Wide-Area Voltage and VAR Control of SCE Transmission Network

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Introduction

- **For reliable operation and quality of service to its customers, a Power System needs to employ two types of controls: Load-Frequency Control, and Voltage Control.**

- **In California, Load-Frequency Control is done by CAISO, and Voltage Control is responsibility of the respective utility companies.**

- **SCE's bulk power transmission system (500 kV & 230 kV) voltage control basically is done manually in accordance with the SOB 17 and system operator's experience and preferences. During past decade an automatic centralized capacitor control (CGCC) has been developed that controls capacitors only, based on a heuristic control criteria.**

Introduction (cont'd)

- **With complexities that is being imposed on transmission system, the manual voltage control is not the appropriate choice (optimal) any more, and certainly will not satisfy operating requirements at all times.**

- **There is also an increased interest in greater power system automation to relieve operators from repetitive tasks and improve system quality and utilization. Voltage control is a perfect choice for transmission system automation.**

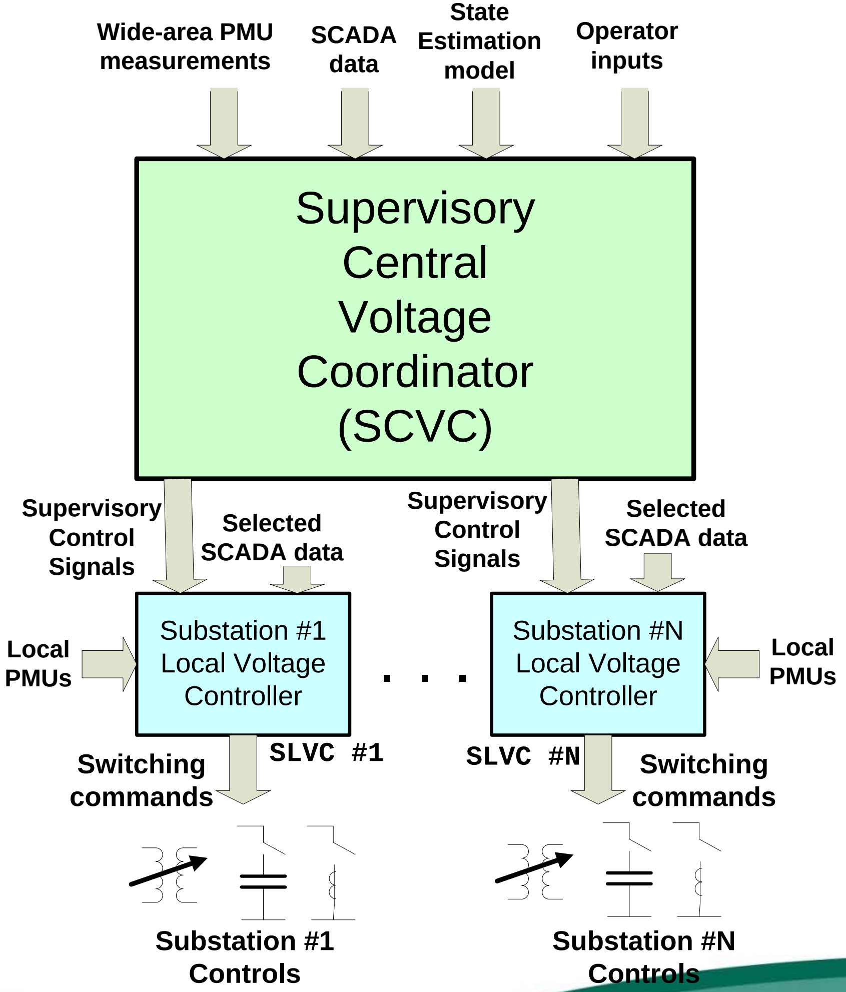
Introduction (cont'd)

- **Multi-level hierarchical voltage control of transmission network is utilized in several European countries, and the accumulated experience is reported to be highly satisfactory. In general, the control is achieved in three levels:**
  - **Primary Voltage Control (Gen, SVC, …)**
  - **Secondary Voltage Control (regions of network)**
  - **Tertiary Voltage Control (system-wide optimization)**

SCE's Wide-Area Transmission Voltage Control System

- The SCE transmission system voltage controller is a two-level controller consisting of a Supervisory Central Voltage Coordinator (SCVC), and a Substation Local Voltage Controller (SLVC). The SCVC performs an OPF type of calculations to determine optimal bus voltage set points, enables/disables each SLVC, and each SLVC maintains the bus voltage set points by controlling local VAR resources in an optimal fashion.
- The control system is aimed at maintaining transmission voltage profile at steady state. SCVC serves as a Tertiary Voltage Control element, and SLVC serves as a Secondary Voltage Control element. Primary Control is not directly activated, but its reactive power output is kept at a minimum so that its full capacity is available during a large disturbance.

Block Diagram of Wide-Area Voltage Control in SCE Transmission Network



Substation Local Voltage Controller (SLVC)

- **Maintain substation bus voltages by switching local VAR devices – transformer banks LTC, capacitor banks and reactor banks.**
- **Maintain VAR output and VAR flow constraints.**
- **Minimize switching of VAR devices.**
- **Alerts and Alarms when getting close to voltage insecurity.**
- **Switching decisions mostly based on local PMU measurements – bus voltages, VAR flows, equipment status, and equipment limitations.**
- **Supervisory guidance from central coordinator – voltage schedules, SLVC enable/disable**

SLVC Design Details

- **Slave Mode (Substation 500 kV SVC in service)**
  - Maintain 115 kV and 230 kV bus voltages by switching local VAR devices – transformer banks LTC, capacitor banks and reactor banks
  - Maintain SVC VAR output within limits and other VAR flow constraints
  - Maintain VAR flow constraints

- **Master Mode (500 kV SVC out of service)**
  - Maintain 115 kV, 230 kV and 500 kV bus voltages by switching local VAR devices – transformer banks LTC, capacitor and reactor banks
  - Maintain VAR flow constraints

- **Automatic switching between Master and Slave Modes using SVC status. Manual override optional.**

SLVC Controller Design Concept Optimal Predictive Controller

Three prediction methods:

- **Local voltage estimator (LVE) based on on-line reactive power flow analysis using local PMU data:**

$$[\Delta \mathbf{Q}] = [\mathbf{B}][\Delta \mathbf{V}]$$

- **Off-line switching estimates (OVE) from off-line power-flow studies**
- **Recent switching analyzer (RSA) from PMU data analysis of recent switching actions**

SLVC Controller Design Concept Execution

- **Exhaustive search among candidate control actions**
  - Calculate effects due to switching each one of candidates.
- **Find feasible subset of actions**
  - Select candidates that are able to solve the alarm. If none, select the best candidate among them.
- **Simple rules for control priority specification**
  - Eliminate low priority and high cost candidates.
- **Final selection of candidate**
  - Take action for candidate that maintains buses closer to the bus voltage set points.

Supervisory Central Voltage Coordinator (SCVC)

- Coordinate switching of substation SLVC controllers
  - Enable specific substation SLVCs as needed
  - Disable other substations to prevent hunting
- Optimize voltage profile towards minimizing VAR losses – convey schedules to substation SLVCs
- Optimal management of VAR resources
- Alerts and Alarms when getting close to voltage insecurity

SCVC Design Details

Supervisory Coordination

- Monitor grid voltage profile and select *optimal* substation controllers to address voltage problems. Issue Enable/Disable commands as needed
- Mostly based on PMU measurements (assuming sufficient PMU measurements of analog and digital states)

Optimal Management

- Optimize grid voltage profile to minimize VAR losses by coordinating substation voltage schedules
- Power-flow formulation – runs periodically

SCVC Design Details

Supervisory Coordination

- System-wide voltage estimator based on on-line reactive power flow analysis using wide-area PMU data:

$$[\Delta \mathbf{Q}] = [\mathbf{B}][\Delta \mathbf{V}]$$

  - Exhaustive search among candidate control actions. Find feasible subsets. Simple rules for control priority specifications. Final selection of candidate

SCVC Design Details

Optimal Management

$$\text{Min} \quad \sum_i \sum_j \left| Q_{ij} + Q_{ji} \right|$$

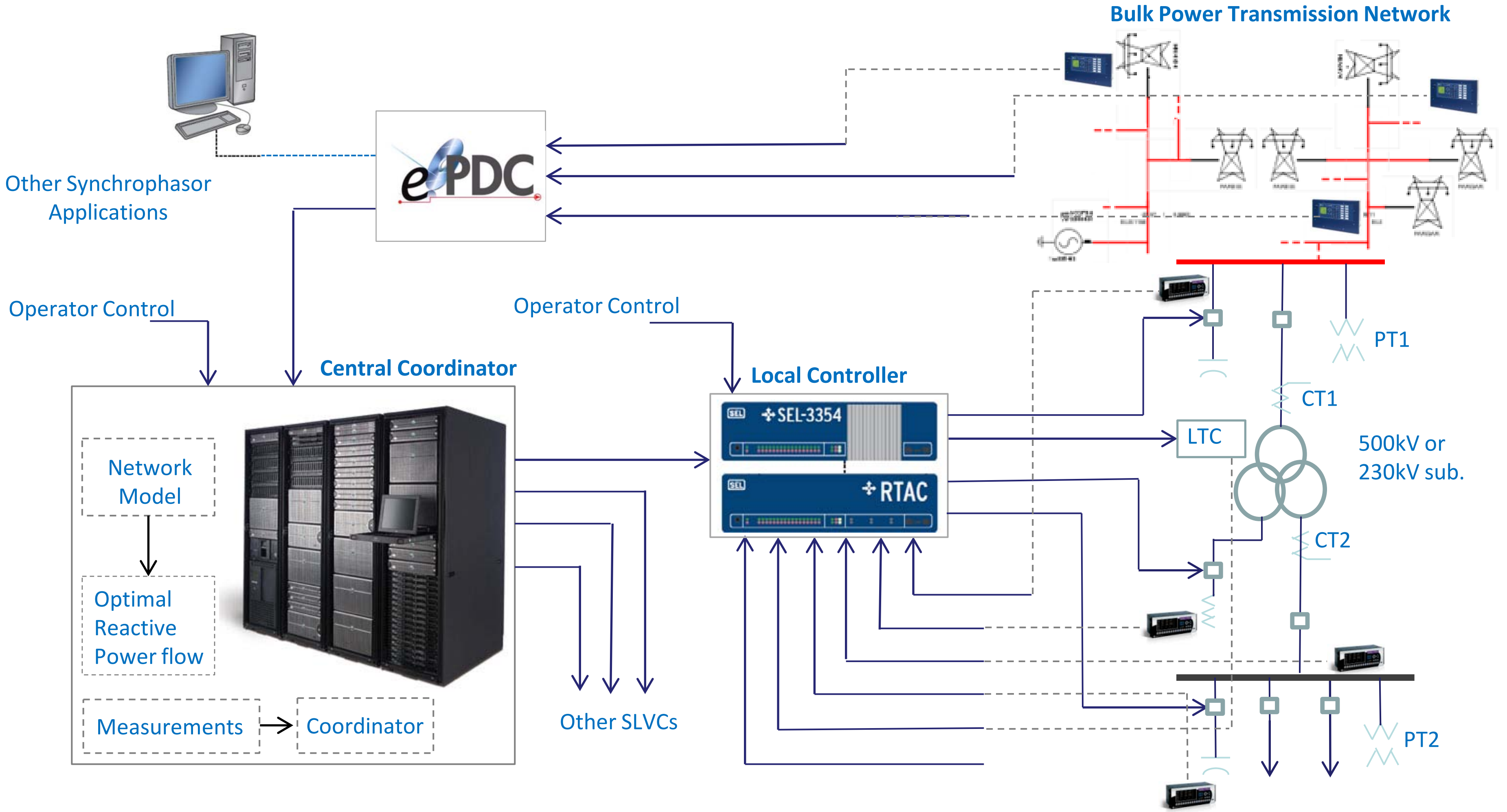
$$V_i^{min} < V_i < V_i^{max}$$

$$Q_i^{min} < Q_i < Q_i^{max}$$

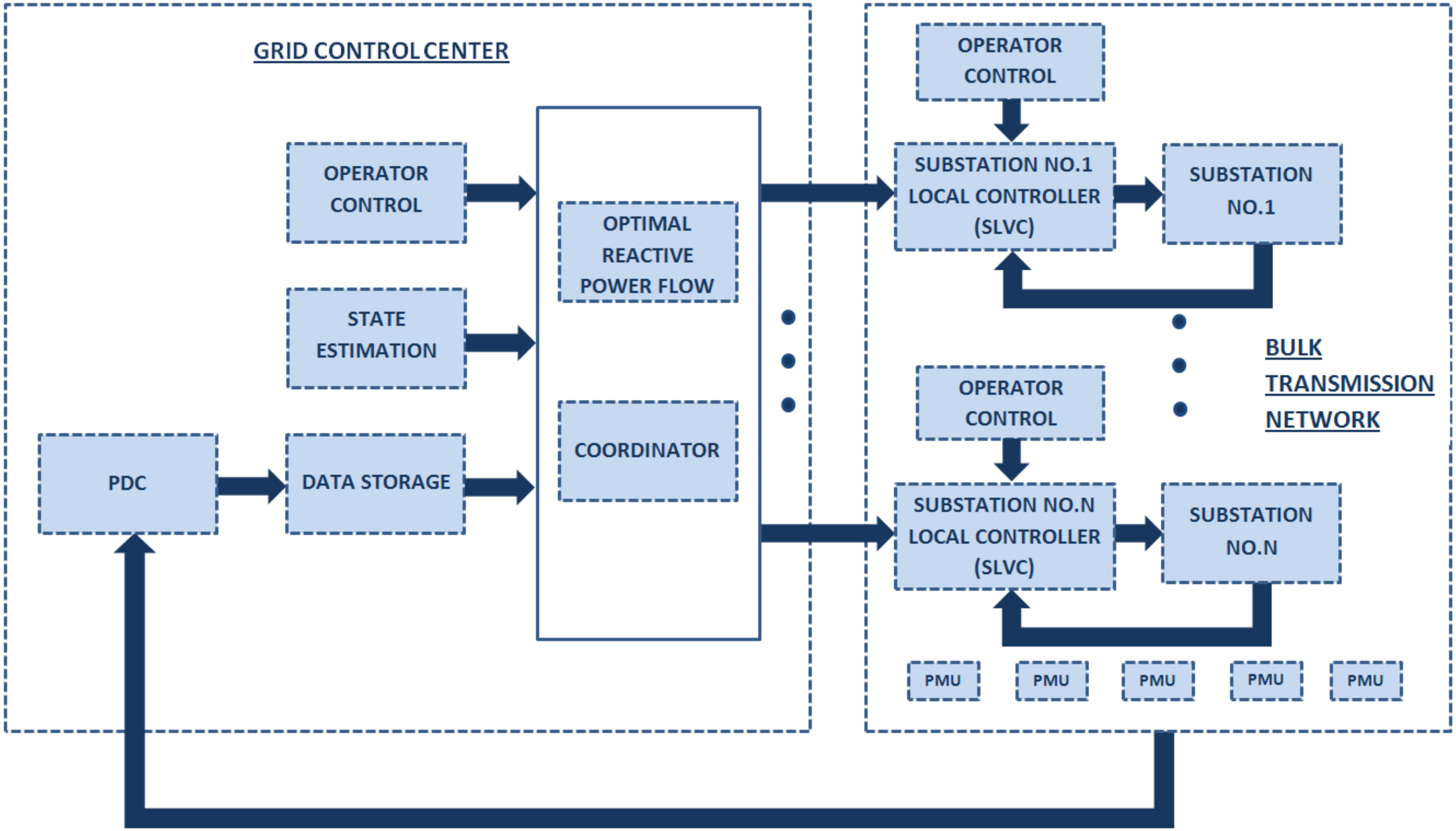
$$P_i = \sum_j Y_{ij} V_i V_j \cos(\delta_i - \delta_j - \theta_{ij})$$

$$Q_i = \sum_j Y_{ij} V_i V_j \sin(\delta_i - \delta_j - \theta_{ij})$$

Functional Diagram
Wide-Area Voltage Control in SCE Transmission Network

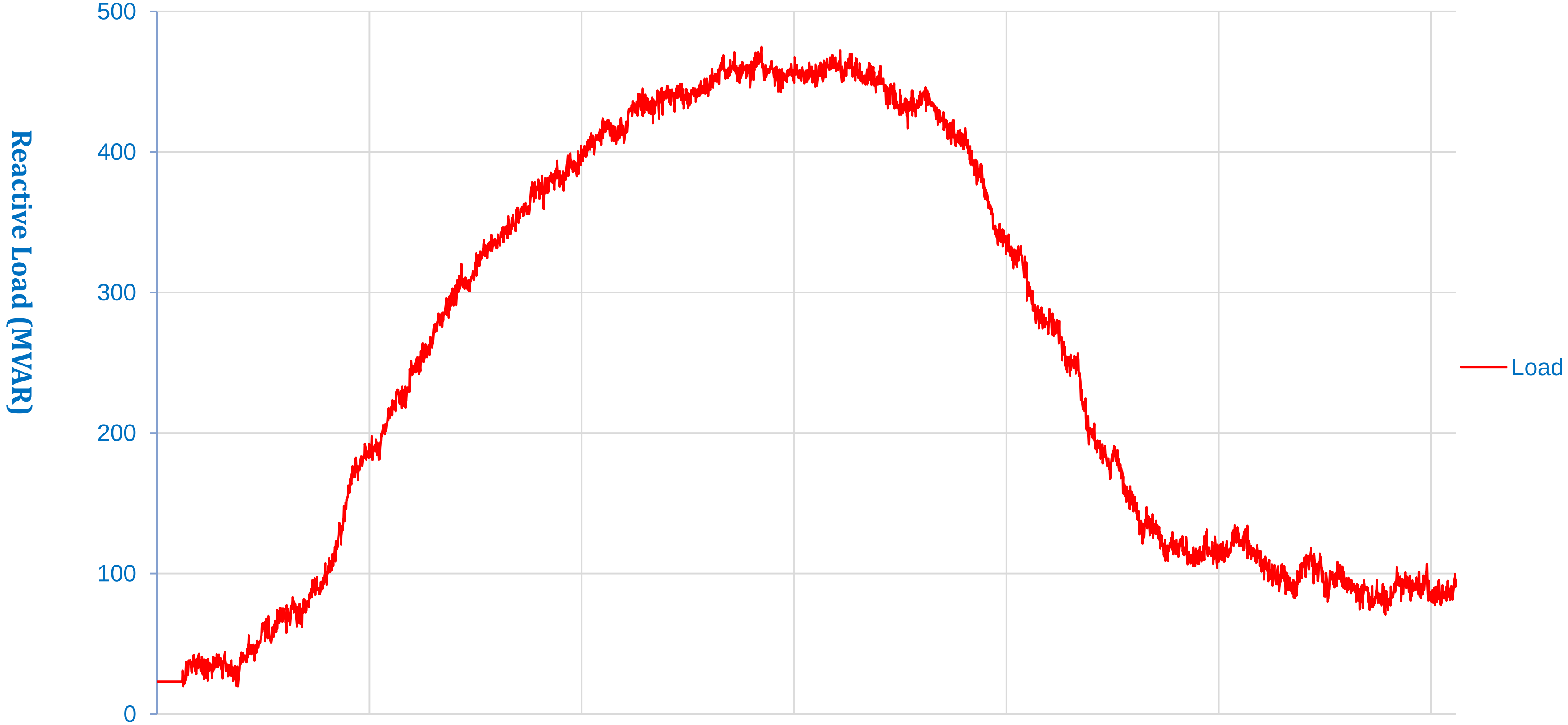


Control Block Diagram
Wide-Area Voltage Control in SCE Transmission Network

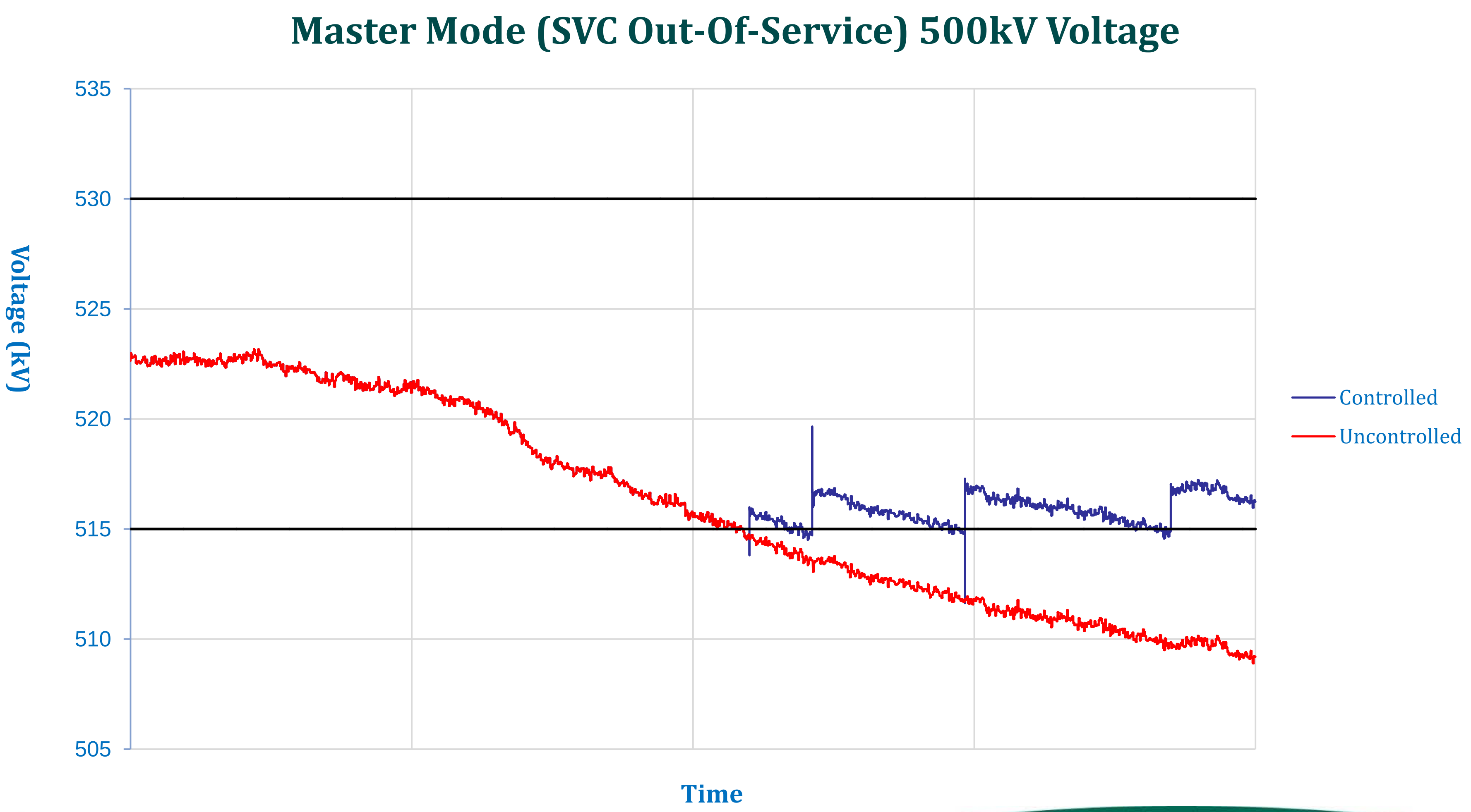


Preliminary RTDS Test

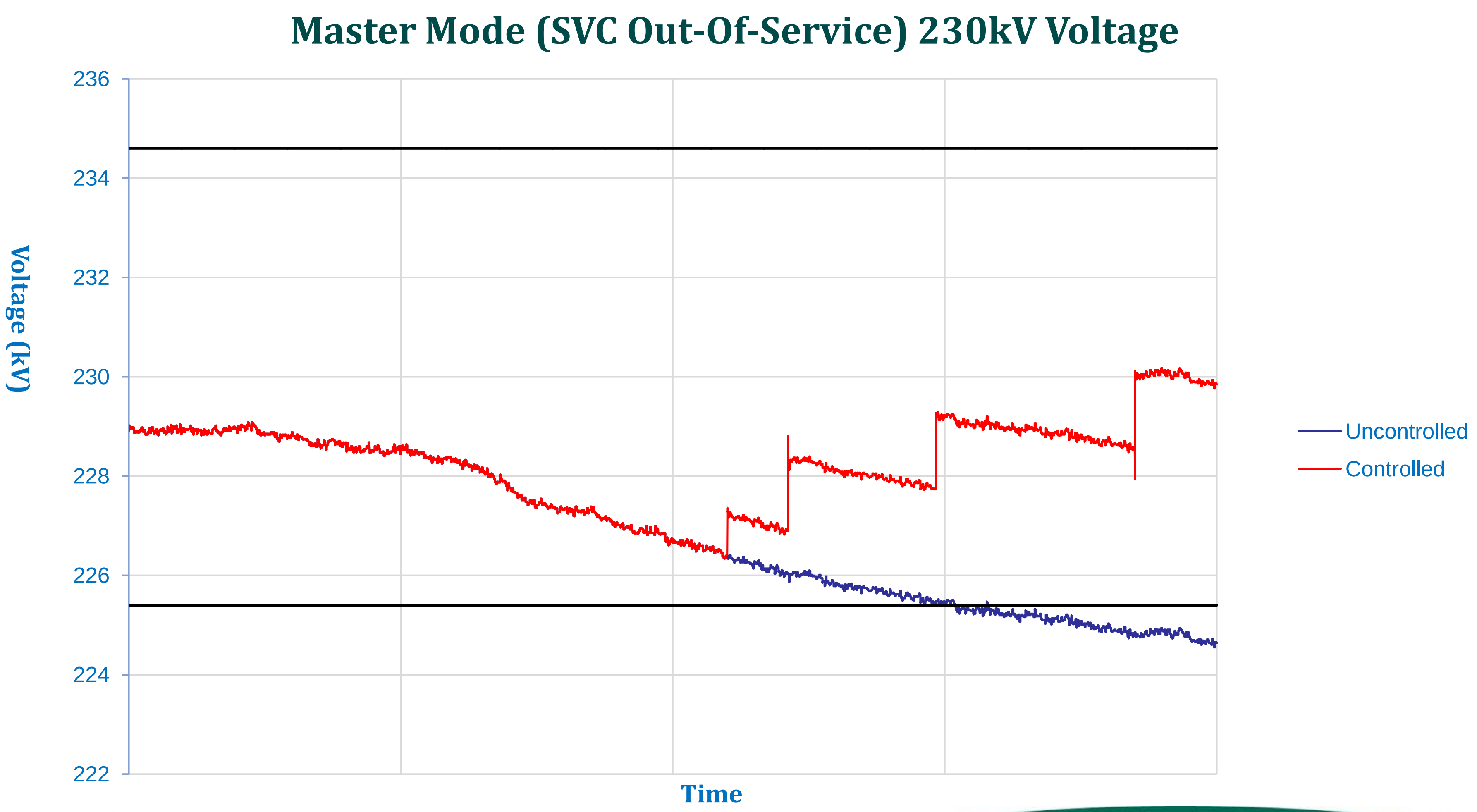
Reactive power load used to test the controller



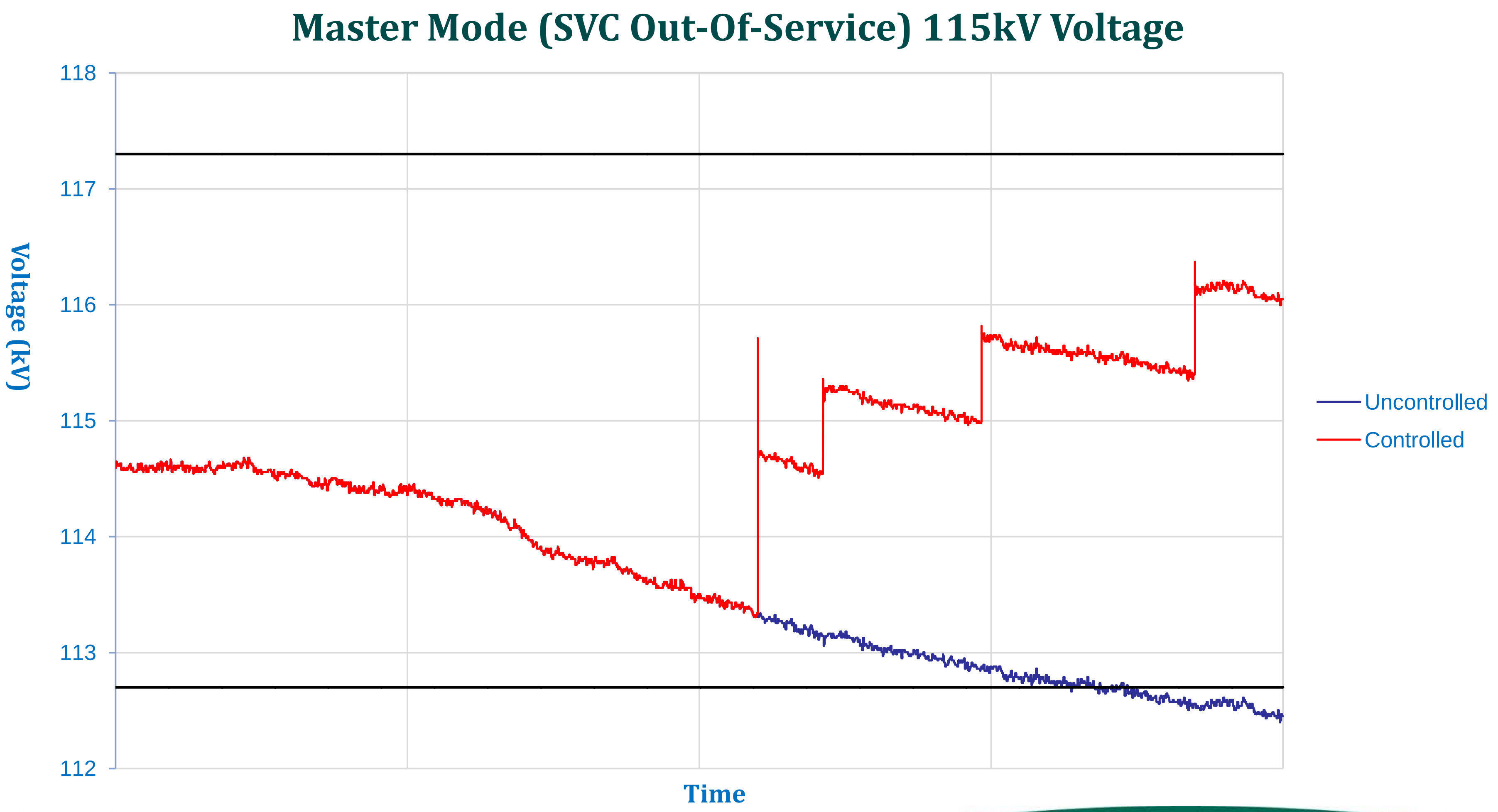
Preliminary RTDS Test



Preliminary RTDS Test

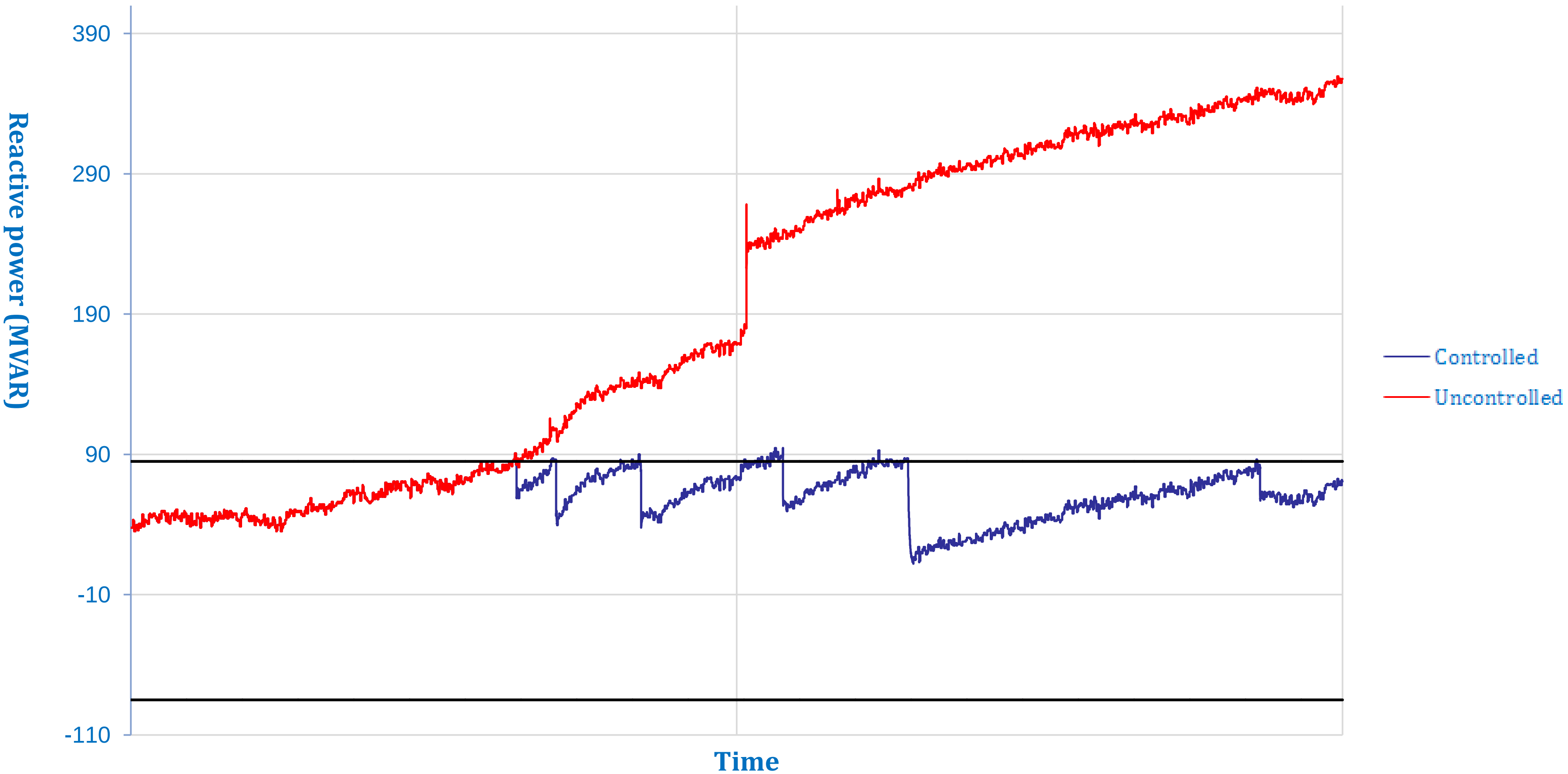


Preliminary RTDS Test



Preliminary RTDS Test

Slave Mode (SVC in service) SVC Reactive Power Output

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