Options for Control of Reactive Power by Distributed Photovoltaic Generators

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Objectives / Outline

- Distribution circuits with a high penetration of PV generation may
  - experience rapid changes in cloud cover. Inducing…
  - rapid variations in PV generation. Causing…
  - reversals of real power flow and potentially large voltage variations

- We seek to control the voltage variations by controlling PV-inverter reactive power generation because
  - it does not affect the PV owners ability to generate, and
  - we can make a significant impact with modest oversizing of inverters

- Control of reactive power also allows for reducing distribution circuit losses, but
  - voltage regulation and loss reduction are fundamentally competing objectives, and
  - analysis and engineering judgment are required to find the appropriate balance

- Questions we will try to (at least partially) answer:
  - Should control be centralized or distributed (i.e. local)?
  - What variables should we use as control inputs?
  - How to turn those variables into effective control?
  - Does the control equitably divide the reactive generation duty?
Simplified Models

Schematic physical model

Power flow model

\[ P_j + iQ_j \]

\[ V_{j-1}, V_j, V_{j+1} \]

\[ p_{j-1}^c, p_{j-1}^g, p_j^c, p_j^g, p_{j+1}^c, p_{j+1}^g \]

\[ q_{j-1}^c, q_{j-1}^g, q_j^c, q_j^g, q_{j+1}^c \]
Power Flow—Voltage Variations and Losses

\[ P_j + iQ_j \]

\[ V_{j-1} \]

\[ p_{j-1}^c \]

\[ q_{j-1}^c \]

\[ V_j \]

\[ p_j^c \]

\[ q_j^c \]

\[ V_{j+1} \]

\[ p_{j+1}^c \]

\[ q_{j+1}^c \]

\[ V_n \]

Loss \( j \) = \( r_j \frac{P_j^2 + Q_j^2}{V_0^2} \)

\[ \Delta V_j = -(r_jP_j + x_jQ_j) \]

Competing objectives

\- Minimize losses \( \rightarrow Q_j = 0 \)

\- Voltage regulation \( \rightarrow Q_j = -(r_j/x_j)P_j \)
**Fundamental Problem—Import versus Export**

\[
\text{Loss}_j = r_j \frac{P_j^2 + Q_j^2}{V_0^2}
\]

\[
\Delta V_j = -(r_j P_j + x_j Q_j)
\]

- Rapid reversal of real power flow can cause undesirably large voltage changes
- Rapid PV variability cannot be handled by current electromechanical systems
- Use PV inverters to generate or absorb reactive power to restore voltage regulation
- In addition... optimize power flows for minimum dissipation
Parameters Available to Affect Control of $V_j$

$P_j + iQ_j$

| 0 | j -1 | j | j +1 | n |
|---|-----|---|-----|---|
| $V_{j-1}$ | $V_j$ | $V_{j+1}$ |

$p_j^c$ $q_j^c$ $p_j^g$ $q_j^g$ $p_{j+1}^c$ $q_{j+1}^c$

- **Not available**—should serve (all types of) load
- **Not available**—should not curtail PV generation
- **Available**—minimal impact on customer, extra inverter duty
- No duty to non-PV-enabled customers
Limits on Control—Inverter Capacity (s)

\[ P_j + iQ_j \]

\[ 0 \quad j-1 \quad j \quad j+1 \quad n \]

\[ V_{j-1} \quad V_j \quad V_{j+1} \]

\[ p_j^c + p_j^g \]

\[ q_j^c + q_j^g \]

\[ |q_j^{(g)}| \leq \sqrt{s^2 - (p_j^{(g)})^2} \]
Availability of Inputs to a Local Control Scheme

Available via advanced metering assuming meter-to-inverter communication

\[ q_j^g = F(p_j^c, q_j^c, p_j^g, V_j) \]

\[ |q_j^g| < \sqrt{s_j^2 - (p_j^g)^2} = q_j^{\text{max}} \]
Consider a Few Simple Schemes

Baseline—Do Nothing—IEEE 1547 compliant

\[ q_j^g = 0 \]

Operation at net unity power factor—RSI study

\[ q_j^g = q_j^c \]

Proportional control on \( V_j \)—EPRI White Paper
Prototypical Distribution Circuit

- $V_0 = 7.2$ kV line-to-neutral
- $n = 250$ nodes
- Distance between nodes = 200 meters
- Line impedance = $0.33 + i \ 0.38$ $\Omega$/km
- 50% of nodes are PV-enabled with 2 kW maximum generation
- Inverter capacity $s = 2.2$ kVA – 10% excess capacity
Import and Export Cases

**Import—Heavy cloud cover**
- \( p^c = \) uniformly distributed 0-2.5 kW
- \( q^c = \) uniformly distributed 0.2\( p^c \)-0.3\( p^c \)
- \( p^g = 0 \) kW
- Average import per node = 1.25 kW

**Export—Full sun**
- \( p^c = \) uniformly distributed 0-1.0 kW
- \( q^c = \) uniformly distributed 0.2\( p^c \)-0.3\( p^c \)
- \( p^g = 2.0 \) kW
- Average export per node = 0.5 kW

**Measures of control performance**
- \( \delta V \)—maximum voltage deviation in transition from export to import
- Average of import and export circuit dissipation relative to “Do Nothing-Base Case”
Performance of Simple Schemes

- Distributed (local) control is sufficient to maintain voltage regulation.
- 10% excess inverter capacity ($s = 1.1 p_{g,\text{max}}$) is sufficient.
- Clearly important differences between different control inputs (here, $q^c$ vs. $V$).
- Volt-control schemes increase dissipation.
- $q^c$ scheme reduces dissipation, but small gains in $\delta V$. 
More Sophisticated Schemes?—Improve Voltage Regulation of $q^g=q^c$

- Use heuristics to infer line flows $P_j$ and $Q_j$—for example, circuit segment $j$ has no voltage drop if
  \[-\Delta V_j = r_j P_j + x_j Q_j = 0\]

- This suggests that the following control scheme for PV-enabled nodes
  \[r_j (p^c_j - p^g_j) + x_j (q^c_j - q^g_j) = 0\]

- Or, equivalently…..
  \[q^g_j = F^V = q^c_j + \alpha (p^c_j - p^g_j)\]

- Blend $F^V$ with $q^g=F^L=q^c$ to achieve both loss reduction and voltage regulation:
  \[q^g_j = F = K q^c_j + (1 - K)[q^c_j + \alpha (p^c_j - p^g_j)]\]
  \[q^g_j = F = K F^L + (1 - K) F^V\]
Performance of Composite Control $F(K)$

- Voltage regulation is somewhat improved, but at a high cost of increased losses
- Can we do better?

$$q_j^g = F = KF^L + (1 - K)F^V$$
Hybrid Control Schemes

- $q^g=q^c$ achieves good loss reduction
- Proportional control on $V_j$ achieves good voltage regulation

Set $q^g=q^c$ when $V_j=1$ p.u.

\[ q^g_j (V_j = 1) = K F^L + (1 - K) F^V \]
Leverage nodes that already have $V_j \approx 1.0$ p.u. for loss minimization

- Provides voltage regulation and loss reduction
- $K$ allows for trade between loss and voltage regulation
- Scaling factor provides related trades

$$q^g_j (V_j = 1) = K F^L + (1 - K) F^V$$
Conclusions

- In high PV penetration distribution circuits where difficult transient conditions will occur, adequate voltage regulation and reduction in circuit dissipation can be achieved by:
  - Local control of PV-inverter reactive generation (as opposed to centralized control)
  - Moderately oversized PV-inverter capacity ($s \sim 1.1 \, p_{g,\text{max}}$)

- Using voltage as the only input variable to the control may lead to increased average circuit dissipation
  - Other inputs should be considered such as $p^c$, $q^c$, and $p^g$.
  - Blending of schemes that focus on voltage regulation or loss reduction into a hybrid control shows improved performance and allows for simple tuning of the control to different conditions.

- Equitable division of reactive generation duty and adequate voltage regulation will be difficult to ensure simultaneously.
  - Cap reactive generation capability by enforcing artificial limit given by $s \sim 1.1 \, p_{g,\text{max}}$