Power System Quality and Reliability

ECEg-6312

WEEK 6

Power Quality Conditioners

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Topic Overview

- This week's discussion focuses on key power quality conditioning techniques used in modern electrical power systems to enhance system performance and reliability.
  1. Shunt compensators
  2. Series compensators
  3. Passive Compensators
  4. Hybrid Power Quality Conditioners
  5. Unified Power Quality Conditioner

Learning Outcomes

By the end of this lesson, students will be able to:

- Explain the role of power quality conditioners in improving power system performance.
- Differentiate between shunt, series, and passive compensators based on their operation and applications.
- Analyze the functioning of shunt and series compensators in mitigating current and voltage disturbances.
- Evaluate the effectiveness of passive compensators for harmonic filtering and reactive power compensation.

1. Introduction

- **Power quality (PQ) degradation** refers to the deviation of voltage and current waveforms from ideal sinusoidal conditions, leading to reduced system **efficiency**, **reliability**, and equipment **lifespan**.
- **Major Causes of Power Quality Degradation:**
  - **Nonlinear Loads:** Draw non-sinusoidal current even under sinusoidal voltage supply
  - **Power Electronic Devices:** High-frequency switching introduces Harmonics
  - **Renewable Energy Integration:** Inverter-based power generation (PV, wind)

2. Power Quality (PQ) Problems

- Power quality problems in power system, industrial process, commercial and residential customers due to non-linear loads and unbalanced systems includes,
  - Voltage sags/swells,
  - Flickers,
  - Unbalance, and
  - Harmonics degrade power quality,
- Which causes equipment **malfunction** and **overheating**.
- **Solution:** Custom Power Devices based on Voltage Source Inverters (VSI).

3. Power Quality Conditioners

- **Power Quality Conditioners (PQCs)** are advanced devices used to mitigate power quality problems such as:
  - Harmonics and Waveform distortion in modern electrical power systems.
  - Voltage disturbances and Reactive power imbalance
- **PQCs** are power electronic-based or passive devices designed to:
  - Improve voltage and current waveform quality
  - Enhance system stability and reliability
  - Ensure compliance with standards such as IEEE 519

Why PQ Conditioning?

- **Power quality (PQ) conditioning is vital for:**
  - Maintaining voltage stability (mitigation of sag, swell, and interruptions)
  - Harmonic suppression to ensure sinusoidal waveforms and reduce distortion (THD)
  - Reactive power compensation and power factor correction
  - Protection of sensitive and critical loads (e.g., data centers, medical equipment)
  - Improving system reliability and continuity of supply
  - Enhancing efficiency of power systems by reducing losses
  - Facilitating integration of renewable energy sources (solar PV, wind) into the grid

4. Types of PQ Conditioners

- **Shunt Compensators:** Controls current-related PQ issues.
  - **Distributed Static Componsator (DSTATCOM)**
  - Sttatic VAR Componsator (SVC)
- **Series Compensators:** Controls voltage-related PQ issues.
  - Dynamic Voltage Restoror (DVR),
  - Static Series Synchronous Componsator (SSSC)
  - Thyristor Controlled Series Componsator (TCSC)
- **Hybrid Compensators:** Combines both for comprehensive compensation.
  - Unified PQ Conditioner (UPQC),
  - Unified Power Flow Controller (UPFC)

A. Shunt PQ Conditioners

- They are connected in parallel with the power system and are primarily used to improve current quality, compensate harmonics, and regulate reactive power.
- **Configuration:**
  - Installed at the Point of Common Coupling and connected in parallel with nonlinear loads
  - Operate as controlled current sources.
- **Main Functions:**
  - Harmonic current compensation, reactive power compensation, power factor correction, and
  - Load balancing (three-phase systems)Hybrid Compensators

Main Types of Shunt PQCs

1. Shunt Active Power Filter (SAPF)

- Eliminates harmonic currents
- Improves power factor

2. DSTATCOM (Distribution STATCOM)

- Provides fast reactive power compensation
- Enhances voltage stability

3. Capacitor Banks

- Provide steady-state reactive power support
- Low-cost solution

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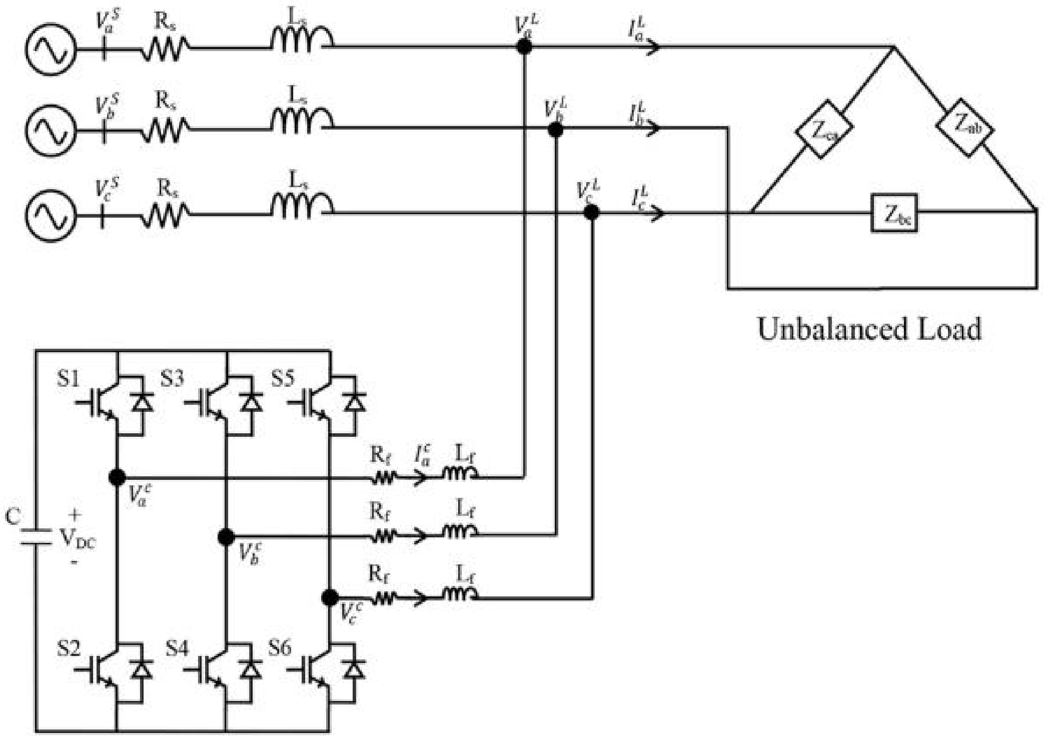
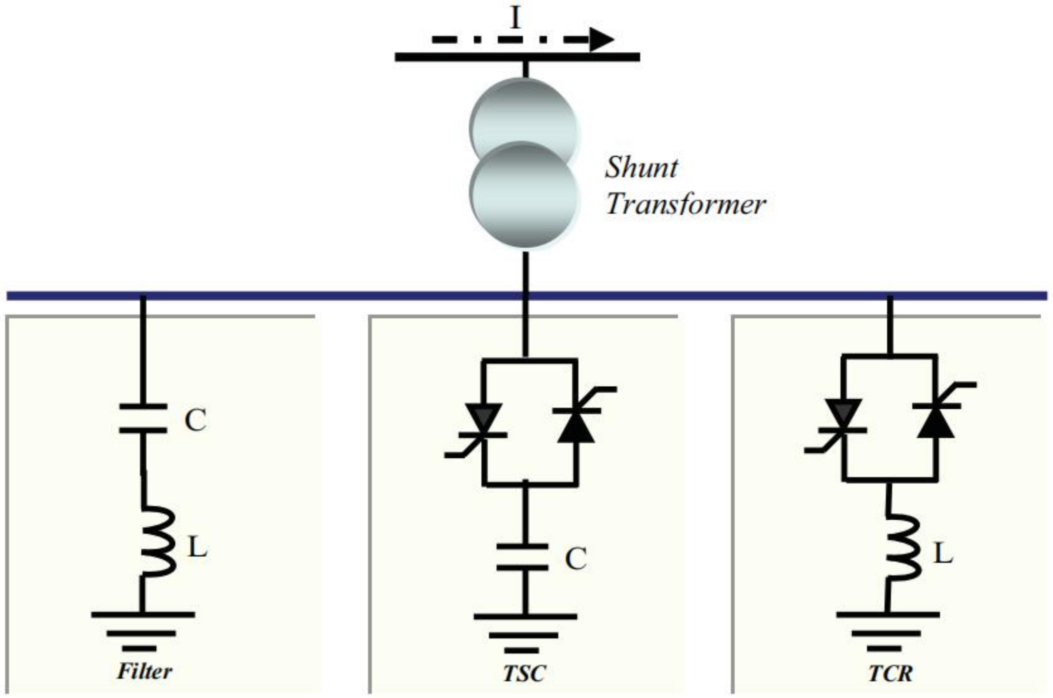


a). DSTATCOM



b). SVC

Figure 1: Shunt Power Quality Conditioner [1],[2].

I. Shunt Active Power Filter (SAPF)

- It is a power electronic-based compensator connected in parallel with the load to eliminate **current harmonics** and **compensate reactive power** in modern power systems.
- **Configuration:**
  - Connected in parallel (shunt) with nonlinear loads
  - Installed at the Point of Common Coupling (PCC)
  - Operates as a controlled current source
- **Primarly Designed for:**
  - Harmonic current and Reactive power compensation

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- Compensation Objective:

$$I_c(t) = -I_h(t) - I_q(t)$$

- Eliminates harmonic + reactive components
- SAPF is mostly impelmented for systems expriences with:
  - High harmonic distortion
  - Nonlinear loads
  - Power electronics

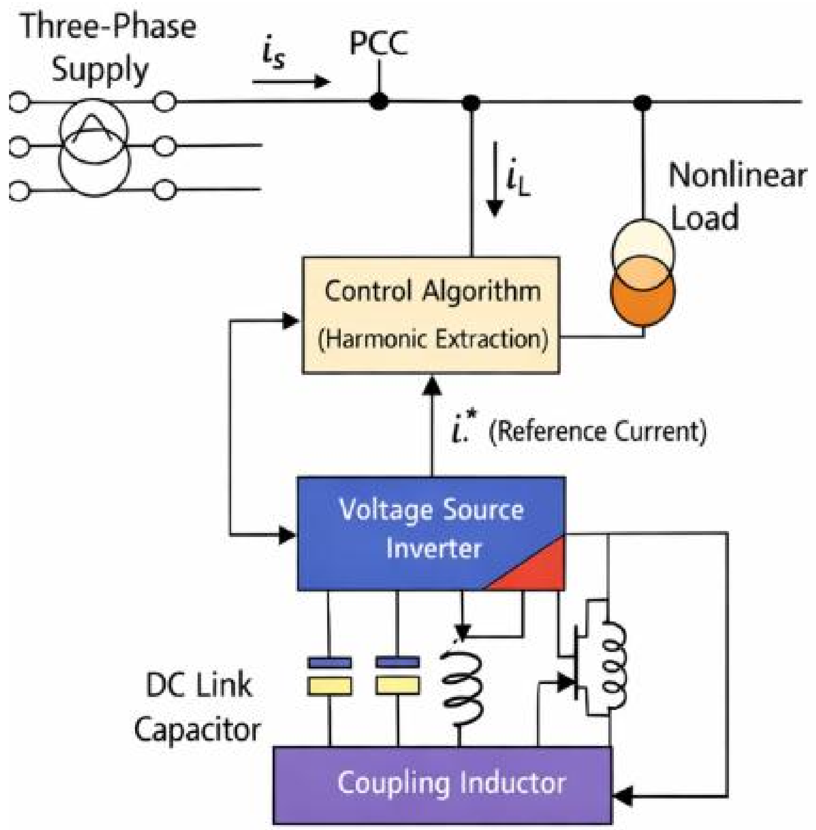

Figure 2: Shunt Active Power Filter [3].

II. Distributed STATCOM (DSTATCOM)

- **The DSTATCOM** is a shunt-connected FACTS device used in distribution systems to provide:
  - — Fast and dynamic reactive power compensation,
  - — Improve voltage stability, and enhance power quality.
- **Operating Principle:**
  - —DSTATCOM generates a controllable AC voltage, **Vc**
  - —Compares with system voltage, **Vs**
  - —Exchanges reactive power based on voltage difference

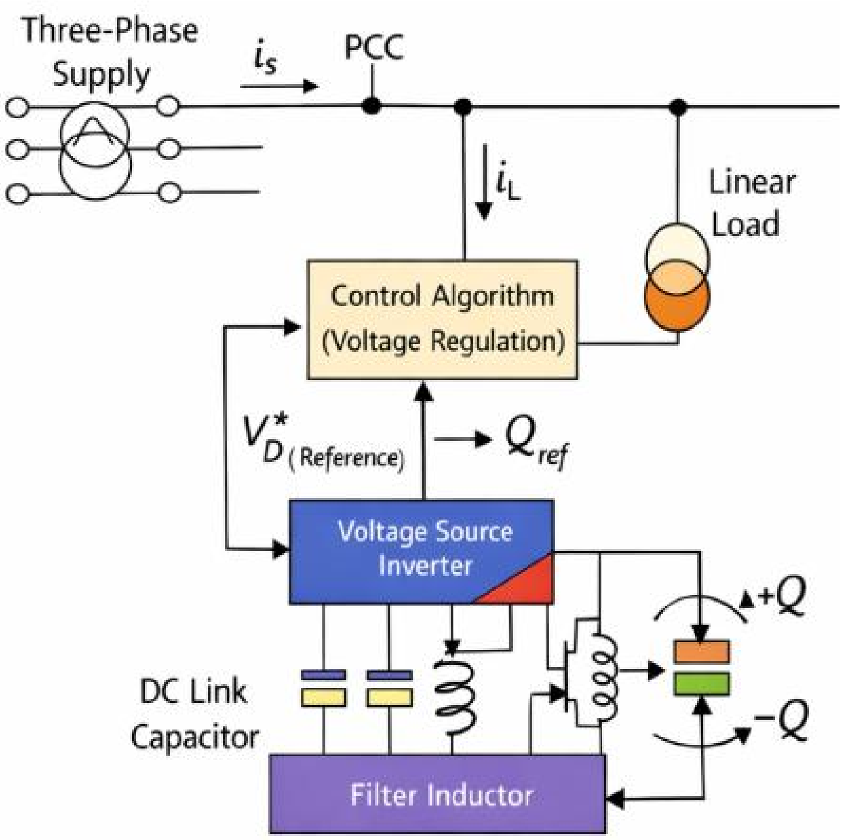

Figure 3: Distributed STATCOM (DSTATCOM) [3].

III. Capacitor Banks

- **Shunt Capacitor Banks** are widely used passive power quality conditioners connected in parallel with the power system to provide:
  - Reactive power compensation,
  - Improve voltage profile, and
  - Enhance overall system efficiency.
- Capacitors inject reactive power locally, reducing burden on the source, $Q_c = V^2/X_c$.

Figure 4: An ABB Shunt Capacitor Bank [3].

B. Series PQ Conditioners

- **Series PQCs** are connected in series with the power system and are primarily used to improve voltage quality by compensating voltage disturbances such as:
  - Voltage sags and swells,
  - Harmonics, and imbalance.
- **Configuration:**
  - Connected in series between source and load
  - Typically interfaced through a series injection transformer
  - Operate as controlled voltage sources

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Main Functions:

- Voltage harmonic compensation
- Voltage sag, swell, and imbalance correction
- Voltage regulation and Flicker reduction

Operating Principle:

- Measure supply voltage
- Detect distortion and disturbances
- Inject compensating voltage in series

Compensation Condition:

$$V_c(t) = -V_h(t)$$

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

where:

- $V_c(t)$ is the compensating voltage,
- $V_L(t)$ is the load voltage,
- $V_S(t)$ is the supply voltage, and
- $V_h(t)$ is the harmonic voltage content.

Main Types of Series PQCs

1. Series Active Power Filter (SeAPF)

- Eliminates voltage harmonics
- Improves voltage waveform quality

2. Dynamic Voltage Restorer (DVR)

- Mitigates voltage sag and swell
- Protects sensitive loads

3. Series Capacitors

- Improve voltage profile
- Enhance power transfer capability

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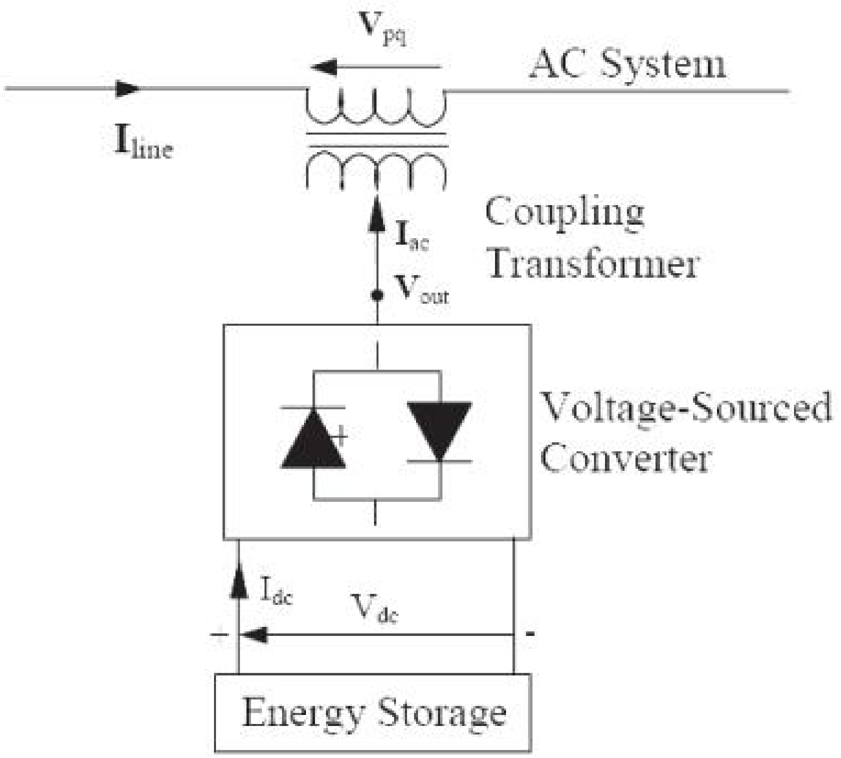
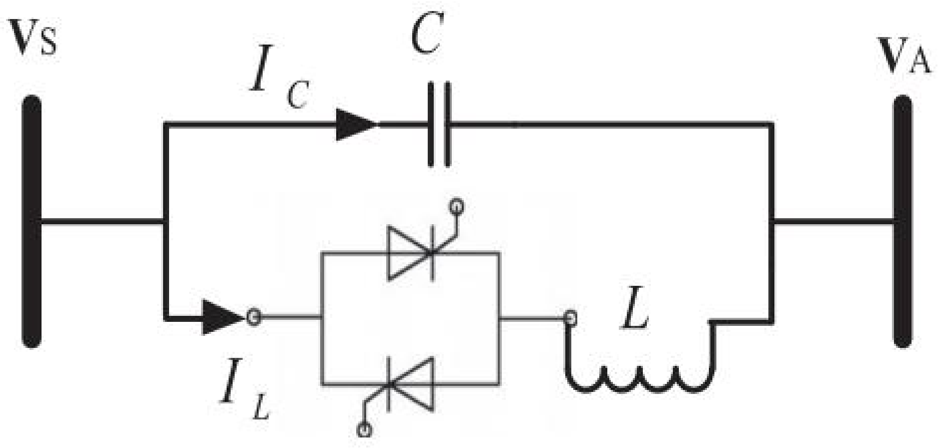


a). DVR



b). TCSC

Figure 5: Series Power Quality Conditioner [2].

I. Series Active Power Filter (SeAPF)

- **SeAPF** is a series-connected power electronic compensator used to improve voltage quality by mitigating **voltage harmonics** and improving waveform quality in power systems.
- **Configuration**
  - Connected in series with the supply line
  - Interfaced through a series injection transformer
  - Installed at the Point of Common Coupling (PCC)
  - Operates as a controlled voltage source

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- **Operating Principle:**
  - Measure distorted supply voltage
  - Extract harmonic and disturbance components
  - Inject compensating voltage in series to restore load voltage
- **Compensation Conditions:**

$$V_c(t) = -V_h(t)$$

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

Control Strategy:

1. Voltage Detection

- Measure source voltage
- Identify harmonics and disturbances

2. Reference Voltage Generation

- Extract unwanted components
- Generate compensating voltage reference

3. PWM Control:

- SPWM or SVPWM for switching

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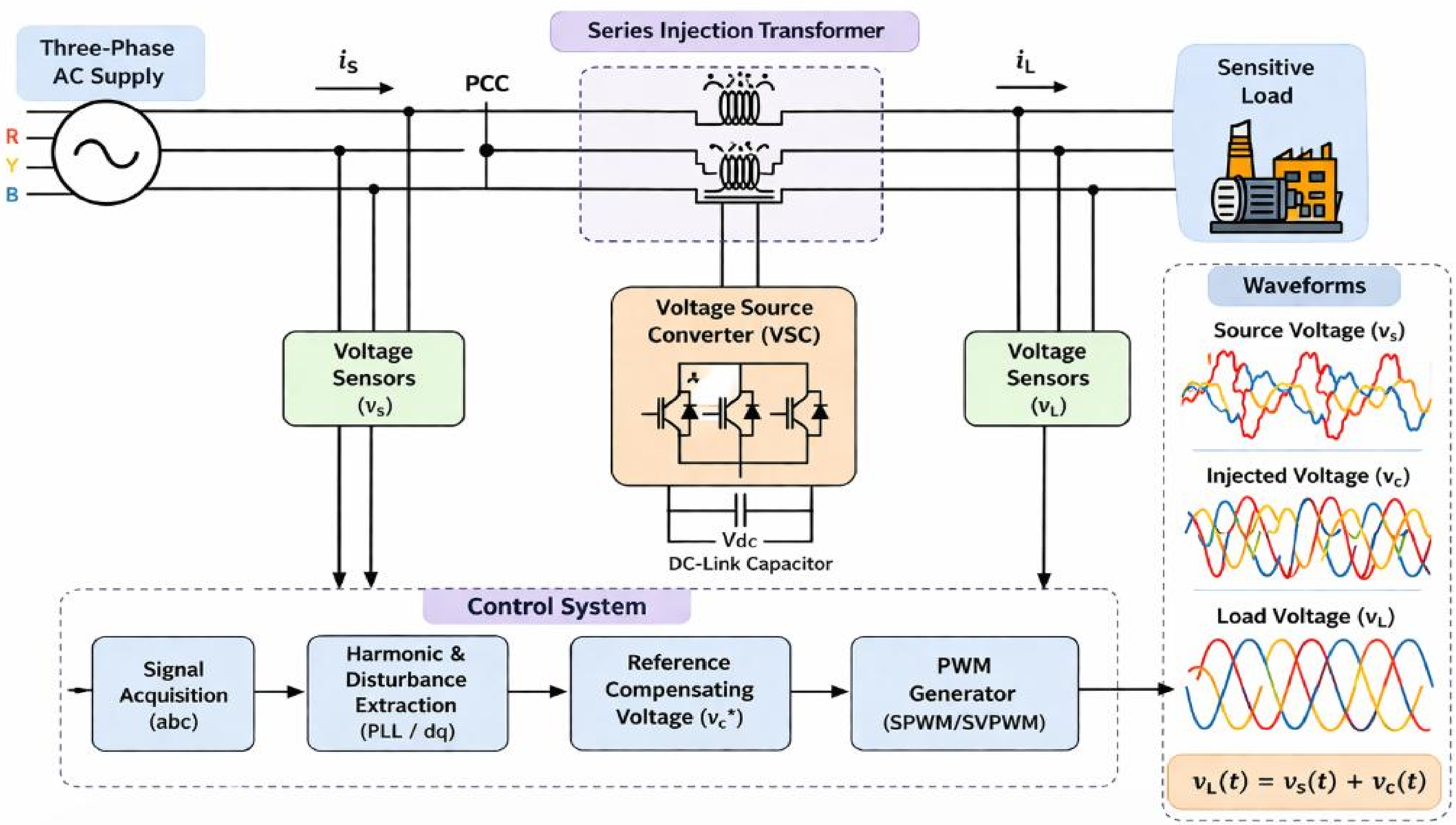

Figure 6: Series Active Power Filter (SeAPF) [4].

II. Dynamic Voltage Restorer (DVR)

- **The DVR** is a series-connected power quality conditioner used to protect sensitive loads from voltage disturbances such as sag and swell by injecting a controlled voltage into the system.
- **Focuses on:**
    - Voltage sag/swell compensation
    - Voltage regulation for sensitive loads
- **Configuration:**
    - Connected in series with the distribution line
    - Installed at the Point of Common Coupling (PCC)
    - Interfaced via a series injection transformer

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- Main Components of the DVR includes:
  - Voltage Source Converter (VSC)
  - DC-link energy storage (capacitor/battery)
  - Series injection transformer
  - Passive filter
  - Control system

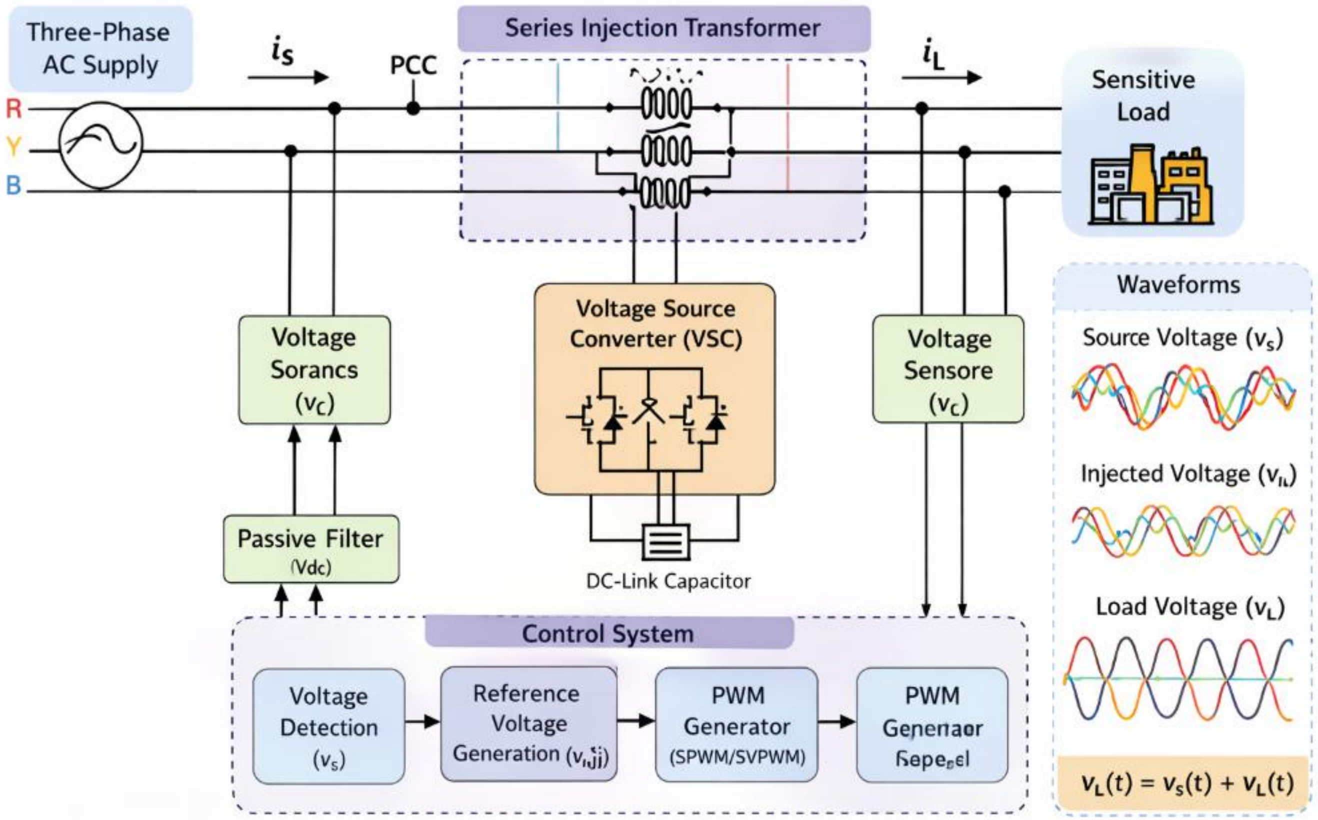

Figure 7: Dynamic Voltage Restorer (DVR) [4].

III. Series Capacitors (SeC)

- Series Capacitors (SeC) are passive power quality conditioners connected in series with transmission or distribution lines to:
  - Improve voltage profile,
  - Enhance power transfer capability, and Reduce line reactance.
- The Series Capacitors (SeC) fundamental operation principle:
  - Capacitors inserted in series with the line
  - Reduce effective line reactance, $X_{eff}=X_L-X_C$
  - Increase power transfer capability, $P=V1V2\sin\delta/X_{eff}$

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- **Configuration:** Connected in series with transmission line and also installed at transmission corridors and substations.
- **Main Functions:**
  - Increase power transfer capability
  - Improve voltage profile
  - Reduce transmission losses
  - Enhance system stability
  - Control power flow

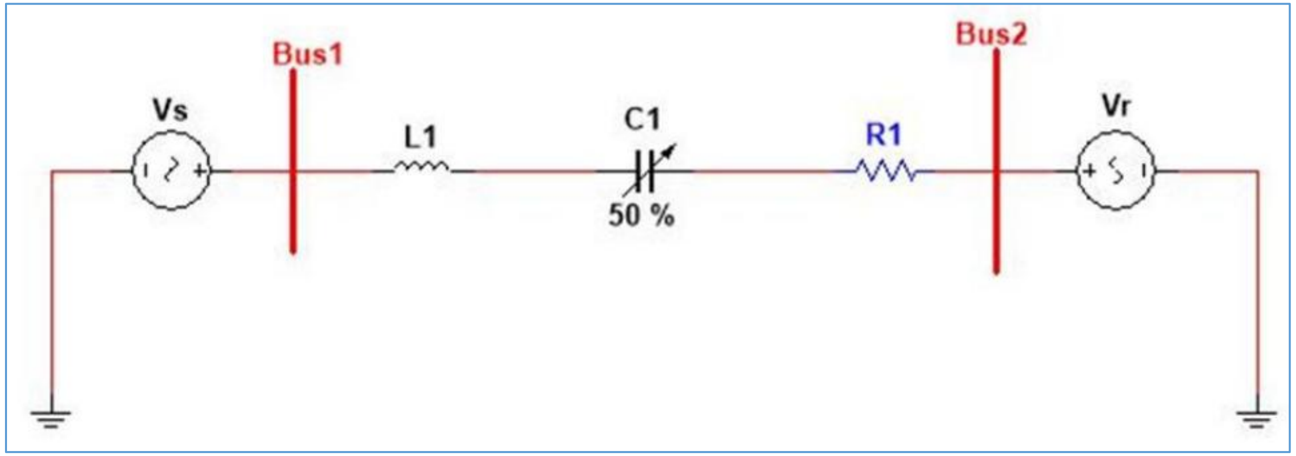

Figure 8: Transmission line with series capacitor compensation [2].

C. Passive PQ Compensators

- Passive compensators are R–L–C based devices used to mitigate harmonics and provide reactive power compensation in a cost-effective and reliable manner.
- Types of Passive Compensators
  - Single-tuned filters
  - High-pass filters
  - Double-tuned filters
  - Shunt capacitor banks
- when it operates, it provides a low impedance path for harmonic currents.

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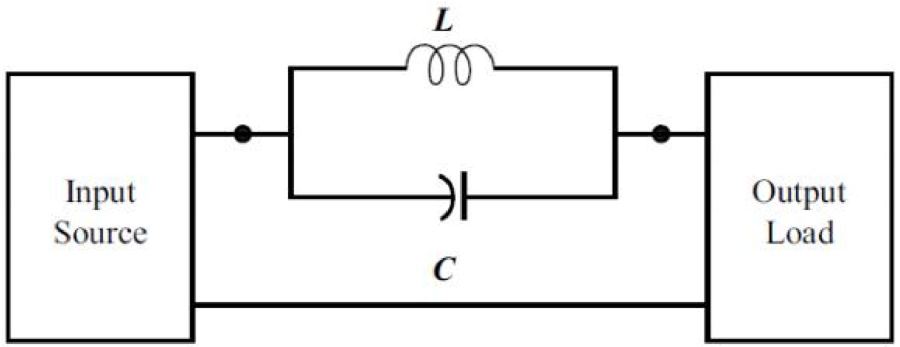
Advantages of passive PQ conditioners:

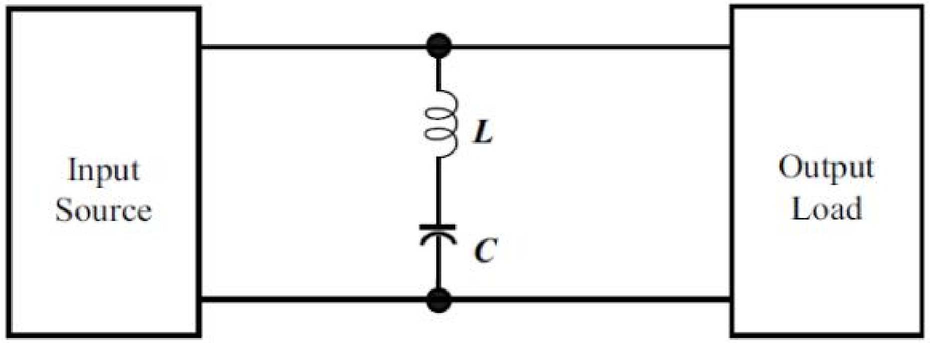
- Simple design and Low cost
- High reliability
- No external control required

Limitations of passive PQ conditioners:

- Fixed compensation
- Risk of resonance
- Limited flexibility
- Performance depends on system impedance



a. Passive Series Filter



b. Passive Shunt Filter

Figure 9: Passive Power Quality Componsators [4].

D. Hybrid PQ Conditioners

- Hybrid Power Quality Conditioners combine passive filters and active power filters to achieve a balance between cost and performance.
- **Operational principles:**
  - Passive filter → handles dominant harmonics
  - Active filter → compensates remaining harmonics
- **Configuration:** Three types of configuration in power system networks
  - Shunt hybrid
  - Series hybrid
  - Combined structures

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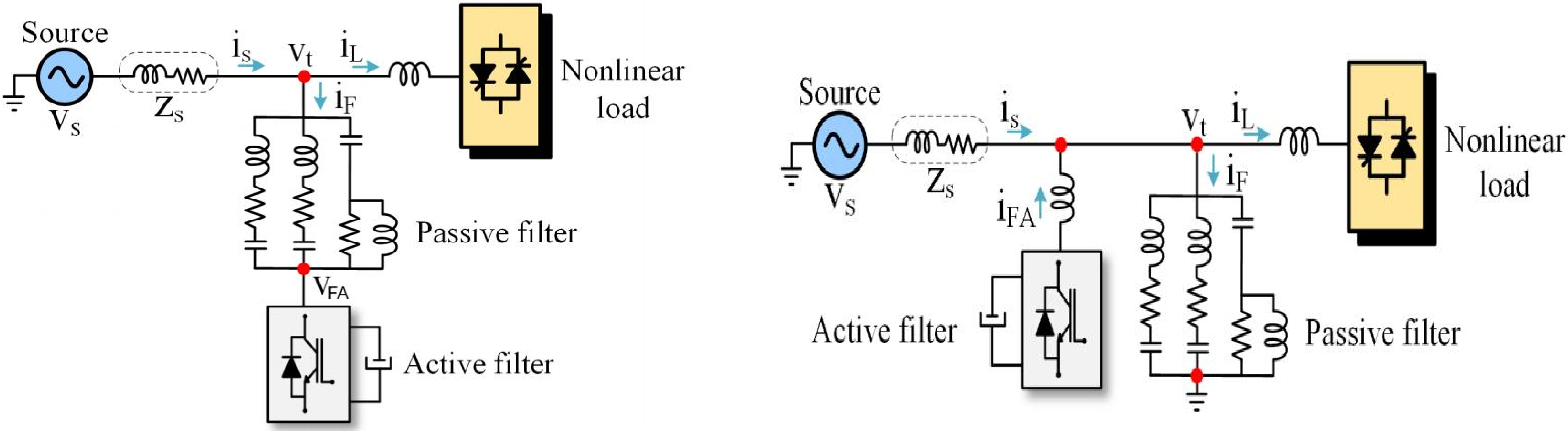

a. Series hybrid filter.

b. Shunt hybrid filter.

Figure 10: Hybrid Power quality conditioner [5]

E. Unified PQ Conditioner (UPQC)

- The Unified Power Quality Conditioner (UPQC) is an advanced device that combines series and shunt active filters to provide comprehensive power quality improvement.
- Configuration:
  - Series Active Power Filter (SeAPF)
  - Shunt Active Power Filter (SAPF)
  - Common DC-link capacitor
- Operating Principle:
  - Series part → compensates voltage disturbances
  - Shunt part → compensates current harmonics

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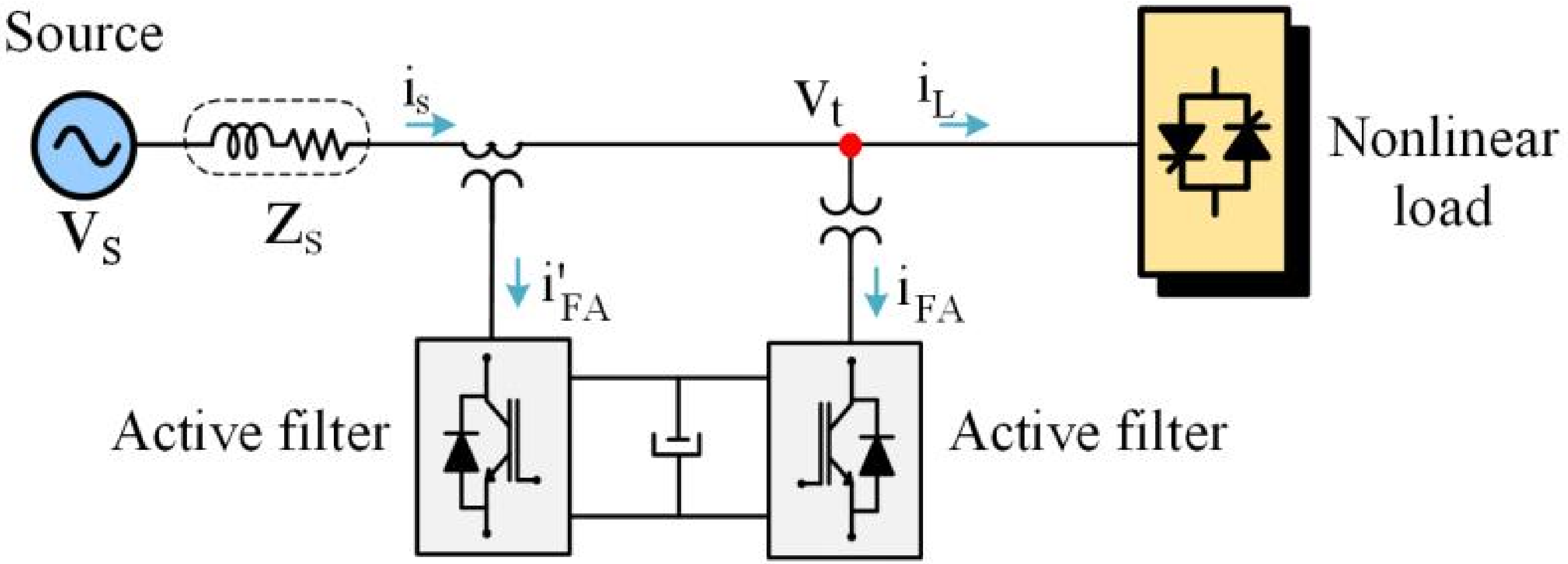

Figure 11: Unified Power Quality Conditioner (UPQC) [5].

References

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Thank You!