IS MY GRID BOUNCING BACK? A CYBER-PHYSICAL RESILIENCE METRIC FOR SMART GRIDS

Safety Meets Security, Stuttgart-Nürtingen, 09 March 2017

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WHAT IS RESILIENCE?

A resilient control system is one that maintains state awareness and an accepted level of operational normalcy in response to disturbances, including threats of an unexpected and malicious nature.

A resilient industrial control system (RICS) is the one that is designed and operated in a way that:

- most of the undesirable incidents can be mitigated;
- the adverse impacts of undesirable incidents can be minimized…
- it can recover to normal operation in a short time.

Power system cyber-physical resilience is the system's ability to maintain continuous electricity flow to customers given a certain load prioritization scheme. A resilient power system responds to cyber-physical disturbances in real-time or semi real-time, …
MEASURE RESILIENCE
MEASURE RESILIENCE

\[ R_{p_i} : \mathbb{R}^+ \to [0,1] : t \mapsto 1 - \frac{\int_{t_0}^t p_i(\tau) d\tau - p_i^T \cdot (t - t_0)}{(t - t_0)(p_i^N - p_i^T)} \]
SO WHAT ABOUT $p(\tau)$?

- Evaluate resilience with respect to one performance indicator…

$$R_{p_i} : \mathbb{R}^+ \rightarrow [0,1]: t \mapsto 1 - \frac{\int_{t_0}^{t} p_i(\tau) d\tau - p_i^T \cdot (t - t_0)}{(t - t_0)(p_i^N - p_i^T)}$$

- … under consideration of related challenges,

$$\dot{p}_i(t) = f(t, r, p_i(t), p_i^N) - g(t, \bar{c}(t), \bar{p}(t)) \cdot \Theta_{p_i}(p_i(t))$$

- where each performance indicator can be a challenge to another indicator.

$$\tau : \mathbb{R}^+ \rightarrow \{x | \text{Performance} \}$$
SYNCHRONOUS ISLANDING USE CASE
CHALLENGES AND PERFORMANCE

Load Change

Cyber Attack (DoS)

Physical

Cyber

Control

Delay

Phase Error

Frequency Error

Settling Time

External Challenge

Performance

Feature

Challenge Relation

Performance

Emission

04.04.2017
FRAMEWORK DESIGN
EVALUATION

![Graphs showing frequency and phase responses with different load steps and delays.](image)

- **Load (MW):** Various steps labeled as $L_0$, approximated load step, and physical load step.
- **Frequency (Hz):** Responses include estimated frequency response, real frequency response, and frequency challenge.
- **Phase Error (rad):** Resilience estimation with different phase responses and delays.

![Phase Resilience vs. Step Size (MW)](image)

- **5ms delay**
- **20ms delay**
- **5ms + 50ms for 15s**
- **50ms delay**

**Time (s):** $t_{0}$, $t_{sp}$, $t_{sf}$

**Step Size (MW):** 20 to 140
EVALUATION