Power System Quality and Reliability

ECEg-6312

WEEK 7

Power Quality Conditioners

Course Instructor: Demsew Mitiku (PhD)

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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. Distribution Static Componsator, **DSTATCOM**
  2. Dynamic Voltage Restorer, **DVR**
  3. Unified Power Quality Conditioner, **UPQC**

Learning Outcomes

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

- Explain the operating principles and applications of DSTATCOM, DVR, and UPQC.
- Develop mathematical and equivalent circuit models for steady-state and dynamic analysis.
- Analyze and design appropriate control strategies for these devices to improve power quality under varying system conditions
- Evaluate and compare their effectiveness in mitigating power quality issues and recommend suitable solutions for practical applications

1. Introduction

- **Power Quality Conditioners** are advanced power electronic devices used to improve the quality, reliability, and stability of electrical power in distribution systems [1].
- **Need for Power Quality Conditioning:**
  - Increased use of sensitive electronic equipment
  - Growth of nonlinear loads (e.g., rectifiers, inverters)
- **Common power quality issues:**
  - Voltage sag and swell
  - Harmonics, Flicker, and Reactive power imbalance

2. Importance of Custom Power Devices

- **Custom power devices** are essential for improving **power quality** in modern electrical systems.
- Most power quality problems originate at the **distribution level**, where loads are directly connected
- Increasing use of nonlinear and sensitive loads leads to power quality problems.
- **Custom power devices enhance:**
  - System reliability
  - Power quality
  - Equipment performance and lifespan

3. Custom Power Devices

- **Main Types of Power Quality Conditioners:**
  - **Distribution Static Compensator**
    - Shunt compensation device for reactive power and voltage control
  - **Dynamic Voltage Restorer**
    - Series compensation device for voltage disturbance mitigation
  - **Unified Power Quality Conditioner**
    - Combines shunt and series compensation for comprehensive solutions

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- Different types of custom power devices are employed based on **specific control objectives and** functionalities.
- **Figure 1** illustrates the potential control strategies for regulating the transmitted active power in a transmission line.

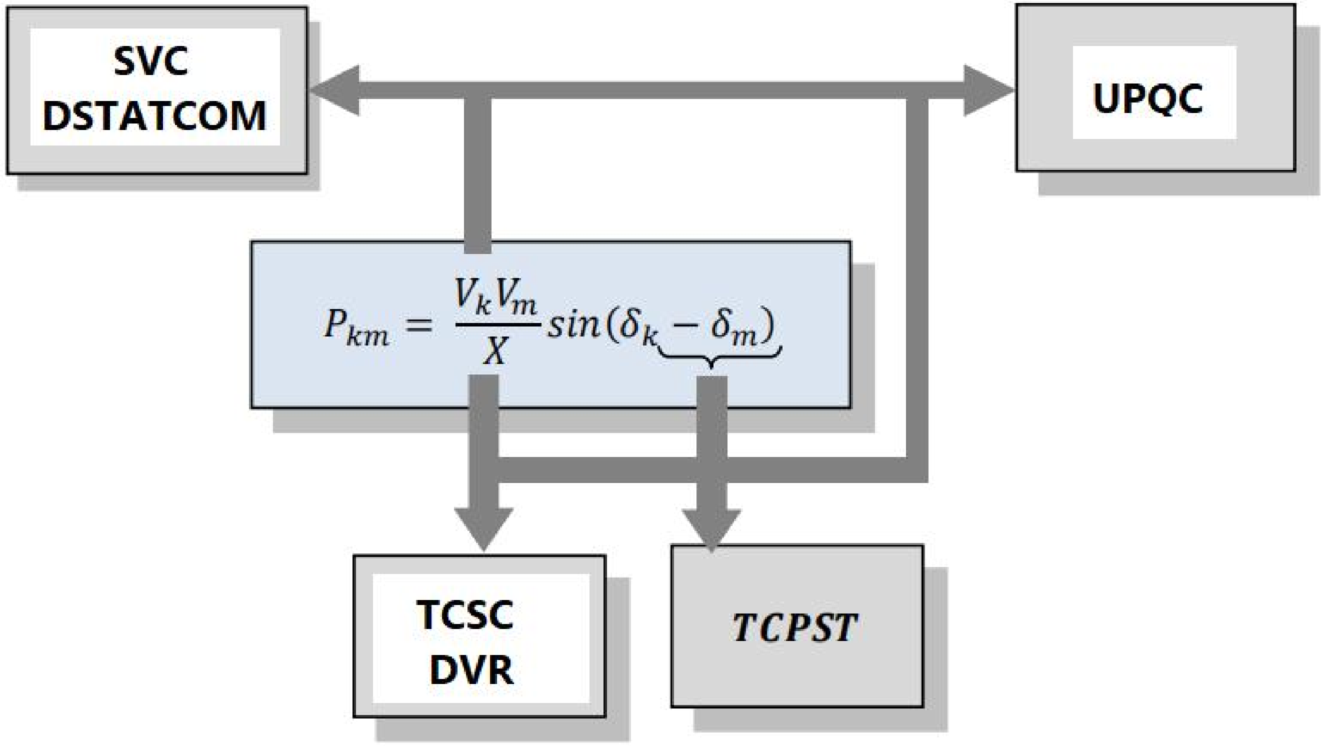

Figure 1: Enhancing power quality: Control strategies for different DFACTS controllers [1].

4. Custom Devices Modeling

- When incorporating the developed models of **DFACTS controllers** into load flow programs, a common approach is to integrate them by modifying the admittance matrix of the interconnected power system network.
- This integration method allows for the simulation and assessment of the impacts of DFACTS controllers throughout the electric network.
- These devices are inserted into the transmission lines and distribution networks, and their specific placement depends on the type of DFACTS being modeled.
- The devices are connected at the PCC or near to the load point.

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- **Figure 2** illustrates the location of the DFACTS device within the power system network.
- The modefied admmittance matrix of the network after incorporating the DFACTS controller is given by:

$$Y_{bus} = \begin{bmatrix} Y'_{ii} & Y'_{ik} \\ Y'_{ki} & Y'_{kk} \end{bmatrix} = \begin{bmatrix} Y_{ii} & Y_{ik} \\ Y_{ki} & Y_{kk} \end{bmatrix} + \begin{bmatrix} y^F_{ii} & y^F_{ik} \\ y^F_{ki} & y^F_{kk} \end{bmatrix}$$

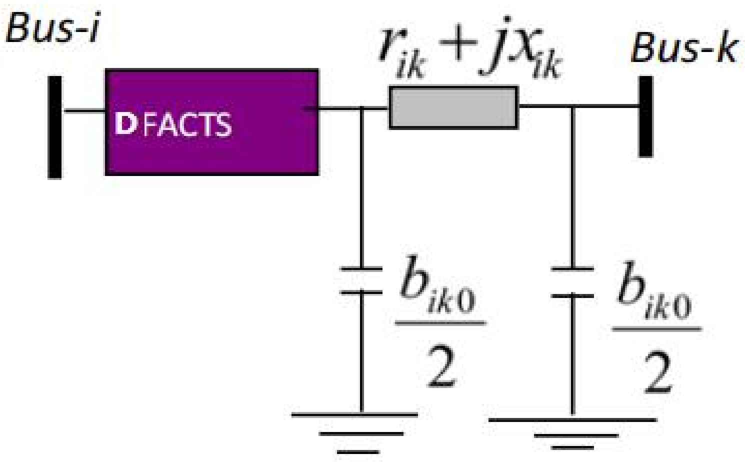

Figure 2: Incorporation of the DFACTS device into a distribution network [1].

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- These **custom power devices** offer various functionalities including:
  - Reactive power compensation and power factor correction,
  - Voltage regulation,
  - Power flow management, and oscillation damping.
- For each particular **custom power devices** and its location within the network, certain coefficients of the nodal matrix Y will be modified.
- These modifications reflect the altered admittance values resulting from the insertion of DFACTS devices at specific points along the network presented in **Figure 3**.

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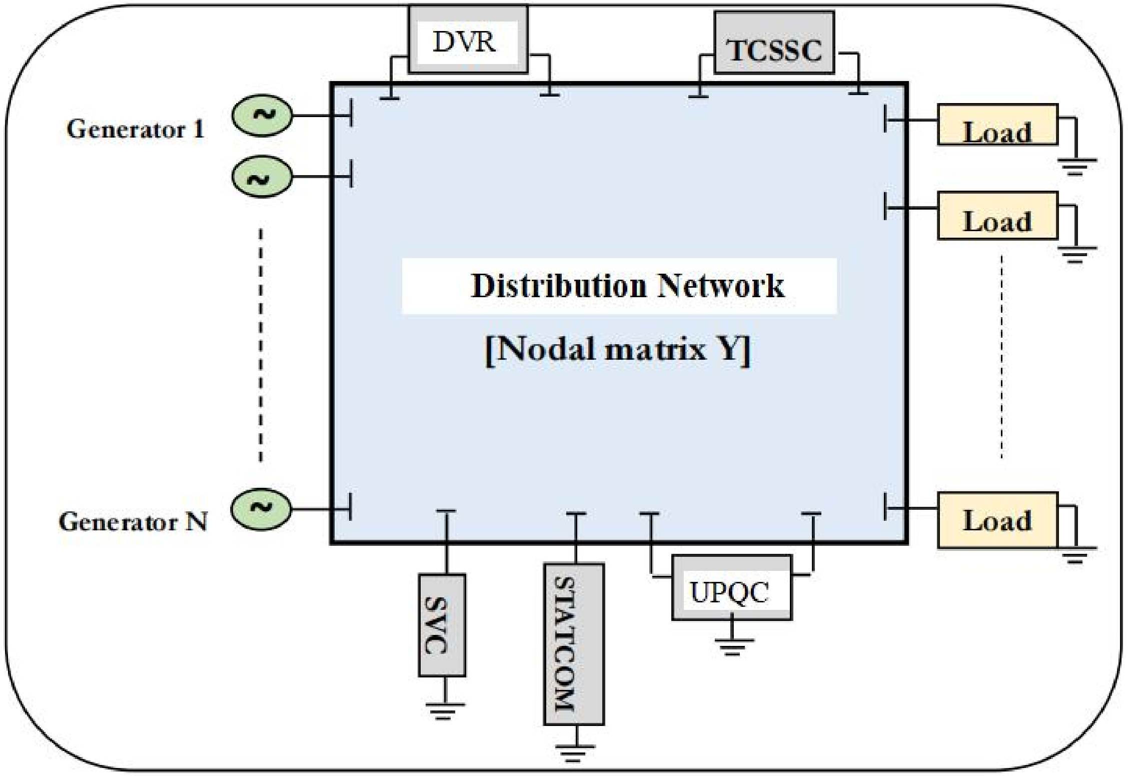

Figure 3: A graphical representation of electric network including DFACTS controllers [1].

A. DSTATCOM MODEL

- **Figure 4** presents the model of a DSTATCOM connected to bus k of an electrical network of N buses [1].
- The DSTATCOM is modeled by a controllable voltage source **Ep** in series with an impedance **Zp**.
- Where Zp = Rp + jXp represents the leakage reactance and ohmic losses of the transformer.

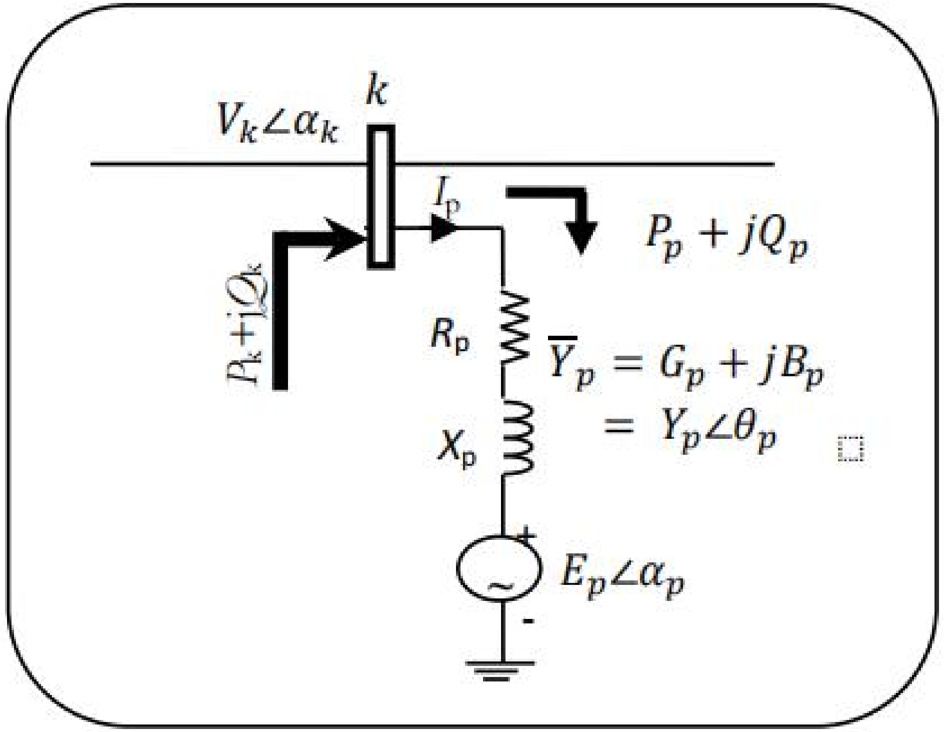

Figure 4: Steady state STATCOM model.

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- The **DSTATCOM** absorbs or provides **reactive power** from the electrical network to maintain the voltage **Vk** constant.
- It therefore works as a voltage regulator.
- In **Figure 4**, the ohmic losses $\mathbf{P_p}$ and the reactive power $\mathbf{Q_p}$ due to the the admittance Yp , is incorporated into the power flow calculation.

$$P_k = P_p + \sum_{j=1}^{N} V_k V_j Y_{kj} \cos(\delta_k - \delta_j - \theta_{kj})$$

$$Q_k = Q_p + \sum_{j=1}^{N} V_k V_j Y_{kj} \sin(\delta_k - \delta_j - \theta_{kj})$$

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- The real and reactive powers injected at bus $\boldsymbol{k}$ for the system without DSTATCOM are represented by the second terms (summation part) in the previous equation.
- Moreover, $\mathbf{P}_p$ and $\mathbf{Q}_p$ represent the variations of the injected powers due to the use of DSTATCOM, and we can therefore write:

$$P_p = Real(V_k I_p^*)$$

$$Q_p = Im(V_k I_p^*)$$

$$P_p = G_p V_k^2 - V_k E_p Y_p \cos(\delta_k - \delta_p - \theta_p)$$

$$Q_p = -B_p V_k^2 - V_k E_p Y_p \sin(\delta_k - \delta_p - \theta_p)$$

Cont'd

- There is <u>**no**</u> active power (**P_{Ep} = 0**) consumed and generated by the DSTATCOM.
- Therefore: $P_{Ep} = Real(E_p I_p^*)$

$$P_{Ep} = -G_p E_p^2 + V_k E_p Y_p \cos(\delta_p - \delta_k - \theta_p) = 0$$

- This dynamic model of the DSTATCOM using the power flow equation controls:
  - The network voltage level
  - the power transfered through an interconnected network,
  - Other power quality challenges like voltage unbalance and flicker phenomenia in the network.
  - Oscilation issue in the network.

B. DVR Dynamic Model

- The purpose of using a **DVR** is to regulate the line voltage for maximum power transfer.
- The **DVR** custom device is modeled by a voltage source **E**s of amplitude and phase angle **δ**s adjustable in series with an impedance $\mathbf{z}_s = \mathbf{r}_s + j\mathbf{x}_s$.

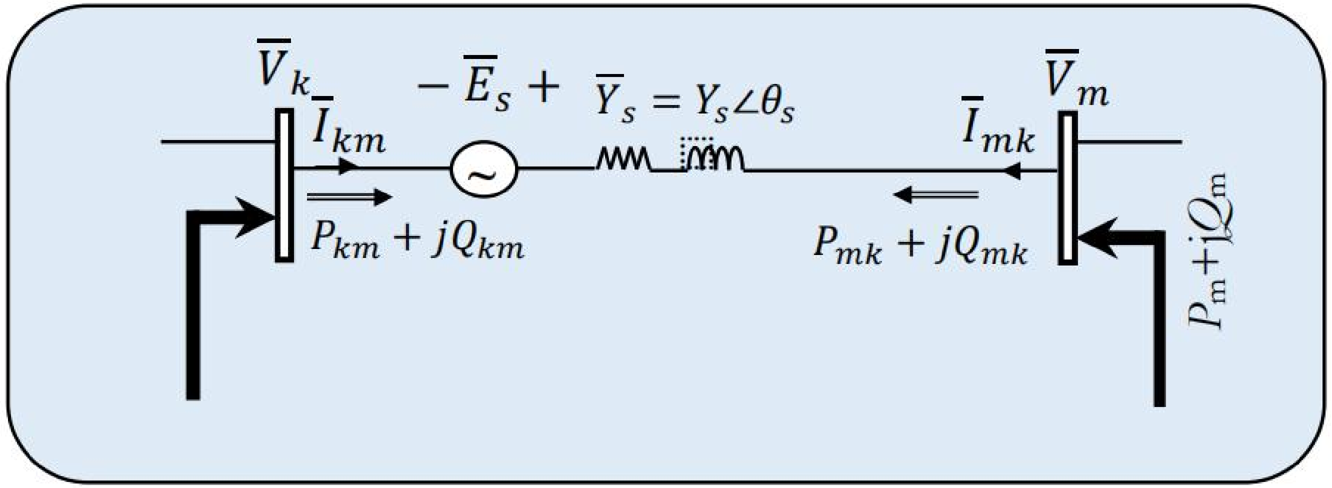

Figure 5: Steady state DVR model.

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- Two new equations to solve the power flow problem.
    - One is obtained by assuming that the power **P**$_{ES}$ consumed by the voltage source is zero.
    - The other is the equality between the transmited power P_{km} and its set point value at a steady state.
- The powers injected at buses $\boldsymbol{k}$ and **m** are expressed as follows:

$$P_k = P_{km} + \sum_{j=1}^{N} V_k V_j Y_{kj} \cos(\delta_k - \delta_j - \theta_{kj})$$

$$Q_k = Q_{km} + \sum_{j=1}^{N} V_k V_j Y_{kj} \sin(\delta_k - \delta_j - \theta_{kj})$$

$$P_m = P_{mk} + \sum_{j=1}^{N} V_m V_j Y_{mj} \cos(\delta_m - \delta_j - \theta_{mj})$$

$$Q_m = Q_{mk} + \sum_{j=1}^{N} V_m V_j Y_{mj} \sin(\delta_m - \delta_j - \theta_{mj})$$

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- The previous four equestions represent the same equations of the system before the use of the DVR and without considering the line (k).
- The transmited powers P_{km}, Q_{km}, P_{mk}, and Q_{mk} are calculated as follows:

$$P_{km} = Real(V_k I_{km}^*)$$

$$Q_{km} = Im(V_k I_{km}^*)$$

$$P_{km} = G_s V_k^2 + V_k E_s Y_s \cos(\delta_k - \delta_s - \theta_s) - V_k V_m Y_s \cos(\delta_k - \delta_m - \theta_s)$$

$$Q_{km} = -B_s V_k^2 + V_k E_s Y_s \sin(\delta_k - \delta_s - \theta_s) - V_k V_m Y_s \sin(\delta_k - \delta_m - \theta_s)$$

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- The transmited powers Pmk, and Qmk from bus *m* to *k* after the incorporation of the DVR are calculated as follows:

$$P_{mk} = Real(V_k I_{mk}^*)$$

$$Q_{mk} = Im(V_k I_{mk}^*)$$

$$P_{mk} = G_s V_m^2 - V_m E_s Y_s \cos(\delta_m - \delta_s - \theta_s) - V_k V_m Y_s \cos(\delta_m - \delta_k - \theta_s)$$

$$Q_{mk} = -B_s V_m^2 - V_m E_s Y_s \sin(\delta_m - \delta_s - \theta_s) - V_k V_m Y_s \sin(\delta_m - \delta_k - \theta_s)$$

- The second term $V_m E_s Y_s \cos(\delta_m - \delta_s - \theta_s)$ *is the active power loss due to converter switching and coupling transformer.*

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- The power consumed by the voltage source ***E***$_s$ is expressed by the following equation:

$$P_{es} = Real(E_s I_{km}^*) = 0$$

$$P_{es} = G_s E_s^2 + V_k E_s Y_s \cos(\delta_s - \delta_k - \theta_s) - E_s V_m Y_s \cos(\delta_s - \delta_m - \theta_s)$$

- This power is consumed by the converter itself due to converter switching operation.
- Voltage regulation relationship:

$$V_m = V_k - Z_{km} I_{km} + E_s$$

$$E_s = V_m^{ref} - (V_k - Z_{km} I_{km})$$

- where, V_m^{ref} is the recieving end reference voltage, and E_s is the voltage injected.

C. UPQC Model

- The UPQC offers control over the real and reactive power flows on the line where it is installed, as well as the voltage magnitude at the connection point.
- In the context of power flow analysis, this translates to controlling the transmitted powers Pk and Qk and adjusting the voltage Vk at a specific bus or node [1], [2].
- Integrating the UPQC into the power flow problem introduces four additional variables:
  - The shunt voltage sources Ep and its phase angle δ_p
  - The series voltage source Es and δ_s from the two VSCs.

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- **Figure 6** illustrates the UPQC model inserted on the power distribution network (k) of an electric network with N nodes.
- The figure showcases the specific arrangement and connections of the UPQC components within the power system.

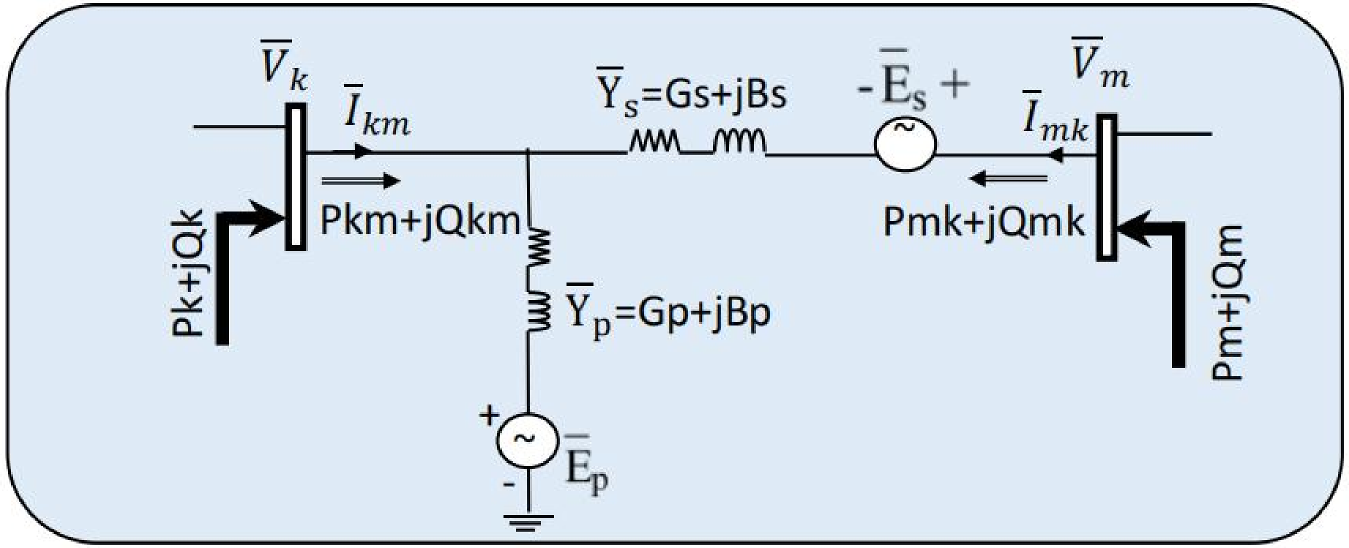

Figure 6: UPQC modeling circuit.

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- By incorporating the UPQC model into the power flow analysis, engineers can study its impact on:
    - Power distribution network,
    - Control power flows, and
    - Regulate voltages within the network.
- The UPQC enables enhanced controllability and flexibility in managing power system quality, operation, and stability.
- Therefore, the UPQC comprises two VSCs connected in series and parallel, allowing control over power flows and voltage regulation.

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- The power flow equations for an electrical network incorporating a UPQC inserted between bus *k* and *m*:

$$P_k = P_{km} + \sum_{j=1}^{N} V_k V_j Y_{kj} \cos(\delta_k - \delta_j - \theta_{kj})$$

$$Q_k = Q_{km} + \sum_{j=1}^{N} V_k V_j Y_{kj} \sin(\delta_k - \delta_j - \theta_{kj})$$

$$P_m = P_{mk} + \sum_{j=1}^{N} V_m V_j Y_{mj} \cos(\delta_m - \delta_j - \theta_{mj})$$

$$Q_m = Q_{mk} + \sum_{j=1}^{N} V_m V_j Y_{mj} \sin(\delta_m - \delta_j - \theta_{mj})$$

- In the above equation, summation terms that represent the same equations as those for a system without a UPQC device, disregarding the line (*km*).

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- To incorporate the effects of the UPQC and account for the transmitted powers, the equations for the transmitted powers P_{km}, and Q_{km}, can be expressed as follows:

$$P_{km} = (G_s + G_p)V_k^2 - V_kE_pY_p\cos(\delta_k - \delta_p - \theta_p) + V_kE_sY_s\cos(\delta_k - \delta_s - \theta_s)$$

$$- V_kV_mY_s\cos(\delta_k - \delta_m - \theta_s)$$

$$Q_{km} =- (B_s + B_p)V_k^2 - V_kE_pY_p\sin(\delta_k - \delta_p - \theta_p) + V_kE_sY_s\sin(\delta_k - \delta_s - \theta_s)$$

$$- V_kV_mY_s\sin(\delta_k - \delta_m - \theta_s)$$

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- The power flow from bus m to k from the series VSC component of the UPQC is formulated as:

$$P_{mk} = G_s V_m^2 - V_m E_s Y_s \cos(\delta_m - \delta_s - \theta_s) - V_k V_m Y_s \cos(\delta_m - \delta_k - \theta_s)$$

$$Q_{mk} = -B_s V_m^2 - V_m E_s Y_s \sin(\delta_m - \delta_s - \theta_s) - V_k V_m Y_s \sin(\delta_m - \delta_k - \theta_s)$$

- The power provided by the shunt component of the UPQC via the DC link is utilized by the series part and it can be expressed as follows:

$$P_{EPS} = Real(E_p I_p^*) - Real(E_s I_s^*) = 0$$

$$= - G_s E_s^2 - G_p E_p^2 + V_k E_p Y_p \cos(\delta_p - \delta_k - \theta_p) - V_k E_s Y_s \cos(\delta_s - \delta_k - \theta_s) + V_m E_s Y_s \cos(\delta_s - \delta_m - \theta_s)$$

- The power supplied by the shunt VSC is consumed by the series VSC and vic versa.

5. Custom Power Device Control

- Custom Power Devices (CPDs) are power electronic controllers used in distribution systems to provide "premium power" tailored to customer needs [2].
- Their control systems are designed to detect **power quality issues** and trigger **fast switching** or **current/voltage** injection to maintain stability.
- CPDs are generally categorized into two main groups based on their function and connection to the network:
  - **Compensating Type (Network Compensating):** DSTATCOM, DVR, and UPQC
  - **Network Reconfiguring Type:** SSCL (Solid state current limmitter), SSB, and SSTS (Solid State Transfer Switch)

A. Control of DSTATCOM

- The control of a DSTATCOM primarily involves managing the exchange of reactive power between the device and the distribution network to maintain:
  - Voltage stability and
  - Improve power quality.
- This is achieved by regulating the switching of a Voltage Source Converter (VSI) to generate a compensating current that cancels out harmonics and corrects the power factor.
- DSTATCOMs generally operate in two main modes depending on the system's needs:
  - Voltage Control Mode (VCM)
  - Current Control Mode (CCM)

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- **Voltage Control Mode (VCM):** The device acts to **regulate** the **terminal voltage** at the Point of Common Coupling (PCC) to a specified reference value.
- **Current Control Mode (CCM):** The device **injects currents** specifically designed to cancel load-induced **harmonics** and **unbalances**, ensuring the source current remains sinusoidal and balanced.
- Various mathematical and intelligent algorithms are used to extract reference currents, voltages, and generate switching pulses.

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- The following control approaches are commonly impelmented for the control of DSTATCOM

1. **Classical Techniques:**
    - **Synchronous Reference Frame (SRF) Theory:** Uses transformation to convert time-varying signals into DC quantities for easier control.
    - **Instantaneous Reactive Power (IRP) Theory:** Calculates required compensation based on instantaneous active and reactive power components.
2. **Adaptive & Intelligent Techniques:**
    - **Artificial Intelligence:** Neural Networks (ANN), Fuzzy Logic, and Deep Learning are used to improve performance under highly nonlinear or transient load conditions.

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1. Instantaneous Reactive Power (IRP) Theory:

- The theory is based on the transformation of three phase quantities to two phase quantitiesin $\boldsymbol{\alpha}-\boldsymbol{\beta}$ frame and calculation of instantaneous active and reactive power in this frame.
- The basic block diagram of the theory is shown in **Figure 7** and the mathematical derivation is explained as follows.
- If the system voltages are given as:

$$V_a = V_m \sin \omega t,\ V_b = V_m \sin(\omega t - 120^0),\ V_c = V_m \sin(\omega t + 120^0)$$

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- The respective load currents are given as:

$$I_L = \sum I_n \sin\left(n\omega t - \theta_n\right)$$

- These phasors can easily transformed into $\alpha - \beta$ coordinates as follows:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

- Where the $\alpha - \beta$ axes are the orthogonal coordinates.
- The conventional instantaneous power on the three phase circuit can be defined as:

$$p = V_\alpha I_\alpha + V_\beta I_\beta \qquad q = V_\alpha I_\beta - V_\beta I_\alpha$$

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- Therefore in the matrix form the instantaneous real and reactive powers are given as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix}$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix}$$

- The instantaneous active and reactive powers p and q can be decomposed into an average and an oscillatory component (p = $\bar{p} + \tilde{p}$ and q = $\bar{q} + \tilde{q}$).
- The compensating currents are calculated to compensate the instantaneous q and the oscillatory component of the instantaneous active power p.

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- In this case the source transmits only the non-oscillating component of active power.
- Therefore the reference source currents $I_{s\alpha}^{*}$and $I_{s\beta}^{*}$ in $\alpha-\beta$ coordinate are expressed as:

$$\begin{bmatrix} I_{s\alpha}^{*} \\ I_{s\beta}^{*} \end{bmatrix} = \frac{1}{V_{\alpha}^{2}+V_{\beta}^{2}} \begin{bmatrix} V_{\alpha} & -V_{\beta} \\ V_{\beta} & V_{\alpha} \end{bmatrix} \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix}$$

- These currents can be transformed in a-b-c quantities to find the reference currents.

$$\begin{bmatrix} I_{sa}^{*} \\ I_{sb}^{*} \\ I_{sc}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} I_{0}^{*} \\ I_{s\alpha}^{*} \\ I_{s\beta}^{*} \end{bmatrix}$$

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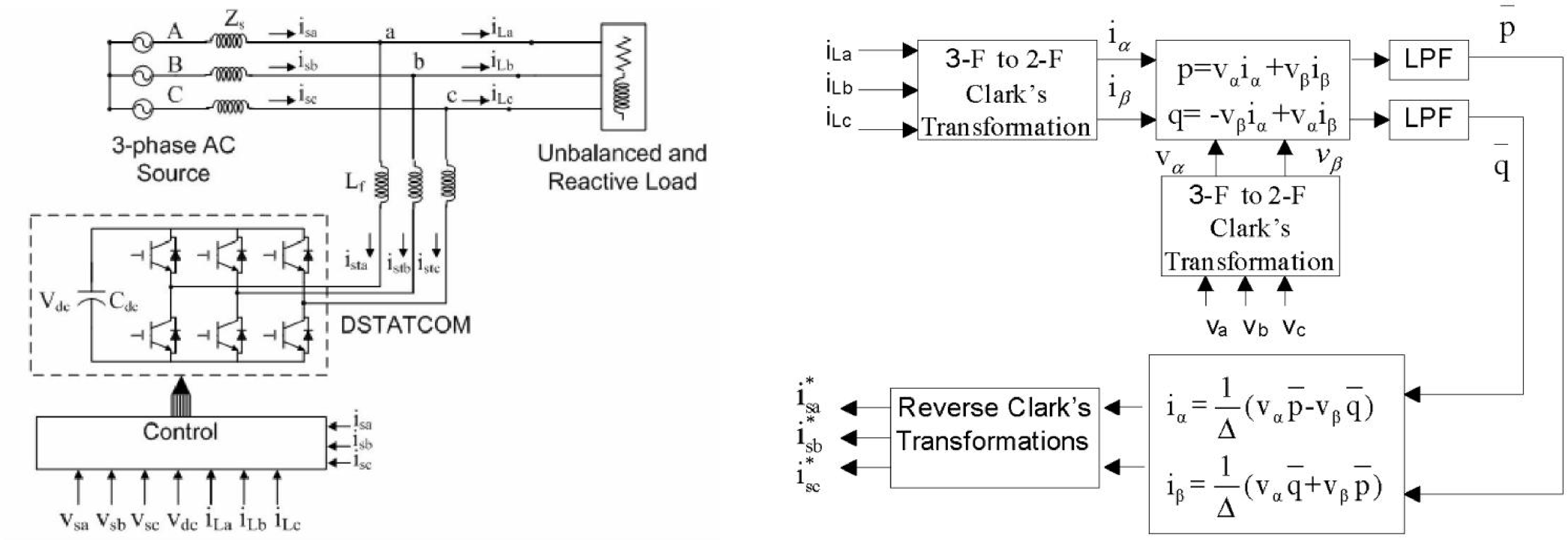

Figure 7: Basic block diagram of the reference current extraction through p-q [2].

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2. Synchronous Reference Frame (SRF) Theory:

- The Synchronous Reference Frame (SRF) control of a DSTATCOM is one of the most robust methods for:
  - Harmonic mitigation,
  - Reactive power compensation, and voltage regulation.
- It converts time-varying **AC signals** into stationary **DC signals** in a **rotating reference frame**, simplifying the extraction of **fundamental** and **harmonic components** for **reactive power compensation,** voltage regulation**,** and **harmonic filtering**.
- Below is a clean, structured technical breakdown aligned with your research-level expectations.

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- The SRF control architecture typically involves sensing 3-∅ **load currents** and the **DC link voltage**.
- These signals are processed through a series of **transformations** and **filters** to generate gating pulses for the Voltage Source Inverter (VSC) control.
- **Key components in the schematic include:**
  - **Park's Transformation:** Converts currents to ***d-q-0*** coordinates.
  - **Phase Locked Loop (PLL):** Synchronizes the rotating frame with the system voltage at the PCC.
  - **Low Pass Filters (LPF):** Extracts the DC components ($i_{d\text{-}dc}$, $i_{q\text{-}dc}$) representing the fundamental active and reactive currents.
  - **PI Controller:** Regulates the DC link voltage and compensates for inverter losses.

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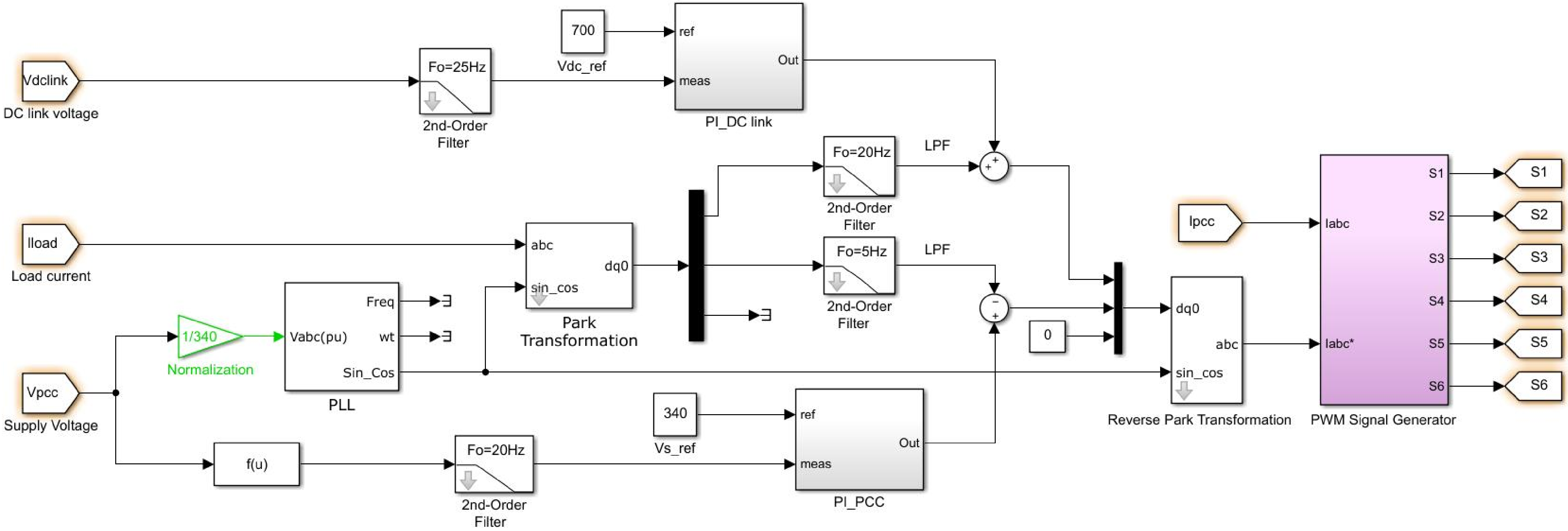

Figure 8: Basic synchronous reference frame DSTATCOM control through d-q.

Mathematical Model

- The mathematical model relies on the transformation of variables from the stationary frame to the synchronously rotating frame.

1. Forward Park's Transformation:

- The load currents (i_{La}, i_{Lb}, i_{Lc}) are converted into the frame using the transformation matrix below, where is the transformation angle generated by the PLL:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix}$$

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2. Extraction of Fundamental Components:

- The d-axis and q-axis currents consist of fundamental (dc) and harmonic (ac) parts:
  - $id=i_{d,DC}+i_{d,AC}$ (Active power component)
  - $iq=i_{q,DC}+i_{q,AC}$(Reactive power component)
- To achieve Unity Power Factor (UPF), the DSTATCOM must supply the entire reactive component ($i_{q,DC}$) and the harmonic components ($i_{d,AC}$, $i_{q,AC}$).

3. DC Bus Voltage Regulation:

- A PI controller calculates the loss current (i_m) required to maintain the DC bus voltage, V_{dc} at its reference, V_{dc_ref}:

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$$i_{loss}(n) = i_{loss}(n-1) + K_p(V_{err}(n) - V_{err}(n-1)) + K_i V_{err}(n)$$

$$V_{err} = V_{dc\_ref} - V_{dc}$$

4. Reference Current Generation:

- The reference direct axis supply current (**i_{d_ref}**) is the sum of the fundamental load active current and the loss current.
- The reference currents are then converted back to the frame via Inverse Park's Transformation for the PWM controller.

References

[1]. Acha E, Claodio R, Esquivel F, et al. (2004) FACTS: modelling and simulation in power networks. John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, England, 2004. https://doi.org/10.1002/0470020164.

[2]. Sahu PR, Lenka RK, Khadanga RK, et al. (2022) Power system stability improvement of FACTS controller and PSS design: A time-delay approach. Sustainability 14: 14649. https://doi.org/10.3390/su142114649.

Thank You!