Grid-forming Inverters for Scalable Microgrids

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December 3rd, 2021
Acknowledgements

Contributions from my postdocs and grad students

Minghui  Nimesh  Rahul  Weiqian  Soham  Pranav  Trager

and generous support from DOE & NSF for my research on:

- Grid-forming systems
- Power electronics
- UNIFI Consortium
Renewable Utilization for Various Grid Sizes

- Engineering challenges grow with system size and complexity
- Need scalable, robust, and resilient methods for system operation
A Vision for the Future Grid

Achieving 2 goals simultaneously:
- Break down barriers that limit adoption of renewable energy
- Realize a bottom-up system that works resiliently at any scale
Desired Characteristics of a GFM Inverter

- Can operate in standalone or with many other GFMs
- Proportional power sharing among parallel units
- Works when connected to a stiff grid or weak grid
- Synchronization without a phase-locked-loop
- Accepts PQ bias signals
- Has current limiter to prevent overcurrents
- Can be integrated with dc-side controls
Interoperability

Phase Balancing

Three-phase voltages

Inverter

Loads

Delta

Wye
Phase Balancing

Interoperability

Delta

Wye

Loads

or

A

B

C

Inverter

Inverter

Inverter

Three-phase voltages

Loads

Delta

or

Wye
Approach #1: Dispatchable Virtual Oscillator Control

- A 2\textsuperscript{nd} order nonlinear oscillator
- Newest GFM type in existence


Approach #1: Dispatchable Virtual Oscillator Control

Control equations are given by

\[
\omega = \omega_0 + \frac{\omega_0 \kappa_1}{V^2} \begin{bmatrix} 1 & 0 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P \\ Q^* - Q \end{bmatrix},
\]

\[
\dot{V} = \omega_0 \kappa_2 V (V_0^2 - V^2) + \frac{\omega_0 \kappa_1}{V} \begin{bmatrix} 0 & 1 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P \\ Q^* - Q \end{bmatrix}.
\]
Illustrating Versatile Performance on Hardware with dVOC Control

$\begin{align*}
&v_1, i_1, v_2, i_2, v_3, i_3 \\
&0 \quad 0 \quad 0 \quad 0
\end{align*}$

Dr. Minghui Lu
Rahul Mallik

$\begin{align*}
&\text{inverters} \\
&\text{loads} \\
&\text{grid}
\end{align*}$

$\begin{align*}
&\equiv \text{ON} \\
&\equiv \text{OFF}
\end{align*}$
Approach #2: Droop Control

- Inspired by machine droop laws
- Oldest GFM method in existence

Approach #2: Droop Control

Control equations are given by

\[
\begin{align*}
\omega &= \omega_0 + \frac{1}{d}\begin{bmatrix} 1 & 0 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P_m \\ Q^* - Q_m \end{bmatrix}, \\
V &= V_0 + \frac{1}{dv} \begin{bmatrix} 1 & 0 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P_m \\ Q^* - Q_m \end{bmatrix}, \\
\frac{1}{\omega_c} \begin{bmatrix} \dot{P}_m \\ \dot{Q}_m \end{bmatrix} &= - \begin{bmatrix} P_m \\ Q_m \end{bmatrix} + \begin{bmatrix} P \\ Q \end{bmatrix}.
\end{align*}
\]
Approach #3: Virtual Synchronous Machine Control

- Emulate machine dynamics digitally
- Popular due to familiar behavior

Approach #3: Virtual Synchronous Machine Control

Control equations are given by

\[ J \dot{\omega} = -\omega + \omega_0 + \frac{d_d}{d_f} (\omega_g - \omega) \]
\[ + \frac{1}{d_f} \begin{bmatrix} 1 & 0 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P \\ Q^* - Q_m \end{bmatrix}, \]
\[ V = V_0 + \frac{1}{d_v} \begin{bmatrix} 0 & 1 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P \\ Q^* - Q_m \end{bmatrix}, \]
\[ \frac{1}{\omega_0} \dot{\eta} = \begin{bmatrix} 0 & 1 \end{bmatrix} R(\alpha) R(\delta) T(\omega_0 t) v, \]
\[ \frac{1}{\omega_0} \dot{\alpha} = \frac{k_P}{\omega_0} \dot{\eta} + k_i \eta, \]
\[ \frac{1}{\omega_c} \dot{Q}_m = -Q_m + Q. \]
A Universal & Unified GFM Model

All 3 GFM types can be boiled down to

\[
\tau_f \frac{d\omega}{dt} = -\omega + \omega_0 + \kappa_d (\omega_g - \omega) \\
+ \kappa_f \begin{bmatrix} 1 & 0 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P_m \\ Q^* - Q_m \end{bmatrix},
\]

\[
\tau_v \frac{dV}{dt} = f_v(V) + \kappa_v \begin{bmatrix} 0 & 1 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} p^* - p_m \\ q^* - q_m \end{bmatrix},
\]

\[
\frac{1}{\omega_0} \frac{d\eta}{dt} = \begin{bmatrix} 0 & 1 \end{bmatrix} R(\alpha) R(\delta) T(\omega_0 t) v,
\]

\[
\frac{1}{\omega_0} \frac{d\alpha}{dt} = \frac{k_P}{\omega_0} \dot{\eta} + k_I \eta,
\]

\[
\tau_p \begin{bmatrix} \dot{P}_m \\ \dot{Q}_m \end{bmatrix} = - \begin{bmatrix} P_m \\ Q_m \end{bmatrix} + \begin{bmatrix} P \\ Q \end{bmatrix}.
\]


A Universal & Unified GFM Model

All 3 GFM types can be boiled down to

\[ \tau_f \frac{d\omega}{dt} = -\omega + \omega_0 + \kappa_d (\omega_g - \omega) \]
\[ + \kappa_f \begin{bmatrix} 1 & 0 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} P^* - P_m \\ Q^* - Q_m \end{bmatrix}, \]

\[ \tau_v \frac{dV}{dt} = f_v(V) + \kappa_v \begin{bmatrix} 0 & 1 \end{bmatrix} R(\psi - \frac{\pi}{2}) \begin{bmatrix} p^* - p_m \\ q^* - q_m \end{bmatrix}, \]

\[ \frac{1}{\omega_0} \frac{d\eta}{dt} = \begin{bmatrix} 0 & 1 \end{bmatrix} R(\alpha) R(\delta) T(\omega_0 t) V, \]

\[ \frac{1}{\omega_0} \frac{d\alpha}{dt} = \frac{k_p}{\omega_0} \dot{\eta} + k_1 \eta, \]

\[ \tau_p \begin{bmatrix} \dot{P}_m \\ \dot{Q}_m \end{bmatrix} = - \begin{bmatrix} P_m \\ Q_m \end{bmatrix} + \begin{bmatrix} P \\ Q \end{bmatrix}. \]

where the parameters are

<table>
<thead>
<tr>
<th>droop</th>
<th>VSM</th>
<th>dVOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_f )</td>
<td>( \tau_v )</td>
<td>( \tau_p )</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>( \frac{1}{\omega_c} )</td>
</tr>
<tr>
<td>J</td>
<td>0</td>
<td>( \frac{1}{d_f} )</td>
</tr>
<tr>
<td>0</td>
<td>( \frac{1}{\omega_0} )</td>
<td>0</td>
</tr>
</tbody>
</table>

A unified model
Showing Interoperability with a Mix of Control Types

\[ P_1^* \rightarrow P_1 \]
\[ P_2^* \rightarrow P_2 \]

\[ v_1, v_2, v_3 \]
\[ i_1, i_2, i_3 \]

\[ 60 \text{ Hz} \]

\[ 0 \text{ Hz} \]

dVOC

droop

GFL

loads

\[ \equiv \text{ON} \]

\[ \equiv \text{OFF} \]
A Single-phase GFM Commercial Product

Features of the inverter building block

- 300 VA single-phase with droop-based GFM controls
- Bidirectional converter can interface PV or batteries

Over 39M+ Enphase inverters shipped for 12 GW of capacity as of September 2021
Can swarms of decentralized single-phase GFMs self-organize into a three-phase system?

Could this system maintain phase balancing when islanded?
Self-balancing Single-phase GFM Hardware Results

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Thanks for your attention!

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