Data-Driven Long Term Voltage Stability Monitoring and Control

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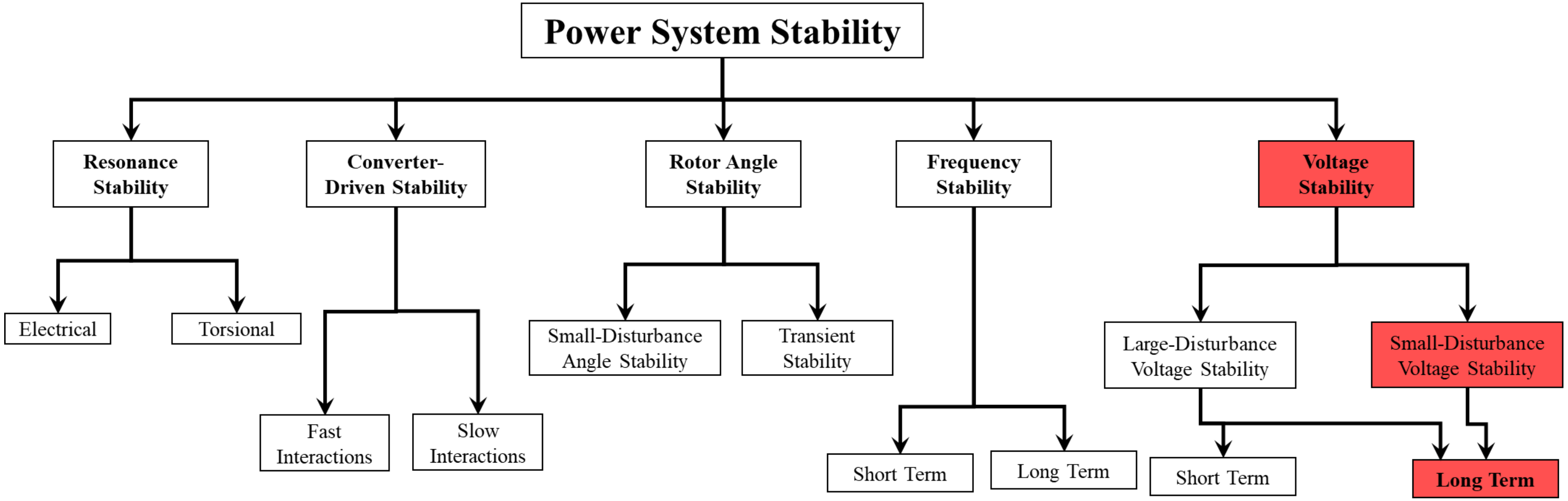
Background and Motivation

- Stability is a key property of the power grid for successful operation

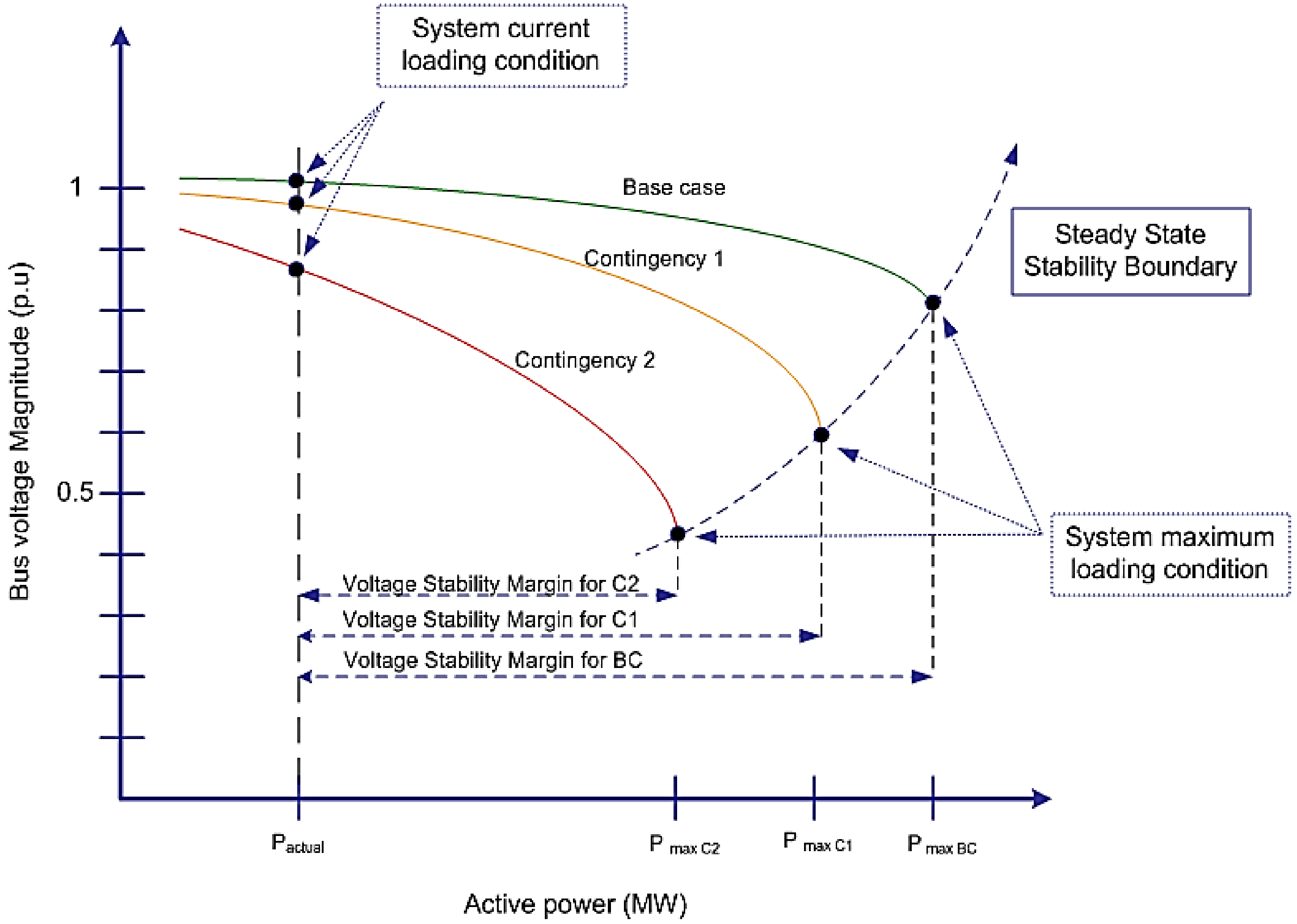


- Voltage stability - The ability of the system to operate with acceptable voltages under normal conditions or after a disturbance
- It is becoming harder to ensure stability using offline studies with renewables – an online approach is needed to monitor and control

2003 US Northeast Blackout

- 2003 Northeast blackout Report found that inadequate preparations for voltage management and the provision of reactive power were among the major contributing factors – 50 Million affected & $6 billion societal cost

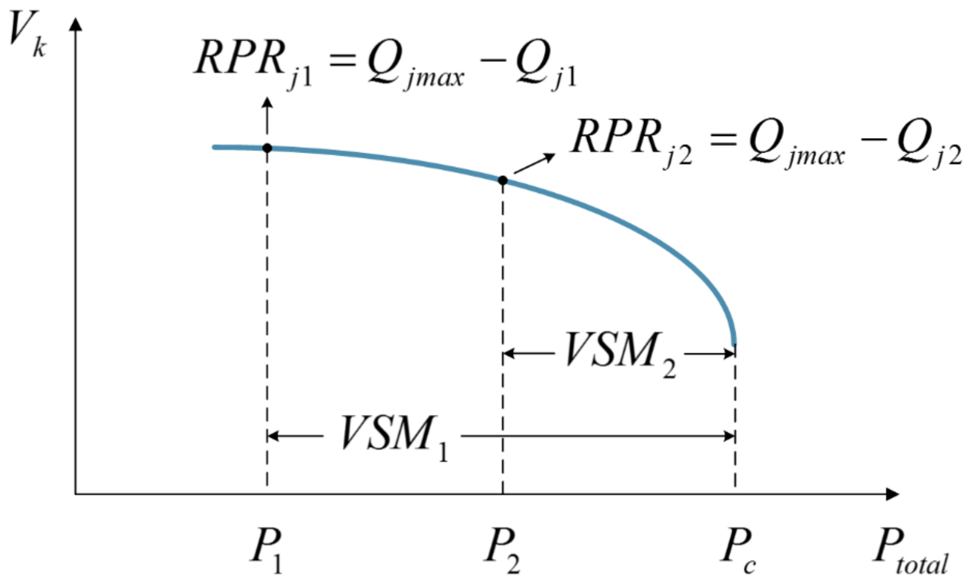
Quantifying Voltage Stability

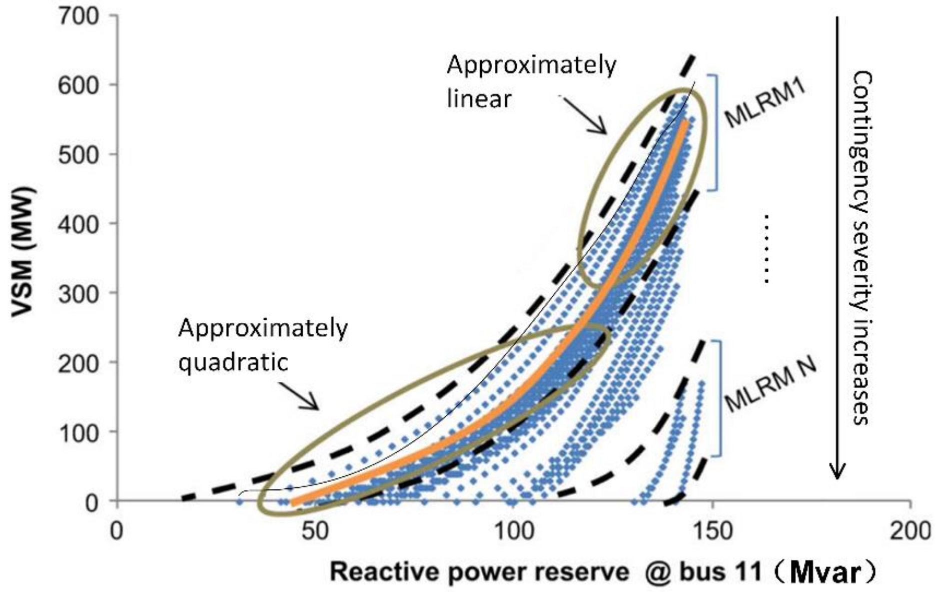


- <u>Just Voltage is not a good indicator or voltage stability</u>
- <u>Long-term Voltage Stability Margin (VSM)</u> is the amount of loading to reach the Critical Point.
- Continuation Power Flow can be used to obtain VSM – Time Consuming
- **Can we learn from map from state to VSM using offline data ??**

Predict VSM in real time using RPR

- Reactive power reserves of generators are key factors impacting VSM

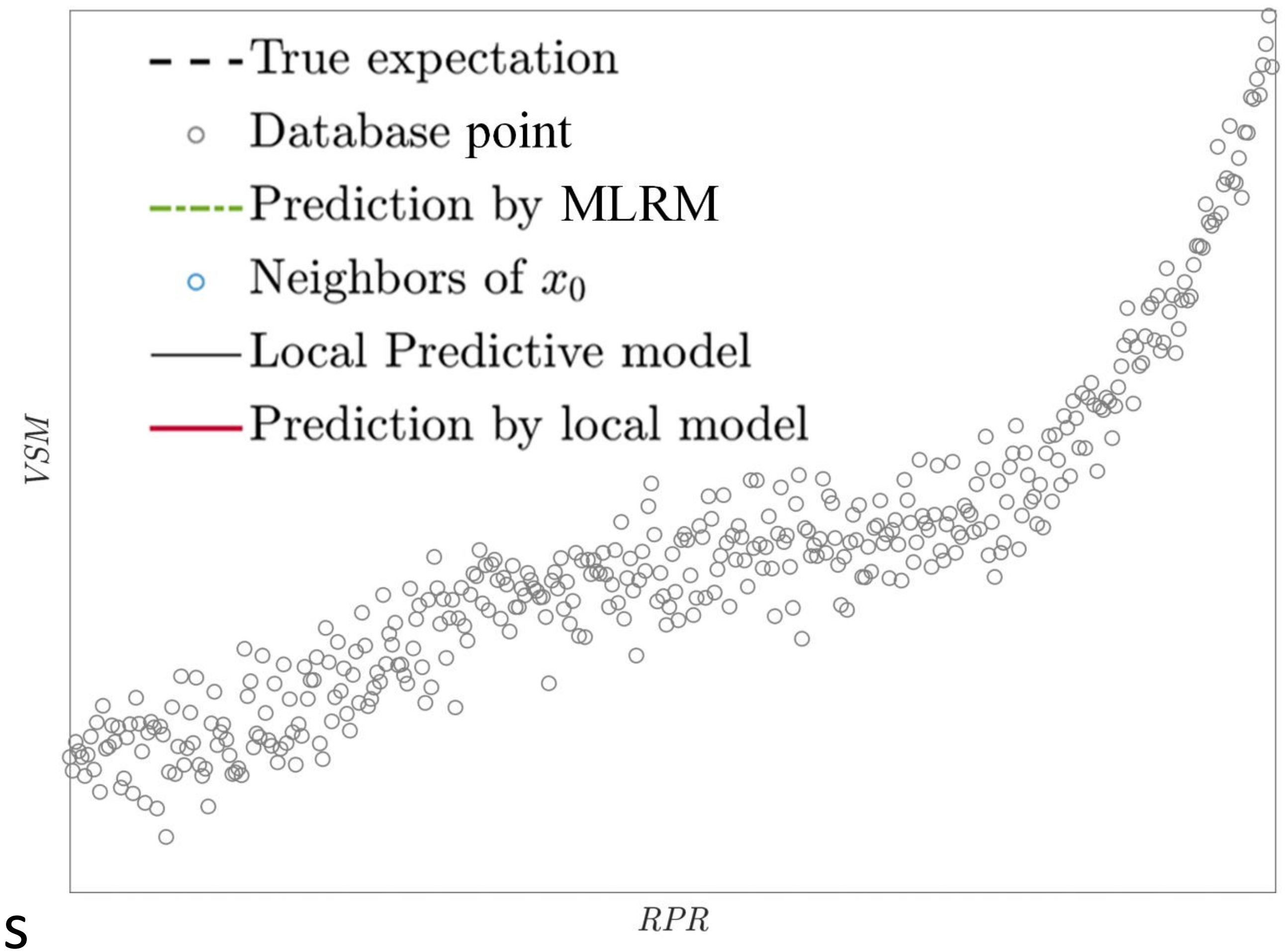




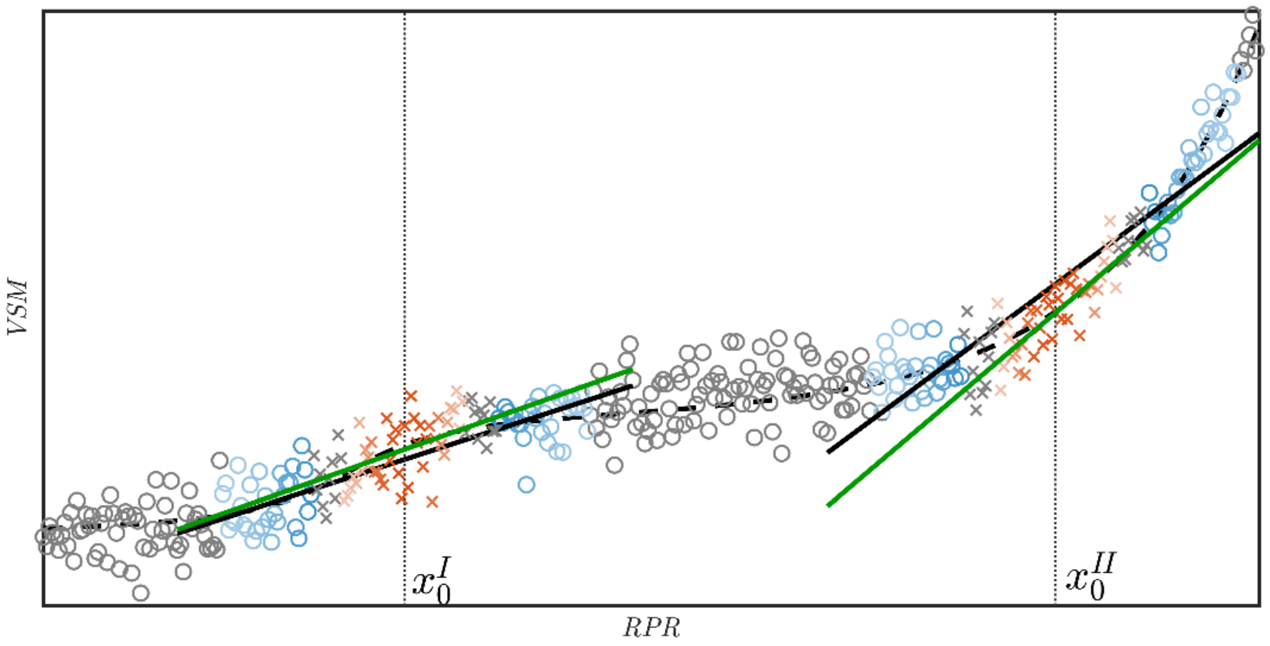
- A database of operating points is obtained via PV curve tracing for various contingencies and scenarios – cluster based on V_{gen} & P_{flow}
- Multilinear models in each cluster that map measurements (e.g. RPRs) to VSM are trained using the database

State to VSM via local regression

- Learn a linear model online for current operating point only using local information
- How to define the neighborhood:
  - Metric: Euclidian, neighborhood component analysis
  - Size or boundary (*K*): KNN
- Regression algorithm: weighted LASSO
  - Weights: tri-cubic kernel
- PCA is used to reduce the dimensions of data before performing regression



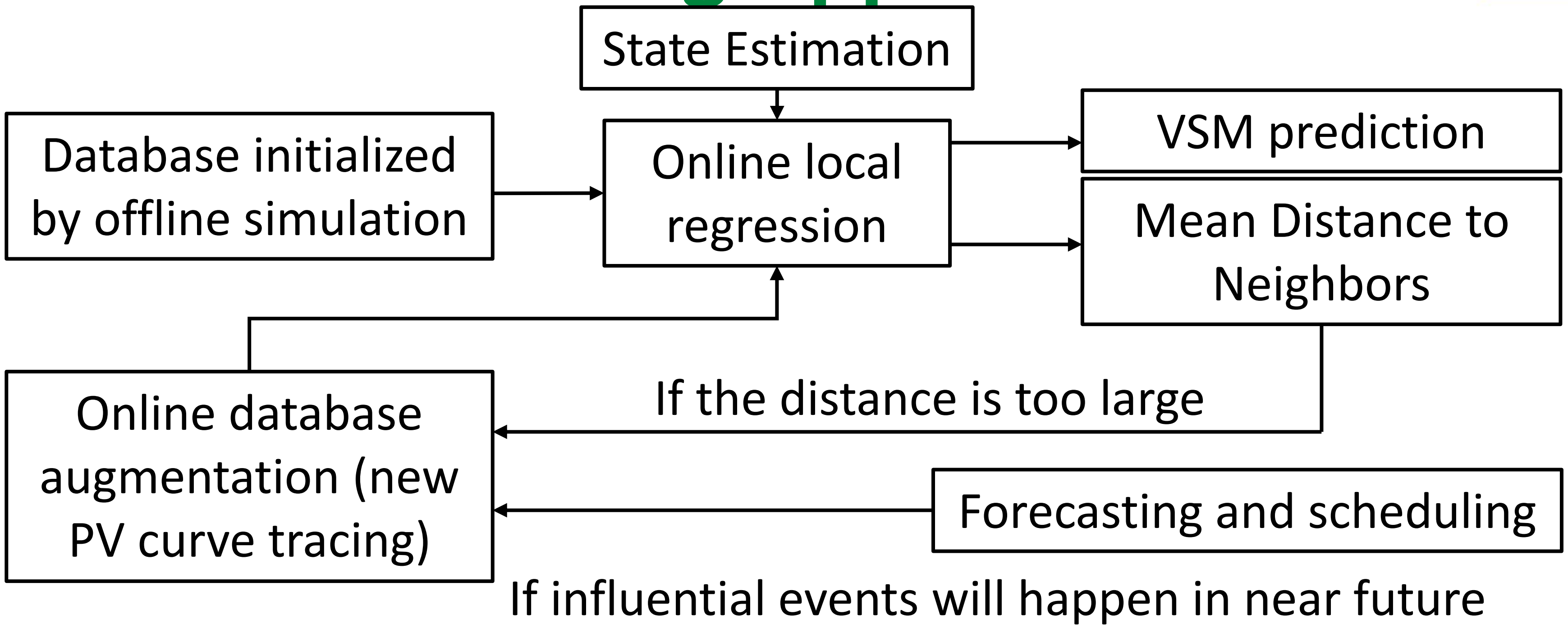
Improve prediction by data augmentation



Prediction is affected by the quality of the neighbors.

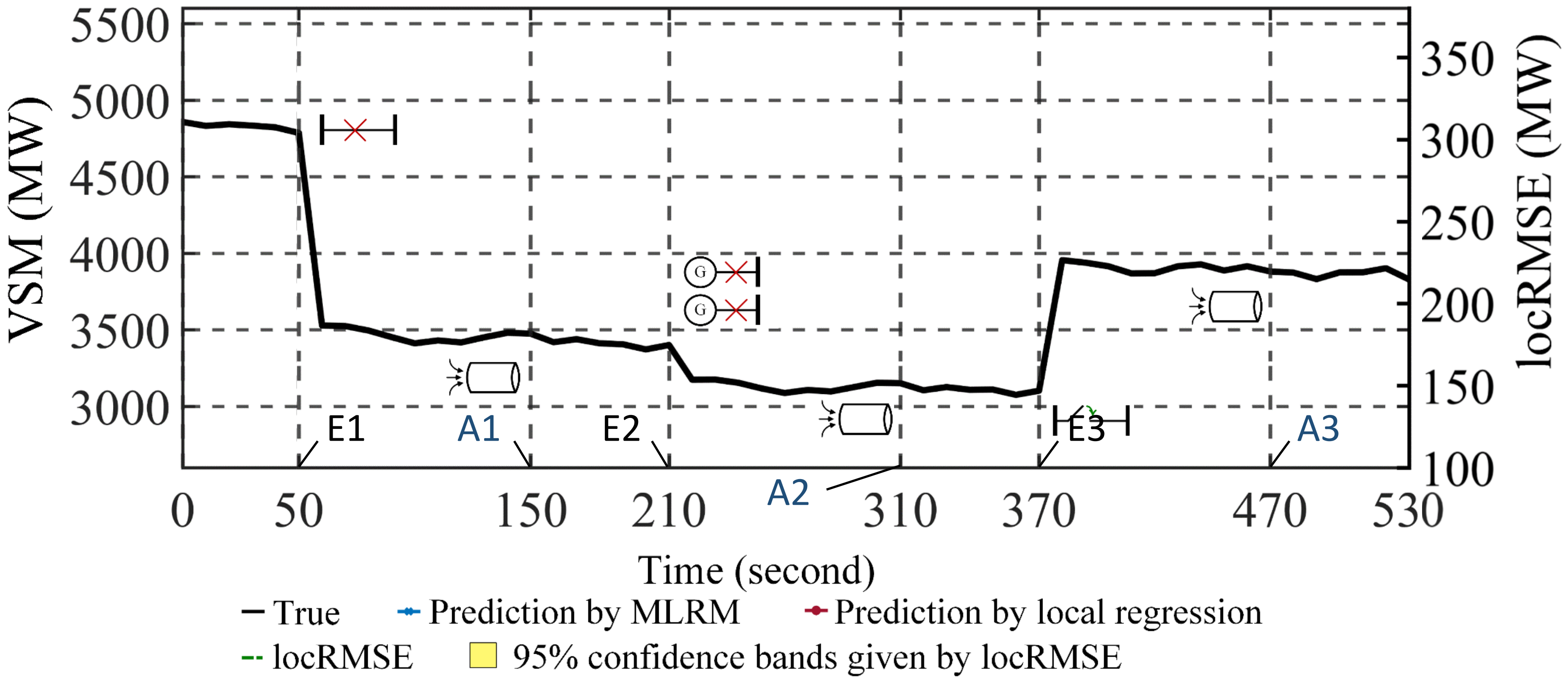
- When the system is operating in unfamiliar conditions, the prediction becomes unreliable due to inadequate data
- Locally adding relevant data can improve the prediction (data augmentation as an implicit regularizer) – improves trust in approach

Overall VSM Monitoring Approach

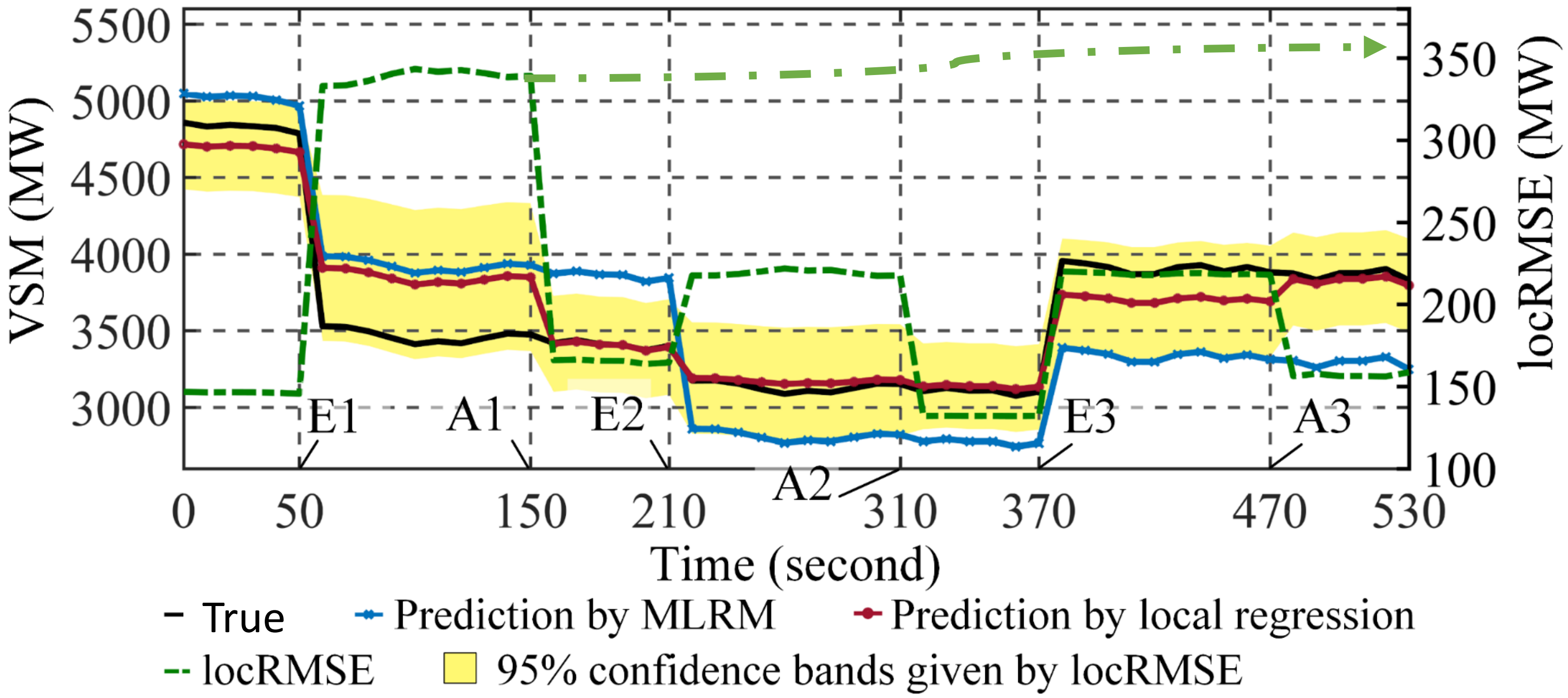


- No training offline – only data generated or historical data.
- Off-line data cannot fully capture non-stationary environment (high renewable penetration, etc.)
- Online trained model can adapt to changing conditions

Demonstration of online adaptation



Demonstration of online adaptation



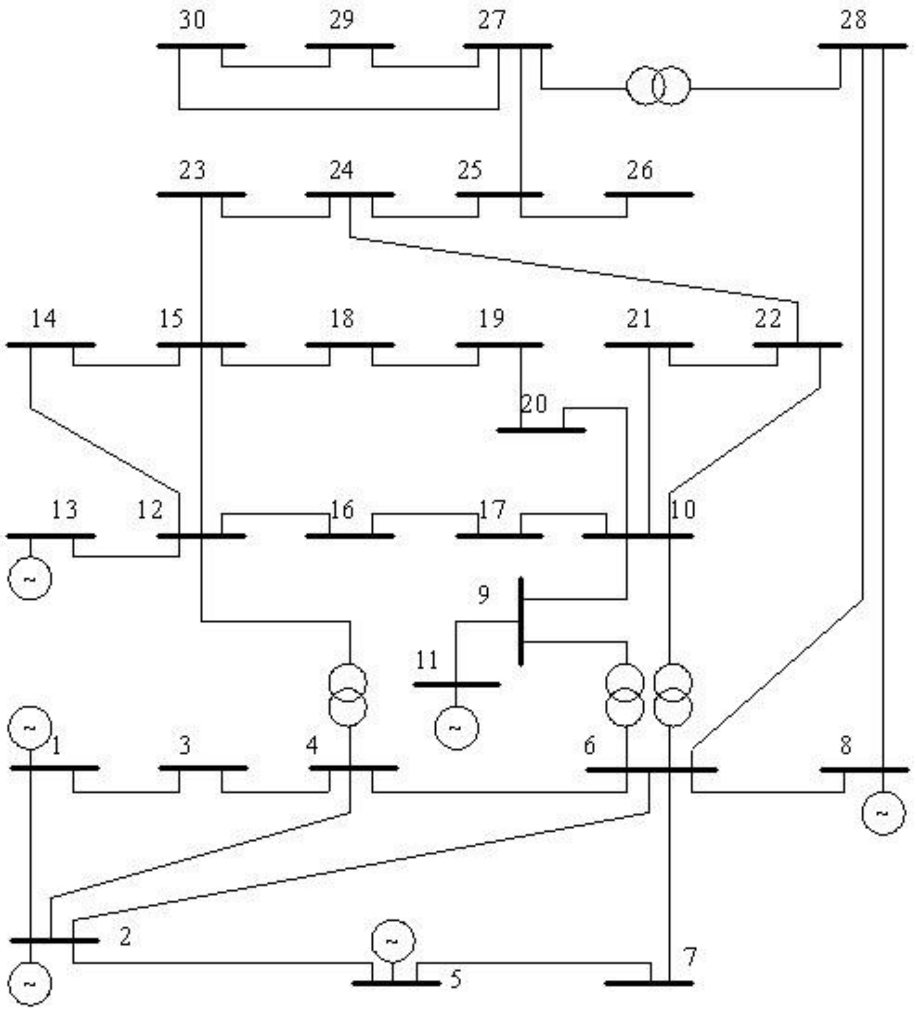
- Proposed method adapts to the changing system condition (46% error reduction)
- Confidence band suggest how much the operators should trust the prediction

Predictive VSM Control Scheme

- “Prediction can utilize correlation, but control should follow causality.”
- When VSM is detected or predicted to be lower than certain threshold, control actions are needed to steer the system back to a secure state - Two enabling factors:
  1. Approach not only gives the current value of VSM, but also is an explicit linear model of VSM that can be embedded in OPF at transmission
  2. Demand response, especially non disruptive direct load control, can be utilized to maintain VSM

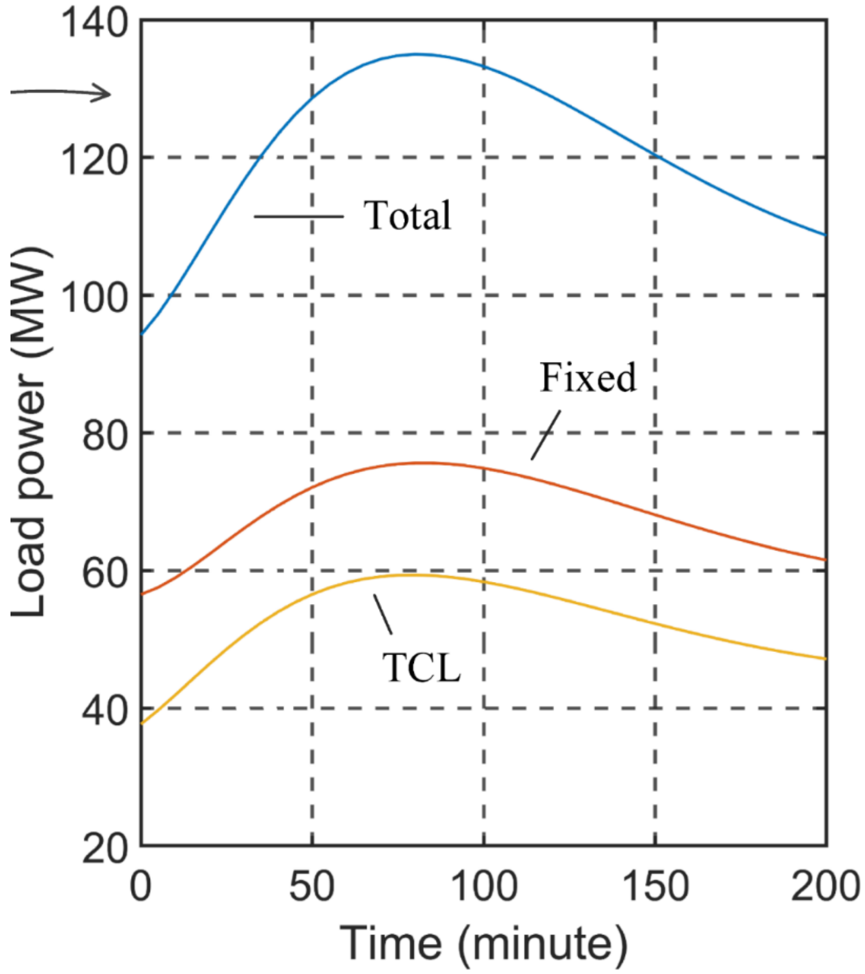
- Forecasting is necessary to properly identify the control so that the impact to end user is minimal – e.g. pre-cool houses in off peak conditions – Model predictive control

Example – IEEE 30 bus system

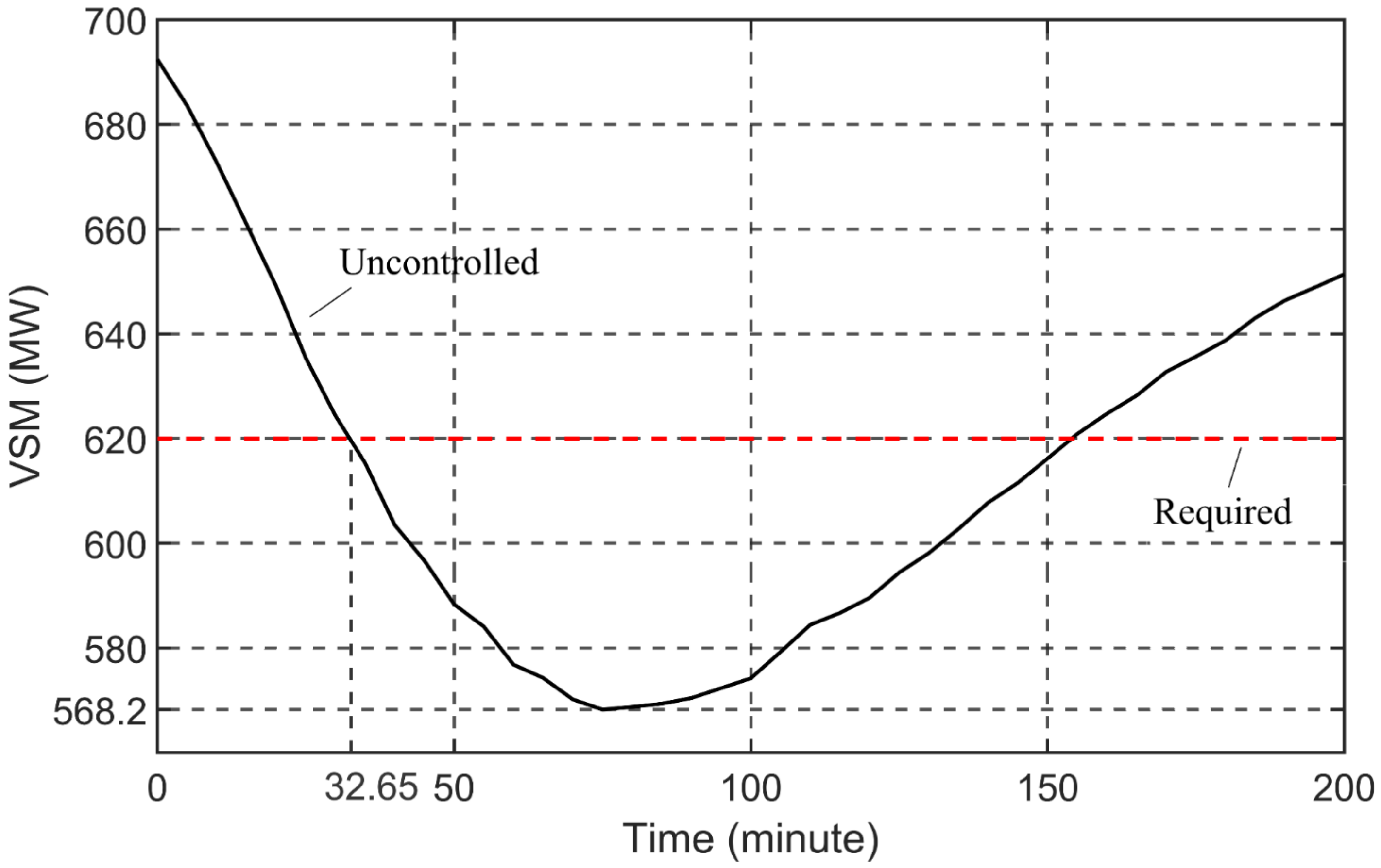


Total system load over time

TCL – Thermostatic Controllable Loads

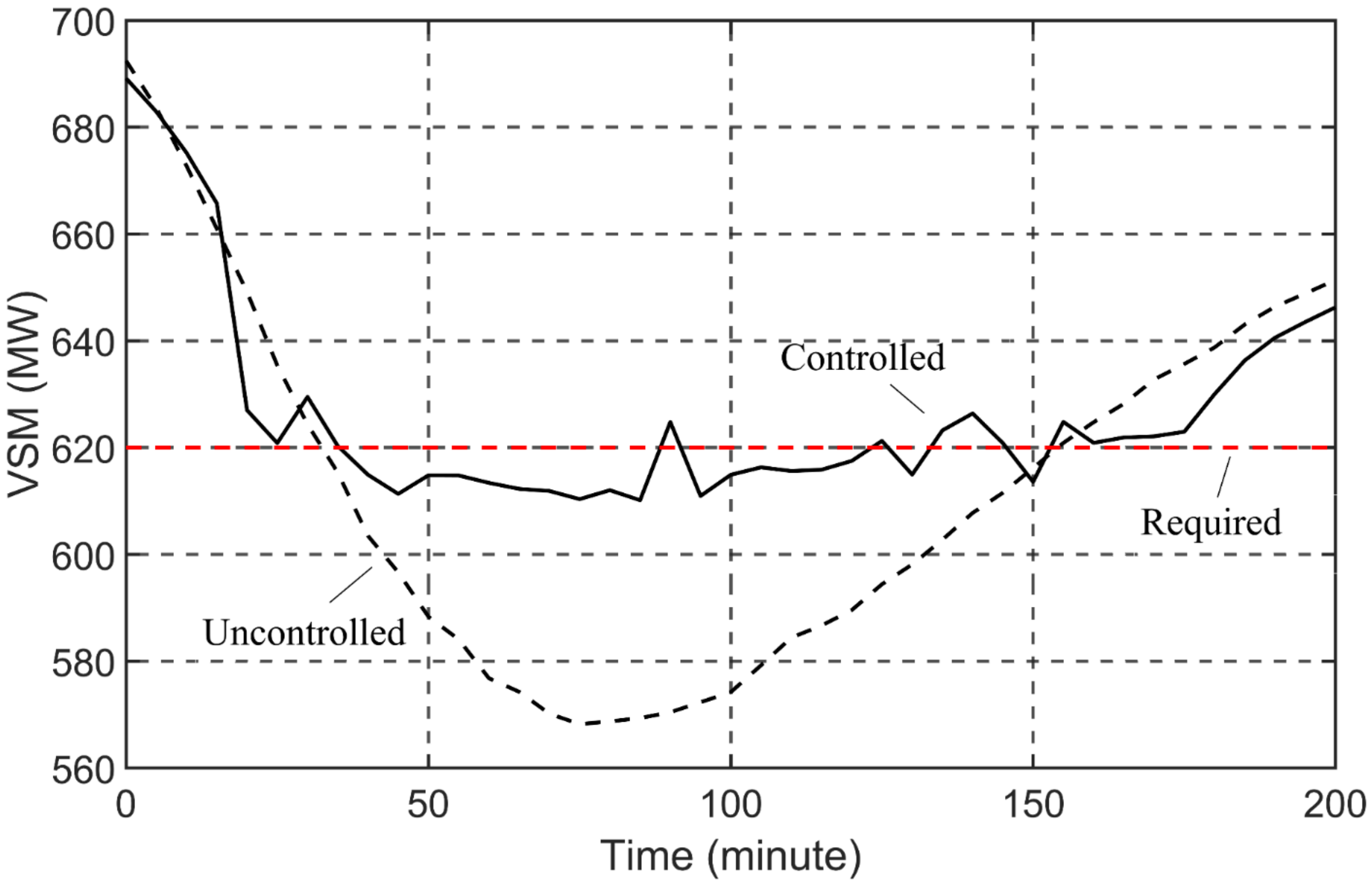


Uncontrolled VSM evolution



- $Margin_{spec} = 620\ MW$
- Exceeds limit after t = 32.65
- Uncontrolled VSM is obtained via PV curve tracing (average of 40 random LIDs)

VSM control via TCL control and Forecast



- $Margin_{spec} = 620\ MW$
- Achieved the goal of maintaining VSM
- Violations due to model errors
- TCL Load behavior is modified to 'flatten' overall load

Conclusion and Ongoing Work

- Increasing renewables are adding uncertainty and variability into the voltage stability monitoring and control
- Simple models combined physical understanding of the phenomenon can give good results for large systems – scalability
- Adapting the data-set to the new operating conditions is a must for practical systems
- These models can be embedded into Economic dispatch/ OPF for maintaining VSM above threshold - "Prediction can utilize correlation, but control should follow causality."
- Current challenge is the large amount of offline data necessary to perform the local linear regression – this data should be in RAM for identifying neighborhood data.
- Leverage deep neural networks to reduce data dependence during online monitoring and control – challenge is to "robustify" the model to perturbations

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Thank You for your Attention
Questions?

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