Persistent-Homology-based Detection of Power System Low-frequency Oscillations using PMUs

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Problem statement

Goal:

- Detect low frequency oscillations in power grids with minimal delay.

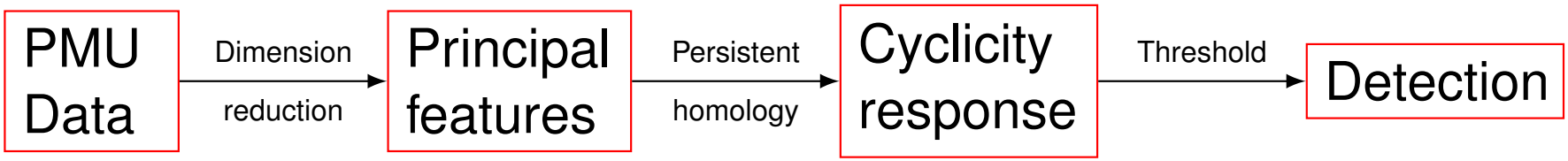
Why?

- Low frequency oscillations can lead to system wide failures, such as the 1996 Western Electricity Coordinating Council (WECC) blackout induced by a 0.25 Hz oscillation.

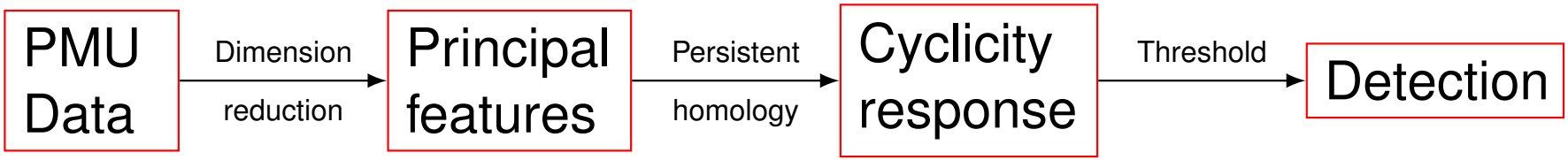
Our approach:

- We use a data-centric approach in contrast to model based approach.
- We utilize synchrophasor data collected from GPS synchronized PMUs.

Methodology



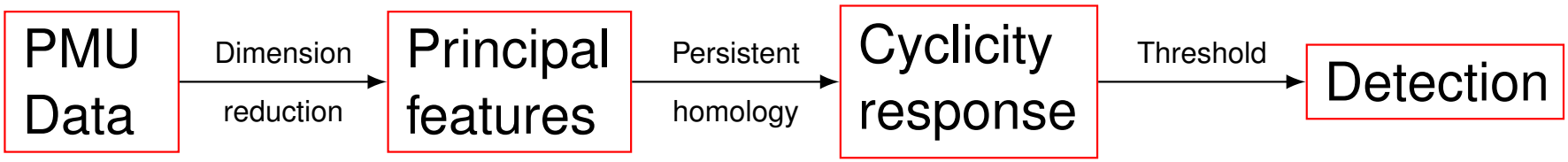
Methodology



PMU Data:

1. $\mathbf{Y}_e := [\mathbf{y}^{(1)}, \ldots, \mathbf{y}^{(N)}]$
2. N PMU measurements
3. $\mathbf{y}^{(\mathbf{i})} := [y_1^{(i)}, \ldots, y_n^{(i)}]^T$, $i = 1, \ldots, N$, n time samples for each PMU.

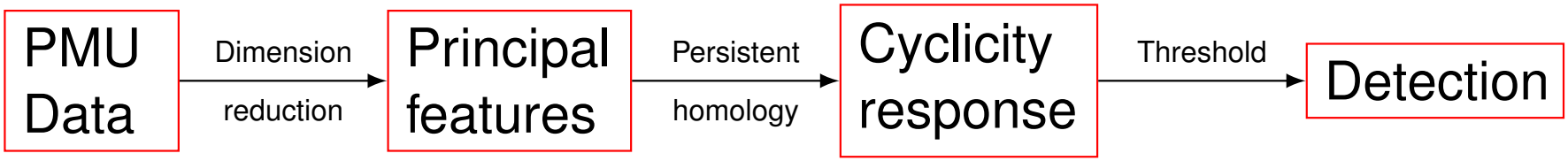
Methodology



Principal features:

1. Obtained using Principal Component Analysis (PCA),
2. $\mathbf{PC_i} = (\mathbf{Y_e} - \mu)\,\mathbf{u_i}$
3. $\mathbf{PC_i}$ is the ith PC, $\mathbf{u_i}$'s, $i = 1, \ldots, N$, the eigenvectors of $\Sigma_{\mathbf{Y_e}}$. $\mu = E[\mathbf{Y_e}]$ is the measurement expectation.

Methodology



Cyclcity response:

1. Convert time signals into a point cloud
2. Analyze the point cloud to infer cyclic behavior in the system

Cyclicity response

Delay embedding theorem

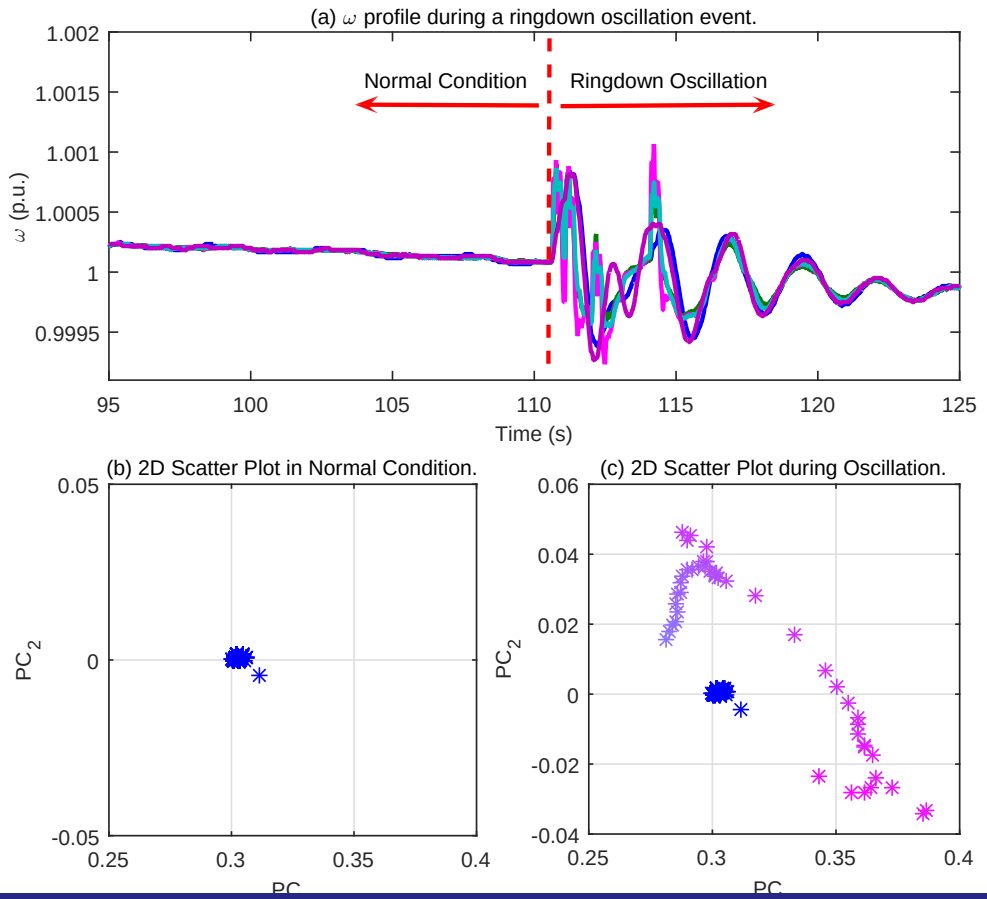
1. Dynamical system $f : X \to X$ with an attractor A,
2. Any *generic* observation function $g : X \to \mathbb{R}^k$,
3. The map

$$G(x) = \left(g(x), g\left(\phi(x)\right), g\left(\phi^2(x)\right), \ldots, g\left(\phi^{k-1}(x)\right)\right)$$

   is an embedding of A, for sufficient large k.
4. In essence: Embedding any generic observation function in a sufficiently high dimension can reveal the topology of the underlying attractor.

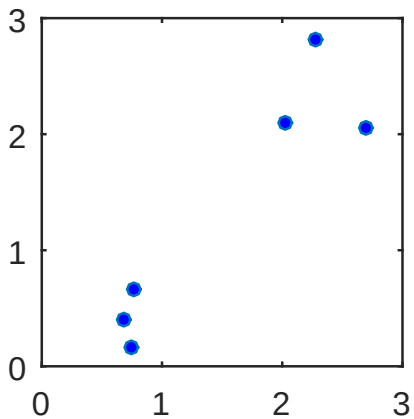
Cyclicity response

Delay embedding theorem

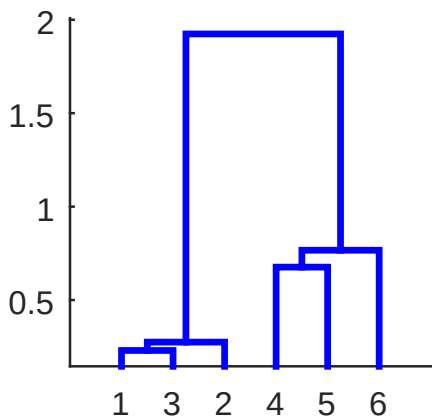


Cyclicity response

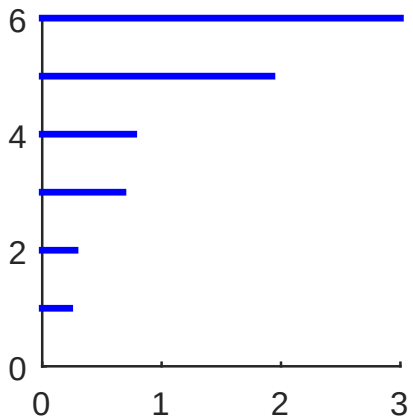
Hierarchical clustering



(a) Point Cloud



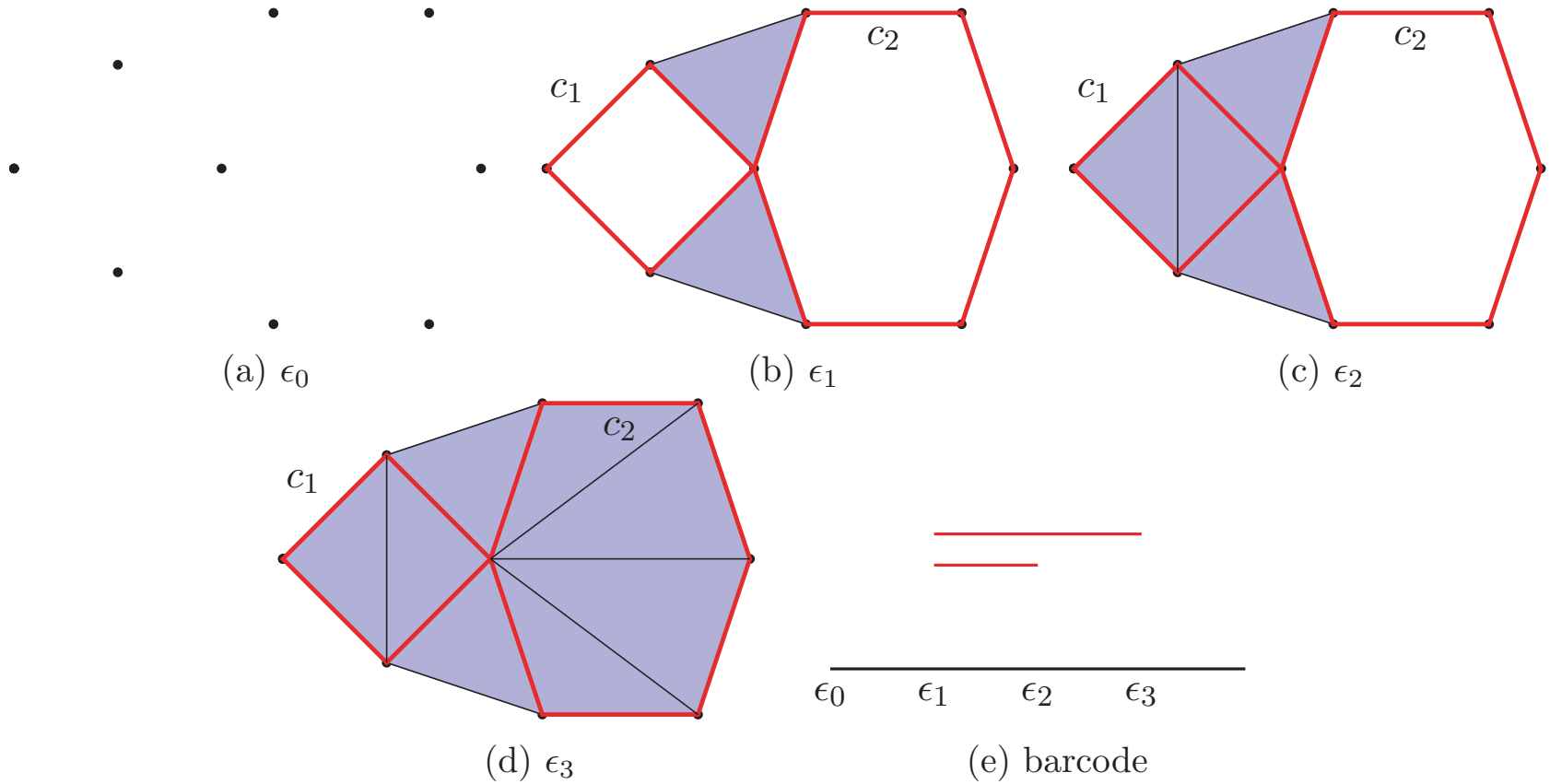
(b) Dendrogram



(c) Barcode

Cyclicity response

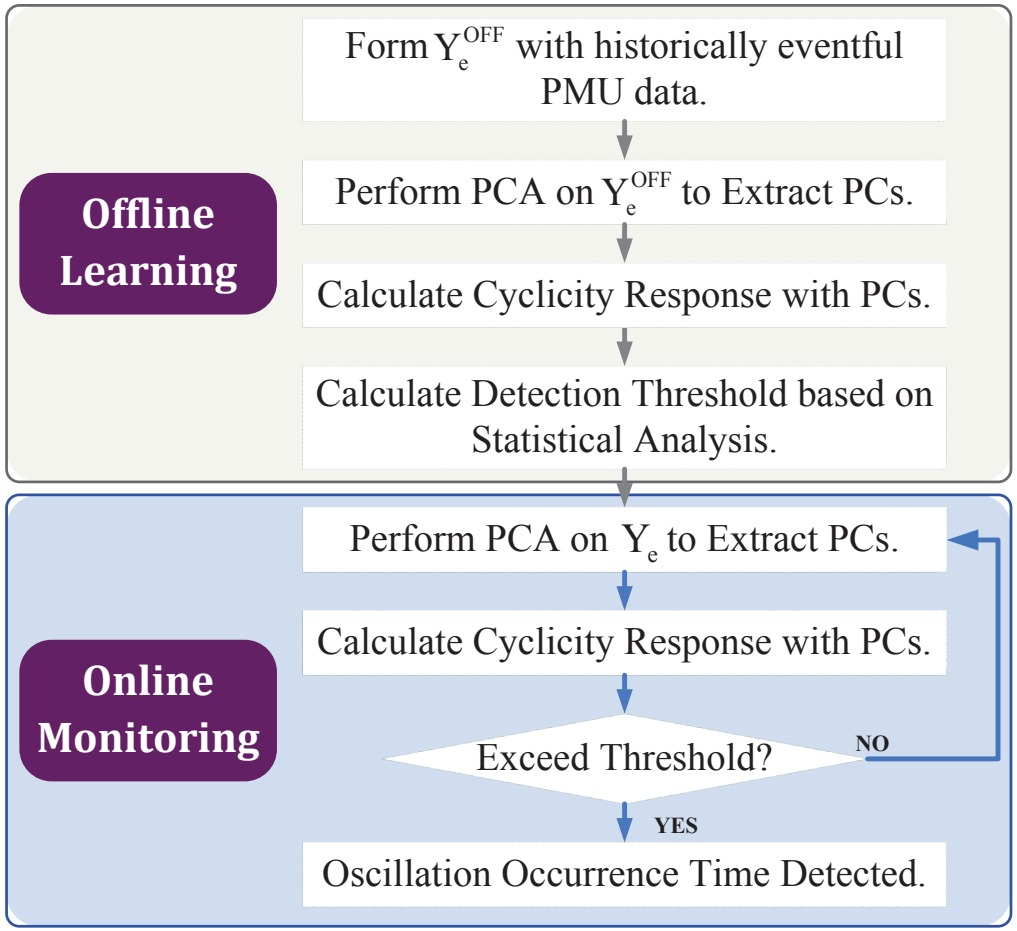
Persistence homology



(a) ϵ_0 (b) ϵ_1 (c) ϵ_2

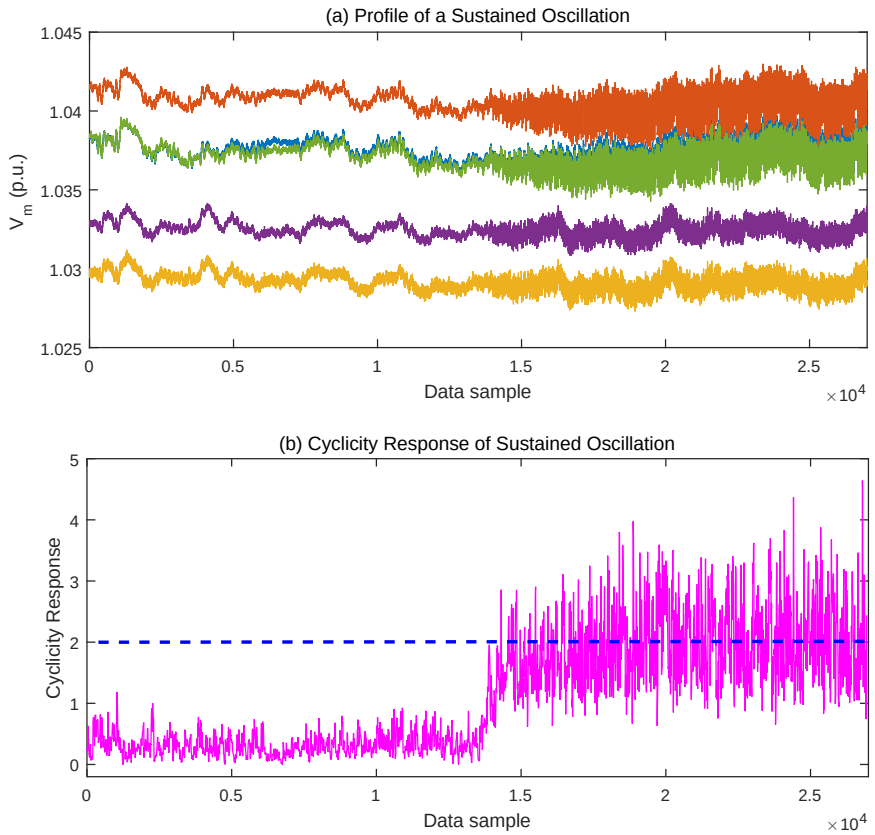
(d) ϵ_3 (e) barcode

Implementation



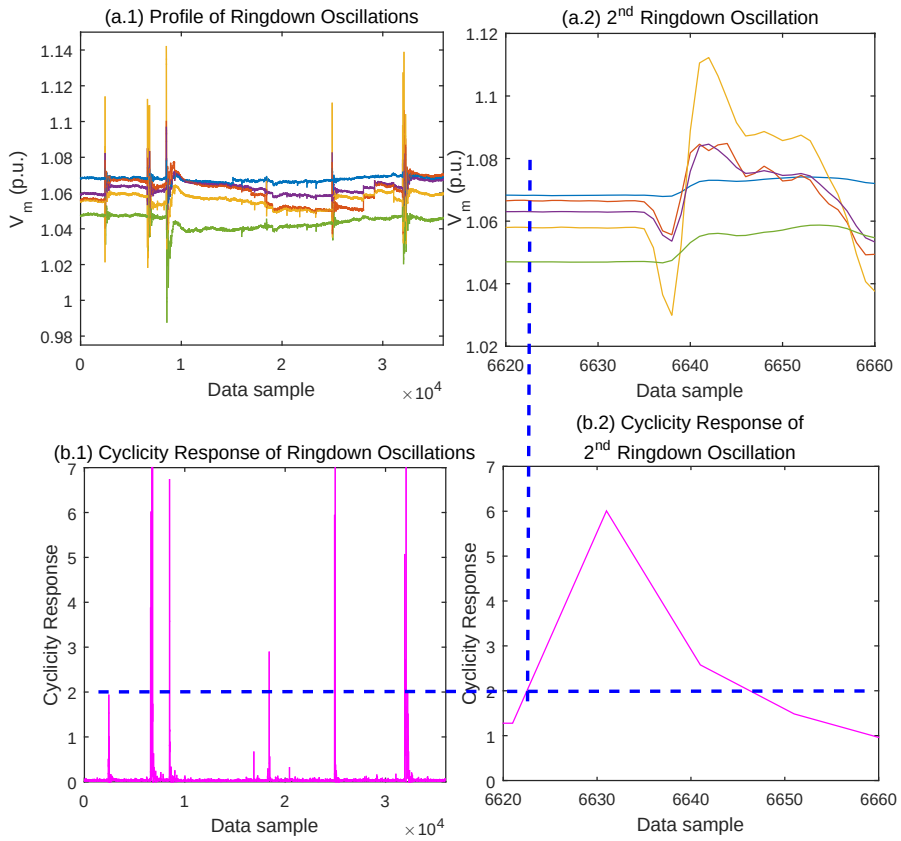
Cyclicity response of oscillatory events

Sustained oscillations



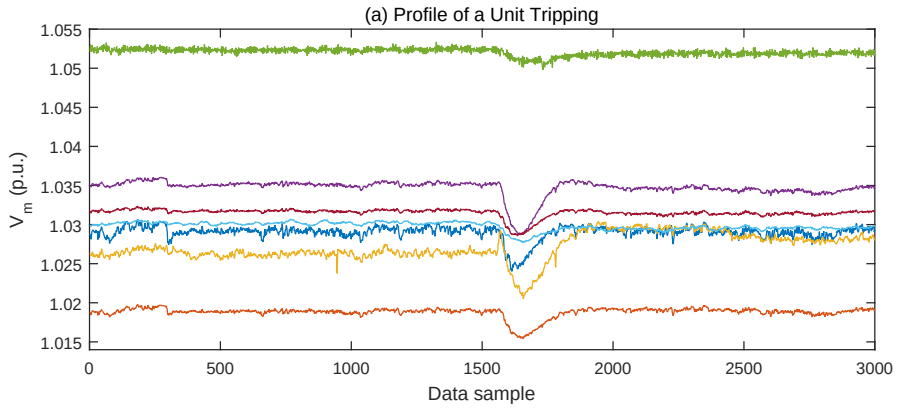
Cyclicity response of oscillatory events

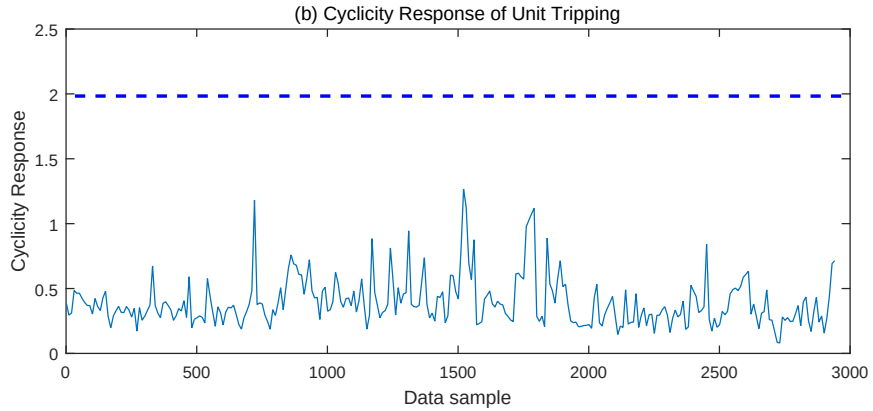
Ringdown oscillations



Cyclicity response of non-oscillatory events

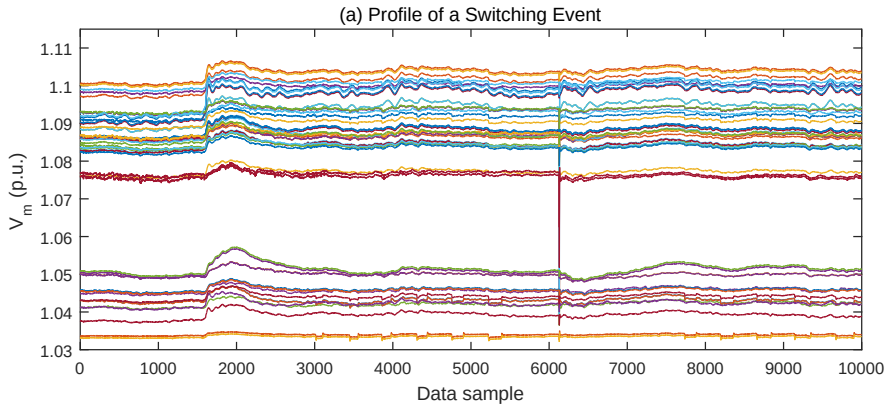
Tripping event

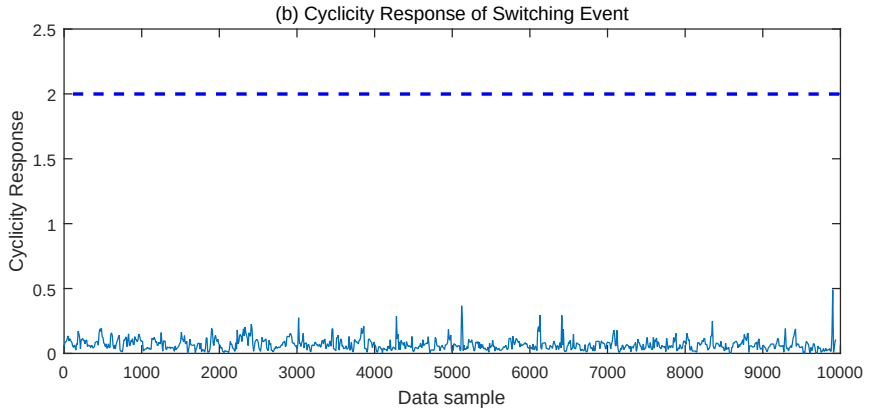




Cyclicity response of non-oscillatory events

Switching event





Thank you!!