Frequency Stability Analysis for Inverters in Low Voltage Distribution Systems

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* Under the instruction of Prof. Dimitry Gorinevsky and Prof. Sanjay Lall
** Based on the previous work by Eric Glover
Traditional Power Grid

- Unidirectional
- Transform LV/HV for transmission
Frequency Control in Generation

- **Primary control**
  - Regulates frequency vs. output power
- **Secondary control**
  - Restores frequency by adjusting turbine valves
Distributed Generation

- Gridtie Inverters
- Droop Inverters
Detailed Simulation

- SimPowerSystems: 3-phase Utility Grid, Inverter, Controls
Detailed Stability Analysis

• Run detailed simulation to ensure the system is stable
  – With all reasonable combinations of 20 parameters
  – 5 samples for each parameter
  – Each simulation takes 3 minutes

• Total simulation time is 0.5 Billion Years
  – $5^{20} \cdot 180s = 1.72 \cdot 10^{16}s = 544$ Million Years
Surrogate Model

• Single phase system
• System linearized around the steady-state
• Lower computational complexity

<table>
<thead>
<tr>
<th></th>
<th>Detailed model</th>
<th>Surrogate model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of samples</td>
<td>$5^{20}$</td>
<td>$5^8$</td>
</tr>
<tr>
<td>Simulation time</td>
<td>$\sim 3$ minutes</td>
<td>$\sim 1$ second</td>
</tr>
<tr>
<td>Total time</td>
<td>$1.72 \cdot 10^{16}$ second</td>
<td>$3.9 \cdot 10^5$ second</td>
</tr>
<tr>
<td>Speed-up</td>
<td></td>
<td>$\sim x 10^{11}$</td>
</tr>
</tbody>
</table>

* More speed-up with sparser parameter samples
Surrogate Model

1 System Models

Grid Interface Circuit

V\_G \rightarrow \text{Grid Interface Circuit} \rightarrow I\_N, V\_N \rightarrow \text{Inverter System} \rightarrow P\_set, Q\_set

\begin{figure}
\centering
\begin{tikzpicture}
\node at (0,0) {\text{Grid Interface Circuit}};
\node at (1,0) {\text{Inverter System}};
\node at (0,1) {V\_G};
\node at (1,1) {I\_N, V\_N};
\node at (2,1) {P\_set, Q\_set};
\node at (0,2) {Z\_G};
\node at (1,2) {L\_CL};
\node at (2,2) {\text{Inverter Gain}};
\node at (2,3) {V\_P};
\node at (2,4) {\text{Phase Converter}};
\node at (2,5) {\text{Control Logic Block}};
\node at (1,4) {V\_M};
\node at (1,5) {P, Q\_d, q};
\node at (1,6) {d, q};
\node at (0,3) {Z\_L};
\node at (0,4) {V\_N};
\node at (0,5) {I\_N};
\node at (1,3) {I\_G};
\node at (1,4) {P, Q\_measurement};
\node at (1,5) {\text{Power Controller}};
\node at (1,6) {\text{PLL}};
\node at (2,0) {I\_N};
\node at (2,1) {V\_C};
\node at (2,2) {V\_P};
\node at (2,3) {V\_M};
\node at (2,4) {V\_P};
\node at (2,5) {\text{Phase Converter}};
\node at (2,6) {\text{Control Logic Block}};
\node at (1,6) {d, q};
\node at (1,7) {P, Q\_measurement};
\node at (1,8) {\text{Power Controller}};
\node at (1,9) {\text{PLL}};
\node at (2,0) {I\_N};
\node at (2,1) {V\_C};
\node at (2,2) {V\_P};
\node at (2,3) {V\_M};
\node at (2,4) {\text{Phase Converter}};
\node at (2,6) {\text{Control Logic Block}};
\end{tikzpicture}
\end{figure}
Gridtie Inverters

- Inject power into the grid with unity power factor:
  \[ P = P_{\text{set}}, \]
  \[ Q = Q_{\text{set}} = 0 \]
Droop Inverters

- Droop equations:
  \[ f_{\text{set}} = f_0 - K_p (P - P_{\text{set}}), \]
  \[ V_{\text{set}} = V_0 - K_v (Q - Q_{\text{set}}) \]

- This adds the inertia to the inverters as that of the primary control in generators
Control Framework

- Stability issues in transient:
  - Set points $P_{\text{set}}, Q_{\text{set}}$
  - Exogenous frequency disturbance $\Delta f_G$

![Step Response](image)

- PI Controllers
• $H_\infty$ norm measures the worst case disturbance amplification from the frequency of $V_G$ to that of $V_N$

$$\|T\|_\infty = \sup \frac{\|\Delta \omega_{V_G}\|_\infty}{\|\Delta \omega_{V_N}\|_\infty}$$

Grid Frequency Variation

\[ \Delta \omega_{V_N} = T(\Delta \omega_{V_G}) \]
Surrogate Model Verification

- Surrogate model matches the detailed simulation model reasonably well.

[P and Q Step Response for the Analysis Model]

Surrogate model

[P and Q Step Response for the Detailed Simulation]

Simulation model
This controller tuning could be, and likely is, suboptimal. An additional method to verify that it was integrated correctly. The controller gains were initially tuned using Simulink channel (8). The P (proportional) controller gains were set to $\text{Volt}/(\text{Watt})$. The same fixed controller tuning was used in all the analysis.

Fig. 8. Transient analysis results: the reasonably tuned PI controllers, to build a very stable system. The results obtained show that the system is stable and the analysis results will not change the conclusions. However, they might further improve the disturbance amplification numbers. A better tuning of the controller would not change the conclusions. A better tuning of the controller and linearized models (transfer functions) were developed for all sample points if line length $l<\infty$. However, this varies based on local regulations. In practical limits of inverter penetration.

The distribution system has no stability issues for all reasonable operating parameters even with high penetration. One of the reasons why such solution might be unavailable is related to the active power supply. Due to regulation, a grid-tie inverter can only allow an acceptable steady state solution. One of the reasons does seem to be a limiting factor. The lack of rotating inertia with wind turbines and fuel cells, in IEEE Trans. on Power Electronics, vol. 11, no. 7, pp. 6575–6592, 2011.

$$\text{Penetration } \alpha$$

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penetration $\alpha$</td>
<td>0.05</td>
<td>0.95</td>
</tr>
<tr>
<td>Load power $P_L$</td>
<td>5kW</td>
<td>40kW</td>
</tr>
<tr>
<td>Power factor $\cos(\psi)$</td>
<td>0.9</td>
<td>1.00</td>
</tr>
<tr>
<td>Line length $l$</td>
<td>0.25km</td>
<td>1km</td>
</tr>
<tr>
<td>PLL rise time</td>
<td>0.02s</td>
<td>0.1s</td>
</tr>
<tr>
<td>PLL overshoot</td>
<td>23%</td>
<td>45%</td>
</tr>
<tr>
<td>LCL power loss</td>
<td>$1 \cdot 10^{-2}$ Watt</td>
<td>5Watt</td>
</tr>
<tr>
<td>LCL settling time</td>
<td>0.12s</td>
<td>0.22s</td>
</tr>
</tbody>
</table>
Analysis Results

Gridtie Inverter

Droop Inverter

$H_\infty$ norm is always less than 2 in all samples explored!
Conclusion

• Frequency stability analysis is evaluated for both gridtie and droop inverters
• Grid frequency disturbance is amplified roughly in proportional to penetration, load power, and line distance
• For a well-tuned inverter, this amplification is reasonably small
• However, the power factor may drop below 0.85 as viewed from the upstream as penetration increases, violating IEEE 1547