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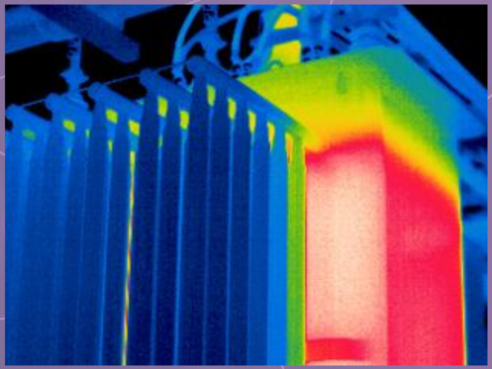
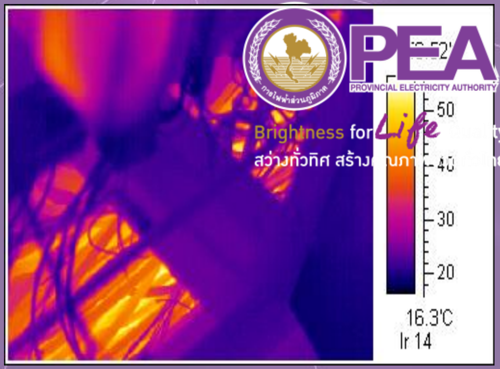
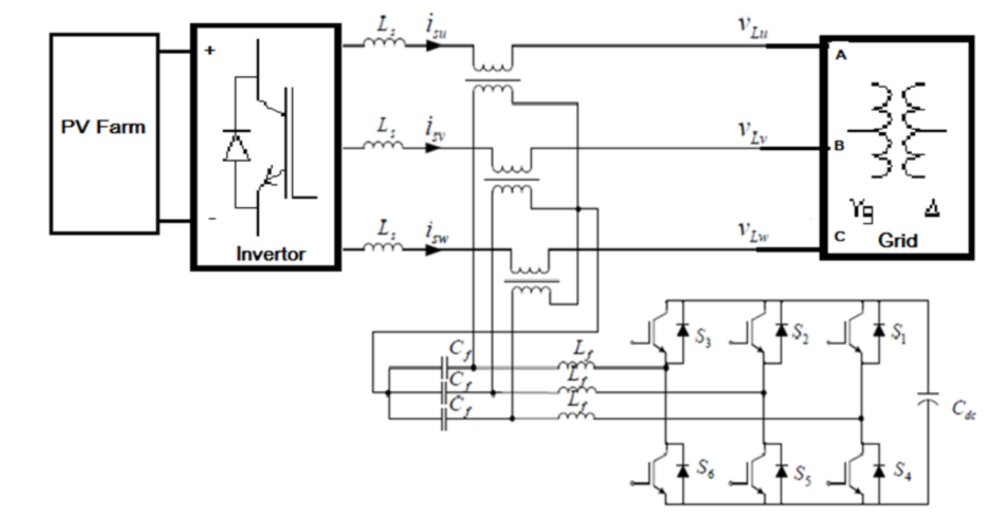
PROVINCIAL ELECTRICITY AUTHORITY
Brightness for Life Quality
สว่างทั่วทิศ สร้างคุณภาพชีวิตทั่วไทย

Harmonic Compensation

for Power Quality Enhancement in Grid Integration of Photovoltaic using Active Power Filter







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AGENDA

Harmonic Compensation for Power Quality Enhancement in Grid Integration of Photovoltaic using Active Power Filter

- Introduction
- Active Power Filter (APF)
- The theory of instantaneous reactive power (PQ)
- The hysteresis approach to control APF for reduction of harmonics
- Result and discussion

PEA Smart grid Roadmap

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	Planning and Pilot Project	Large Scale Expansion	Power quality and service efficiency improvement
Smart Energy	• Electricity networks in 4 cities automated system. • Unmanned substation • Micrograms • Energy Storage / Solar Rooftop • Network supports of DG • The integration of Enterprise System • Mobile Workforce in 4 cities	• Optimal Asset management • Complete of MWM • Completion of unmanned substation • Expand fully automated network covering major cities across the country • The penetration of renewable energy sources and energy storage in communities	• Automated electricity networks nationwide/self-healing features enabled • Smart community network integrated with a large renewable energy resources • Perfect cyber security system • The balanced and forecast system production corresponds to energy utilization • Virtual power plants created
Smart Life	• Advanced Metering Infrastructure (AMI) in 26 municipalities of PEA service area • Demand response management	• AMI development completion • Energy management completion in all large/medium cities • The system provides power usage information via the internet • Domestic consumers can produce their own electricity; surpluses can be sold to utility • Home/building energy management automation reduces electricity bills	• Power consumers can buy or sell electricity in real time • Users can choose to buy electricity from different supplies • Optimal Energy management
Smart Community	• Public charging station	• The extensive use of electric transportation • The penetration of intelligent public street and community lighting in communities • Bundled services with other utilities (common billing etc.)	• Intelligent electric vehicle charging to reduce peak demand • Two ways power supply of electric vehicles (vehicle to grid –V2G)

2012 Stage 1 : 2017 Stage 2 : 2022 Stage 3 : 2026

INTRODUCTION

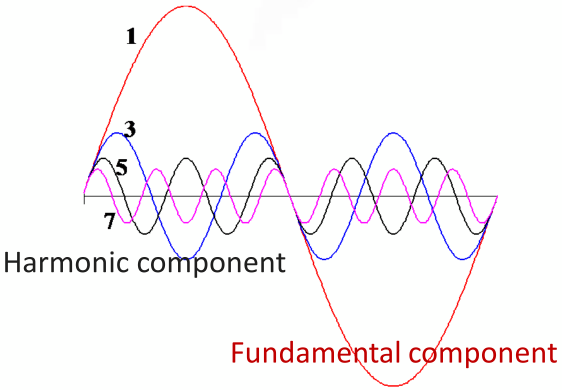
Harmonic is a signal whose frequency is a multiple of the frequency of a reference signal

Harmonics are due to periodic distortion of the voltage or current waveform

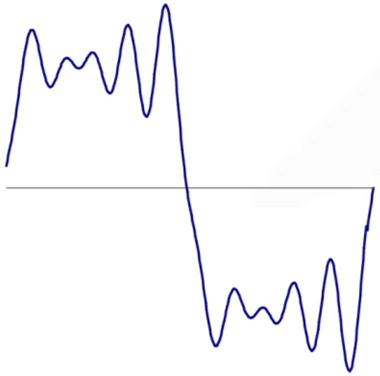
The distortion comes from nonlinear devices, principally loads

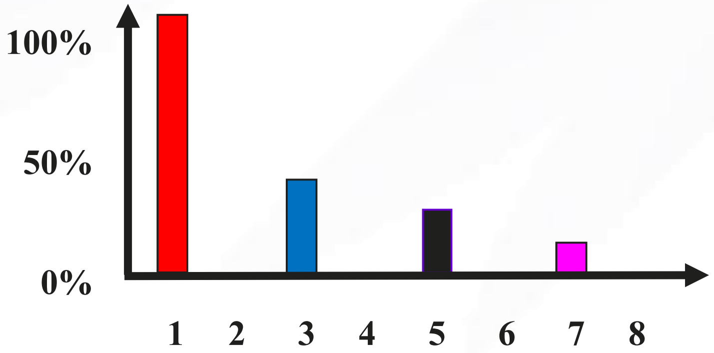
Harmonic Sources

- Ferromagnetic devices-
  - Transformers, motors
- Arcing devices-
  - arc furnaces, fluorescent lighting
- Power converters



Distorted waveform

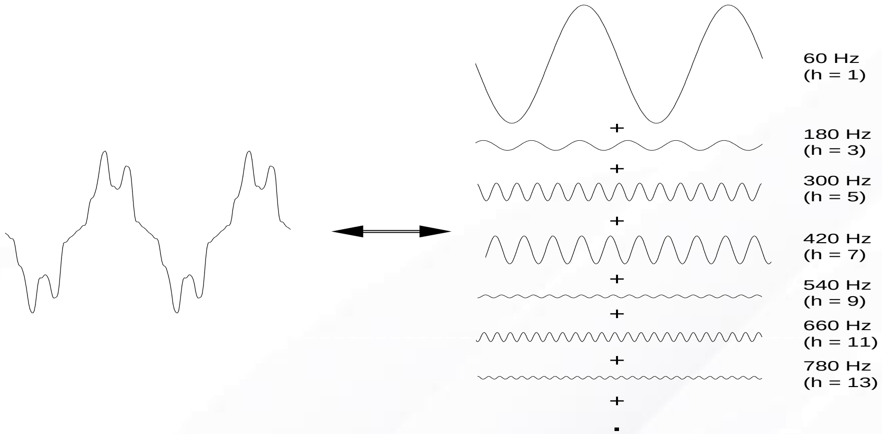




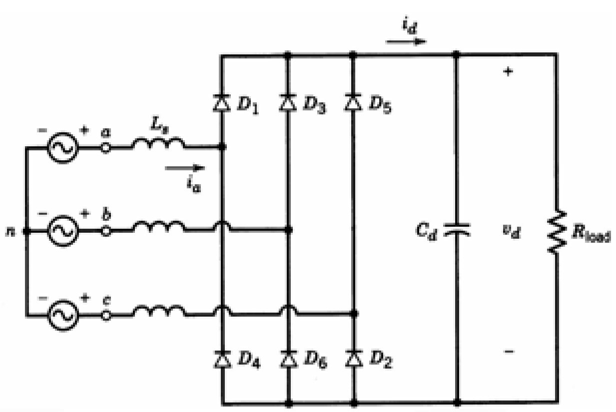
Decomposition into Harmonic Components – Fourier series

$$v(t) = V_{dc} + \sum_{h=1}^{\infty} \sqrt{2} V_h \sin(h\omega_0 t + \theta_h)$$

$$i(t) = I_{dc} + \sum_{h=1}^{\infty} \sqrt{2} V_h \sin(h\omega_0 t + \delta_h)$$



Harmonic Sources – 6-pulse rectifier
e.g. Variable Speed Drives or Medium Frequency Furnaces

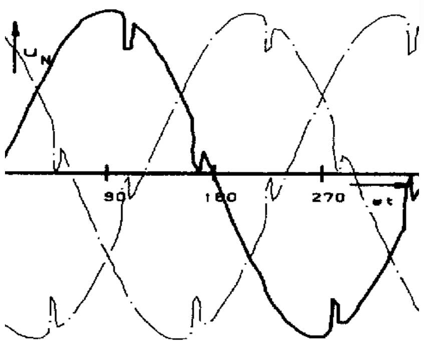


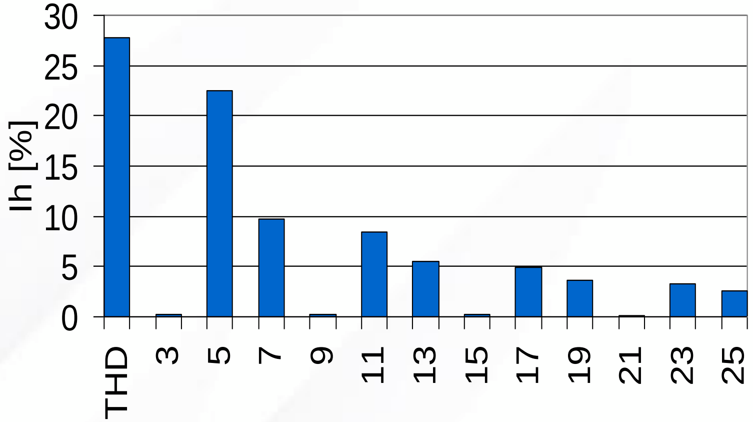
$h = p\,m \pm 1$

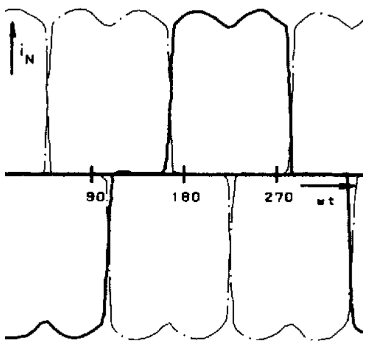
$h = 6\,m \pm 1$

$i_h = I1/h$ *

$\varphi \approx \alpha$





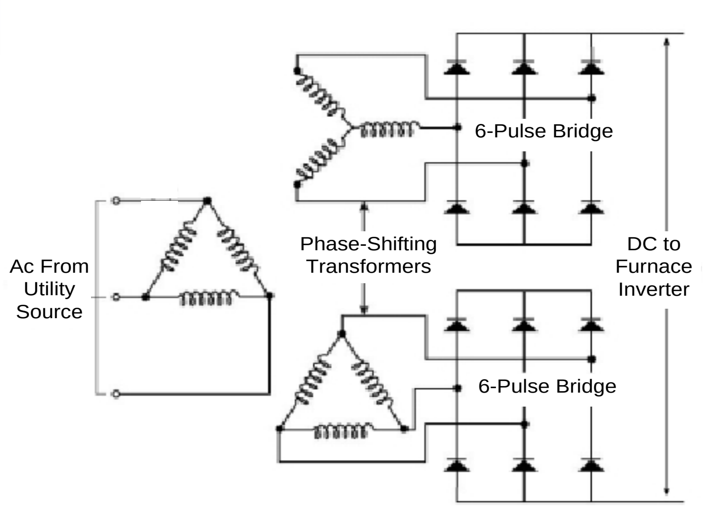


h=harmonic; p=pulse number; m= 1,2,3 ,... ; f_N= system frequency ;

* for smoothed d.c. only

φ = phase displacement between current and voltage; α = converters firing angle

Harmonic Sources – 12-pulse rectifier
e.g. Variable Speed Drives or Medium Frequency Furnaces

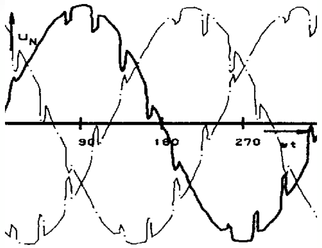


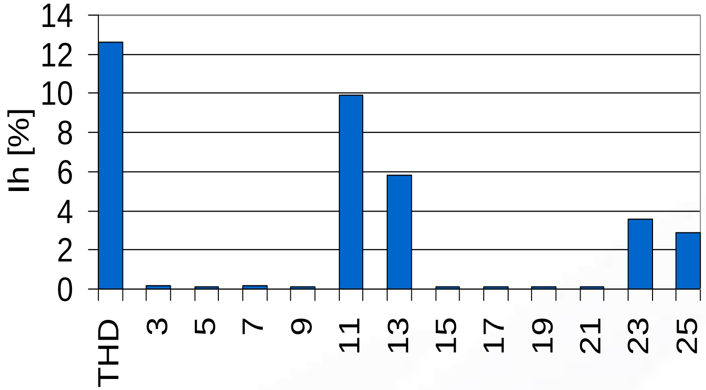
$h = p\,m \pm 1$

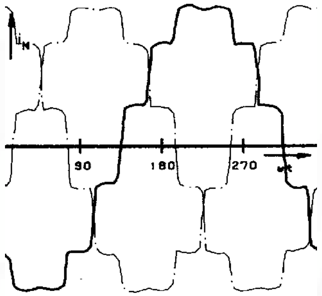
$h = 12\,m \pm 1$

$i_h = I1/h$ *

$\varphi \approx \alpha$







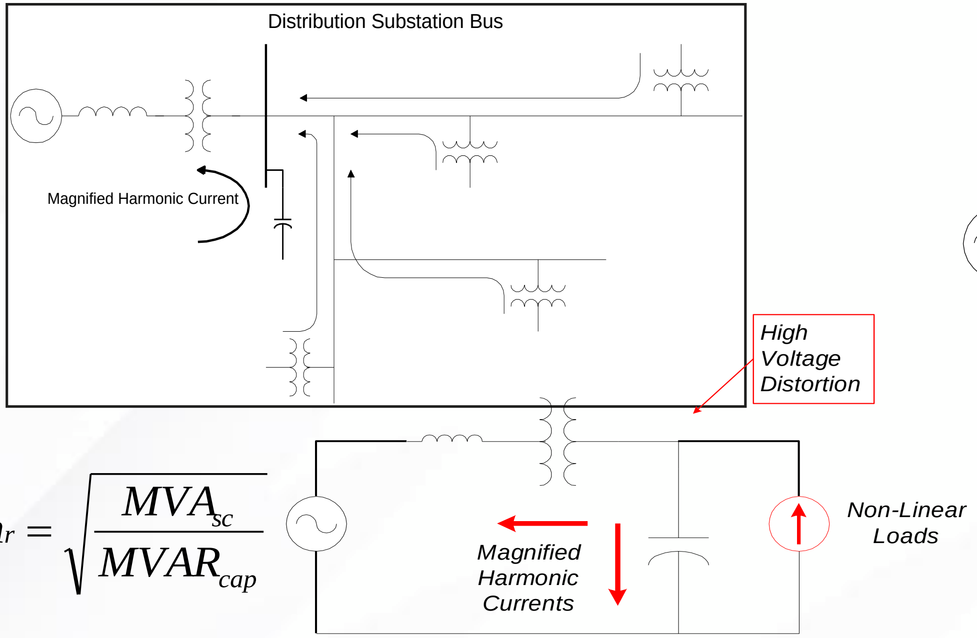
h=harmonic; p=pulse number; m= 1,2,3 ,... ; f_N= system frequency;

* for smoothed d.c. only

INTRODUCTION

Undesirable Effects of Harmonics

- Overheating resulting in need of derating of the equipment.
- Potential for problems with excessive ground currents (stray voltages, telephone interference, relay mis-operation) on systems with single phase loads.
- Capacitors for power factor correction and cable systems aggravate the problem by causing resonances.



$$h_r = \sqrt{\frac{MVA_{sc}}{MVAR_{cap}}}$$

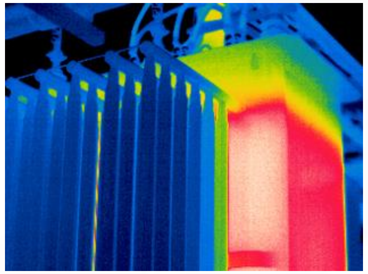
Parallel Resonance

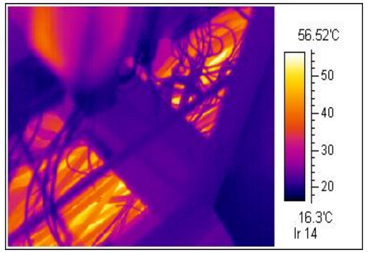
Are harmonic levels increasing?

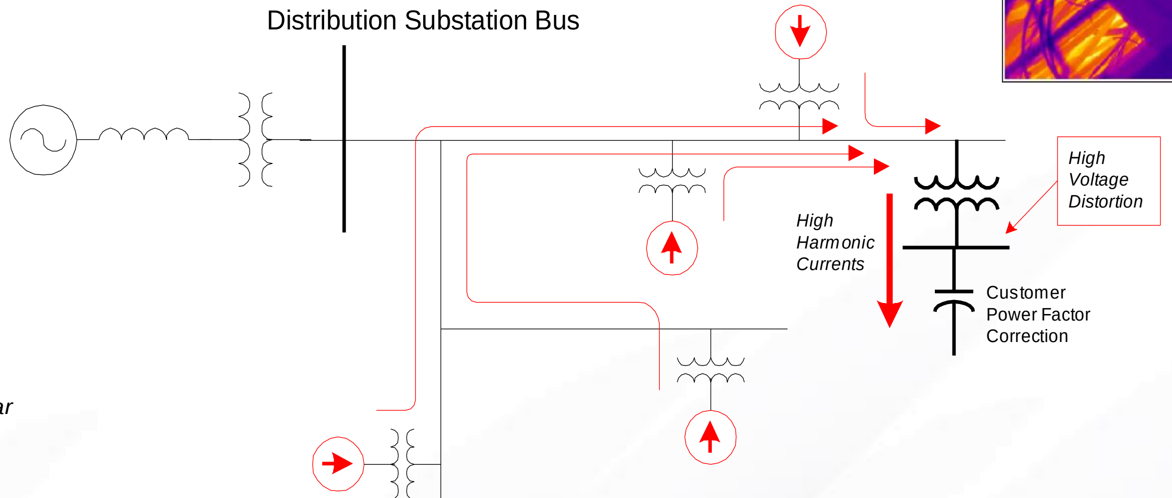
Changing system characteristics
- More power factor correction
- More cable

Changing load
- More harmonic generation
- Less damping

Other characteristics







Series Resonance

INTRODUCTION

IEEE Standard 519-1992- Current Distortion Limits

Odd harmonics Distortion limits (%I_L) for individual customers

Base voltage Limit (kV)	I_{SC}/I_L	h<11	11≤h<17	17≤h<23	23≤h<35	35≤ h
0.12 – 69	<20	4.0	2.0	1.5	0.6	0.3
	20-50	7.0	3.5	2.5	1.0	0.5
	50-100	10.0	4.5	4.0	1.5	0.7
	100-1000	12.0	5.5	5.0	2.0	1.0
	>1000	15.0	7.0	6.0	2.5	1.4
69.001 – 161	<20	2.0	1.0	0.75	0.3	0.15
	20-50	3.5	1.75	1.25	0.5	0.25
	50-100	5.0	2.25	2.0	0.75	0.35
	100-1000	6.0	2.75	2.5	1.0	0.5
	>1000	7.5	3.5	3.0	1.25	0.7
> 161	<50	2.0	1.0	0.75	0.3	0.15
	≥50	3.0	1.5	1.15	0.45	0.22

The limits applicable for normal conditions
For shorter periods (e.g. startup) limits may be exceeded by 50%

Table 11-1—Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

NOTE — High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Even harmonics are limited to 25% of the odd harmonic limits
The limits applicable for normal conditions
For shorter periods (e.g. startup) limits may be exceeded by 50%
Tables applicable for 6-pulse convertors
For higher pulse number (q), limits may be increased by a factor of sqrt(q/6) provided non-characteristic harmonics are less than 25% of the specified limit.

INTRODUCTION

PRC-PQG-01/1998: PEA's Regulation on the Power Network System Interconnection code B.E.2559(2016)
Current Distortion Limits at point of common coupling

Base voltage limit	MVAsc**	Current Distortion Limits (A rms)																	
PCC Voltage (kV)	Base	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
0.400	10	48	34	22	56	11	40	9	8	7	19	6	16	5	5	5	6	4	6
11 and 12	100	13	8	6	10	4	8	3	3	3	7	2	6	2	2	2	2	1	1
22, 24 and 33	500	11	7	5	9	4	6	3	2	2	6	2	5	2	1	1	2	1	1
69	500	8.5	6	4.3	7.3	3.3	4.9	2.3	1.6	1.6	4.9	1.6	4.3	1.6	1	1	1.6	1	1
115 and above	1,000	5	4	3	4	2	3	1	1	1	3	1	3	1	1	1	1	1	1

$$MVA_{SC1} \neq MVA_{SC-BASE}$$

$$I_h = \frac{I_{hp} \times MVA_{SC1}}{MVA_{SC-BASE}}$$

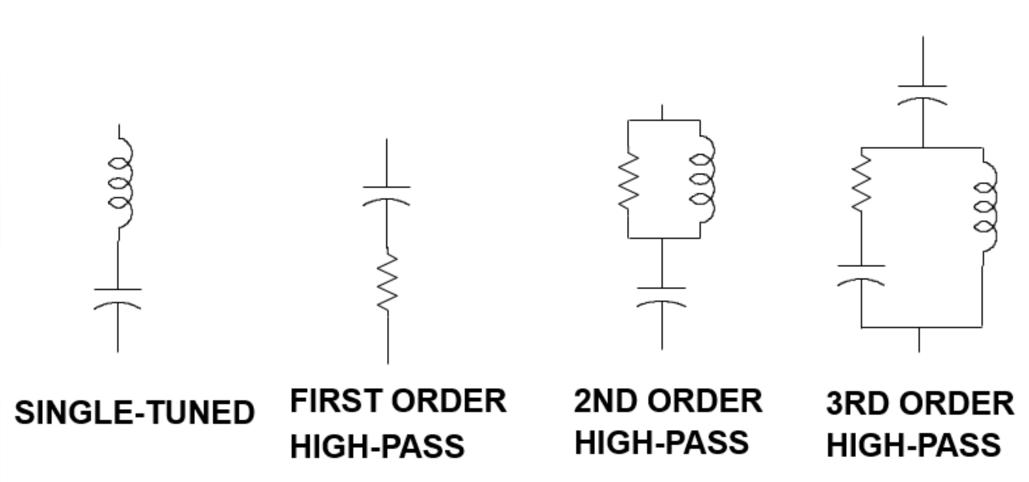
Where;
I_h = Harmonic Current (A) h order that is allowed to flow in the system when $MVA_{sc} = MVA_{sc1}$
I_{hp} = Harmonic Current (A) h order in table 1
MVA_{sc1} = Minimum MVA_{sc} at PCC
$MVA_{sc\text{-}Base}$ = Base MVA_{sc} for harmonic current from table 1

INTRODUCTION

Devices for Controlling Harmonic Distortion

- Chokes for ASD applications
- Zig-zag transformers
- Passive Filters
- Active filters

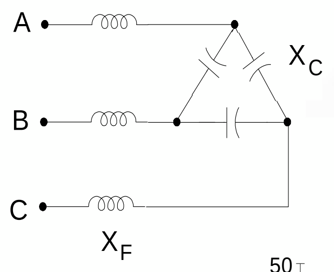
Shunt Passive Filter Configurations



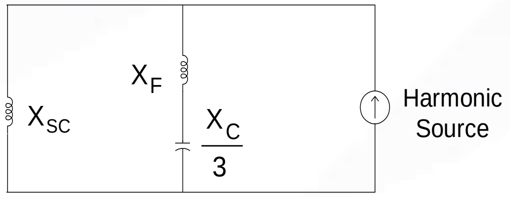
Effect of Notch Filter on the Frequency Response Characteristics

$$h_{notch} = \sqrt{\frac{X_C}{3X_F}}$$

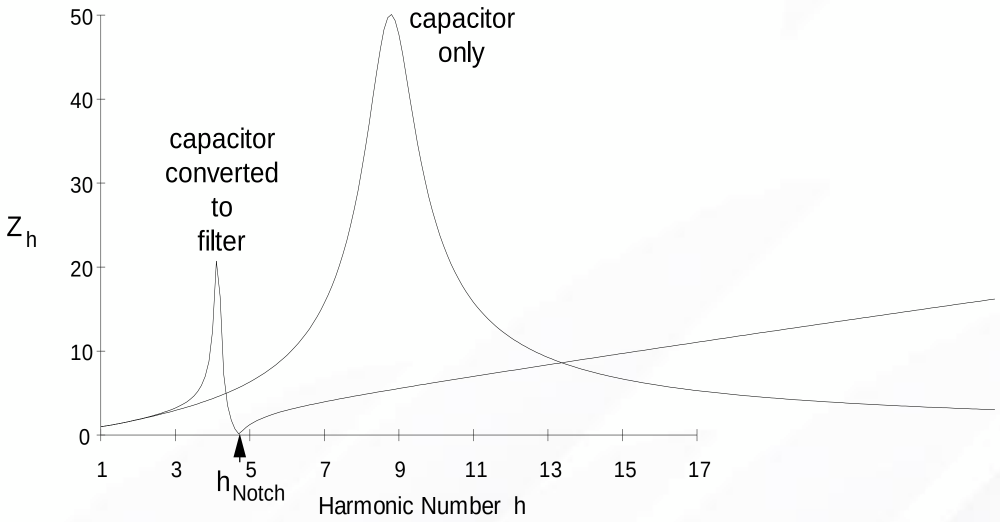
(a) Typical low voltage filter configuation.



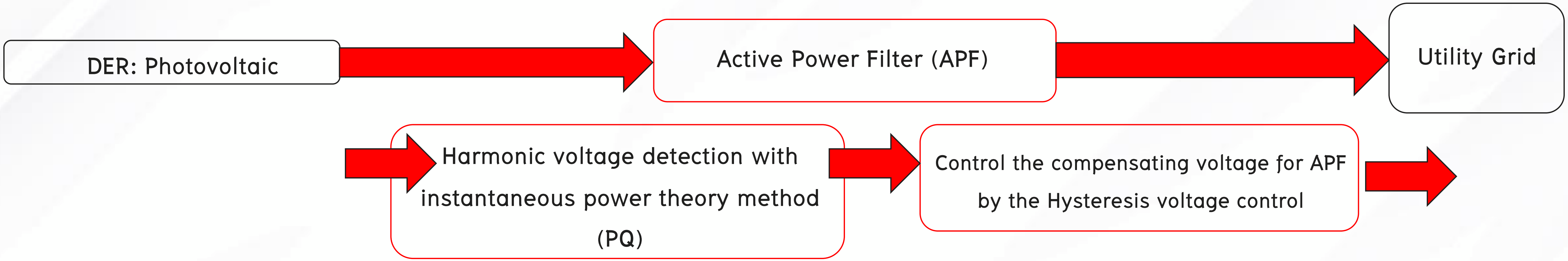
(b) Equivalent circuit of system with filter.

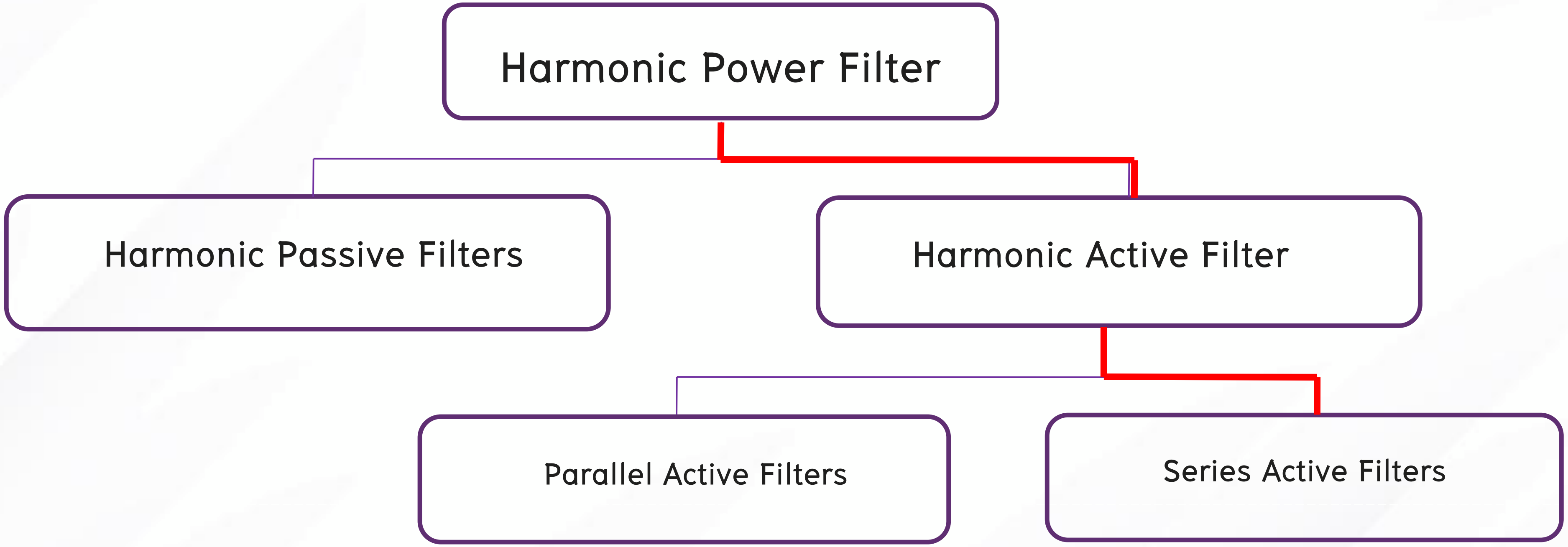


(c) System frequency response (Z_1 = 1.0).

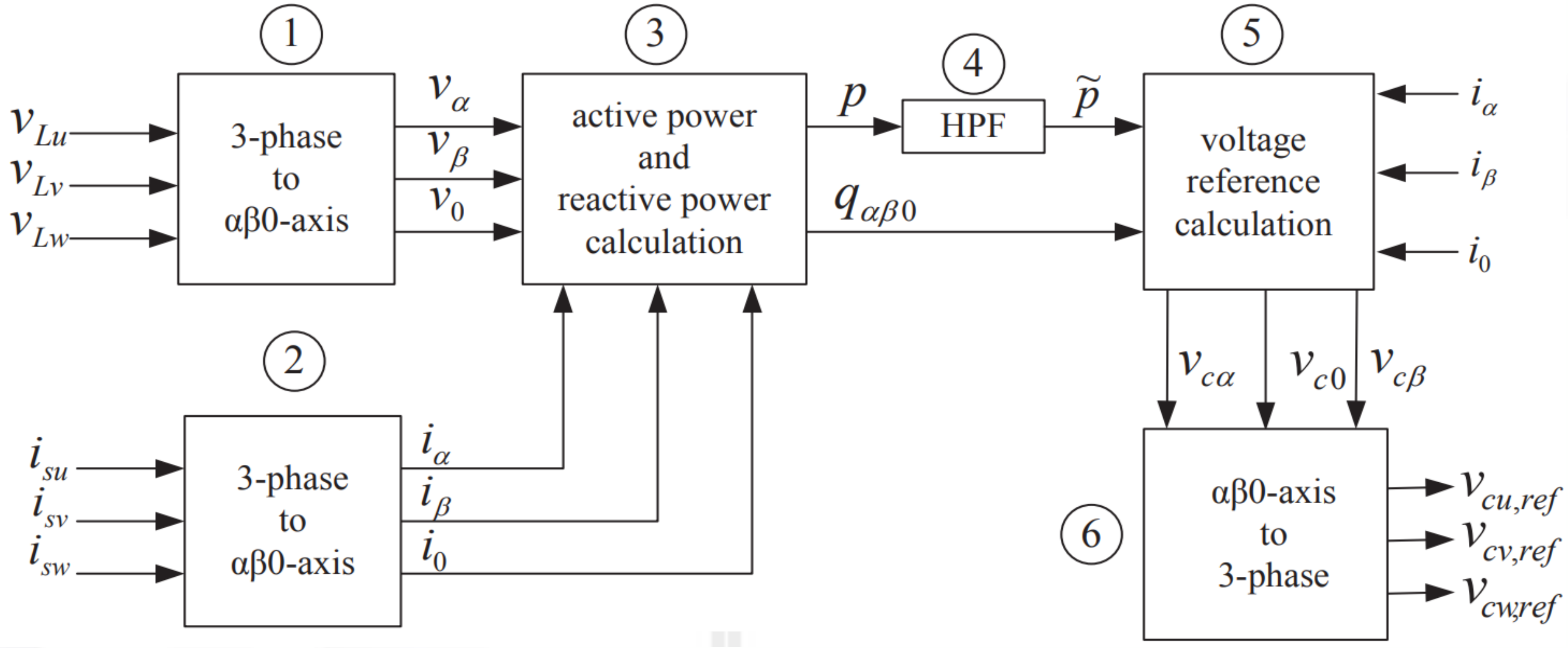


Voltage Harmonics Compensation





Harmonic voltage detection with instantaneous power theory method (PQ)

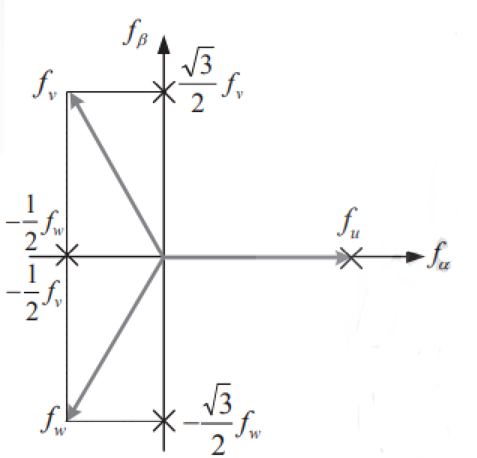


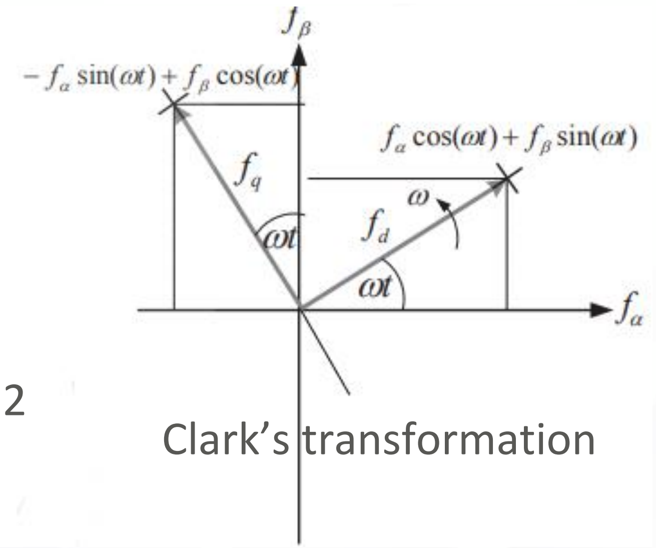
$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} f_u \\ f_v \\ f_w \end{bmatrix}$$

Equation 1

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix}$$

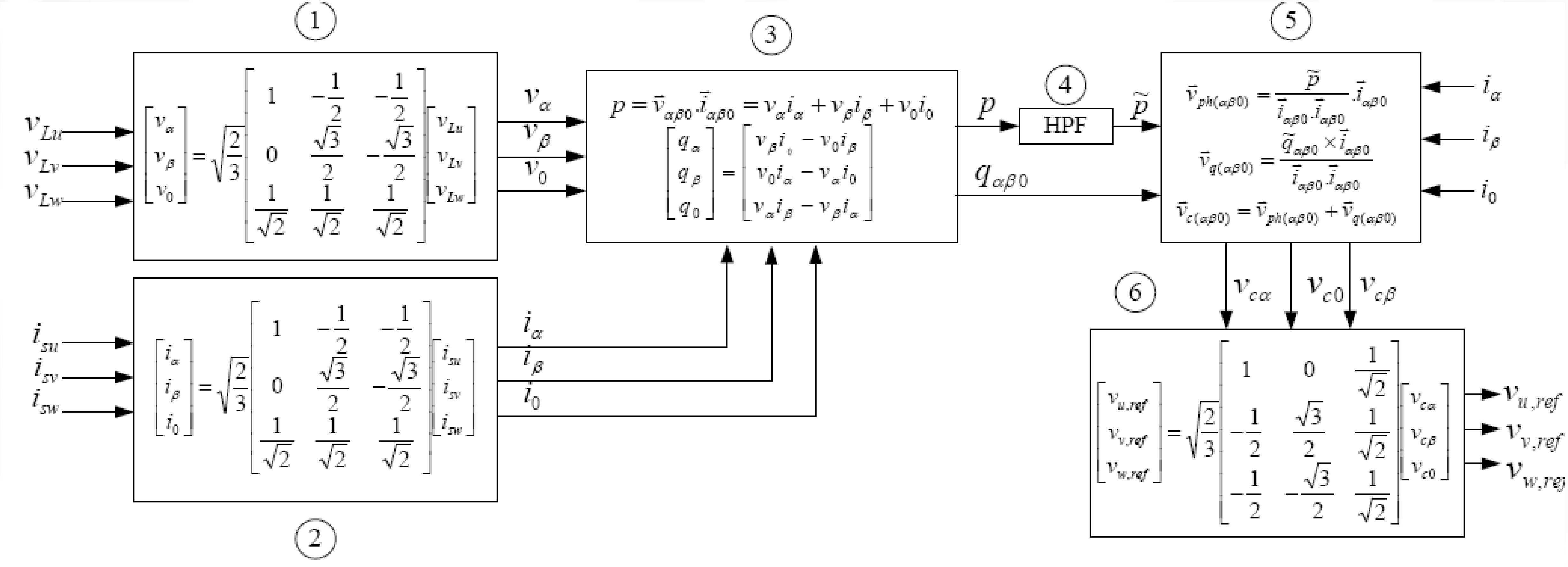
Equation 2



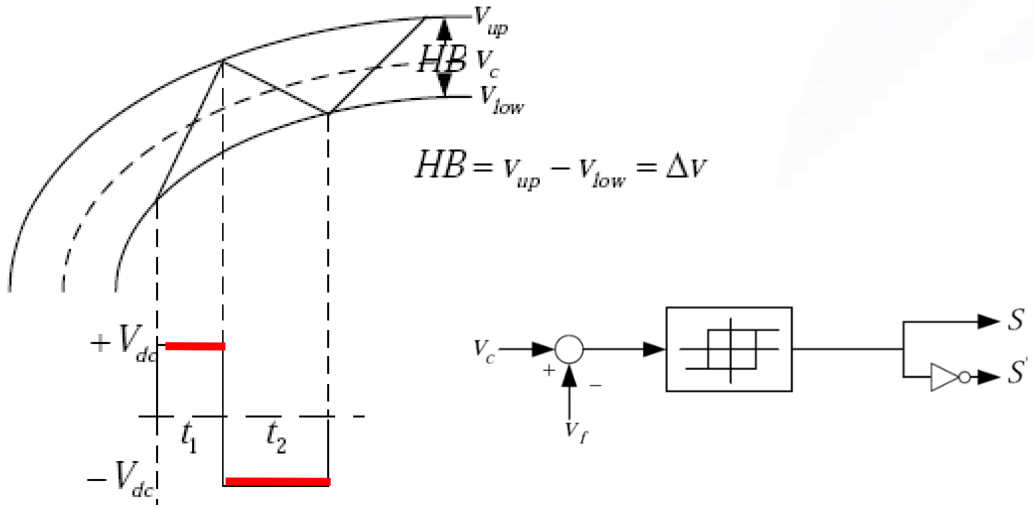


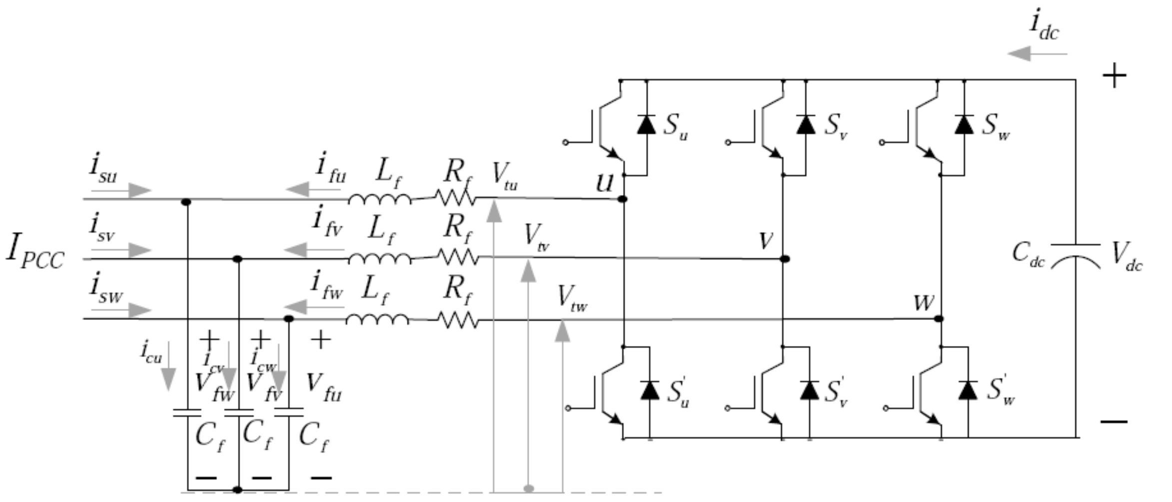
Clark's transformation

Harmonic voltage detection with instantaneous power theory method (PQ)



Hysteresis voltage control





The hysteresis voltage control conditions:

Case 1: $V_c \leq V_{low}$

- Switch S close circuit (dc+V) and switch S‘ open circuit

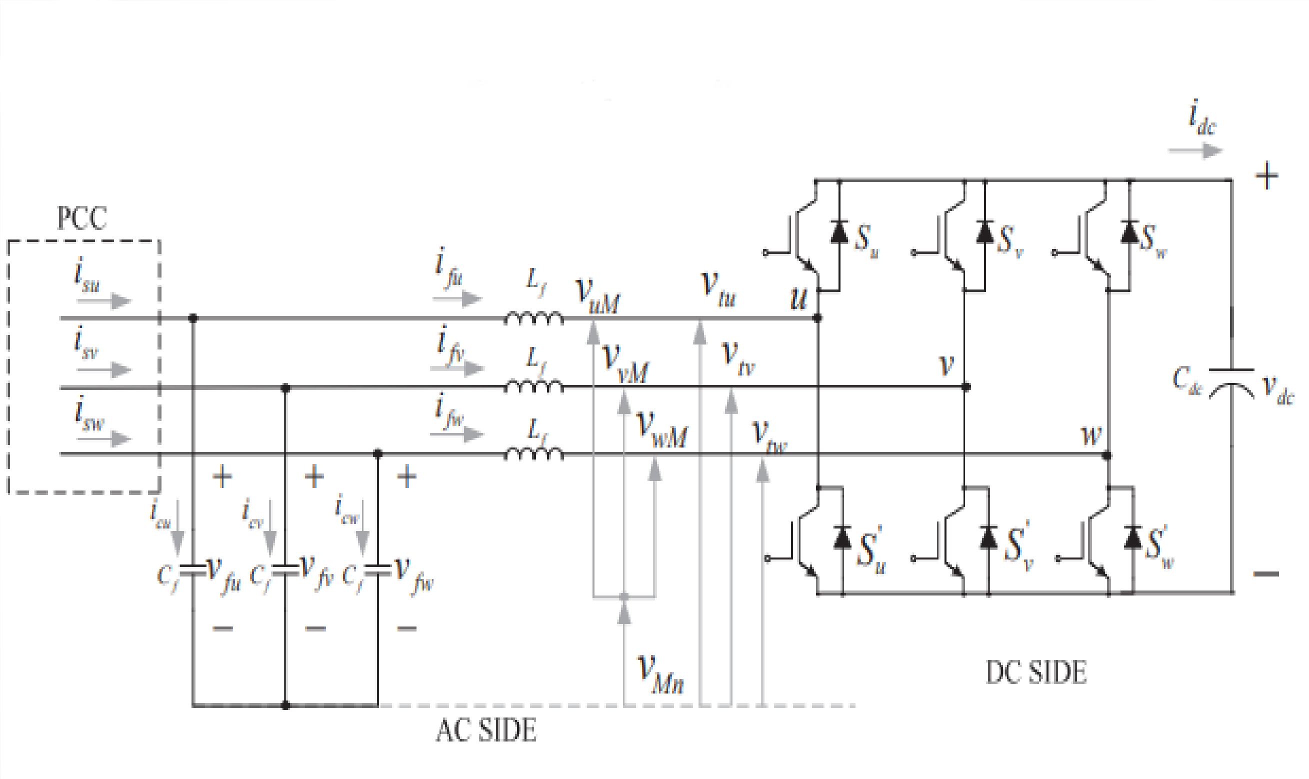
Case 2: $V_c \geq V_{up}$

- Switch S open circuit and switch S‘ close circuit (dc-V)

Case 3: $V_{low} < V_c < V_{up}$

- Switch S and S' does not change status

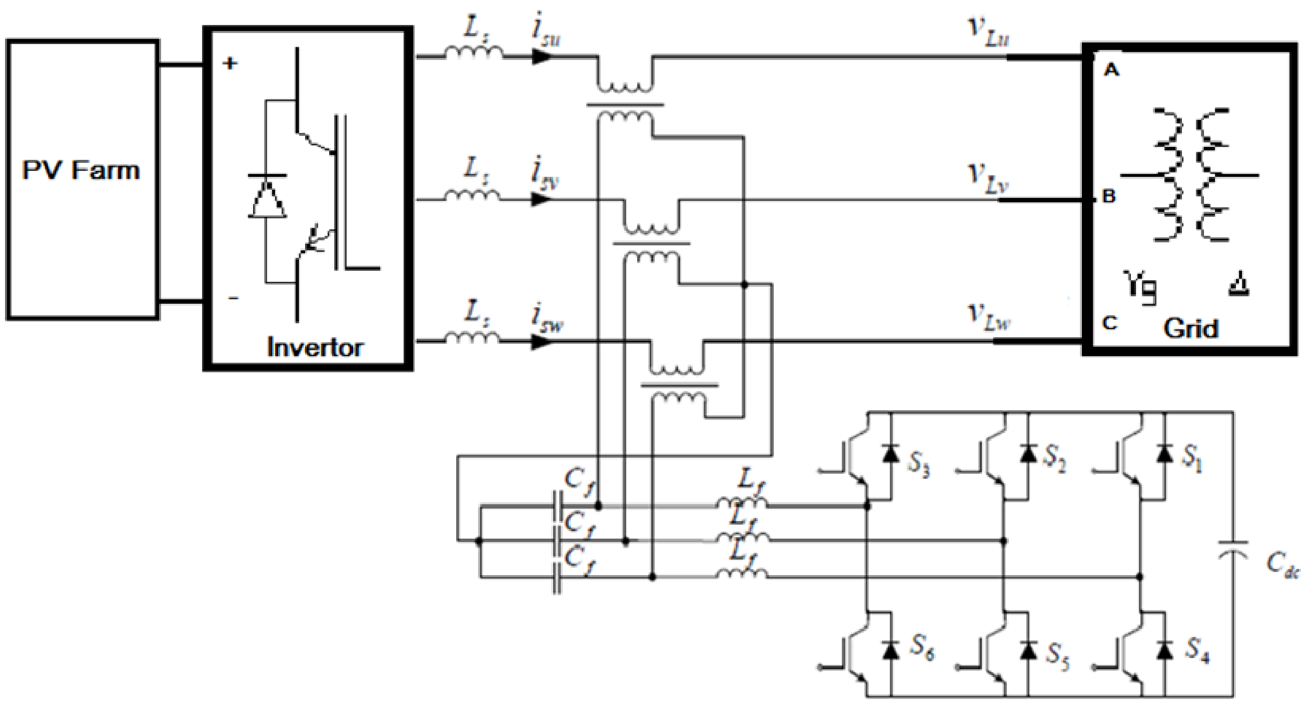
APF Model

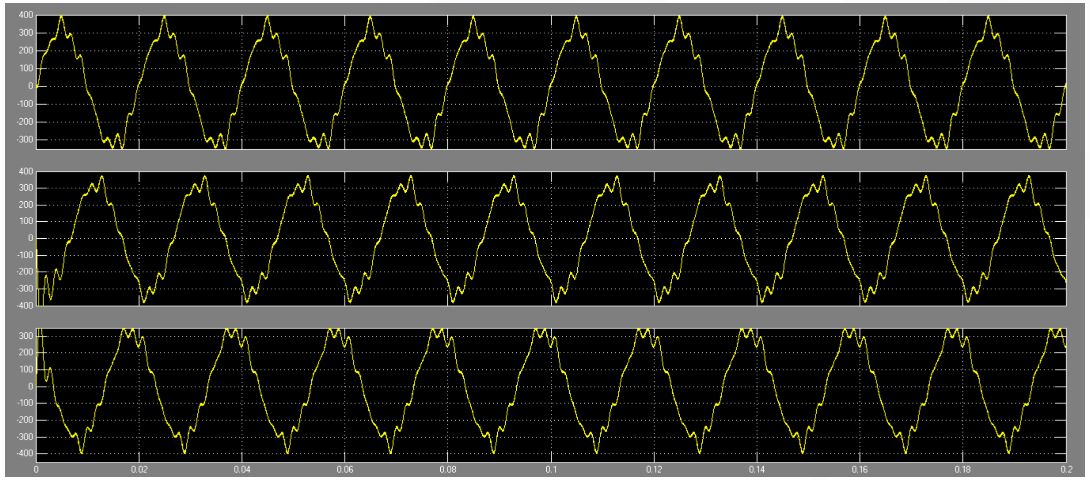


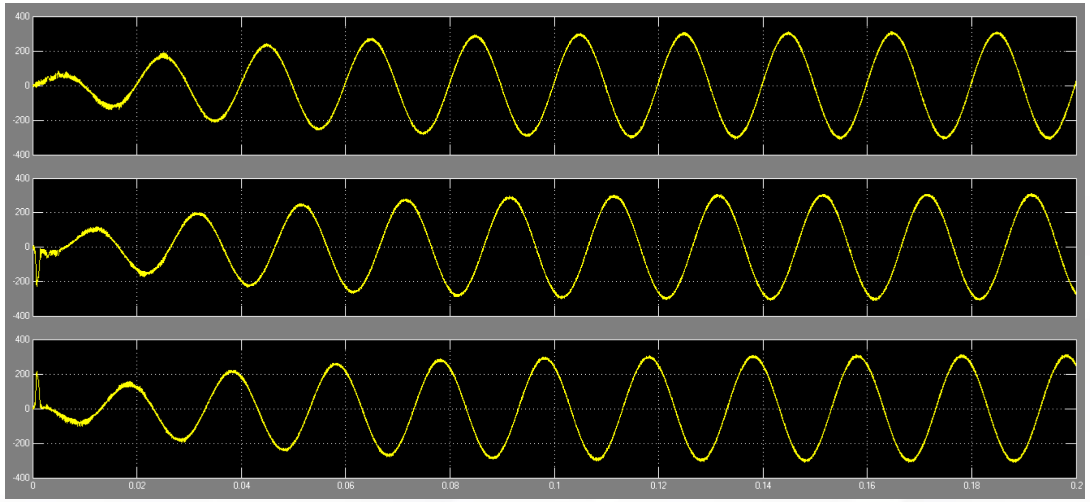
The series active power filter is structured as a voltage source inverter circuit, uses IGBT as a power electronic switch.

And the **AC side of the circuit** is connected to a three-phase current source at the PCC point through it filter capacitors (*Cf*) and filter inductance *(Lf)* in all three phases. With the inverter circuit output voltage *(Vtu, Vtv, Vtw)* that directly affecting the voltage compensation *(Vfu, Vfv, Vfw)*. **In order to** control such the voltages to have the similar wave form to the reference voltage *(Vcu,ref,, Vcv,ref,, Vcw,ref)* obtained by calculationg the harmonic voltage by PQ method.

Simulation results







	Before compensation	After compensation
$\%THD_{v,u}$	11.39	1.77
$\%THD_{v,v}$	11.06	2.04
$\%THD_{v,w}$	11.66	1.96
$\%THD_{v,av}$	11.37	1.92

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Thank you for your attention

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