Improving Power System Resilience by Employing Energy Storage

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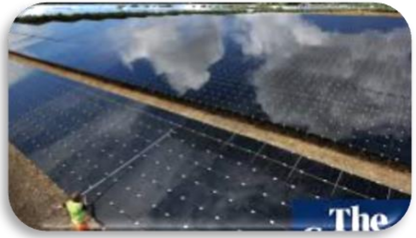
Introduction and Motivation

New vulnerabilities to the power system

- ✓ Extreme weather
- ✓ Cyber-physical attacks
- ✓ Sudden changes in renewable generation or loads

Improving the grid resilience

- ✓ Withstand and recover from disruptive events
- ✓ Minimize the duration, intensity, and the negative impacts



Energy Storage Contribution

During unusual grid events

- ✓ Extreme weather
- ✓ Cyber-physical attacks
- ✓ Sudden changes in renewable generation or loads

Energy storage units can be properly managed to improve grid resilience by

- ➢ Restoring load and energizing the grid
- ➢ Optimizing energy resource utilization
- ➢ Maintaining supply-demand balance
- ➢ Prevent instability in the grid

Clarification

Four Dimensions of Resilience According to The National Infrastructure Advisory Council :

- **Robustness:** the ability to absorb shocks and continue operating
- **Resourcefulness:** the ability to skillfully manage a crisis as it unfolds
- **Rapid Recovery**: the ability to get services back as quickly as possible
- **Adaptability:** the ability to incorporate lessons learned from past events to improve resilience

Power System Dynamic Analysis

Power System consisting of

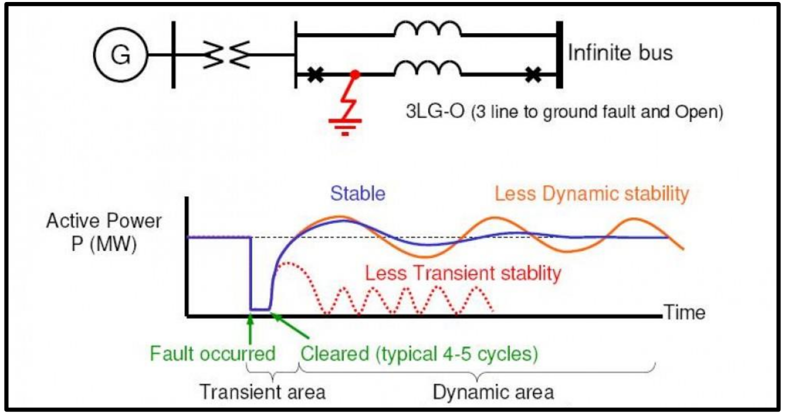
- ✓ Conventional synchronous generator,
- ✓ Renewable energy sources,
- ✓ Energy storage,
- ✓ Loads

Suitable model and control

- ✓ Develop the Differential-Algebraic equations
- ✓ Design Optimal controller for storage

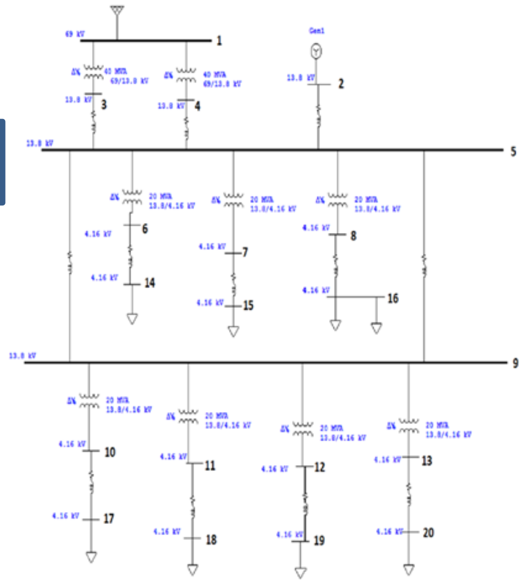
Investigate

- ✓ Effective energy flow control
- ✓ Transient stability

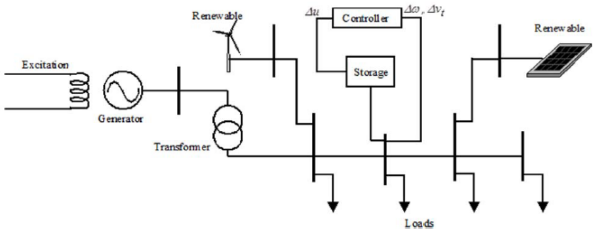


Case Studies

- **A campus grid connected to the main grid comprised of**
  - ✓ a steam turbine equipped with exciter, power system stabilizer (PSS), and steam governor
  - ✓ loads,
  - ✓ energy storage (battery/thermal)
  - ✓ distributed generation



- **An isolated micro-grid comprised of**
  - ✓ a conventional synchronous generator powered by a steam turbine (exciter PSS, governor)
  - ✓ constant and variable loads,
  - ✓ energy storage (battery/ thermal)
  - ✓ renewable sources of energy (wind and solar)



Modeling

- **Synchronous Generator Model**

flux-decay model (one axis model)

$$\dot{E}_q' = \frac{1}{T_{do}'}\left(-E_q' - \left(X_d - X_d'\right)I_d + E_{fd}\right) \quad (1)$$

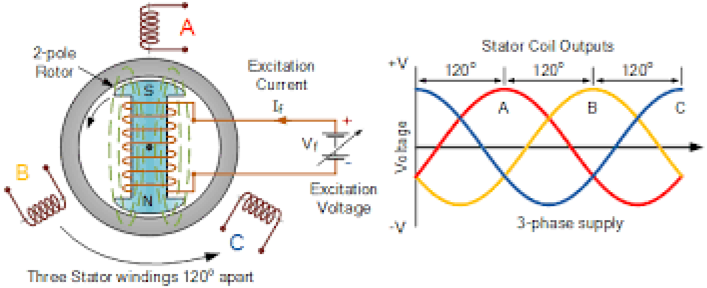
$$\dot{\delta} = \omega_i - \omega_s \quad (2)$$

$$\dot{\omega} = \frac{\omega_s}{2H}\left(P_m - E_q' I_q - \left(X_q - X_d'\right)I_d I_q\right) \quad (3)$$

$$0 = R_s I_d - X_q I_d + V_d \quad (4)$$

$$0 = R_s I_q - X_d' I_d + V_q - E_q' \quad (5)$$

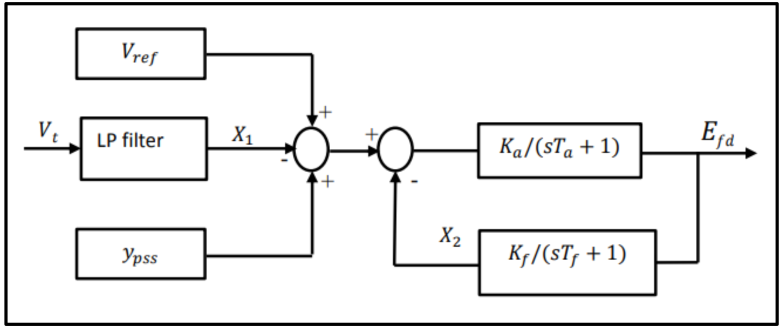
$$0 = V_t^2 - \left(V_d^2 + V_q^2\right) \quad (6)$$



Modeling

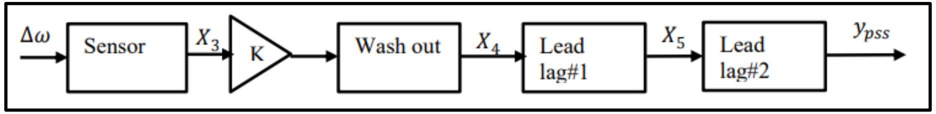
- **Exciter**

$$E_{fd} = \frac{K_a}{s.T_a + 1}\left(-\frac{V_t}{s.T_r + 1} - \frac{E_{fd}.K_f}{s.T_f + 1} + y_{pss} + V_{ref} \right) \qquad (7)$$



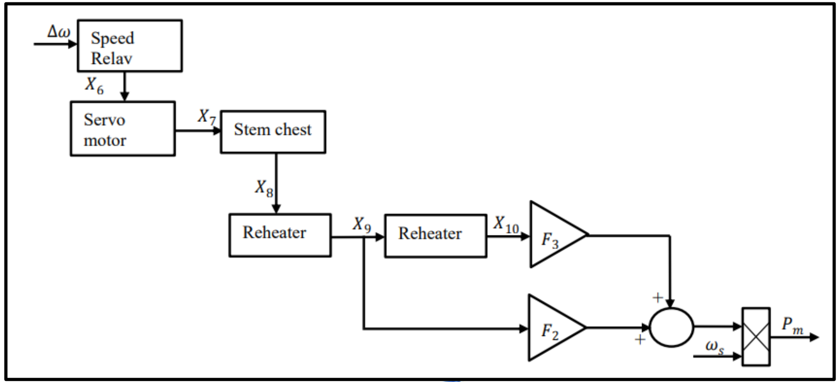
- **PSS**

$$\frac{y_{pss}}{\Delta\omega} = \left(\frac{s.T_{2n} + 1}{s.T_{2d} + 1}\right)\left(\frac{s.T_{1n} + 1}{s.T_{1d} + 1}\right)\left(\frac{1}{sT_s + 1}\right)\left(\frac{s}{sT_w + 1}\right) \qquad (8)$$



- **Governor**

$$\frac{P_m}{\Delta\omega} = \left(\frac{1}{sT_3 + 1}\right)\left(\frac{1}{sT_5 + 1}\right)\left(\frac{1}{sT_{sm} + 1}\right)\left(\frac{1}{sT_{sr} + 1}\right)\left(F_2\frac{1}{sT_4 + 1} + F_3\right) \qquad (9)$$



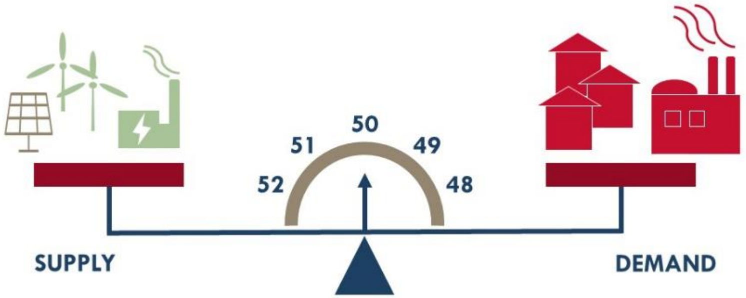
Modeling

- **Power Balance Equations**

  - For the generator at bus *i*

$$0 = V_{di} I_{di} + V_{qi} I_{qi} - V_i \sum_{j=1}^{N} V_j Y_{ij} \cos(\theta_i - \theta_j - \phi_{ij}) - P_{Li}$$

$$0 = V_{qi} I_{di} - V_{di} I_{qi} - V_i \sum_{j=1}^{N} V_j Y_{ij} \sin(\theta_i - \theta_j - \phi_{ij}) - Q_{Li} \qquad (10)$$



  - For load buses or the non-generator buses

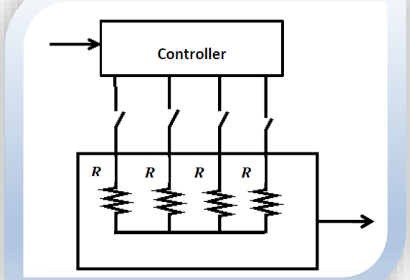
$$0 = -V_i \sum_{j=1}^{N} V_j Y_{ij} \cos(\theta_i - \theta_j - \phi_{ij}) - P_{Li}$$

$$0 = -V_i \sum_{j=1}^{N} V_j Y_{ij} \sin(\theta_i - \theta_j - \phi_{ij}) - Q_{Li} \qquad (11)$$

Modeling

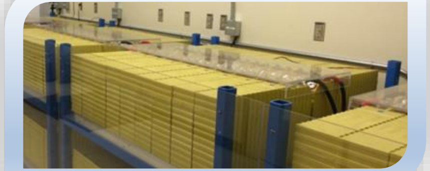
- **Resistor-type Thermal Storage**

$$P_{si} = G_{si}V_i^2; \quad Q_{si} = 0 \qquad (12)$$



- **Battery Storage**

$$P_{Bi} = P_{Bi}^{ref} \qquad Q_{Bi} = 0 \qquad (13)$$



- **Renewable Energy Source Model**

$$0 = -V_i \sum_{j=1}^{N} V_j Y_{ij} \cos\left(\theta_i - \theta_j - \phi_{ij}\right) + P_{Ri}$$

$$0 = -V_i \sum_{j=1}^{N} V_j Y_{ij} \sin\left(\theta_i - \theta_j - \phi_{ij}\right) + Q_{Ri} \qquad (14)$$

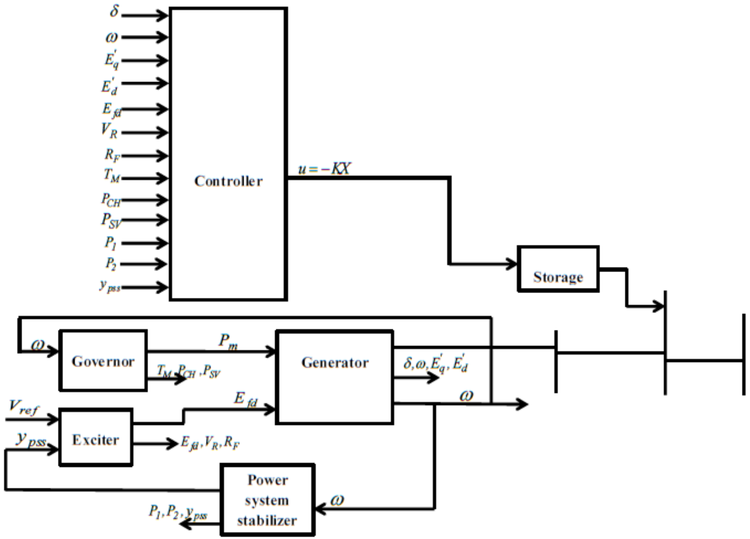
Control Design

- **State Space Representation**

$$\Delta\dot{x} = A_1\Delta x + B_1\Delta y + C_1\Delta u \quad (15)$$

$$0 = C\Delta x + D\Delta y + E\Delta u \quad (16)$$

$$\Delta\dot{x} = A\Delta x + B\Delta u \quad (17)$$



- **Optimal Controller**

$$J = \int_0^{\infty} \left(x^T Q x + u^T R u\right) dt \quad (18)$$

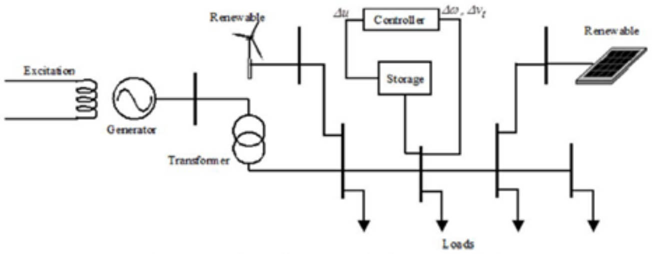
$$u = -Kx \quad (19)$$

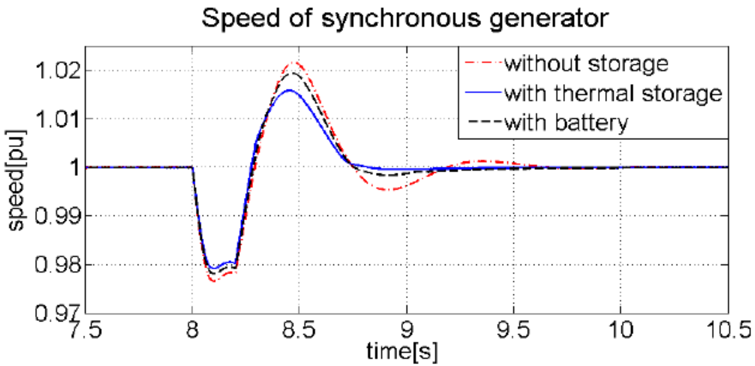
$$K = R^{-1} B^T P \quad (20)$$

$$A^T P + PA - PBR^{-1} B^T P + Q = 0 \quad (21)$$

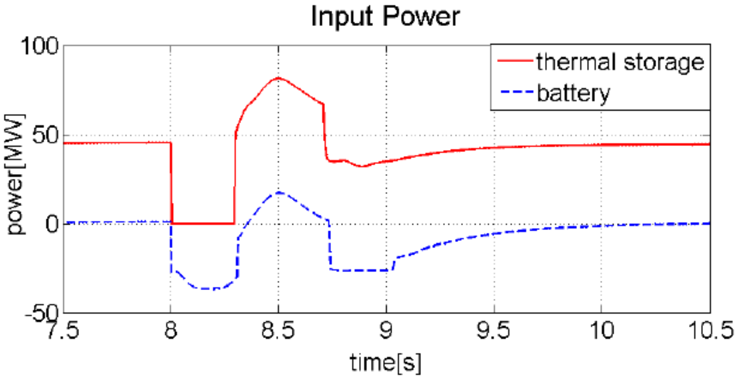
Simulation Results

- ❑ **Rapid Recovery**





(a)



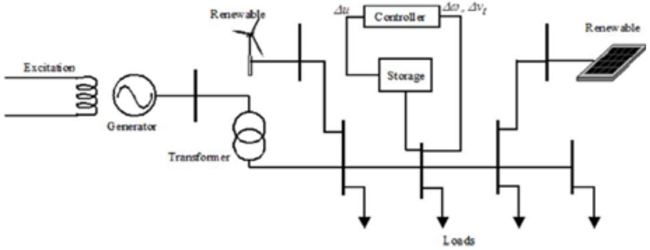
(b)

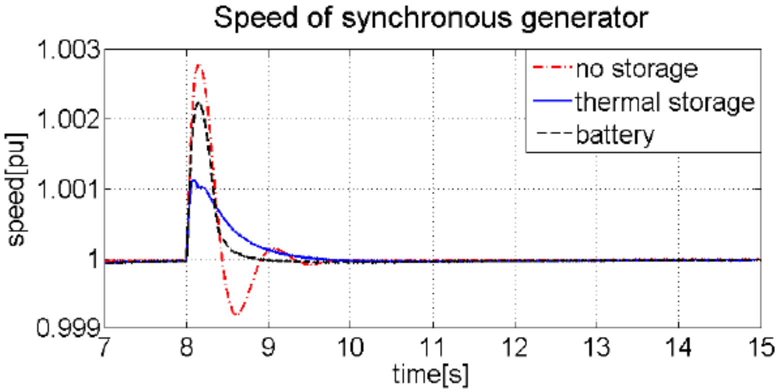
(a) Frequency oscillations of the micro grid under disturbance with no storage, with thermal storage, and with battery;

(b) Active power absorbed by the thermal storages and battery (negative absorbed power in battery shows an injection or discharge of power to the micro grid)

Simulation Results

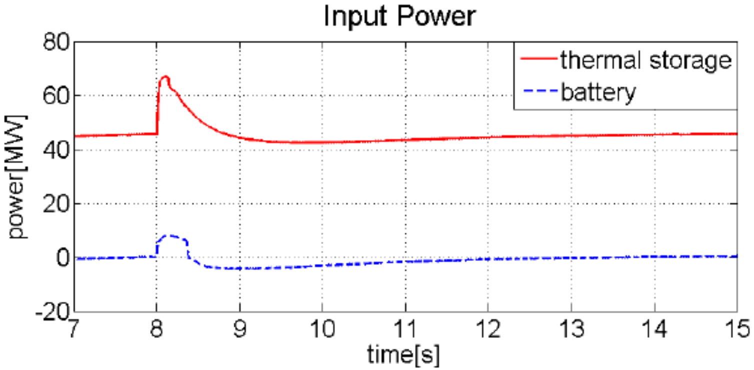
❑ Rapid Recovery





(a)

(a) Frequency oscillations of the micro grid under 20% load change in the load with no storage, with thermal storage, and with battery;

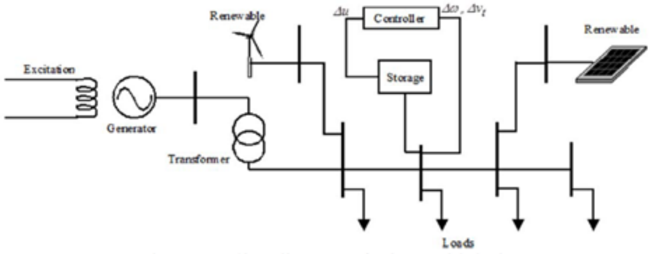


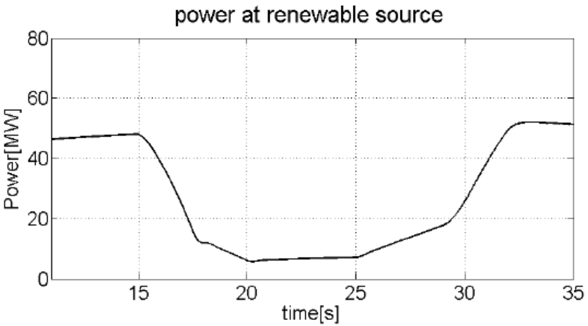
(b)

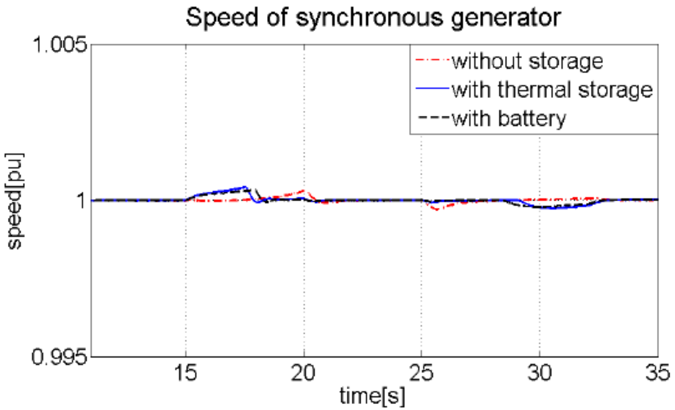
(b) Active power absorbed by the thermal storage and battery

Simulation Results

- Rapid Recovery

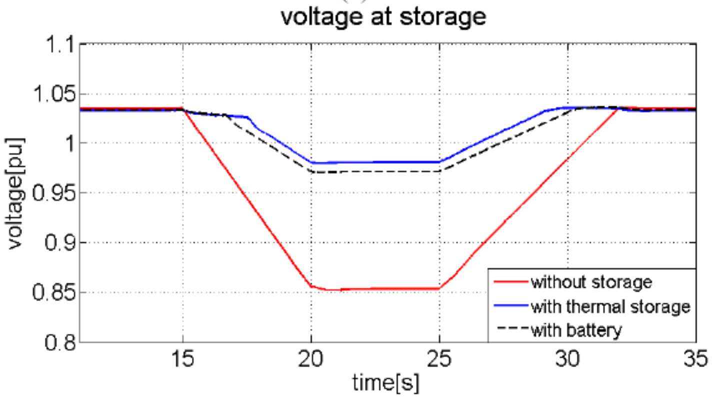






(a)

(a) Frequency oscillations of the micro grid caused by the intermittent renewable source with no storage, with resistor type thermal storage, and with battery;

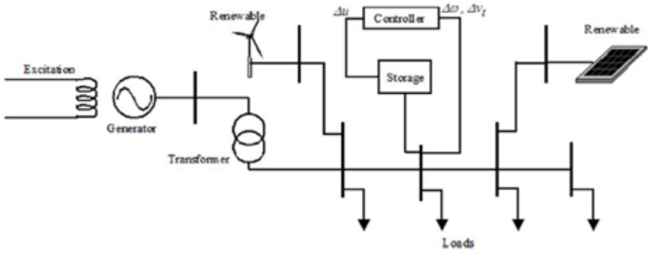


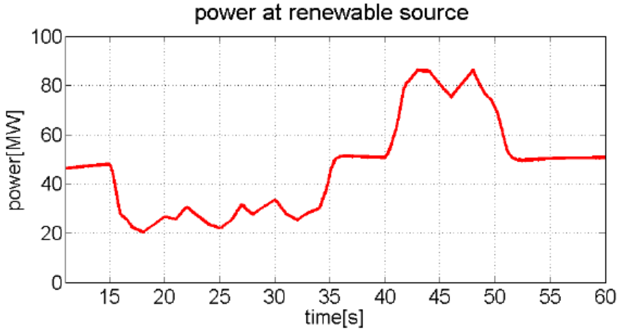
(b)

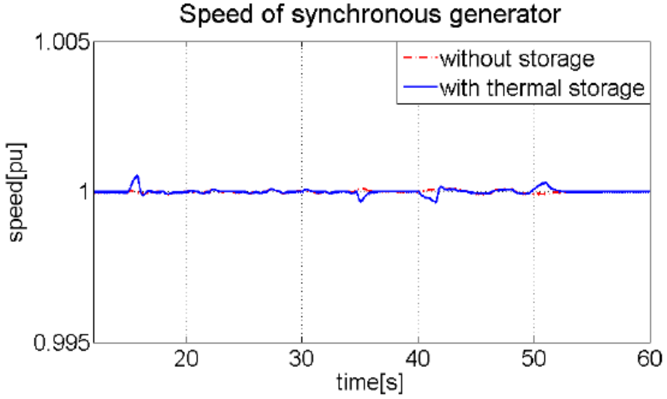
(b) Voltage profile at a selected bus in the micro grid in the absence and presence of storage and battery

Simulation Results

❑ Rapid Recovery

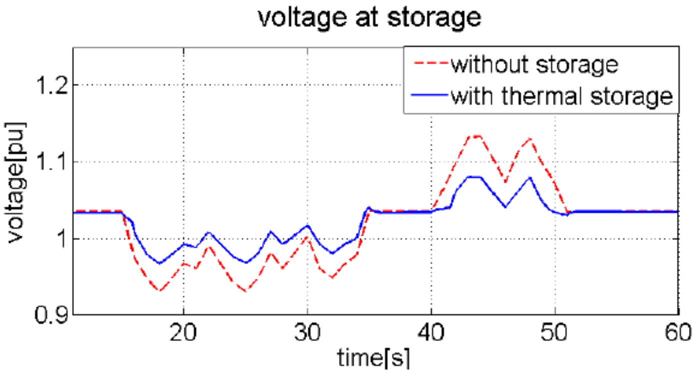






(a)

(a) Frequency oscillations of the micro grid caused by the intermittent renewable source with no storage and with resistor type thermal storage;

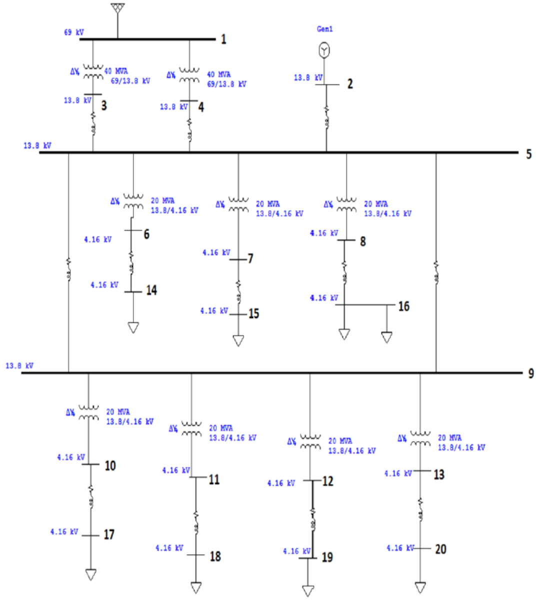


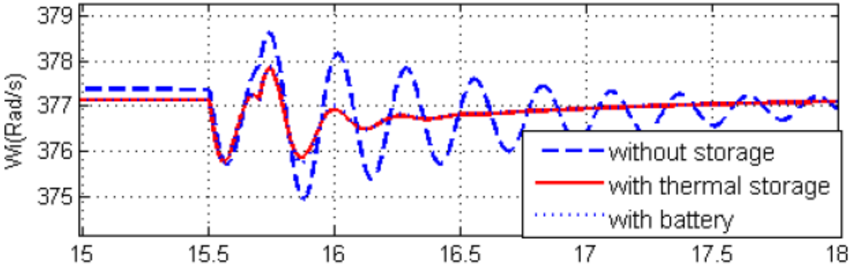
(b)

(b) Voltage profile at a selected bus in the micro grid in the absence and presence of thermal storage

Simulation Results

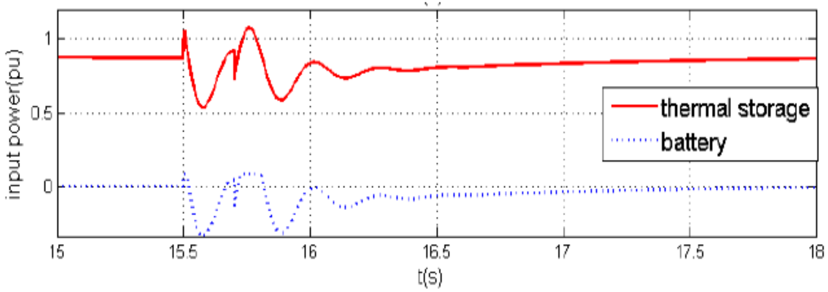
❑ Robustness





(a)

(a) Speed of the generator with and without the storages;

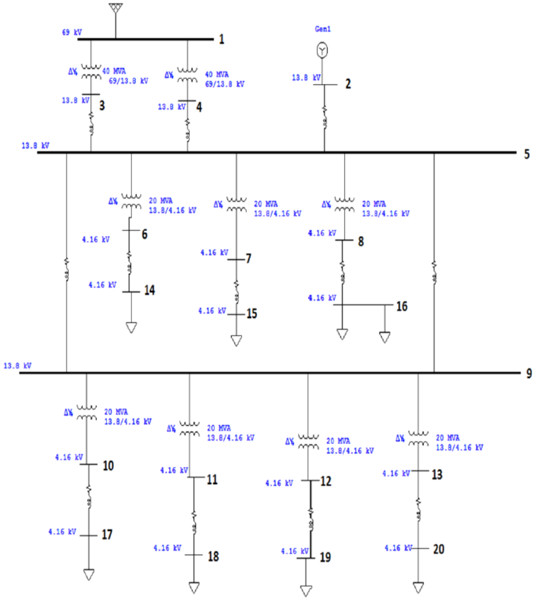


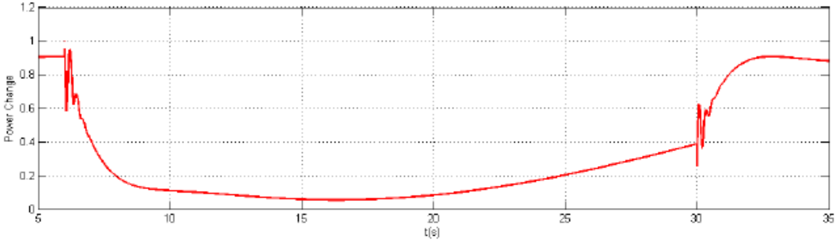
(b)

(b) Active power absorbed by the thermal storage and battery

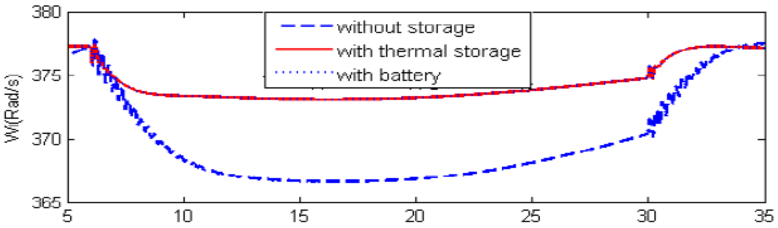
Simulation Results

❑ Robustness



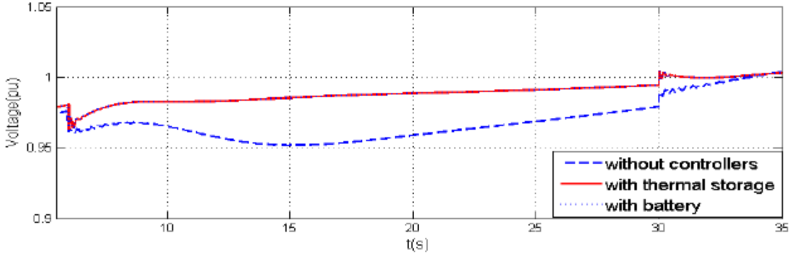


Intermittent changes in the power generated by renewable sources;



(a)

(a) Frequency oscillation of the generator with and without the storages;



(b)

(b) Closer look at the voltage profile of a selected bus with and without the controllers

Summary

Energy storage will have significant stabilizing effects on the system

1) Dynamic behavior of the grid is shown to be improved and stability is recuperated faster by storage

2) Storage’s performance is robust against the sudden change of load and generation

3) Storage provides a flatter energy generation trend despite the intermittent nature of the renewable resources.

THANK YOU

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