2020 Microgrid R&D Peer Review

Enhancing the Resiliency of a Cyber-Microgrid System

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Enhancing the Resiliency of a Cyber-Microgrid System

Objectives & Outcomes
Distributed Energy Resources (DERs) can be used as resiliency sources in a distribution system to increase reliability, resiliency, and overall system efficiency when the utility is unavailable. To operate microgrids, a proper control strategy needs to be developed and system stability must be studied. As a practical system, the communication system and distinct types of DERs (synchronous-based and inverter-based) are incorporated.

Technical Scope
- A microgrid control scheme is proposed, and transient stability of microgrid in a resiliency mode is studied.
- Microgrid control relies on the communication system to deliver the control commands. A networked control methodology is developed to study the impact of communication latency.
- With the high penetration of inverter-based DERs, instability is observed. A coordinated control is proposed to stabilize the system.

Funding Summary ($K)

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<tr>
<th>Year</th>
<th>FY19 Funded</th>
<th>FY20, Funded</th>
<th>FY21 Authorized/Requested</th>
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<td>$220K</td>
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Progress and Results
Since Last Peer Review Meeting

• Decentralized control for resilient distribution systems

• **What has been done:**
  
  • Implementation of microgrid control in a test feeder model, dynamics and stability analysis. *(FY18)*
  
  • A communication model is developed and integrated with the physical system model for IEEE 13-node test feeder to evaluate the impact of communication delays. *(FY19)*
  
  • An analytical method to determine the reporting period/delay time is completed and tested. *(FY19)*
  
  • Instability is observed when the grid-forming inverter-based (GFIB) generator operates with synchronous generators (SGs). Supplementary control is designed to mitigate the instability. *(FY20)*
  
  • Detection and mitigation techniques are developed based on the determined critical communication latency. *(FY20)*
  
  • A nonlinear method is developed for stability analysis of SG-GFIB. *(FY20)*

• **What will be done:**
  
  • Development of stability and control strategy of SG-GFIB microgrids with a communication system.
The goal of project is to use microgrids as resiliency sources. The field test demonstrated the feasibility and extended the study scope, including operation, control, communication, and system stability.

**Scope of Study: Microgrid as a Resiliency Source**

- Field Test
  - Microgrid Control - Frequency and Voltage Dynamics
  - Networked Control System
  - Detection and Mitigation for Communication Latency
  - Dynamics of SG-GFIB System & Supplementary Control

FY17
FY18
FY19
FY20
Field test reveals a proper control is needed for stable operation in a resiliency mode. Coordinated control is developed and tested on IEEE 13-node distribution system.

i. Stability: System frequency and voltage control is needed (Microgrid control system).

ii. Dispatch: Power and reactive power sharing capability is needed (Droop control).
Transient Stability: Heavy Load Pick Up

- Simulations results provide frequency and voltage behavior with and without the microgrid control system.
- Without microgrid control, the responses diverge and collapse eventually. The proposed control scheme maintains system stability.
Transient Stability: Short Circuit Fault

- Simulation results provide frequency and voltage responses with and without the microgrid control system.
- Although the system is stable with or without the microgrid control, microgrid control achieves a faster response and steers frequency and voltage back to 1 p.u.
Networked Control System

- To evaluate control performance under the influence of *communication*, a communication link is added to the test model.
- Performance of a communication system, including data acquisition and exchange, is critical to stability of a microgrid in a resiliency mode.
  - Data acquisition: *reporting period* for data acquisition is assumed to have a time scale of seconds.
  - Data exchange: *communication delay* for data exchange is in the order of milliseconds.
Networked Control System

- The control scheme is tested under given communication latencies including reporting periods ($h$) and communication delays ($\tau$).
- With long communication latencies, the frequency and voltage start to diverge, and the system becomes unstable and power dispatch fails.
Networked Control System

- Analytical method, "Networked Control System (NCS)," used to analyzed system stability involving the communication system.
- System modeled in state space and converted to an augmented closed-loop system by adding reporting periods (h) and communication delays (τ).
- System is unstable if any eigenvalue of transition matrix (\( \Phi \)) located outside unit circle, i.e., magnitude larger than 1.

\[
\dot{x}(t) = Ax(t) + Bu(t) \\
y(t) = Cx(t) \\
u(t^+) = -Kx(t - \tau) \\
t \in \{kh + \tau, k = 0, 1, 2, \ldots \}
\]

\[
z((k + 1)h) = \Phi z(kh) \\
\Phi = \begin{bmatrix}
\Phi - \Gamma_0(\tau)K & \Gamma_1(\tau) \\
-K & 0
\end{bmatrix}
\]

![Eigenvalues Location, h = 1, τ = 0](image1)

- stable

![Eigenvalues Location, h = 2, τ = 0](image2)

- unstable
Networked Control System

- Time-domain simulation is used to validate analytical method. The stability regions obtained by the two methods are close.
- Critical threshold for communication latency is determined. Critical reporting period is 1.6 seconds for study system.

### Stability Regions
by State Space Analysis (Linearized Model)

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### Stability Regions Validated
by Time-Domain Simulation (Nonlinear Model)

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Dynamics of SG-GFIB System and Supplementary Control

- Two-node system used to illustrate stability issue of SG-GFIB system. Instability occurs due to heavy load.
- Incremental form, $\Delta P_{\text{dis}}$, can be formulated. A dynamic system is created with interactions between SG and GFIB ($\delta_{ij}$, phase angle difference).

\[
\Delta P_{\text{dis}} = \delta_{ij} + D_{\text{eqij}} \dot{\delta}_{ij} + \frac{\omega_{\text{ref}} E_i E_j |Y_{ij}|}{M_j} \sin(\delta_{ij} - \beta_{ij}) + \frac{1}{M_j R_{gj} T_{gj}} \delta_{ij}
\]

\[
D_{\text{eqij}}(\delta_{ij}) = \frac{\omega_{\text{ref}} E_i E_j |Y_{ij}|}{D_{pi}} \cos(\delta_{ij} + \beta_{ij}) \quad \text{Damping}
\]
To improve time-varying damping, a supplementary control loop is proposed to enhance system stability.

Supplementary loop can regulate phase shift $\Delta \delta_i$ and amplitude change $\Delta E_i$ of the GFIB terminal ac voltage.

- Dynamic modeling of the multiple-inverter and multiple-SG system with supplementary controls is developed.

$$\dot{x}(t) = A_c(t)x(t) + EF_1(Cx(t)) \quad A_c(t) = A(t) - B(t)KH$$

feedback control gains
• Linear Matrix Inequality (LMI) method is proposed to analyze system stability and estimate Region of Attraction (ROA).

Lyapunov function

\[ V = x^T P x - \sum \lambda_l \left( \cos(\delta_l + \delta_l^{SEP} - \beta_l) - \sin(\delta_l^{SEP} - \beta_l) \delta_l \right) - \lambda_l \cos(\delta_l^{SEP} - \beta_l) \]

LMI feasibility criteria

\[
\begin{bmatrix}
A_{ci}^T P + P A_{ci} & P E + A_{ci}^T C^T \Lambda + C^T T \\
E^T P + \Lambda \bar{C} A_{ci} + T \bar{C} & \Lambda \bar{C} E + E^T \Lambda - 2T
\end{bmatrix} < 0
\]

Solve the LMI for \( P > 0, \Lambda = \text{diag}(\lambda_l) > 0 \)

• Regional stability can be established if the LMI is feasible.
• In convex optimization of LMI system, interior-point method is used to obtain the optimal solution.

Dynamics of SG-GFIB System and Supplementary Control

- Supplementary control is applied to IEEE 13-node system with two synchronous-based and three inverter-based DERs.
- LMI analysis shows the proposed control method expands ROA.

\[ \text{SEP} = (-0.0738 \text{ rad}, -0.0775 \text{ rad}) \]
\[ \text{UEP} = (-1.2368 \text{ rad}, -1.1437 \text{ rad}) \]
Publications

Under review:

- L. A. Lee, et al., “Dynamics and Control of Microgrids as a Resiliency Source.” (with PNNL)

Published or Accepted for Publication:

Lessons Learned

• **What Worked Well**
  - Microgrid as a resiliency resource for distribution grids
  - System stability study for a microgrid control system
    - Transient stability test
    - Stability analysis of networked control system
    - Stability analysis of SG-GFIB system
  - Systematic analysis by networked control system and detection and mitigation techniques
  - Close collaboration with PNNL team

• **What Could be Improved**
  - Systematic method for control of the SG-GFIB system
  - Detailed models of communication system (can be adopted from the MBB project)
  - Actual distribution system models and parameters (collaboration with VT Electric Service distribution system)
Plan for FY21

- Systematic and scalable approach to operation and control of the microgrid with multiple SG-GFIB generation sources.
- Study of requirements and performance of the communication system.
- Developing the model of Virginia Tech Electric Service (VTES) system.
- Test the microgrid control and communications capabilities with the VTES real system data
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