Power System Quality and Reliability

ECEg-6312

WEEK 2

Voltage Variation Sources, Impacts, and Mitigation Mechanisms

Course Instructor: Demsew Mitiku (PhD)

March 2026

Topic Overview

This weeks discussion covers the following main topics:

- Voltage sags and short interruptions
- Flicker and long-duration voltage variations
- Sources and typical magnitude ranges
- Impact on sensitive loads and power electronic circuits
- Mitigation techniques and protective equipment
- Applicable standards and limits

Learning Outcomes

After this lesson, students should be able to:

- Define and classify voltage sags, swells, interruptions, flicker, and long-duration variations according to international standards.
- Distingush disturbance type from magnitude-duration characteristics.
- Identify the sources and thier impacts of voltage variation disturbances
- Derive voltage sag magnitude due to faults using voltage divider and symmetrical component analysis.
- Recommend a mitigation strategy for voltage variation disturbances.

1. Voltage Variations

Defination:

- Voltage variations are fluctuations in the **root-mean-square (RMS)** voltage value compared to the nominal supply voltage **[1]**.
- Which are caused by **load changes** on the distribution network, **motor startups**, or **network switching** operation.
- According to international standards, specifically **EN 50160**, for low-voltage (230V) networks, 95% of the 10-minute average voltage must remain within **±10%** of the nominal value (207V – 253V) over a one-week period **[2]**.

Cont’d...

The most common voltage variation phenomenea are categorized as [3]:

- Short Duration Voltage Variation
  - Voltage Sag/Dips.
  - Voltage Swell, and Interuuption
- Long Duration Voltage Variation
  - Overvoltage,
  - Undervoltage, and Sustained Interruption
- Flicker/ Voltage Fluctuation

1.1. Short Duration Voltage Variation

Defination:

- Short-duration voltage variations are temporary deviations in RMS voltage magnitude that last from 0.5 cycles to 1 minute, typically caused by faults, motor starting, or sudden load changes [3].
- According to IEEE Std 1159, short-duration voltage variations are categorized as:
  - Voltage Sag/Dips
  - Voltage Swell, and
  - Voltage Interuuption

Cont'd...

1. Voltage Sag/Dips

- According to IEEE Std 1159, a voltage sag is: A reduction in RMS voltage to 0.1–0.9 p.u. at the power frequency for a duration from 0.5 cycles to 1 minute [3].
- Mathematical Representation

A. Basic Expression (Per Unit Form)

  – If nominal RMS voltage is: V_{nom} ,

$$V_{sag} = \frac{V_{rms}}{V_{nom}}$$

  – where, $0.1 \leq V_{sag} \leq 0.9$ p.u

Cont'd...

B. Percentage Voltage Sag

– If nominal RMS voltage is: V_{nom} ,

$$\%V_{sag} = \frac{V_{nom} - V_{rms}}{V_{nom}} \times 100$$

– where, $10 \leq \%V_{sag} \leq 90$

C. Time-Domain Representation

– Voltage sag can also be expressed as a time-varying RMS function:

$$V(t) = \begin{cases} V_{nom}, & t < t_1 \\ V_{sag}, & t_1 \leq t \leq t_2 \\ V_{nom}, & t > t_2 \end{cases}$$

Where: t1, t2 → start and end time of sag

Cont'd...

D. Fault-Based Approximation (Voltage Divider Model)

– For a simple system during a fault:

$$V_{sag} = V_{nom} \frac{Z_{fault}}{Z_{system} + Z_{fault}}$$

– This shows that sag severity depends on:

- Source impedance
- Fault location
- Fault impedance

Cont'd...

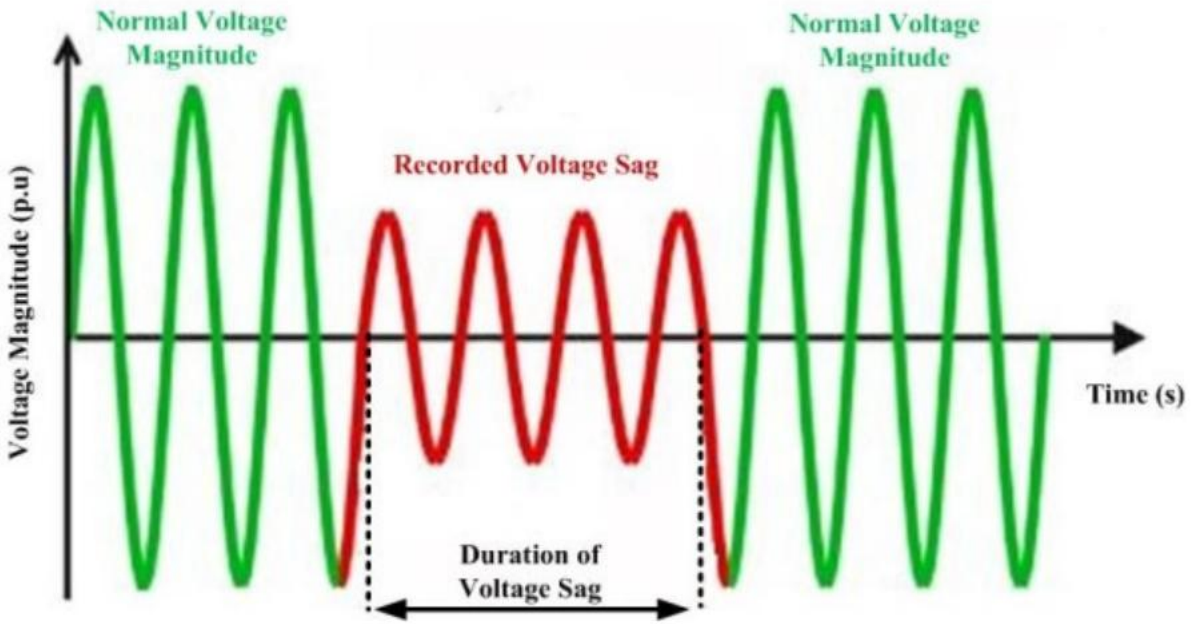


Figure 1: Voltage Sag Phenomanea [4]

Table 1. Voltage Sag Phenomanea

Type	Duration	Voltage Magnitude
Instantaneous	0.5 - 30 cycle	0.1–0.9 p.u
Momentary	30 cycle - 3 s	0.1–0.9 p.u
Temporary	3 s - 1 minute	0.1–0.9 p.u

Cont'd...

2. Voltage Swell

- **According to IEEE Std 1159:** A voltage swell is an increase in RMS voltage to 1.1–1.8 p.u. at power frequency for a duration of 0.5 cycles to 1 minute [3].
- Mathematical Representation
  – If nominal RMS voltage is: V_{nom} ,

$$V_{swell} = \frac{V_{rms}}{V_{nom}}$$

  – where, $1.1 \leq V_{swell} \leq 1.8$ p.u

Cont'd...

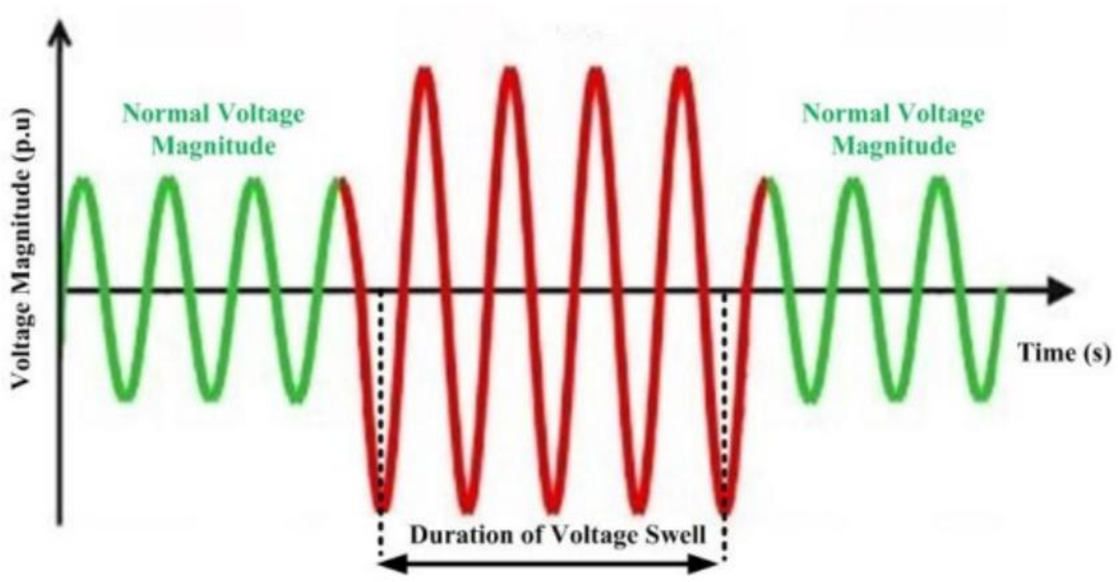


Figure 2: Voltage Swell Phenomanea [4]

Table 2. Voltage Swell Phenomanea

Type	Duration	Voltage Magnitude
Instantaneous	0.5 - 30 cycle	1.1–1.8 p.u
Momentary	30 cycle - 3 s	1.1–1.8 p.u
Temporary	3 s - 1 minute	1.1–1.8 p.u

Cont'd...

3. Short Duration Voltage Interruption

- A short-duration voltage interruption is a condition where the RMS voltage drops to less than 0.1 per unit (p.u.) of the nominal voltage for a duration ranging from 0.5 cycles to 1 minute [3].
- Mathematical Representation
  - If nominal RMS voltage is: V_{nom} ,

$$V_{Inerp} = \frac{V_{rms}}{V_{nom}} < 0.1\ p.u$$

1.2. Long-Duration Voltage Variations

Defination

- Long-duration voltage variations are defined as deviations in RMS voltage magnitude lasting longer than 1 minute.
- Typically caused by sustained load changes, network configuration issues, or inadequate voltage regulation [3].
- According to IEEE Std 1159, long-duration voltage variations are categorized as:
  - Overvoltage
  - Undervoltage
  - sustained Interruption

Cont'd...

1. Overvoltage

- **According to IEEE Std 1159:** An overvoltage is an increase in RMS voltage to 1.1–1.2 p.u. at power frequency for more than duration > 1 minute.
- Mathematical Representation
  - If nominal RMS voltage is: V_{nom} ,

$$V_{overv} = \frac{V_{rms}}{V_{nom}}$$

  - where, $1.1 \leq V_{swell} \leq 1.2$ p.u

Cont'd...

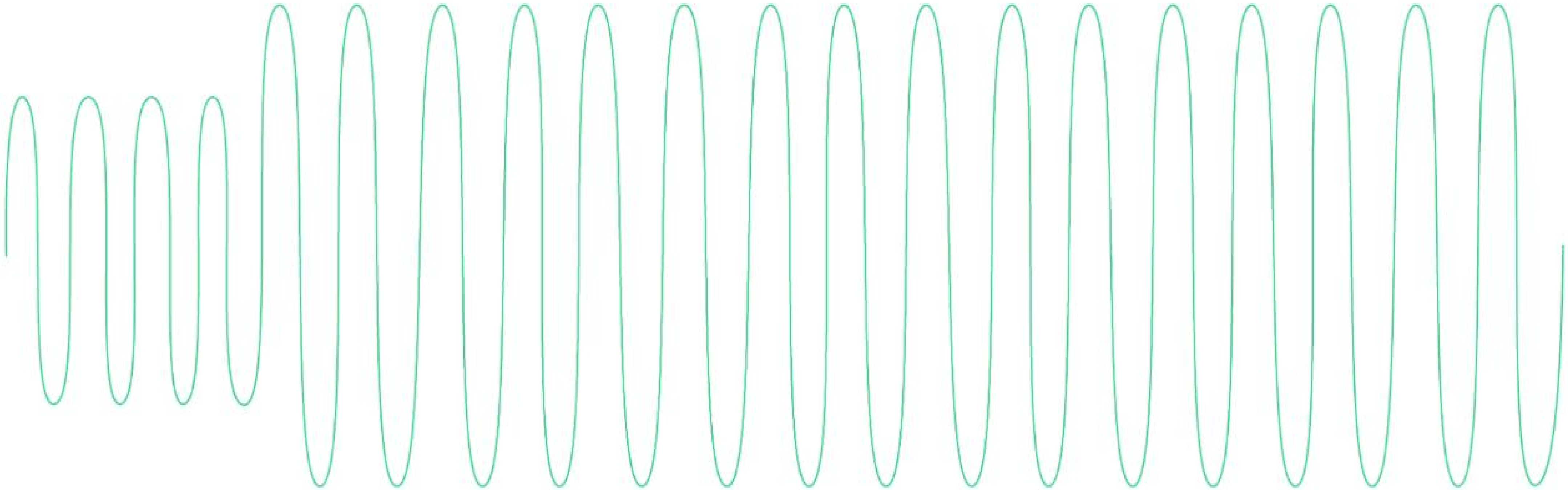


Figure 3: Illustration of overvoltage

Cont'd...

2. Undervoltage

- **According to IEEE Std 1159:** An undervoltage is a decrease in RMS voltage from 0.8–0.9 p.u. at power frequency for more than duration > 1 minute.
- Mathematical Representation
  - If nominal RMS voltage is: V_{nom} ,

$$V_{underv} = \frac{V_{rms}}{V_{nom}}$$

  - where, $0.8 \leq V_{swell} \leq 0.9$ p.u

Cont'd...

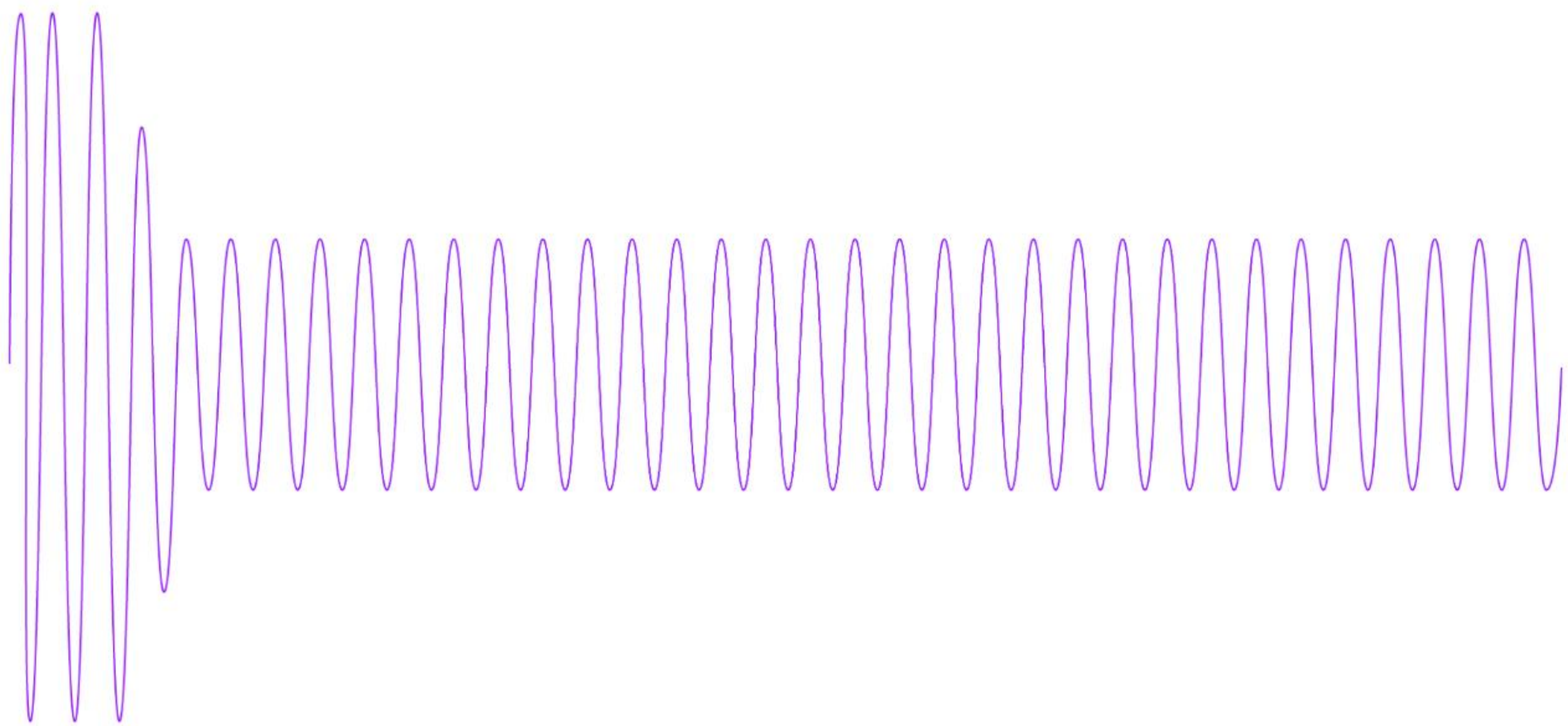


Figure 4: Illustration of undervoltage

Cont'd...

3. Sustained Interruption

- **According to IEEE Std 1159:** A sustained Interruption is a decrease in RMS voltage below 0.1 p.u. at power frequency for more than duration > 1 minute.
- Mathematical Representation
  - If nominal RMS voltage is: V_{nom} ,

$$V_{sus,\,i} = \frac{V_{rms}}{V_{nom}}$$

  - where, $V_{sus,\,i} \leq 0.1$ p.u

Cont'd...

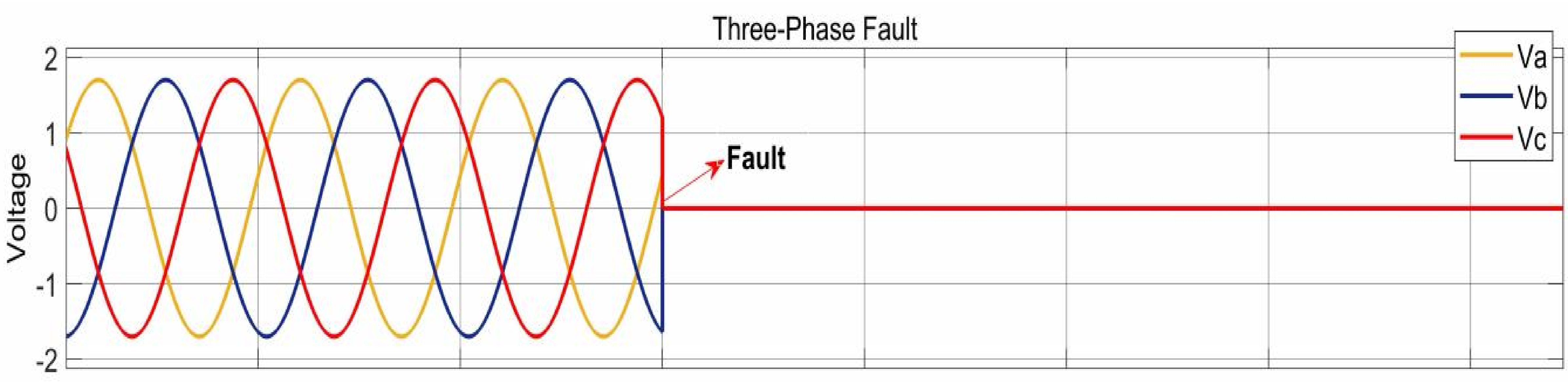


Figure 5: Illustration of Sustained Interruption Due to a Three Phase Fault [5].

1. 3. Flicker/Voltage Fluctuation

- **According to IEEE Std 1159:**
- Mathematical Representation: Pst and Plt are standardized indices used to quantify flicker severity.
  - **Pst** (short-term flicker severity, 10 min) percentiles
  - **Plt** (long-term flicker severity, 2 hours) percentiles
- According to IEC 61000-4-15:

$$P_{lt} = \sqrt[3]{\frac{1}{N}\sum_{i=1}^{N} P_{st,i}^{3}}$$

- Acceptable limit typically: $P_{st} \leq 1.0$ and N=12

Cont'd...

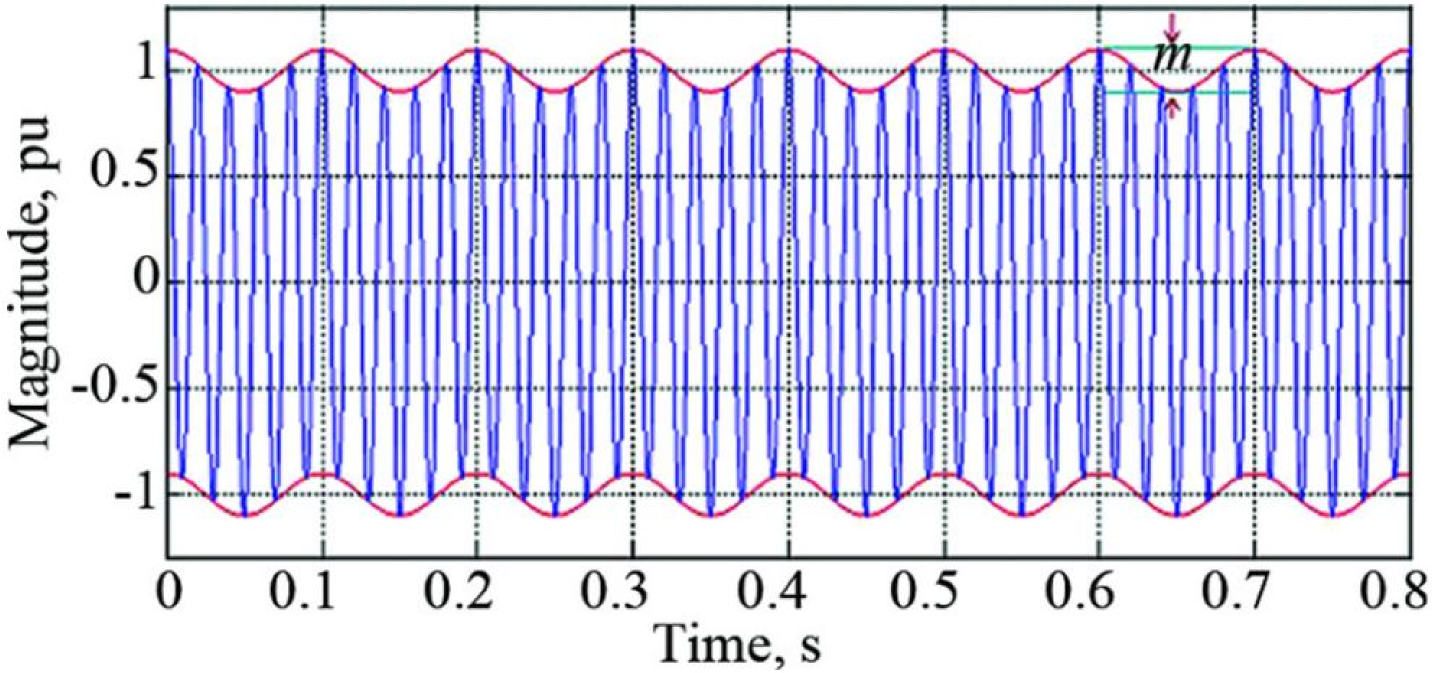


Figure 6: Illustration of voltage flicker.

2. Sources of Voltage Variations

- Voltage variations arise due to changes in **system operating conditions** that affect the RMS voltage magnitude in power networks.
- The main sources include:
  - Load Variations
  - Motor Starting
  - Faults in the Power System
  - Network Switching Operations
  - Distributed Energy Resources (DERs)
  - Transformer Tap-Changer Operations

Cont'd...

A. Load Variations

- Sudden increase or decrease in load demand
- Switching of large industrial loads
- Arc furnaces, welding machines, and fluctuating loads
- Causes voltage drop (undervoltage or voltage dips) or rise (overvoltage or voltage swell)
- The duration of load variation affects the nature of voltage variation whether it is voltage sag, swell, undervoltage, overvoltage, or sustained interruption

Cont'd...

B. Motor Starting

- Large induction motors draw high inrush current (5–7 times rated current)
- Leads to temporary voltage sag (dip)
- Common in industrial plants and pumping systems

C. Faults in the Power System

- Short-circuit faults (L-G, L-L, L-L-G, 3-phase)
- Cause severe voltage sag or interruption
- Magnitude depends on fault location and system impedance

Cont'd...

D. Network Switching Operations

- **Switching of:** Capacitor banks, Transmission lines, and Transformers
- **Can cause:** Voltage swell, Voltage Sag, and Transient overvoltage

E. Distributed Energy Resources (DERs)

- Integration of: Solar PV, BESS, and Wind energy systems
- Intermittent generation leads to voltage fluctuations and flicker
- Reverse power flow may cause overvoltage

3. Impacts of Voltage Variation

- **Voltage variations** (sag, swell, overvoltage, undervoltage, interruptions, and flicker) significantly affect sensitive loads, particularly those based on power electronic converters and digital control circuits.
- Voltage variations significantly affect the **performance**, efficiency, and **reliability** of electrical power systems and connected equipment.

Cont’d...

A. Impact of Voltage Sag (0.1–0.9 p.u.)

- **On Sensitive Loads**
  - Computer systems reset or shut down
  - PLC malfunction
  - Data corruption
  - Contactors drop out
  - Variable Speed Drives (VSD) trip due to DC-link undervoltage

- **On Power Electronic Circuits**
  - For a rectifier-fed DC link: $V_{dc}=2V_m/pi$
  - IGBT/MOSFET misfiring
  - Control instability
  - Increased input current (to maintain power) which impacts high powerloss

Cont'd...

B. Impact of Voltage Swell / Overvoltage (1.1 - 1.8 p.u.)

- **On Sensitive Loads**
  - Insulation stress
  - Lamp damage
  - Premature aging
  - Motor core saturation

- **On Power Electronic Circuits**
  - DC-link overvoltage
  - Capacitor overstress
  - Semiconductor breakdown

Cont’d...

C. Impact of Undervoltage (<0.9 p.u.)

- **On Sensitive Loads**
  - Motor overheating (higher current draw)
  - Reduced torque: $T \propto V^2$
  - 10% voltage drop → ~19% torque reduction
  - Increased copper losses

- **On Power Electronic Circuits**
  - Reduced modulation index margin
  - Reduced output capability
  - Increased harmonic distortion

Cont'd...

D. Impact of Short Interruption (<0.1 p.u.)

- Immediate shutdown of electronic systems
- UPS switching
- Industrial process interruption
- Memory loss in digital controllers
- Semiconductor manufacturing
- Data centers
- Hospitals

Cont'd...

E. Impact of Voltage Flicker (±5%)

- **On Loads:**
  - Visible lamp flicker
  - Human discomfort
  - Torque oscillations in motors
- **On Power Electronics:**
  - Control loop oscillations
  - DC-link ripple
  - Harmonic distortion increase

4. Mitigation Mechanism

- Voltage variations can be effectively mitigated using a combination of network control strategies, energy storage solutions, and load level mitigation.

A. Network-Based Solutions

1. **Dynamic Voltage Restorer (DVR):** Series-connected converter which restores load voltage during sag.
   - Injection voltage: $V_{inj}=V_{load}-V_{sag}$

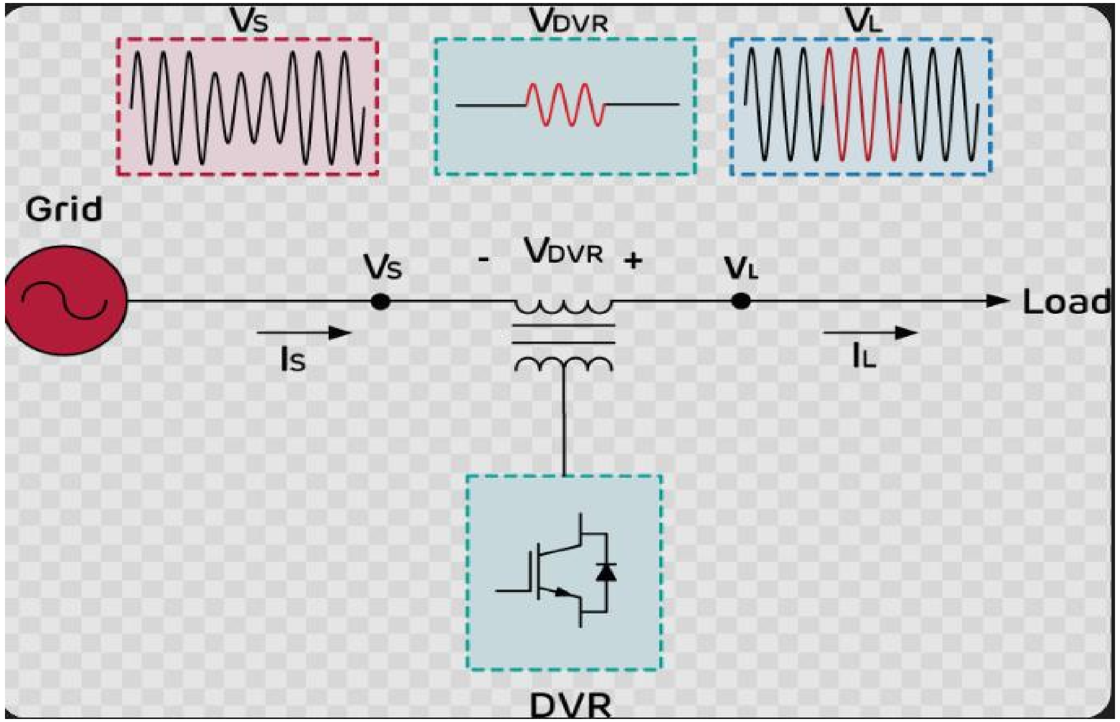


Figure 7: Dynamic Voltage Restorer

Cont'd...

2. **STATCOM/DSTATCOM:**

- **Shunt connected device** based on voltage source inverter (VSI) that generates a controllable AC voltage:
  - If $V_{conv} > V_{load} \rightarrow$ injects Q (capacitive mode)
  - If $V_{conv} < V_{load} \rightarrow$ absorb Q (inductive mode)
- The reactive power exchanged, Q is:

$$Q = \frac{V_{load}(V_{conv} - V_{load})}{X}$$

- where Q → reactive power exchanged, $V_{conv} \rightarrow$ converter output voltage, and $V_{load} \rightarrow$ is load voltage

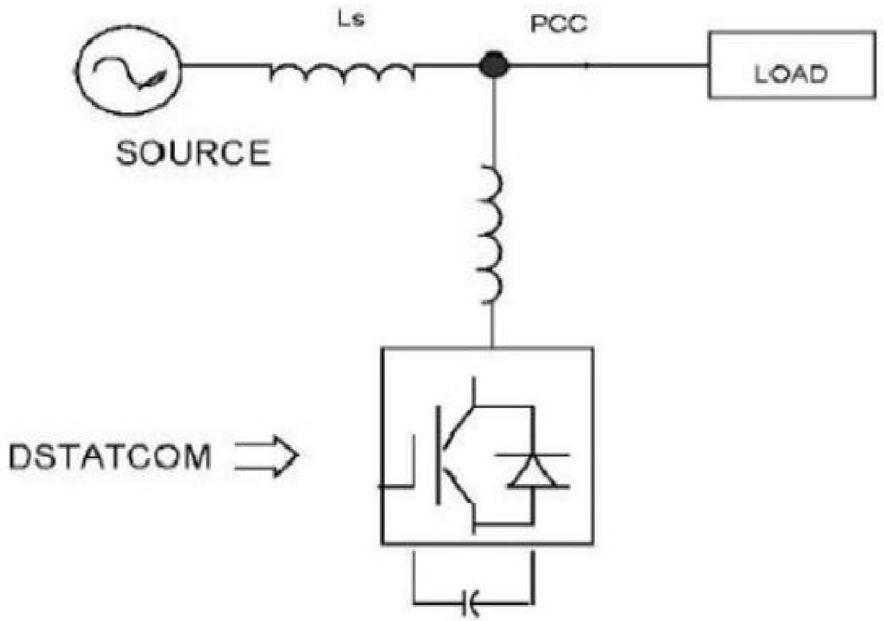
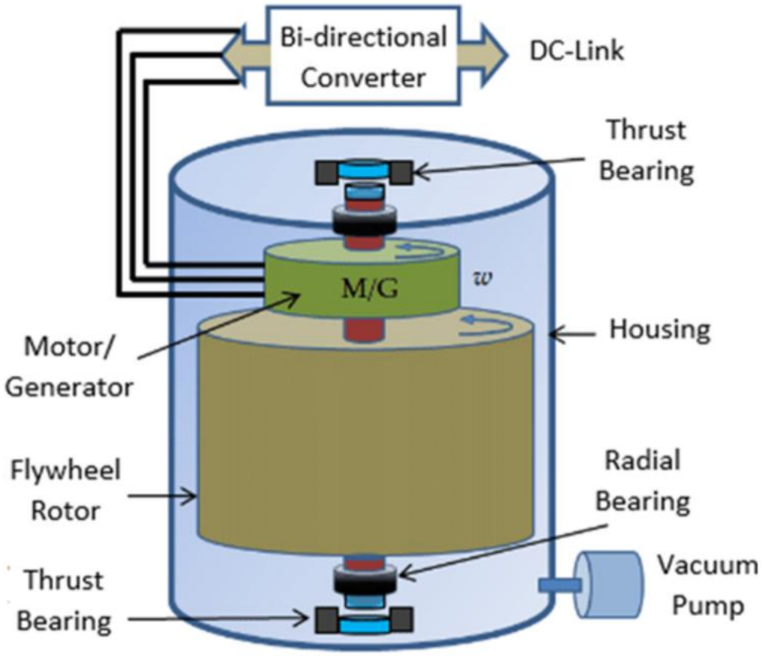


Figure 8: DSTATCOM Configuration

Cont'd...

B. Energy Storage Solutions

- Battery Energy Storage System (BESS)
- Flywheel systems
- Supercapacitors
- Critical for microgrid voltage support.



a). Flywheel

b). Battery

Figure 9: Energy Storage Solutions

Cont'd...

C. Load-Level Mitigation

- **Power Factor Correction at Load Side:** Use capacitor banks near loads.
- **Soft starters for motors:** Gradually increase motor voltage during startup.
- **Load Scheduling:** Shift heavy loads to off-peak periods and avoid simultaneous operation of large loads.
- **Demand Response (DR) Programs:** Adjust load based on grid conditions or price signals.
- **Load Balancing (Three-Phase Systems):** Distribute loads evenly across phases.
- **Variable Frequency Drives (VFDs):** Control motor speed and torque smoothly.

5. International Standards

- **Key International Standard Definitions of Voltage Variation:**
  - EN 50160 (Europe): Sets quality characteristics, requiring voltage to stay within ±10% for 95% of the week, with 100% within +10%/-15%.
  - IEC 61000-3-3 & 61000-4-30: Define rapid voltage changes (RVCs) occurring over short timeframes.
  - IEEE Std 1159: Defines long-duration variations (over 1 minute) as undervoltage or overvoltage.
  - IEC 60038: Defines international standard voltage levels.

Summary

Table 3: Voltage Variation Summary Table

No.	Type	Magnitude (p.u)	Duration	Cause/Sources
1.	Voltage Sag	0.1 - 0.9	0.5 cycle - 1 minute	Short-circuit faults (L–G, L–L, 3 phase)
2.	Voltage Swell	1.1 - 1.8	0.5 cycle - 1 minute	Sudden load disconnection, Energization of capacitor banks
3.	Interruption	< 0.1	0.5 cycle - 1 minute	Severe faults and protection system operation
4.	Undervoltage	0.8 - 0.9	> 1 minute	Overloaded feeders, Poor voltage regulation
5.	Overvoltage	1.1 - 1.2	> 1 minute	Light load conditions Excessive capacitor compensation
6.	Flicker	± 5%	Repititive	Arc furnaces, Welding machines

References

[1]. R. C. Dugan, M. F. McGranaghan, S. Santoso, and H. W. Beaty, Electrical Power Systems Quality, 3rd ed. New York, NY, USA: McGraw-Hill, 2012.

[2]. European Committee for Electrotechnical Standardization, Voltage characteristics of electricity supplied by public distribution networks, EN 50160, 2010.

[3]. IEEE, IEEE Recommended Practice for Monitoring Electric Power Quality, IEEE Std 1159-2019, 2019.

[4]. N. B. Kadandani and I. Abubakar, “On exploring the power quality enhancement capability and other ancillary functionalities of solid state transformer application in the distribution system,” Bayero Journal of Engineering and Technology, vol. 18, no. 2, pp. 28–39, May 2023.

[5] V. N. Ogar, S. Hussain, and K. A. A. Gamage, “Transmission line fault classification of multi-dataset using CatBoost classifier,” Signals, vol. 3, no. 3, pp. 468–482, 2022.

Thank You!