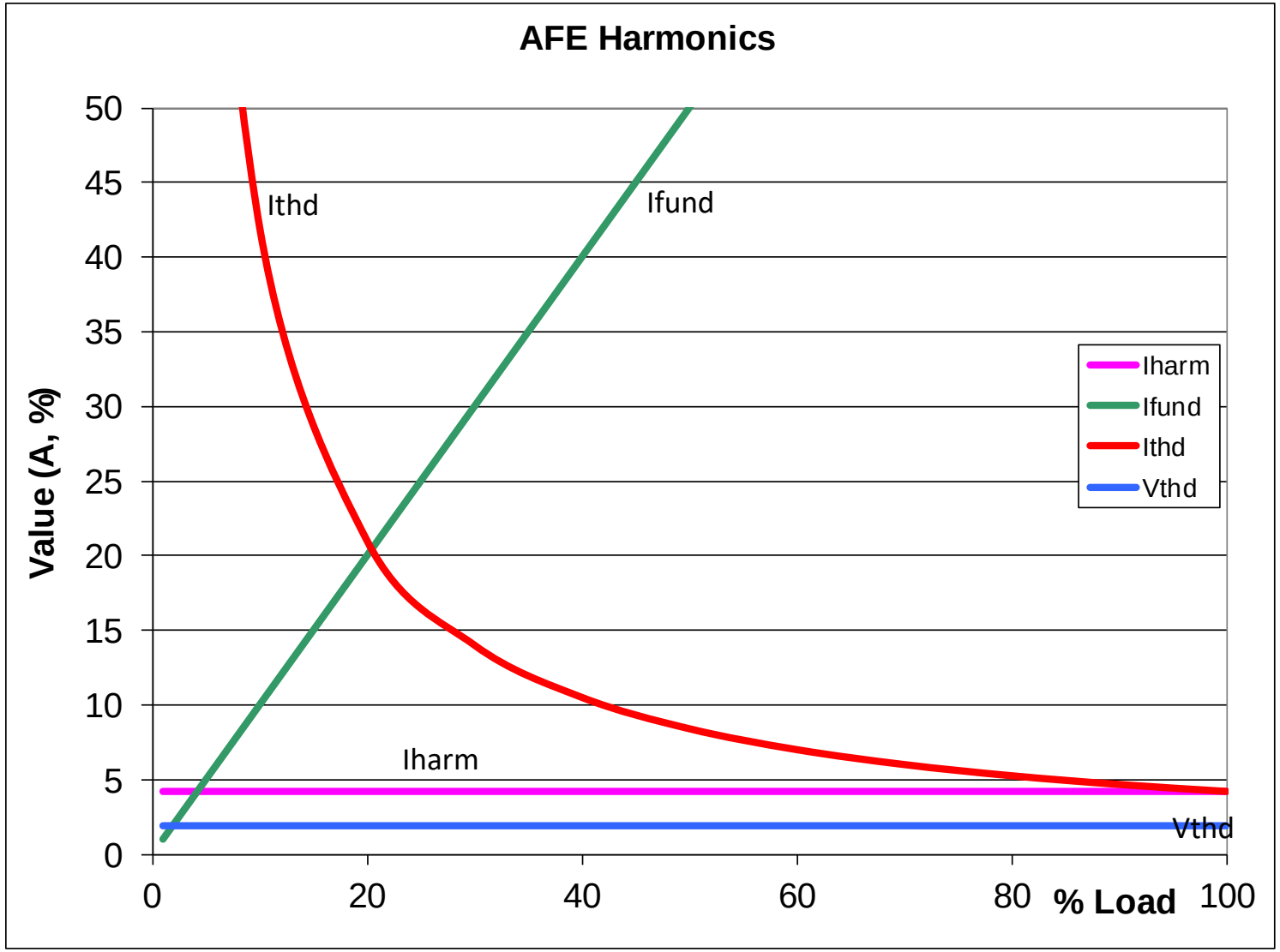
	Special applications[a]	General system	Dedicated system[b]
Notch depth	10%	20%	50%
Notch area (A_N)[c, d]	16400	22800	36500

[a]Special applications include hospitals and airports.
[b]A dedicated system exclusively supplies a specific user or user load.
[c]In volt-microseconds at rated voltage and current.
[d]The values for A_N have been developed for 480 V systems. It is necessary to multiply the values given by V/480 for application at all other voltages.

Rule of Thumb –

Keep notch depth less than 10% if any other equipment will be connected to that same point of common coupling.

Ithd and Vthd vs %Load



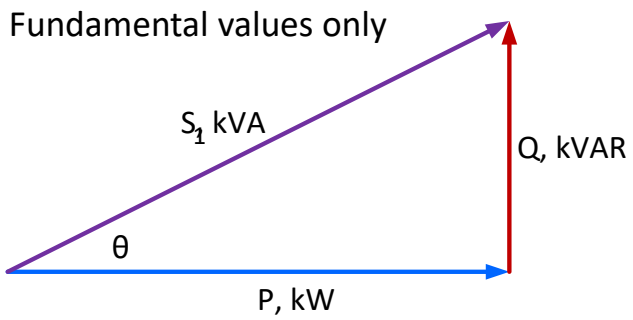
What about Power Factor?

What is Total Power Factor?

- **Displacement PF**

- COS of angle between fundamental current and voltage due to reactive current

- $\boldsymbol{PF_{disp} = cos(\theta) = P/S_1}$

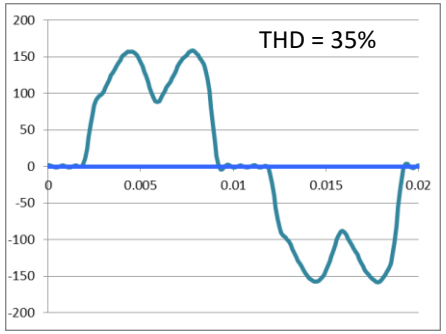


- **Distortion PF**

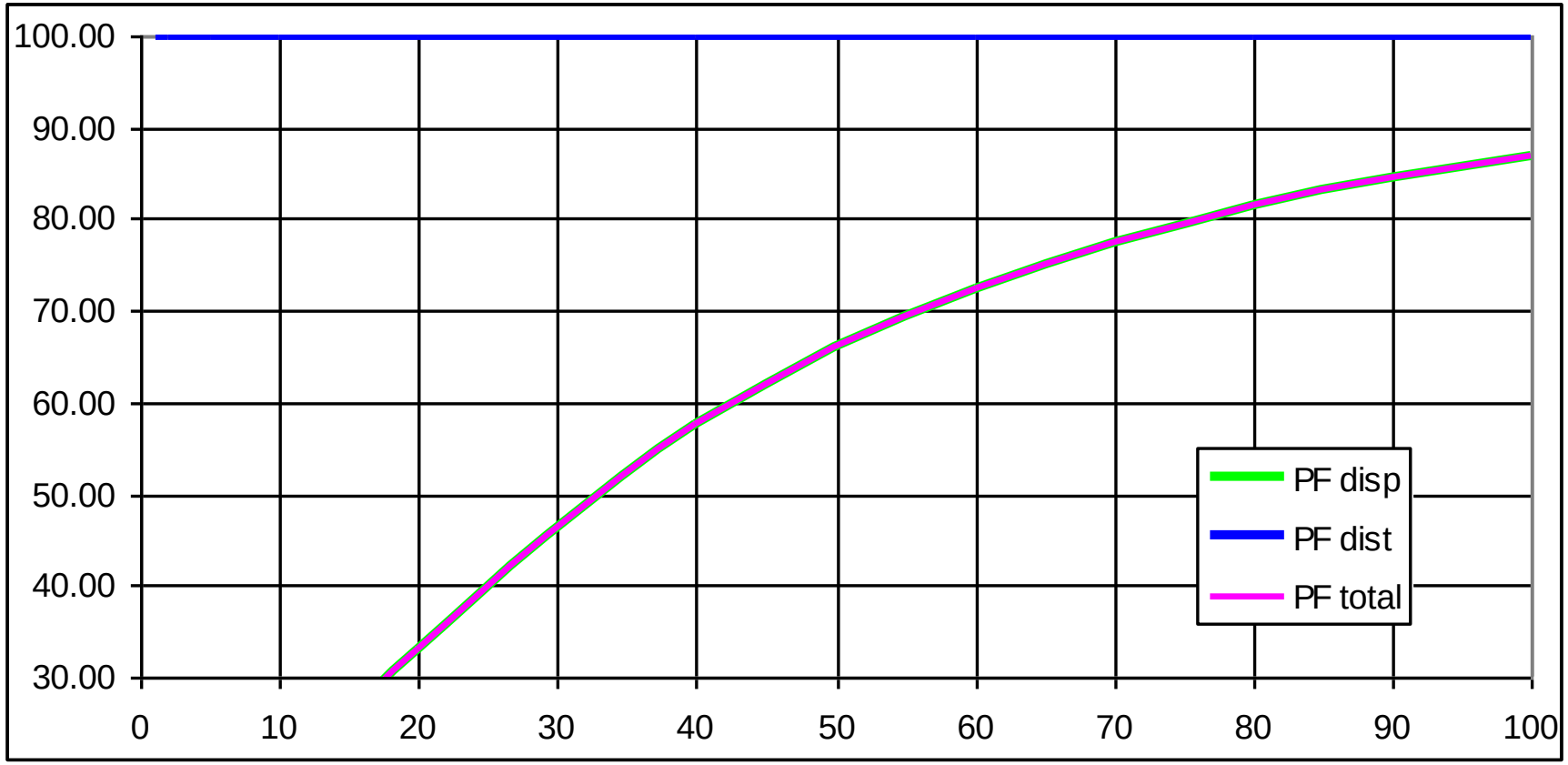
- Calculation based upon the current THD due to harmonic currents

- $\boldsymbol{PF_{dist} = \frac{1}{\sqrt{1+THD^2}} = S_1/S}$

$$\boldsymbol{PF_{total} = PF_{disp} \times PF_{dist} = \frac{P\ [kw]}{S\ [kVA]}}$$

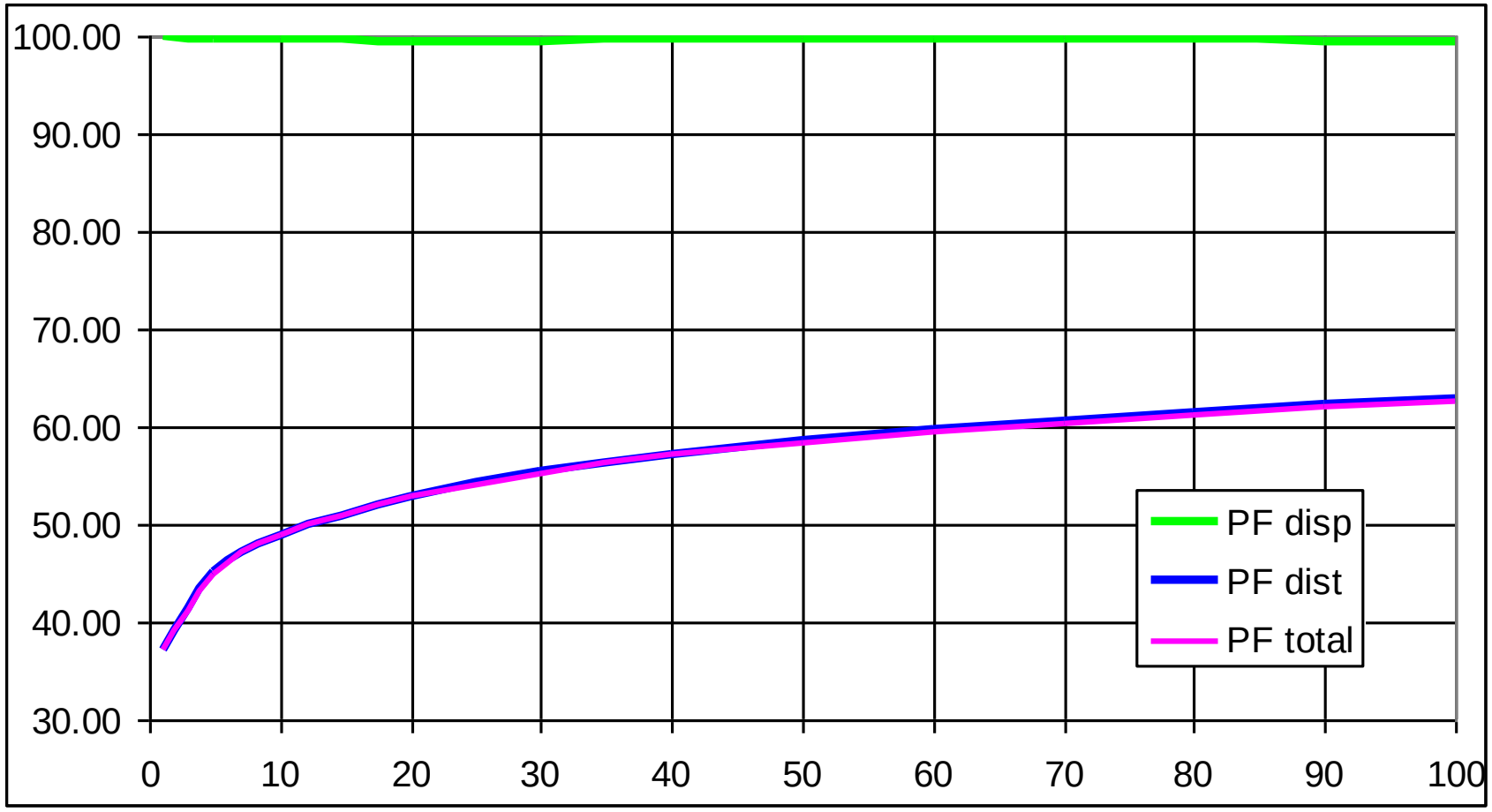


PF of a Motor Across the Line

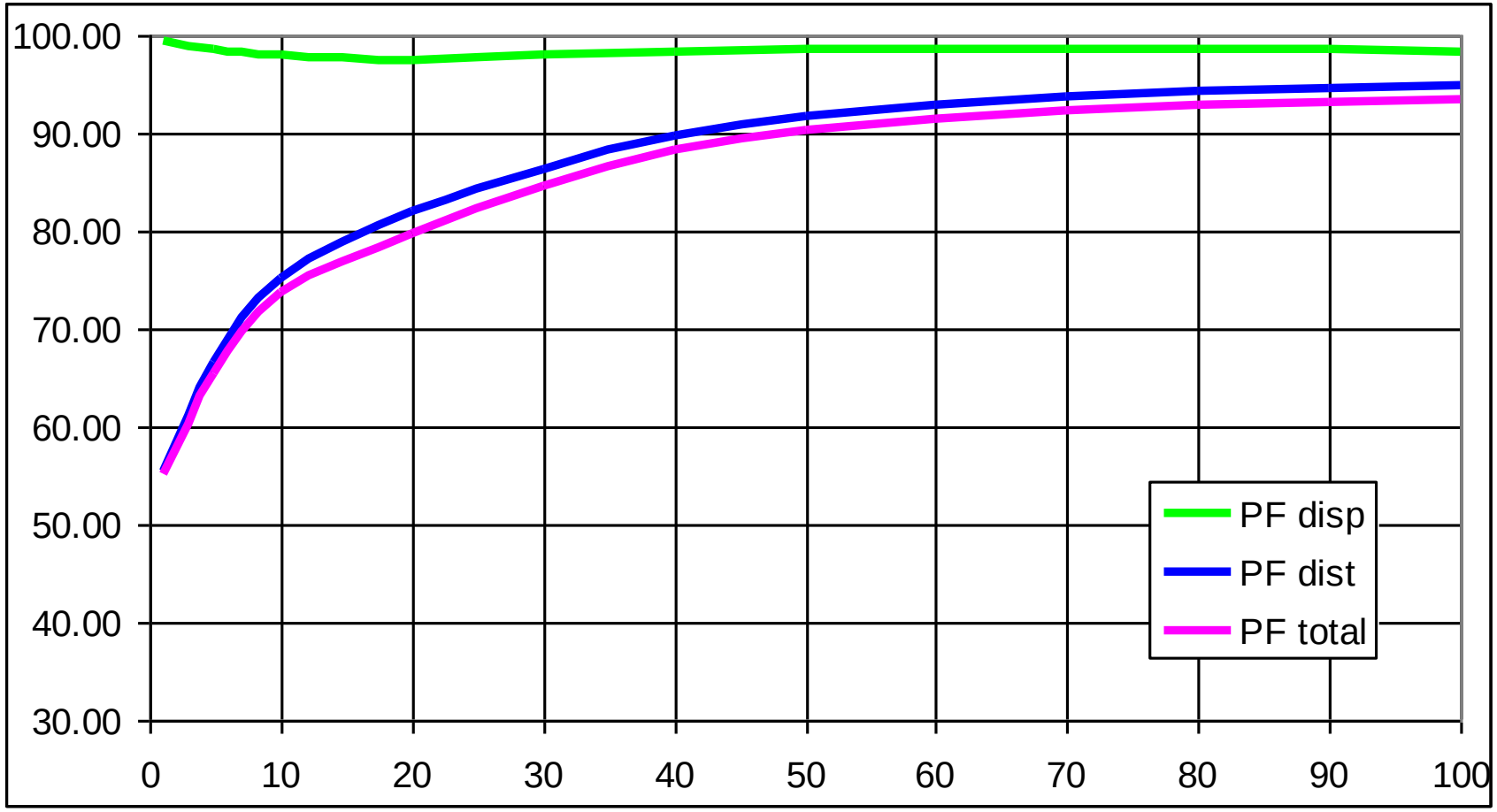


% Load

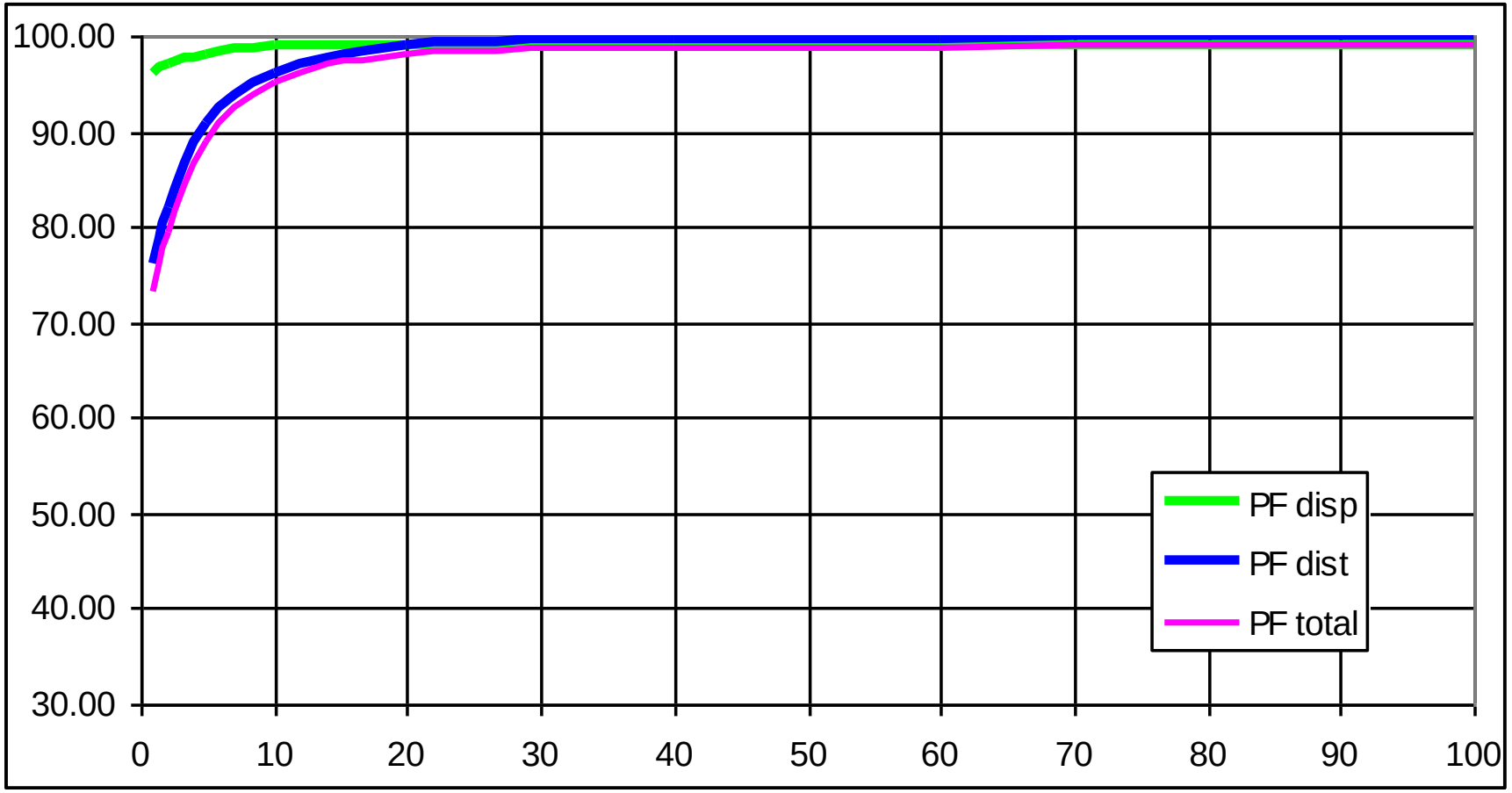
PF of a Drive w/o LR or LC vs Load



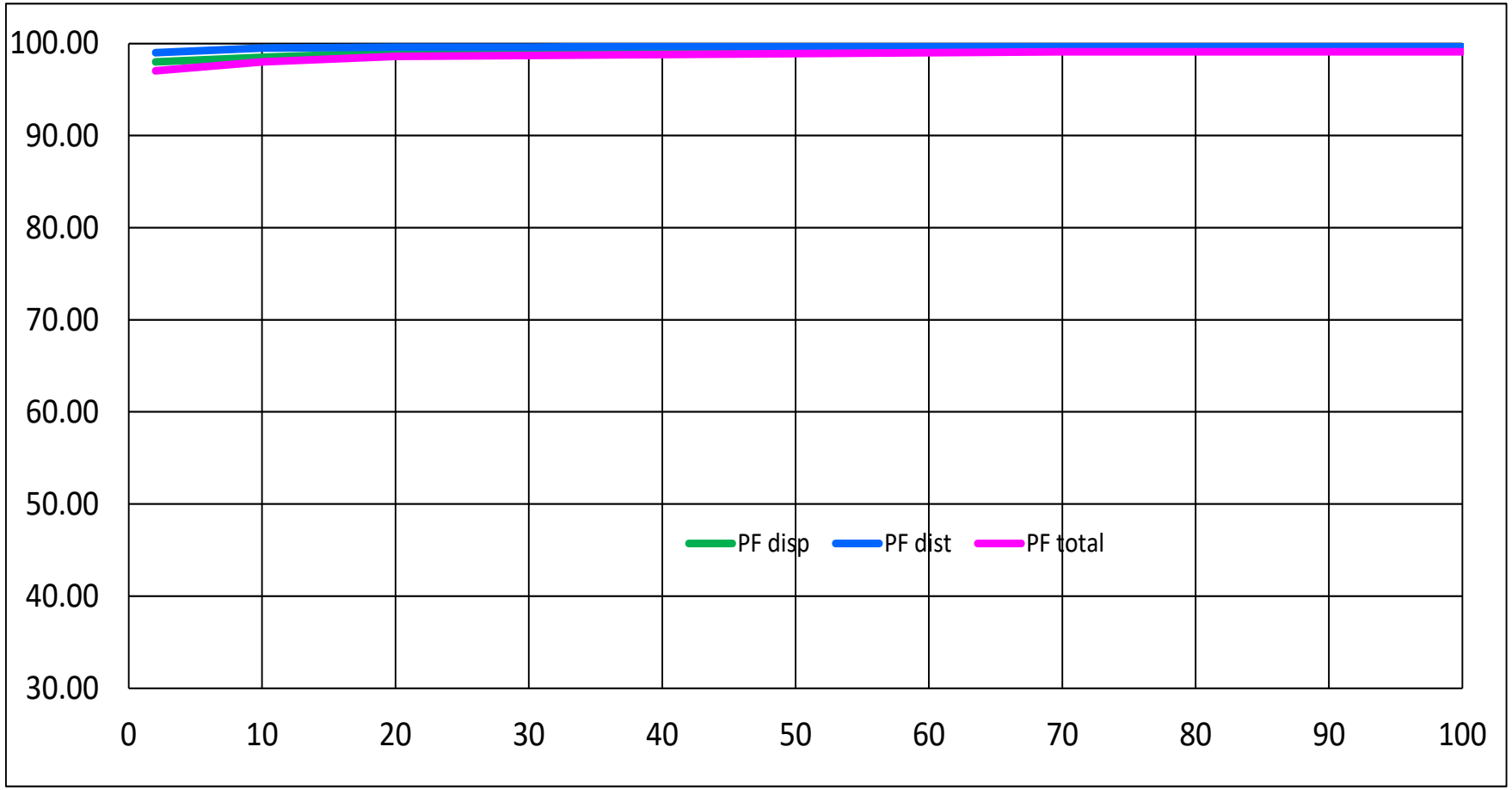
PF of a Drive w/LR or LC vs Load



PF of an 18-Pulse Drive vs Load



PF of an AFE Drive



End of Part 1