Voltage Control Strategies for Distribution Systems with High Penetration of Photovoltaics

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Outline

• Background
• Basic Concepts
• Classification of Inverter Control Strategies
• Case Studies
• Comparison of Inverter Control Strategies
• Current Trends
• Conclusions
Rising Trend of Small-scale Photovoltaic Generation

Distributed PV Generation in US (2014-2016)

- Small-scale PV generation accounted for 37% of annual generation from solar in U.S.
- Residential installations increasing
  - Decreasing cost
  - Trend of clean energy source

Source: U.S. Energy Information Administration, Electric Power Monthly
Inverter Control Strategies for Voltage Support

- Unidirectional flow of power
- Protection and control available for unidirectional power flow

- High PV penetration and low load
- Reverse power flow causes **voltage rise**
- PV power curtailed
- Limits PV installation capacity

- Legacy devices
  - LTCs, voltage regulators, capacitor banks
  - Fails under bidirectional power flow

- Control for voltage regulation at both distribution and DG connection points required

- Inverter based voltage control strategies needed to maintain power quality under high PV penetrations

\[ \Delta V \approx \frac{PR + QX}{V} \]
Inverter Control Technologies for Voltage Control

First Generation
- Active Power Curtailment
- Reactive Power Control
  - Controlling power factor
  - Controlling reactive power
- Dynamic Volt/VAR Control

Local Control

Second Generation
- Adaptive Local Control
- Shifting Volt/VAR Control
- Shifting Volt/WATT Control
- Online droop adjustment

Inverter Control Technologies

Third Generation
- Optimal inverter dispatch
  - Minimize loss
  - Minimize curtailment
- Coordination of OLTC, Switched bank capacitors, and other devices

Centralized Control

Distributed Control
- Active reactive power management
- Distributed optimal inverter dispatch
Case Studies Around the World

1. California
   - SMUD & NREL
     - PRECISE
     - In-Line Power Regulators
   - HECO & NREL
     - VROS Project
     - First utility to activate volt-VAR system-wide

2. Hawaii
   - SMUD & NREL
   - HECO & NREL

3. Germany
   - Dettighofen Grid
     - 821.3 kWp low-voltage grid
     - 4.5% voltage rise due to reverse power flow
     - APC and RPC reduced voltage rise by 3%
     - Peak shifting with battery storage
     - 0.017 USD/kWh vs 3.58 USD/kWh

4. China
   - Taiwan Power Company
     - 3750 kWp solar farm field testing
     - Variable power factor and APC
     - 6519 kWh to 269 kWh curtailment reduction

5. Japan
   - NEDO
     - Power conditioning subsystem (PCS)
     - 80% PV penetration
     - 553 residential PV systems
     - Total of 2.1 MW
     - Battery use to minimize output power loss
Active Power Curtailment (APC) Based on Droop

- Curtailing the active power is one of the solution to prevent the overvoltage in Low Voltage (LV) network

- **Linear Droop**

  \[ m = \frac{\Delta P}{\Delta V} \]

- **Quadratic Droop**

  \[ P_{\text{inv}} = P_{\text{MPPT}} - m(V - V_{\text{cri}})^2 \]

- \( P_{\text{inv}} \): Power injected by PV inverter
- \( P_{\text{MPPT}} \): Maximum power available from PV array
- \( V_{\text{cri}} \): Voltage above which controller comes into action
- \( m \): Slope factor or droop constant
- \( V \): Local Voltage at the point of connection

\[ \Delta V \approx \frac{PR}{V} \]

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Approaches to Reactive Power Control (RPC)

Coordinated Active Reactive Power Support

- Normal operation
- Local reactive power support
- Neighborhood reactive power support
- Neighborhood active and reactive power support

PV Power Computation Using Solar Irradiance Data

- One-hour resolution irradiance data from [18] converted into minutes
- PV power computed using irradiance

\[ P = \eta \times I \times A \]

\( \eta \): efficiency (16.7%), \( A \): area (50,2605 [m²]) [19], \( I \): irradiance \( \frac{W}{m^2} \)

Comparison

- Year long voltage profile
  - OVP, LDAPC and QDAPC maintain the voltage below limit
  - ARPM cannot fully eliminate overvoltage
- Energy loss for a year
  - Curtailment energy loss is lowest in ARPM because of the use of reactive power,
  - However this increases loss in the feeder and transformer

Centralized Control

- Achieve best coordination between available controllable sources
  - DG inverters, tap settings, capacitors banks etc.
  - e.g. optimal dispatch of PV inverters

- Need for solving non-convex, non-linear optimization
  - Objective is to reduce curtailment, loss and maximize PV injection

- Heavily dependent on communication network

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Distributed Control

- No central controller
  - Implemented with computations local to node
  - Augmented through limited information from nearby nodes
  - Cooperation among nodes possible
    - For example – power loss minimization

- An example*:
  - Information collected from few inverters operating as agents
  - Information shared on a common cyber layer
  - Feedback signal approach to find optimal reactive power requirement

Comparison of Local and Centralized Control Method

- Controlling reactive as well as active power reduces curtailment significantly compared to active power control only
  - Both in local and central control
- Central control benefits from the communications
  - Minimum curtailment possible

K. Duwadi, F. B. Dos Reis, R. Fourney, R. Tonkoski, and T. M. Hansen, “Optimal Inverter dispatch (OID) and time constrained OID in low voltage distribution network by leveraging linearized approximate power flow” [under preparation]
Neural Network Based Online Droop Adjustment

- A supplementary controller to set droop in APC method
- **Reinforcement learning based approach**
  - A reward signal is designed
  - Restricts voltage crossing the critical voltage limit with minimum curtailment possible
- Objective function was designed to minimize curtailment in each house
  - Limit voltage with critical limit
  - Inject maximum available power

Reduced Curtailment with Online Droop Adjustment

Linear APC

Energy Loss = 22.72 kWh

Adaptive APC

Energy Loss = 18.77 kWh

Voltage within Critical Limit

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Current Trends

- Voltage issues with connection of large loads in a distribution system with high PV penetration
- Distributed optimization*
  - Benefits of reduce curtailment
  - Avoiding the dependences of centralized approached
  - Coordination of controllers OLTC
- Multiple Agents**
  - Attending the privacy of costumers
  - Equilibrium of the game bids
- Tackling the challenges
  - Privacy of customers
  - Fairness of participants
  - Markets in the distribution system

Conclusions

- Voltage Droops are still the most popular method for active and reactive power support for overvoltage prevention
- Coordination of active and reactive power can lead to reduction on curtailment of PV
- Communication infrastructure is required to optimize the performance of local active and reactive power support
- Supplementary controllers can help reduce these requirements and get closer to optimal solution.
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