Voltage and Reactive Power Control

Fundamentals of Electrical Power Systems - Week 10

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Outline

Why Voltage Control Matters

Definition

Voltage control is the process of maintaining voltage levels within acceptable limits throughout the power system to ensure reliable operation and quality power delivery.

Consequences of poor voltage control:

- Equipment damage and reduced lifespan
- Inefficient operation and increased losses
- Voltage instability and potential collapse
- Customer equipment malfunction

Standard

Typical acceptable range: $\pm 5\%$ to $\pm 10\%$ of nominal voltage

Voltage-Reactive Power Relationship

Fundamental relationship in power systems:

- Voltage levels are closely related to reactive power flow
- Reactive power injection raises voltage
- Reactive power absorption lowers voltage
- Active power flow has less impact on voltage

Key Equations

For a transmission line:

$$\Delta V \approx \frac{PR + QX}{V} \quad (1)$$

Where $X \gg R$ in transmission:

$$\Delta V \approx \frac{QX}{V} \quad (2)$$

Power Quality Considerations

Key power quality parameters affected by voltage control:

1. **Voltage magnitude variation**
   - Voltage sags and swells
   - Long-term overvoltage/undervoltage
2. **Harmonics & Total Harmonic Distortion (THD)**
   - Distorsi gelombang arus dan tegangan akibat beban non-linear
   - Dampak penetrasi converter/inverter elektronika daya
   - Penggunaan filter pasif dan filter aktif (APF)
3. **Voltage unbalance**
4. **Voltage flicker**
   - Rapid voltage fluctuations
   - Caused by varying loads
5. **Harmonic distortion**
   - Non-sinusoidal voltage waveforms
   - Related to reactive compensation devices power electronics

Overview of Voltage Control Methods

Classification by time response and location:

Method	Response	Location
Generator excitation	Fast (continuous)	Generation
OLTC transformers	Slow (discrete)	Transmission/Distribution
Shunt capacitors/reactors	Medium (discrete)	Transmission/Distribution
SVC/STATCOM	Fast (continuous)	Transmission
Series compensation	Fixed/Fast	Transmission

Coordinated Control

Modern power systems use coordinated control of multiple devices for optimal voltage profile management.

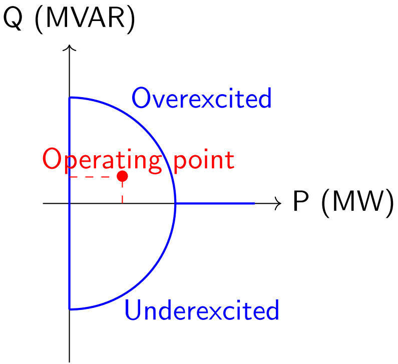
Primary voltage control method:

Key components:

- Automatic Voltage Regulator (AVR)
- Excitation system (DC or AC)
- Power system stabilizer (PSS)
- Terminal voltage sensor

Capabilities:

- Continuous reactive power control
- Fast response (<1 second)
- Limited by generator capability curve

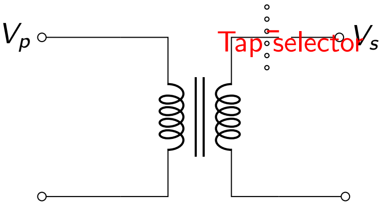


On-Load Tap Changer Transformers

Discrete voltage control through tap changing:

Principle:

- Varies transformer turns ratio
- Adjusts secondary voltage
- Operates under load
- Typical range: $\pm 10\%$ in 32 steps



Control strategy:

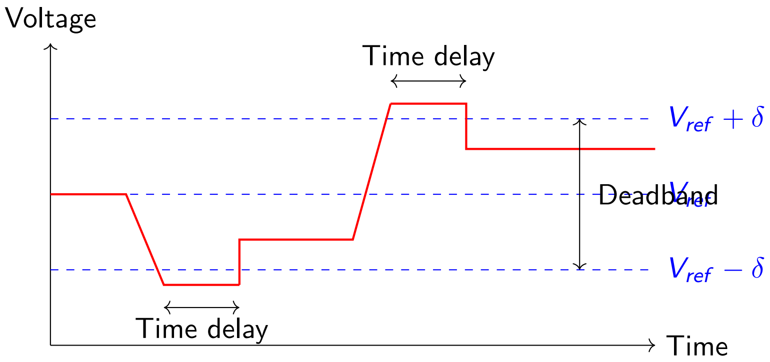
$$V_s = V_p \times \frac{N_s}{N_p} \times (1 + n \times \delta)$$

where n = tap position, δ = step size

Advantages:

- No continuous reactive power consumption
- Wide voltage adjustment range

OLTC Control Characteristics



Control Logic

OLTC changes tap when voltage is outside deadband for a preset time delay (typically 30-90 seconds) to avoid excessive tap operations.

Fixed or switchable reactive power sources:

Shunt Capacitors:

- Inject reactive power
- Raise bus voltage
- Reduce line losses
- Improve power factor

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

Applications:

- Substations
- Distribution feeders
- Industrial plants

Shunt Reactors:

- Absorb reactive power
- Lower bus voltage
- Compensate Ferranti effect
- Control overvoltage

$$Q_L = -\frac{V^2}{\omega L} = -\frac{V^2}{X_L}$$

Applications:

- Long transmission lines
- Cable systems
- Light load conditions

Capacitor Bank Sizing and Placement

Optimal placement considerations:

1. **Loss reduction:**

$$\text{Loss Reduction} = \frac{Q_C^2 R}{V^2} \tag{3}$$

2. **Voltage improvement:**

$$\Delta V = \frac{Q_C X}{V} \tag{4}$$

3. **Economic analysis:**
   - Installation cost
   - Energy loss savings
   - Demand charge reduction

Rule of Thumb

For radial distribution: place capacitors near the center of reactive load to minimize losses. Typically 2/3 of distance from source.

Flexible AC Transmission Systems (FACTS)

Power electronics-based voltage control:

Device	Type	Function
SVC	Shunt	Variable reactive power, voltage control
STATCOM	Shunt	Advanced voltage control, better performance
TCSC	Series	Impedance control, power flow control
SSSC	Series	Series reactive compensation
UPFC	Combined	Unified power flow controller

Advantages over conventional methods:

- Fast response (milliseconds)

Static VAR Compensator (SVC)

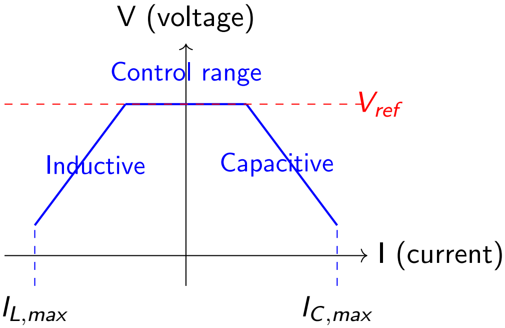
Thyristor-based reactive power control:

Components:

- Thyristor Controlled Reactor (TCR)
- Thyristor Switched Capacitor (TSC)
- Fixed capacitor (FC)
- Control system

Characteristics:

- Response time: 20-40 ms
- Capacitive to inductive range
- V-I characteristic: slope



Operating Principle

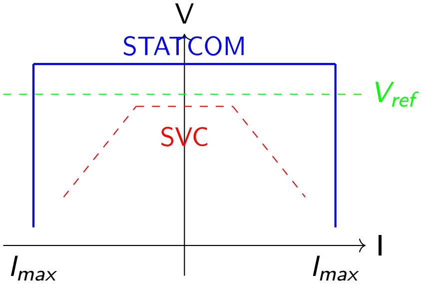
SVC adjusts firing angle of thyristors to control reactive power continuously from full

STATCOM - Advanced Shunt Compensation

Voltage Source Converter (VSC) based device:

Advantages over SVC:

- Better performance at low voltage
- Smaller footprint
- No harmonics (with PWM)
- Independent V-I characteristic



Reactive power output:

$$Q = \frac{V_s(V_s - V)}{X_L}$$

where V_s = STATCOM voltage,
V = system voltage,
X_L = coupling reactance

Key Feature

STATCOM maintains constant current at rated capacity regardless of voltage!

Reactive Power Optimization Problem

Objective: Minimize losses while maintaining voltage constraints

Mathematical formulation:

Optimization Problem

$$
\begin{aligned}
\text{Minimize:} \quad & f(x) = \sum_{i=1}^{N_L} P_{loss,i} \\
\text{Subject to:} \quad & V_{min} \leq V_i \leq V_{max}, \quad i = 1, \ldots, N_b \\
& Q_{G,min} \leq Q_{G,i} \leq Q_{G,max}, \quad i \in N_G \\
& Q_{C,min} \leq Q_{C,i} \leq Q_{C,max}, \quad i \in N_C \\
& \text{Power flow equations satisfied}
\end{aligned}
$$

Control variables:

- Generator terminal voltages

Voltage Sensitivity Analysis

Understanding voltage-reactive power relationships:

Sensitivity matrix:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \quad (5)$$

V-Q sensitivity:

$$\frac{\partial V}{\partial Q} = [J_4 - J_3 J_1^{-1} J_2]^{-1} \quad (6)$$

Applications:

- Identify weak voltage buses
- Determine optimal location for reactive compensation
- Assess voltage stability margins
- Plan reactive power dispatch

Interpretation

High sensitivity → Small Q change causes large V change → Priority location for compensation

Coordinated Voltage Control Strategies

Hierarchical control structure:

1. **Primary control (local):**
   - Generator AVR
   - Individual OLTC control
   - Fast response (seconds)
2. **Secondary control (regional):**
   - Coordinated tap changing
   - Capacitor bank switching
   - SVC/STATCOM setpoint adjustment
   - Medium response (minutes)
3. **Tertiary control (system-wide):**
   - Optimal power flow (OPF)
   - Economic dispatch with voltage constraints
   - Planning for daily/seasonal variations
   - Slow response (hours)

Voltage Control in Bengkulu Power System

Specific challenges and solutions:

Challenges:

- Long distribution feeders in rural areas
- High renewable integration (hydro, geothermal)
- Load variations (daily/seasonal)
- Limited grid infrastructure

Solutions:

- Strategic capacitor placement
- OLTC at distribution substations
- Generator voltage control coordination
- Distributed generation support

Case Study

Integration of PLTP Hululais and PLTA Musi requires careful reactive power coordination to maintain voltage profile in Bengkulu grid.

Impact of Distributed Generation on Voltage

DG integration challenges:

- **Voltage rise:** High DG penetration can cause overvoltage
- **Reverse power flow:** Changes voltage profile along feeder
- **Variability:** Solar and small hydro output variations
- **Reactive power capability:** Inverter-based DG control modes

Mitigation strategies:

1. Active power curtailment (last resort)
2. Reactive power control from inverters
3. Dynamic OLTC control
4. Energy storage integration
5. Grid reinforcement

Bengkulu Context

PLTMH installations in rural Bengkulu require voltage control coordination with distribution

Computational Tools for Voltage Analysis

Using Octave/MATPOWER for voltage control studies:

Available analysis functions:

- `runpf`: Power flow analysis for voltage profile
- `runopf`: Optimal power flow with voltage optimization
- Sensitivity analysis matrices
- Custom scripts for capacitor placement

Example applications:

1. Determine optimal tap settings
2. Calculate required reactive compensation
3. Assess voltage stability margins
4. Evaluate impact of DG integration

Practice

Today's worksheet will guide you through voltage control analysis using MATPOWER.

Key Takeaways

1. **Voltage control is essential** for power system reliability and power quality
2. **Multiple control methods** work together:
   - Generator excitation (fast, continuous)
   - OLTC (slow, discrete)
   - Shunt compensation (various speeds)
   - FACTS devices (fast, continuous)
3. **Reactive power** is the key to voltage control: $\Delta V \approx QX/V$
4. **Optimization** minimizes losses while maintaining voltage limits
5. **Coordination** of multiple devices provides better performance than individual control
6. **Modern challenges:** DG integration, renewable variability, smart grid requirements

Next Steps

This week's activities:

- **Worksheet:** Calculate voltage control requirements and capacitor sizing
- **Computer Lab:** Use MATPOWER to analyze voltage profiles and optimize reactive power
- **Problem Set:** Apply concepts to realistic Bengkulu power system scenarios (C1-C6 levels)
- **Reading:** Review textbook chapters on voltage control and FACTS devices

Next week: Economic Operation of Power Systems and Dispatch Optimization

Thank You!

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