Communication Enabled Distributed Control and Dynamic Optimization in a Microgrid

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April 5, 2019

Outline

Motivation

Legacy Power System

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- Legacy power system is centralized and one way generation.
- Transmission and distribution is facilitated by transmission system operator(TSO), distribution system operator (DSO) and power Aggregator/Retailer.

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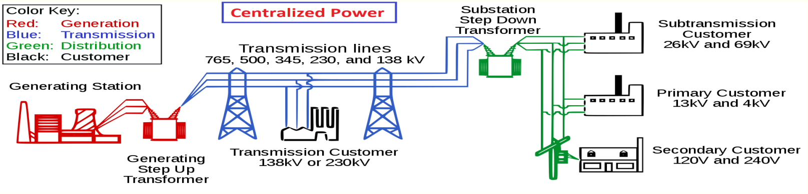

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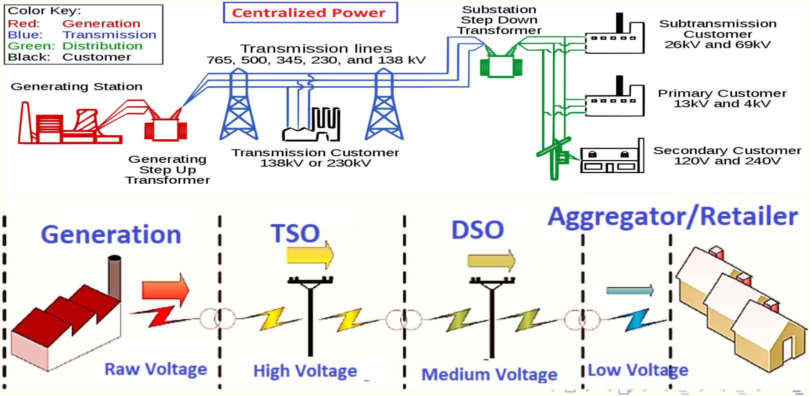

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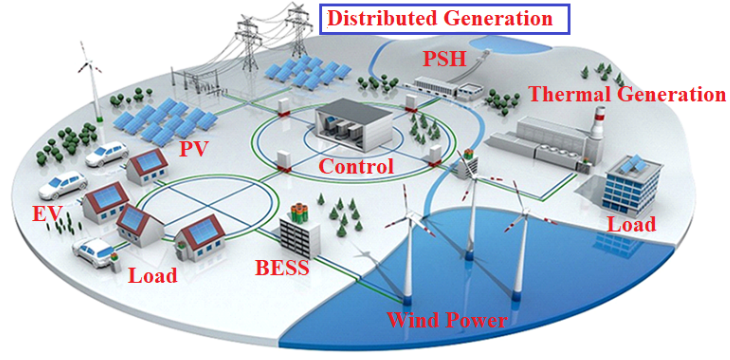


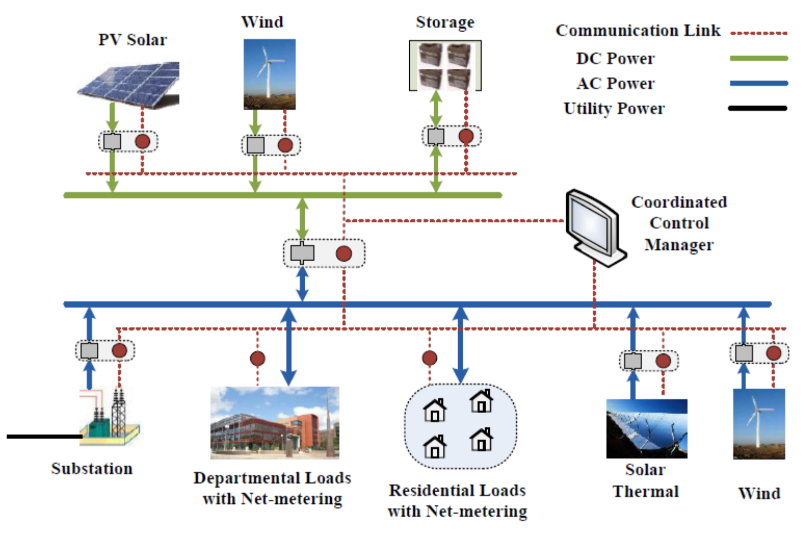
Motivation

Classification of Microgrids

Source: Navigant Research

Motivation

A Typical Campus Microgrid



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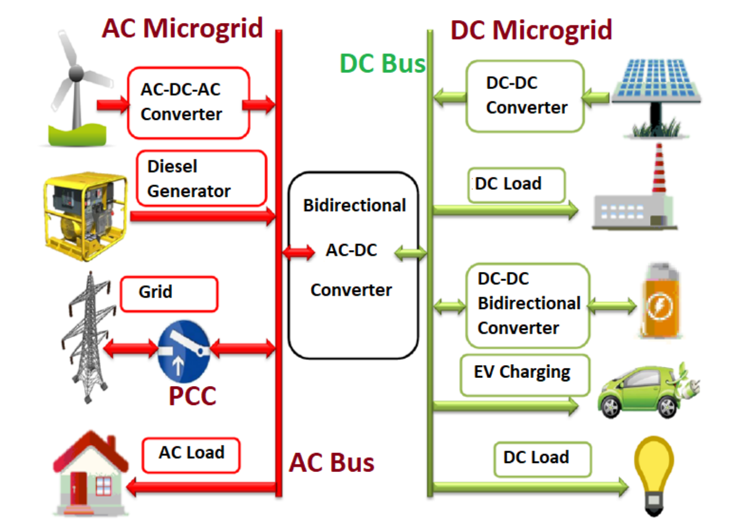
AC and DC Microgrids



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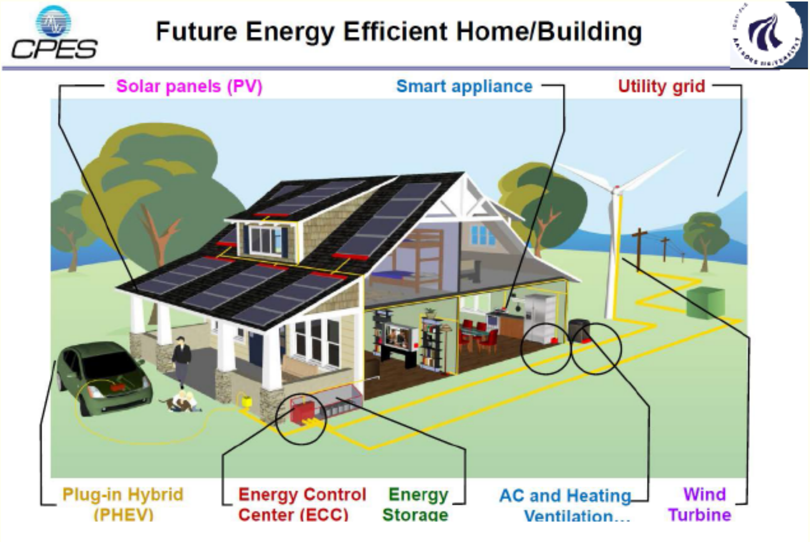
A Hybrid NanoGrid



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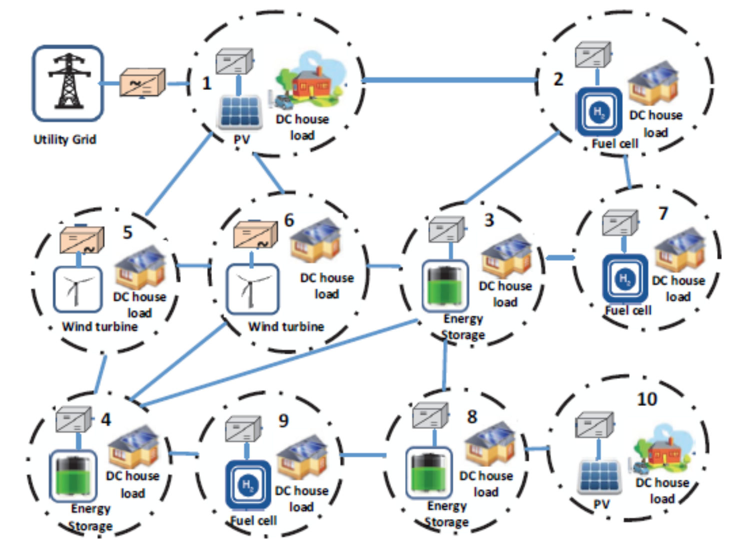
Energy Trading in DC Microgrid [Xu et al., 2019]



Motivation

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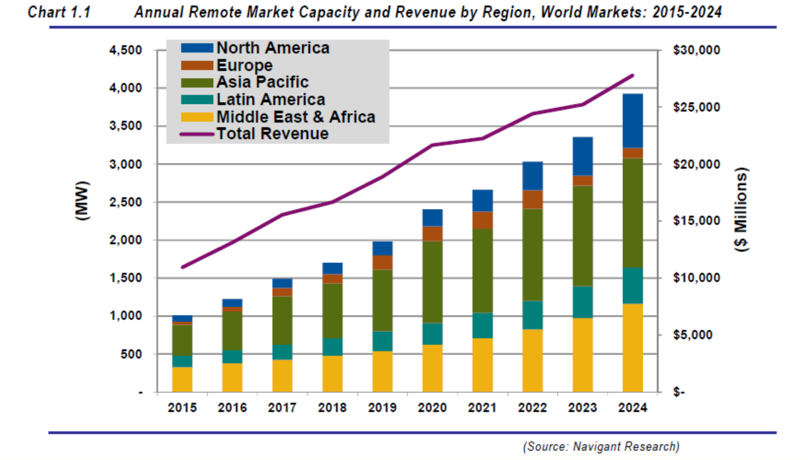
Microgrid Market Capacity and Revenue



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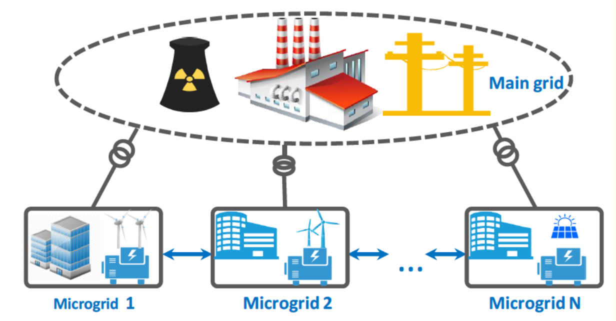
Emerging Multi-Microgrids as New Power Sharing Solutions



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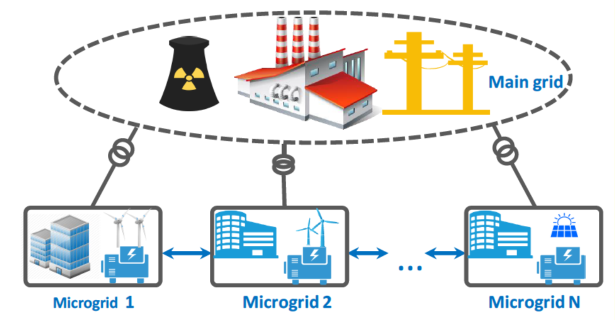

- Microgrids can operate in island or grid-connected mode.

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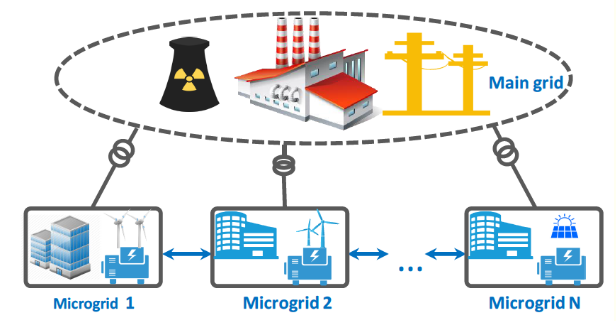

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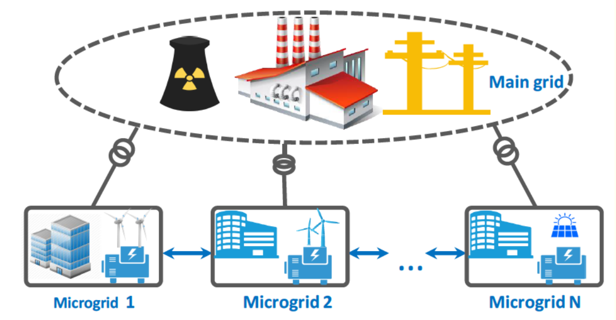

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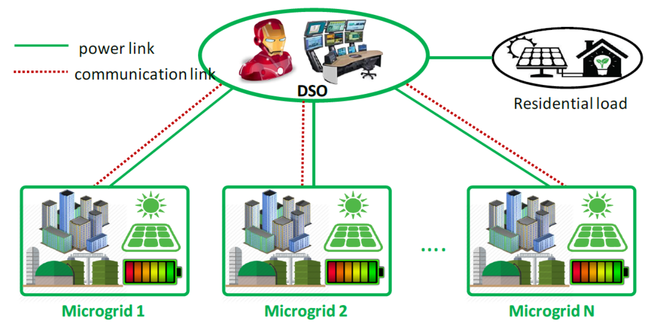

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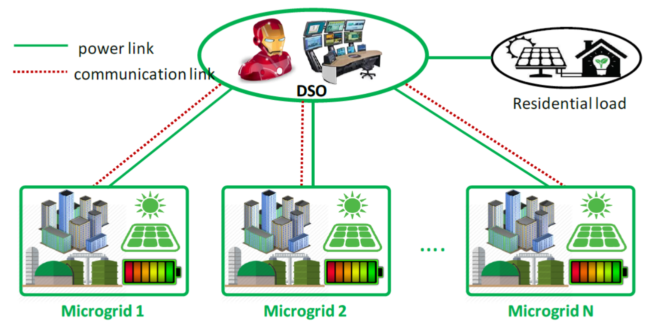

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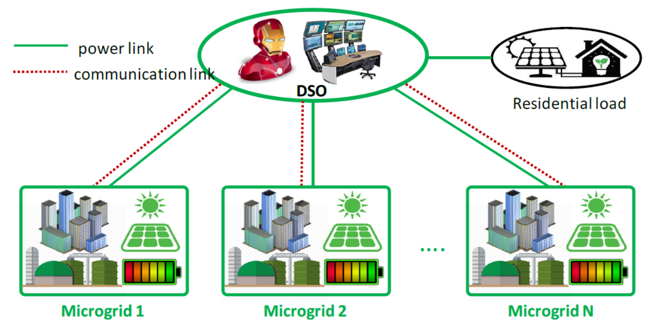

- Multiple Microgrids can exchange power.
- A Distribution System Operator (DSO) can also facilitate power exchange via power link.
- Information is exchanged via communication links.

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Operational Modes of a Microgrid

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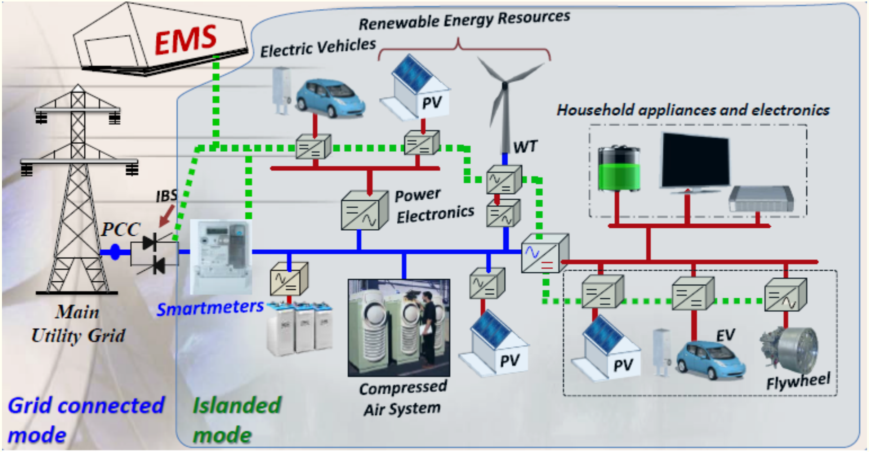

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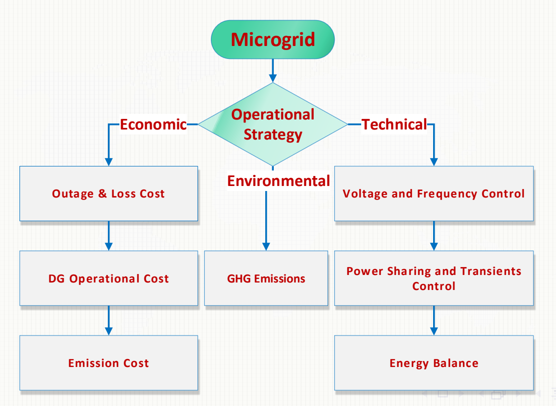
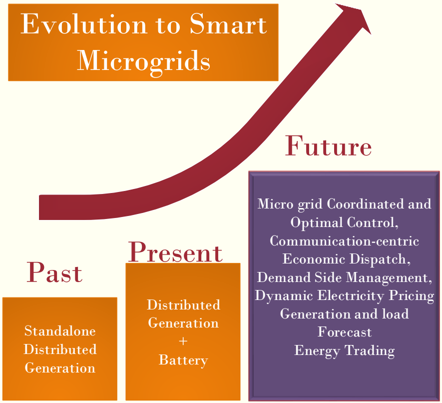


Motivation

Microgrid Research Trend



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- Microgrids are being clustered into multi-microgrids.
- Microgrids come with new challenges.

Microgrid Challenges

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Online and offline optimization is required for energy management.

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Operate DGs with minimum generation costs and satisfy constraints.

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Information and Communication Technology(ICT):

Microgrid Challenges (contd.)

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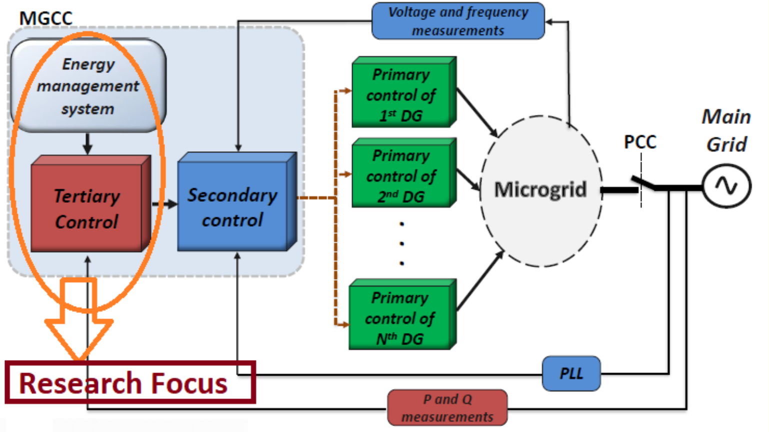
Research Focus

Economic Dispatch at tertiary level, energy management,transient control and optimal power sharing:



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Problems Addressed in this Research

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- A multi-objective Non-linear constrained optimization problem for a microgrid with self-triggered data sampler for conservation of communication bandwidth.

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- Develop a Multi-agent system framework for fast convergence of the proposed algorithms.

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Dissertation Contributions:Publications from Research Work

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- **Jameel Ahmad**, Muhamamd Tahir and Sudip. K. Mazumder, **"Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid"** in IEEE Systems Journal, vol. 13, no. 1, pp. 802-812, March 2019.
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Other Related Research Contributions

Other Related Contributions During PhD Research 2016-2019

- Sajjad Haider Shami, **Jameel Ahmad**, Raheel Zafar, Muhammad Haris, Sajid Bashir. **"Evaluating wind energy potential in Pakistan's three provinces, with proposal for integration into national power grid"** in Elsevier's Renewable and Sustainable Energy Reviews.Volume 53,2016, Pages 408-421. Impact Factor=9.184

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Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

First contribution: Dynamic Economic Dispatch

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Proposed solution: DPC

A novel Dynamic Performance Controller (DPC) is proposed that provided ED with improved dynamic performance. DPC is based on optimized proportional−integral−derivative control using an **Augmented Lagrangian based approach**.

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Existing Work Economic Dispatch (ED of DGs: minimize the generation cost while meeting the load demands as well as operational constraints. Three variants: Dynamic economic dispatch (DED), centralized DED and distributed DED :

- The DED problem is formulated as a two stage primal-dual problem using Lagrangian relaxation [Fisher, 2004].
- Centralized DED:all the DGs are controlled from a central control center [Chen and Chen, 2001], [Tsikalakis and Hatziargyriou, 2011].
- Distributed DED using a MAS architecture [Cherukuri and Cortés, 2015], [Xu and Li, 2015], [Elsayed and El-Saadany, 2015].

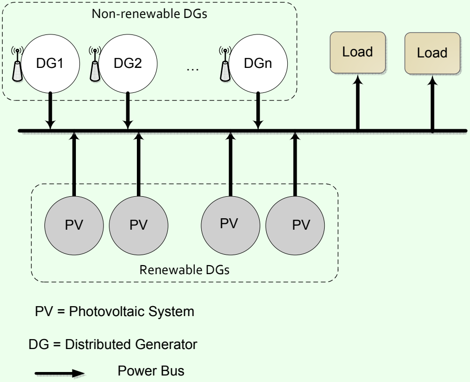
Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Existing Work-contd.

- [Xu and Li, 2015] offers a distributed consensus control for optimized management of DG resources for an islanded mode of microgrid operation.
- [Guerrero et al., 2011, Bidram et al., 2013, Dehkordi et al., 2017] provides a three layer hierarchical control.
- **Droop control** is used for secondary control [Dehkordi et al., 2017].
- Cost-based droop schemes for economic dispatch in islanded microgrids is presented in [Chen et al., 2017].
- key limitations of the droop control: load sharing and inferior dynamic performance.
- **The above mentioned solution approaches suffer from limited dynamic performance of economic dispatch.**

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Proposed Microgrid System Architecture



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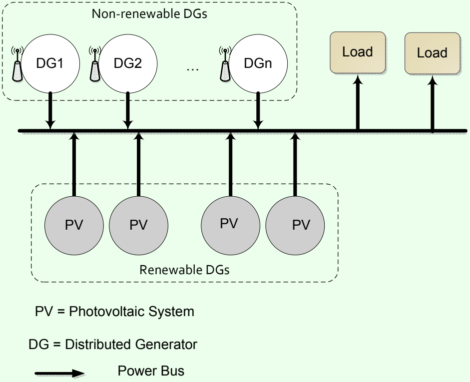

DGs and Renewable Energy Sources Considered

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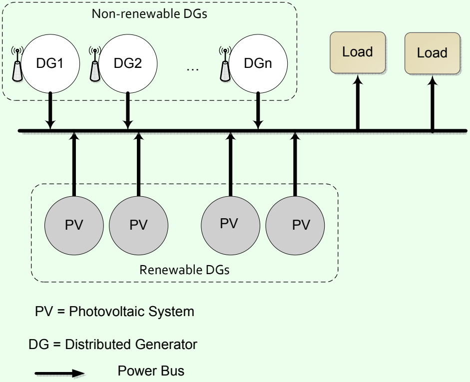

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- Renewable Energy sources are only PV Power .

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Distributed Optimization and Multi-Agent System (MAS) for MG

Proposed Procedure for Distributed Optimization and MAS

- Propose a connectivity graph for a set of DGs in a Microgrid

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- Determine the system dynamic equations from system model
- Incorporate Laplacian in system dynamic equations

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- Determine the system dynamic equations from system model
- Incorporate Laplacian in system dynamic equations
- Solve distributed optimized control algorithm iteratively and update agents

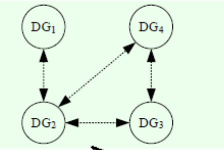
Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Determination of Laplacian Matrix

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Determination of Laplacian Matrix

Connectivity among DGs



$$D = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 2 \end{bmatrix}.$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}.$$

Laplacian Matrix
M=D-A

$$M = \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 3 & -1 & -1 \\ 0 & -1 & 2 & -1 \\ 0 & -1 & -1 & 2 \end{bmatrix}$$

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A Quadratic Cost Objective Function C_i

$$\sum_i C_i(p_i) = \sum_i \alpha_i p_i^2 + \beta_i p_i + \gamma_i, \quad \forall i \tag{1}$$

- $p_i \in \mathbf{p}, \; \mathbf{p} \in \mathbb{R}^N$ represents the power delivered from generator i.
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- Supply-Demand Constraint: $\sum_i p_i = L_d$ where L_d is total load demand

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Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

ED Optimization Problem Formulations and its Lagrange Function

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

ED Optimization Problem Formulations and its Lagrange Function

ED Optimization Problem

$$
\begin{aligned}
&\textbf{minimize} \sum_i \omega_i C_i(p_i) \\
&\textbf{subject to} \\
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Lagrange Dual Function

$$
\begin{aligned}
L(\mathbf{p}, \lambda, \mathbf{\Phi}, \rho, \sigma) = & \sum_i \omega_i C_i(p_i) \\
& + \lambda(L_d - \sum_i p_i) + \Phi^t[\mathbf{Mp} + \delta] \\
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Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Primal-Dual Dynamics and Integral Control Action

- Solve the Lagrange function using Partial Derivatives of L with respect to p, λ, Φ, ρ, σ
- $\dot{p} = \frac{\partial L}{\partial p}; \quad \dot{\lambda} = \frac{\partial L}{\partial \lambda}; \ \ \dot{\phi} = \frac{\partial L}{\partial \phi}; \ \dot{\rho} = \frac{\partial L}{\partial \rho}; \quad \dot{\sigma} = \frac{\partial L}{\partial \sigma}$

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Primal-Dual Dynamics

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\begin{aligned}
\dot{p}_i = k_{p_i} \left(\omega_i C_i'(p_i) + \Phi^t M_i - \lambda - \rho + \sigma \right) \\
\dot{\lambda} = k_\lambda \left\{ L_d - \sum_i p_i \right\}^+ \\
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integral control action u_i

Let $u_i = \Phi^t M_i - (\lambda + u_\rho - u_\sigma)$ is the Integral control action.

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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$$u_i = \Phi^t M_i - \left(\int_0^t k_\lambda (L_d - \sum_i p_i(\tau))^+ d\tau + u_\rho - u_\sigma\right) \tag{5}$$

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Proposed Control: Optimized PID based Economic Dispatch

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Proposed Control: Optimized PID based Economic Dispatch

Augmented Lagrange Function

$$
\begin{aligned}
& L_a(\mathbf{p}, \lambda, \Phi, \rho, \sigma, \tilde{\mathbf{p}}) = \\
& \sum_i \omega_i C_i(p_i) + \sum_i \frac{k_p}{2}\left(L_d - \sum_i p_i\right)^2 \\
& + k_i \Big\{ \lambda \left(L_d - \sum_i p_i\right) + \Phi^t [\mathbf{M}\mathbf{p} + \delta] \\
& + \sum_i \rho(p_{min} - p_i) + \\
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- To improve it, a dynamic performance controller (DPC) based solution is developed.

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- To improve it, a dynamic performance controller (DPC) based solution is developed.
- We extend the Lagrangian to construct **an Augmented Lagrangian function** L_a
- k_p, k_i and k_d are respectively, proportional, integral and derivative gains of the controller.

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Updated Primal-Dual Dynamics for Proposed PID based Economic Dispatch

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Updated Primal Dual Dynamics

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\dot{p}_i &= k_{p_i}\left(\omega_i C_i'(p_i) + u_i\right) \\
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Control Law for Optimized PID

$$
u_i = -k_i[\lambda + \rho - \sigma - \Phi^t M_i] + k_d(p_i - \tilde{p}_i) - k_p \psi\left(\dot{\lambda}\right), \quad \forall i \tag{8}
$$

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Adding Pollutant Emission Cost

- Further extending optimization problem by incorporating pollutant emission cost minimization for CO_2.

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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Emission Cost

Pollutant emission cost, $E_i(p_i)$, follows quadratic cost [Jubril et al., 2014], [Kanchev et al., 2014] and is given by

$$\sum_i E_i(p_i) = \sum_i a_i p_i^2 + b_i p_i + c_i, \quad \forall i \tag{9}$$

where a, b and c are pollutant emission cost coefficients.

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Adding Reliability Cost $f_r(p_{pv})$ for PV Power

- Add a reliability cost component to the objective function.

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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- $f_r(p_{pv}) = 1 - Pr(p_{pv} < x)$, which effectively is a measure of at least obtaining power p_{pv} from the PV source.

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Reliability Cost of PV Power

$$f_r(p_{pv}) = \frac{e^{-a(p_{pv}-c)}}{1 + e^{-a(p_{pv}-c)}} \tag{10}$$

$a = 0.0259$ and $c = 129$

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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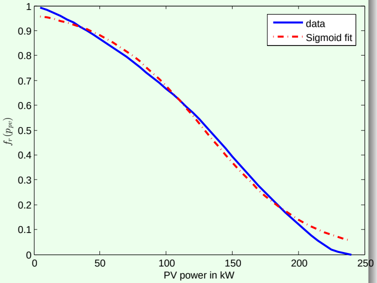
Sigmoid Fit



Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Re-visiting Multi-objective Optimization Problem Formulation

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Re-visiting Multi-objective Optimization Problem Formulation

Final Optimization Problem

$$\textbf{minimize} \sum_i \{\omega_i C_i(p_i) + \frac{1}{\omega_{re}} E_i(p_i)\} - \omega_{re} \log(f_r(p_{pv}))$$

subject to

$$\sum_i p_i + p_{pv} = L_d + L_{EV}$$

$$\sum_i p_i \geq L_d$$

$$p_{min} \leq p_i \leq p_{max}$$

$$\mathbf{Mp} + \delta \geq 0 \tag{11}$$

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p_{pv} is power output from PV panels.
L_{EV} is a distributed load due to charging electric vehicles.

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

System Parameters for Simulation

System Paramters

DG	Rating
DG1&DG2(MVA)	2.0& 1.5
DG3&DG4(MVA)	1.8&2.5
Load demand(MW)	1-4
Communication rate among DGs	250 kbps

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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Parameter	DG1	DG2	DG3	DG4
$\alpha \times 10^{-5}$	0.01	1.5	2.5	2
$\beta \times 10^{-3}$	5	2	2.5	4
γ	0.10	0.15	0.09	0.075
a	4.091	2.543	4.258	5.426
b	-5.554	-6.047	-5.094	-3.550
c	6.490	5.638	4.586	3.380

[J1]: Jameel Ahmad, Muhamamd Tahir and Sudip. K. Mazumder, "Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid" in IEEE Systems Journal, vol. 13, no. 1, pp. 802-812, March 2019.

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Case1:Consensus Among DGs for Optimal Power Generation

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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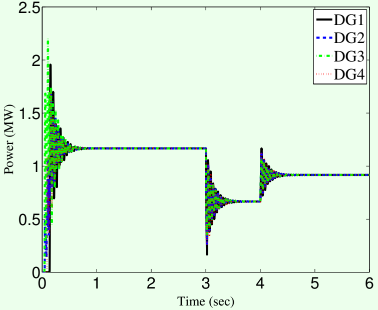
Consensus Condition: $\delta = 0$ in $\mathbf{Mp} + \delta \geq 0$

Conventional Control



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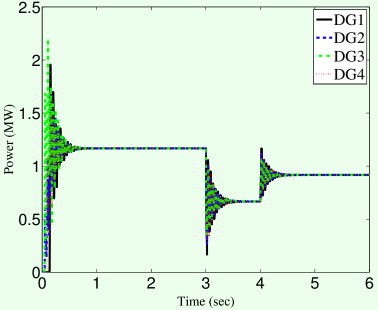
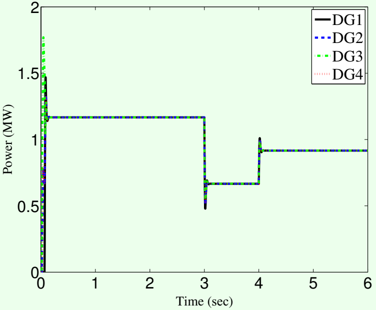
Consensus Condition: $\delta = 0$ in $\mathbf{Mp} + \delta \geq 0$

Conventional Control



Optimized PID control



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Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Case 2: Power Sharing and Response to Load Transient

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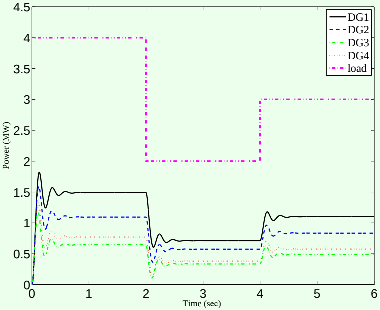
Conventional Control



Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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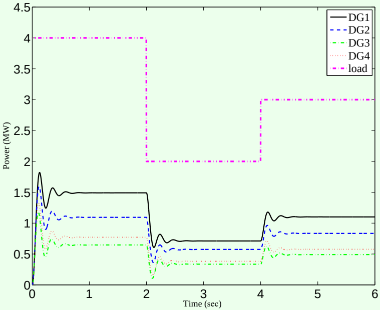

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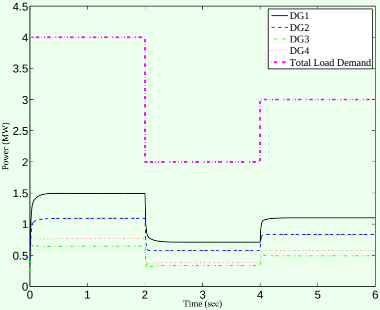

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Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Tuning Parameters

Optimized PID Controller Gains

Parameter	DG1	DG2	DG3	DG4
Without Generator Power Limits				
k_p	0.03	0.13	0.07	0.04
k_i	.03	.03	.03	.03
k_d	.2	.36	.4	.12
With Generator Power Limits				
k_p	0.015	0.065	0.035	0.02
k_i	1	1.5	2.5	1.5
k_d	.4	.72	0.8	0.4

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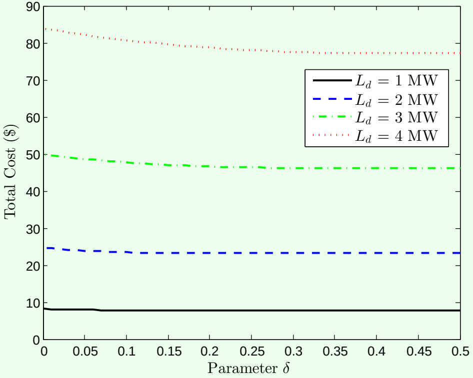
Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Case 3: Effect of δ on Minimizing Generation Cost for Different Loads

Parametric Graph between Generation Cost and δ



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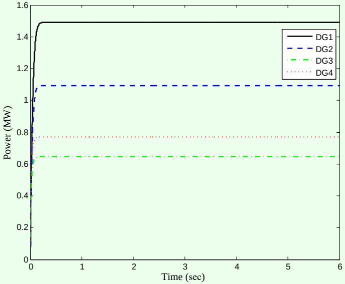
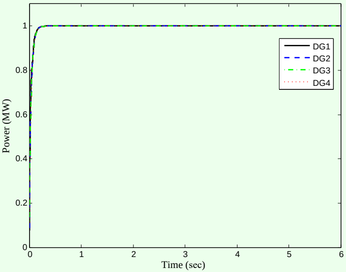
Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Case 4: Effect of δ Variation on Power Allocation to Different DGs

Proportional Power Sharing with $\delta = 0.8$



Equal Power Sharing with $\delta = 0.0$



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Case 5: Effect of Electric Vehicle Load on the Performance

PI Control with EV load

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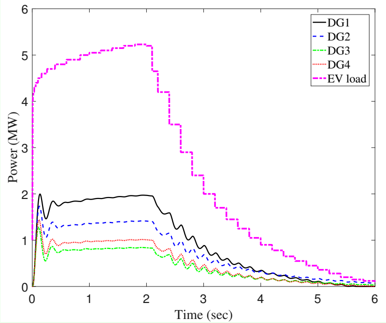

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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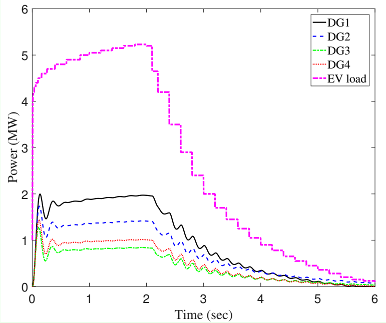

Optimized Control with EV load

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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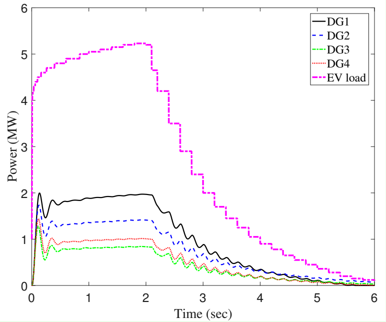

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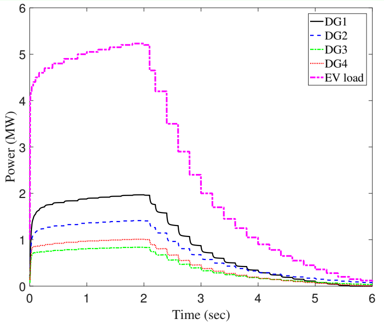

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Case 6: Effect of Pollutant Emission and PV Power Reliability

Emission Trade-off

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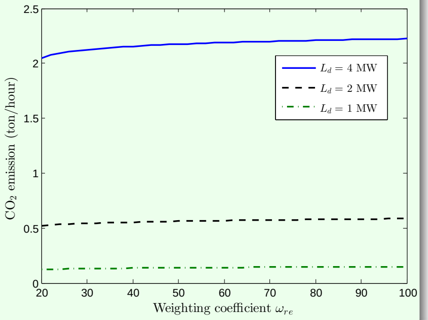

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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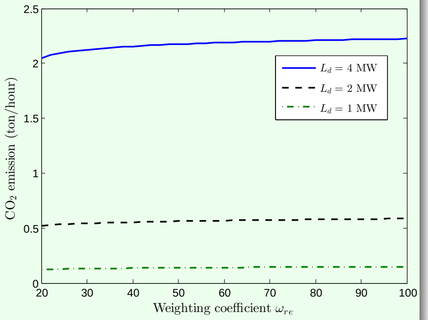

PV Power Trade-off

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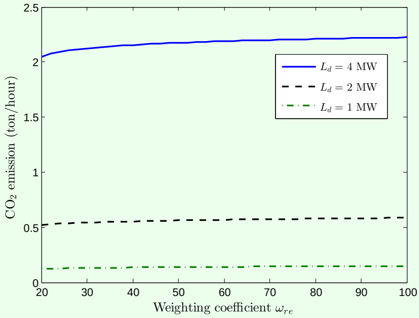

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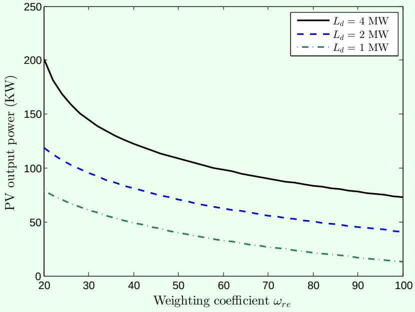

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Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

Case 7: Impact of Frequency-dependent and Voltage-dependent Loads An exponential load model with $k_{pv} = 1.7$ and $k_{pf} = 1$ [Zeineldin and Kirtley, 2009] with both voltage and frequency dependence.

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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$$L_d(E, w) = P_o \left(\frac{E}{E_o}\right)^{k_{pv}} \left(1 + k_{pf}\frac{w - w_o}{w_o}\right) \tag{12}$$

Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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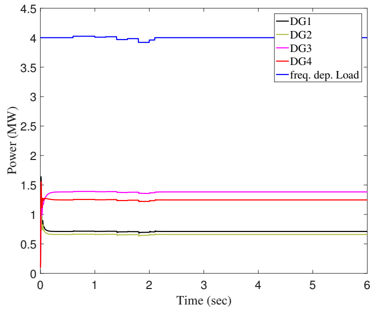
Frequency-dependent Load



Dynamic Economic Dispatch and Transient Control of Distributed Generators in a Microgrid

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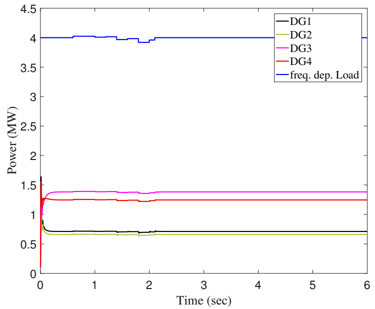
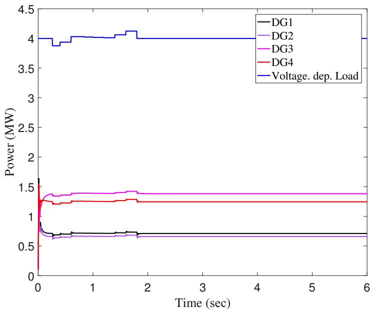
Frequency-dependent Load



Voltage-dependent Load



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Outline

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Multi-Microgrid Power System and Associated Challenges:

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Multi-Microgrid Power System and Associated Challenges:

- Optimal power sharing of DGs between multi-microgrids, control of load-side and generator-side transients, and economic-emission dispatch (EED).

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

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Existing solutions:

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Existing solutions: Control strategies for power sharing and ED fall short in providing good dynamic performance of multi-microgrids. Solutions are not scalable and too complicated.

Proposed solution:

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

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Proposed solution:

- A hierarchical distributed energy management of multi-microgrids with Energy Routing is proposed.

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Existing Work

- [Boroojeni et al., 2017, Harmon et al., 2017, Bedi et al., 2018, Han et al., 2018] cluster of microgrids or multi-microgrids (MMG) are used for distributed energy management.
- [Ahmad et al., 2018] uses Dynamic ED that can respond to fast fluctuations in the generation as well as load demand for single microgrid .
- [Li et al., 2018] and [Hossain et al., 2016] have provided a mechanism for interconnected microgrids to control energy flow among microgrids and ensure supply-demand balance.
- [Xu et al., 2018a] proposes a distributed multi-energy management framework of interconnected biogas-solar-wind microgrids, exchanges energy with interconnected MGs and via the transactive market.
- [Chen et al., 2017] provides Cost-based droop schemes for economic dispatch in islanded microgrids.
- **The above mentioned solution approaches suffer from limited dynamic performance of economic-emission dispatch of MMGs.**

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Proposed Multi-Microgrid (MMG) Architecture

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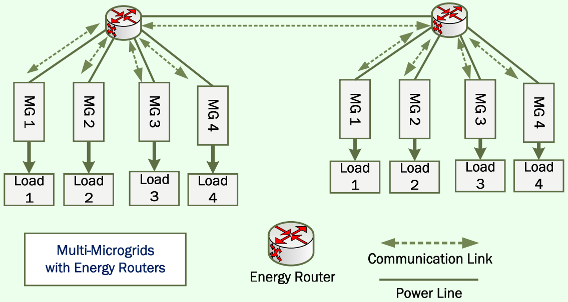
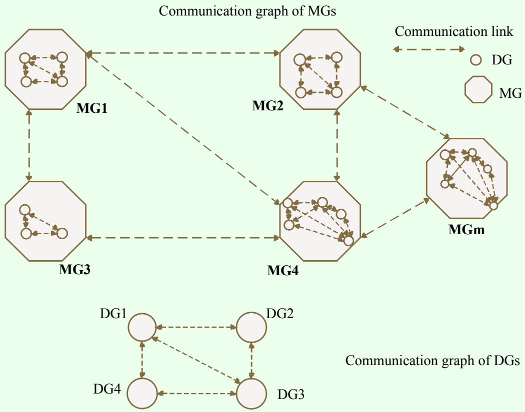


Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Agent Communication in Multi-Microgrids

Microgrids and Communication between DG Agents



Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Key contributions

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Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Defining Multi-Objective Cost Function for Multi-Microgrids

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Economic-Emission Cost of an MG

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Defining Multi-Objective Cost Function for Multi-Microgrids

Economic-Emission Cost of an MG

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Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

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Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

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Adding above two equations

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Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

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Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Additional Costs

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Additional Costs

$C_m(p_m^{(PV)})$: Cost Function for Lumped Intermittent PV Power [Zhang et al., 2017]

$$C_m(p_m^{(PV)}) = m_1 p_m^{(PV)} + \epsilon_m \exp(m_2 - p_m^{(PV)}) \quad \forall m, \tag{16}$$

where $m_1 > 0$, $m_2 > 0$ and $\epsilon_m > 0$. The first term denotes the direct operating cost while second term denotes the penalty on on curtailment of PV power generation.

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

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$B_m(p_m^{(B)}$: Operational Cost of Battery Energy Storage System (BESS) [Zheng et al., 2018]

$$\sum_m B_m(p_m^{(B)}) = \sum_m \eta_p p_m + \eta_c \left| p_m \right| + \eta_{loss} p_m^2, \quad \forall m \tag{17}$$

Storage Batteries are operational with reasonable depth of discharge (DOD).η_p and η_c are electricity price and battery cost parameter, and $\eta_l oss$ is the loss cost parameter.

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

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Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Additional Costs: The Cost of Power Exchange through Energy Router

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Additional Costs: The Cost of Power Exchange through Energy Router

Cost of Power Transfer, F from k^{th} MG to m^{th} MG

$$F = u_m p_{k,m}^2 \tag{18}$$

where u_m is cost coefficient for power transfer between MGs. $p_{k,m}$ is power flowing from k^{th} MG to m^{th} MG. The value of u_m is taken as 1.

- Cost of power exchange between MGs connected through energy router is modeled as a quadratic cost function.

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- The quadratic cost function enables the system to keep efficiency loss to minimum by reducing conversion losses incurred by the power converter.
- Line losses are reduced due to power flow between generators and loads that are far apart.

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Constrained Multi-Objective Optimization Problem for Multi-Microgrids

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Constrained Multi-Objective Optimization Problem for Multi-Microgrids

$$\textbf{minimize} \sum_{m}\sum_{i} D_i(p_{i,m}^{(G)}) + C_m(p_m^{(PV)}) + B_m(p_m^{(B)}) + \sum_{k} F_m(p_{k,m})$$

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

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subject to

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$$\textbf{subject to} \quad \mathbf{M_m p_m} + \delta_m \geq 0; \;\; p_{i,m}^{min} \leq p_{i,m}^{(G)} \leq p_{i,m}^{max}$$

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$$\textbf{subject to} \quad \mathbf{M_m p_m} + \delta_m \geq 0; \quad p_{i,m}^{min} \leq p_{i,m}^{(G)} \leq p_{i,m}^{max}$$

$$\sum_i p_{i,m}^{(G)} + p_m^{(PV)} + p_m^{(B)} + (\sum_k p_{k,m} - \sum_j p_{m,j}) = L_{dm} + L_{dm}^{(EV)} \tag{19}$$

- $p_{i,m}^{(G)}$: Power generated by i^{th} DG in m^{th} MG; $p_m^{(PV)}$ and $p_m^{(B)}$: PV Power and Battery Power from m^{th} MG

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- $p_{i,m}^{(G)}$: Power generated by i^{th} DG in m^{th} MG; $p_m^{(PV)}$ and $p_m^{(B)}$: PV Power and Battery Power from m^{th} MG
- $p_{k,m}$: Power flowing from k^{th} MG to m^{th} MG and governed by energy router,

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Constrained Multi-Objective Optimization Problem for Multi-Microgrids

$$\textbf{minimize} \sum_m \sum_i D_i(p_{i,m}^{(G)}) + C_m(p_m^{(PV)}) + B_m(p_m^{(B)}) + \sum_k F_m(p_{k,m})$$

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- $L_{dm} + L_{dm}^{(EV)}$: Total load as sum of conventional load, L_{dm} and distributed electric vehicle charging load, $L_{dm}^{(EV)}$ in m^{th} MG,

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

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$$\textbf{minimize} \sum_m \sum_i D_i(p_{i,m}^{(G)}) + C_m(p_m^{(PV)}) + B_m(p_m^{(B)}) + \sum_k F_m(p_{k,m})$$

$$\textbf{subject to} \quad \mathbf{M_m p_m} + \delta_m \geq 0; \quad p_{i,m}^{min} \leq p_{i,m}^{(G)} \leq p_{i,m}^{max}$$

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- $p_{i,m}^{(G)}$: Power generated by i^{th} DG in m^{th} MG; $p_m^{(PV)}$ and $p_m^{(B)}$: PV Power and Battery Power from m^{th} MG
- $p_{k,m}$: Power flowing from k^{th} MG to m^{th} MG and governed by energy router,
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- $\sum_k p_{k,m} - \sum_j p_{m,j}$: Difference of total power received by m^{th} MG from k MGs and total power delivered by m^{th} MG to j MGs

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Constrained Multi-Objective Optimization Problem for Multi-Microgrids

$$\textbf{minimize} \sum_m \sum_i D_i(p_{i,m}^{(G)}) + C_m(p_m^{(PV)}) + B_m(p_m^{(B)}) + \sum_k F_m(p_{k,m})$$

$$\textbf{subject to} \quad \mathbf{M_m p_m} + \delta_m \geq 0; \quad p_{i,m}^{min} \leq p_{i,m}^{(G)} \leq p_{i,m}^{max}$$

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- $\sum_k p_{k,m} - \sum_j p_{m,j}$: Difference of total power received by m^{th} MG from k MGs and total power delivered by m^{th} MG to j MGs

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Partial Lagrangian $\mathcal{L}_a$ Formulation for Multi-Microgrids

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Partial Lagrangian $\pounds_a$ Formulation for Multi-Microgrids

Partial Lagrange Function

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Partial Lagrangian $\pounds_a$ Formulation for Multi-Microgrids

Partial Lagrange Function

$$
\begin{aligned}
\textbf{minimize}\ \Big(\pounds_a(\mathbf{p}^{(\mathbf{G})}_{\mathbf{i,m}}, \mathbf{p}_{\mathbf{k,m}}, \mathbf{p}^{(\mathbf{PV})}_{\mathbf{m}}, \mathbf{p}^{(\mathbf{B})}_{\mathbf{m}}, \lambda)\Big) = \\
\sum_m \Big\{ \sum_i D_i(p^{(G)}_{i,m}) + B_m(p^{(B)}_m) + C_m(p^{(PV)}_m) + \sum_k F_m(p_{k,m}) \Big\} \\
+ \sum_m \lambda_m \Big\{ L_{dm} + L^{(EV)}_{dm} - \sum_i p^{(G)}_{i,m} - p^{(PV)}_m - p^{(B)}_m \\
-(\sum_k p_{k,m} - \sum_j p_{m,j}) \Big\} \\
\textbf{subject to} \quad \mathbf{M_m p_m} + \delta_m \geq 0, \\
p^{min}_{i,m} \leq p^{(G)}_{i,m} \leq p^{max}_{i,m}
\end{aligned} \qquad (20)
$$

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Decomposition of Lagrangian $\mathcal{L}_a$ into Sub problems Augmented Lagrangian $\mathcal{L}_a$ can be decomposed into two sub-problems which can be solved independently.

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Decomposition of Lagrangian $\mathcal{L}_a$ into Sub problems Augmented Lagrangian $\mathcal{L}_a$ can be decomposed into two sub-problems which can be solved independently.

Microgrid Sub-problem

$$\text{min} \sum_i D_i(p_{i,m}^{(G)}) + B_m(p_m^{(B)}) + C_m(p_m^{(PV)})$$

$$\lambda_m \left\{ L_{dm} + L_{dm}^{(EV)} - \sum_i p_{i,m}^{(G)} - p_m^{(PV)} - p_m^{(B)} \right\}$$

$$\text{subject to} \quad \mathbf{M_m p_m} + \delta_m \geq 0,$$

$$p_{i,m}^{min} \leq p_{i,m}^{(G)} \leq p_{i,m}^{max} \tag{21}$$

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Decomposition of Lagrangian $\mathcal{L}_a$ into Sub problems Augmented Lagrangian $\mathcal{L}_a$ can be decomposed into two sub-problems which can be solved independently.

Microgrid Sub-problem

$$\begin{aligned} \textbf{min} \sum_i D_i(p_{i,m}^{(G)}) + B_m(p_m^{(B)}) + C_m(p_m^{(PV)}) \\ \lambda_m \Big\{ L_{dm} + L_{dm}^{(EV)} - \sum_i p_{i,m}^{(G)} - p_m^{(PV)} - p_m^{(B)} \Big\} \\ \textbf{subject to} \quad \mathbf{M_m p_m} + \delta_m \geq 0, \\ p_{i,m}^{min} \leq p_{i,m}^{(G)} \leq p_{i,m}^{max} \end{aligned} \tag{21}$$

Energy Router Sub-problem

$$\textbf{minimize} \quad F_m(p_{k,m}) - \lambda_m \Big\{ \sum_k p_{k,m} - \sum_j p_{m,j} \Big\} \tag{22}$$

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Decomposition of Lagrangian $\pounds_a$ into Sub problems Augmented Lagrangian $\pounds_a$ can be decomposed into two sub-problems which can be solved independently.

Microgrid Sub-problem

$$\textbf{min} \sum_i D_i(p_{i,m}^{(G)}) + B_m(p_m^{(B)}) + C_m(p_m^{(PV)})$$
$$\lambda_m \Big\{ L_{dm} + L_{dm}^{(EV)} - \sum_i p_{i,m}^{(G)} - p_m^{(PV)} - p_m^{(B)} \Big\}$$
$$\textbf{subject to} \quad \mathbf{M_m p_m} + \delta_m \geq 0,$$
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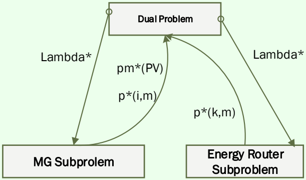
Energy Router Sub-problem

$$\textbf{minimize} \quad F_m(p_{k,m}) - \lambda_m \Big\{ \sum_k p_{k,m} - \sum_j p_{m,j} \Big\} \tag{22}$$

Dual Problem

$$\textbf{max} \quad g(\lambda) = \pounds(\mathbf{p_{i,m}^{*(G)}}, \mathbf{p_{k,m}^{*}}, \mathbf{p_{m}^{*(PV)}}, \mathbf{p_{m}^{*(B)}}, \lambda) \tag{23}$$

Dual Decomposition



Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Dual Problem Formulation for m_{th} Microgrid

$$
\begin{aligned}
\pounds_c(\mathbf{p}, \mathbf{p_m^{(PV)}}, \mathbf{p_m^{(B)}} \lambda, \Phi, \tilde{\mathbf{p}}) = \\
\sum_i (D_i(p_i)) + C_m(p_m^{(PV)}) + B_m(p_m^{(B)}) \\
+k_1^{(i)} \lambda (L_d + L_d^{(EV)} - \sum_i p_i - p_m^{(PV)}) - p_m^{(B)}) + \Phi^t [\mathbf{Mp} + \delta] \\
+\frac{k_2^{(i)}}{2} \sum_i (p_i - \tilde{p}_i)^2 + \frac{k_3^{(i)}}{2} (L_d + L_d^{(EV)} - \sum_i p_i - p_m^{(PV)} - p_m^{(B)})^2
\end{aligned}
$$

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Update Equations Based on Gradient Descent-Ascent Primal-Dual Dynamics

- The solution to the optimal control problem is an iterative procedure.

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Update Equations Based on Gradient Descent-Ascent Primal-Dual Dynamics

- The solution to the optimal control problem is an iterative procedure.
- $\forall k \in \{1, ..., T\}$

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Update Equations Based on Gradient Descent-Ascent Primal-Dual Dynamics

- The solution to the optimal control problem is an iterative procedure.
- $\forall k \in \{1, ..., T\}$

Dynamics Update Equations

$$\boxed{\begin{aligned}
p_i^{k+1} &= p_i^k + k_{p_i}\left(D_i'(p_i^k) + u_i^k\right), \quad \forall i \\
p_{PV}^{k+1} &= p_{PV}^k + k_{p_{PV}} C_m'(p_{PV}^k) \\
p_B^{k+1} &= p_B^k + k_{p_B} B_m'(p_B^k) \\
\tilde{p}_i^{k+1} &= \tilde{p}_i^k + \tilde{k}_{p_i}(p_i^k - \tilde{p}_i^k), \quad \forall i \\
\lambda_i^{k+1} &= \lambda_i^k + k_{\lambda_i}\left\{L_d + L_d^{(EV)} - \sum_i p_i^k - p_{PV}^k - p_B^k\right\}^+, \forall i \\
\phi_i^{k+1} &= \phi_i^k + k_{\phi_i}\left\{[\mathbf{M}\mathbf{p}^{\mathbf{k}}]_i + \delta_i\right\}^+, \quad \forall i
\end{aligned}} \tag{24}$$

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Update Equations Based on Gradient Descent-Ascent Primal-Dual Dynamics

- The solution to the optimal control problem is an iterative procedure.
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Dynamics Update Equations

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p_B^{k+1} &= p_B^k + k_{p_B} B_m'(p_B^k) \\
\tilde{p}_i^{k+1} &= \tilde{p}_i^k + \tilde{k}_{p_i}(p_i^k - \tilde{p}_i^k), \quad \forall i \\
\lambda_i^{k+1} &= \lambda_i^k + k_{\lambda_i}\left\{L_d + L_d^{(EV)} - \sum_i p_i^k - p_{PV}^k - p_B^k\right\}^+, \forall i \\
\phi_i^{k+1} &= \phi_i^k + k_{\phi_i}\left\{[\mathbf{M}\mathbf{p}^{\mathbf{k}}]_i + \delta_i\right\}^+, \quad \forall i
\end{aligned}} \tag{24}$$

Control law u_i^{k+1}

$$\boxed{u_i^{k+1} = u_i^k - k_1^{(i)}[\lambda^k - (\Phi^t)^k M_i] + k_2^{(i)}(p_i^k - \tilde{p}_i^k) - k_3^{(i)}\psi(\lambda^k), \quad \forall i} \tag{25}$$

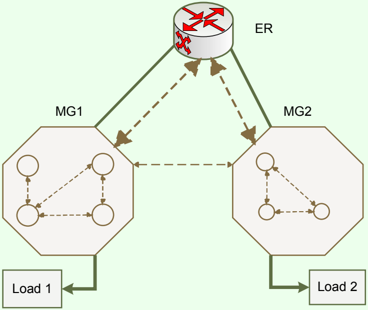
Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Test Case: Power and Communication Framework for Two Microgrids

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Test Case: Power and Communication Framework for Two Microgrids

Inter-Microgrid Communication through Agents

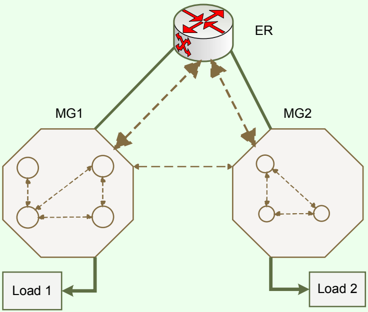


Communication between DGs

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Test Case: Power and Communication Framework for Two Microgrids

Inter-Microgrid Communication through Agents



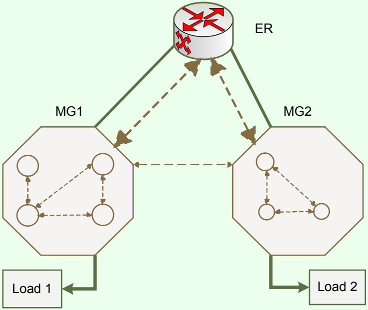
Communication between DGs

Laplacian Matrices for Two Microgrids

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Test Case: Power and Communication Framework for Two Microgrids

Inter-Microgrid Communication through Agents

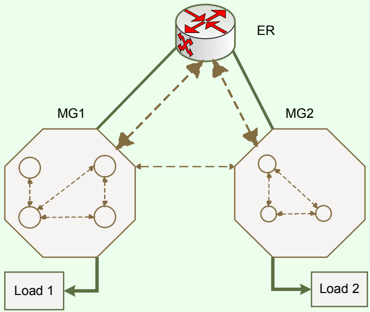


Communication between DGs

Laplacian Matrices for Two Microgrids

Test Case: Power and Communication Framework for Two Microgrids

Inter-Microgrid Communication through Agents



Communication between DGs

Laplacian Matrices for Two Microgrids

- The Laplacian matrix is responsible for connectivity among DGs.

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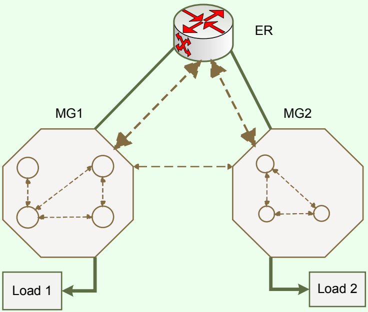
Test Case: Power and Communication Framework for Two Microgrids

Inter-Microgrid Communication through Agents



Communication between DGs

Laplacian Matrices for Two Microgrids

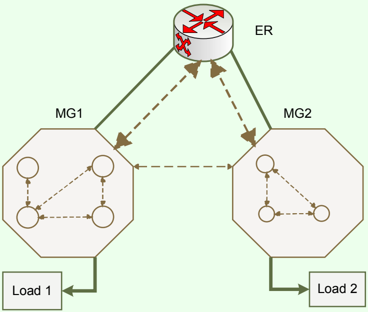
- The Laplacian matrix is responsible for connectivity among DGs.
- M_1=Laplacian matrix of DGs in MG1

$$M_1 = \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 3 & -1 & -1 \\ 0 & -1 & 2 & -1 \\ 0 & -1 & -1 & 2 \end{bmatrix}. \quad (26)$$

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Test Case: Power and Communication Framework for Two Microgrids

Inter-Microgrid Communication through Agents



Communication between DGs

Laplacian Matrices for Two Microgrids

- The Laplacian matrix is responsible for connectivity among DGs.
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$$M_1 = \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 3 & -1 & -1 \\ 0 & -1 & 2 & -1 \\ 0 & -1 & -1 & 2 \end{bmatrix}. \tag{26}$$

- M_2=Laplacian matrix of DGs in MG2

$$M_2 = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}. \tag{27}$$

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Generation and Emission Cost Coefficients for Two Microgrids

Simulation Parameters

	Parameter.	DG1	DG2	DG3	DG4
MG1	α	1×10^{-5}	1.5×10^{-5}	2.5×10^{-5}	2×10^{-5}
	β	5×10^{-3}	2×10^{-3}	2.5×10^{-3}	4×10^{-3}
	γ	0.10	0.15	0.09	0.075
	a	4.091×10^{-3}	2.543×10^{-3}	4.258×10^{-3}	5.426×10^{-3}
	b	-5.554×10^{-3}	-6.047×10^{-3}	-5.094×10^{-3}	-3.550×10^{-3}
	c	6.490×10^{-3}	5.638×10^{-3}	4.586×10^{-3}	3.380×10^{-3}
	Max Power (MW)	2.0	1.5	1.8	2.5
	Max PV Power (MW)	1			
	Load Demand (MW)	$1-4$			
	EV Load (kW)	500			
MG2	α	1.5×10^{-5}	2.5×10^{-5}	2×10^{-5}	
	β	1.8×10^{-3}	2.4×10^{-3}	4×10^{-3}	
	γ	0.120	0.080	0.075	
	a	2.543×10^{-3}	4.258×10^{-3}	5.426×10^{-3}	
	b	-6.047×10^{-3}	-5.094×10^{-3}	-3.550×10^{-3}	
	c	5.638×10^{-3}	4.586×10^{-3}	3.380×10^{-3}	
	Max Power (MW)	1.6	1.5	1.9	
	Max PV Power (MW)	1			
	Load Demand (MW)	$1-4$			
	EV Load (kW)	400			

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Dynamic Gains and BESS Parameters

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Dynamic Gains and BESS Parameters

Gain values for DPC

Parameter	DG1	DG2	DG3	DG4
$k_3^{(i)}$	0.006	.006	0.008	0.008
$k_2^{(i)}$	.01	.01	.01	.01
$k_1^{(i)}$	.1	.18	.2	.06

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Dynamic Gains and BESS Parameters

Gain values for DPC

Parameter	DG1	DG2	DG3	DG4
$k_3^{(i)}$	0.006	.006	0.008	0.008
$k_2^{(i)}$	.01	.01	.01	.01
$k_1^{(i)}$	.1	.18	.2	.06

BESS Parameters

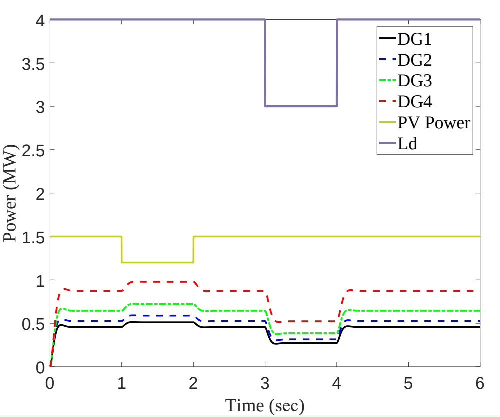
BESS	η_p	η_c	η_{loss}	Min. output(kW)	Max. output(kW)
1	0.15	.01	0.1	-50	50
2	.2	.01	.12	-50	50
3	.3	.0.01	.1	-50	50

[J2]: Jameel Ahmad, Muhamamd Tahir and Sudip. K. Mazumder, "Improved Dynamic Performance and Hierarchical Energy Management of Microgrids with Energy Routing" in IEEE Transactions on Industrial Informatics. Oct 24, 2018.

Improved Dynamic Performance and Hierarchical Distributed Energy Management of Multi-Microgrids with Energy Routing

Case 1: Effect of Load and PV Power Transients on DG powers

PV Power Transient and Load Transient



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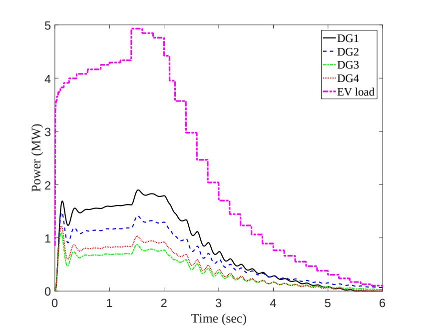
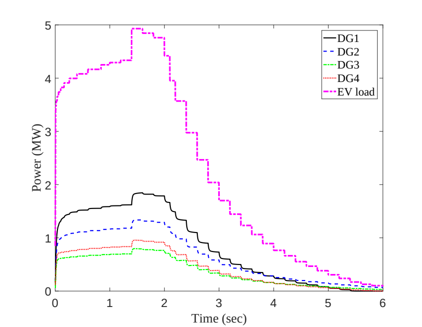
Case 2: PI and Optimized DPC Performance with Time-varying EV Load

(a) PI Control

(b) Optimized DPC

Performance with Time-varying EV Load





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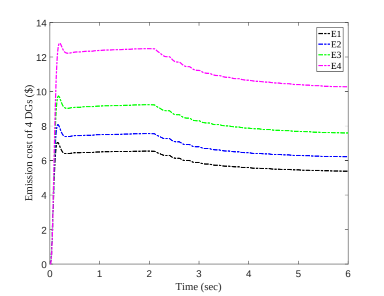
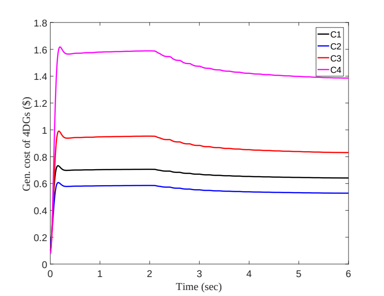
Case 3:Emission & Generation Cost Adaptation with EV load

(a)Emission Cost

(b) Thermal Generator Cost

Emission and Generation Cost





[J2]: Jameel Ahmad, Muhamamd Tahir and Sudip. K. Mazumder, "Improved Dynamic Performance and Hierarchical Energy Management of Microgrids with Energy Routing" in IEEE Transactions on Industrial Informatics. Oct 24, 2018.

Case 4: Power Exchange between Two Microgrids(MGs)

MG1 and MG2 DG Power Variation

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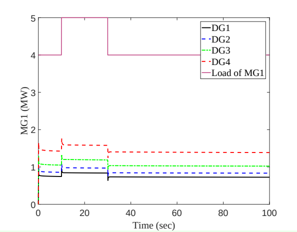

MG1 DGs Powers

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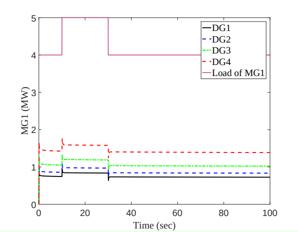
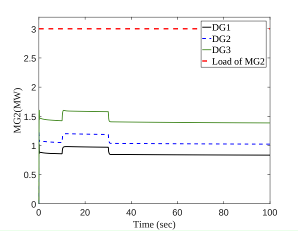


MG1 DGs Powers



MG2 DGs Powers

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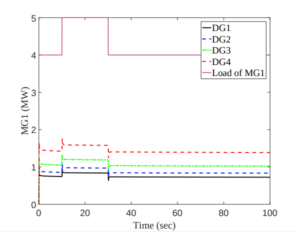

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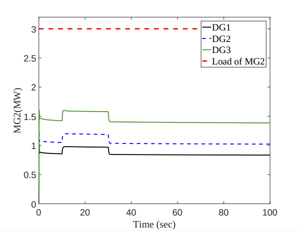

MG2 DGs Powers

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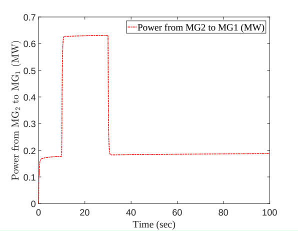

Power Sharing between MGs

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Case 5: Plug and play (PnP) Capability Verification of Microgrids

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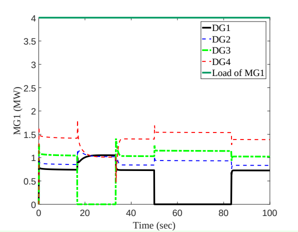

MG1 DGs with PnP

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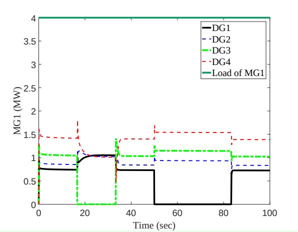

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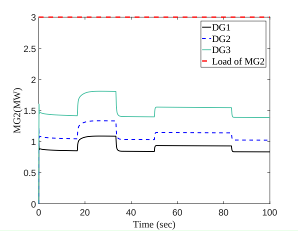

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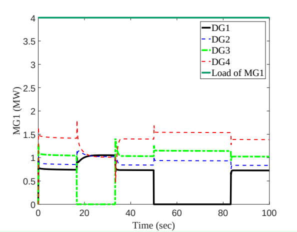

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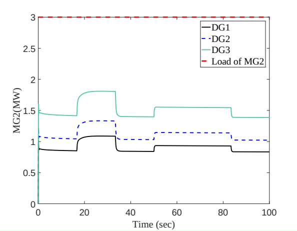

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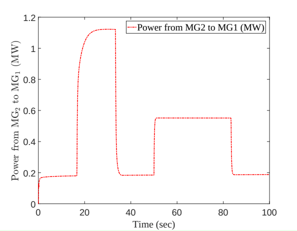
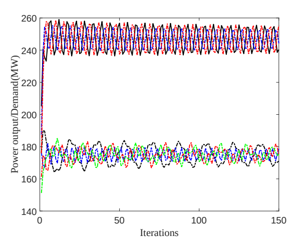


Power Sharing during PnP

[J2]: Jameel Ahmad, Muhamamd Tahir and Sudip. K. Mazumder, "Improved Dynamic Performance and Hierarchical Energy Management of Microgrids with Energy Routing" in IEEE Transactions on Industrial Informatics. Oct 24, 2018.

Case 6: Comparison with ADMM [Zhang et al., 2017] Power output/demand

DG Powers in [Zhang et al., 2017]



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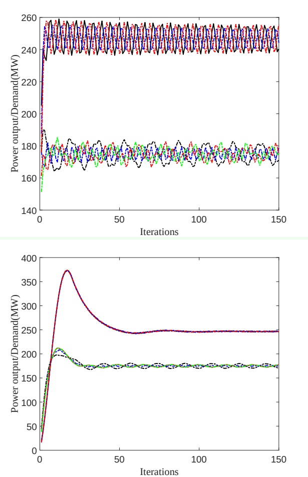

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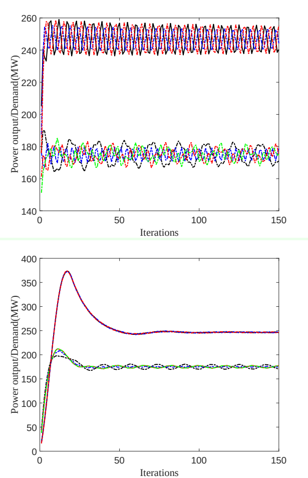

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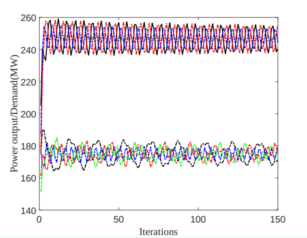
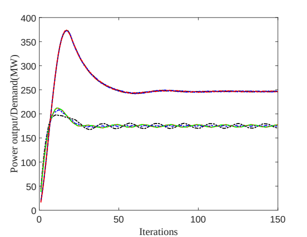
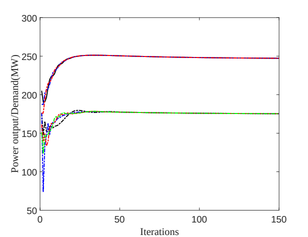




DG Powers using proposed DPC Control



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Outline

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Challenges:

- Microgrid's network communication infrastructure is implemented through wireless system and controls using micro-processors/DSPs with limited bandwidth, energy resources and computing capability.

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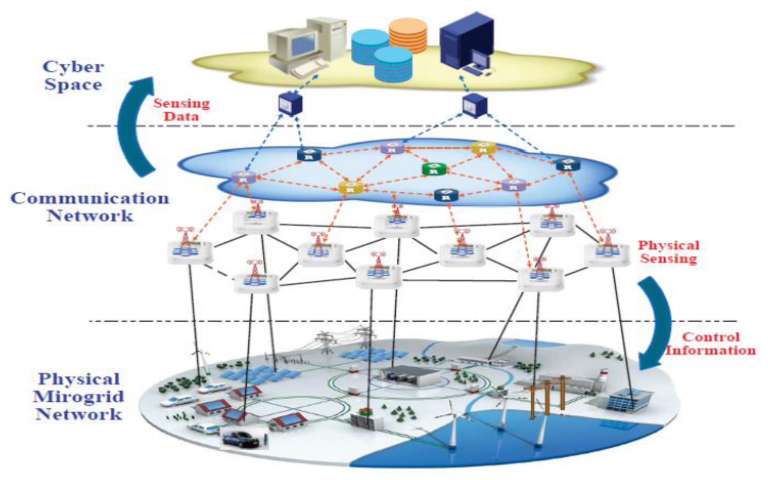
Cyber-Physical Interface in a Microgrid



Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Time-triggered vs. Event-Triggered Control

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Time-triggered vs. Event-Triggered Control Networked control and Cyber-physical systems: Recent developments in computer and communication technologies are leading to an increasingly networked and wireless world.

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ETC and STC can thus be seen as control strategies introducing feedback in the sensing, communication, and actuation processes.

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Existing Work

- [Tallapragada and Chopra, 2014]: Proposed decentralized event-triggers for control of nonlinear systems.
- [Thomas et al., 2016]: Proposed distributed dynamic consensus for economic dispatch of DC microgrids[Zaery et al., 2015] and reduced communication.
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Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Motivation for Self-Triggered Control

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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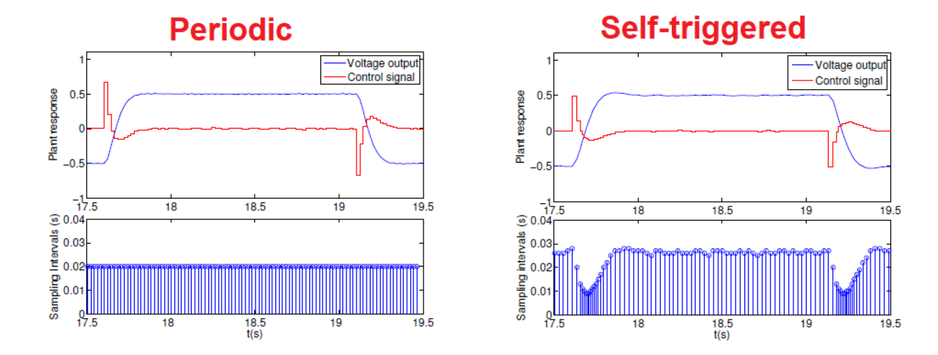
Self-triggered control (STC): (STC) is proactive as at an event-time the next event-time is precomputed based on current state or output information of the plant.

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

An example: Periodic vs Self-triggered Voltage Control



A. Camacho et al., "Self-triggered networked control systems: An experimental case study," 2010 IEEE International Conference on Industrial Technology, Vina del Mar, 2010, pp. 123-128.

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Periodic vs. Event-triggered vs. Self-triggered control

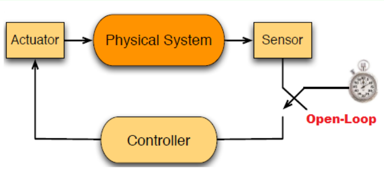
Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Periodic vs. Event-triggered vs. Self-triggered control

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Periodic vs. Event-triggered vs. Self-triggered control

Periodic Control



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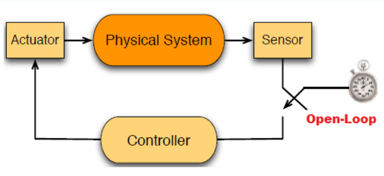
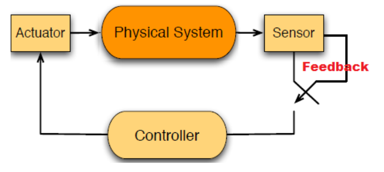


Event-Triggered Control



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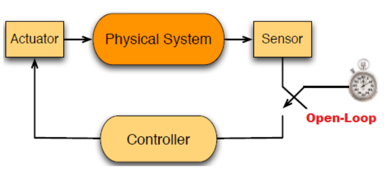

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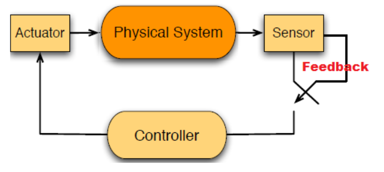
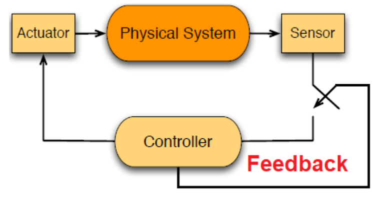


Self-triggered Control



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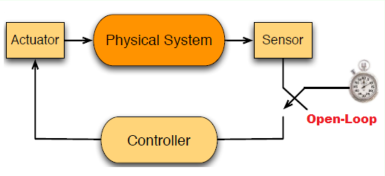

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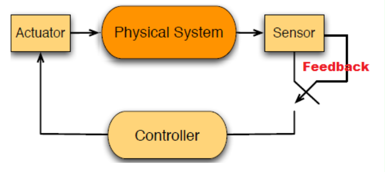

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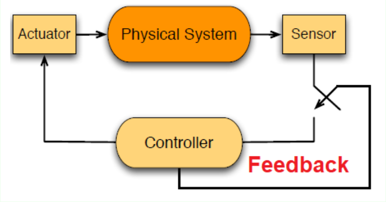

Self-Triggered Data Sampling

- In self-triggered control, the current state is used to compute the input to controller and also the next time for control law.

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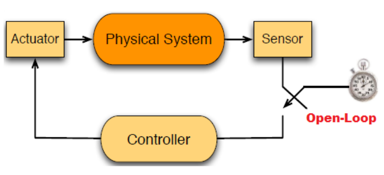

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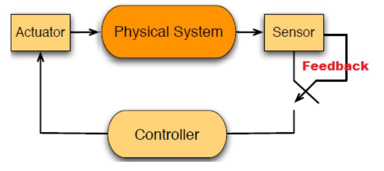

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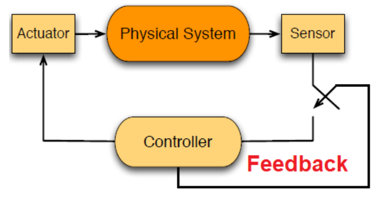

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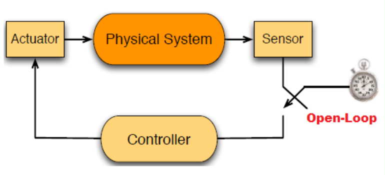
Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Periodic vs. Event-triggered vs. Self-triggered control

Periodic Control



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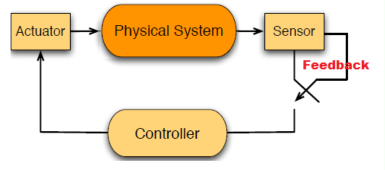

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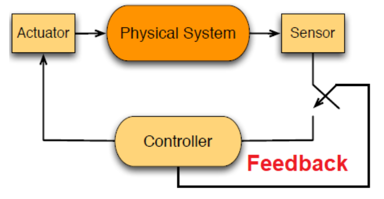

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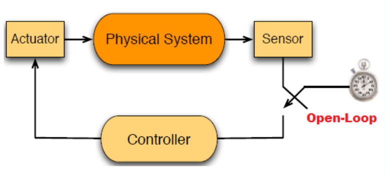
- Event-triggered control continuously monitors the state and gives input to controller when an event occurs.
- Aperiodic information exchange results in variable sampling rate with reduced transmission bandwidth.

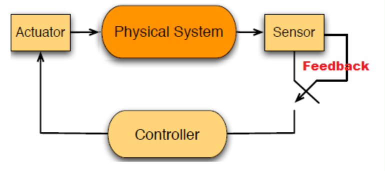
Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Periodic vs. Event-triggered vs. Self-triggered control

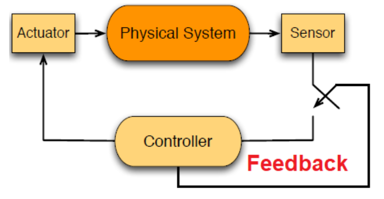
Periodic Control



Event-Triggered Control



Self-triggered Control



Self-Triggered Data Sampling

- In self-triggered control, the current state is used to compute the input to controller and also the next time for control law.
- Event-triggered control continuously monitors the state and gives input to controller when an event occurs.
- Aperiodic information exchange results in variable sampling rate with reduced transmission bandwidth.

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Microgrid and Communication Graph of DGs

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Microgrid and Communication Graph of DGs

Microgrid Under Consideration

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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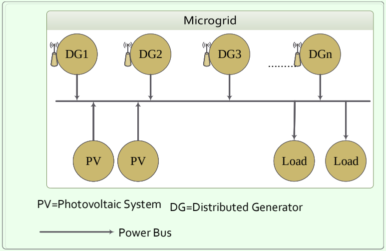

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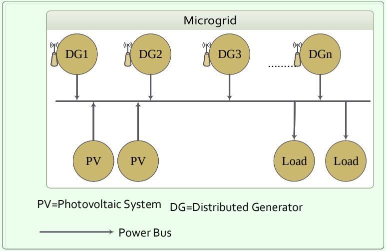

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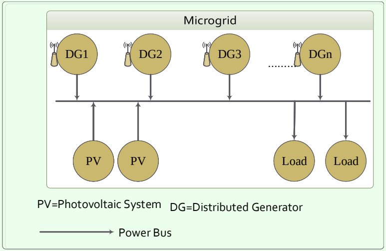
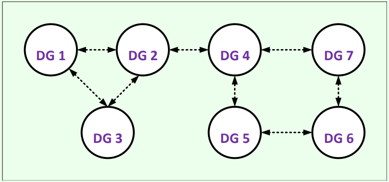


Connectivity Graph of 7 DGs



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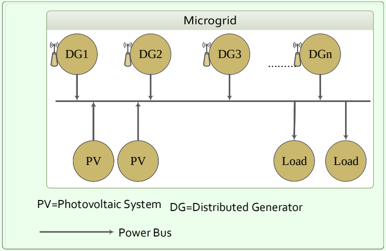

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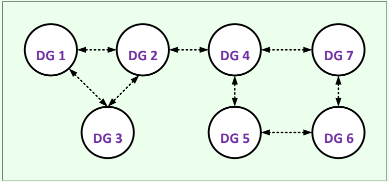

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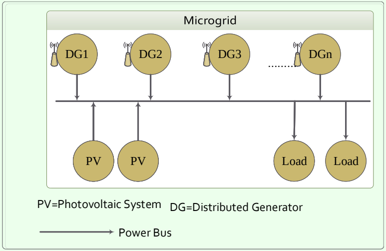
Microgrid Under Consideration



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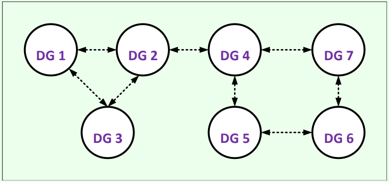

Laplacian Matrix for 7 DGs

$$M = \begin{bmatrix} 2 & -1 & -1 & 0 & 0 & 0 & 0 \\ -1 & 3 & -1 & -1 & 0 & 0 & 0 \\ -1 & -1 & 2 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 4 & -1 & -1 & -1 \\ 0 & 0 & 0 & -1 & 2 & -1 & 0 \\ 0 & 0 & 0 & -1 & -1 & 3 & -1 \\ 0 & 0 & 0 & -1 & 0 & -1 & 2 \end{bmatrix}. \quad (28)$$

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Non-linear Optimization Problem Formulation

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Non-linear Optimization Problem Formulation

Optimization Problem

$$\textbf{min} \sum_i F_i(p_i) + T(p^{(PV)})$$

Subject to

$$\sum_i p_i + p^{(PV)} = L_d + L_d^{(EV)},$$

$$\mathbf{Mp} + \delta \geq 0,$$

$$p_i^{min} \leq p_i \leq p_i^{max} \quad (29)$$

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PV Cost Model

$$T(p^{(PV)}) = m_1 p^{(PV)} + \epsilon_m \exp(m_2 - p^{(PV)}) \quad (30)$$

where $m_1 = 0.9$, $m_2 = 1.7$, $\epsilon_m = 108$.

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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Non-linear Economic-Emission Cost Model

$$\sum_i F_i(p_i) = \sum_i A_i p_i^2 + B_i p_i + C_i + \zeta \exp(\eta p_i), \ \ \forall i, \quad (31)$$

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Non-linear System Dynamic Equations

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Non-linear System Dynamic Equations

Power Dynamics

$$\dot{p} = \frac{\partial F}{\partial p} \qquad \dot{p}_i = k_{p_i}\left(F_i'(p_i) + u_i\right), \quad \forall i$$

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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Continuous-time Non-Linear Dynamic Power Equations for Distributed Generators

$\dot{p}_i = 2A_i p_i + B_i + \zeta_i \eta_i \exp(\eta_i p_i) + u_i, \quad \forall i$

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Non-linear System Dynamics

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Non-linear System Dynamics

Continuous-time Nonlinear System Model

$$\dot{p} = f(p, k(p)) = f(p, u) \tag{32}$$

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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- where p is a state vector and u is an input vector

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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  $\|f(p, k(p(t)) - f(p, k(p(k))\| \leq \mathbf{L}\|(k(p(t) - k(p(k))\|$

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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Discrete-time Nonlinear System Model

$$\dot{p} = f(p, k(p_k)) \tag{33}$$

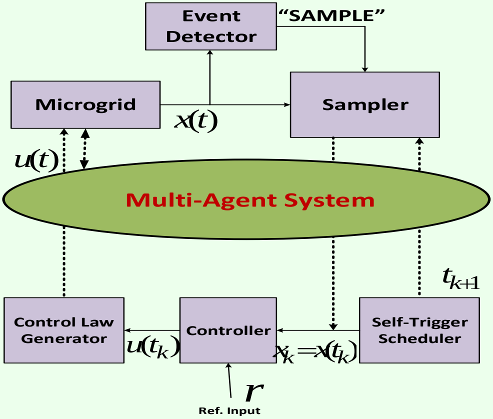
Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Proposed Self-Triggered Data Sampler

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Proposed Self-Triggered Data Sampler

Self-Triggered Data Sampler



Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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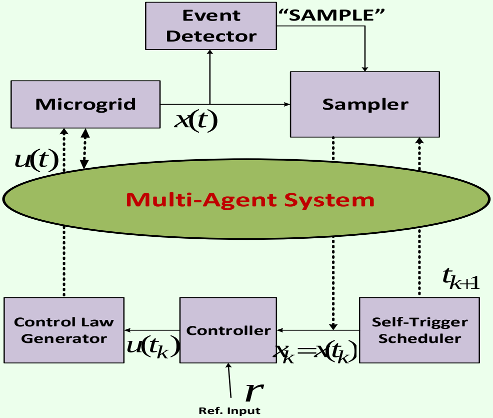
Self-Triggered Data Sampler



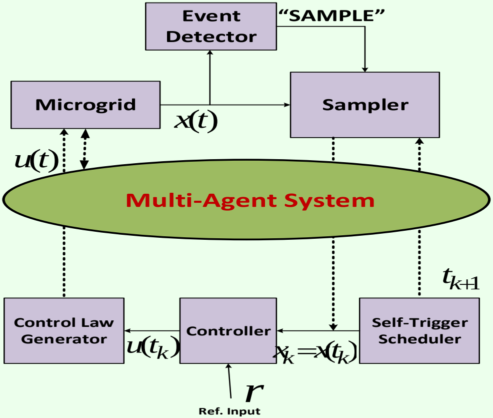
Self-Triggered Action

- Event detector continuously monitors system states.

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Proposed Self-Triggered Data Sampler

Self-Triggered Data Sampler



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Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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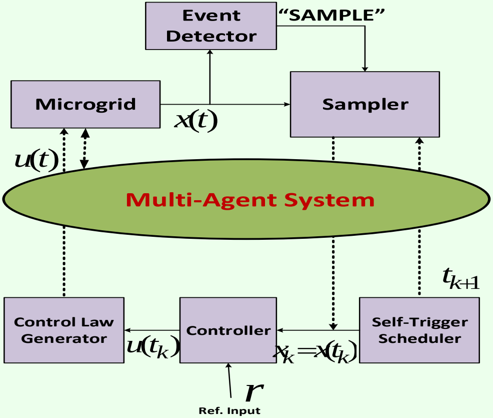

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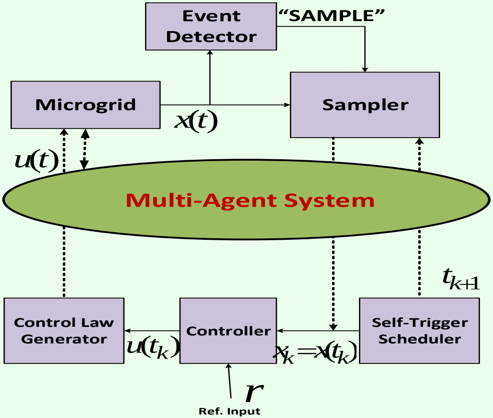
Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Proposed Self-Triggered Data Sampler

Self-Triggered Data Sampler



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- Event detector continuously monitors system states.
- A sampling event is triggered when the sampler receives a "sample" message.
- A self-triggered sampling event is triggered when $t = t_{k+1}$. This time stamp is provided by self-triggered scheduler.
- The state and control law are represented by $x(t) = p(t)$ and $u(t)$ respectively.

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Self-Trigger Condition

- Design a self-triggered sampler such that system $\dot{p} = f(p, k(p_k))$ is Ultimately Uniformly Bounded (UUB).

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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Sampling Time

$$t_{k+1} = t_k + \beta_s(p(t_k)) \tag{34}$$

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- Then origin of the closed loop system with state feedback control principle u is asymptotically stable over the set K_k. Ensure $t_{k+1} - t_k \geq 0$ for k.

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Trigger Condition

The control signal is updated whenever it hits a threshold γ such that the Euclidean norm of $E(t)$ is

$$\|E(t)\| := \|f(p(t), k(p_k)) - f(p(t), k(p(t)))\| \leq \gamma, \gamma > 0 \tag{35}$$

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Self-Trigger Condition-Contd.

Self-Trigger Condition

$$\boxed{\begin{aligned} u(s) &= k(p(s)); && (36)\\ E(s) &= f(p(t), u(t_k)) - f(p(t), u(s)); && (37)\\ \varphi(p(t), u(s)) := \frac{d}{ds}E(s) &= -\frac{d}{ds}f(p(t), u(s)); && (38)\\ E(s_k) &= 0 && (39)\end{aligned}}$$

$$\boxed{\begin{aligned} t_{k+1} &= t_k + \beta_s(p(t_k)); && (40)\\ \beta_s(p(t_k)) &= \frac{1}{L_{\varphi,u}} \ln(1 + \frac{\gamma L_\varphi(p,u)}{\|\varphi(p^*, k(p_k)\|}); && (41)\\ t_{k+1} &= t_k + \frac{1}{L_{\varphi,u}} \ln(1 + \frac{\gamma L_\varphi(p,u)}{\|\varphi(p^*, k(p_k)\|}) && (42)\end{aligned}}$$

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

DGs and Simulation Parameters

Parameter	DG1	DG2	DG3	DG4	DG5	DG6	DG7
$\alpha \times 10^{-5}$	1	1.5	2.5	2	1.5	2.5	2
$\beta \times 10^{-3}$	5	2	2.5	4	2	2.5	4
χ	0.10	0.15	0.09	0.075	0.15	0.09	0.075
$a \times 10^{-3}$	4.091	2.543	4.258	5.426	2.543	4.258	5.426
$b \times 10^{-3}$	-5.554	-6.047	-5.094	-3.550	-6.047	-5.094	-3.550
$c \times 10^{-3}$	6.490	5.638	4.586	3.380	5.638	4.586	3.380
K_p	14.4	15.75	14.40	11.25	9.00	13.50	13.50
K_i	36.00	40.00	32.00	28.80	24.00	27.20	40.00
K_d	4.94	5.49	4.39	3.95	3.29	3.73	5.49
Max Power (MW)	2	2	2	2	2	2	2
Load Demand (MW)	$1 - 10$						
EV Load (kW)	500						

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Case 1: Variation of $\Delta t = t_{k+1} - t_k$ during transients

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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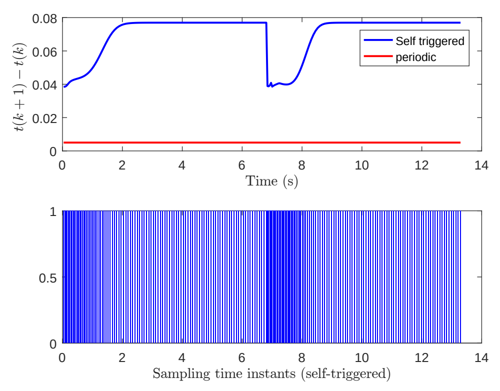
Self-Triggered PID Performance during Transients



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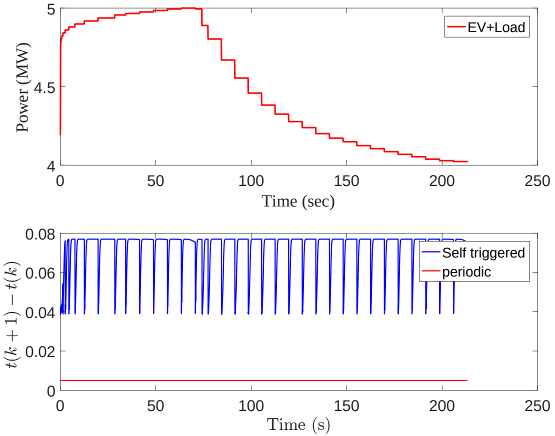
Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Case 2:Inter-sample time $\Delta t = t_{k+1} - t_k$ Variation for EV Load

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Case 2:Inter-sample time $\Delta t = t_{k+1} - t_k$ Variation for EV Load



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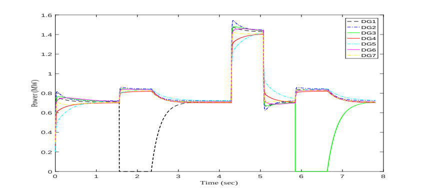
Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

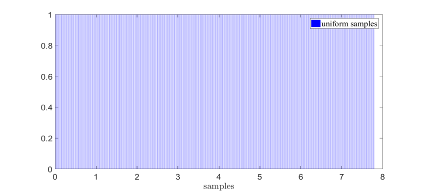
Case 3: DG powers with load and generator transients

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Case 3: DG powers with load and generator transients

PID periodic sampling

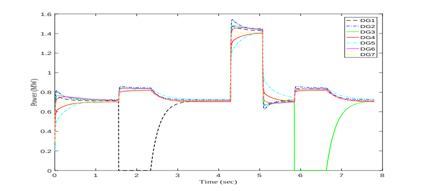


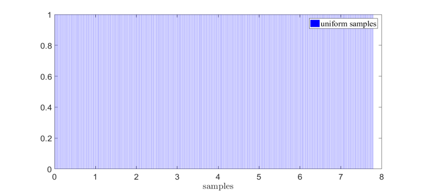


Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

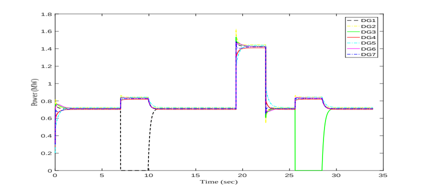
Case 3: DG powers with load and generator transients

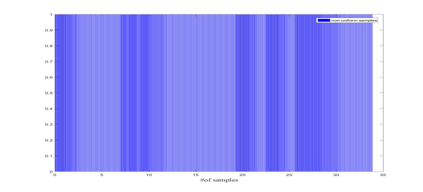
PID periodic sampling





PID self-triggered sampling





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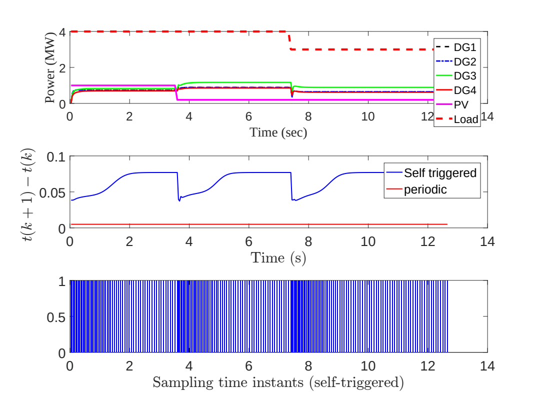
Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Case 4:Effect of PV and Load Transients

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Case 4:Effect of PV and Load Transients

Increased Sampling Rate during Transients



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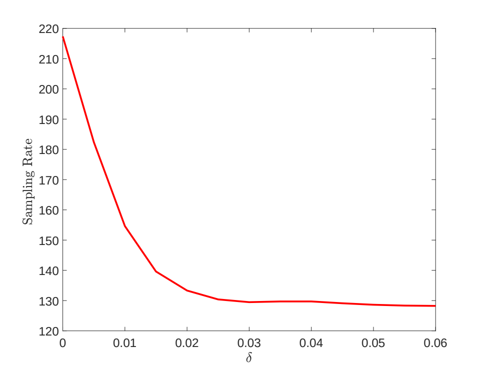
Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Case 5: Variation of Sampling Rate with Parameter δ

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Case 5: Variation of Sampling Rate with Parameter δ

Parametric Graph



[J3]: Jameel Ahmad, Muhamamd Aqeel Aslam, Muhamamd Tahir and Sudip. K. Mazumder , **"Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid"** Submitted in IEEE Transactions on Cybernetics.26-Mar-2019

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

Case 6: Variation of Sampling Rate with Parameter γ

Self-Triggered Data Sampler for Non-linear Dynamic Optimization of a Microgrid

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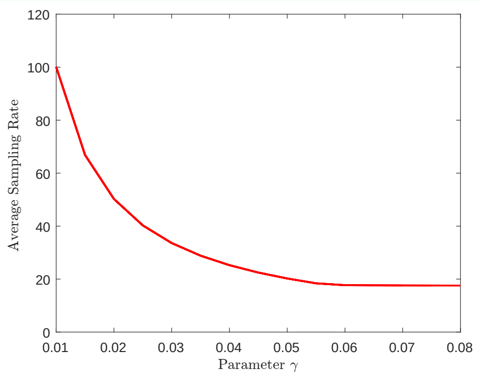
Parametric Graph



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Future Work-I

- **Distributed Energy Management in DC Nanogrids using Energy Routing:** DC nanogrids powering community houses for rural electrification are gaining widespread acceptance by researchers[Nasir et al., 2019, Nasir et al., 2018, Liu et al., 2018, Chandrasena et al., 2015]. However distributed energy management in a hierarchical structure have not yet been given much attention.

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- **Peer-to-peer(P2P) Energy Trading and Management in Microgrids and Blockchains:**In a P2P energy sharing prosumers directly trade energy with each other without involving a third-party intermediary. This results in local energy balance, self-sufficiency and decentralization[Andoni et al., 2019].

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- **Peer-to-peer(P2P) Energy Trading with Compressive Sensing:**Central energy manager algorithms can be developed for P2P case. State vector of all microgrids consisting of power generation, demand and surplus power can be transmitted using compressive sensing technique [Khan et al., 2017, Xu et al., 2018b] to reduce data traffic towards central control system.

Future Work-II

- **Energy Trading for Vehicle-to-Grid (V2G):**Electric vehicles can supply energy to microgrid or vice versa. Multiple MGs can then aggregate power through a distribution network operator (DNO) and supply it to main grid thus regulating voltage and stabilizing the grid though charging/discharging of EVs.

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- **Deep Learning in Smart Multi-Energy Systems** Deep learning can be used for forecasting the intermittency and stochastic nature of renewable sources. Forecasting output power of these sources is inevitable for accurate operation, planning and economic dispatch. The forecasting can also be for demand forecast and dynamic prices of electricity for energy markets. Dynamic performance of Multi-microgrids and Multi-Energy Systems [Shi et al., 2018, Cao et al., 2018] can be improved with short-term forecasting. Machine learning techniques such as Convolution Neural networks (CNN), Deep Neural Network (DNN) and Ensemble Kernal Machine (EKM) can be employed. While many predictive models have been already proposed to perform this task, the area of deep learning algorithms remains yet unexplored and benchmark algorithms are still missing.

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