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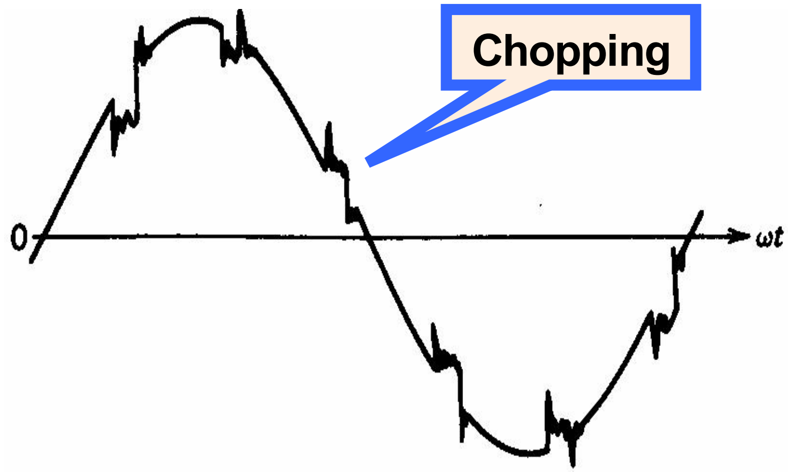
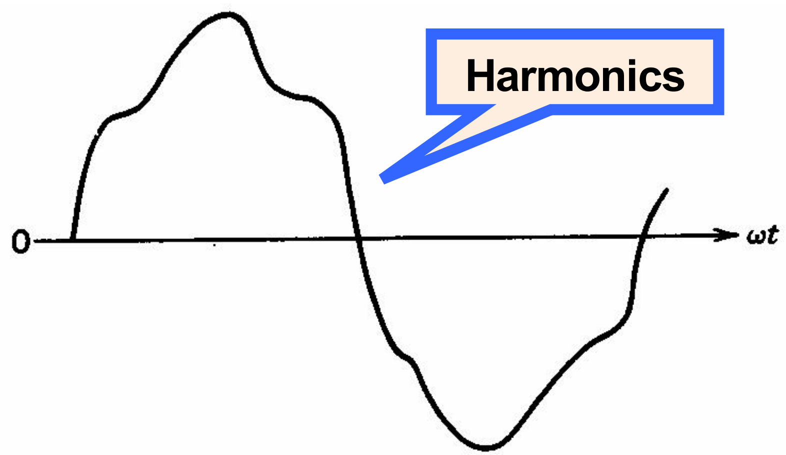
Power Line Disturbances 1/4

Types of disturbances





- ✓ Overvoltage
- ✓ Undervoltage (Brownout)
- ✓ Outage (Blackout)
- ✓ Voltage Spikes
- ✓ Chopped voltage waveform
- ✓ Harmonics
- ✓ Electromagnetic interference (EMI)

Power Line Disturbances 2/4

Sources of disturbances

Types of disturbances	Sources of disturbances
Overvoltage	Sudden decrease system load
Undervoltage	Starting induction motor, Overload
Outage	Many accidents
Voltage Spikes	Result of switching in or out
Chopped voltage	Converters are used to interface the power electronics equipment with the utility system
Harmonics	Variety of sources
EMI	Rapid switching of voltages & current

Power Line Disturbances 3/4

Depending factors of disturbances

- Type and magnitude of the power line disturbance
- Type of equipment and how well it is designed
- Type of power conditioning equipment

Results of disturbances

Types of disturbances	Results of disturbances
Overvoltage & Undervoltage	Equipment to trip out
Voltage Spikes	Hardware failure
Outage	Depend on the duration & equipment design
Chopped voltage & Harmonics	Potential of interfering with the equipment

Power Line Disturbances 4/4

Effect on sensitive equipment

Table 11-1 Typical Range of Input Power Quality and Load Parameters of Major Computer Manufacturers

Parameters[a]	*Range or Maximum*
1. Voltage regulation, steady state	+5, −10 to +10%, −15% (ANSI C84.1—1970 is +6, −13%)
2. Voltage disturbances	
a. Momentary undervoltage	−25 to −30% for less than 0.5 s, with −100% acceptable for 4–20 ms
b. Transient overvoltage	+150 to 200% for less than 0.2 ms
3. Voltage harmonic distortion[b]	3–5% (with linear load)
4. Noise	No standard
5. Frequency variation	60 Hz ± 0.5 Hz to ±1 Hz
6. Frequency rate of change	1 Hz/s (slew rate)
7. 3ϕ, Phase voltage unbalance[c]	2.5–5%
8. 3ϕ, Load unbalance[d]	5–20% maximum for any one phase
9. Power factor	0.8–0.9
10. Load demand	0.75–0.85 (of connected load)

[a]Parameters 1, 2, 5, and 6 depend on the power source, while parameters 3, 4, and 7 are the product of an interaction of source and load, and parameters 8, 9, and 10 depend on the computer load alone.

[b]Computed as the sum of all harmonic voltages added vectorially.

[c]Computed as follows:

$$\textit{Percent}\text{ phase voltage unbalance} = \frac{3(V_{\max} - V_{\min})}{V_a + V_b + V_c} \times 100$$

[d]Computed as difference from average single-phase load.

Source: IEEE Std. 446, "Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications."

Typical Range of Input Power Quality

Harmonics

❖ Line current distortion

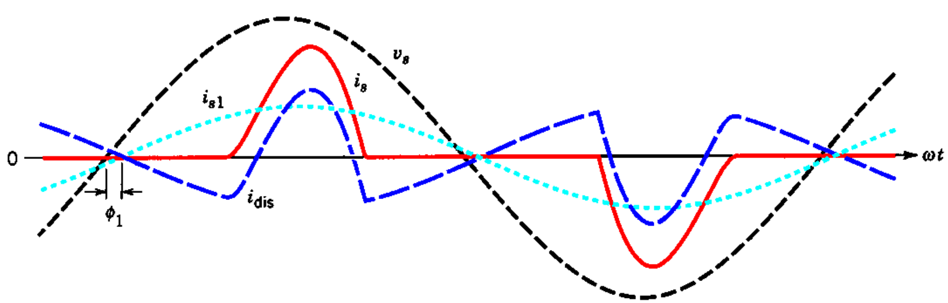
Line current is distorted by single phase rectifier. We will assume v_s is purely sinusoidal.

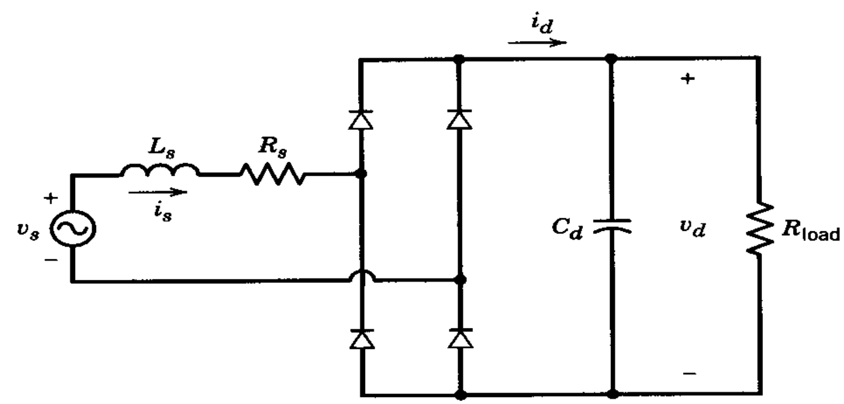
$$v_s = \sqrt{2}V_s \sin \omega_1 t$$

$$i_s(t) = i_{s1}(t) + \sum_{h\neq 1} i_{sh}(t)$$

$$i_s(t) = \sqrt{2}I_{s1}\sin(\omega_1 t - \phi_1) + \sum_{h\neq 1}\sqrt{2}I_{sh}\sin(\omega_h t - \phi_h)$$

ϕ_1 is phase angle between v_s & i_s and rms value of i_s : $I_S = \sqrt{\dfrac{1}{T_1}\int_0^{T_1} i_s^2(t)dt} = \sqrt{I_{s1}^2 + \sum_{h\neq 1} I_{sh}^2}$





Line current distortion

Harmonics

❖ Line current distortion

Amount of distortion in input waveform is called *total harmonic distortion* (THD).

$$i_{dis}(t) = i_s(t) - i_{s1}(t) = \sum_{h \neq 1} i_{sh}(t)$$

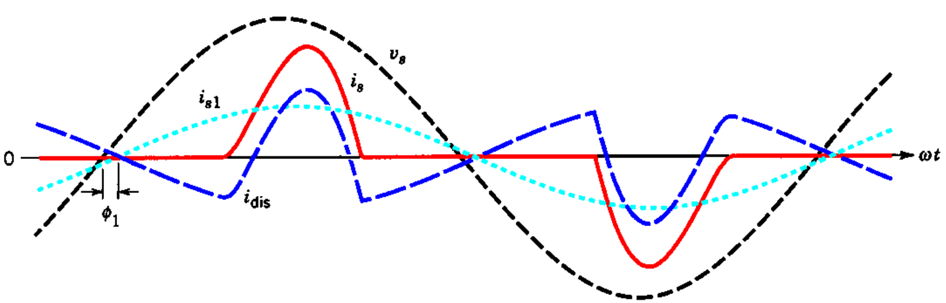
rms value of i_{dis}

$$I_{dis}(t) = \sqrt{I_s^2 - I_{s1}^2} = \sqrt{\sum_{h \neq 1} I_{sh}^2}$$

THD in current is

$$\%THD_i = 100 \times \frac{I_{dis}}{I_{s1}} = 100 \times \frac{\sqrt{I_s^2 - I_{s1}^2}}{I_{s1}} = 100 \times \sqrt{\sum_{h \neq 1} \left(\frac{I_{sh}^2}{I_{s1}^2}\right)}$$

In many applications, it is important to know $I_{s,peak}$ of i_s ratio of total rms current I_s.



$$Crest\ Factor = \frac{I_{s,peak}}{I_s}$$

Line current distortion

Harmonics

❖ Line voltage distortion

Distorted currents drawn by loads such as the diode bridge rectifiers can result in distortion in the utility voltage waveform

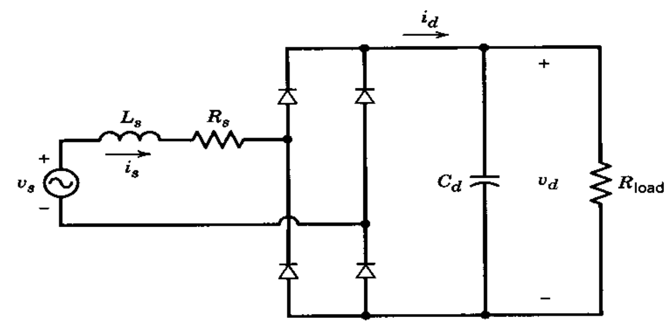


Figure 5-20 Practical diode–bridge rectifier with a filter capacitor.

$$v_{PCC} = v_s - L_{s1}\frac{di_s}{dt}$$

i_s : fundamental & harmonic components

$$v_{PCC} = (v_s - L_{s1}\frac{di_s}{dt}) - L_{s1}\sum_{h=1}\frac{di_{sh}}{dt}$$

$$(v_{PCC})_1 = v_s - L_{s1}\frac{di_s}{dt}$$

$$(v_{PCC})_{dis} = -L_{s1}\sum_{h=1}\frac{di_{sh}}{dt}$$

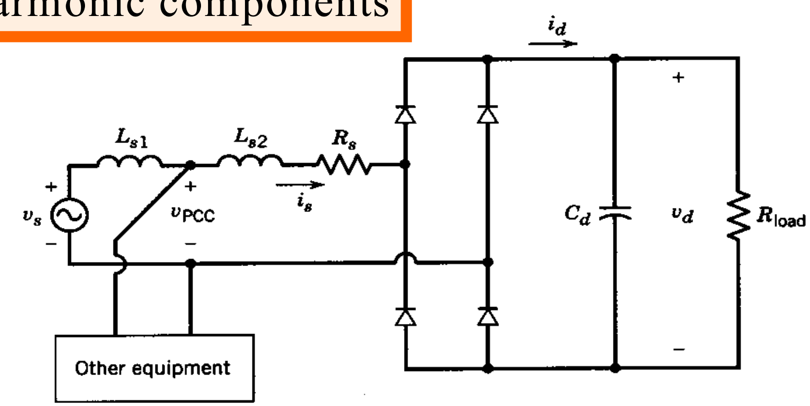


Figure 5-25 Line-voltage notching and distortion.

Harmonics

❖ Line voltage distortion

The total harmonic distortion THD_V in the voltage at the point of common coupling is computed to be approximately 5.7%.

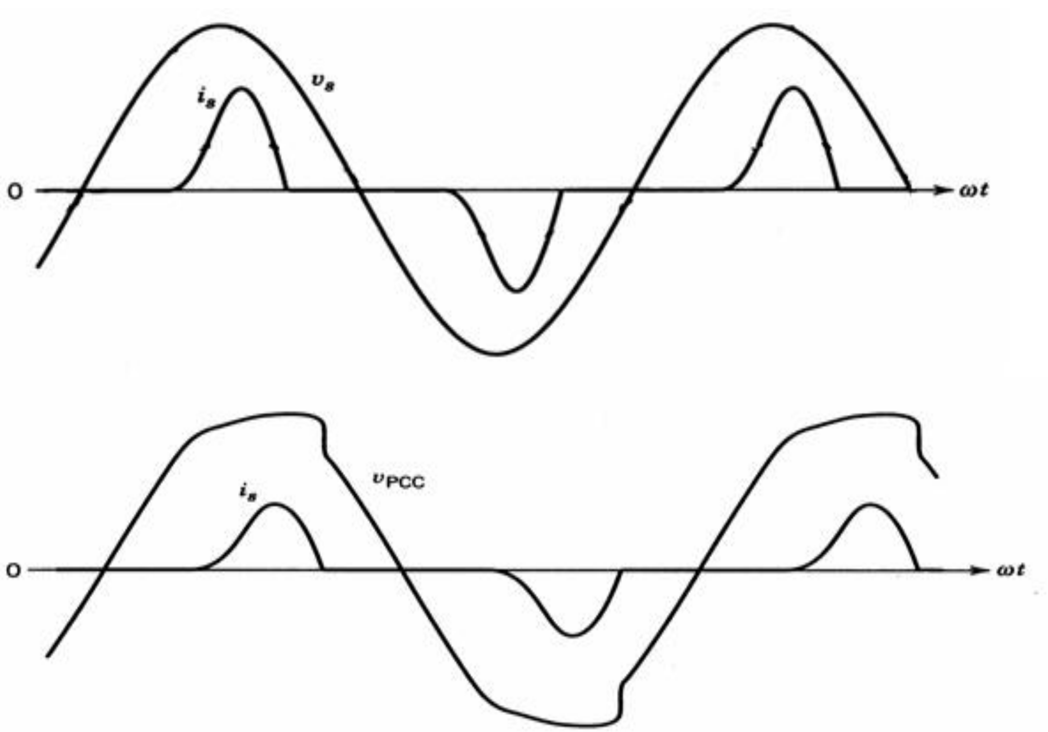


Figure 5-26 Voltage waveform at the point of common coupling in the circuit of Fig. 5-25.

$$(v_{PCC})_{dis} = -L_{s1} \sum_{h=1} \frac{di_{sh}}{dt}$$

Harmonics

❖ Line voltage distortion

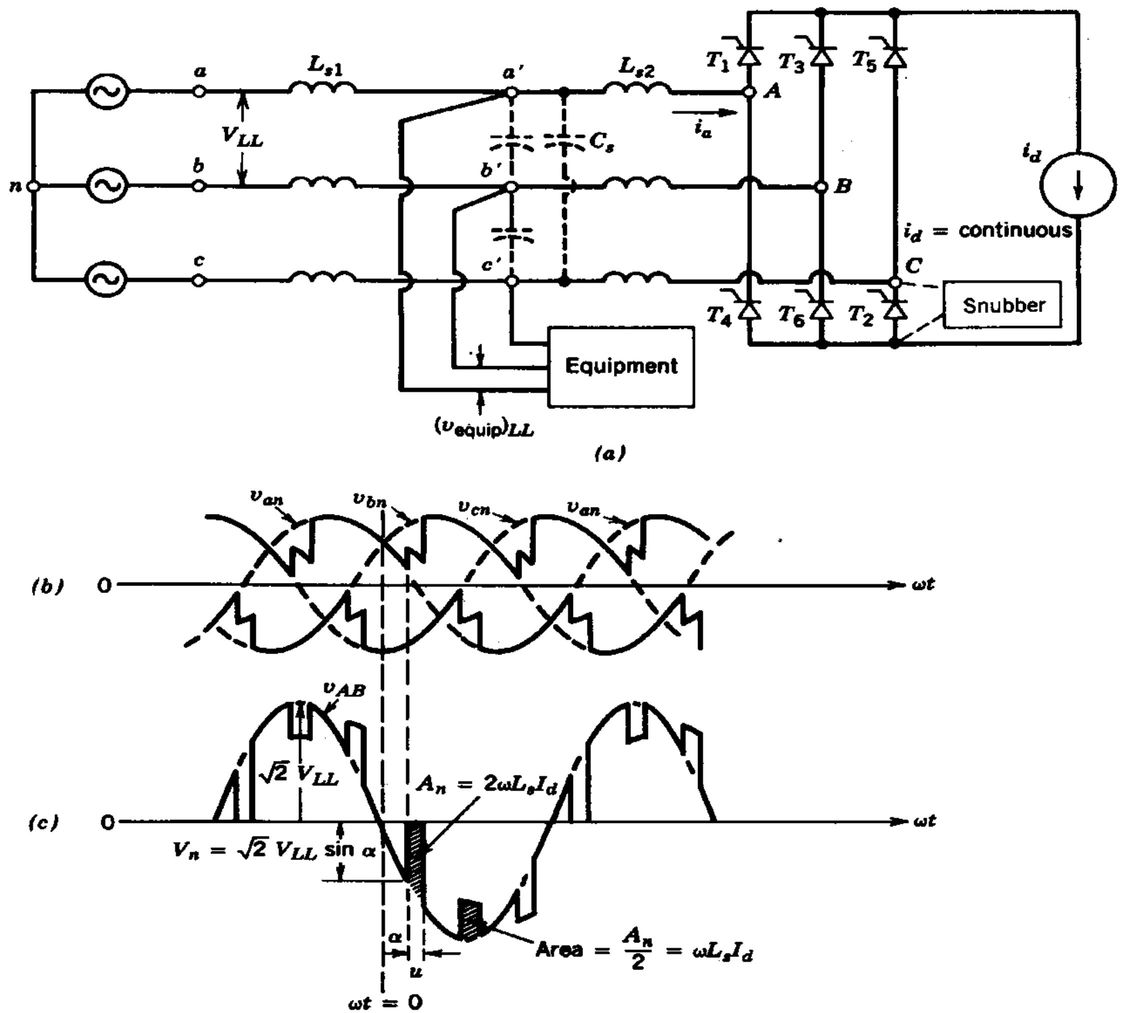


Figure 6-35 Line notching in other equipment voltage: (*a*) circuit, (*b*) phase voltages, (*c*) line-to-line voltage v_{AB}.

Harmonics

In addition to voltage waveform distortion, some other problems due to harmonic currents are following:

- Additional heating & possible overvoltages
- Errors in metering & malfunction of utility relays
- Interference with communication & control signal, and so on.

One approach to minimize this impact is to filter harmonic currents & EMI produced by power electronic equipment.

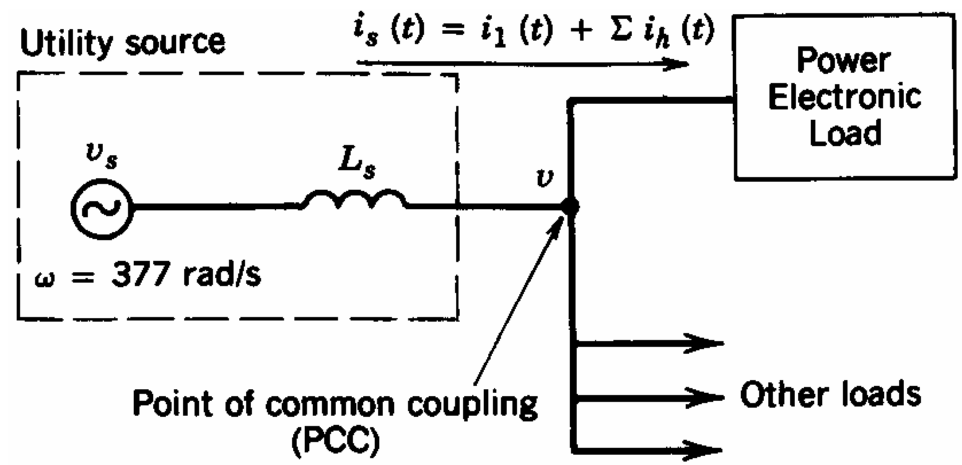


Figure 18-1 Utility interface.

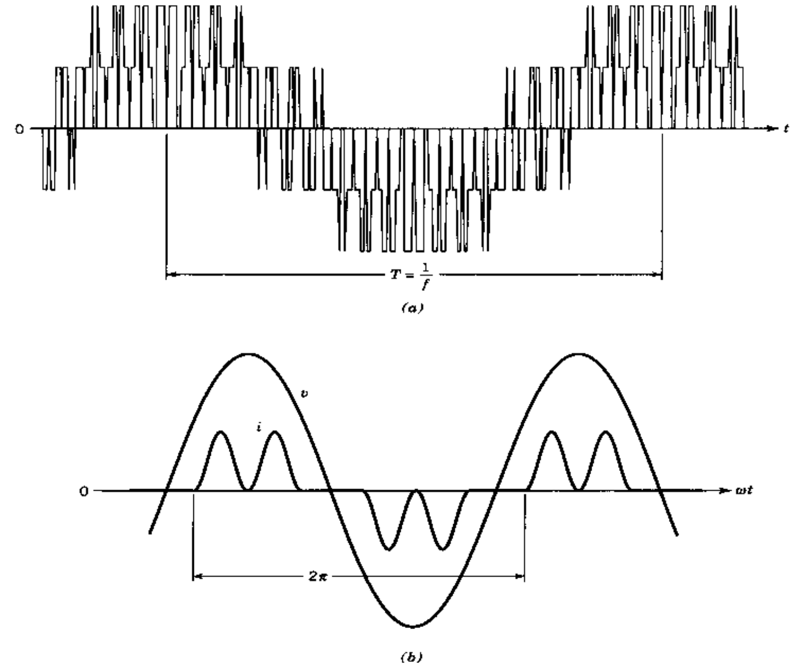
Harmonics

❖ Non sinusoidal Waveforms of Current & Voltage

In power electronic circuits, dc or low frequency ac waveforms are synthesized by using segments of an input waveform.

Ac motor voltage produced by inverter

Distorted current waveform by equipment



Nonsinusoidal waveform in steady-state

Repetition frequency is called fundamental frequency, waveforms contain components at unwanted frequencies that are harmonics of fundamental frequency.

Harmonic Standards & Recommended Practices

Various standards & guidelines have been established that specify limits on magnitudes of harmonic currents and harmonic voltage distortion at various harmonic frequencies.

1. EN 50 006
2. IEC Norm 555-3,
3. VDE 0838, VDE 0160, VDE 0712
4. ANSI/IEEE Std. 519-1981, 519-1992

Table 18-2 Harmonic Current Distortion (I_h/I_1)

	Odd Harmonic Order h (%)					*Total Harmonic Distortion (%)*
I_{SC}/I_1	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	
<20	4.0	2.0	1.5	0.6	0.3	5.0
20–50	7.0	3.5	2.5	1.0	0.5	8.0
50–100	10.0	4.5	4.0	1.5	0.7	12.0
100–1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Note: Harmonic current limits for nonlinear load connected to a public utility at the point of common coupling (PCC) with other loads at voltages of 2.4–69 kV. I_{sc} is the maximum short-circuit current at PCC. I_1 is the maximum fundamental-frequency load current at PCC. Even harmonics are limited to 25% of the odd harmonic limits above.

Source: Reference 1.

Harmonic Standards & Recommended Practices

Table 18-3 lists the quality of voltage that utility must furnish user.

Tables 18-2 & 18-3 are very broad in their scope & apply to wide voltage & power ranges.

Table 18-3 Harmonic Voltage Limits (V_h/V_1) (%) for Power Producers (Public Utilities or Cogenerators)

	2.3–69 kV	*69–138 kV*	*> 138 KV*
Maximum for individual harmonic	3.0	1.5	1.0
Total harmonic distortion	5.0	2.5	1.5

Note: This table lists the quality of the voltage that the power producer is required to furnish a user. It is based on the voltage level at which the user is supplied.

Source: Reference 1.

Power & Power Factor

Average power

$$P = \frac{1}{T_1}\int_0^{T_1} p(t)dt = \frac{1}{T_1}\int_0^{T_1} v_s(t)i_s(t)dt$$

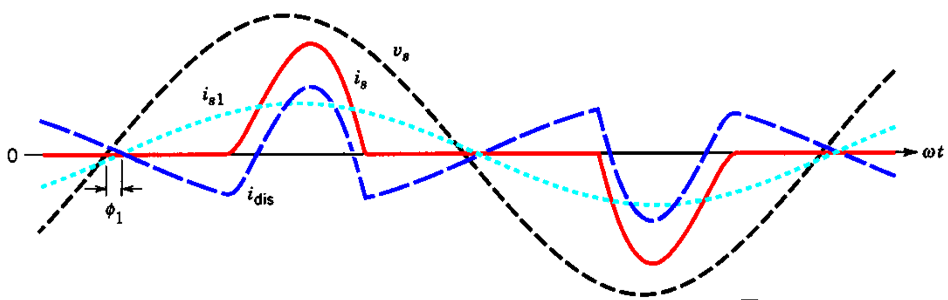
$$P = \frac{1}{T_1}\int_0^{T_1} \sqrt{2}V_s \sin\omega_1 t \bullet \sqrt{2}I_{s1}\sin(\omega_1 t - \phi_1)dt = V_s I_{s1}\cos\phi_1$$

Apparent power

$$S = V_s I_s$$

indicates how effectively equipment draws power from the utility.

$$PF = \frac{P}{S} = \frac{V_s I_{s1}\cos\phi_1}{V_s I_s} = \frac{I_{s1}}{I_s}\cos\phi_1$$



Displacement Power Factor

$$DPF = \cos\phi_1$$

Line current distortion

$$PF = \frac{I_{s1}}{I_s}DPF = \frac{1}{\sqrt{1+THD_i^2}}DPF$$

Power Conditioners

❖ Need of power conditioner to Improve Utility Interface

Large harmonic content. Poor waveform of current also affects power electronic equipment itself in the following ways:

- Power available from wall outlet is reduced to approximately two-thirds.
- Dc side filter Cap is severely stressed due to large peak pulse current.
- Losses in bridge are due to current-dependent forward voltage drop.
- Components in EMI filter must be designed for higher peak pulse current.
- If line frequency TR is used at input, it must be highly overrated.

Power Conditioners

Definition

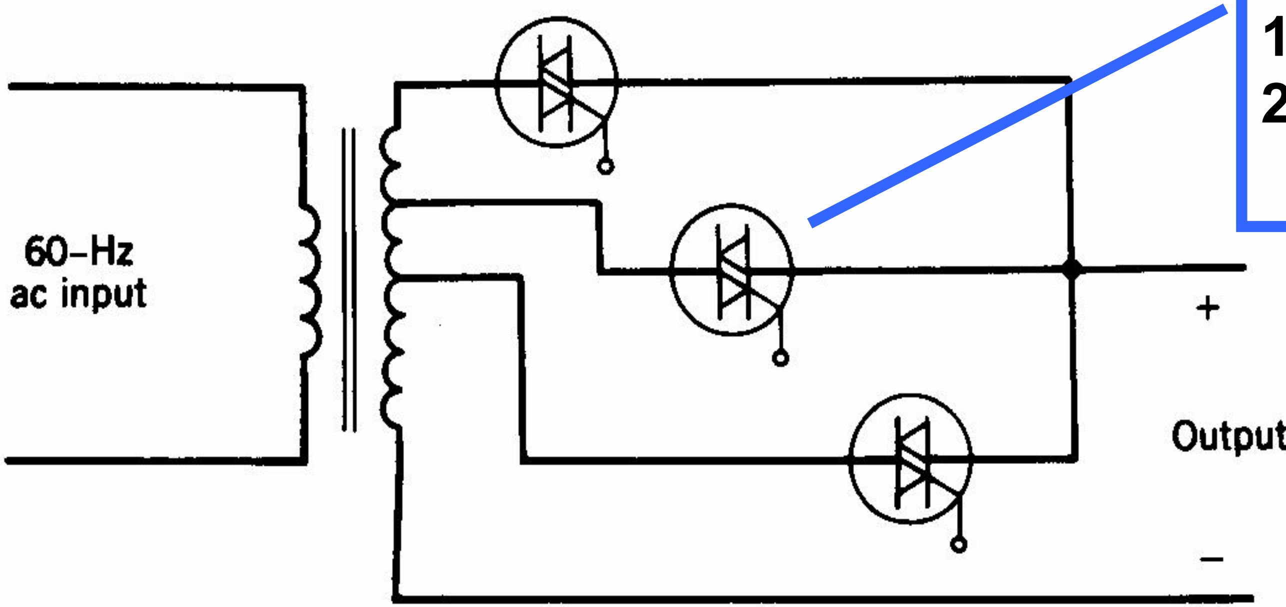
Power conditioners provide an effective way of suppressing some or all of the electrical disturbances other than the power outages and frequency deviations.

Types of Conditioner

TYPES	EFFECTS
MOV	Prevent line voltage spike, (MOV: metal oxide varistor)
EMI Filter	Prevent chopped wave form & high-frequency
Isolation TR	Galvanic isolation & Prevent voltage spike
Ferro resonant TR	Voltage regulation & Prevent spike, noise
Linear Conditioner	Use Sensitive applications to supply clean power

Power Conditioners

Electronic tap changer



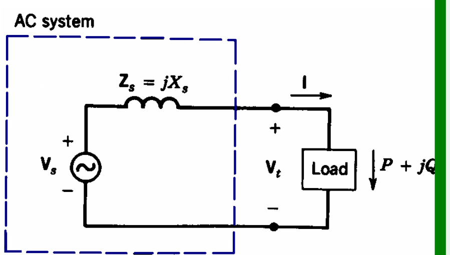
1. Triac
2. Back-to-back thyristors

Replace a mechanical contact

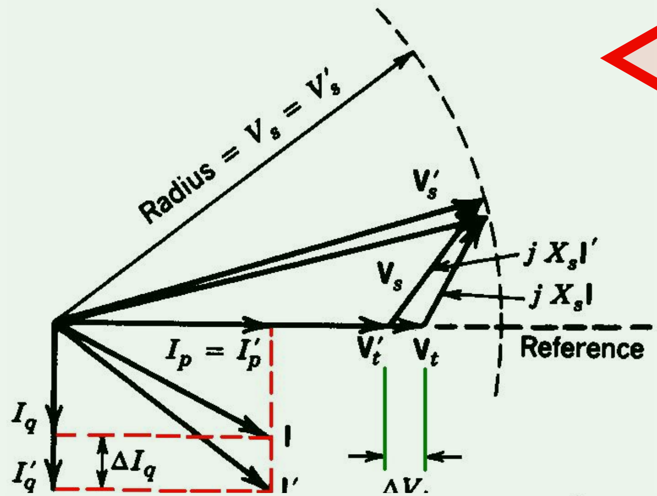
Allow a bidirectional current flow

Static var Compensators

Effect of Reactive Power on Voltage Magnitude (by I_p & I_q)



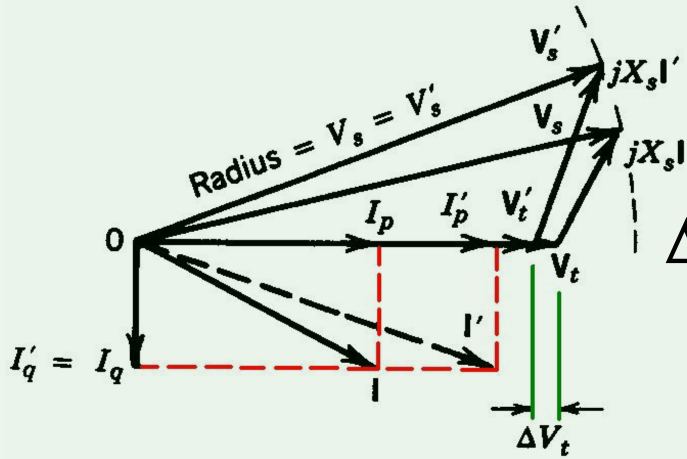
Equivalent Circuit



Change in I_q

$$\Delta I_q \Rightarrow I_p : Constant$$

$$\Rightarrow \Delta V : Drop!$$



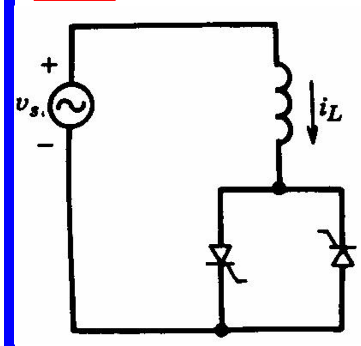
Change in I_p

$$\Delta I_p \Rightarrow I_q : Constant$$

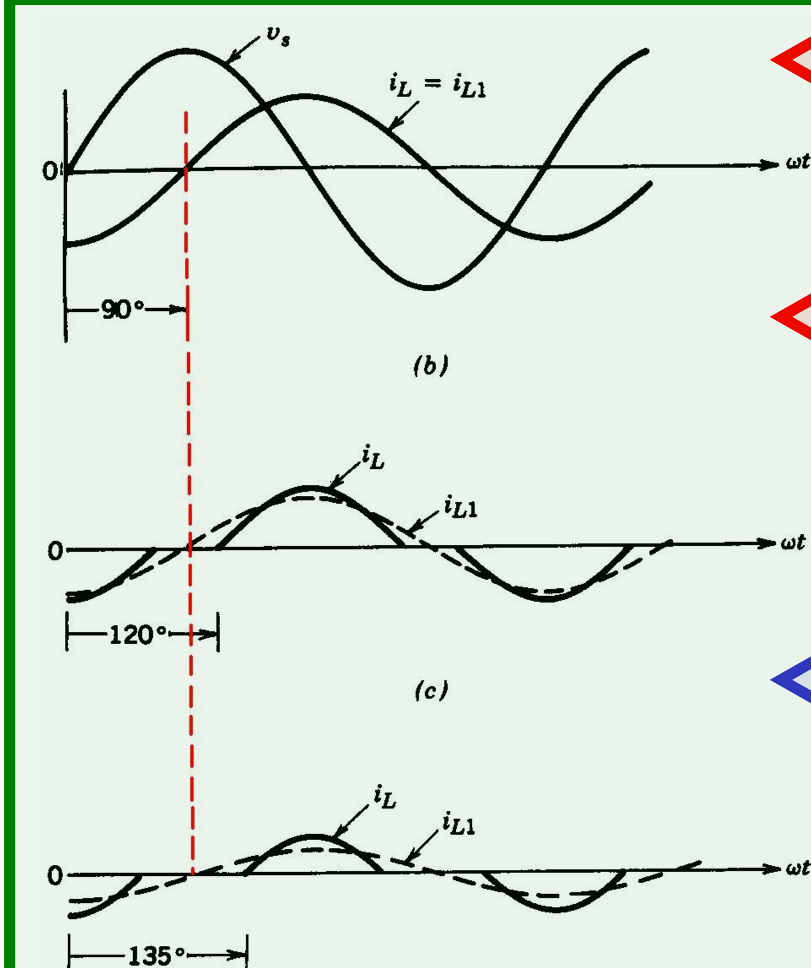
$$\Rightarrow \Delta V : Small \ \ Drop!$$

Static var Compensators

Thyristor-Controlled Inductor (TCI) – TYPE 1



Equivalent Circuit



α = 0˚

- Thyristor ☞ Diode
- Sinusoidal current

α = 0˚ ~ 90˚

- I_L Lags behind V_s by 90˚

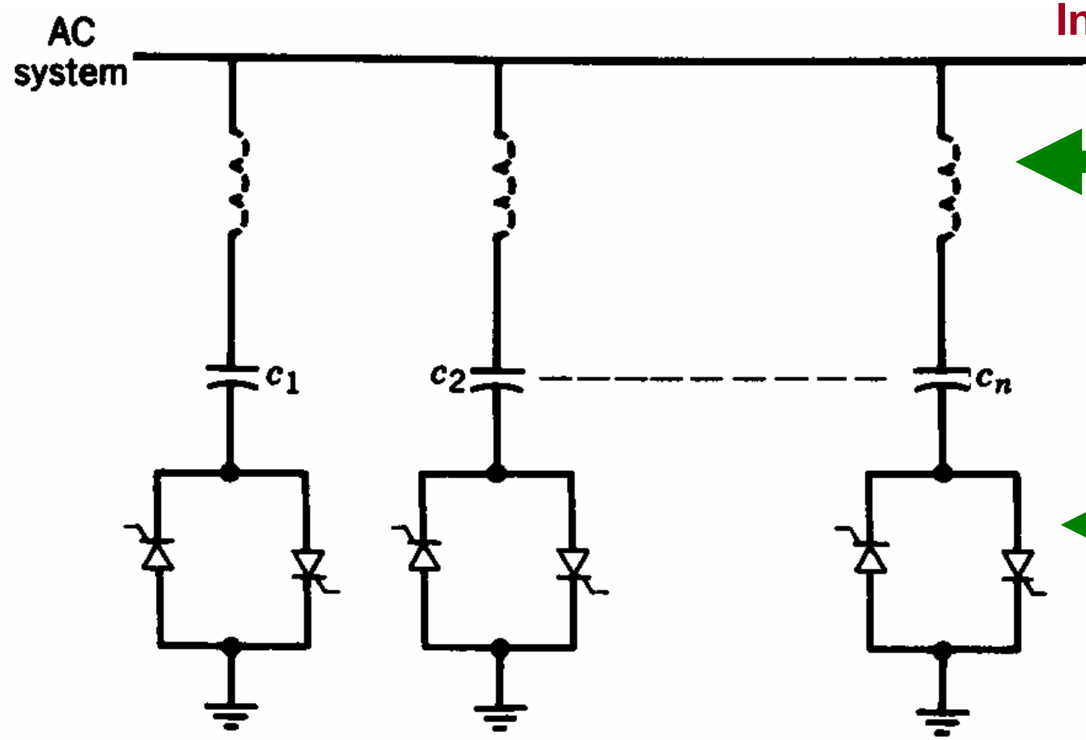
α = 120˚, 135˚

- Available Control!
- α↑ ☞ I_L↓

Static var Compensators

Thyristor-Switched Capacitors (TSCs) – TYPE 2

Integral Half-cycle control



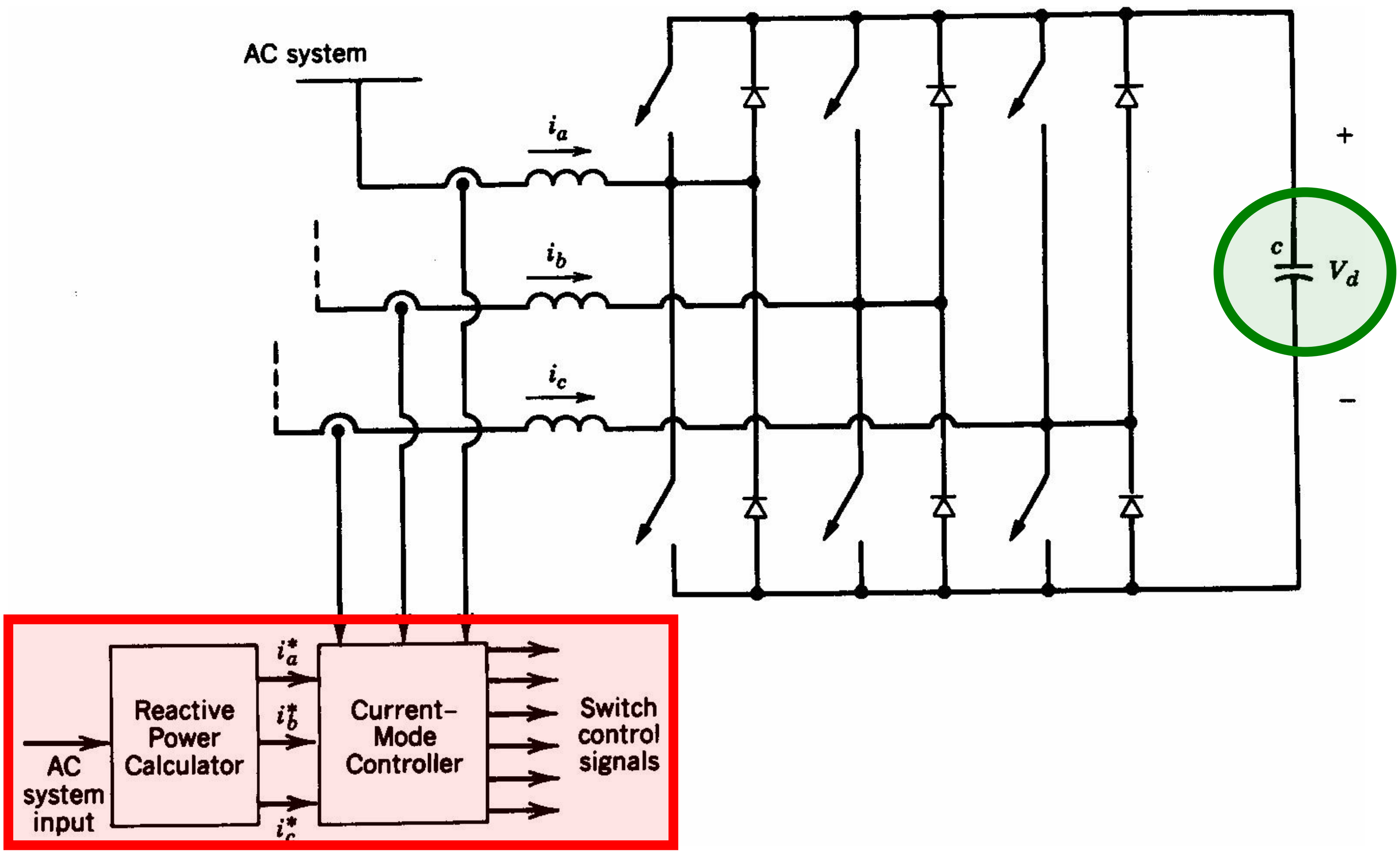
Limit !!
Overcurrents
At Switch-on

Back-to-Back
Connected
Thyristor

- Transient current at switching must be minimized

Static var Compensators

Instantaneous VAR Controller (SATCOM) – TYPE 3



Improved Single-Phase Utility Interface

Passive Circuits

Simplest approach is add to inductor on ac side of rectifier.

- Improved current waveform
- Output V_d lower (~10%) compared with no-inductance case.
- Peak-to-peak ripple in the rectifier output voltage v_d is less.
- Overall energy efficiency remains essentially the same.

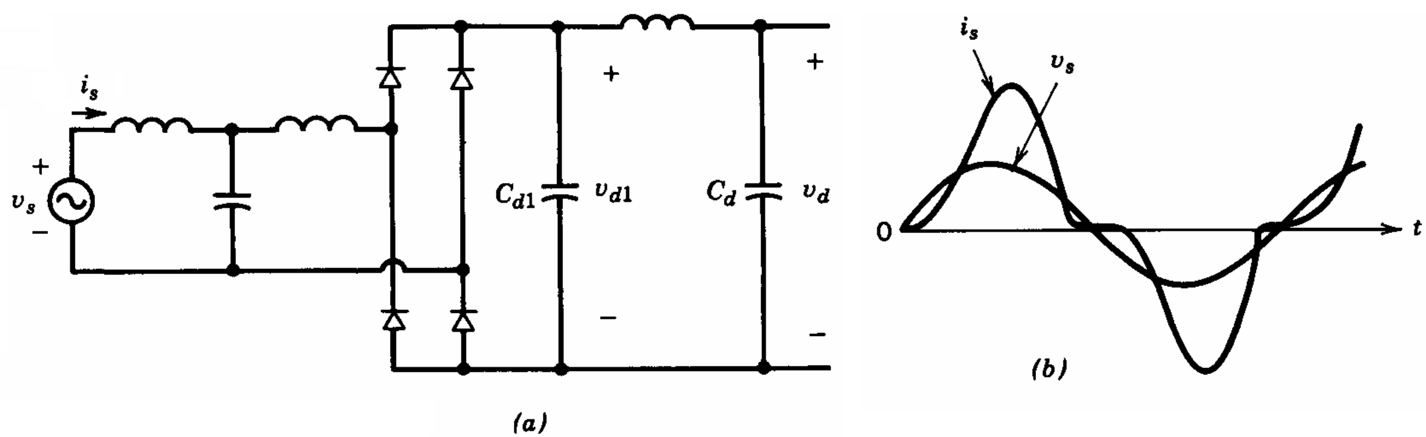
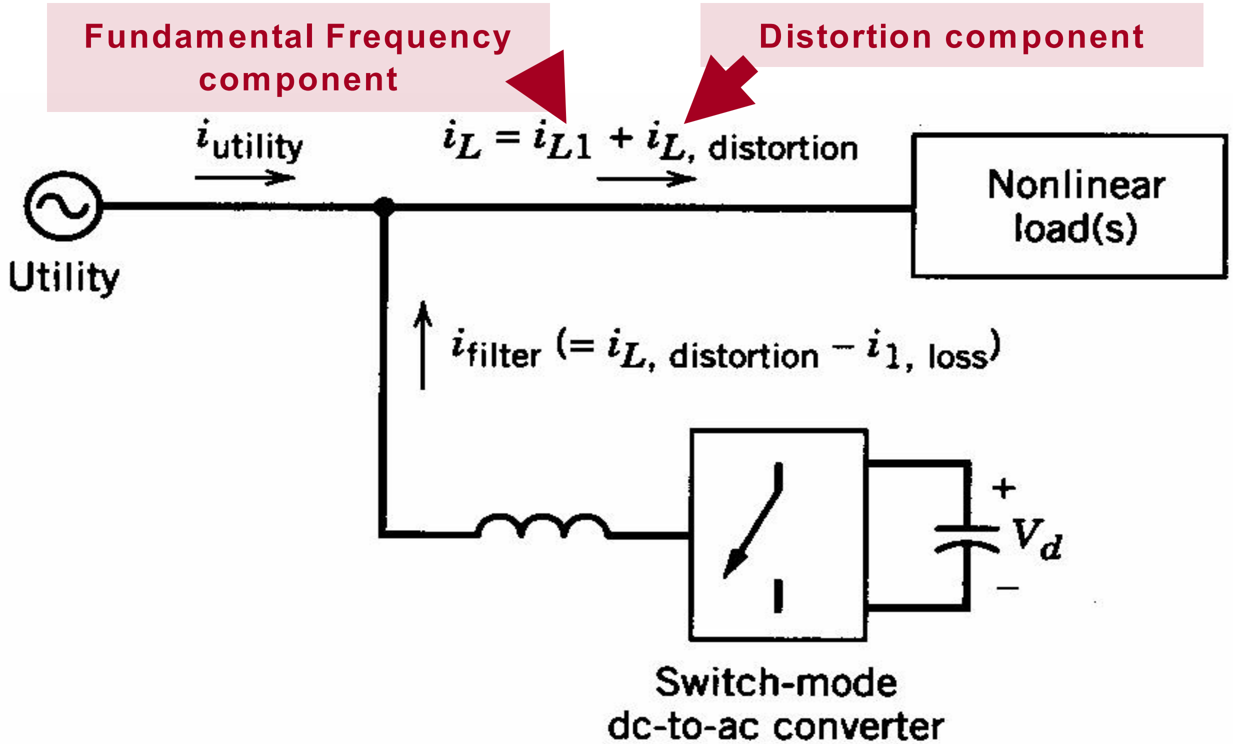


Figure 18-3 Passive filters to improve i_s waveform: (a) passive filter arrangement; (b) current waveform.

Active Power Filters

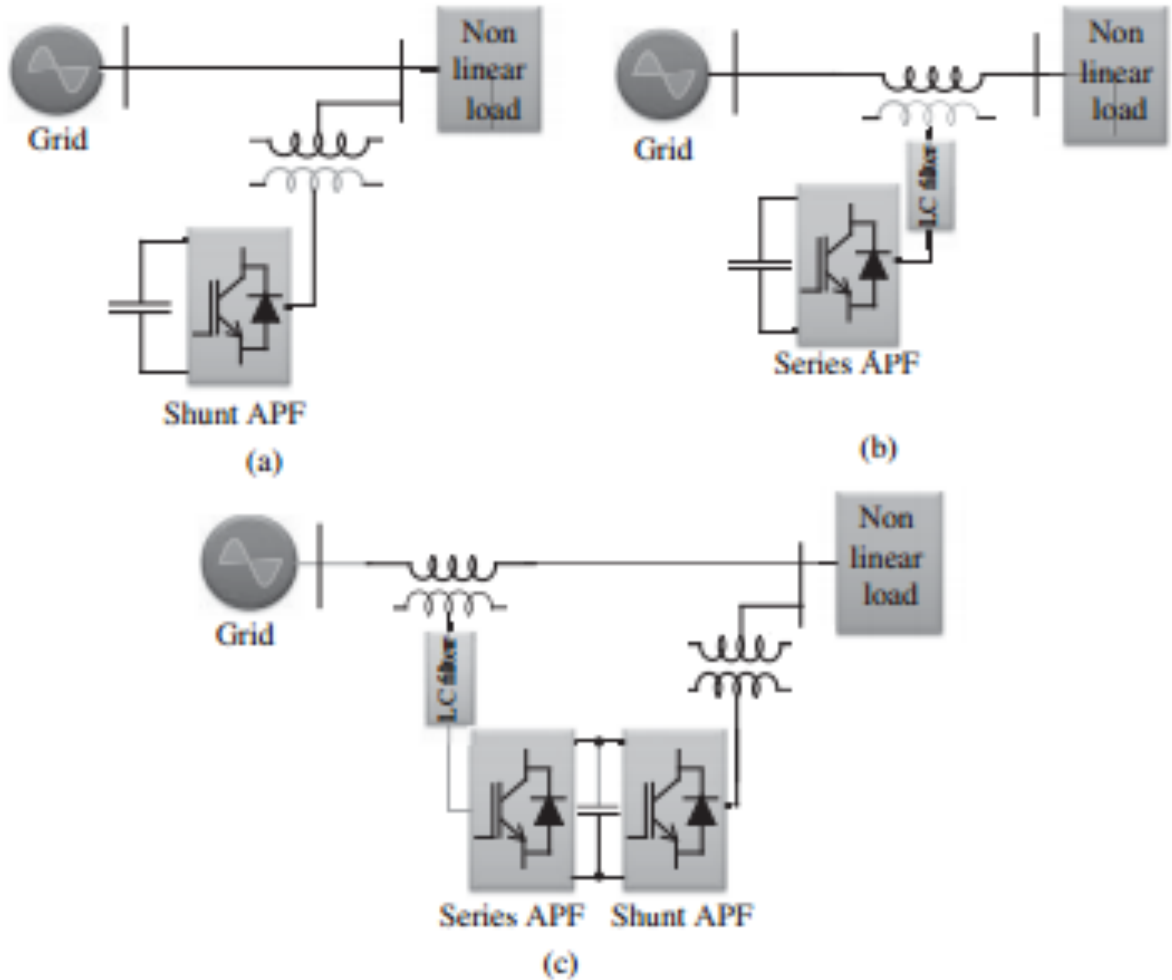
Active Filters for Harmonic Elimination and Reactive power compensation



Active filters inject a nullifying current so that the current drawn from the utility is nearly sinusoidal

Active Power Filters

Active Filters for Harmonic Elimination and Reactive power compensation



Active Power Filters

Shunt Active Filter

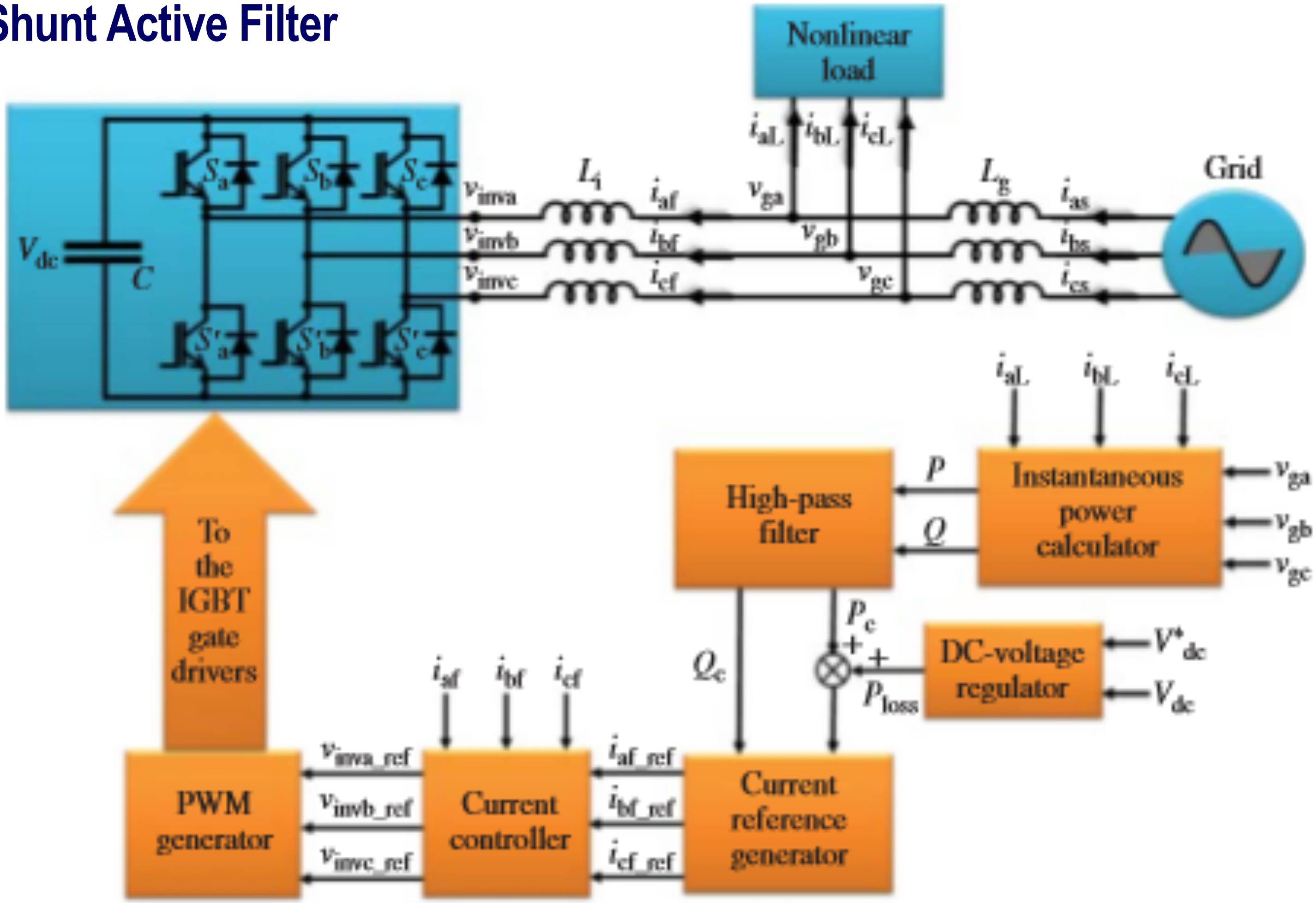
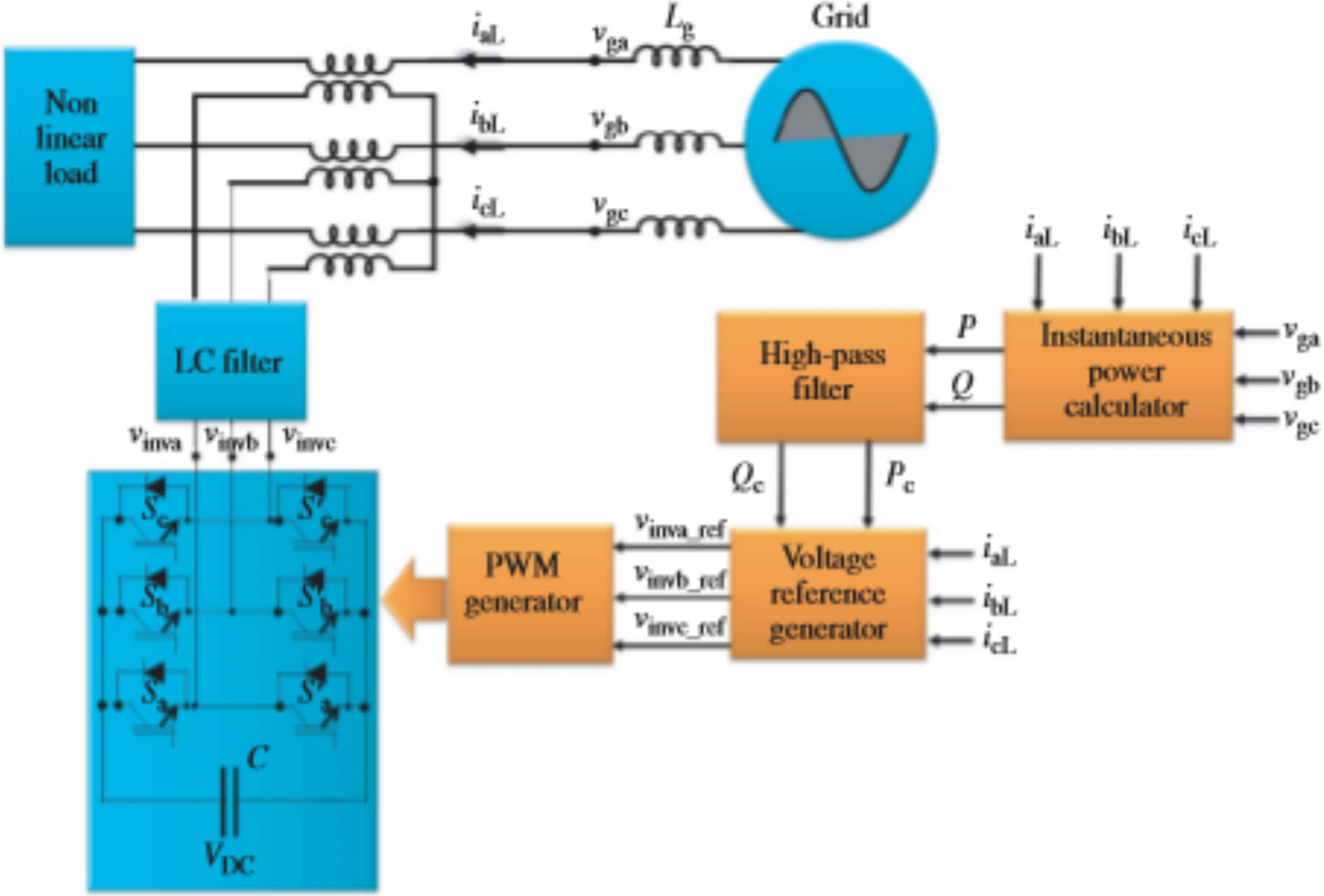


Figure 17.18 Block diagram of shunt APF using instantaneous reactive power theory

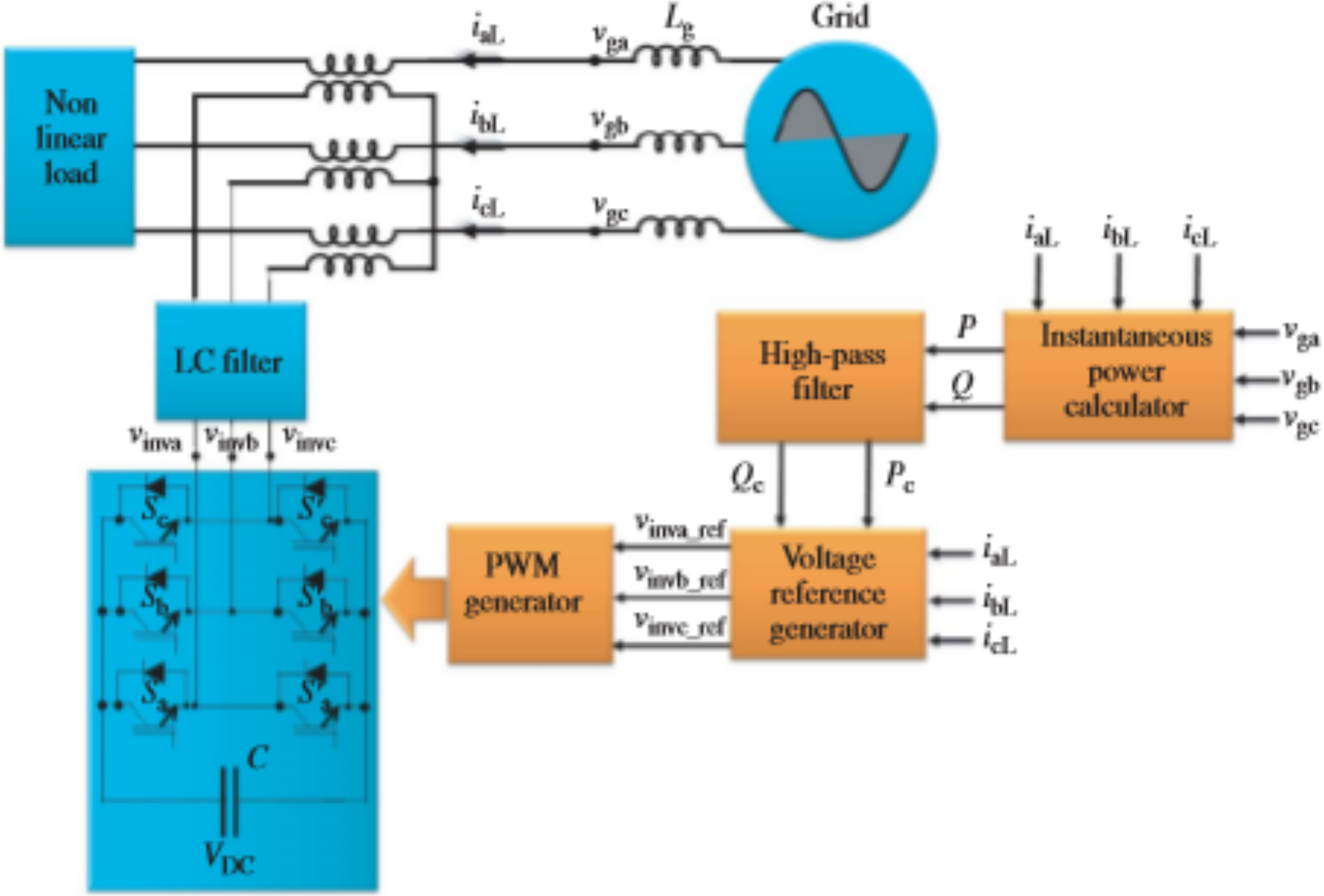
Active Power Filters

Series Active Filter



Active Power Filters

Series Active Filter



Active Power Filters

Hybrid Active Filter and UPQC

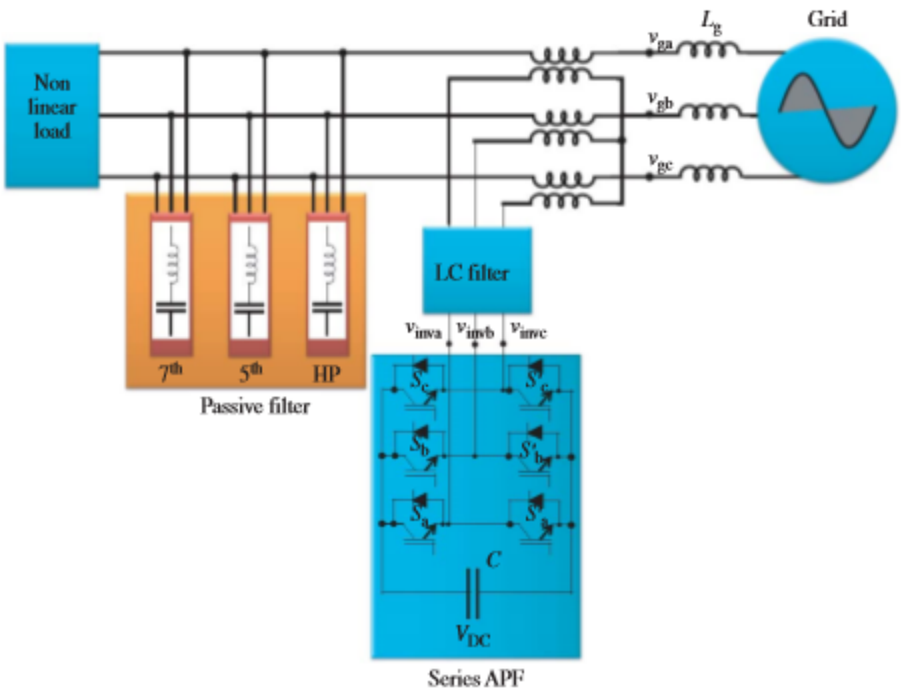


Fig. Hybrid filter (combined series APF and parallel passive filter)

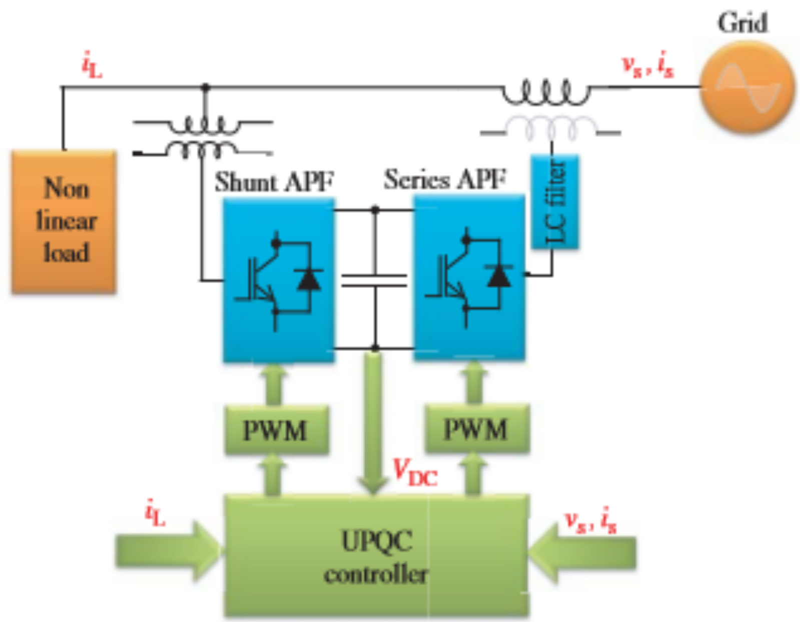


Fig. Unified Power Quality Conditioner

Active Shaping of the Input Line Current

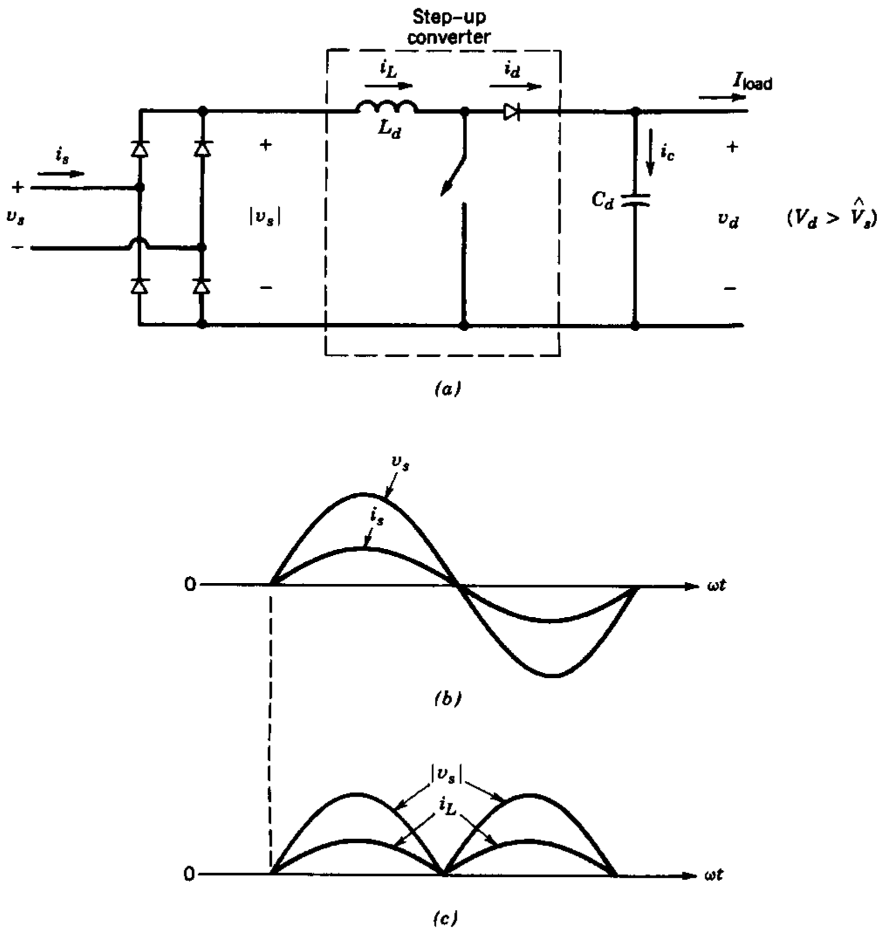


Figure 18-4 Active harmonic filtering: (*a*) step-up converter for current shaping; (*b*) line waveforms; (*c*) v_s and i_L.

By using PFC for current shaping.

The choice of PFC is based on:

-Electrical isolation between utility & output of system either is not needed

- to stabilize V_d slightly in excess of peak of maximum ac input voltage.

- Power flow is always unidirectional from utility to PFC.

- Cost, power losses, size should be small as possible.

Active Shaping of the Input Line Current

Following additional observations are made:

- v_d contains a 120Hz ripple frequency. Feedback control circuit used to control V_d at a desired value cannot compensate this ripple without distorting input line current.
- If I_{rip} is kept to a small, then laminated iron core inductor is good choice compared to high frequency ferrite materials.
- Higher f_S is allows lower value of L_d, but increased switching losses.
- V_d much larger than 10% beyond peak input ac voltage will cause efficiency to decline.
- To limit in-rush current at start-up, a current limiting resistor in series with L_d can be used.
- Step-up converter topology is well suited for input current shaping.
- A small filter capacitor must be used across output of rectifier to prevent ripple in i_L from entering utility system.

Active Shaping of the Input Line Current

Advantages of an ACS:

- V_d can be stabilized to a nearly constant for large variations in line voltage.
- V_d can be stabilized to a nearly constant value, volt-ampere ratings of semiconductor devices
- Because of absence of large peaks in input current, size of EMI filter components is smaller.
- For equal ripple in v_d, only one-third to one-half the capacitance C_d is needed compared .
- Energy efficiency from v_s to V_d of such a circuit is typically 96% compared with efficiency of 99% in conventional arrangement without ACS.

Interface for bidirectional power flow

It is possible overcome these limitation by using a switch-mode converter.

In normal mode
as rectifier

In braking mode
as inverter

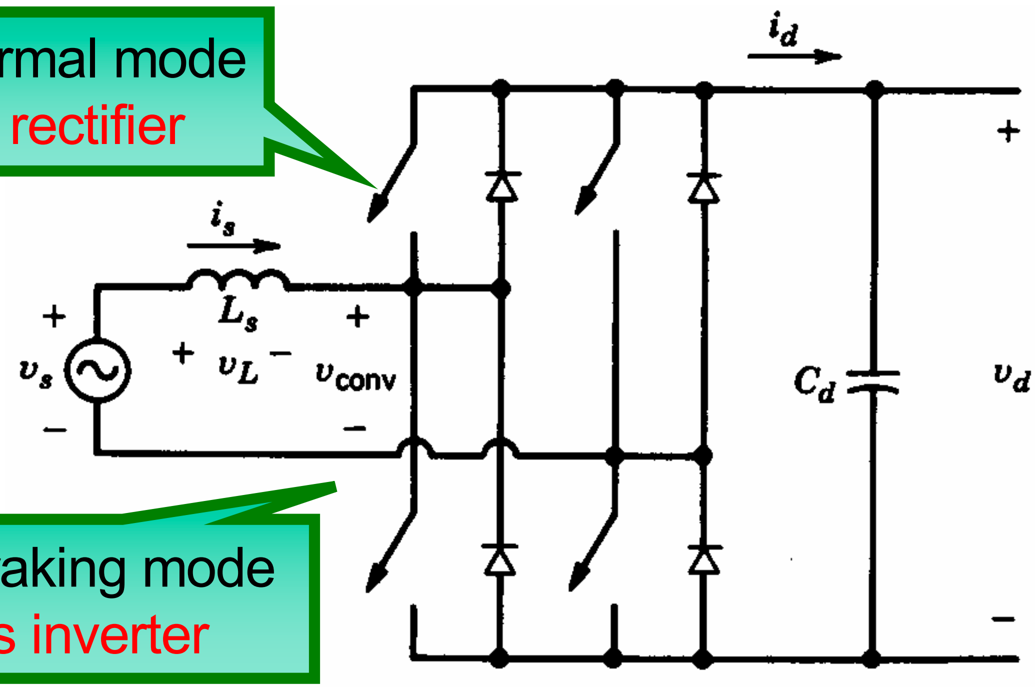


Figure 18-8 Switch-mode converter for the utility interface.

$$v_s = v_{\text{conv}} + v_L$$

$$v_L = L_s \frac{di_s}{dt}$$

$$\mathrm{V}_s = \mathrm{V}_{\text{conv1}} + \mathrm{V}_{L1}$$

$$V_{L1} = j\omega L_s \mathrm{I}_{s1}$$

Rectifier being dominant mode of operation.

Interface for bidirectional power flow

$$P = V_s I_{s1} \cos\theta = \frac{V_s^2}{\omega L_s}\left(\frac{V_{conv1}}{V_s}\sin\delta\right) \qquad (18\text{-}24)$$

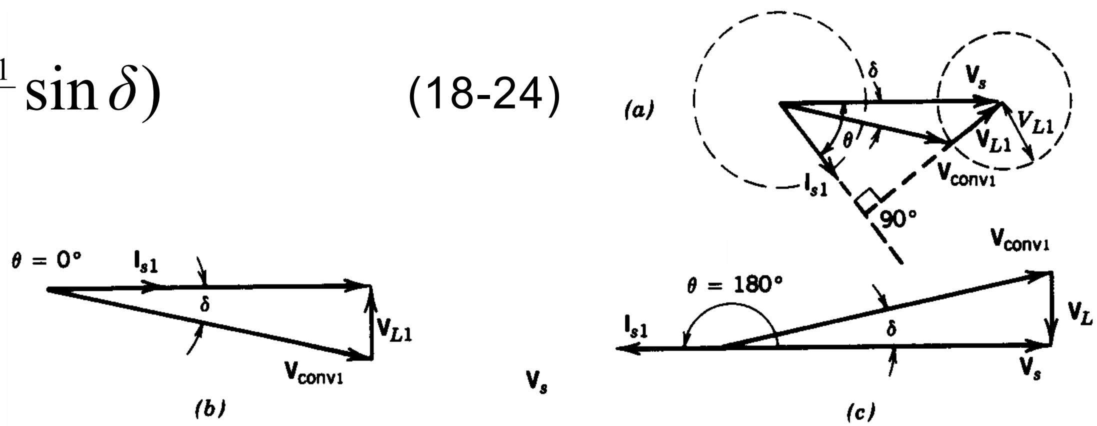


Figure 18-9 Rectification and inversion: (*a*) general phasor diagram; (*b*) rectification at unity power factor; (*c*) inversion at unity power factor.

$$Q = V_s I_{s1} \sin\theta = \frac{V_s^2}{\omega L_s}\left(1 - \frac{V_{\mathrm{conv1}}}{V_s}\cos\delta\right) \qquad (18\text{-}25)$$

$$\mathrm{I_{s1}} = \frac{\mathrm{V_s - V_{conv1}}}{j\omega L_s} \qquad (18\text{-}26)$$

$$V_{conv1} = [V_s^2 + (\omega L_s I_{s1})^2]^{1/2} \qquad (18\text{-}27)$$

$$V_{conv1} \approx V_s \qquad (18\text{-}28)$$

High Fs used and so small L_s

Interface for bidirectional power flow

V_d should be sufficiently large magnitude, so v_{conv1} is produced by PWM. This is necessary to limit ripple in the input current i_s. V_d must be greater than peak of input ac voltage.

$$V_d > \sqrt{2} V_s \qquad (18\text{-}29)$$

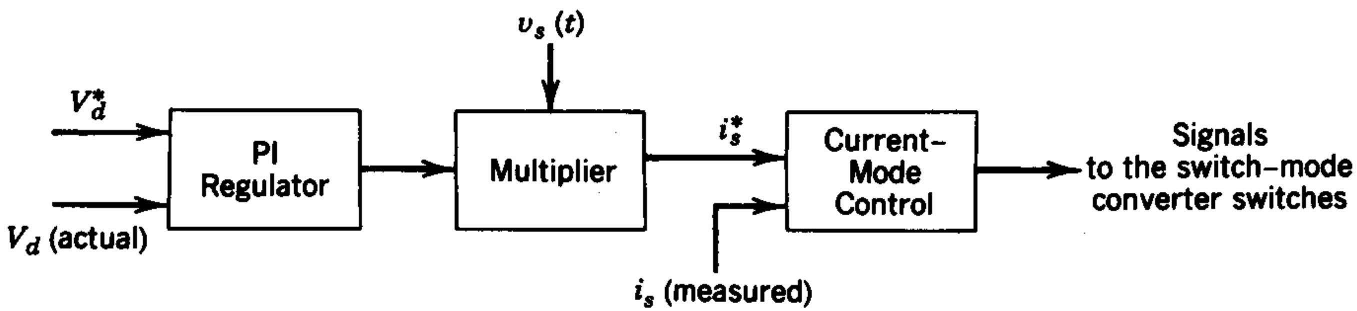


Figure 18-10 Control of the switch-mode interface.

Magnitude & direction of power flow are automatically controlled by regulating V_d at its desired value.

Interface for bidirectional power flow

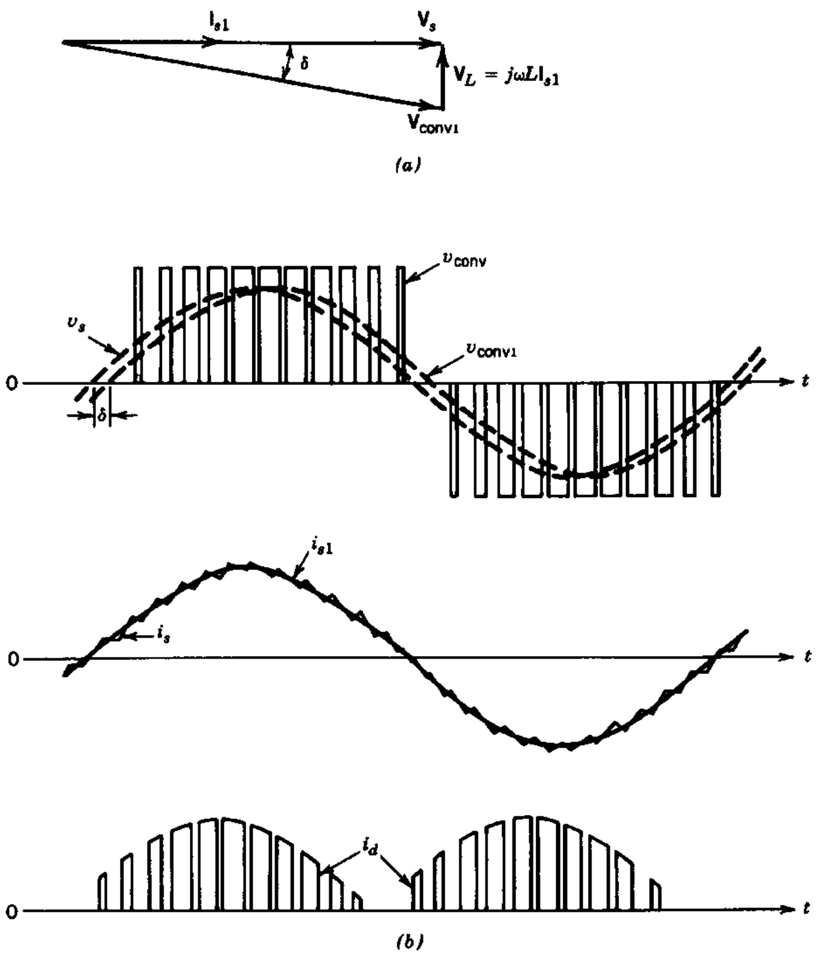


Figure 18-11 Waveforms in the circuit of Fig. 18-8 at unity power factor of operation: (*a*) phasor diagram; (*b*) circuit waveforms.

i_s nearly sinusoidal & V_d is dc. i_d consists of a ripple at twice line frequency.

This ripple can be minimized by LC filter.

Improved 3 phase utility Interface

One way to improve input current waveform is to increase ac side inductor. The 4 quadrant switch-mode converter is capable of supplying nearly sinusoidal input current at a unity power factor.

$$(V_{conv})_{LL} \approx V_{LL} \qquad (18\text{-}30)$$

$$V_{LL_1} = \frac{\sqrt{3}}{\sqrt{2}}(\hat{V}_{AN})_1 = \frac{\sqrt{3}}{2\sqrt{2}} m_a V_d \approx 0.612 m_a V_d \qquad m_a \le 1 \qquad (5\text{-}57)$$

$$V_d > 1.634 V_{LL} \qquad (18\text{-}31)$$

$$I_d = \frac{3V_s I_s}{V_d}\cos\varphi 1 \qquad (18\text{-}32)$$

$$I_d = \frac{3V_s I_s}{V_d} \qquad (18\text{-}33)$$

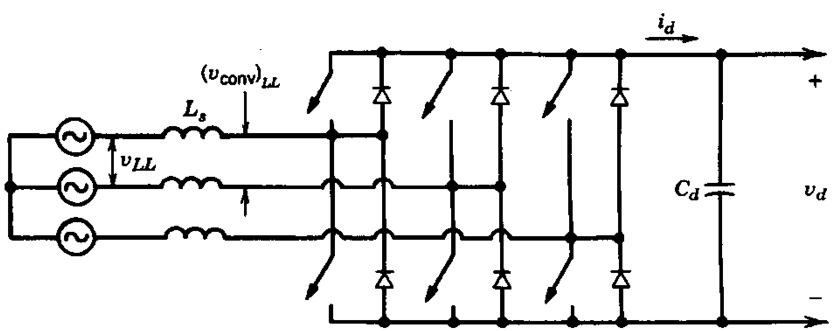


Figure 18-12 Three-phase, switch-mode converter.

Only high-switching-frequency current flows through C_d, only a small capacitance is needed.

Electromagnetic Interference

Because of rapid changes in V & I within switching converter, PEE is a source of EMI with other equipment as well as with its own proper operation.

EMI is transmitted in two forms: radiated & conducted.

Metal cabinet used for housing power converters reduce the radiated component of EMI.

Conduced noise is consists of differential mode & common mode.

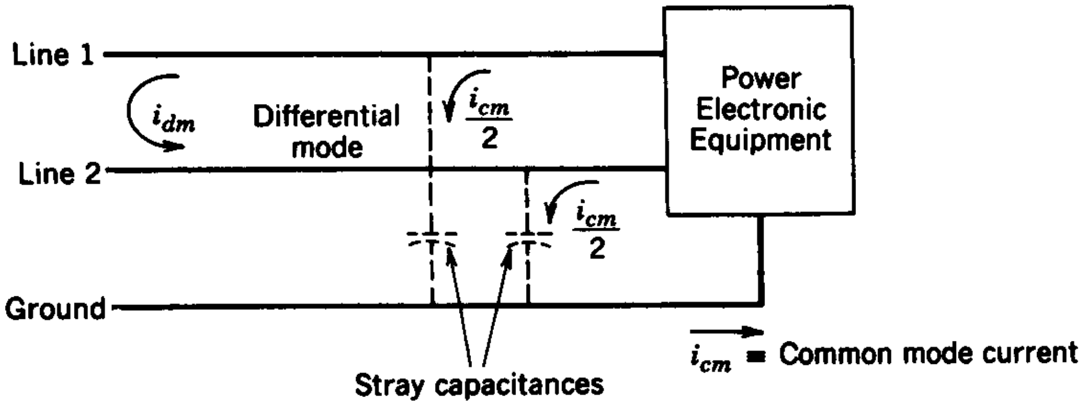


Figure 18-13 Conducted interference.

Generation of EMI

Because of short rise & fall times, these waveforms contain significant energy levels at harmonic frequencies in the RF region, several orders above fundamental frequency.

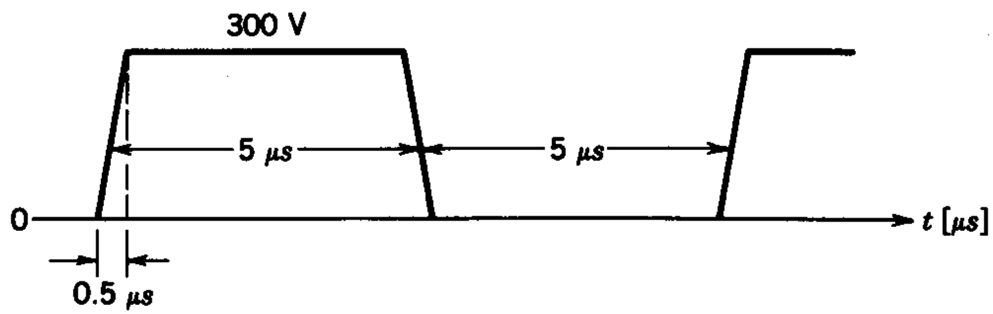


Figure 18-14 Switching waveform.

Transmission of differential-mode noise is through input line to utility system and through dc-side network to load on the power converter.

Transmission of common-mode noise is entirely through “parasitic” or stray capacitors & stray electric and magnetic fields.

EMI Standards

There are various CISPR, IEC, VDE, FCC, & military standards that specify maximum limit on conducted EMI. FCC & VDE standards for the RF equipment used in industrial, commercial, & residential equipment.

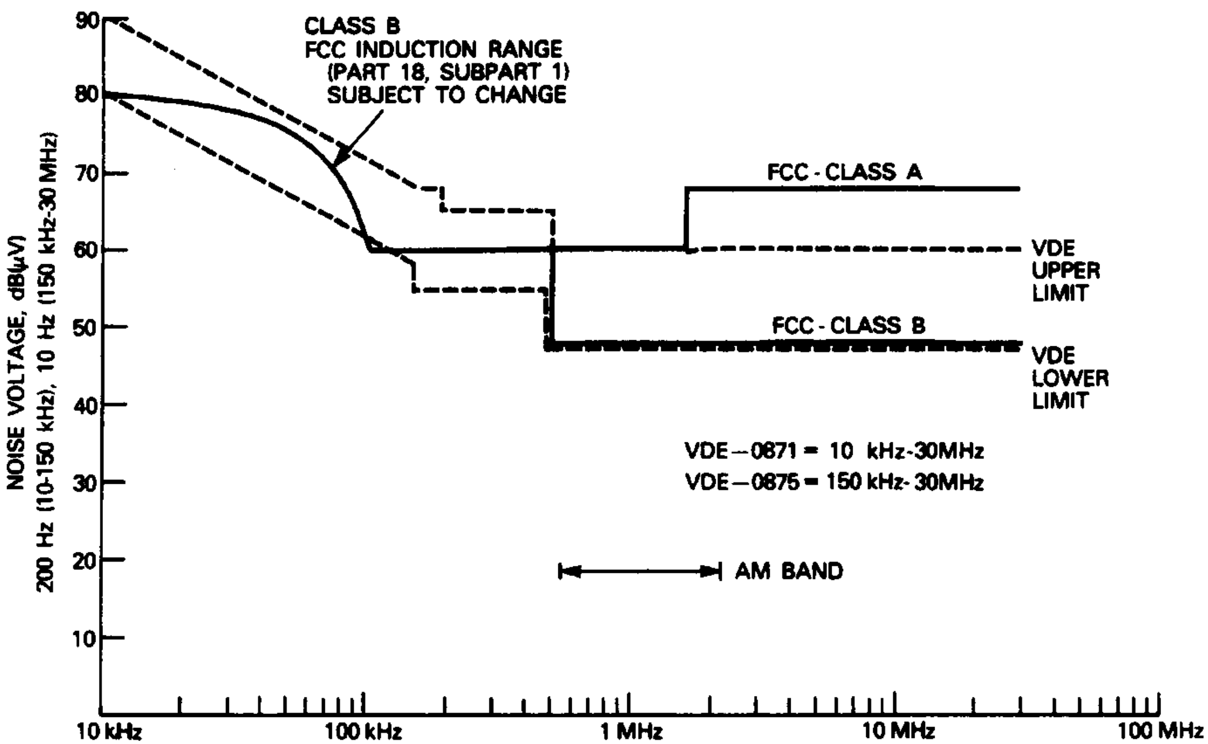


Figure 18-15 The FCC and VDE standards for conducted EMI.

Reduction of EMI

Most cost effective way of dealing with EMI is to prevent the EMI from being generated at its source, which can significantly reduce radiated & conduced interference before the application of filters, shielding, & like.

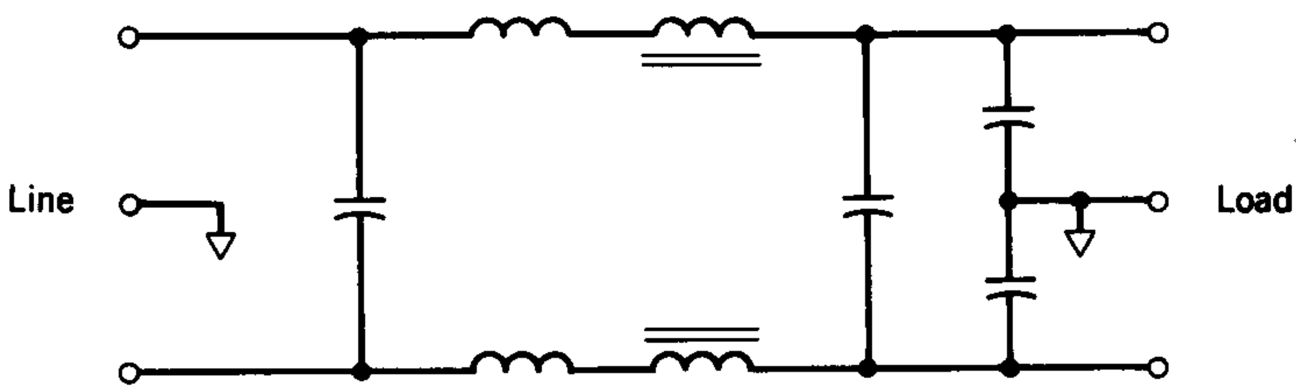
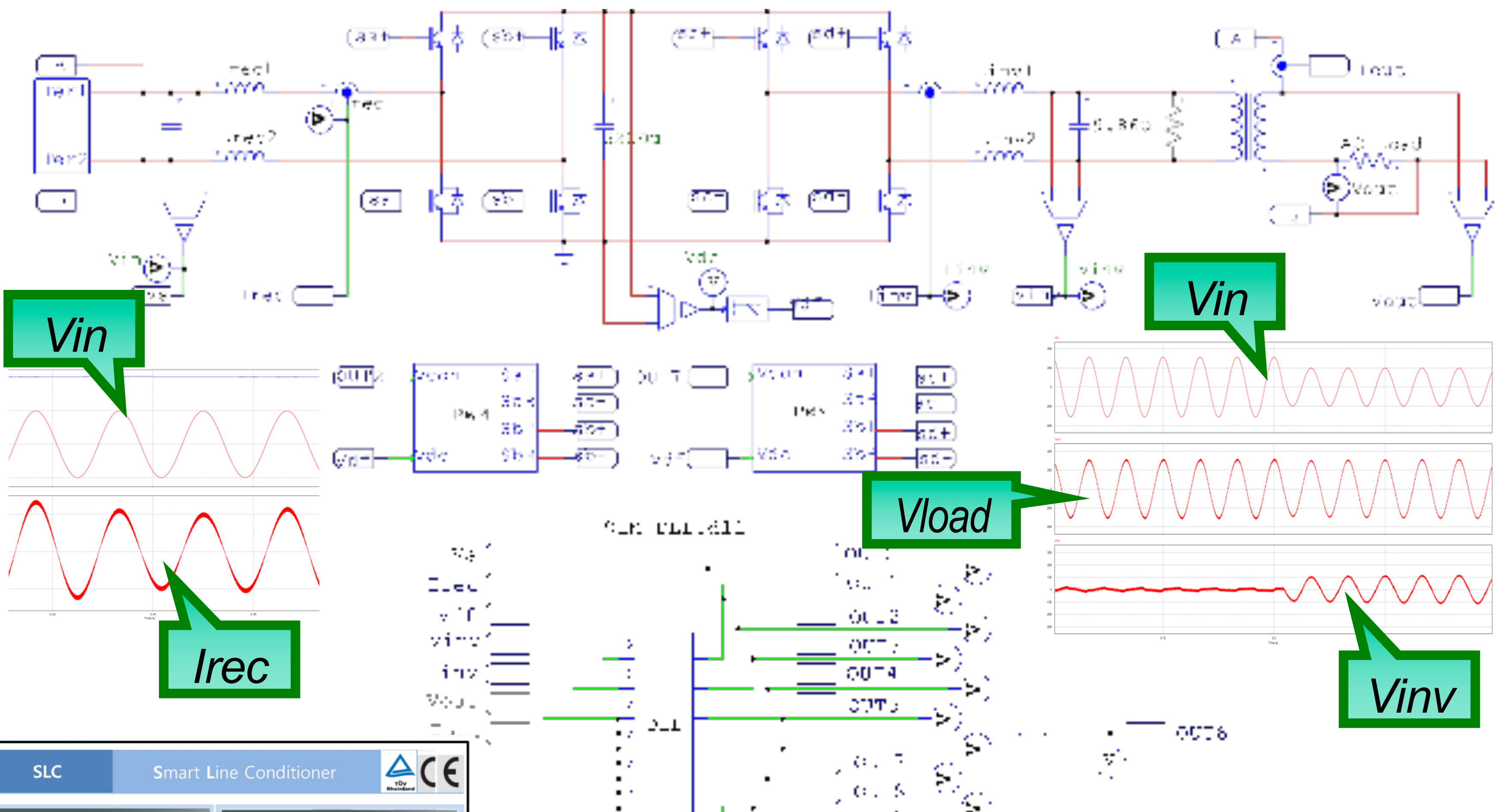
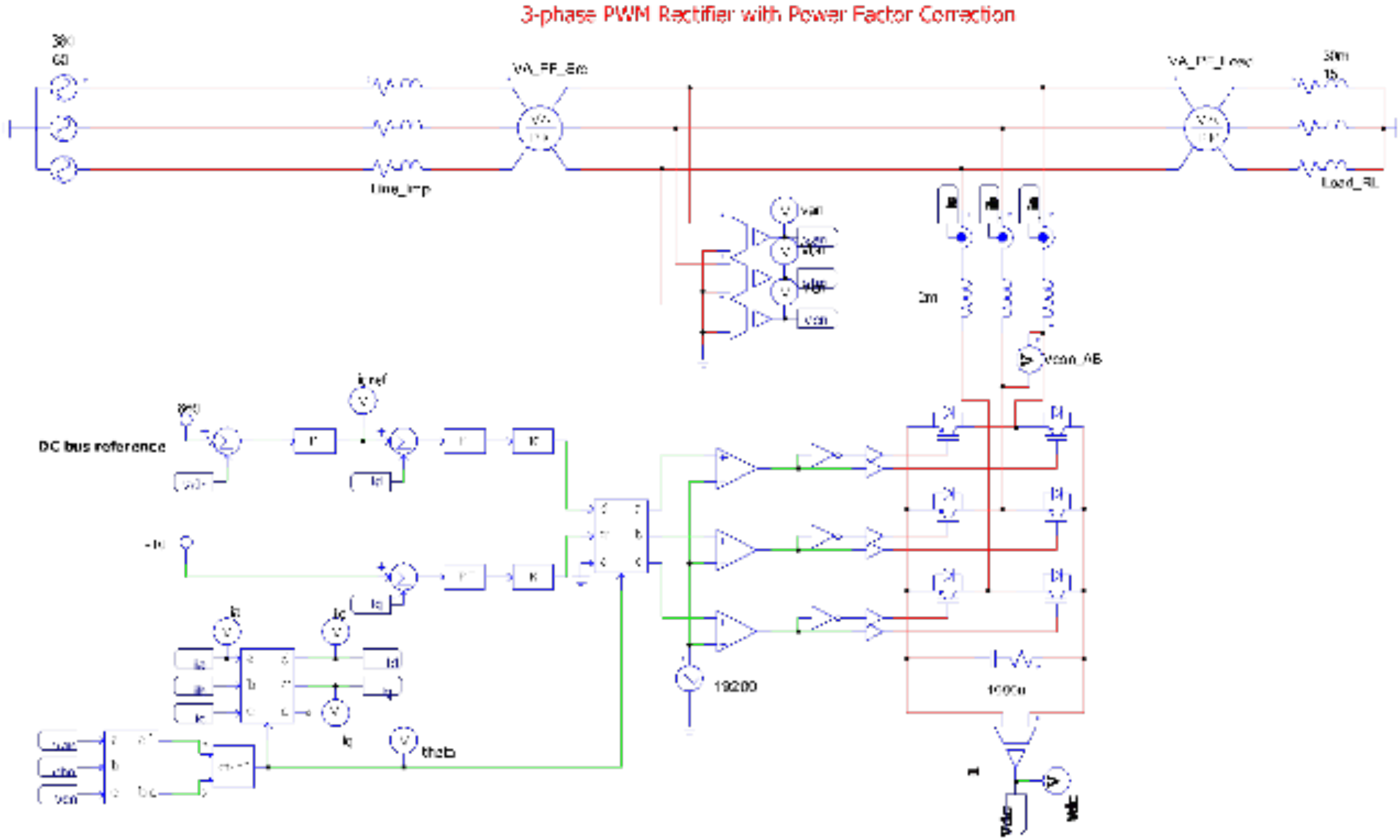


Figure 18-16 Filter for conducted EMI.

Smart Line Conditioner

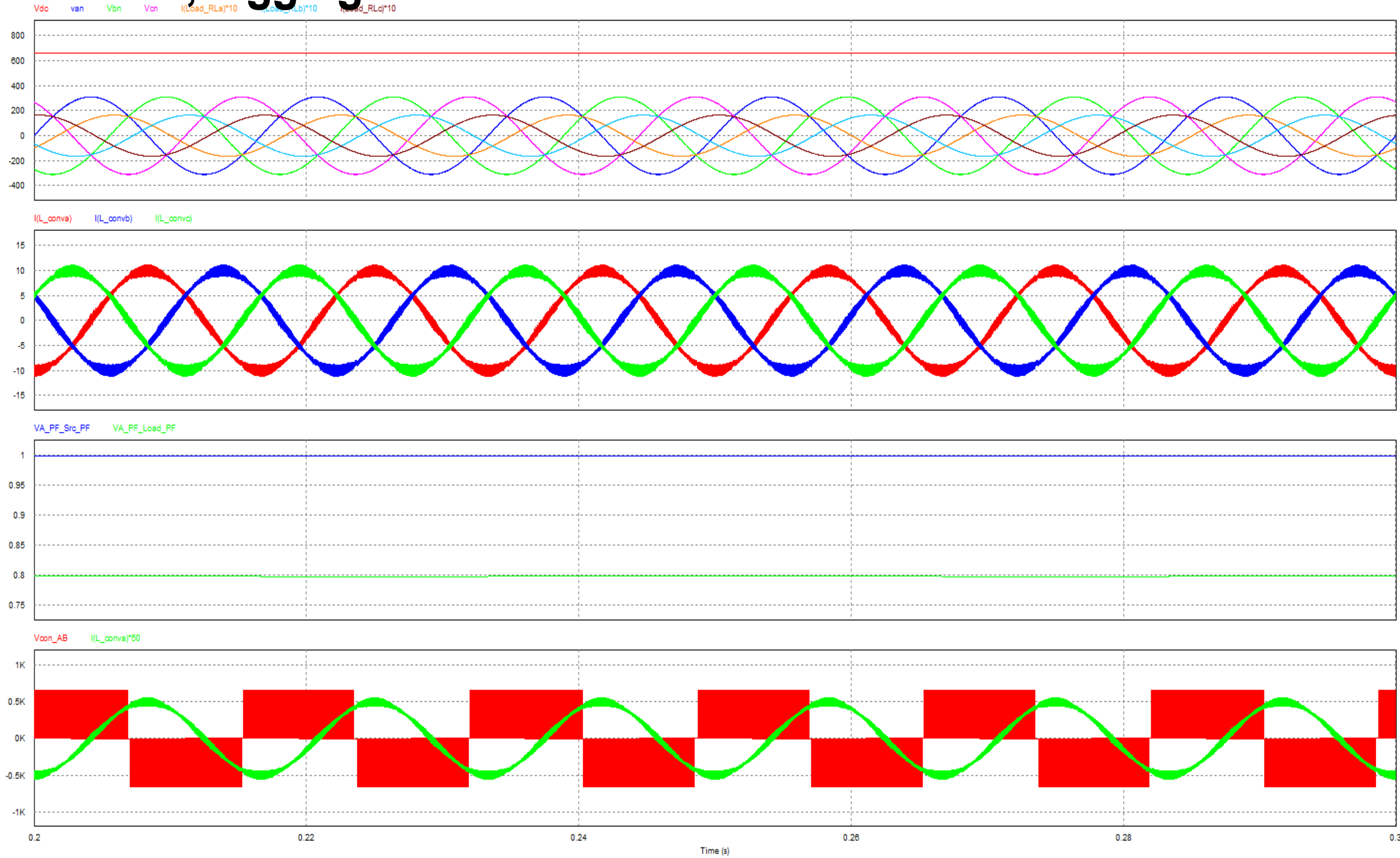


Static VAR Compensator



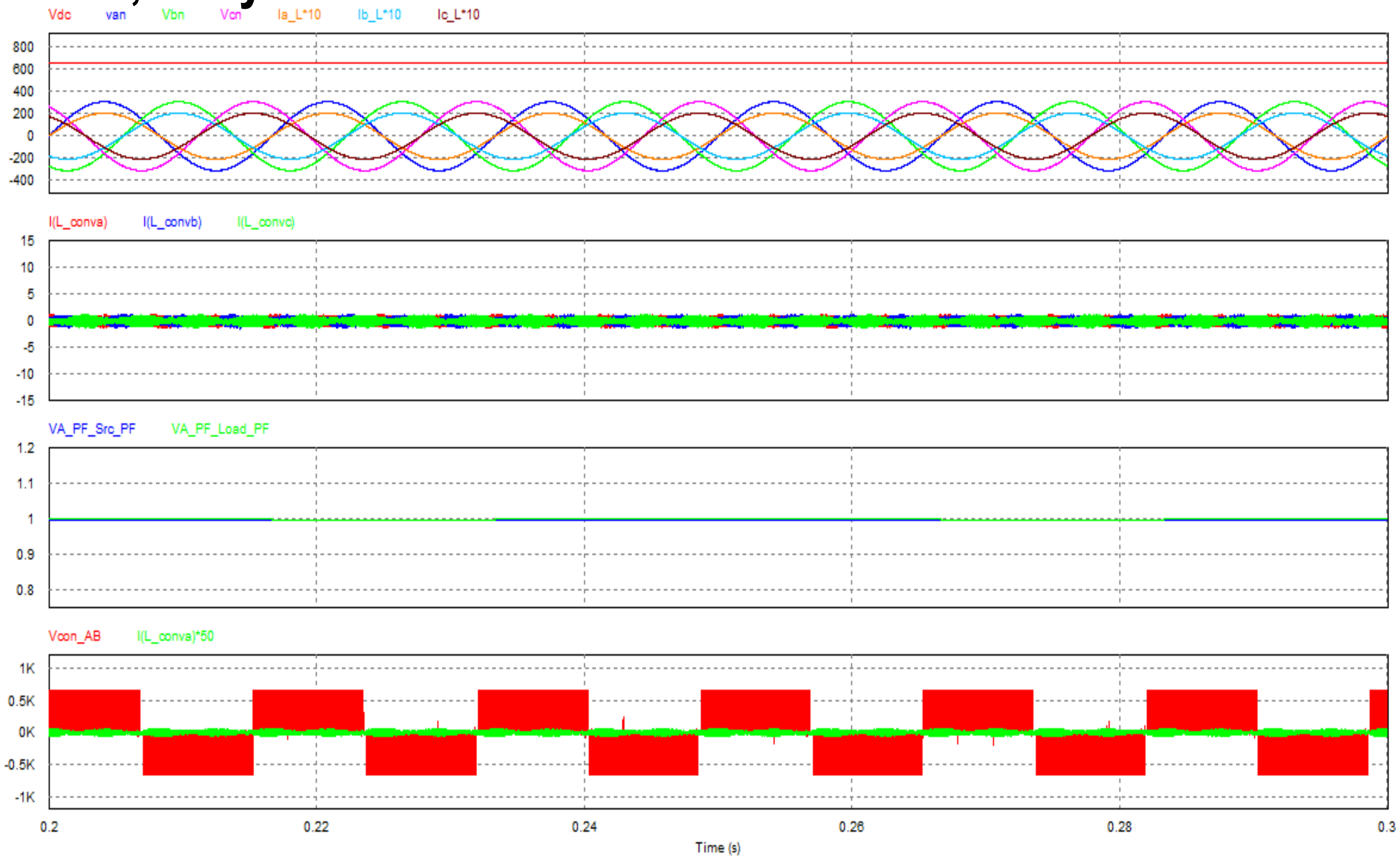
Static VAR Compensator

❖ PF = 0.8, lagging load



Static VAR Compensator

- PF = 1, Unity PF load



Static VAR Compensator

- PF = 0.8, Leading load