Parallel Operation of Distributed Generators by Virtual Synchronous Generator Control in Microgrids

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• Introduction

• Parallel Inverters

• Synchronous Generator + Inverter

• Conclusion
Contents

• Introduction
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• Conclusion
Inertial feature of Synchronous Generators

**Synchronous Generator**

\[
W = \frac{1}{2} J \omega_m^2
\]

Kinetic Energy of Rotating Mass

\[
P_m - P_e = J \omega_m \frac{d\omega_m}{dt} + D(\omega_m - \omega_g)
\]

Swing Equation

Frequency fluctuation under active power transition limited by the inertia

**DC/AC Inverter**

Active Power \( P \)

No intrinsic relation

Frequency \( \omega \)

Undesirable frequency dynamics

\( P_m \): Shaft power
\( P_e \): Output power
\( \omega_m \): Rotor frequency
\( \omega_g \): Grid frequency
\( J \): Moment of inertia
\( D \): Damping factor
Concept of VSG Control

- Conventional Droop Control
- Load Sharing
- Smooth Transition between Islanding and Grid-connection
- Swing Equation Emulation
- Inertia Support
- Virtual Synchronous Generator (VSG) Control
- A New Concept of Inverter Control in AC Microgrid

Mathematical Equation:

\[ P_{in} - P_{out} = J \omega_m \frac{d\omega_m}{dt} + D(\omega_m - \omega_g) \]
To apply VSG control to DC-AC inverters in microgrids

Objectives

- Two topics to be discussed
  - Parallel Inverters
  - Synchronous Generator + Inverter
What is the benefit?

Without Frequency Restoration

Frequency during Loading transition

With Frequency Restoration

Frequency during Three-phase ground fault cleared in 0.1 s

- Slower frequency variation rate
- Less maximum frequency deviation
- Less maximum frequency deviation
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Microgrid: Parallel Inverters

2 parallel DGs equipped with VSG control

MGCC

Grid

BUS

Microgrid Central Controller (MGCC)
Frequency and voltage restoration

DG1 $S_{base1}=10\,\text{kVA}$

DG2 $S_{base2}=5\,\text{kVA}$

$P_{0,i}, Q_{0,i}$
VSG Control Scheme (Basic Part)

Swing Equation

\[ P_{in} - P_{out} = J \omega_m \frac{d\omega_m}{dt} + D^* P_{base} \frac{\omega_m - \omega_g}{\omega_0} \]

Swing Equation

- \( J \): Virtual inertia
- \( D \): Damping factor
- \( \omega_m \): Virtual rotor frequency

V–Q Droop Controller

- \( k_q \): V–Q droop coef.
- \( Q_0 \): Set value of reactive power

\[ \dot{V}_{bus} + k_q Q_0 = P_0 \]

\( P_0 \): Set value of active power

\( \omega_0 \): Constant

\( \dot{\omega}_m + k_p P_0 = P_0 \)

\( k_p \): \( \omega \)–P droop coef.

\( \omega_m \): Virtual rotor frequency

Governor Model

\[ P_{in} = \omega_m \int \omega_0 \]

\( \omega_0 \): Constant

\( P_0 \): Active power

\[ Q_{ref} = \omega_m \int \omega_0 \]

\( Q_0 \): Reactive power

\( k_q \): Virtual damper

\( V_{bus} \): Bus voltage

\( V_{out} \): Output voltage

\( Z_{line} \): Line impedance

\( Lf \): Filter inductance

\( C_f \): Filter capacitance

\( V_{pwm} \): PWM voltage

\( \theta_{pwm} \): PWM phase angle

\( \omega_m \): Virtual rotor frequency

\( \omega_0 \): Constant

\( P_{in} \): Active power input

\( P_{out} \): Active power output

\( Q_{out} \): Reactive power output

\( \omega_0 \): Constant

\( \omega_m \): Virtual rotor frequency

\( k_p \): \( \omega \)–P droop coef.

\( P_0 \): Set value of active power

\( E_0 \): Bus voltage

\( Q_0 \): Set value of reactive power

\( V_{bus} \): Bus voltage

\( V_{out} \): Output voltage

\( Z_{line} \): Line impedance

\( Lf \): Filter inductance

\( C_f \): Filter capacitance

\( V_{pwm} \): PWM voltage

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\( \omega_0 \): Constant

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\( P_{out} \): Active power output

\( Q_{out} \): Reactive power output

\( \omega_0 \): Constant

\( \omega_m \): Virtual rotor frequency

\( k_p \): \( \omega \)–P droop coef.

\( P_0 \): Set value of active power
VSG Control Scheme 
(Enhanced Part)

**Stator Impedance Adjuster**

- Constant part
  - Transient power sharing
  - Increased damping

- Transient part
  - Overcurrent limiting

**Bus voltage estimator**

Estimate bus voltage for proper reactive power sharing
## Control Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG1 Power Rating $S_{base1}$</td>
<td>10 kVA</td>
<td>LPF cut-off Frequency $T_{fp_{i}}$</td>
<td>$7.96 \times 10^{-3}$ s</td>
</tr>
<tr>
<td>DG2 Power Rating $S_{base2}$</td>
<td>5 kVA</td>
<td>LPF cut-off Frequency $T_{fq_{i}}$</td>
<td>$7.96 \times 10^{-3}$ s</td>
</tr>
<tr>
<td>Nominal Voltage $E_0$</td>
<td>200 V</td>
<td>Q Ctrl. PI Gain $K_{pq_{i}}^*$</td>
<td>0.0125 pu</td>
</tr>
<tr>
<td>Nominal Frequency $\omega_0$</td>
<td>376.99 rad/s</td>
<td>Q Ctrl. PI Time Constant $T_{iq_{i}}$</td>
<td>$1.25 \times 10^{-4}$ s</td>
</tr>
<tr>
<td><strong>Inertia Constant $M_{i}^*$</strong></td>
<td>8 s</td>
<td>Sec. Ctrl. PI Gain $K_{psec}^*$</td>
<td>1 pu</td>
</tr>
<tr>
<td>Damping Factor $D_{i}^*$</td>
<td>17 pu</td>
<td>Sec. Ctrl. PI Time Constant $T_{isec}$</td>
<td>0.05 s</td>
</tr>
<tr>
<td>Set Value of Active Power $P_{0_{i}}^*$ (default)</td>
<td>1 pu</td>
<td>DG1 Cont. Virtual Stator Reactor $L_{ls0_{1}}$</td>
<td>6.39 mH</td>
</tr>
<tr>
<td>Set Value of Reactive Power $Q_{0_{i}}^*$ (default)</td>
<td>0 pu</td>
<td>DG2 Cont. Virtual Stator Reactor $L_{ls0_{2}}$</td>
<td>13.81 mH</td>
</tr>
<tr>
<td>Active Power Droop Coef. $k_{p_{i}}^*$</td>
<td>20 pu</td>
<td>Trans. Virtual Stator Imp. Gain $k_{z_{i}}^*$</td>
<td>1.79 pu</td>
</tr>
<tr>
<td>Reactive Power Droop Coef. $k_{q_{i}}^*$</td>
<td>5 pu</td>
<td>Trans. Virtual Stator Imp. Ratio $X/R_{i}$</td>
<td>5</td>
</tr>
</tbody>
</table>
Simulation Results

Loading Transition

Droop Control

VSG Control

Reduced frequency deviation

Islanding

Loading Transition
Simulation Results
Three-Phase Ground Fault

Droop Control

VSG Control

Reduced frequency deviation

3P Ground Fault
Fault Current During Three-Phase Ground Fault

Without Transient Stator Impedance

With Transient Stator Impedance

Fault Current is limited by Transient Stator Impedance
Effect of Constant Stator Reactance

Without Constant Stator Reactance

With Constant Stator Reactance

Simulation

Experiment

Oscillation damped
Oscillation eliminated

Loading Transition

Islanding

$P_{0.2}$ Change

Oscillation eliminated
Oscillation damped

Loading Transition

$P_{0.2}$ Change
State-Space Model of Islanded Microgrid

\[
\begin{align*}
\dot{x} &= Ax + Bw \\
y &= Cx + Dw
\end{align*}
\]

Loading Transition Change of Active Power Set Value

**Disturbance:**

\[
w = [\Delta P_{load} \quad \Delta P_{0\_1} \quad \Delta P_{0\_2}]^T
\]

**Output:**

\[
y = [\Delta \omega_{m1} \quad \Delta \omega_{m2} \quad \Delta P_{out1} \quad \Delta P_{out2}]^T
\]

- The damping ratio of oscillation in output parameters is determined by the eigenvalues of state matrix \(A\).
Relation between Output Reactance and Damping Ratio

- Total output reactance $X$ increases
  - $\Rightarrow$ Damping ratio $\zeta$ increases

Radial lines: Damping ratio $\zeta$
Circle lines: Damped natural frequency $\omega_n$

Oscillation can be damped by increasing output reactance
Transient Load Sharing

Poles and Zeros of \( \frac{\Delta P_{\text{out1}}}{\Delta P_{\text{load}}} \)

Poles and Zeros of \( \frac{\Delta P_{\text{out2}}}{\Delta P_{\text{load}}} \)

\[ X_i^* = \frac{X_i P_{\text{basei}}}{V_{\text{basei}}^2} \] is the total output reactance of \( i \)th VSG in per unit value

- When the disturbance is a loading transition
  - If the total output reactance of each VSG is of the same per unit value, poles are cancelled by zeros and oscillation is eliminated
**Design of Constant Stator Reactance**

- How to design $L_{ls0}$ to avoid oscillation?
  - Large value to provide damping
  - Same total output reactance for all VSG in parallel

$$X = X_{ls0} + X_f + X_{line} = 0.7\text{pu}$$

$$(X_{ls0} = \omega_m L_{ls0})$$

$X$: Total output reactance

$X_{ls}$: Virtual stator reactance

$X_f$: Filter reactance

$X_{line}$: Line reactance
Effect of Constant Stator Reactance

Without Constant Stator Reactance

With Constant Stator Reactance

Reactive power sharing improved
Cause of Poor Reactive Power Sharing

If the input of droop controller is equal, reactive power should be shared properly.

$V_{out}$: Output voltage of DG
$V_{bus}$: Bus voltage
Bus Voltage Estimator for Proper Reactive Power Sharing

**V–Q Droop Controller**

- $k_q$: V–Q droop coef.
- $Q_0$: Set value of reactive power

Estimate bus voltage for proper reactive power sharing
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• Stand-alone microgrid in remote area
• SG (10 kVA): Round-rotor moved by gas engine
• DG (10 kVA): Photovoltaic panels
• Load: Three-phase loads and single-phase Loads
## Issues of Small Rating SG

### SG Controller

![SG Controller Diagram]

- Poor inertia
- Slow governor response

### SG Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage $E_0$</td>
<td>200 V</td>
<td>Set value of active power $P_{0,sg}^*$</td>
<td>1 pu</td>
</tr>
<tr>
<td>Rated power $S_{base,sg}$</td>
<td>10 kVA</td>
<td>Set value of reactive power $Q_{0,sg}^*$</td>
<td>0 pu</td>
</tr>
<tr>
<td>Nominal frequency $\omega_0$</td>
<td>376.99 rad/s</td>
<td>$\omega - P$ droop coefficient $k_{p,sg}^*$</td>
<td>20 pu</td>
</tr>
<tr>
<td>Inertia constant $M_{sg}^*$</td>
<td>0.16 s</td>
<td>$V - Q$ droop coefficient $k_{p,sg}^*$</td>
<td>5 pu</td>
</tr>
<tr>
<td>AVR PI $K_{pAVR}^*$</td>
<td>20 pu</td>
<td>Governor time constant $T_{d,sg}^*$</td>
<td>1 s</td>
</tr>
<tr>
<td>AVR PI $T_{iAVR}^*$</td>
<td>0.025 s</td>
<td>AVR LPF cut-off frequency</td>
<td>20 Hz</td>
</tr>
</tbody>
</table>

### Impedance Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_d^* = X_q^*$</td>
<td>0.219 pu</td>
</tr>
<tr>
<td>$X''_d = X_q''$</td>
<td>0.027 pu</td>
</tr>
<tr>
<td>$X''''_d = X_q''''$</td>
<td>0.01 pu</td>
</tr>
<tr>
<td>$T_{do}'$</td>
<td>6.55 s</td>
</tr>
<tr>
<td>$T_{do}''$</td>
<td>0.039 s</td>
</tr>
<tr>
<td>$T_{qo}'$</td>
<td>0.85 s</td>
</tr>
<tr>
<td>$T_{qo}''$</td>
<td>0.071 s</td>
</tr>
</tbody>
</table>
Simulation of Single SG Operation

Initial loading : 3P 1 kW, 0.5 kvar
Connected loading : 1P 4.8 kW, 2.1 kvar

Ripples due to 3P unbalance introduced by 1P loading

Slow governor response cannot restore this frequency drop immediately

Rotor frequency decreased rapidly due to poor inertia
Control Requirements of DG

1. Reduce SG rotor frequency deviation
   - If SG rotor frequency drop below 90%, SG may be unstable
   - Virtual Synchronous Generator (VSG) Control
     - Generate virtual inertia to provide transient frequency support
     - Share active and reactive power with the SG

2. Eliminate Negative-Sequence Current from SG
   - Prevent SG from overheating and torsional stresses
     - Active power filter (APF)

3. Both 1+2 should be realized in ONE inverter
Proposed Modified VSG Control

**Diagram**

- **Distributed Generator**
- **Energy Storage**
- **PWM**
- **Energy Storage**
- **Stator Impedance Adjuster**
- **Governor Model**
- **Swing Equation Function**
- **DDSRF**
- **LPF**
- **PI**
- **Q Droop**
- **Q ref dg**
- **Pin dg**
- **P out dg**
- **V out dg**
- **V comp(αβ)**
- **I out dg**
- **I out dg(αβ)**
- **I out dg(abc)**
- **V out dg(abc)**
- **V out sg(abc)**
- **θ g**
- **θ m dg**
- **P m dg**
- **ω m dg**
- **ω g dg**
- **E0**
- **Z ls**
- **L f**
- **C f**
- **Z line**
- **BUS**

**Equations**

- \( Q_0 \)
- \( V_{out\_dg} \)
- \( Q_{ref\_dg} \)
- \( P_{in\_dg} \)
- \( P_{out\_dg} \)
- \( \omega_{g\_dg} \)
- \( \omega_{m\_dg} \)
- \( \theta_{m\_dg} \)
- \( \theta_{g\_sg} \)

**Notations**

- \( V_{comp(αβ)} \)
- \( I_{out\_sg(dq)} \)
- \( I_{out\_dg} \)
- \( I_{out\_dg(αβ)} \)
- \( V_{out\_dg(abc)} \)
- \( V_{out\_sg(abc)} \)
- \( LPF \)
- \( Q_{out\_dg} \)
• Applied to both DG and SG voltage and current to extract positive and negative sequence components
• Output power, voltage and current of DG are calculated from only positive sequence components
  • Prevent ripples due to negative sequence from entering the controller

\[
P_{\text{out}_d\text{g}} = v_{\text{out}_d\text{g}_d}^+ i_{\text{out}_d\text{g}_d}^+ + v_{\text{out}_d\text{g}_q}^+ i_{\text{out}_d\text{g}_q}^+
\]
\[
Q_{\text{out}_d\text{g}} = -v_{\text{out}_d\text{g}_d}^+ i_{\text{out}_d\text{g}_d}^+ + v_{\text{out}_d\text{g}_q}^+ i_{\text{out}_d\text{g}_q}^+
\]
\[
V_{\text{out}_d\text{g}} = \sqrt{(v_{\text{out}_d\text{g}_d}^+)^2 + (v_{\text{out}_d\text{g}_q}^+)^2}
\]
\[
i_{\text{out}_d\text{g}} = \sqrt{(i_{\text{out}_d\text{g}_d}^+)^2 + (i_{\text{out}_d\text{g}_q}^+)^2}
\]

\[T^\pm = T(\pm \theta_g) \text{ and } T^{\pm 2} = T(\pm 2\theta_g)\]

\[
T(\theta_g) = \begin{bmatrix}
\cos \theta_g & \sin \theta_g \\
-\sin \theta_g & \cos \theta_g
\end{bmatrix}
\]

LPF: 1\textsuperscript{st} order low pass filter (cut-off frequency 40 Hz)
SG Neg.-Seq. Compensation

Stator Impedance Adjuster

Virtual Stator Impedance Calculator

ΔR_{is} = R_{is}

1/\sqrt{1+(X/R)^2}

1/\sqrt{1+(R/X)^2}

ΔL_{is} = L_{is}

L_{is0}

SG Neg.-Seq. Compensation

Control SG Neg.-Seq. to be 0
## Parameter Design of Inverter

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<tbody>
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<td>200 V</td>
<td>Set value of active power $P_{0,\text{dg}}^*$</td>
<td>1 pu</td>
</tr>
<tr>
<td>Rated power $S_{\text{base,\text{dg}}}$</td>
<td>10 kVA</td>
<td>Set value of reactive power $Q_{0,\text{dg}}^*$</td>
<td>0 pu</td>
</tr>
<tr>
<td>Nominal frequency $\omega_0$</td>
<td>376.99 rad/s</td>
<td>$\omega - P$ droop coefficient $k_{\text{p,\text{dg}}}$</td>
<td>20 pu</td>
</tr>
<tr>
<td>Inertia constant $M_{d\text{g}}^*$</td>
<td>0.16 s</td>
<td>$V - Q$ droop coefficient $k_{q,\text{dg}}^*$</td>
<td>5 pu</td>
</tr>
<tr>
<td>Damping factor $D_{\text{dg}}^*$</td>
<td>8.7 pu</td>
<td>Governor time constant $T_{d,\text{dg}}$</td>
<td>0 s</td>
</tr>
<tr>
<td>Constant virtual stator inductance $L_{\text{iso}}$</td>
<td>1.122 mH</td>
<td>Transient virtual stator impedance gain $k_{Z}^*$</td>
<td>0.69 pu</td>
</tr>
<tr>
<td>SG output reactor $L_{\text{ad,\text{sg}}}$</td>
<td>1.836 mH</td>
<td>Transient virtual stator impedance $X/R$ ratio</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PI Controller for Reactive Power</td>
<td></td>
</tr>
<tr>
<td>$K_{p\text{q}}$</td>
<td>0.05 pu</td>
<td>$T_{i\text{q}}$</td>
<td>$1.25 \times 10^{-2}$ s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PI Controller for SG Neg.-Seq. Compensation</td>
<td></td>
</tr>
<tr>
<td>$K_{\text{p,\text{neg}}}$</td>
<td>0.1 pu</td>
<td>$T_{i,\text{neg}}$</td>
<td>0.01 s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cut-off frequency of LPF for $Q_{\text{out,\text{dg}}}$</td>
<td>20 Hz</td>
</tr>
</tbody>
</table>

All parameters in red should be set equal to SG in per unit value to ensure proper transient and steady power sharing.

*Design of Parameters in blue will be discussed in detail*
Governor Time Constant $T_{d\_dg}$

Set equal to SG in order to share transient active power?

Low frequency oscillation indicated by oscillatory conjugated eigenvalues.
Output reactance of DG and SG should be set equal to share transient power, but how about the value?

Realized by tuning virtual stator inductance $L_{ls0}$ for DG and adding an additional output reactor $L_{ad\_sg}$ for SG
Simulation of 1P Loading Transition

Initial loading: 3P 1 kW, 0.5 kvar
Connected loading: 1P 4.8 kW, 2.1 kvar

Improved SG rotor frequency deviation (Frequency Support of VSG)

Initial loading: 3P 2 kW, 1 kvar
Connected loading: 1P 9.6 kW, 4.2 kvar (2x of SG only case)
Simulation of 1P Loading Transition

Ripples due to unbalance have been eliminated w/o DDSRF and SG Neg. Seq.

with DDSRF and SG Neg. Seq.
Phase Current

w/o DDSRF and SG Neg. Seq.

with DDSRF and SG Neg. Seq.

Balanced SG current
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Conclusion

• VSG control can provide inertia support for microgrids, leading to less fluctuant frequency

• Parallel inverters and SG + inverter operations were established, and several related issues were solved

Future Plan

• Operation of Multiple SGs + Multiple inverters
Thank you for your kind attention!

For more details, please refer to:

