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

Voltage Drop Calculations

Normal voltage range: -6% to +10%

At the receiving end

\[ S = V_r I^* = P + jQ \]

Take \( V_r \) to be real so \( V_r^* = V_r \)

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

Then \( V_s = V_r + ZI = V_r + (R+jX)(P-jQ)/V_r \)

\[ = \left[ V_r + \frac{RP+XQ}{V_r} \right] + j\left[ \frac{XP - RQ}{V_r} \right] \] \hspace{1cm} (2)

Hence, \( V_s = V_r + \Delta V_{in} + j\Delta V_{out} \) \hspace{1cm} (3)
Approximation for small voltage drops and Small Resistance

Approximation for small voltage drops

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

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

Hence $V_s - V_r \approx \frac{RI_{\text{in}} + XI_{\text{out}}}{V_r}$  \hspace{1cm} (4)

$\angle V_s - \angle V_r \approx \frac{XI_{\text{in}} - R I_{\text{out}}}{V_r}$  \hspace{1cm} (5)

Approximation for small resistance

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

Hence $V_s - V_r \approx \frac{XQ}{V_r} = XI_{\text{out}}$  \hspace{1cm} (6)

$\angle V_s - \angle V_r \approx \frac{XP}{V_r^2} = \frac{XI_{\text{in}}}{V_r}$  \hspace{1cm} (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.

Calculation of Voltage Regulation

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

$$V_s - V_r \approx \frac{RI_{in} + XI_{out}}{V_r} = R\cos\phi + X\sin\phi$$ (1)

- It has been proved that

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}} = \frac{V_s - V_r}{V_r} = \frac{RI_{in} + XI_{out}}{V_r} = \frac{RP + XQ}{V_r^2}$$ (2)

Voltage Regulation

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

No Voltage Drop!
Line Losses

\[ V_r I^* = P + jQ \quad I = \frac{(P - jQ)}{V_r} \quad I^2 = \frac{(P^2 + Q^2)}{V_r^2} \]

- Losses = \( I^2R = R \cdot \frac{(P^2 + Q^2)}{V_r^2} \)
- 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,

\[ V = f(P, Q) \] (1)

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

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

- Equation (2) can be rearranged as,

\[ dV = \frac{dP}{(\partial P/\partial V)} + \frac{dQ}{(\partial Q/\partial V)} \] (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.

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

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

- From equation (5), we obtain

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

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

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

\[ \begin{array}{c c c}
V_s & Z & V_r \\
\downarrow & \rightarrow & \downarrow \\
P, Q
\end{array} \]

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 ($\Delta V_r = 0$) we have,

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

- 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.
Voltage correction by DG

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

\[ P = (P_L - P_G) \quad Q = (Q_L - Q_G) \]

- When DG is not present.

\[ P = P_L \quad Q = Q_L \]

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

\[ V^I = V_x^I + jV_y^I \]

where:

\[ V_x^I = \frac{RP_a + XQ_a}{V} \]

\[ V_y^I = \frac{XP_a - RQ_a}{V} \]
Voltage regulators and shunt capacitors for Voltage Correction

- 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 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.

- Tap changers can be used to support the downstream voltage but do not respond quickly to load changes.

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

Sensitivity analysis for distributed load

Reactive power injection
- \( R < X \)
- \( R = X \)
- \( R > X \)

Real power injection

\( + : R < X, \quad \circ : R = X, \quad * : R > X \)
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

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

<table>
<thead>
<tr>
<th>DG mode</th>
<th>P Gen.</th>
<th>Q Gen.</th>
<th>DG Voltage</th>
<th>End Voltage</th>
<th>$\Delta V$ at DG connect</th>
<th>$\Delta V$ at end point</th>
<th>Sensitivity ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>No DG</td>
<td>0</td>
<td>0</td>
<td>0.9417</td>
<td>0.9400</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>DG-P</td>
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<td>0</td>
<td>0.9750</td>
<td>0.9733</td>
<td>0.0333</td>
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<td>1.8:1</td>
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<tr>
<td>DG-Q</td>
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<td>0.0500</td>
<td>0.9602</td>
<td>0.9586</td>
<td>0.0185</td>
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<tr>
<td>DG-PQ</td>
<td>0.0437</td>
<td>0.0240</td>
<td>0.9800</td>
<td>0.9783</td>
<td>0.0383</td>
<td>0.0383</td>
<td></td>
</tr>
</tbody>
</table>

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 \( \varepsilon \) 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 \( \Delta V \) 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

Maximum sensitivity line
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.