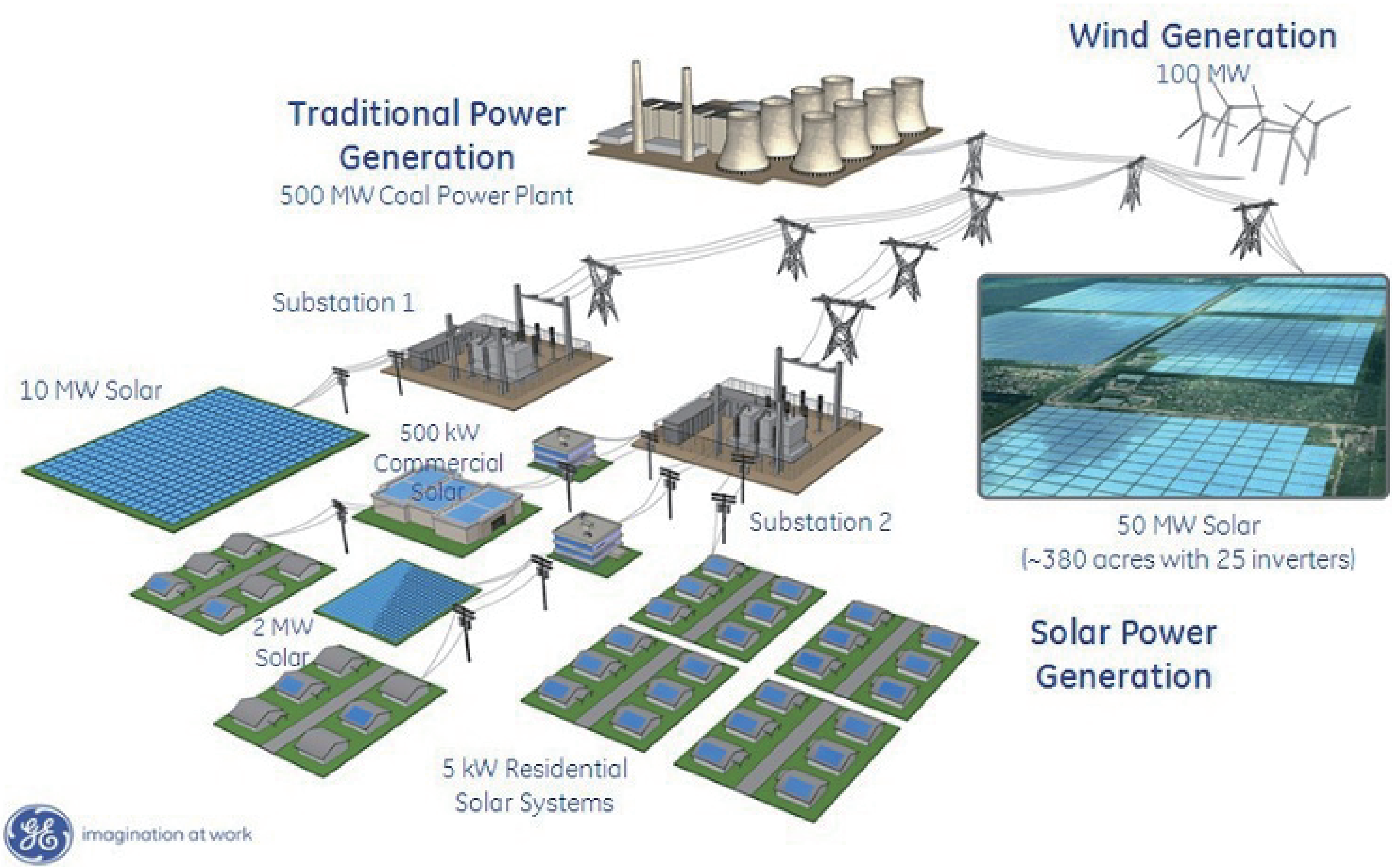
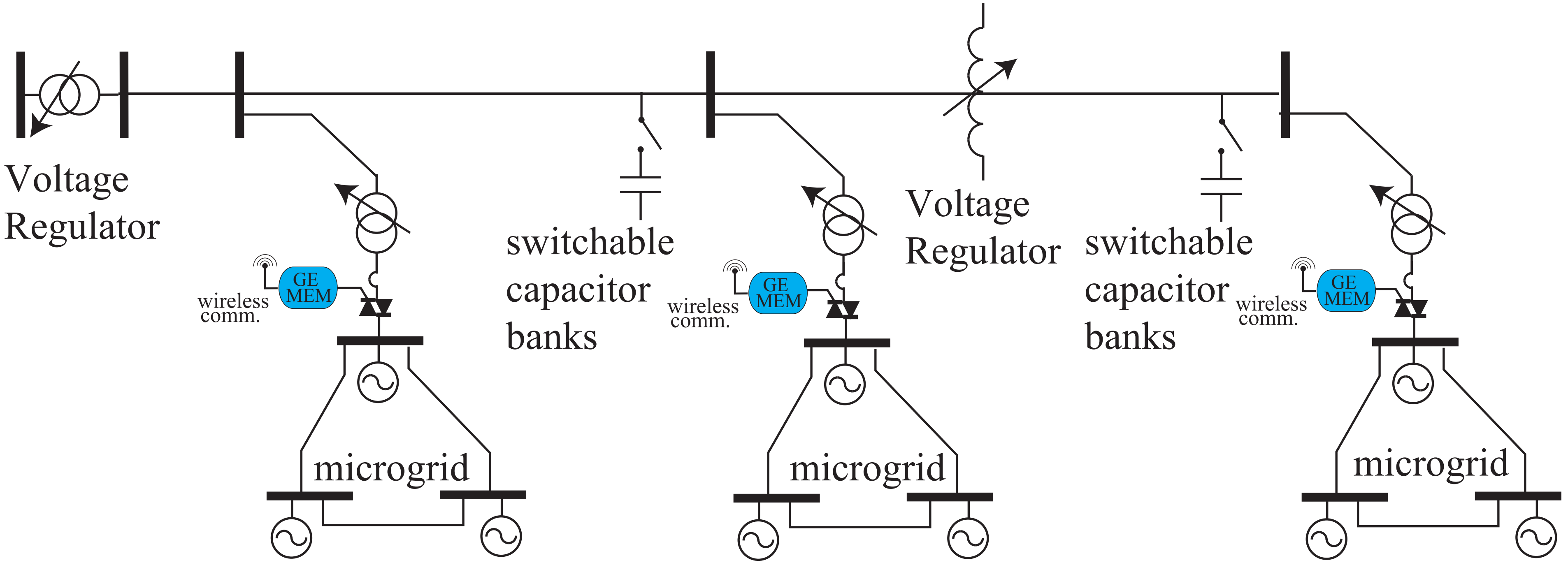
Coupling Low Voltage Microgrids into Mid-Voltage Distribution Systems



Distribution System Control Architecture

Radial system structure with buses connected to primary substation:

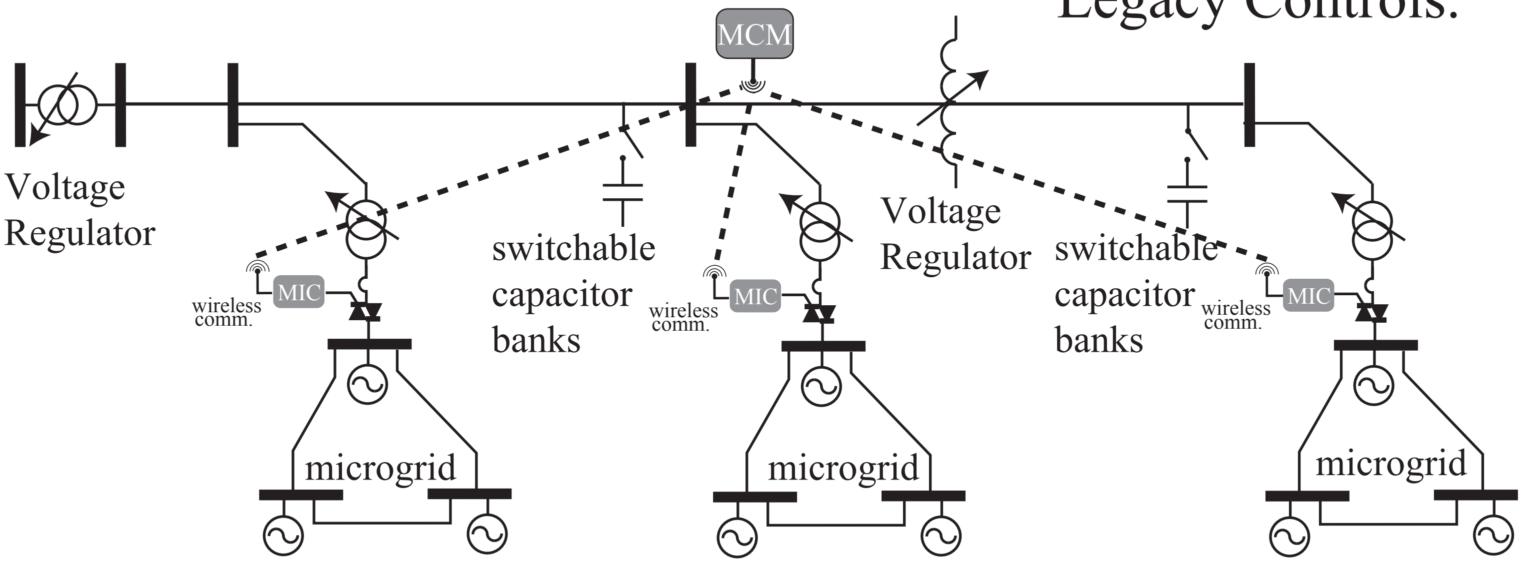


- Each bus connected to a **microgrid**;
- Representing typical **rural distribution network**;
- Usually with **severe** voltage-rise problem;

Project Objective and Approach

- **Objective**:
  Maximize real power exported by coupled low-voltage microgrids.

- **Issues**:
  - Voltage Rise Problem;
  - Transient Stability;
  - Legacy Controls.



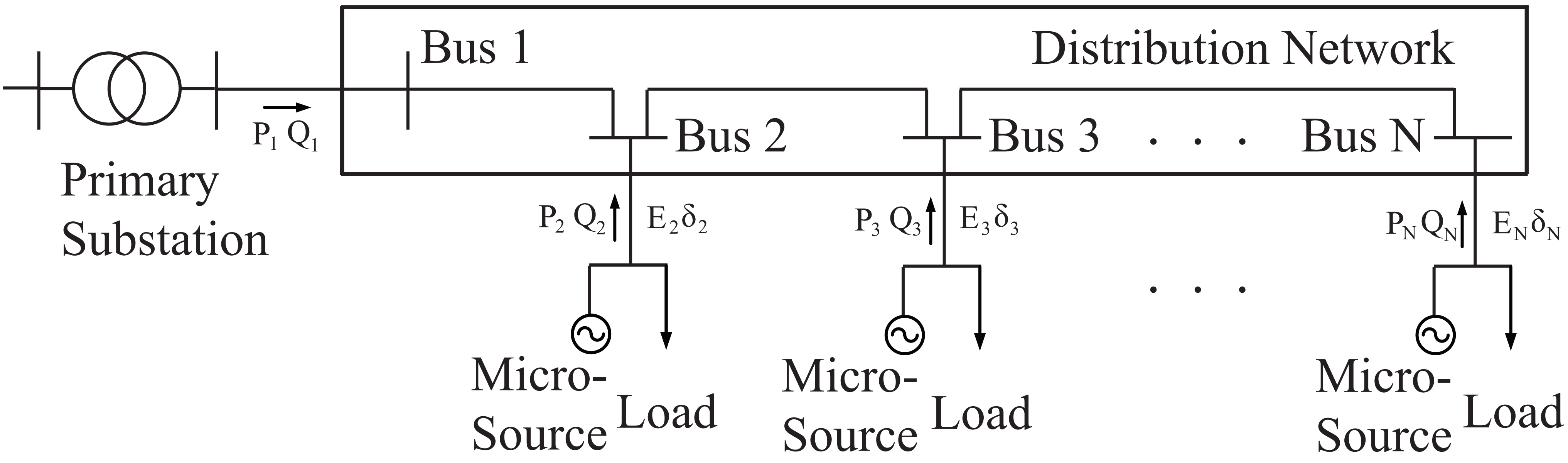
- **Approach**:
  - Two-layer Voltage Control Architecture: **Decentralized Voltage Controler Reactive Power Dispatch**
  - Simulation Studies and Analysis.

- **Benefits**:
  - Minimize impact on DSO voltage regulation policies;
  - Maximize real power exported back to distribution network.

Talk Outline

- **Distribution System Model**
- **Voltage Rise Problem**
- **Proposed Controller Architecture**
- **Optimization Problem**
- **Task Status and Schedule**

System Model



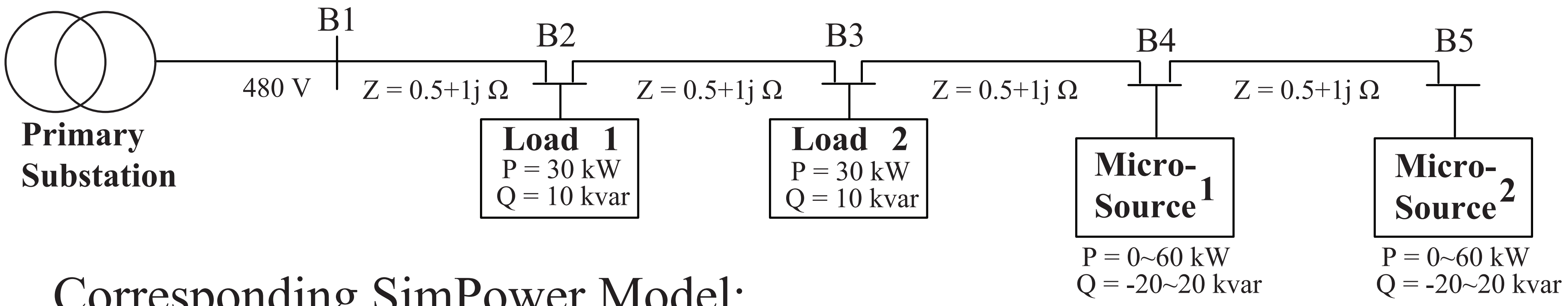
- A **microgrid** can be represented as a **microsource** and a **load**;
- Distribution network is a **passive system** that only consumes power;
- Define **voltage magnitude** and **phase angle** of ith bus as:

  $E_i, \delta_i \quad (\text{i} = 2,3,\cdots,\text{N})$
- **Real** and **reactive power** injected through ith bus:

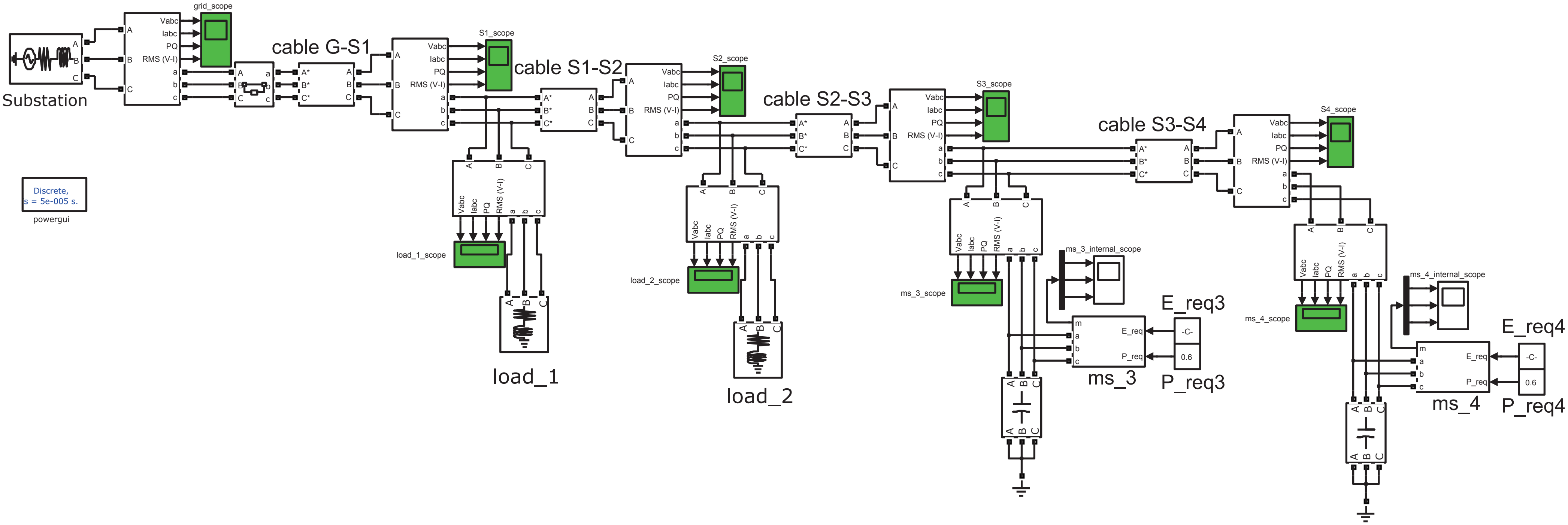
  $P_i, Q_i \quad (\text{i} = 1,2,\cdots,\text{N})$
- Bus 1 is reference bus with $E_1 = 1.0\ pu$ and $\delta_1 = 0\ rad$.

System Model

Schematic diagram of a **five-bus** example system:

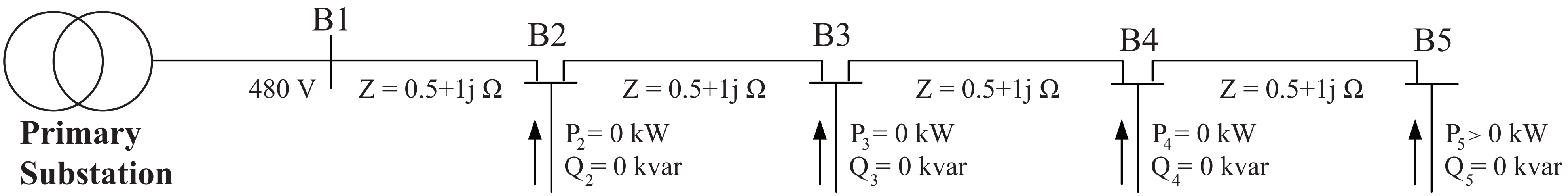


Corresponding SimPower Model:

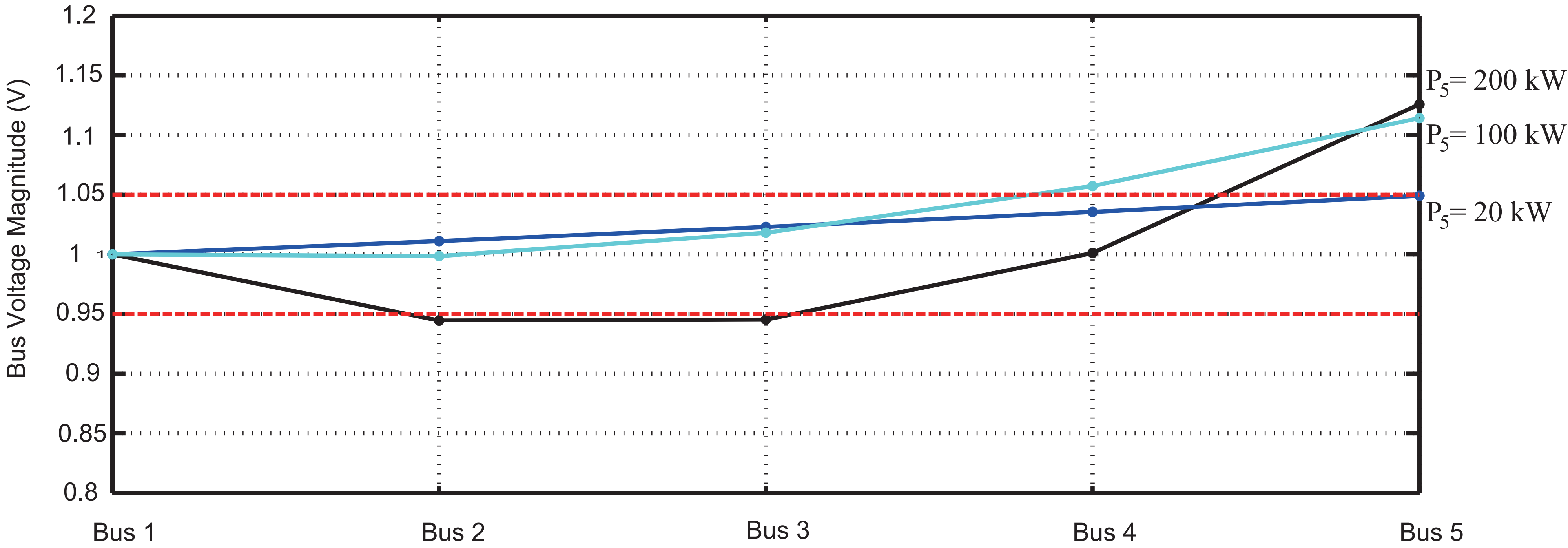


Voltage Rise Problem Illustration

Example with farthest bus injecting real power:

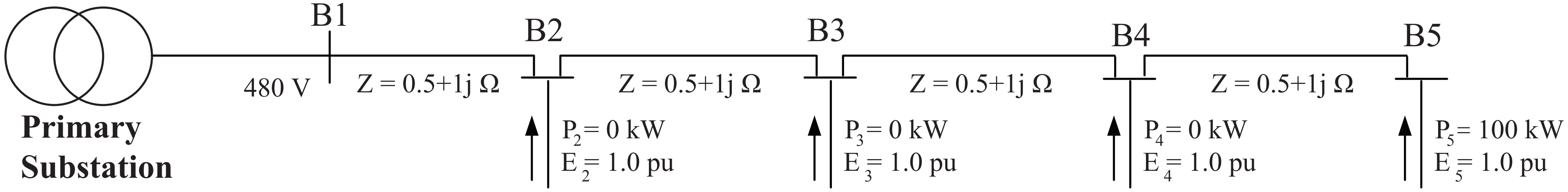


Bus voltage magnitudes of the distribution network:

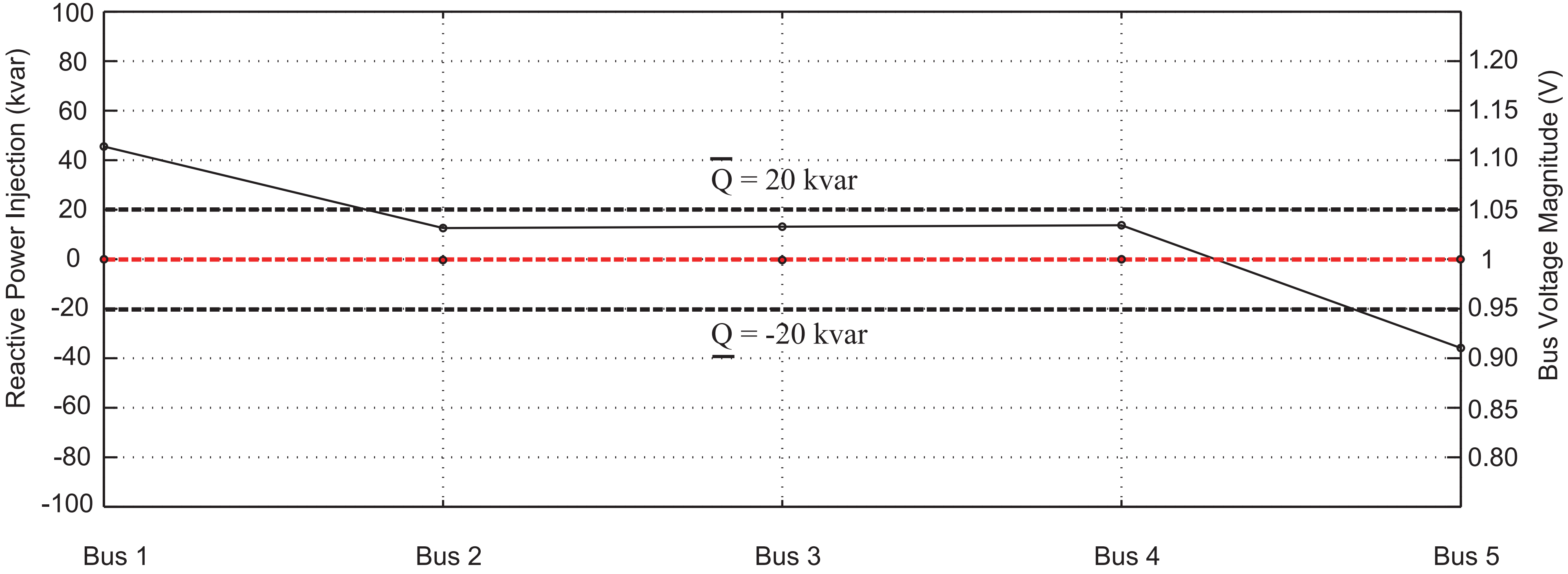


Reactive Power Control Illustration

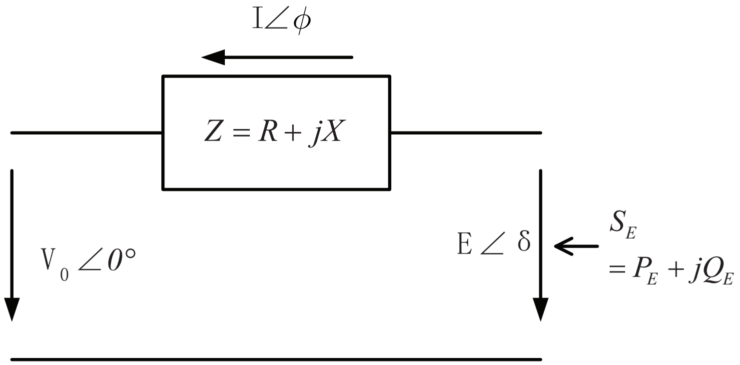
Example with farthest bus 100 kW real power injection, and keep all bus voltages to be 1.0 pu:



Reactive power support required to maintain 1.0 pu bus voltages:

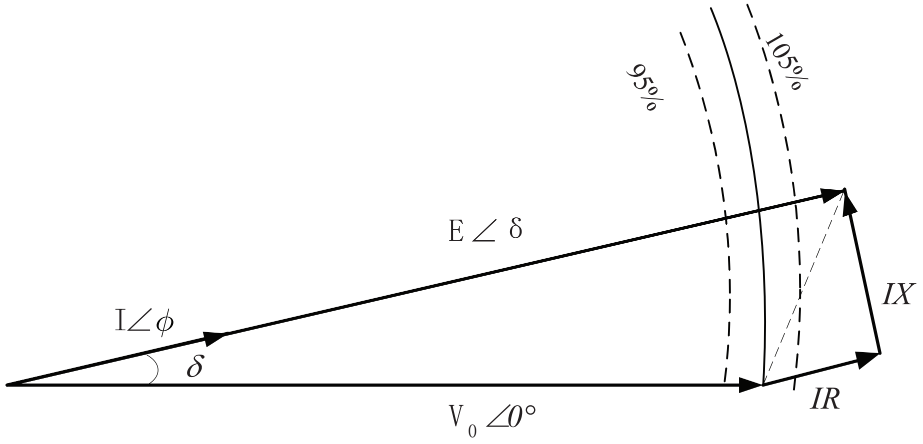


Voltage Rise Problem



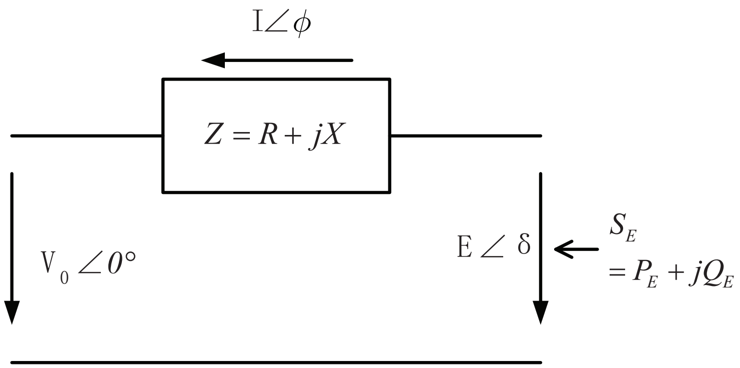
- Distribution line impedance, Z=R+jX
  Substation voltage $V_0\angle 0°$
  Line current, $I\angle\phi$
- Injected Power, $S_E = P_E + jQ_E$
  Terminal voltage, $E\angle\delta$

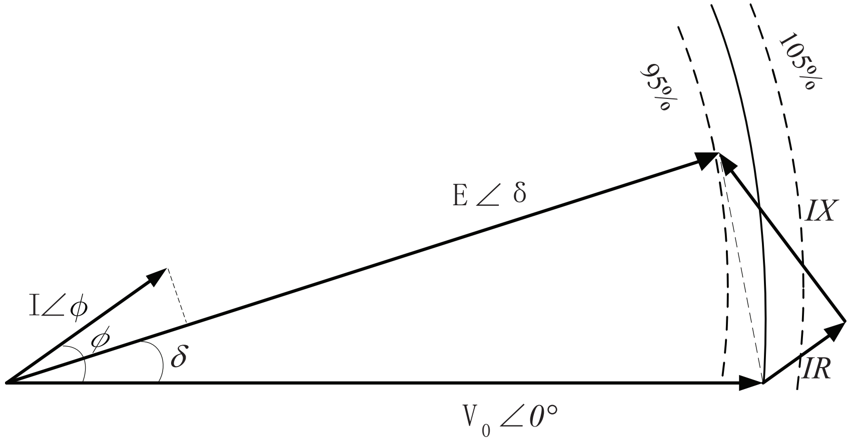
Without reactive power support: $P_E > 0$ $Q_E = 0$



- Phasor diagram shows injected power’s impact on current flows result in line voltages that exceed the **5% voltage regulation rule**.

Reactive Control of Voltage Rise Problem





- Total Injected Power:
  $S_E = P_E + jQ_E = EI\angle(\delta - \phi)$
- We reduce voltage rise by forcing line current to lead terminus voltage
- This strategy implies
  $Q_E = EI\sin(\delta - \phi) < 0.$
- Voltage rise can be reduced by absorbing reactive power at the terminal bus.
- Reactive control mechanisms:
  static var compensator, voltage
  regulator, capacitor banks,
  and Q-E droop controls

Ancillary Services

Coupled microgrids can **provide reactive power support**, while **exporting real power** to the distribution network.

Defined by **Federal Energy Regulatory Commission (FERC):**

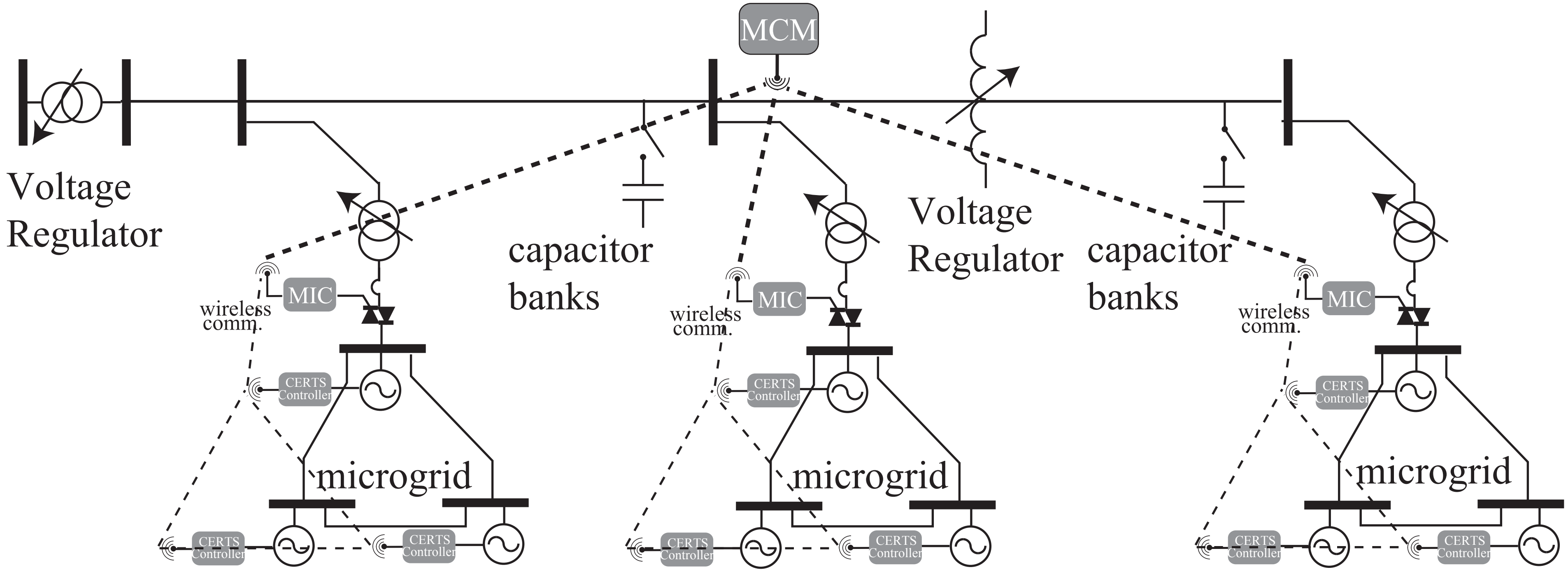
> "... those necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system."

Six Ancillary Services:

Scheduling and Dispatch;
Load Following;
Operating Reserves.
Energy Imbalance;
Real-power-loss Replacement;
Voltage Control.

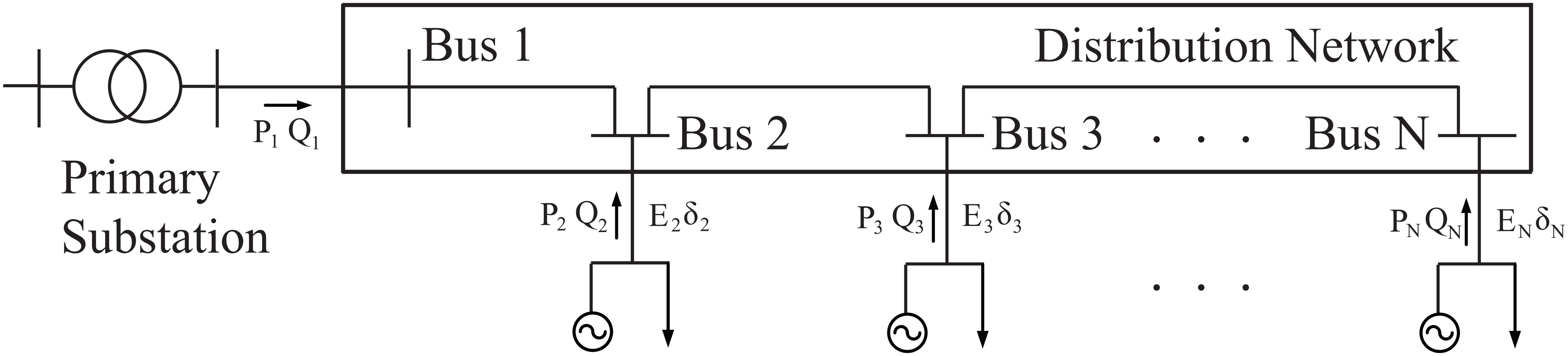
Coupled microgrids provide **"voltage control"** service, and become a **player** in the market.

Providing Other Ancillary Services



- **Microgrid Consortium Manager (MCM):**
  - Predicting consortium's overall capacity;
  - Using the prediction to bid in ancillary service market;
  - Distributing service bid among participating microgrids.
- **Microgrid Interface Controller (MIC):**
  - Maintaining set points with both P-freq & Q-E droop control;
  - Rearranging if a microgrid's capacity or network topology changes.

Objective Function



- **Maximizing real power exportation by downstream buses;**
- **Minimizing real power loss along the distribution line.**

Cost function is accordingly defined as:

$$J(P,E)=\sum_{i=2}^{N}(P_{cap,i}-P_{load,i}-P_i)+\sum_{i=1}^{N}P_i=\sum_{i=2}^{N}(P_{cap,i}-P_{load,i})+P_1$$

The cost function worked on is actually:

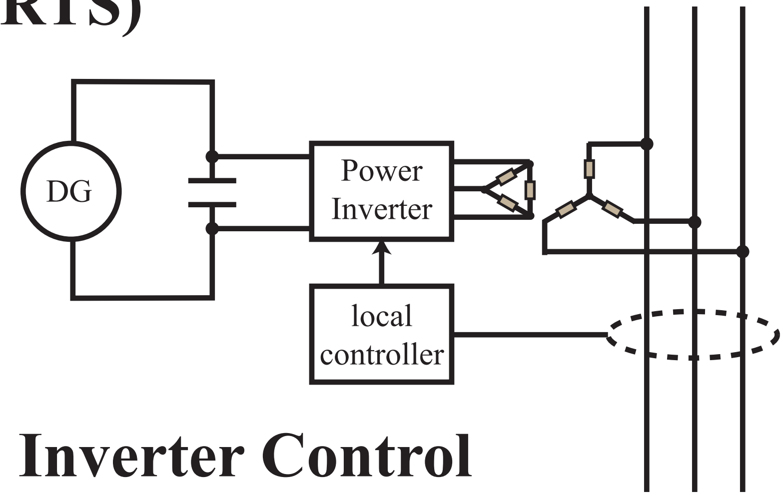
$$J(P,E)=P_1=E_1\sum_{j=1}^{N}E_j(G_{BUS,1j}\cos(\delta_1-\delta_j)+B_{BUS,1j}\sin(\delta_1-\delta_j))$$

Optimization Problem

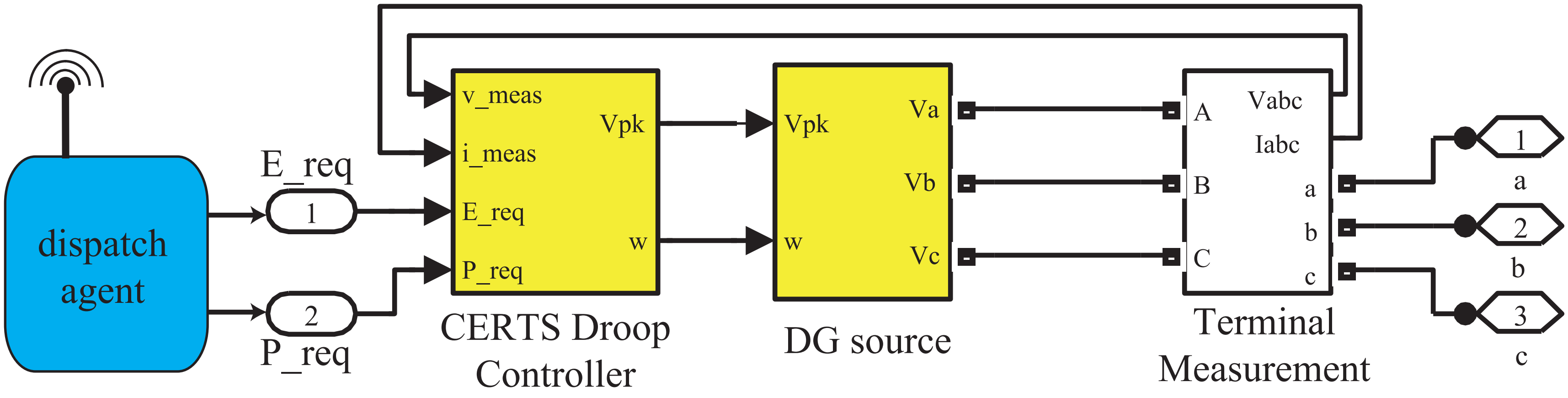
Minimize	$E_1 \sum_{j=1}^{N} E_j(G_{BUS,1j}\cos(\delta_1-\delta_j)+B_{BUS,1j}\sin(\delta_1-\delta_j))$	Expression of P_1
w.r.t.	$E_i, P_i \quad (i=2,3,\cdots,N)$	Voltage Magnitude and Real Power Injected at ith Bus;
Subject to	$\underline{P_{gen,i}} \le P_{gen,i} \le \overline{P_{gen,i}}$ $\underline{Q_{gen,i}} \le Q_{gen,i} \le \overline{Q_{gen,i}} \quad (i=2,3,\cdots,N)$	Real an Reactive Power Constraints Determined by Generation Capability;
	$\underline{P_{ln,\,j}} \le P_{ln,\,j} \le \overline{P_{ln,\,j}}$ $\underline{Q_{ln,\,j}} \le Q_{ln,\,j} \le \overline{Q_{ln,\,j}} \quad (j=1,2,\cdots,N-1)$	Real and Reactive Power Flow Constraints of jth Distribution Line;
	$\underline{E_i} \le E_i \le \overline{E_i} \quad (i=2,3,\cdots,N)$	Voltage Regulation Rule at ith Bus;
	$P_i = E_i \sum_{j=1}^{N} E_j(G_{BUS,ij}\cos(\delta_i-\delta_j)+B_{BUS,ij}\sin(\delta_i-\delta_j))$ $(i=1,2,\cdots,N)$ $Q_i = E_i \sum_{j=1}^{N} E_j(G_{BUS,ij}\sin(\delta_i-\delta_j)+B_{BUS,ij}\cos(\delta_i-\delta_j))$	Real and Reactive Power Balance Relationship at ith Bus.

CERTS Microsource Controller

- **Decentralized Inverter Controls (CERTS)**
  - Mimic P-freq & Q-E droop control;
  - Provide small-signal stability;
  - Interface to any DG unit.

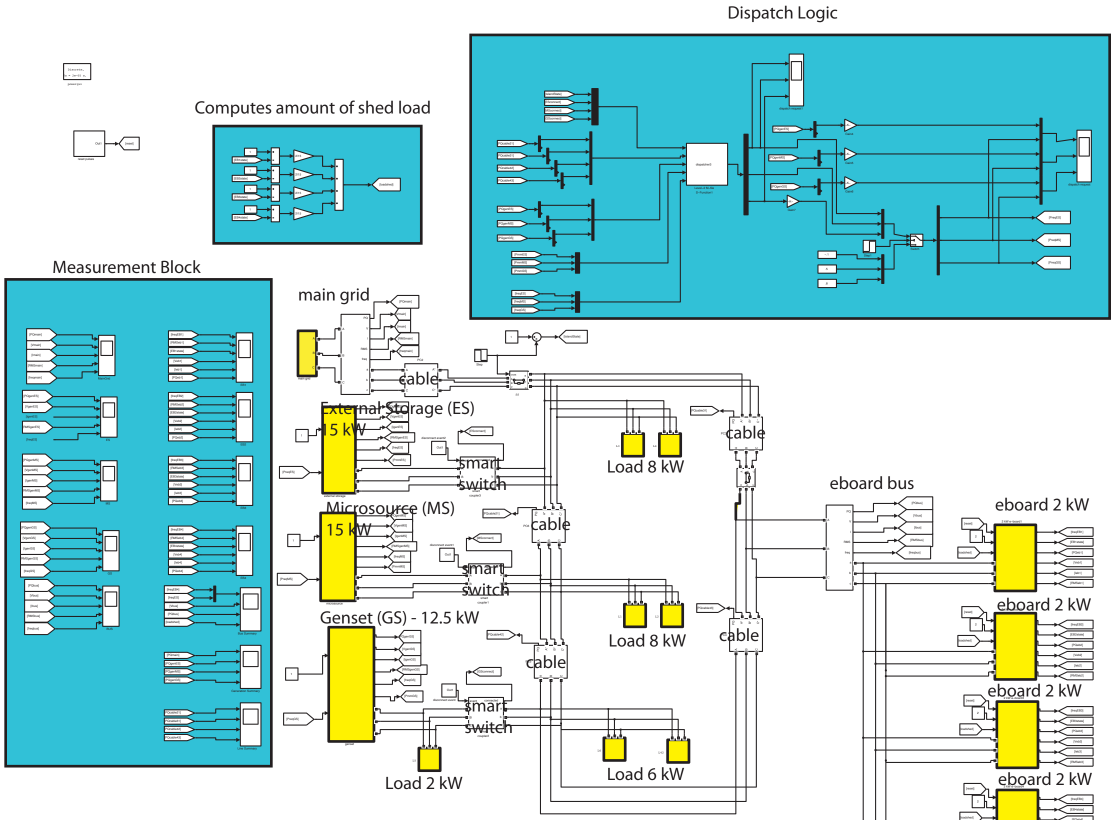


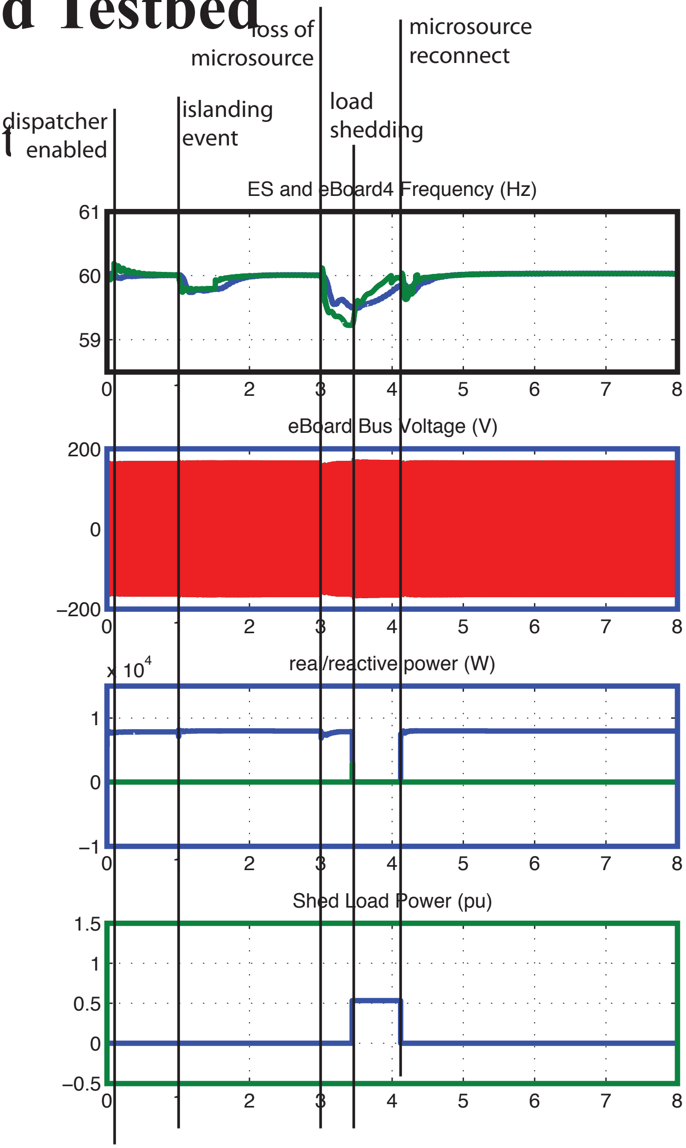
- **Distributed Dispatch Integrated into Inverter Control**
  - Dispatcher generates P and E set points, as inputs to the CERTS inverter controller.



Microgrid Simulation Example

- **simPower Simulation of UWM Microgrid Testbed**
  - validated against UWM testbed
  - 42.5 kW Generation (storage, micorsource, genset
  - 32 kW real load (8 kW can be automatically shed



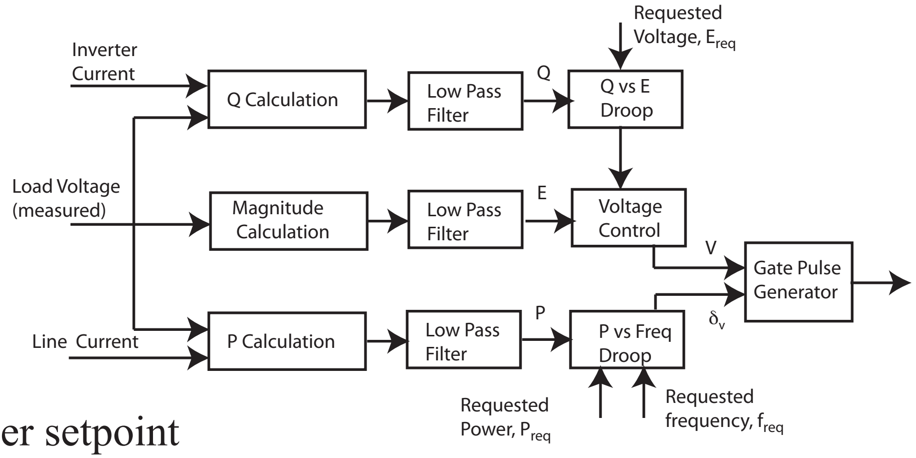


Transient Stability

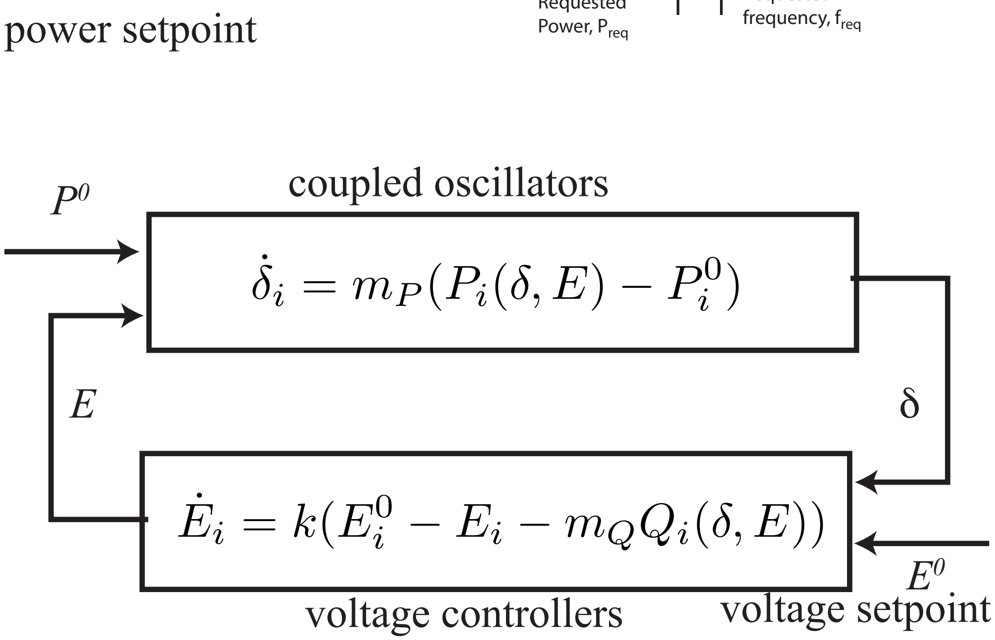
- System State equations

$$
\begin{aligned}
\dot{\delta}_i &= m_P(P_i - P_i^0) \\
\dot{E}_i &= k(E_i^0 - E_i - m_Q Q_i) \\
P_i &= E_i \sum_{j=1}^{n} E_j Y_{ij} \cos(\delta_i - \delta_j + \alpha_{ij}) \\
Q_i &= E_i \sum_{j=1}^{n} E_j Y_{ij} \sin(\delta_i - \delta_j + \alpha_{ij})
\end{aligned}
$$

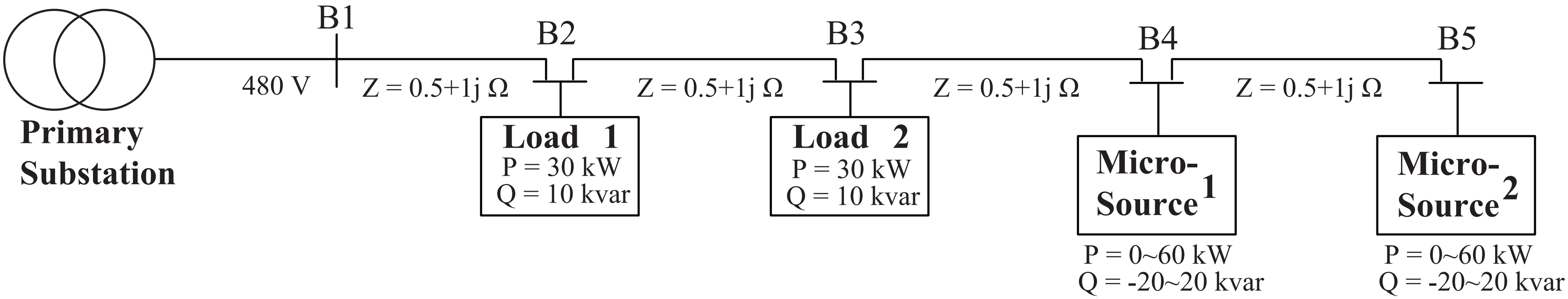
CERTS Controller for Fast Inverters



- This system interconnects two networked systems
  - System of coupled nonlinear oscillators (δ)
  - Voltage control system (E)
- Stable interconnection occurs when the oscillators are synchronized.



Example of Optimization Problem



B1 B2 B3 B4 B5

480 V

Z = 0.5+1j Ω

Primary Substation

Load 1
P = 30 kW
Q = 10 kvar

Load 2
P = 30 kW
Q = 10 kvar

Micro-Source 1
P = 0~60 kW
Q = -20~20 kvar

Micro-Source 2
P = 0~60 kW
Q = -20~20 kvar

- Set points of microgrid determined by the optimization problem:

$P_{req,1} = 60$ kW $E_{req,1} = 1.0433$ pu $P_{req,2} = 60$ kW $E_{req,2} = 1.0426$ pu

P_1	Q_1	E_2	E_3	E_4	E_5
43.54 kW	-55.35 kvar	0.9570 pu	0.9650 pu	1.0334 pu	1.0502 pu

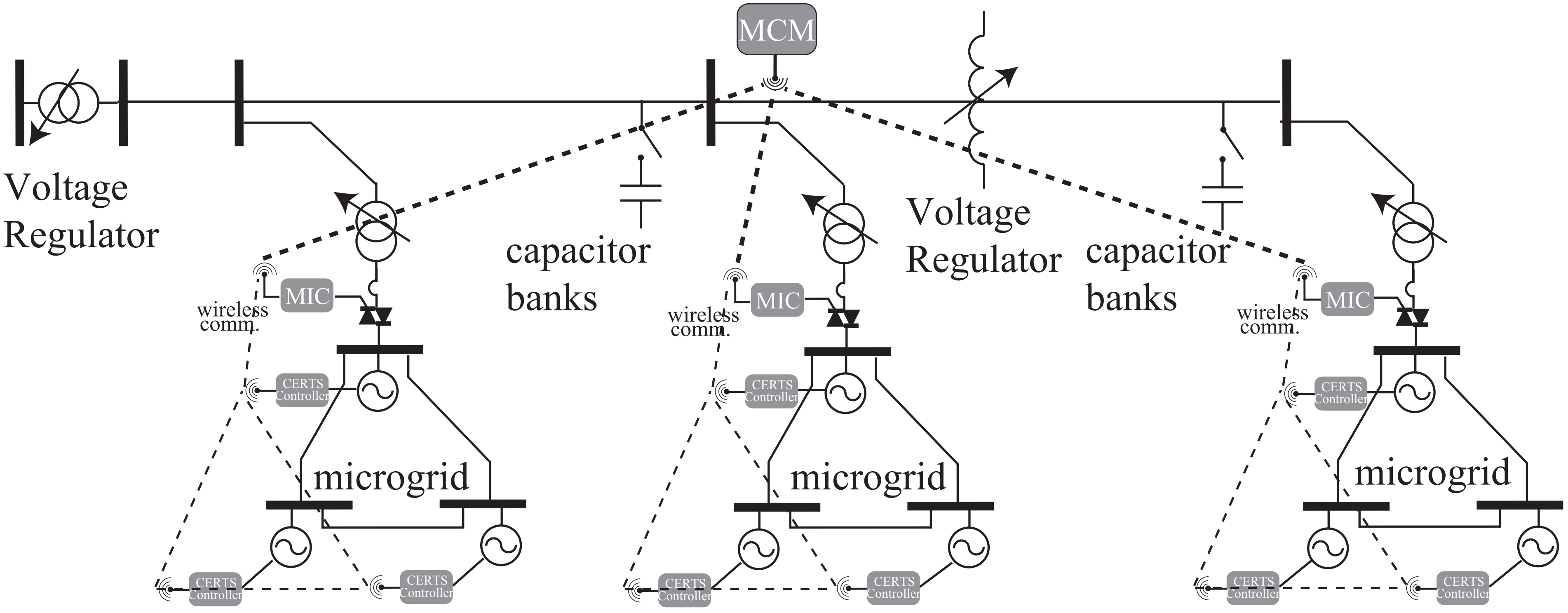
- For comparison, we can use set points as:

$P_{req,1} = 60$ kW $E_{req,1} = 1$ pu $P_{req,2} = 60$ kW $E_{req,2} = 1$ pu

In this situation, even though more reactive power support is provided, voltages of two load buses exceed the upper and lower limits defined by voltage regulation rule.

Future Work

- **Verification of Compatibility with Legacy Equipments:**
  - Algorithm must not contradict with current control mechanism;
  - Must consider both automatic controller and DSO controls;
  - Use simpower model to verify the compatibility.



Task 1 Summary

- **Task 1.1 - Algorithm Development**

- Algorithm determine “exported real power” and “voltage levels”, microgrid controllers automatically supply reactive power to maintain voltage levels.
- Zhao Wang currently developing algorithms for optimal power and voltage assignment.
- Algorithm development to be completed by mid Nov. 2011, technical report by Jan. 2012.

- **Task 1.2 - Simulation Development**

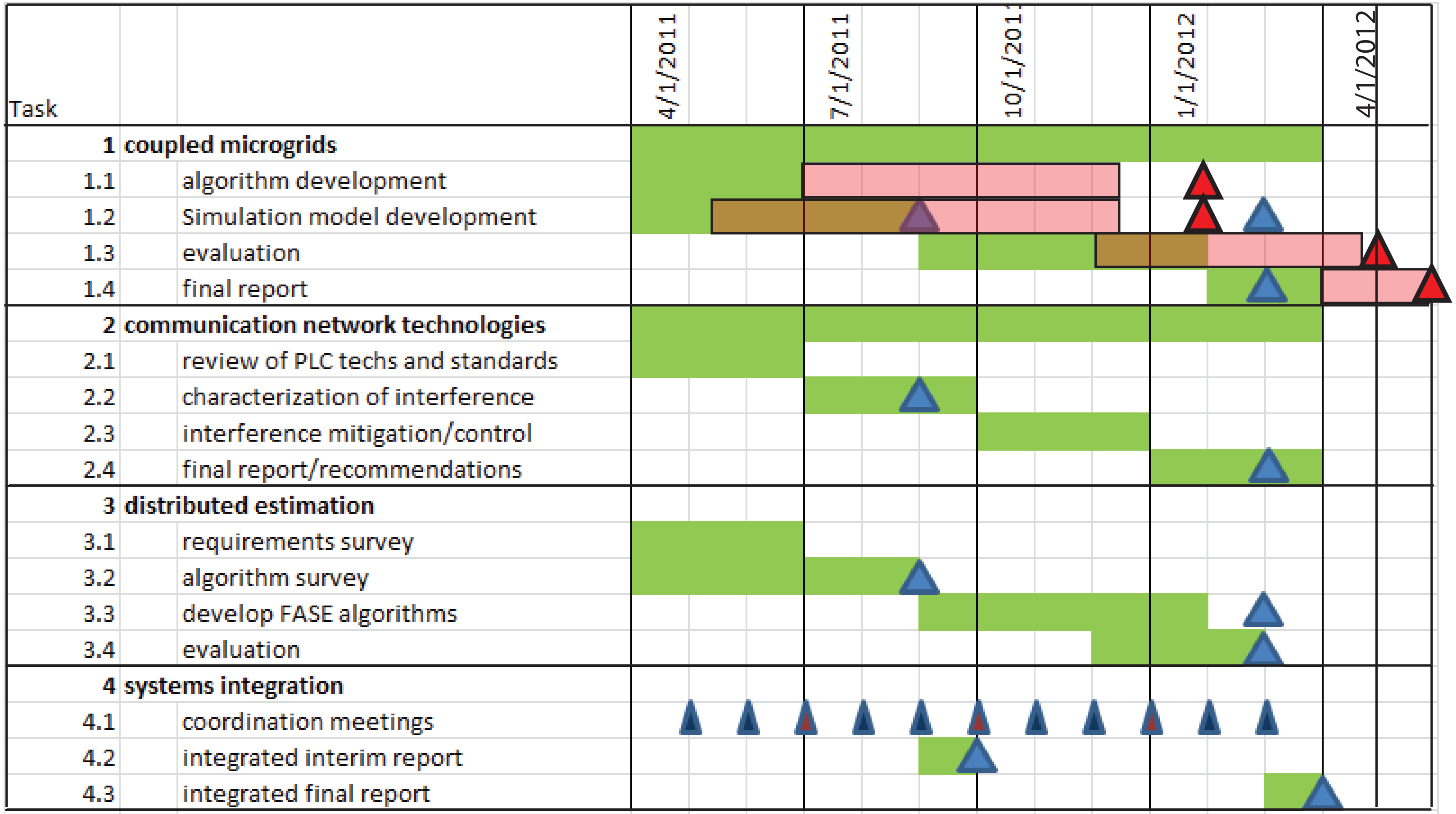
- Prototype simPower models of distribution line and microgrid completed in mid-July 2011.
- Current simulations include UWM controllers, and use capacitor banks for voltage control.
- Zhao Wang currently integrating microgrid controller and optimization algorithm into MV distribution line simulation.
- Integration to be completed by mid Nov. 2011, technical report by Jan. 2012.

- **Task 1.3 - Evaluation**

- Not started yet, and expected start date is Jan. 2012.
- Goal is to integrate capacitor banks and microgrid controls into simulation, and study interaction of microgrid control with automatic capacitor bank controls.
- Expected completion by end of Apr. 2012, findings to be presented in project final report by May 2012.

Task 1 Overview - Coupled Microgrid

- Task 1.1 (algorithm development) about 4 months behind schedule
- Task 1.2 (simulation) to be done in parallel with task 1.1
- Interim Technical Report on Task 1.1/1.2 to be completed by January 2012
- Task 1.3 (evaluation) to start in November 2011 and complete in April 2012
- Final Report to be finished by May 2012.



Task	
1	**coupled microgrids**
1.1	algorithm development
1.2	Simulation model development
1.3	evaluation
1.4	final report
2	**communication network technologies**
2.1	review of PLC techs and standards
2.2	characterization of interference
2.3	interference mitigation/control
2.4	final report/recommendations
3	**distributed estimation**
3.1	requirements survey
3.2	algorithm survey
3.3	develop FASE algorithms
3.4	evaluation
4	**systems integration**
4.1	coordination meetings
4.2	integrated interim report
4.3	integrated final report