Smart Microgrid Network with Decentralized Power Sharing: Modelling, Management and Optimization

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Outline

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- Understanding Microgrid Architecture
- Network of microgrids: Benefits
- Network of microgrids: Challenges
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- Optimization Techniques
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- Conclusion & Impact.

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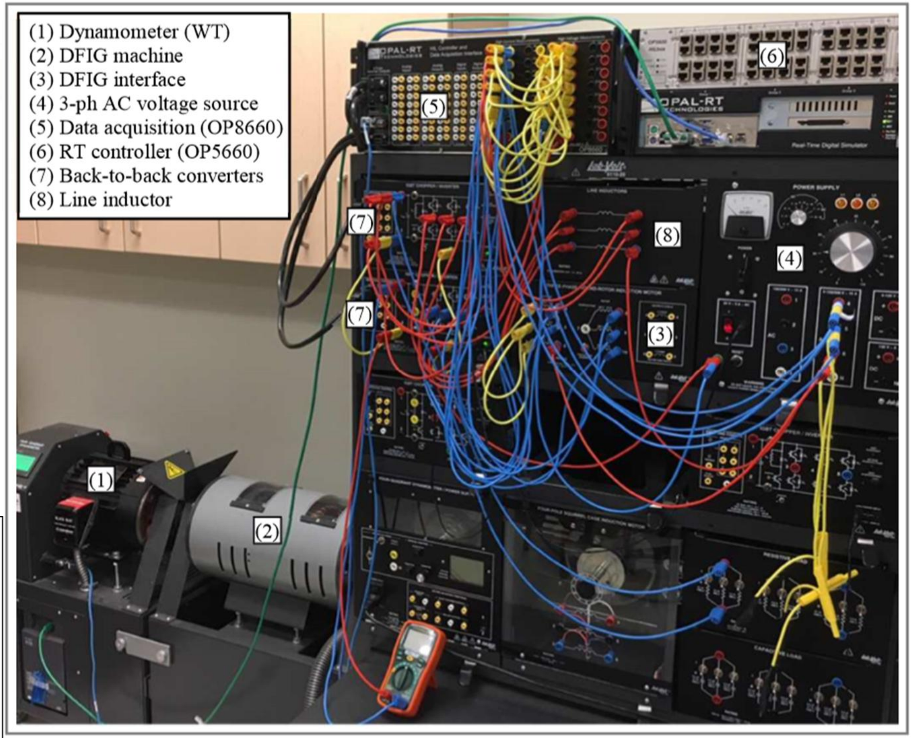
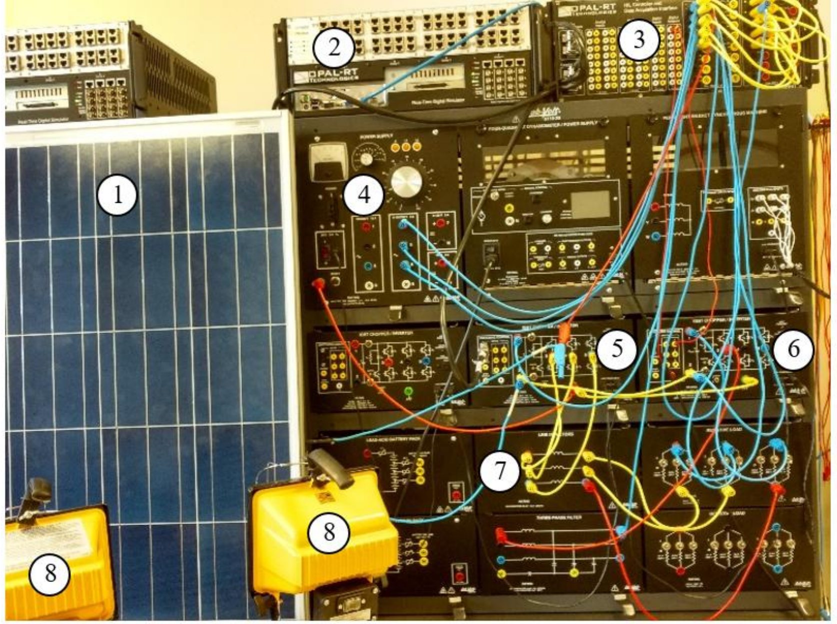
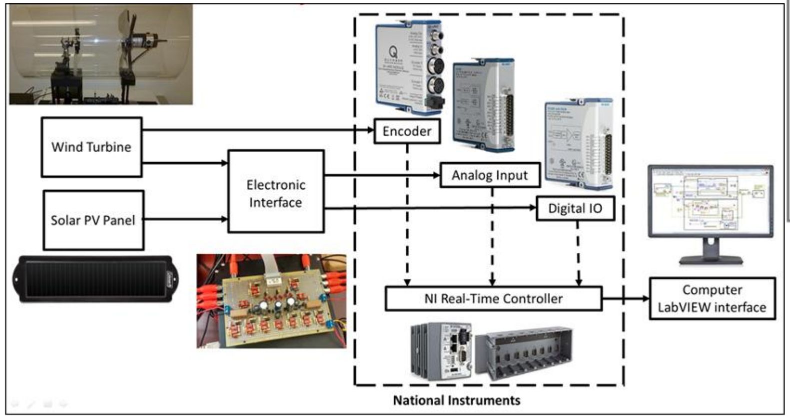
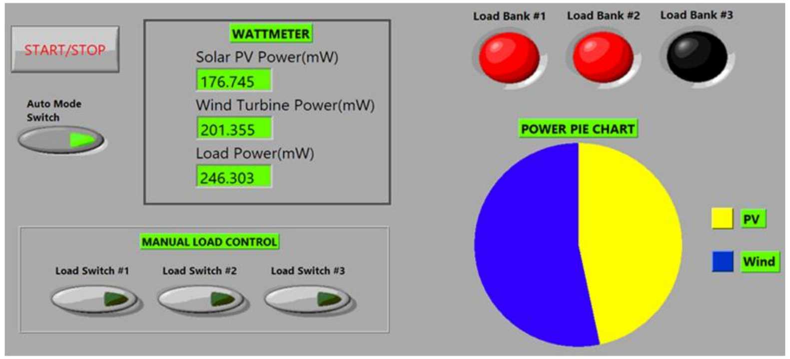
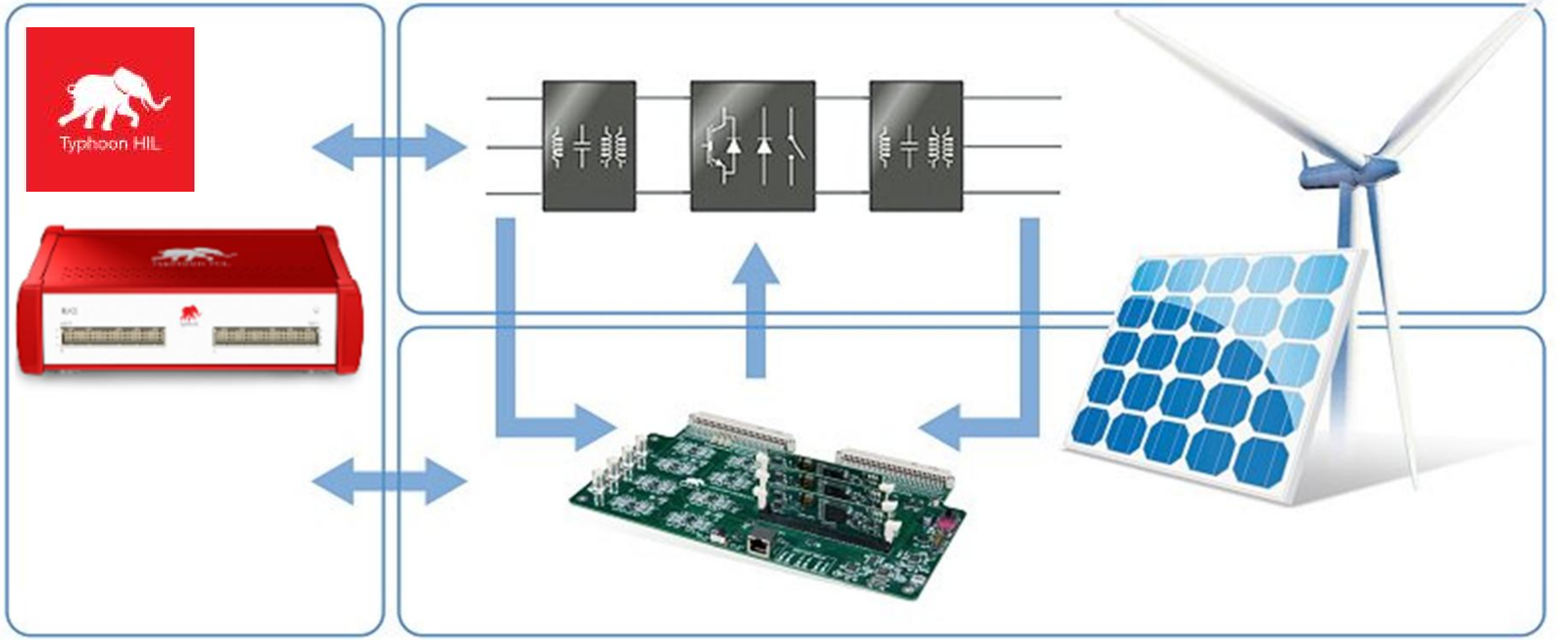




(1) Solar panel; (2) RT Controller (OP5600); (3) DAQ (OP8660);
(4) Grid emulator; (5) Inverter; (6) Converter; (7) RL filter; (8) Lamps.







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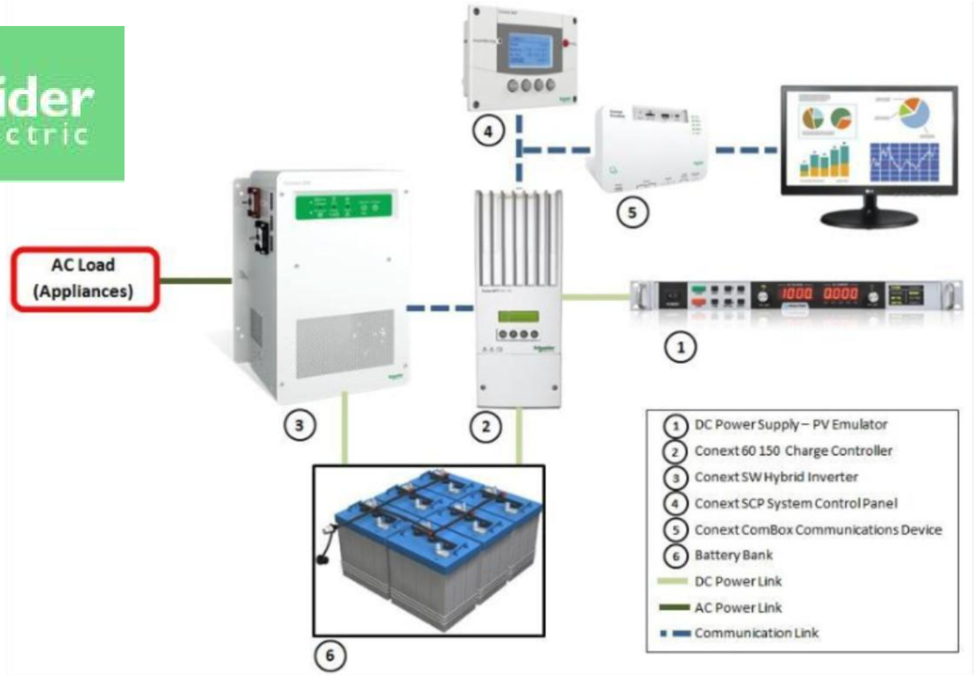

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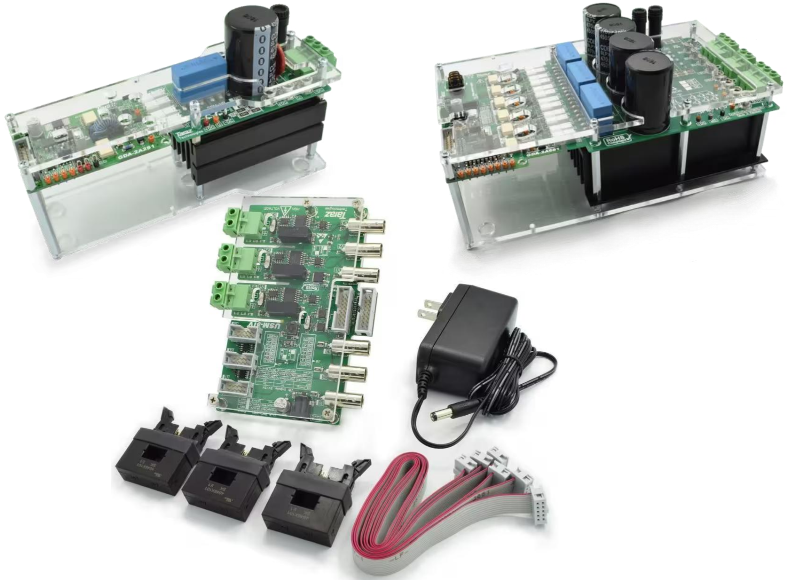
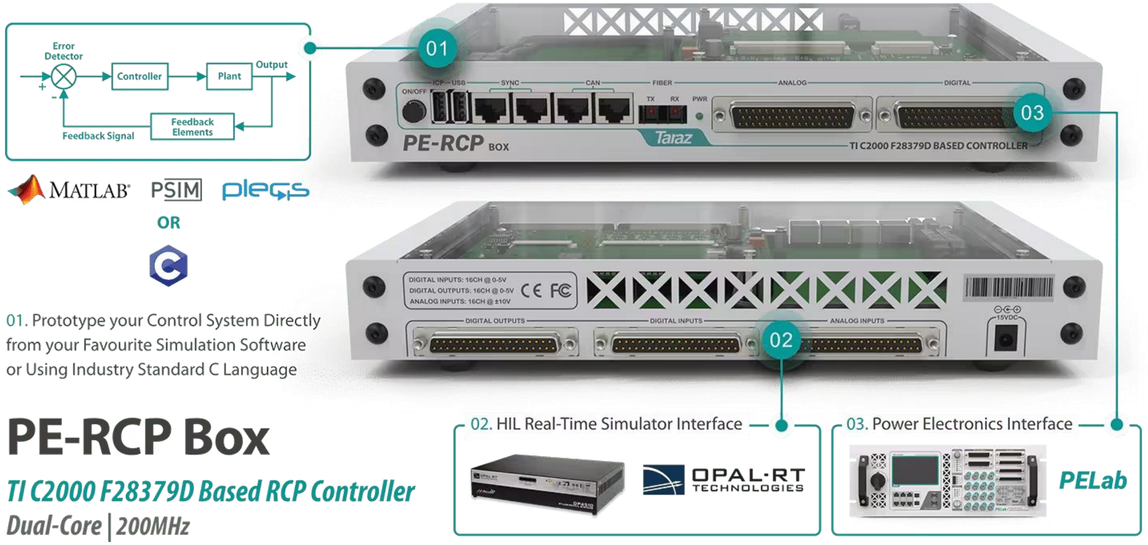




Understanding Microgrid Architecture

Core Components

Modern microgrids integrate distributed energy resources including solar panels, wind turbines, battery storage systems, and conventional generators. These components work together through intelligent control systems that monitor and balance supply with demand in real-time.

The decentralized architecture enables autonomous operation during grid outages while maintaining seamless integration with the main power grid during normal

Network Topology

Smart microgrids utilize mesh network configurations that allow bidirectional power flow between nodes. This topology enhances resilience by creating multiple pathways for energy distribution, ensuring continuous operation even when individual connections fail.

Advanced communication protocols enable peer-to-peer energy trading and coordinated control across the entire network infrastructure.

Network of Microgrids

Challenges of Networked Microgrids

1. Complex control and communication requirements.
2. Regulatory and interconnection standards.
3. High upfront costs and financial barriers.
4. **Energy Management Complexity**

The presence of multiple interconnected energy systems requires **dynamic energy management** to balance supply and demand. This involves forecasting, real-time monitoring, and managing the variability of renewable resources, which requires sophisticated energy management software and expertise.

Network of Microgrids

Key Benefits of Networked Microgrids:

1. Enhanced resilience and reliability.
2. Resource optimization.
3. Economies of scale.
4. Increased integration of renewable energy.
5. Support for urban and rural applications.

Decentralized Power Sharing Mechanisms

Peer-to-Peer Trading

Direct energy transactions between prosumers without intermediaries, enabled by blockchain technology and smart contracts for transparent, secure exchanges.

Dynamic Load Balancing

Automated distribution of power across network nodes based on real-time demand patterns, generation capacity, and storage availability.

Energy Storage Coordination

Intelligent management of distributed battery systems to optimize charging cycles, extend lifespan, and provide grid stabilization services.

Demand Response

Coordinated adjustment of consumption patterns across participating nodes to match available generation and reduce peak demand stress.

Mathematical Modeling Framework

Accurate mathematical models form the foundation for effective microgrid operation. These models capture the complex interactions between generation sources, storage systems, loads, and network constraints. Key modeling approaches include:

Power Flow Analysis

Equations describing voltage, current, and power distribution across network branches using AC or DC approximations.

Dynamic State Models

Time-series representations of generation variability, load forecasting, and battery state-of-charge evolution.

Optimization Objectives

Multi-objective functions balancing cost minimization, reliability maximization, and environmental impact reduction.

> Sophisticated models must balance computational complexity with real-time operational requirements, often employing linearization techniques and predictive algorithms to enable rapid decision-making.

Energy Management Strategies

1 **Forecasting Phase**

Predict generation from renewable sources and anticipated load patterns using machine learning algorithms and historical data analysis.

2 **Scheduling Phase**

Develop optimal dispatch schedules for controllable resources, storage charging/discharging, and grid import/export decisions.

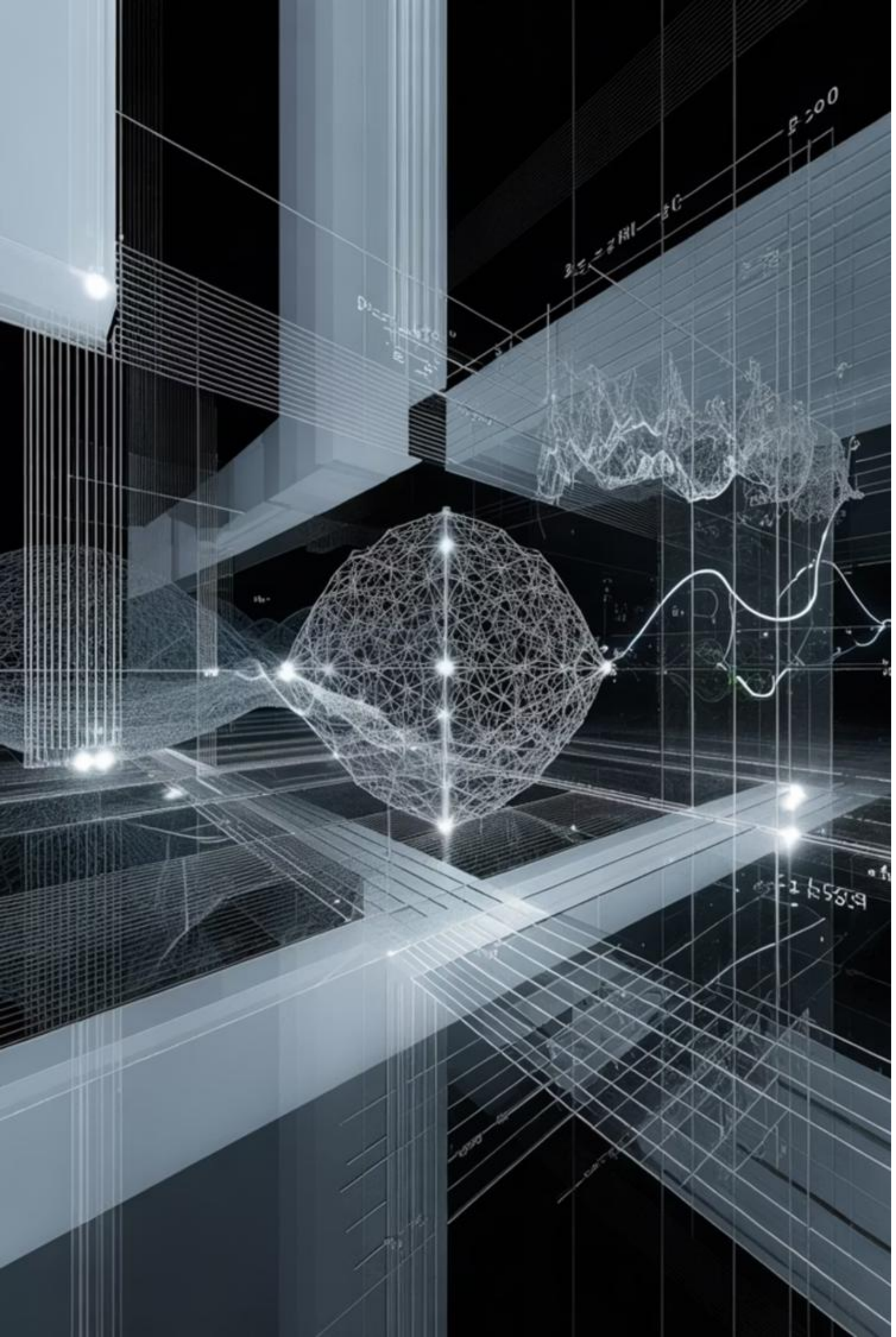
3 **Real-Time Control**

Execute scheduled operations while continuously adjusting for forecast errors and unexpected events through feedback control loops.

4 **Performance Monitoring**

Track key performance indicators, validate model accuracy, and update parameters to improve future operational decisions.

Effective energy management requires hierarchical control architectures that coordinate decisions across multiple time scales, from milliseconds for frequency regulation to hours for economic dispatch planning.



Optimization Techniques

Linear Programming

Efficient solution methods for convex optimization problems with linear constraints, widely used for unit commitment and economic dispatch.

Mixed-Integer Programming

Handles discrete decision variables such as generator on/off states, enabling more realistic modeling of operational constraints.

Stochastic Optimization

Incorporates uncertainty in renewable generation and load through scenario-based or robust optimization approaches.

Multi-Agent Systems

Distributed optimization where autonomous agents negotiate to reach consensus on power sharing without centralized coordination.

Metaheuristic Algorithms

Genetic algorithms, particle swarm optimization, and similar techniques for complex non-convex problems with multiple local optima.

Model Predictive Control

Rolling horizon optimization that continuously updates decisions based on latest forecasts and system measurements.

ELSEVIER

Electric Power Systems Research
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Optimization and energy management for cluster of interconnected microgrids with intermittent non-polluting and diesel generators in off-grid communities

Adel Merabet [a b], Ahmed Al-Durra [b], Tarek El-Fouly [b], Ehab F. El-Saadany [b]

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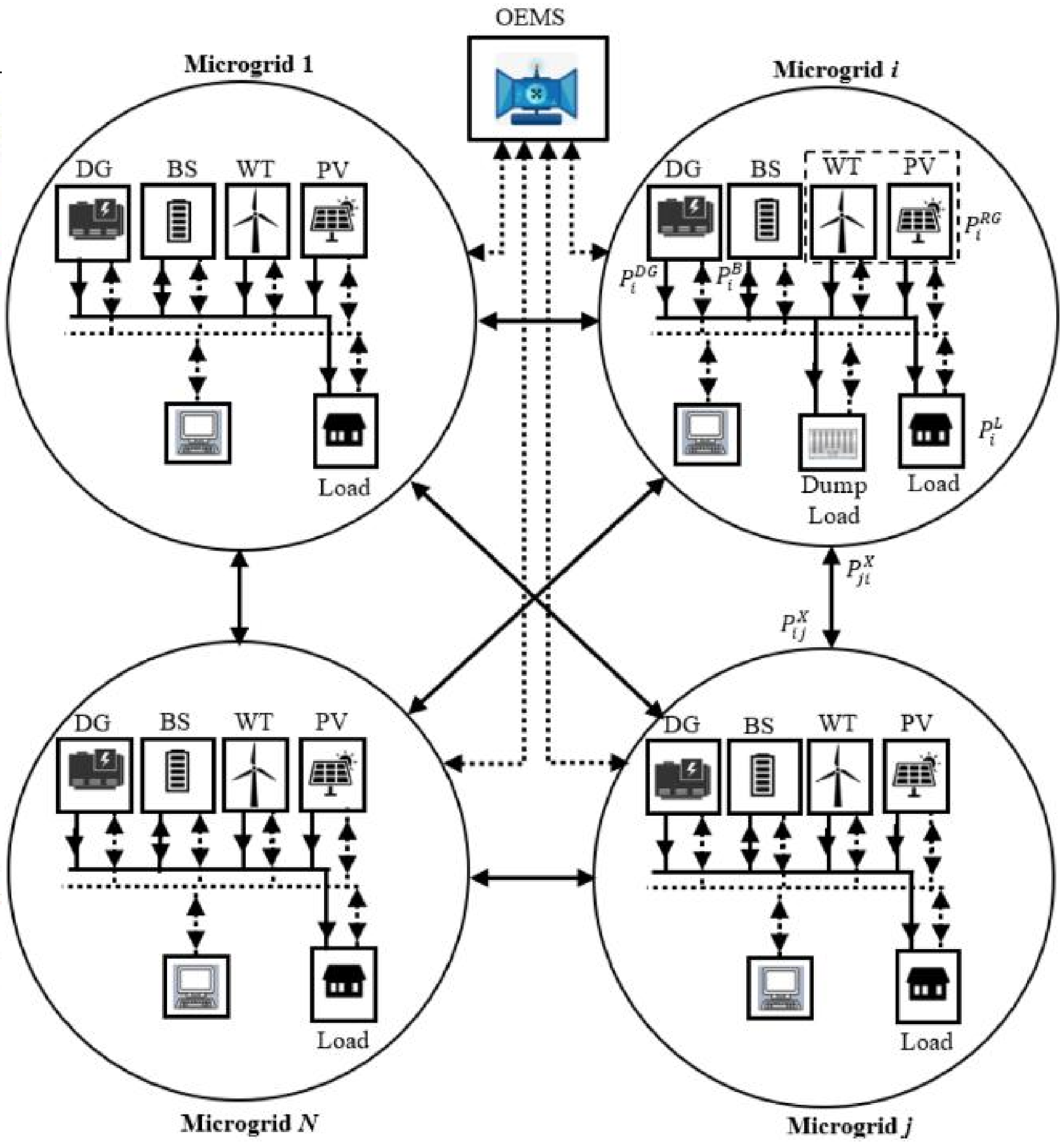
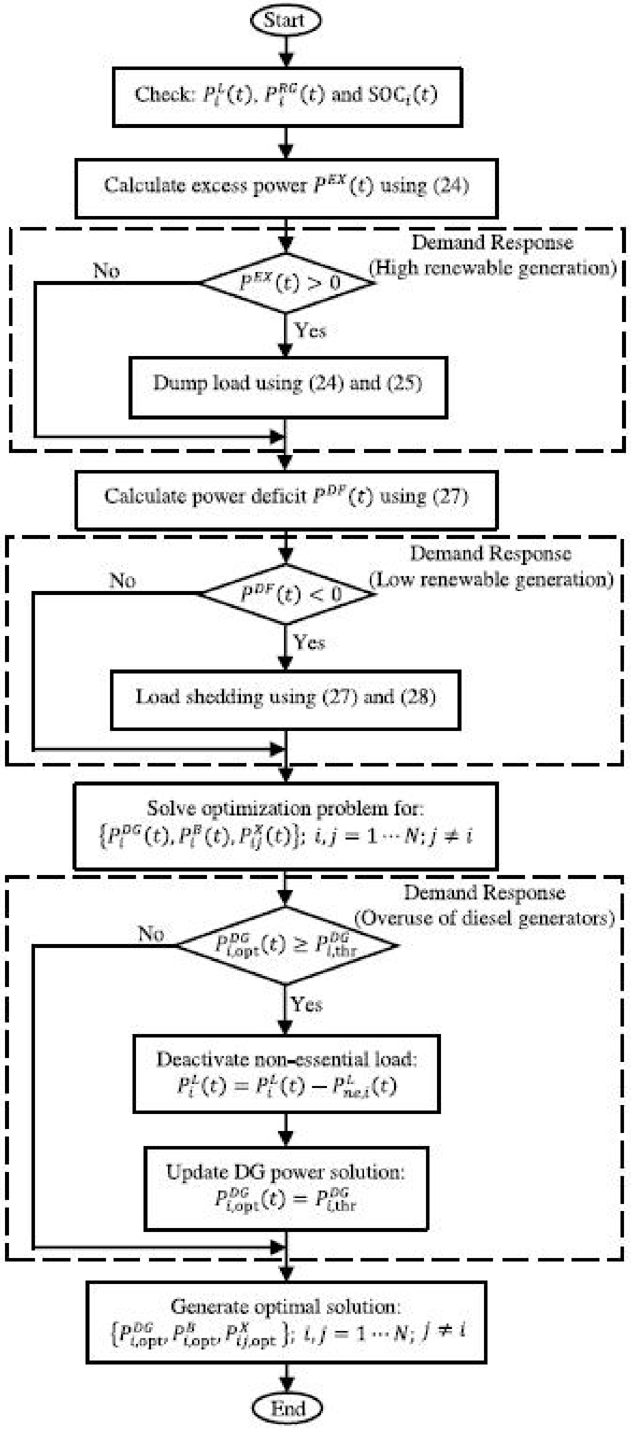


Network of interconnected microgrids based on intermittent non-polluting and diesel generators in off-grid communities.

Flowchart of the optimization and energy management system for the cluster of microgrids in off-grid communities.



Algorithm 1

Optimization procedure for network of microgrids.

1: **Initialization**

Provide: Number of microgrids, N, cost coefficients for DG, c_i^{DG}, battery storage, c_i^B, and power exchange, c_{ij}^X; $i, j = 1 \cdots N; j \neq i$.

2: **Data Collection and Calculation**

Check: Load power, $P_i^L(t)$, and renewable power, $P_i^{RG}(t)$, for $i = 1 \cdots N$

Calculate: variable $u_i(t)$ for power direction

$u_i(t) = 1\ \{0\}$; if $\left(P_i^L(t) - P_i^{RG}(t)\right) > 0\ \left\{\left(P_i^L(t) - P_i^{RG}(t)\right) < 0\right\}$

3: **Optimization**

Decision variables:

$$X = \left\{P_i^{DG}(t), P_i^B(t),\ P_{ij}^X(t)\right\};\ i, j = 1 \cdots N;\ j \neq i$$

Cost function:

$$\min_X F(X) = \sum_i^N c_i^{DG} \frac{P_i^{DG}(t)\Delta t}{\eta_i\left(P_i^{DG}(t)\right)} + \sum_{i=1}^N c_i^B \left|P_i^B(t)\right| \Delta t + \sum_{i=1}^N \sum_{\substack{j=1 \\ j \neq i}}^N c_{ij}^X P_{ij}^X(t) \Delta t$$

Equality constraints:

$$P_i^{DG}(t) + P_i^B(t) + u_i(t) \sum_{\substack{j=1 \\ j \neq i}}^N P_{ji}^X(t) - (1 - u_i(t)) \sum_{\substack{j=1 \\ j \neq i}}^N P_{ij}^X(t) = P_i^L(t) - P_i^{RG}(t);\ i = 1 \cdots N$$

Inequality constraints:

$$P_i^{DG}(t) - P_i^{DG}(t - \Delta t) \leq P_{i,\mathrm{up}}^{DG}$$

$$P_i^{DG}(t - \Delta t) - P_i^{DG}(t) \leq P_{i,\mathrm{dw}}^{DG}$$

$$P_{ij}^X(t) \leq (1 - u_i(t)) u_j(t) \left|P_i^L(t) - P_i^{RG}(t)\right|;\ i, j = 1 \cdots N;\ j \neq i$$

Bounds constraints:

Lower bounds:

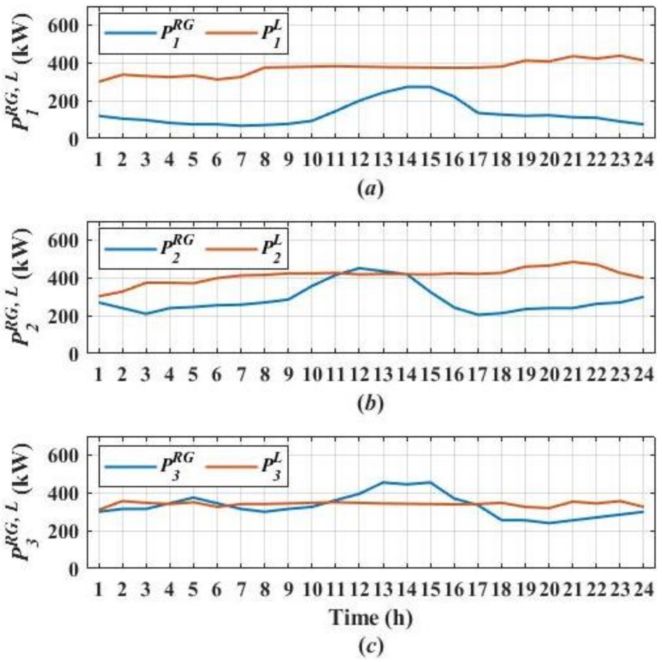
$$\begin{bmatrix} 0 & \cdots & 0 & -(1 - u_1(t)) P_{1,\max}^B & \cdots & -(1 - u_N(t)) P_{N,\max}^B & 0 & \cdots & 0 \end{bmatrix}_{1 \times (N^2 + N)}$$

Upper bounds:

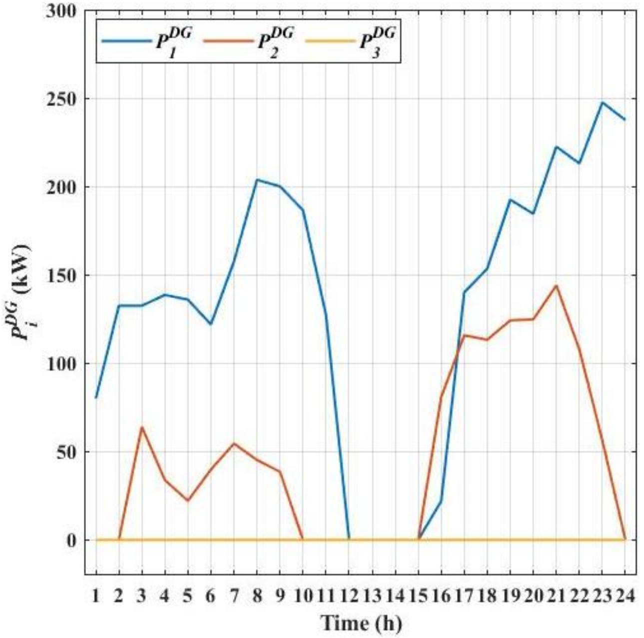
$$\begin{bmatrix} P_{1,\max}^{DG} & \cdots & P_{N,\max}^{DG} & u_1(t) P_{1,\max}^B & \cdots & u_N(t) P_{N,\max}^B & (1 - u_1(t)) u_2(t) \left|P_1^L(t) - P_1^{RG}(t)\right| & \cdots & (1 - u_N(t)) u_{N-1}(t) \left|P_N^L(t) - P_N^{RG}(t)\right| \end{bmatrix}_{1 \times (N^2 + N)}$$

Optimize and generate optimal solution:

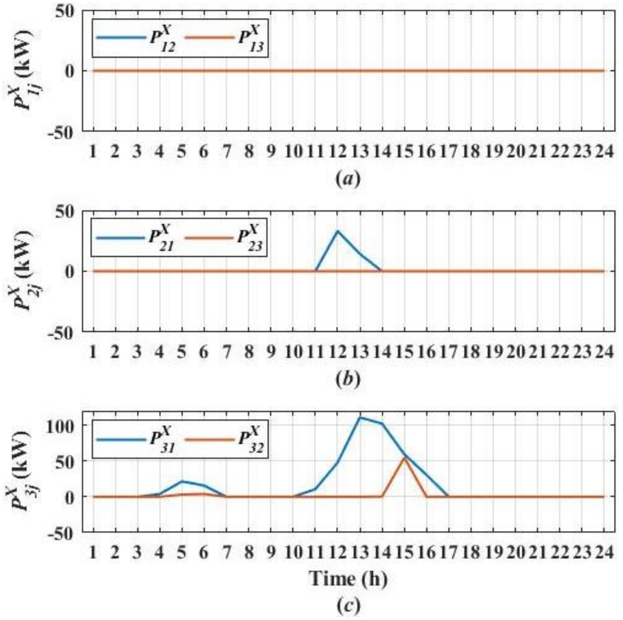
$$X_{\mathrm{opt}} = \left\{P_{i,\ \mathrm{opt}}^{DG}, P_{i,\ \mathrm{opt}}^B,\ P_{ij,\ \mathrm{opt}}^X\right\};\ i, j = 1 \cdots N;\ j \neq i$$



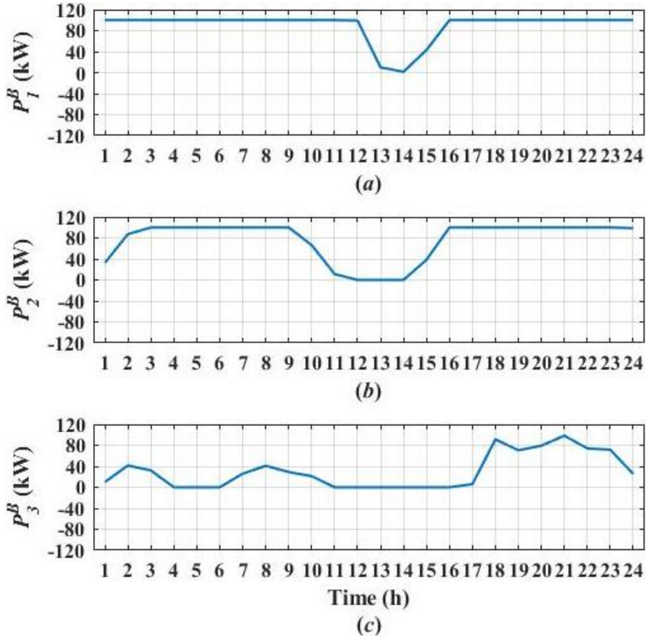
P_1^{RG} P_1^L
$P_1^{RG,\,L}$ (kW)
(a)
P_2^{RG} P_2^L
$P_2^{RG,\,L}$ (kW)
(b)
P_3^{RG} P_3^L
$P_3^{RG,\,L}$ (kW)
Time (h)
(c)



P_1^{DG} P_2^{DG} P_3^{DG}
P_i^{DG} (kW)
Time (h)



P_{12}^X P_{13}^X
P_{1j}^X (kW)
(a)
P_{21}^X P_{23}^X
P_{2j}^X (kW)
(b)
P_{31}^X P_{32}^X
P_{3j}^X (kW)
Time (h)
(c)



P_1^B (kW)
(a)
P_2^B (kW)
(b)
P_3^B (kW)
Time (h)
(c)

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Research papers

Multifunctional energy management system for optimized network of microgrids considering battery degradation and load adjustment

Adel Merabet [a b], Ahmed Al-Durra [b], Tarek El Fouly [b], Ehab F. El-Saadany [b]

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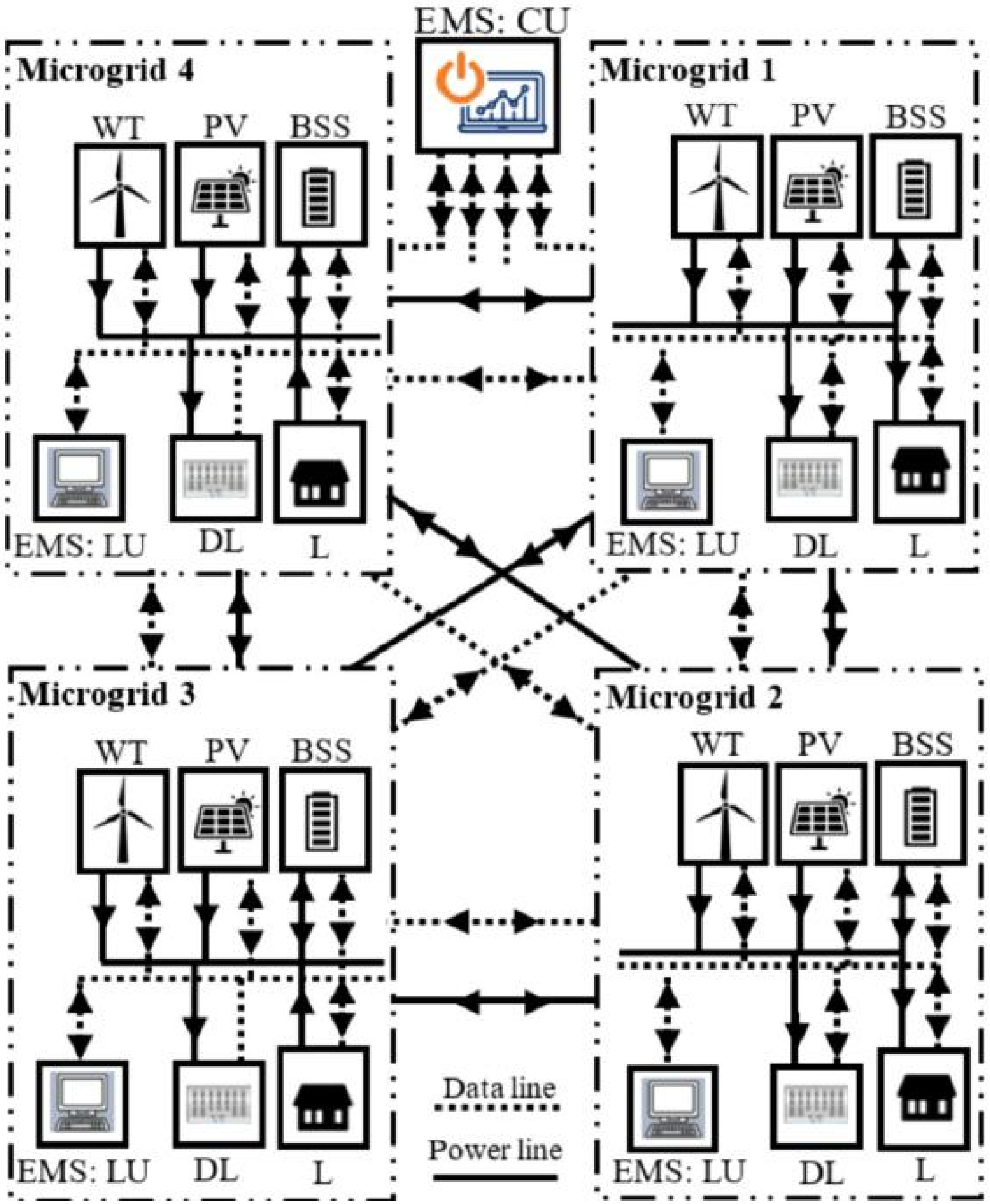
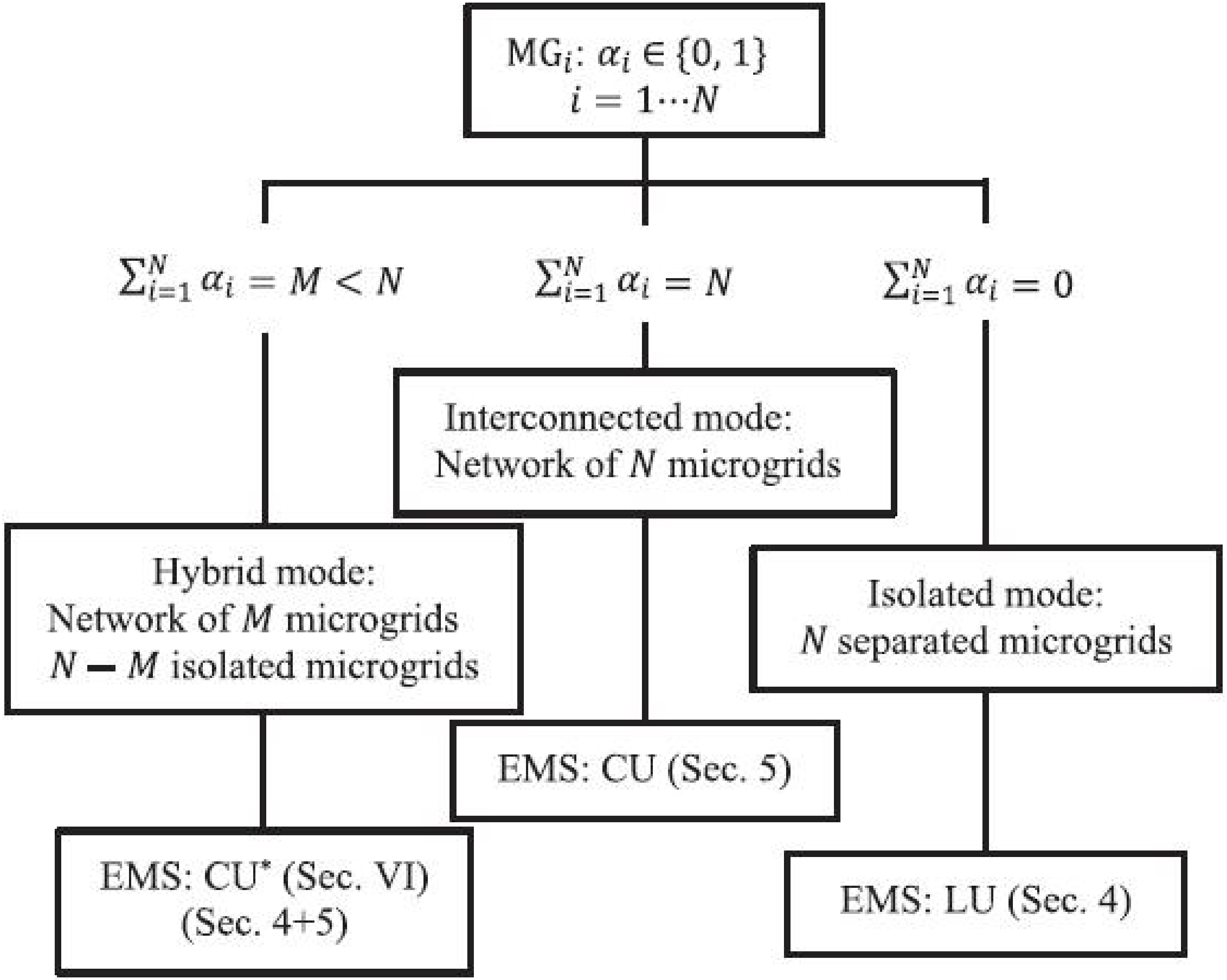
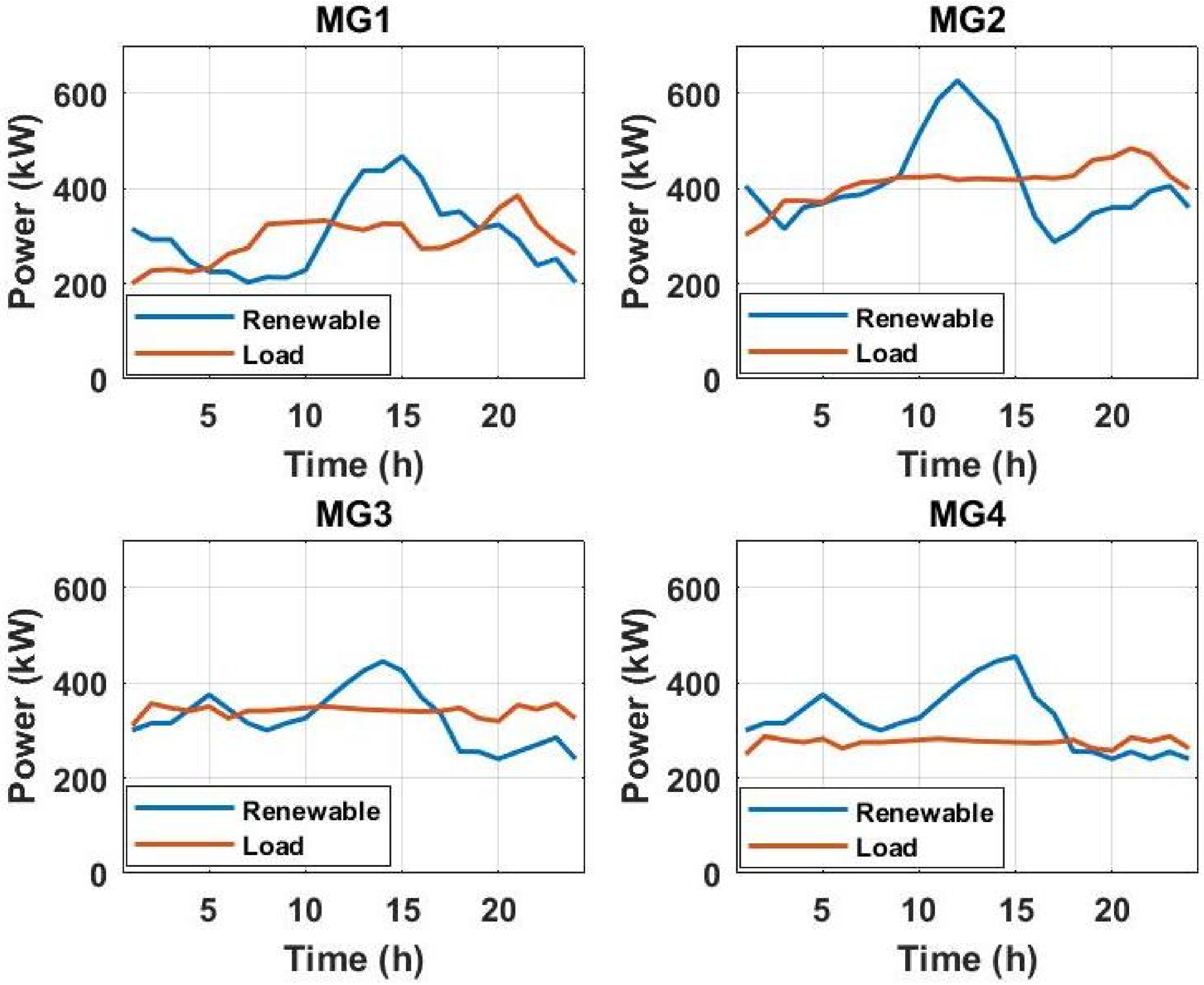


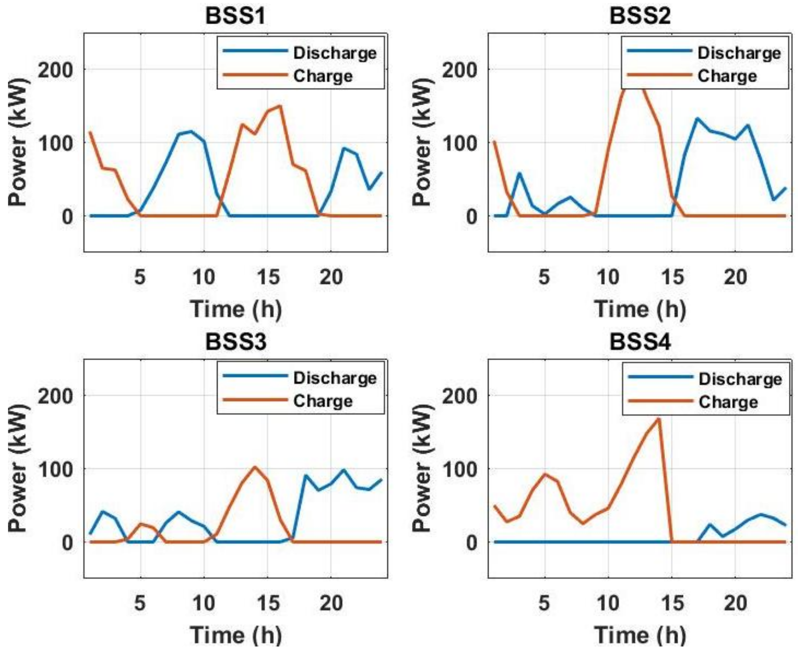
Network of interconnected microgrids based on renewable resources and battery storage.

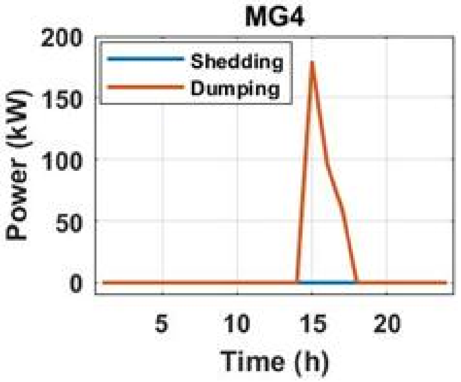


Multifunctional energy management system for network of microgrids under different modes

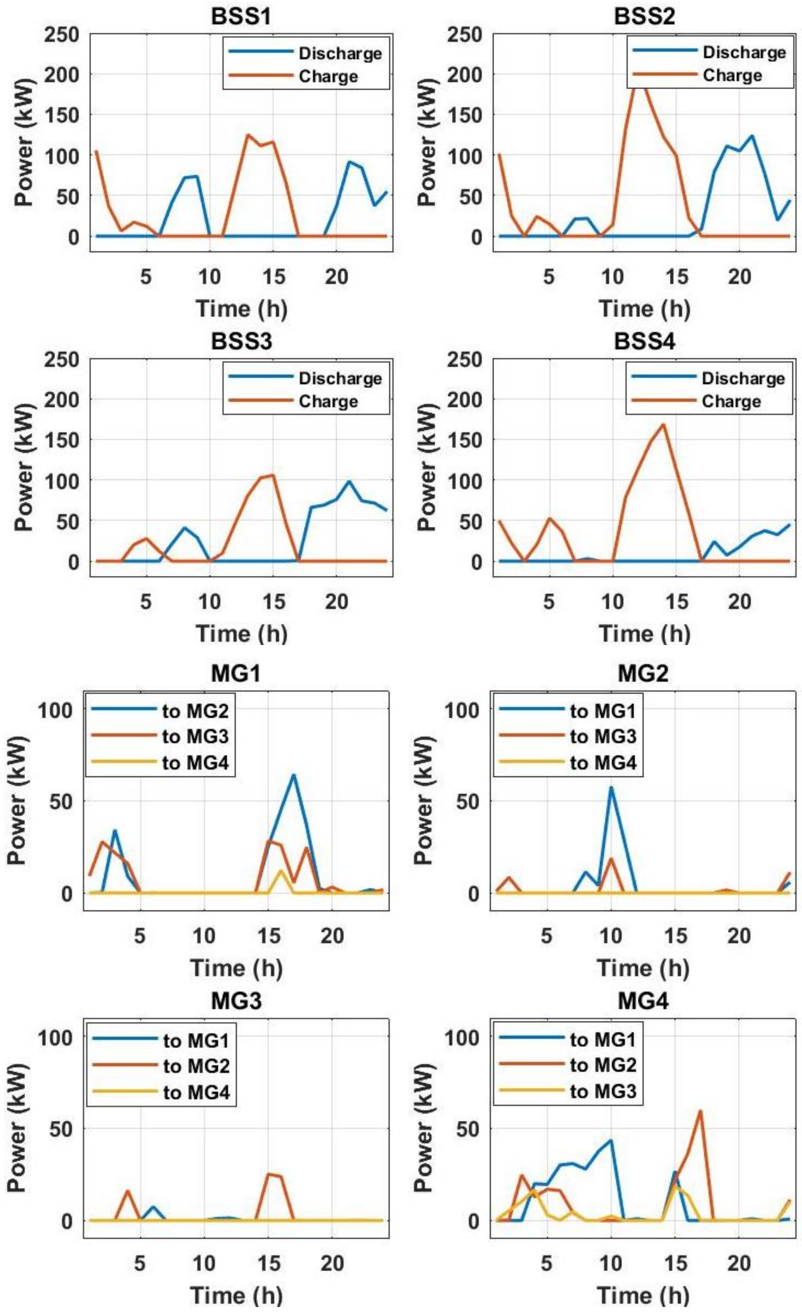

MG1
MG2
MG3
MG4
Power (kW)
Time (h)
Renewable
Load
0
200
400
600
5
10
15
20

Network of disconnected microgrids.





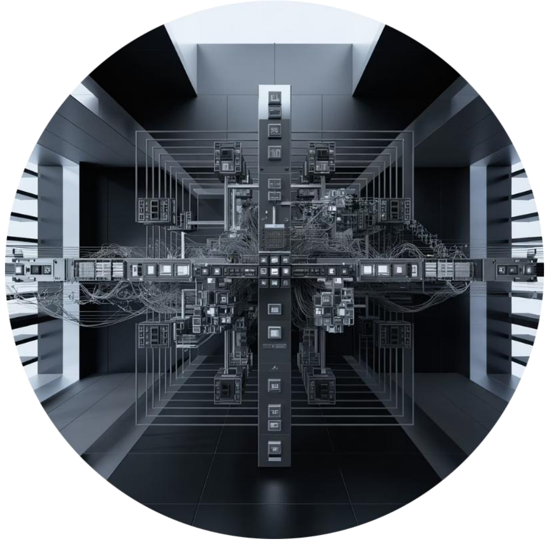
Network of **interconnected** microgrids.



Current & Future Research Directions

AI-Driven Control

Deep learning and reinforcement learning for adaptive control strategies that improve performance through continuous learning from operational data.

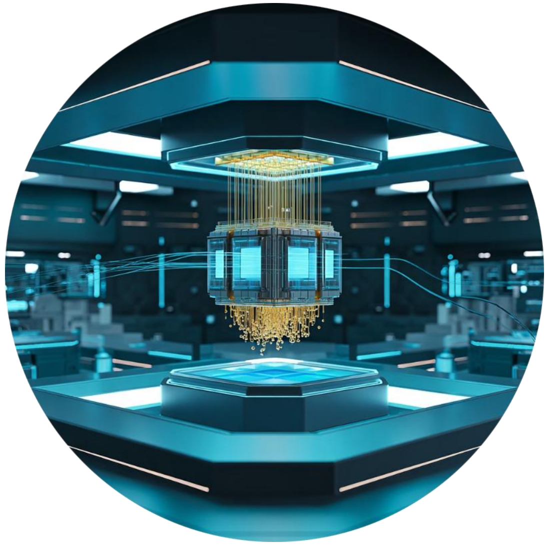


Blockchain Integration

Distributed ledger technology for transparent, secure energy transactions and automated settlement through smart contracts.

Vehicle-to-Grid

Integration of electric vehicles as mobile storage resources, enabling bidirectional power flow and enhanced grid flexibility.



Quantum Computing

Leveraging quantum algorithms to solve complex optimization problems that are intractable for classical computers.

Conclusion and Impact

Smart microgrid networks with decentralized power sharing represent a transformative approach to energy distribution that addresses critical challenges in modern power systems. Through sophisticated modeling, intelligent management strategies, and advanced optimization techniques, these systems enable higher renewable energy penetration, improved reliability, and reduced operational costs.

The integration of distributed energy resources, energy storage, and intelligent control creates resilient networks capable of autonomous operation while maintaining grid connectivity. As technology advances and regulatory frameworks evolve, decentralized microgrids will play an increasingly vital role in the transition to sustainable, efficient, and democratized energy systems.

Enhanced Resilience

Reduced vulnerability to grid failures and natural disasters

Environmental Benefits

Lower carbon emissions through renewable integration

Economic Efficiency

Optimized resource utilization and reduced energy costs

Thank You For Your Attention.

Questions ?

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