Options for Control of Reactive Power by Distributed Photovoltaic Generators

Petr Sulc[1]

Konstantin Turitsyn[1]

Scott Backhaus[2]

Michael Chertkov[1]

[1]Theoretical Division, Los Alamos National Laboratory

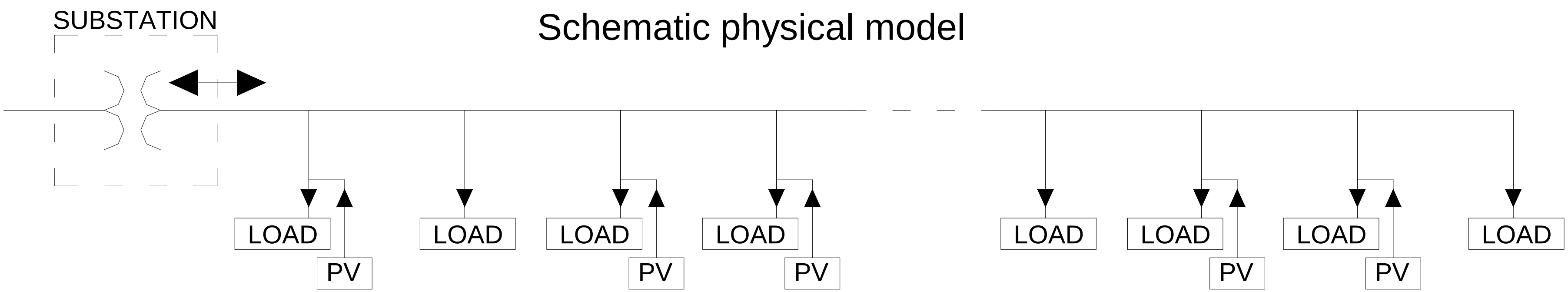
[2] Materials, Physics and Applications Division, Los Alamos National Laboratory

Objectives / Outline

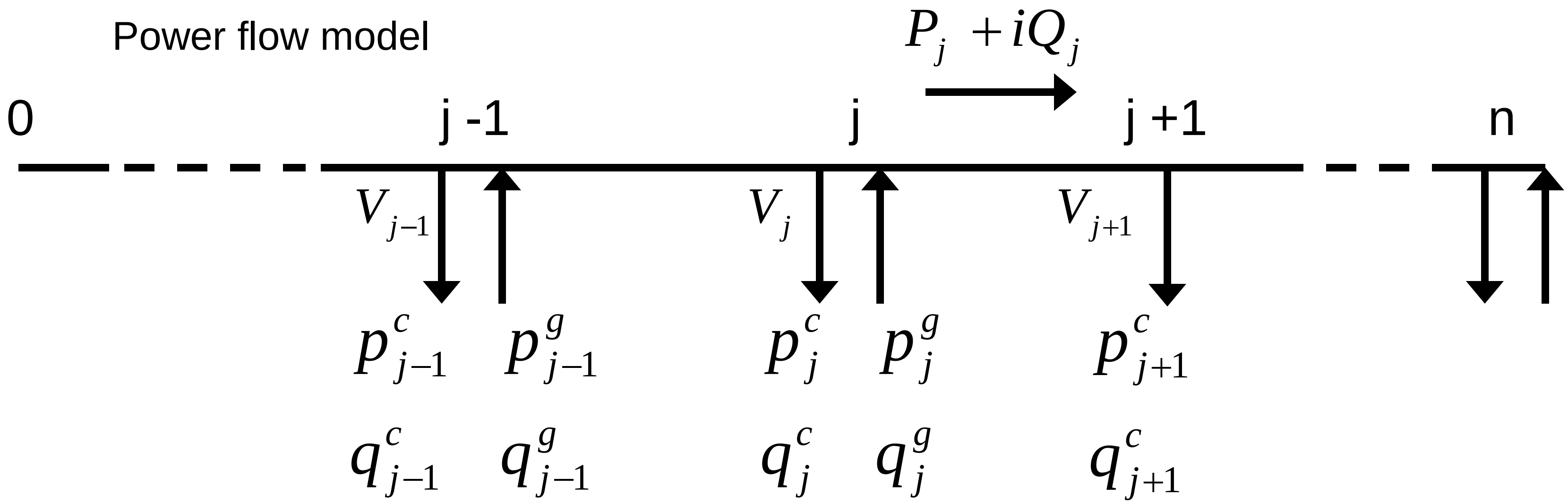
- **Distribution circuits with a high penetration of PV generation may**
  - experience rapid changes in cloud cover. Inducing…
  - rapid variations in PV generation. Causing…
  - reversals of real power flow and potentially large voltage variations
- **We seek to control the voltage variations by controlling 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
- **<u>Questions we will try to (at least partially) answer:</u>**
  - 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

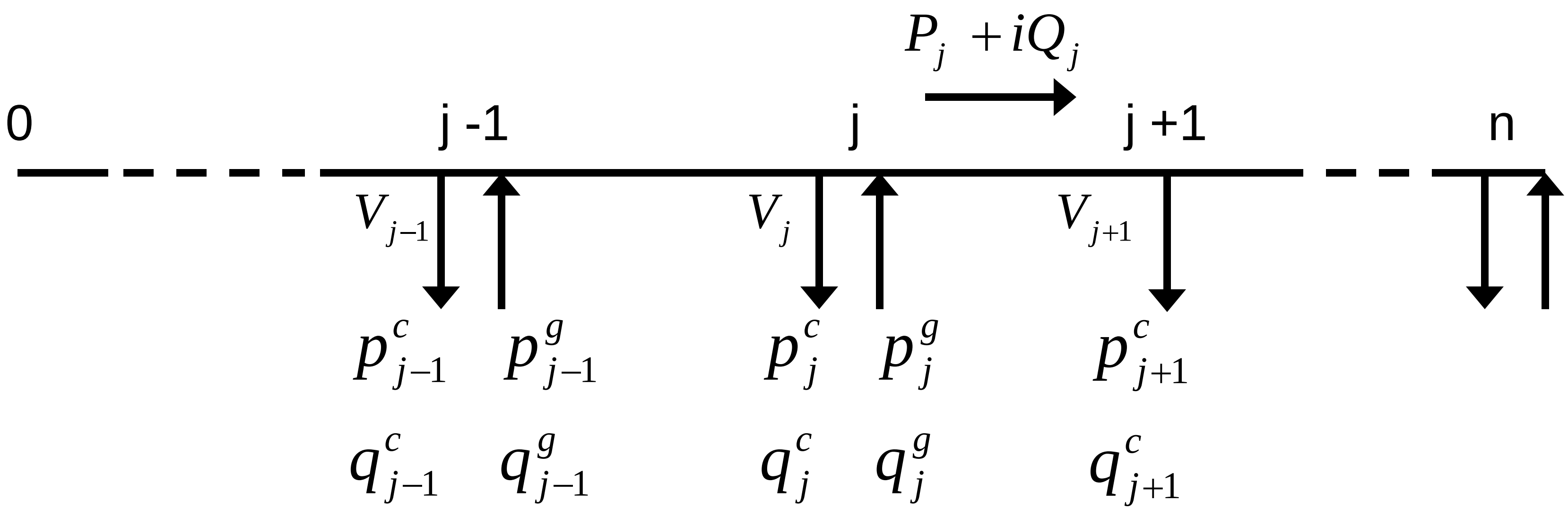
Schematic physical model



Power flow model



Power Flow—Voltage Variations and Losses



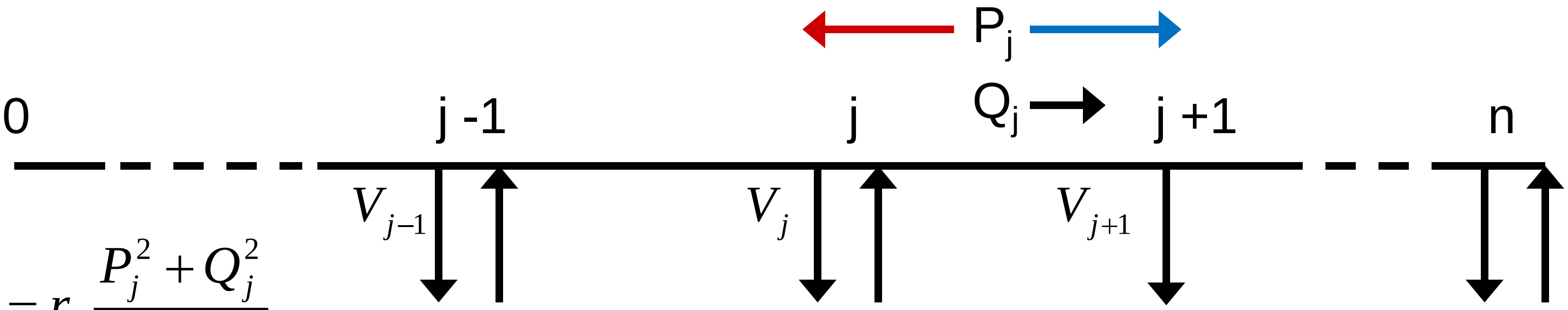
$$Loss_j = r_j \frac{P_j^2 + Q_j^2}{V_0^2}$$

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

<u>Competing objectives</u>

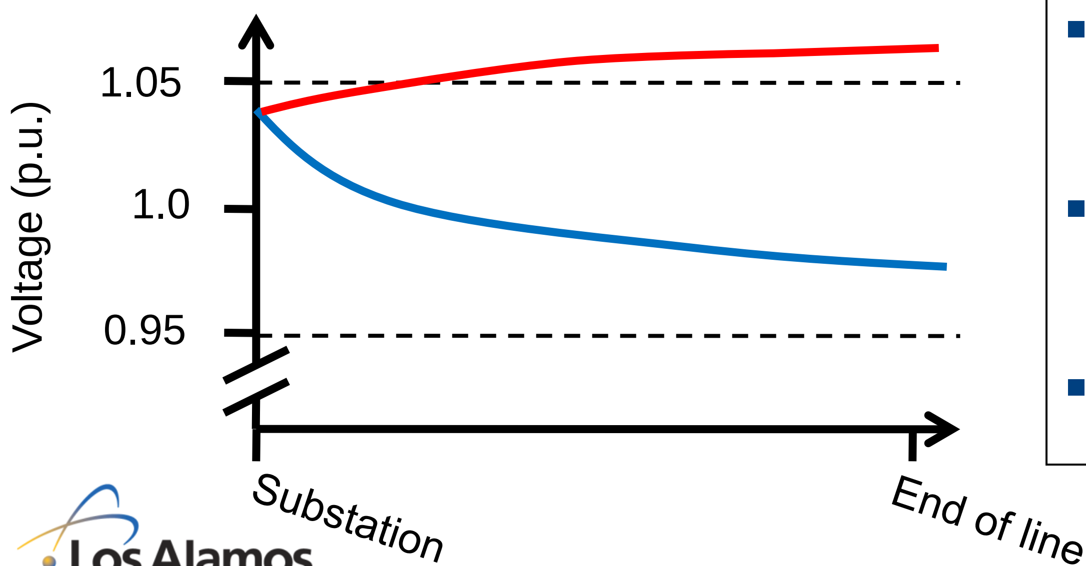
- Minimize losses → $Q_j=0$
- Voltage regulation → $Q_j=-(r_j/x_j)P_j$

Fundamental Problem—Import versus Export



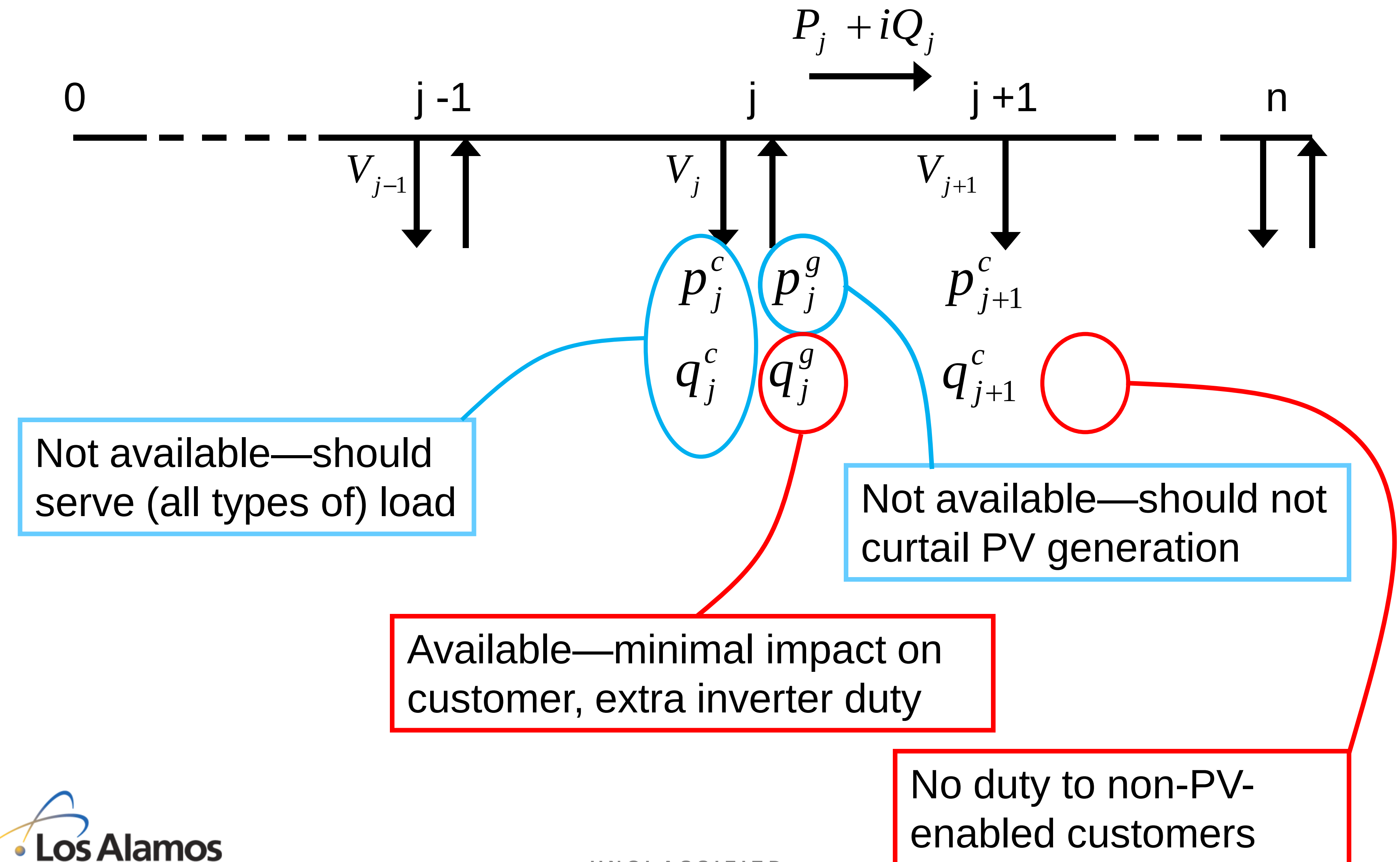
$$Loss_j = r_j \frac{P_j^2 + Q_j^2}{V_0^2}$$

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

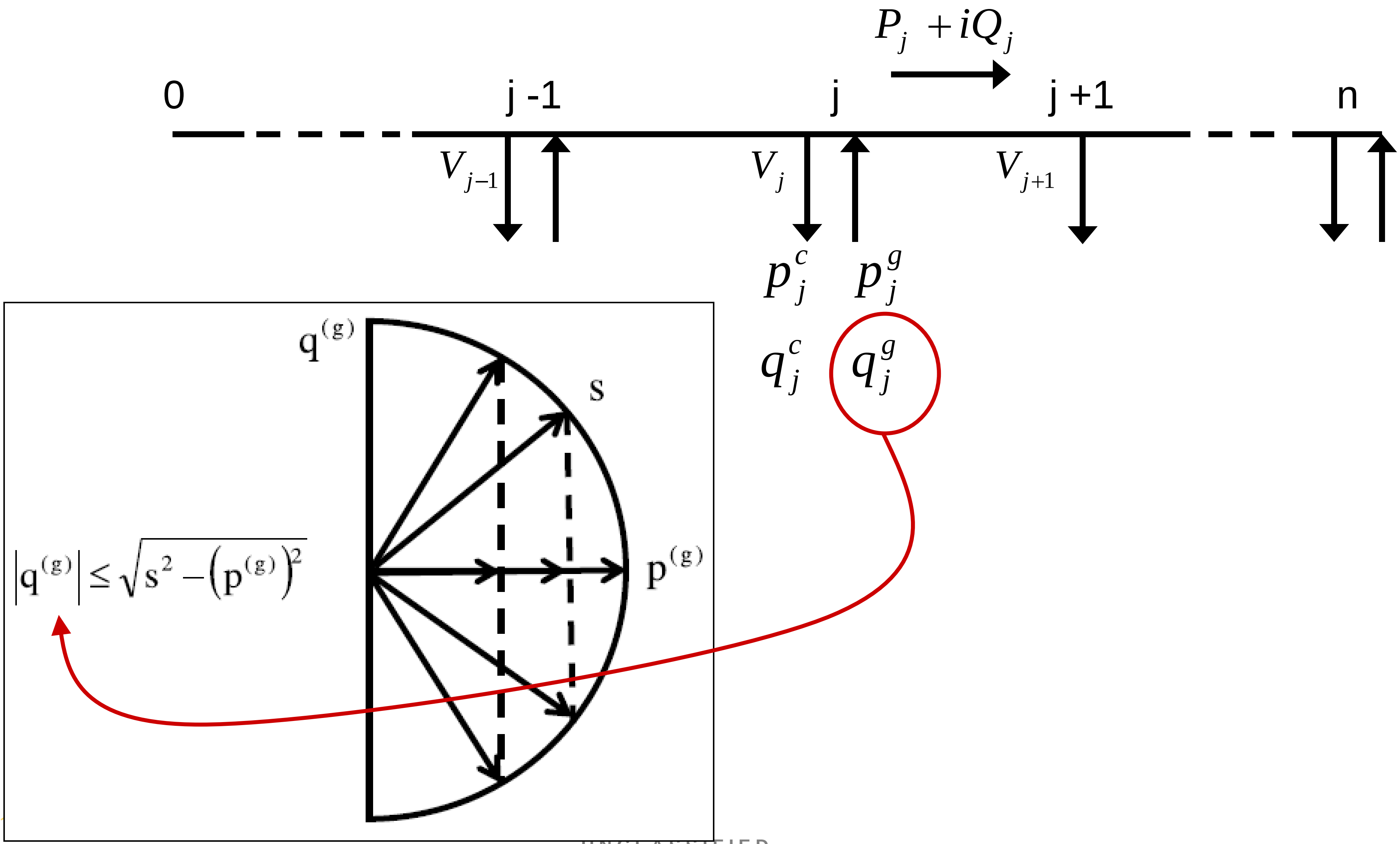


- Rapid reversal of real power flow can cause undesirably large voltage changes
- Rapid PV variability cannot be handled by current electro-mechanical systems
- Use PV inverters to generate or absorb reactive power to restore voltage regulation
- In addition… optimize power flows for minimum dissipation

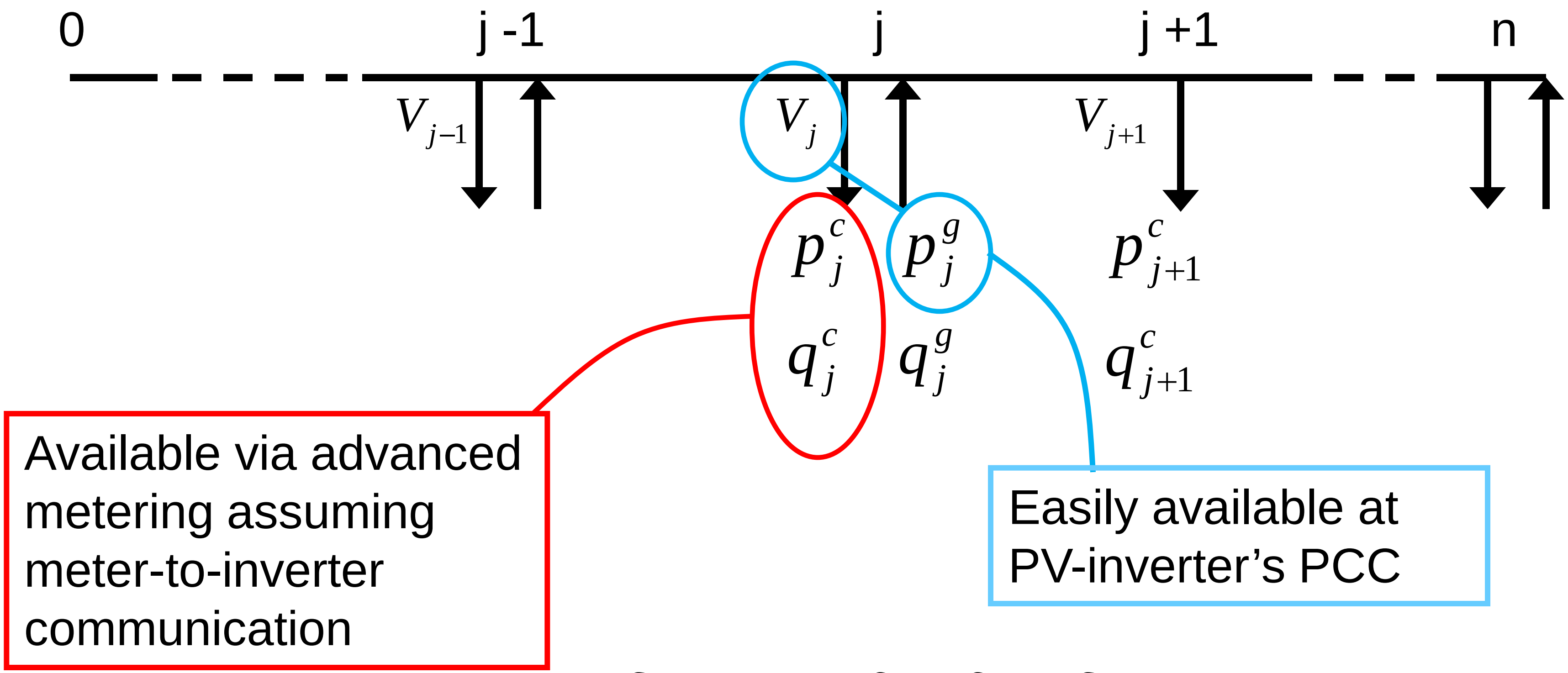
Parameters Available to Affect Control of V_j



Limits on Control—Inverter Capacity (s)



Availability of Inputs to a Local Control Scheme



$$q_j^g = F(p_j^c, q_j^c, p_j^g, V_j)$$

$$\left|q_j^g\right| < \sqrt{s_j^2 - (p_j^g)^2} = q_j^{\max}$$

Consider a Few Simple Schemes

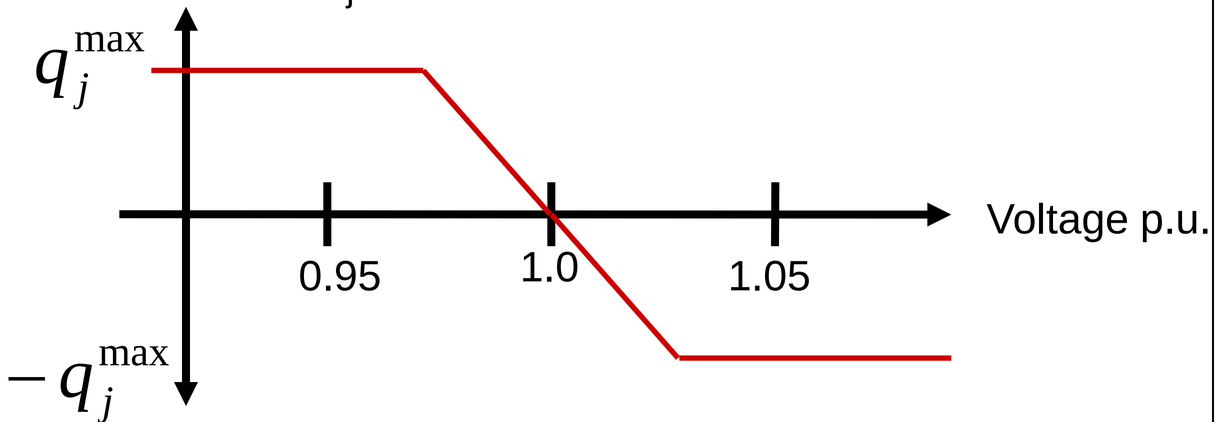
Baseline—Do Nothing—IEEE 1547 compliant

$$q_j^g = 0$$

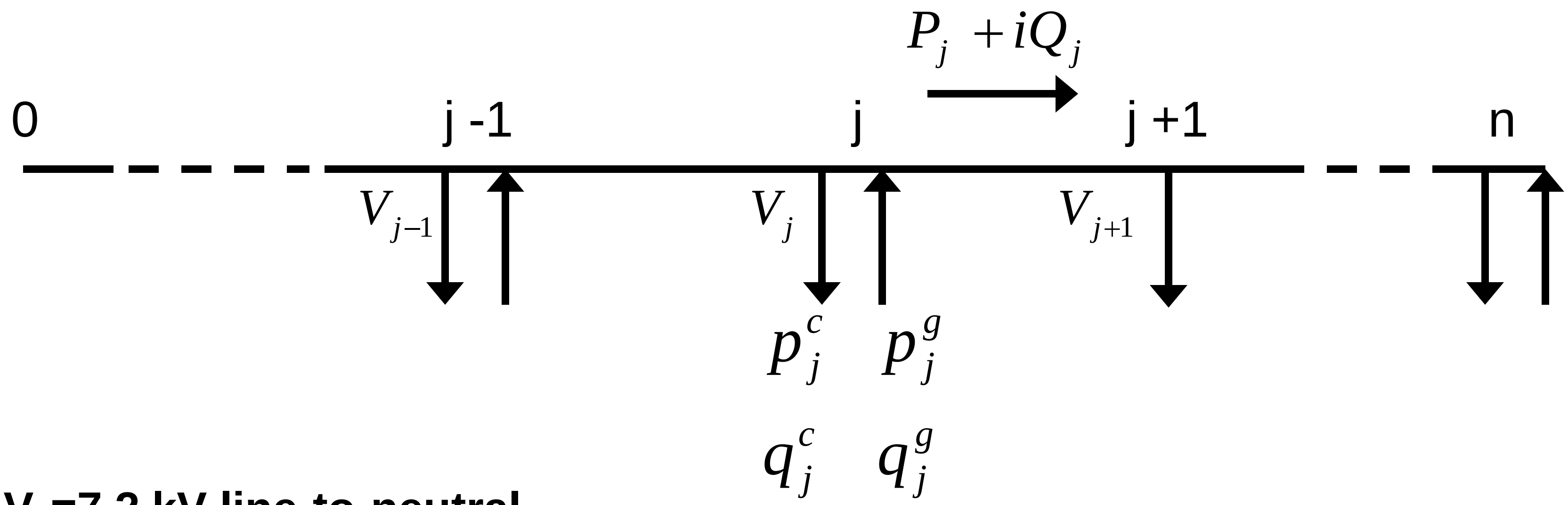
Operation at net unity power factor—RSI study

$$q_j^g = q_j^c$$

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 Ω/km**
- **50% of nodes are PV-enabled with 2 kW maximum generation**
- **Inverter capacity s=2.2 kVA – 10% excess capacity**

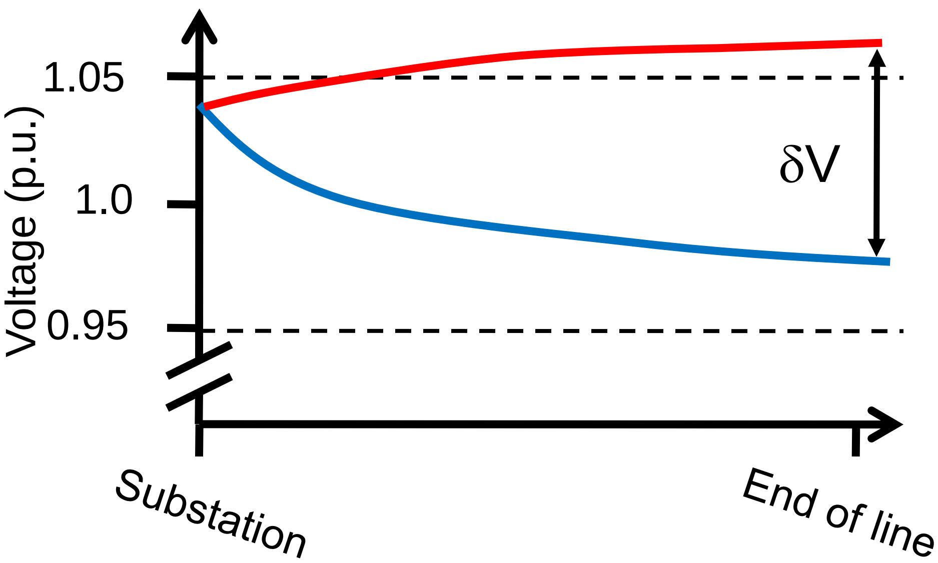
Import and Export Cases

Import—Heavy cloud cover

- p^c = uniformly distributed 0-2.5 kW
- q^c = uniformly distributed $0.2p^c$-$0.3p^c$
- p^g = 0 kW
- Average <u>import</u> per node = 1.25 kW

Export—Full sun

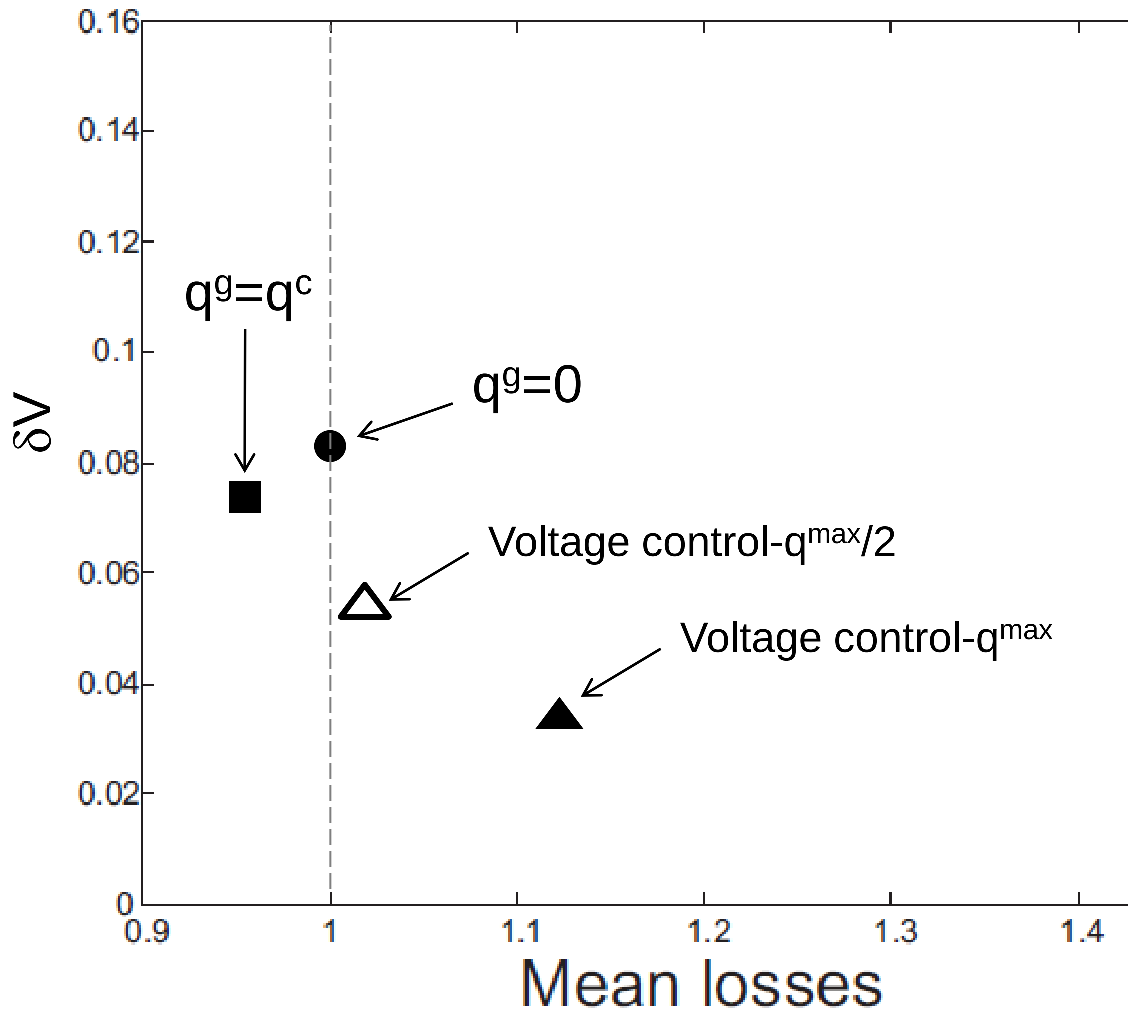
- p^c = uniformly distributed 0-1.0 kW
- q^c = uniformly distributed $0.2p^c$-$0.3p^c$
- p^g = 2.0 kW
- Average <u>export</u> per node = 0.5 kW



Measures of control performance

- δV—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 ($s=1.1\ p^{g,max}$) 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 δV.**

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**

$$r_j(p_j^c - p_j^g) + x_j(q_j^c - q_j^g) = 0$$

- **Or, equivalently…..**

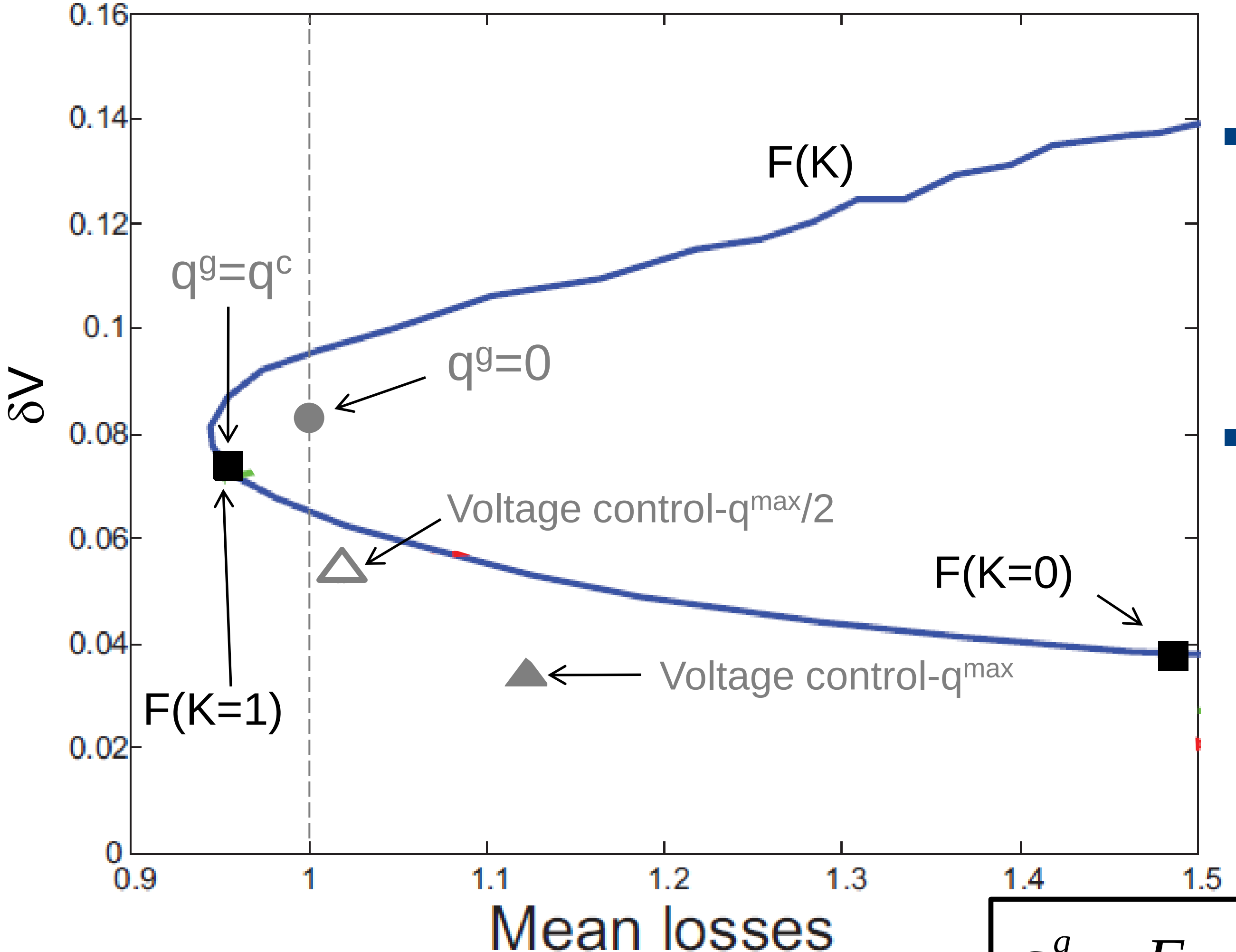
$$q_j^g = F^V = q_j^c + \alpha(p_j^c - p_j^g)$$

- **Blend F^V with $q^g=F^L=q^c$ to achieve both loss reduction and voltage regulation:**

$$q_j^g = F = Kq_j^c + (1-K)[q_j^c + \alpha(p_j^c - p_j^g)]$$

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

Performance of Composite Control F(K)

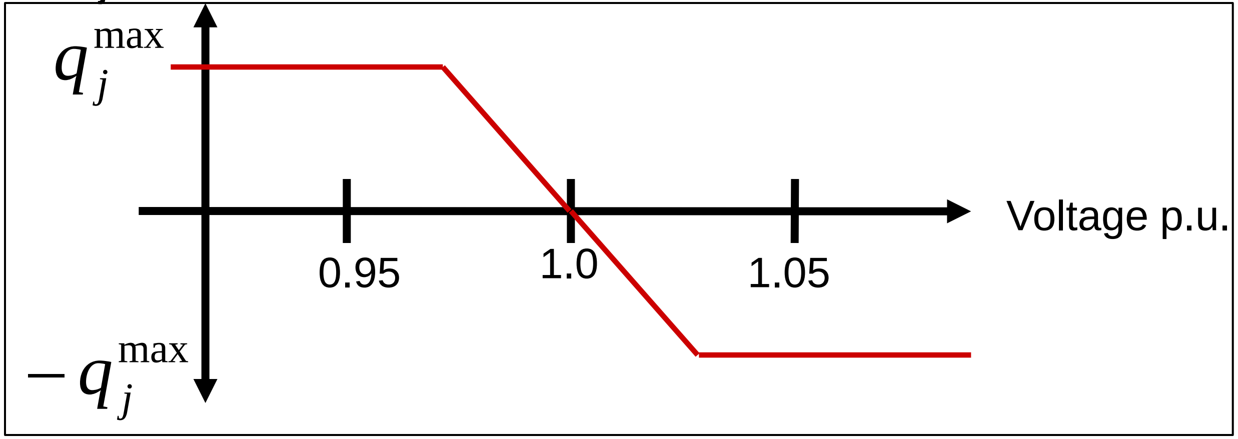


- **Voltage regulation is somewhat improved, but at a high cost of increased losses**
- **Can we do better?**

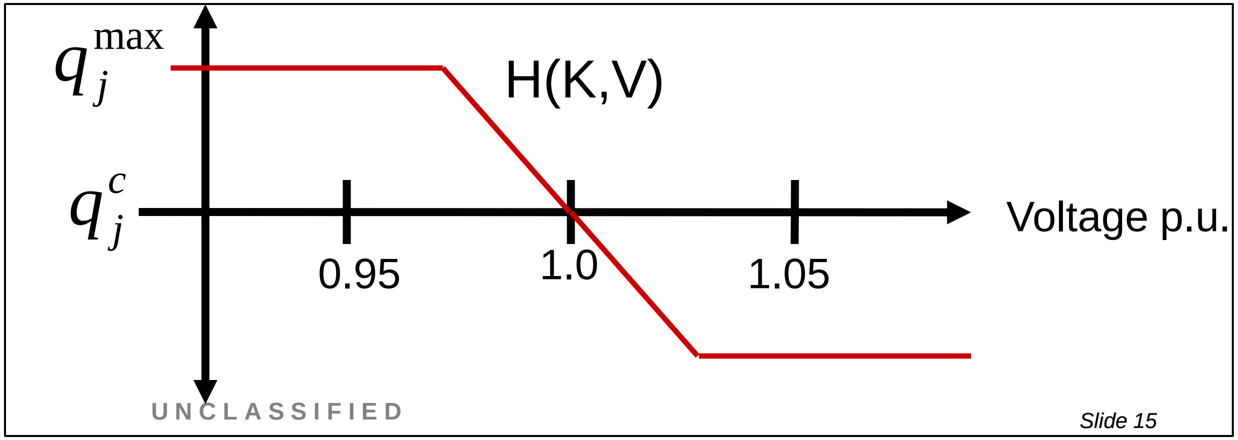
$$q_j^g = F = KF^L + (1-K)F^V$$

Hybrid Control Schemes

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

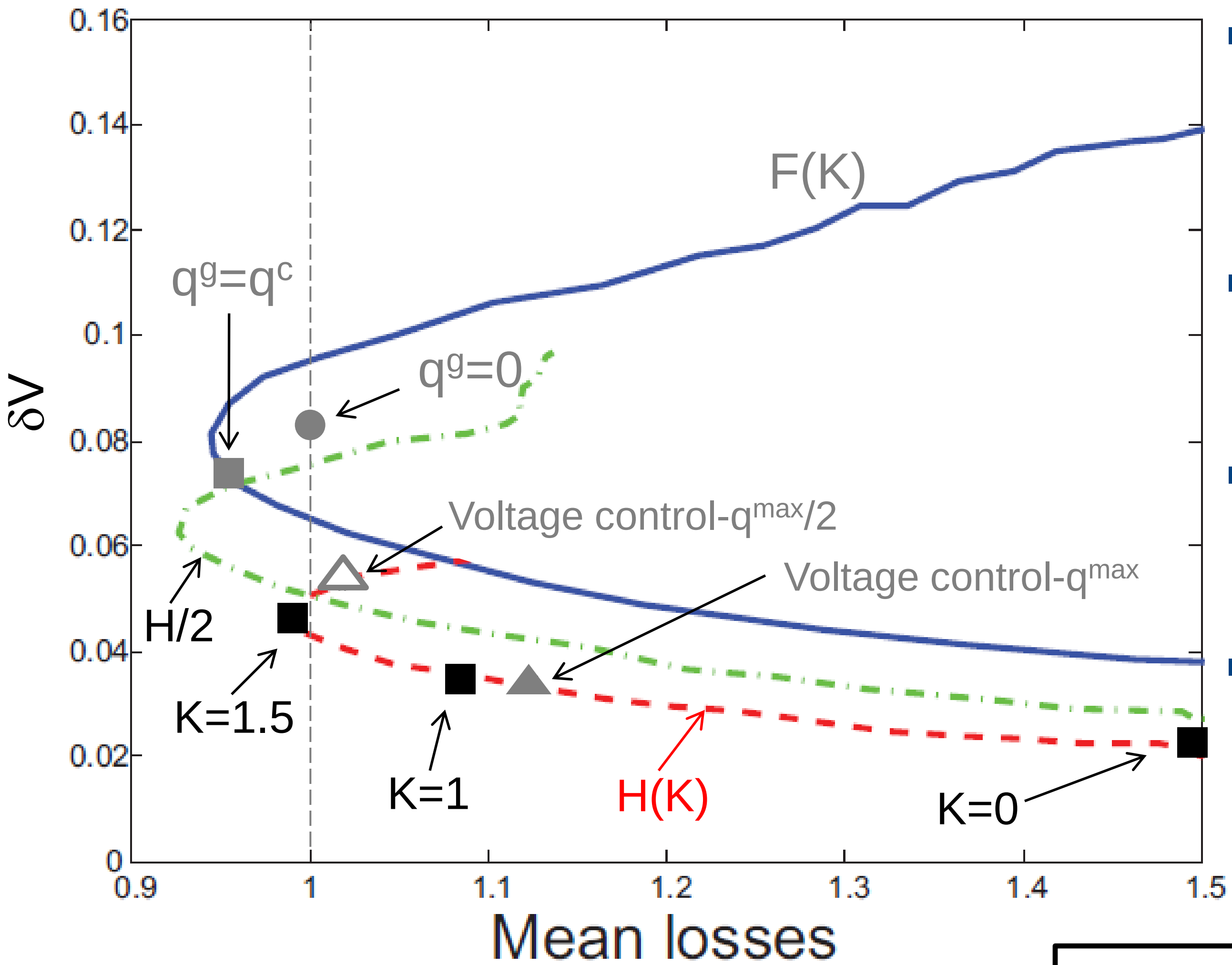


- Set $q^g = q^c$ when $V_j = 1$ p.u.



$$q_j^g(V_j = 1) = KF^L + (1-K)F^V$$

Performance of Hybrid Control H(K,V)



- **Leverage nodes that already have V_j~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**

$$q_j^g(V_j = 1) = KF^L + (1-K)F^V$$

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 ($s \sim 1.1\ p^{g,max}$)

- **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 $s \sim 1.1\ p^{g,max}$