Power System Quality and Reliability

ECEg-6312

WEEK 5

Mitigation and Control of harmonics in Power System

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Topic Overview

This weeks discussion covers the following main topics:

- Fundamentals of harmonic mitigation
- Filtering techniques in power systems
- Passive harmonic filter design and analysis
- Active harmonic filter design and control strategies
- Comparative evaluation of mitigation techniques
- Practical implementation in modern power systems and microgrid

Learning Outcomes

At the End of This Lesson, Students Will Be Able To:

- Analyze harmonic distortion and its impact on power systems
- Design passive harmonic filters for specific harmonic orders
- Develop and model active harmonic filters (APF)
- Apply dq and p–q control strategies for harmonic compensation
- Evaluate filter performance using THD and system indices
- Integrate harmonic mitigation techniques into microgrid and smart grid systems

1. Introduction to Harmonic Mitigation

- **Definition**
  - Harmonic mitigation refers to the set of techniques used to reduce or eliminate harmonic distortion in power systems to maintain acceptable power quality and system reliability.
- **Harmonics are generated by nonlinear loads, such as:**
  - Power electronic converters (rectifiers, inverters)
  - Variable Frequency Drives (VFDs)
  - Arc furnaces and welding equipment

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- **Harmonics** are sinusoidal components at integer multiples of the fundamental frequency
- **For a 50 Hz system:**
  - 5th harmonic → 250 Hz
  - 7th harmonic → 350 Hz
- **Mathematical Representation:**

$$I(t) = I_1 \sin(\omega t + \varphi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \varphi_n)$$

- $\boldsymbol{I_1}$ is the fundamental component and $\boldsymbol{I_n}$ is nth harmonic component

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- **Harmonics** significantly degrade power system performance by introducing additional losses, thermal stress, and operational instability in electrical equipment and networks:
  - Increased I^2R losses
  - Overheating of transformers and motors
  - Voltage distortion
  - Maloperation of protection devices
  - Resonance in power systems

2. Harmonic Quantification

- **Harmonic quantification** is essential for evaluating the severity of waveform distortion and designing appropriate mitigation strategies.
- It provides measurable indices to assess compliance with standards such as IEEE 519.

- **Total Harmonic Distortion (THD):**

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} X_n^2}}{X_1}$$

- **Individual Harmonic Distortion (IHD):**

$$IHD_V = \frac{X_n}{X_1}$$

- **Total Demand Distortion (TDD):**

$$TDD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_L}$$

- where, X_n is the nth harmonic signal.

3. Harmonic Mitigation Techniques

- Harmonic mitigation techniques are employed to reduce distortion, improve power quality, and ensure reliable system operation in modern power systems with increasing nonlinear loads.
- Main Categories of Harmonic Mitigation:
  - Passive Filtering Techniques
  - Active Filtering Techniques
  - Hybrid Filtering Techniques
  - Source-Level Mitigation Techniques
  - System-Level Solutions

3.1. Passive Filtering (PF) Techniques

- **Passive filtering techniques** use R–L–C components to suppress harmonic distortion by providing low-impedance paths for harmonic currents, thereby preventing their propagation into the power system.
- **How it works?**
  - At tuned harmonic frequencies → filter impedance is minimum
  - Harmonic currents are diverted into the filter
  - Fundamental frequency → filter presents high impedance

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- Types of Passive Filters (PF)

1. Single-Tuned Filter (Band-Pass Filter)

  - Designed to eliminate a specific harmonic order (e.g., 5th, 7th)
  - Resonance Condition:

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

  - Key Features:
    - High effectiveness for targeted harmonics
    - Most widely used in industrial systems

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2. Double-Tuned Filter

- Designed to suppress two harmonic frequencies simultaneously
- Combination of two tuned branches
- **Application:** Common for 5th and 7th harmonics

3. High-Pass Filter

- Provides low impedance to high-frequency harmonics
- **Types:** First-order, Second-order, and C-type filter
- **Application:** Eliminates higher-order harmonics (above 11th, 13th)

Design Considerations of PF

- Proper design of passive harmonic filters is critical to ensure effective harmonic suppression, system stability, and avoidance of resonance under varying operating conditions.
- To design a passive harmonic filter the following methodological approach should be followed:

1. Harmonic Spectrum Analysis:

  - Perform FFT analysis of load current/voltage
  - Identify: Dominant harmonic orders (e.g., 3rd, 5th, 7th, 11th) and Magnitude and phase of harmonics
  - This is the basis for filter tuning and sizing

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2. Selection of Tuning Frequency

- Typically tuned slightly below the target harmonic frequency:

$$f_{\text{tuned}} \approx (0.95 \text{ to } 0.98) \times f_{harmonic}$$

- The reason is to void detuning due to:
  - Component tolerances
  - Temperature variation
  - System frequency deviations

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3. Reactive Power Rating (Capacitor Sizing)

- Capacitor provides both Harmonic filtering and Reactive power compensation

$$Q_C = \frac{V^2}{X_C}$$

- Where, $X_C = \frac{1}{2\pi f C}$ and V is the system voltage and it should be maintained at its nominal value.
- Must satisfy system VAR requirements without causing overcompensation

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4. Inductance Calculation

- Inductance in a passive harmonic filter is calculated to resonate with a capacitor at a specific harmonic frequency (f_r) to bypass harmonic currents.
- The passive filter inductance value is computed from resonance condition:

$$L = \frac{1}{(2\pi f_r)^2 C}$$

$$f_r = n f_1$$

- Ensures filter is tuned to the desired harmonic frequency

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5. Quality Factor (Q) Selection

- The Quality Factor ($Q=\frac{1}{R}\sqrt{\frac{L}{C}}$) of a passive harmonic filter dictates its **selectivity**, bandwidth, and ability to handle **frequency drifts**.
- Typical values for passive shunt filters range between 30 and 60, providing a balance between effective attenuation of specific harmonics and robustness against system frequency changes.
- A higher Q, indicates a narrower band with sharper filtering, whereas a lower value provides a wider bandwidth to handle network fluctuations.

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6. Location and Placement

- Install close to harmonic source
- Avoid placing at weak buses prone to resonance
- Consider system topology and load distribution

7. Compliance with Standards

- Ensure design meets limits defined by
- IEEE 519 power quality and compatability standard
- **Verify:** THD limits, Individual harmonic limits, and total demand distortion (TDD) limits.

Advantages and Limitations of PF

- **Advantages**
  - Simple and robust design
  - Low cost compared to active filters
  - High reliability (no switching devices)
  - Provides reactive power compensation

- **Limitations**
  - Fixed compensation (non-adaptive)
  - Risk of resonance
  - Performance affected by system parameter variations
  - Large size for low-frequency harmonics

3.2. Active Filtering (AF) Techniques

- **Active filtering techniques** utilize power electronic converters and advanced control algorithms to dynamically compensate harmonic distortion in power systems.
- Unlike passive filters, they provide **adaptive and real-time** harmonic mitigation.

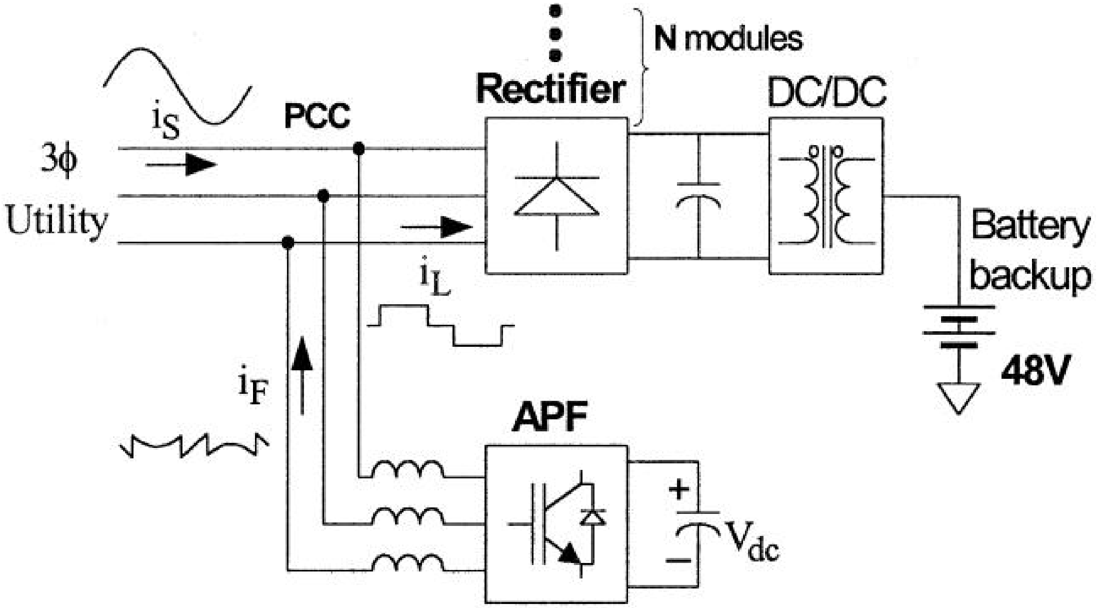

Figure 1: Active Harmonic Filtering Techniques [1].

A. Basic Operating Principles of AF

- Active harmonic filters (AF) operate by **detecting**, extracting, and compensating harmonic components in real time using power electronic converters and advanced control algorithms.
- The idea is to inject a compensating signal $I_C(t)$ that cancels harmonic distortion $I_h(t)$ in the system.
- Mathematical Representation:

$$I_s(t) = I_L(t) + I_C(t)$$

- $I_s(t)$ is supply current, $I_L(t)$ is load current, and $I_C(t)$ is compensating current.
- Condition for Ideal Compensation: $I_C(t) = -I_h(t)$

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Active harmonic filtering follows a five step process:

1. Measurement

- Sense load voltage and current signals
- Use current and voltage sensors

2. Harmonic Detection

- Extract harmonic components from distorted signals using:
  - Instantaneous power theory (p–q)
  - Synchronous reference frame (dq)
  - Fourier-based methods (FFT)

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3. Reference Signal Generation

- Generate reference compensating current:
- Equal magnitude
- Opposite phase to harmonic components

4. Control and Switching

- Controller processes error between reference and actual current
- Generates switching signals using:
  - PWM or Hysteresis control

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5. Compensation Injection

- Voltage Source Converter (VSC) injects compensating current into the system
- Harmonics are canceled at the point of common coupling (PCC)

The following Key Functional Blocks are used:

- Signal measurement unit (Source, load, and componsating currents)
- Harmonic extraction algorithm
- Reference current generator
- Current controller and Power converter (VSC)

B. Types of Active Harmonic Filters

- Active Harmonic Filters (AFs) are classified based on their **connection topology** and **compensation objective**.
- Each type is designed to address specific power quality issues such as **current** harmonics, **voltage** distortion, and **reactive power** control.
- Based on **connection topology** it is catagorized in three groups:
  - Shunt Active Power Filter (SAPF)
  - Series Active Power Filter (SeAPF)
  - Hybrid Active Power Filter (HAPF)

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1. Shunt Active Power Filter (SAPF)

- It is the most widely used active filtering technique, designed to compensate **current** harmonics, **reactive power**, and **load unbalance** in power systems.
- Connected in parallel (shunt) with the nonlinear load
- Installed at the Point of Common Coupling (PCC)
- It detects distorted load current and extracts the harmonic components
- And finally injects a **compensating current** into the system

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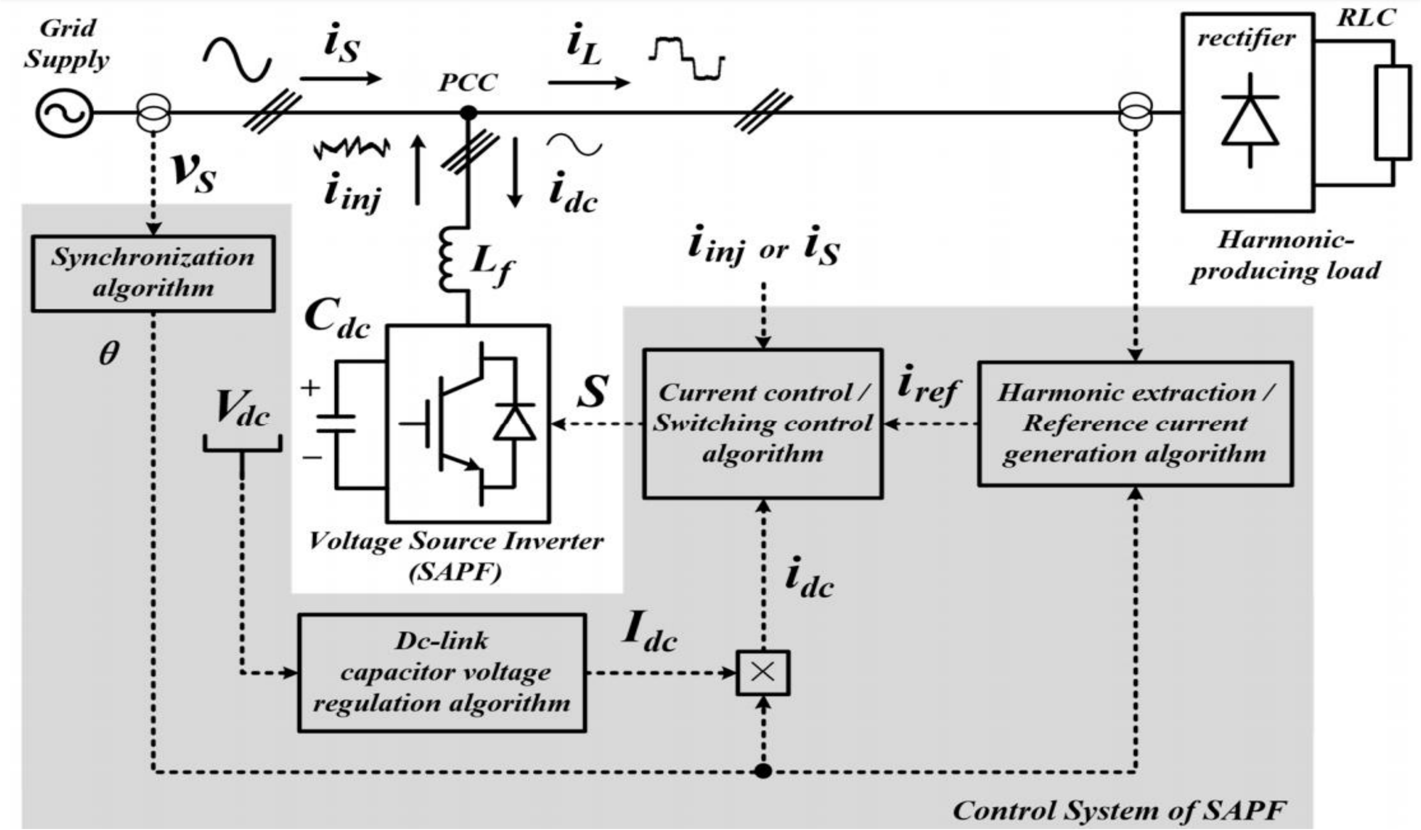

Figure 2: VSI-based shunt active power filter (SAPF) and the associated control algorithms in its control system [2].

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2. Series Active Power Filter (SeAPF)

- Designed to compensate voltage-related power quality issues, including voltage harmonics, sag/swell, and imbalance, by injecting a controlled voltage in series with the supply.
- Connected in series with the supply line between source and load through a series transformer
- Operates at the Point of Common Coupling (PCC)
- It detects the distorted supply voltage and extracts harmonic and disturbance components to inject compensating voltage to restore a pure sinusoidal load voltage

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- **Compensation Condition**
  - The componsating coltage is equivalent with the harmonic distortion level:

$$V_C(t) = -V_h(t)$$

  - Load Voltage:

$$V_L(t) = V_S(t) + V_C(t)$$

  - Result → Load voltage becomes sinusoidal and regulated
  - Main Components of the SeAPF includes: Voltage Source Converter (VSC), Series injection transformer, DC-link capacitor, Voltage sensors, and Digital controller

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The Control Strategy of Series Active Power Filter follows a three step process:

1. Voltage Detection

- Measure source voltage waveform and Identify distortions and disturbances

2. Reference Voltage Generation

- Extract harmonic and disturbance components
- Generate compensating voltage reference

3. PWM Control:

- Use SPWM to generate switching signals

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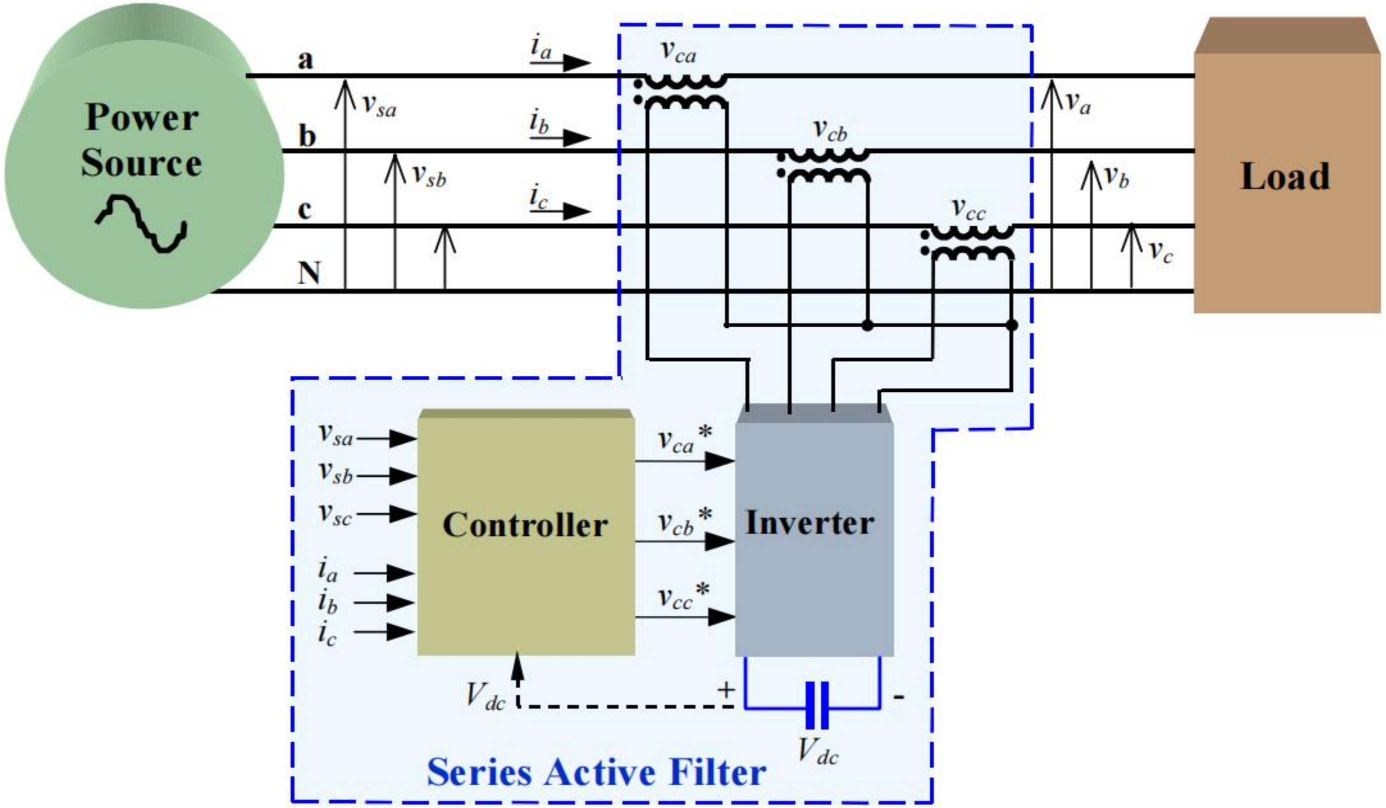

Figure 2: VSI-based Series active power filter [3].

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3. Hybrid Active Power Filter (HAPF)

- It combines passive filters (RLC-based) and active power filters (converter-based) to achieve cost-effective and high-performance harmonic mitigation in power systems.
- Parallel combination of:
  - Passive harmonic filter (PHF) and Active power filter (APF)
- Passive filter → tuned to dominant harmonics (e.g., 5th, 7th)
- Active filter → compensates residual harmonics and dynamic variations

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- Operating Principle:
  - Passive filter absorbs bulk harmonic currents
  - Active filter injects compensating current to eliminate remaining distortion
- Compensation Condition

$$I_C(t) = -(I_h(t) - I_{pf}(t))$$

- $I_h(t)$: Total harmonic current, $I_{pf}(t)$: Harmonics absorbed by passive filter, and $I_C(t)$ is Active filter compensating current
- Passive filter → no control strategy (frequency selective)

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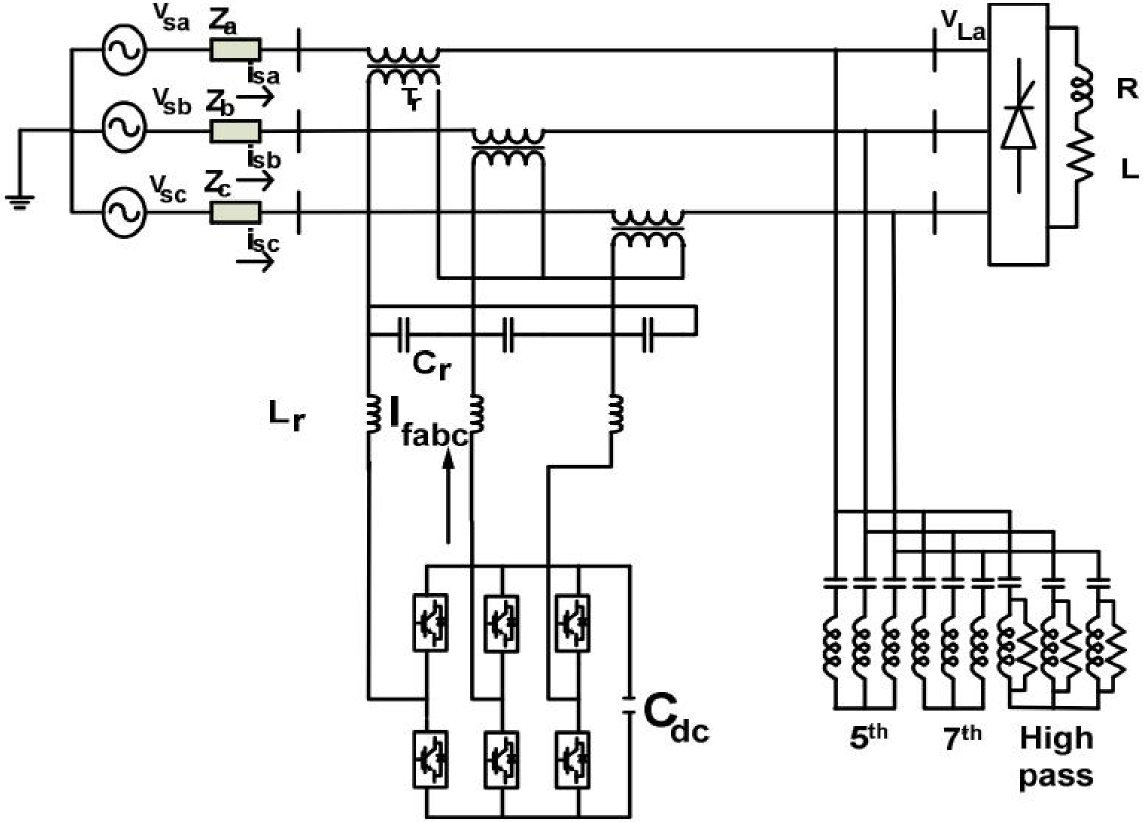

Figure 4: Structure of Hybrid Active Power Filter [3].

C. Control of Active Power Filter

- Control strategies are the **core** of Active Power Filters (APFs), responsible for:
  - Accurate harmonic detection, Reference signal generation, and
  - Real-time compensation.
- The effectiveness of an APF largely depends on the **speed**, **accuracy**, and **robustness** of its control algorithm.
- **The Control Structure:** Measurement of voltages and currents, Harmonic extraction, Reference signal generation, Current/voltage control and PWM signal generation

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1. **Instantaneous Power Theory (p–q Theory)**
   - Based on Clarke Transformation (abc → αβ)
   - Separates instantaneous power into: Real power (p) and Imaginary power (q)
2. **Synchronous Reference Frame Theory (dq Method)**
   - Transforms signals from abc → dq rotating frame
   - The fundamental components are DC while the harmonics are AC ripples.
3. **Hysteresis Current Control**
   - Maintains current within a predefined band (±h)
   - Switching occurs when current exceeds limit

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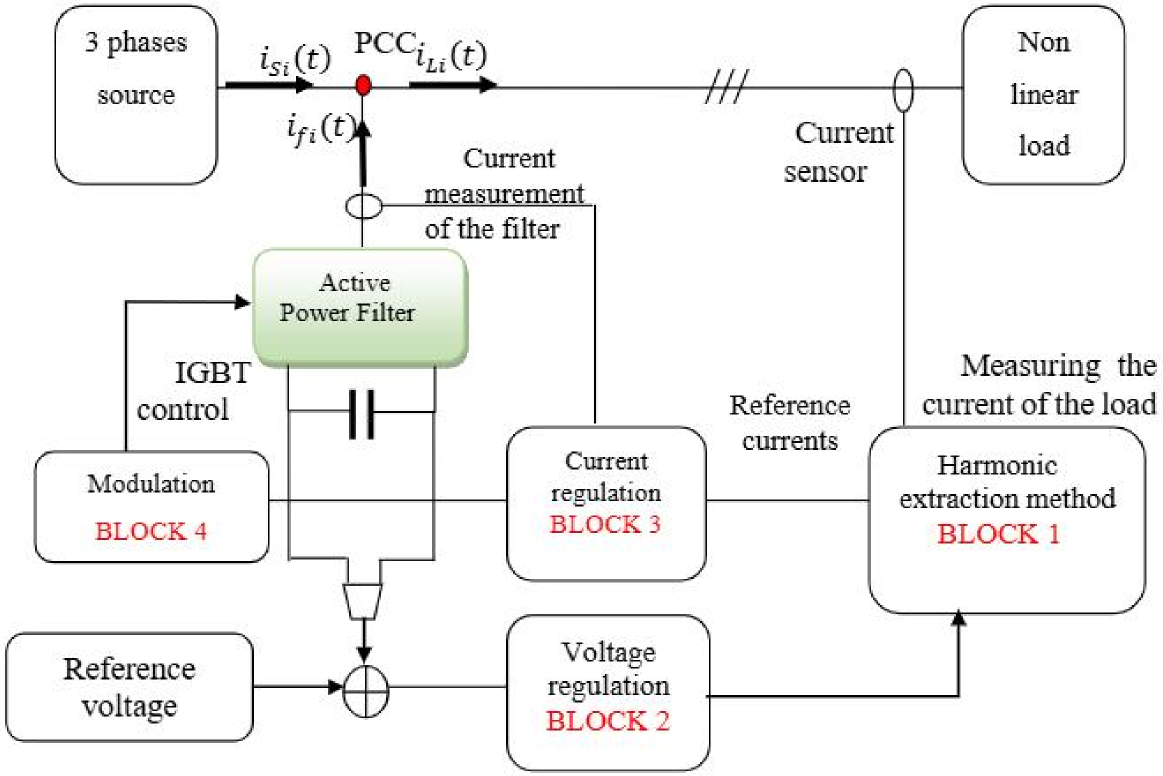

Figure 5: Simplified diagram of the APF control strategy [4].

4. Comparision of Mitigation Techniques

Table 1: Comparative Evaluation of Harmonic Mitigation Techniques

Types	**Feature**								
	Cost	Complexity	Harmonic Compensation	Dynamic Response	Flexibility	Resonance Risk	Q support	Voltage Regulation	Application
Passive Filters	low	low	specific	poor	low	high	yes	no	stable loads
Active Filters	high	high	wide range	excellent	high	none	yes	limited	dynamic loads
Hybrid Filters	medium	medium	wide range	very good	medium	reduced	yes	limited	large systems
Series-Shunt (UPQC)	very high	very high	comprehensive	excellent	very high	none	yes	yes	critical systems

5. Filters in Modern Power Systems

- **Harmonic mitigation** in modern power systems and microgrid requires integrated, adaptive, and optimized solutions due to:
  - The high penetration of renewable energy sources,
  - Power electronic converters, and Nonlinear loads.
- **In modern grid:**
  - **Passive Filters** are installed at industrial buses and capacitor banks
  - **Active Filters** are installed at Point of Common Coupling (PCC) which provides a real-time harmonic compensation

References

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[4] P. U. Panati, S. Ramasamy, M. Ahsan, J. Haider, and E. M. G. Rodrigues, “Indirect effective controlled split source inverter-based parallel active power filter for enhancing power quality,” Electronics, vol. 10, no. 8, p. 892, 2021, doi: 10.3390/electronics10080892.

Thank You!