Voltage Regulation by Distributed Generation

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Energy Efficiency Training Program

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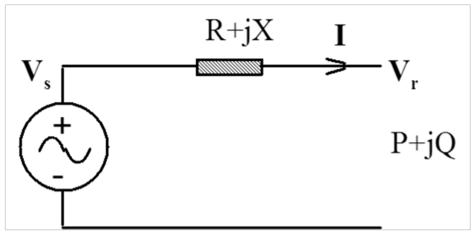
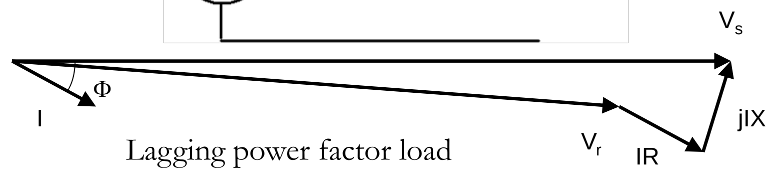
Overview

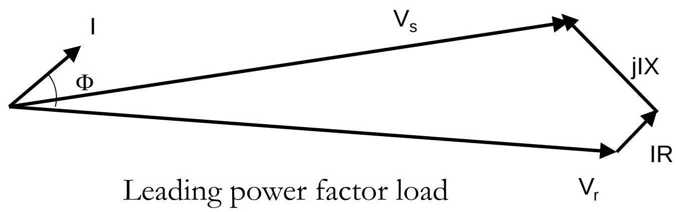
- Understanding the concept of voltage regulation by a DG system
- Method to determine the optimal ratio of real and reactive power injection from DG for maximum voltage support
- Voltage control approach for DG system to ensure the best performance
- Investigation for network support by considering:
  - The options to maintain acceptable voltage profile,
  - The control strategies to maintain acceptable profiles at lowest cost, and
  - The energy injection for voltage specification.

Voltage Drop in a Distribution Feeder



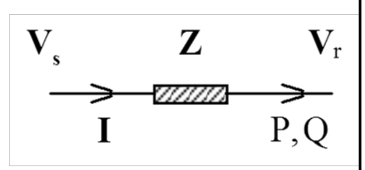


Lagging power factor load



Leading power factor load

Voltage Drop Calculations



Normal voltage range: - 6% to +10%

At the receiving end $\mathbf{S} = \mathbf{V}_r \mathbf{I}^* = P + jQ$

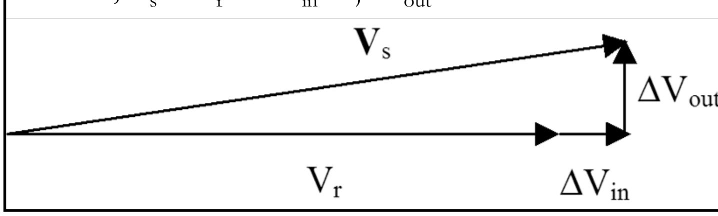
Take $\mathbf{V}_r$ to be real so $\mathbf{V}_r^* = \mathbf{V}_r$

& $\mathbf{I} = S^*/V_r^* = (P-jQ)/V_r$ (1)

Then $\mathbf{V}_s = V_r + \mathbf{ZI} = V_r + (R+jX)(P-jQ)/V_r$

$$= \left[V_r + \frac{RP + XQ}{V_r} \right] + j\left[\frac{XP - RQ}{V_r} \right] \quad (2)$$

Hence, $\mathbf{V}_s = V_r + \Delta V_{in} + j\Delta V_{out}$ (3)



Approximation for small voltage drops and Small Resistance

Approximation for small voltage drops

From the diagram, roughly $\Delta V_{in} \rightarrow$ magnitude phase

$\Delta V_{out} \rightarrow$ phase change

Hence $$V_s - V_r \approx \frac{RP + XQ}{V_r} = RI_{in} + XI_{out} \quad (4)$$

$$\angle V_s - \angle V_r \approx \frac{XP - RQ}{V_r^2} = \frac{XI_{in} - RI_{out}}{V_r} \quad (5)$$

Approximation for small resistance

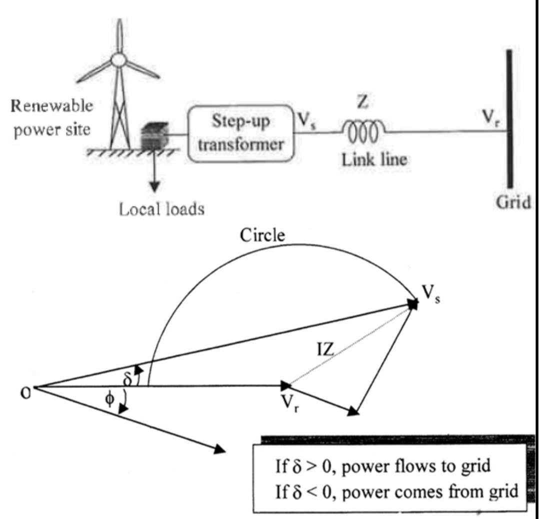
For higher voltage lines, R is often much smaller than X

Hence $$V_s - V_r \approx \frac{XQ}{V_r} = XI_{out} \quad (6)$$

$$\angle V_s - \angle V_r \approx \frac{XP}{V_r^2} = \frac{XI_{in}}{V_r} \quad (7)$$

Voltage Regulation: Issue and Concern

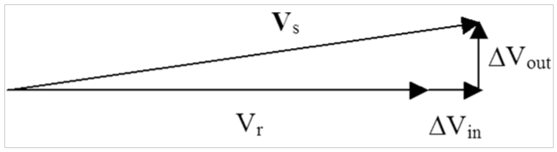
- Voltage regulation is a strong function of the load power factor.
- Voltage regulation is greater for lagging power factor, and the least or even negative for leading power factor.
- If V_r and I are held constant and the power factor of the load is varied from zero lagging to zero leading, the vector V_s will vary such that its end point will lie on a circle since IZ is constant.

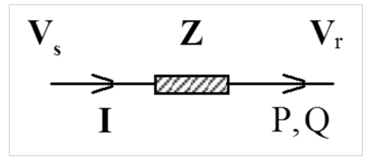


Mukund R. Patel, "Wind and Solar Power Systems", CRC Press

Calculation of Voltage Regulation

- Voltage drop is due to the flow of P, Q in the line and also depend on load demand.





- It has been proved that

  $V_s - V_r \approx \frac{RP + XQ}{V_r} = RI_{in} + XI_{out} = RI\cos\Phi + XI\sin\Phi$ (1)

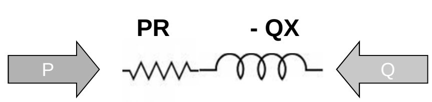
- Voltage regulation (VR) for a distribution line is

  $VR = (V_{nl} - V_{fl})/V_{fl} = (V_s - V_r)/V_r$

  $= (RI_{in} + XI_{out})/V_r = (RP + XQ)/V_r^2$ (2)

Voltage Regulation

- Voltage Regulation (VR) = $(RP + XQ) / V_r^2$
- If P and Q flow in opposite directions…
- QX can cancel out PR!

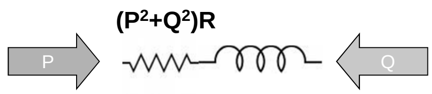


- No Voltage Drop!

Line Losses

$\mathbf{V}_r\mathbf{I}^* = \mathrm{P} + \mathrm{jQ}$ $\quad \mathbf{I} = (\mathrm{P} - \mathrm{jQ})/\mathrm{V}_r$ $\quad \mathrm{I}^2 = (\mathrm{P}^2 + \mathrm{Q}^2)/\mathrm{V}_r^2$

- Losses = $I^2R = R. (P^2 + Q^2) / V_r^2$
- So even if P and Q flow in opposite directions…
- P^2 and Q^2 add together not cancel!



Relation between V, P and Q

- The phase voltage V at a node is a function of real power, P and reactive power, Q at that node, and can be expressed as,

$$V = f(P,Q) \qquad (1)$$

- Therefore, the total differential of V can be written as,

$$dV = \frac{\partial V}{\partial P}\cdot dP + \frac{\partial V}{\partial Q}\cdot dQ \qquad (2)$$

- Equation (2) can be rearranged as,

$$dV = \frac{dP}{(\partial P/\partial V)} + \frac{dQ}{(\partial Q/\partial V)} \qquad (3)$$

- Equation (3) indicates that the change in voltage at a bus depends on the two quantities, which are $\partial P/\partial V$ and $\partial Q/\partial V$.

Relation between V, P and Q (Continued)

- Consider a line with series impedance R + jX and zero shunt admittance.

$$V_s - V_r = \frac{RP + XQ}{V_r} \quad (4) \qquad (V_s - V_r)V_r = RP + XQ \quad (5)$$

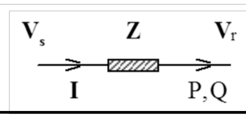
where V_s is constant, and V_r depends on P and Q.

- From equation (5), we obtain

$$\frac{\partial P}{\partial V_r} = \frac{V_s - 2V_r}{R} \quad (6) \qquad \frac{\partial Q}{\partial V_r} = \frac{V_s - 2V_r}{X} \quad (7)$$

- Substituting eqs (6) and (7) into equation (3), we get

$$dV_r = \frac{dP}{\partial P / \partial V_r} + \frac{dQ}{\partial Q / \partial V_r} = \frac{dP \cdot R + dQ \cdot X}{V_s - 2V_r} \quad (8)$$



Relation between V, P and Q (Continued)

- Voltage change at the receiving-end is

$$dV_r = \frac{dP}{\partial P / \partial V_r} + \frac{dQ}{\partial Q / \partial V_r} = \frac{dP \cdot R + dQ \cdot X}{V_s - 2V_r} \quad (8)$$

- For constant sending-end voltage V_s and for no change in receiving-end voltage (ΔV_r=0) we have,

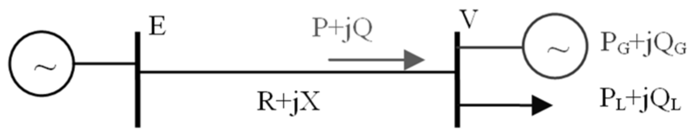
$$R\,dP + X\,dQ = 0 \Rightarrow R\,dP = -X\,dQ \Rightarrow dQ = -\frac{R}{X}dP \quad (9)$$

- This describes the change in Q to maintain the same voltage for a given change in P.
- To have zero voltage drop (zero voltage regulation), inject a sufficient amount of Q so that it satisfy RP = -XQ
- The other option, inject P and Q locally so that line power flows will become zero.

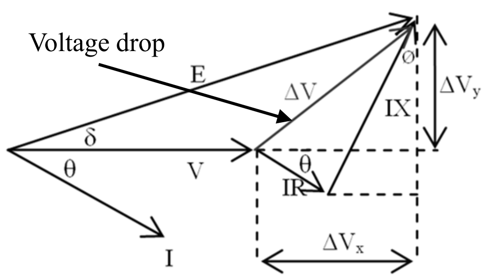
$P = P_0(\overline{V})^2$

Voltage correction by DG

- A power system with DG presence can be expressed by a Thevenin equivalent system



- Phasor diagram of the equivalent system



$$\Delta V_x = \frac{RP + XQ}{V}$$

$$\Delta V_y = \frac{XP - RQ}{V}$$

Voltage correction by DG (cont.)

- When DG is present

$$P = (P_L - P_G) \qquad Q = (Q_L - Q_G)$$

- When DG is not present

$$P = P_L \qquad Q = Q_L$$

- Thus, voltage change by DG (i.e. the change of voltage drop) is

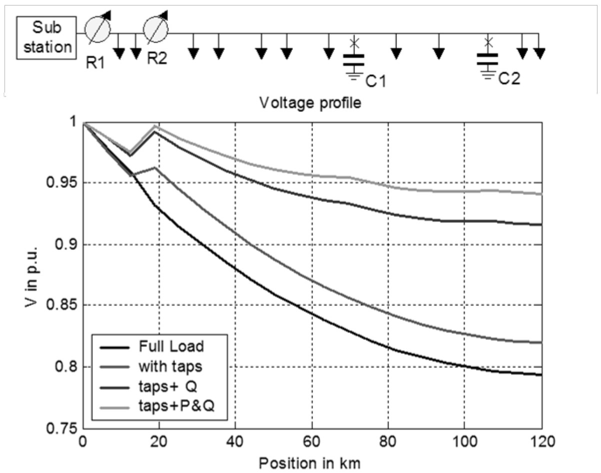
$$V^I = V_x^I + jV_y^I$$

where:

$$V_x^I = \frac{RP_G + XQ_G}{V}$$

$$V_y^I = \frac{XP_G - RQ_G}{V}$$

Voltage regulators and shunt capacitors for Voltage Correction



•Tap changers can be used to support the down stream voltage but do not respond quickly to load changes.

•Curve 'Full Load' is the profile without regulator or capacitor which is mostly below 0.94 p.u. voltage.

•'With Taps', the voltage profile moves up with the the regulator (R2).

• A set of capacitor banks (C1 and C2), moves the profile to curve 'taps +Q'.

•Introducing generation at the capacitor bank locations is an extreme measure but can also raise the voltage.

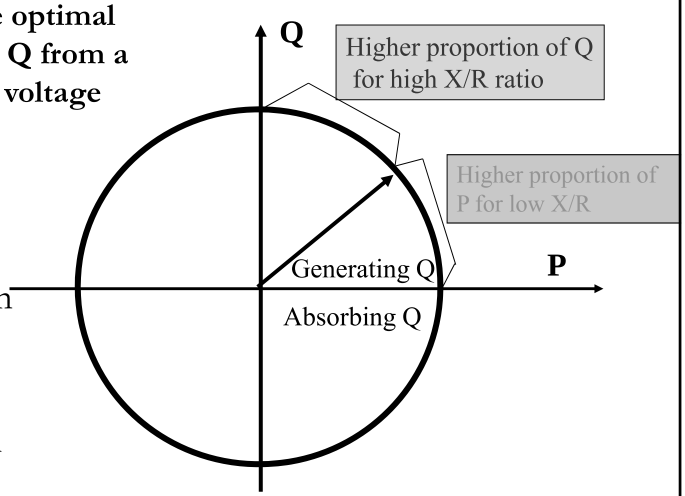
Effect of P and Q injections from DG on voltage support

- Normally, DG is operating with unity power factor (only produces real power).
- Other (typical) voltage supporting device (i.e. capacitor) produces only reactive power.
- Yet, it is found that DG operating with both real and reactive power is the best for voltage support.

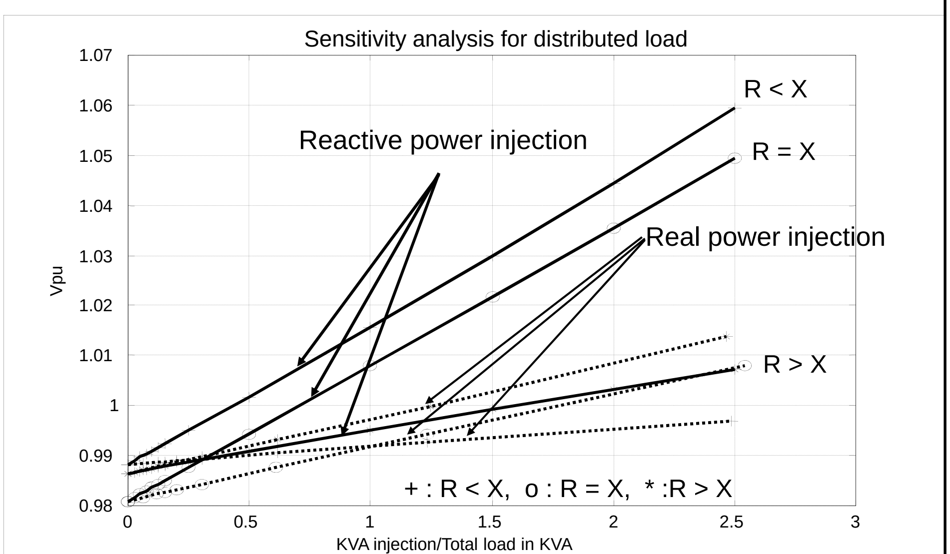
Combined PQ role for Voltage Support

How to determine optimal injection of P and Q from a DG for maximum voltage support?

- High P effectiveness, high fuel cost: high pf solution
- High Q effect, low fuel cost: low pf solution



What is effective for Acceptable voltage Profile



Determine the optimal operating condition of DG

- Representing the system by a Thevenin equivalent system looking from DG connection point
- Developing the relationship between line parameters and bus voltage
- Examining $\frac{\partial V}{\partial P_{DG}}$ and $\frac{\partial V}{\partial Q_{DG}}$
- Determining optimal ratio of P_{DG}/Q_{DG}

Voltage sensitivity for a SWER System

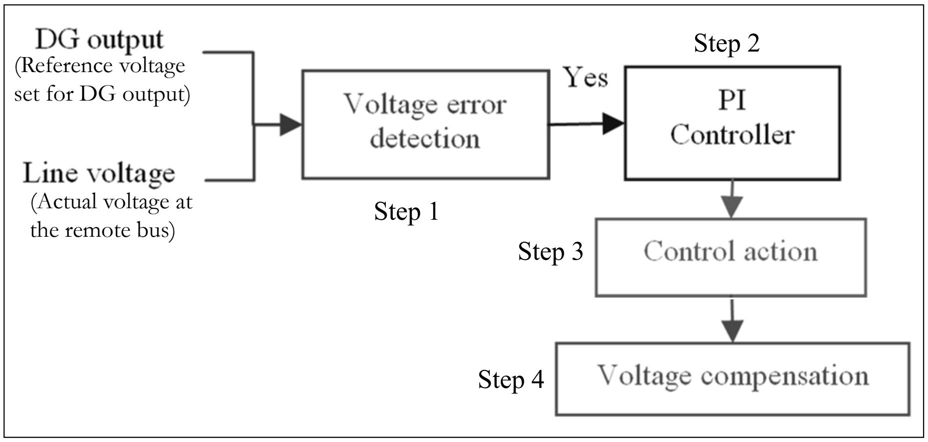
Z_{line} = 1.828 + j0.876 ohms/km, Source voltage V_s = 19.1 kV and source impedance Z_s = 70.53 + j57.73 ohms, Load buses N = 20 , Total load = 352 kW load at 0.8 pf, DG size = 50 kVA

DG mode	P Gen.	Q Gen.	DG Voltage	End Voltage	ΔV at DG connect	ΔV at end point	Sensitivity ratio
No DG	0	0	0.9417	0.9400	-	-	-
DG-P	0.0500	0	0.9750	0.9733	0.0333	0.0333	1.8:1
DG-Q	0	0.0500	0.9602	0.9586	0.0185	0.0186	
DG-PQ	0.0437	0.0240	0.9800	0.9783	0.0383	0.0383	

Note: All are in p.u. and system base is 1MVA

P and Q generations are required at the ratio of 1.8:1 at steady-state situation to improve the network voltage effectively. This performance is a 15% improvement over a pure P solution.

Method of Voltage regulation by DG



Step 1: Voltage error detection

- Voltage error: $\Delta V = |V_m| - |V_r| + \varepsilon$

  where: V_m is remote end actual voltage, V_r is reference voltage, and ε is tolerance factor.

- V_m is chosen to the voltage at the remote end as the remote bus is the **most voltage-unsafe** bus.
- V_m can be obtained by: a) Online measurement

  b) Line Drop Compensator
- V_r can be set to any desired value (typically it can be set to the lower voltage limit)

Step 2: Derive Control parameters with PI Controller

- DG controller is adjusted to improve the voltage by injecting both real and reactive power at the optimal ratio of line voltage sensitivity.
- The output of DG PI Controller can be expressed as:

$$M = K_p \Delta V + K_I \int \Delta V$$

where: M is controller output signal, K_P and K_I are proportional and integral constants, and ΔV is voltage error.

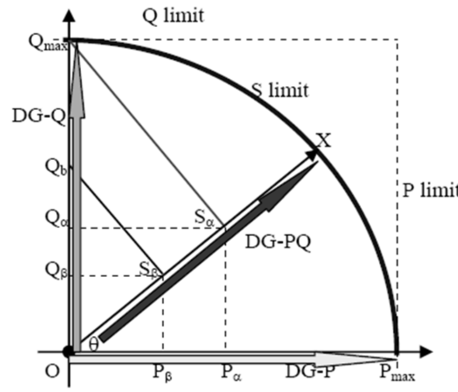
- K_P and K_I are adjusted to provide sufficient voltage correction.

Step 3 & 4: Control action and Voltage Compensation

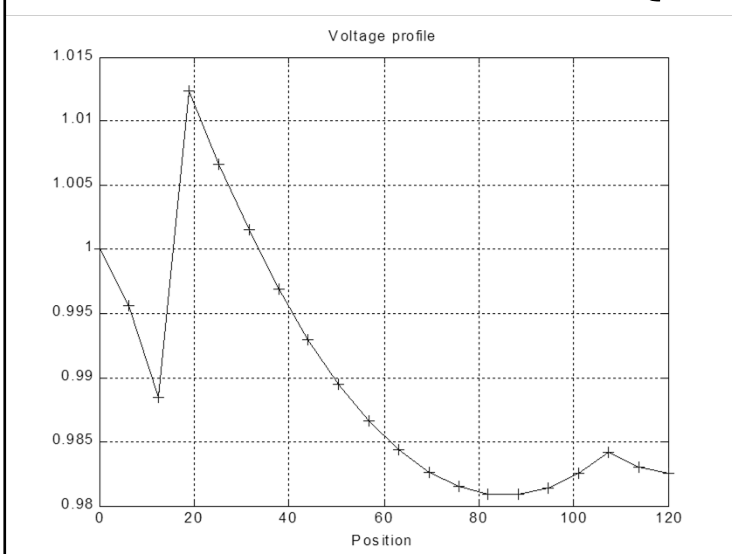
- The voltage compensation is achieved by following control actions:
  - 'Switch on'
  - 'Increasing output'
  - 'Decreasing output'
  - 'Switch off'
  - 'Doing nothing'

Control Issue with DG

- DG controller can be designed for injection of real power, reactive power or real power and reactive power both.
- DG can be operated as DG-P, DG-Q or DG-PQ mode.
- Best-suited control strategy to maintain acceptable profiles at lowest cost should be determined.

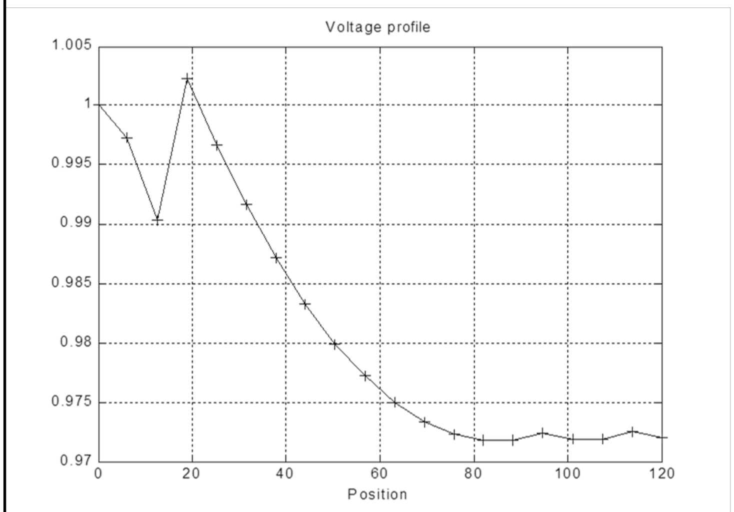


Voltage profile with 352 kW load and 100kVA DG-PQ



- Power loss = 8.87 kW and Lowest voltage = 0.9808 p.u.

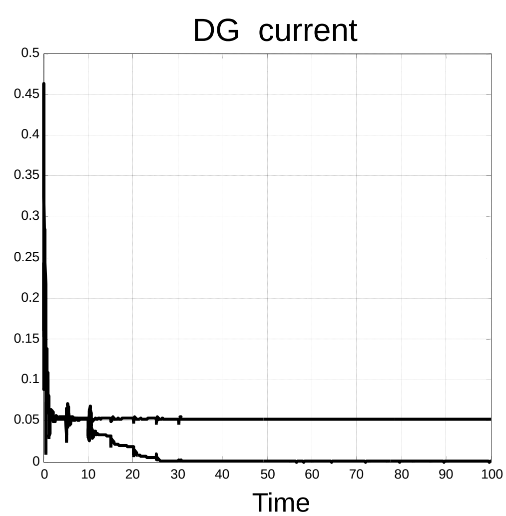
Voltage profile with 352 kW load and 2x50kVA DGs



- Power loss = 8.145 kW and Lowest voltage = 0.9718 p.u.

DG in single DG case provides better voltage support compared to the case of Multiple DGs with same capacity of single DG

Reference level implement priority role



- DG2 position is moved just to the next position of the regulator and DG1 position remains same.
- With higher V_{ref}, tap changer takes over from DG in Steady State, but Still available for transient

Region of influence

- The line characteristics and loading determine the strength of influence of voltage controllers
- Integral controllers placed in the zone of strong influence of others can have adverse interaction
- Setting different voltage references of different DGs can play a role for graduated response.

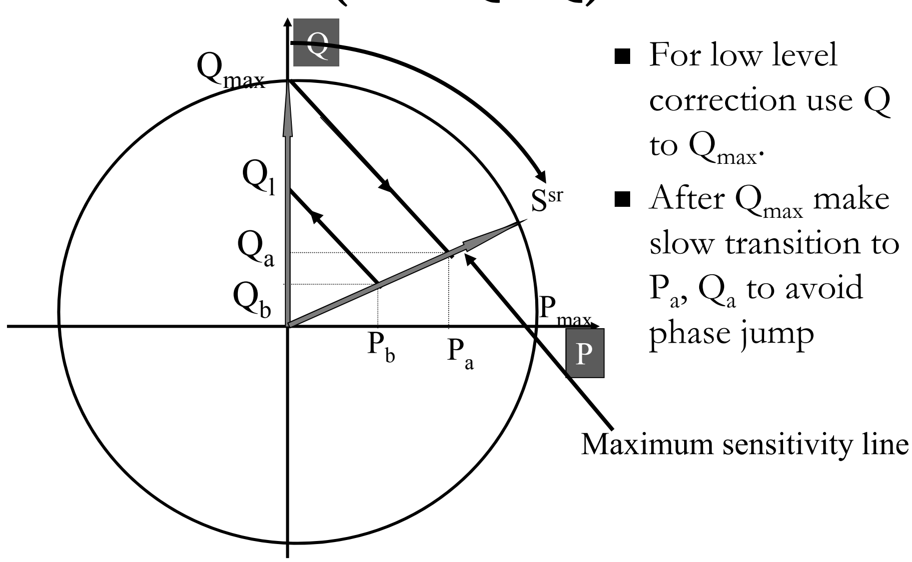
Inherent support from rotary generation

- The internal voltage of generator does not change rapidly, so sudden changes of terminal voltage tend to be limited by internal voltage.
- There will be a transient current overload until the field control acts.
- With inverter there is much lower transient overload capability but faster active control.

Steady State Voltage Support

- The best power factor for DG injection to achieve voltage correction becomes higher for high resistance lines.
- Multiple DG can aid voltage profile of feeder and should provide higher reliability. Setting the voltage references of separate DG's can provide a graduated response to voltage correction.
- Fuel cost is high for synchronous DG. So use reactive power only mode where possible. When extended overload expected commence real power generation.

Transition from Q Mode to PQ Mode (DG-QPQ)



- For low level correction use Q to Q_{max}.
- After Q_{max} make slow transition to P_a, Q_a to avoid phase jump

Conclusions

- A system with Distributed Generation (DG) has greater load carrying capacity and can support peak-shaving. A network with DG can correct for poor voltage profile, especially needed during peak time of the day.
- DG operation with Q priority is most economical, as it requires generation of less energy and reduces the fuel requirement to meet same level of voltage specification.

Conclusions (Continued)

- A technique for voltage support using DG system has been presented.
- A voltage regulation method can be developed based on
  - Optimal power injection from DG, and
  - Power output of DG is controlled by the PI controller.
- Voltage control technique can provide an effective solution for poor voltage problem.