Enhancing Distribution Grid Resilience Through Model Predictive Controller Enabled Prioritized Load Restoration Strategy

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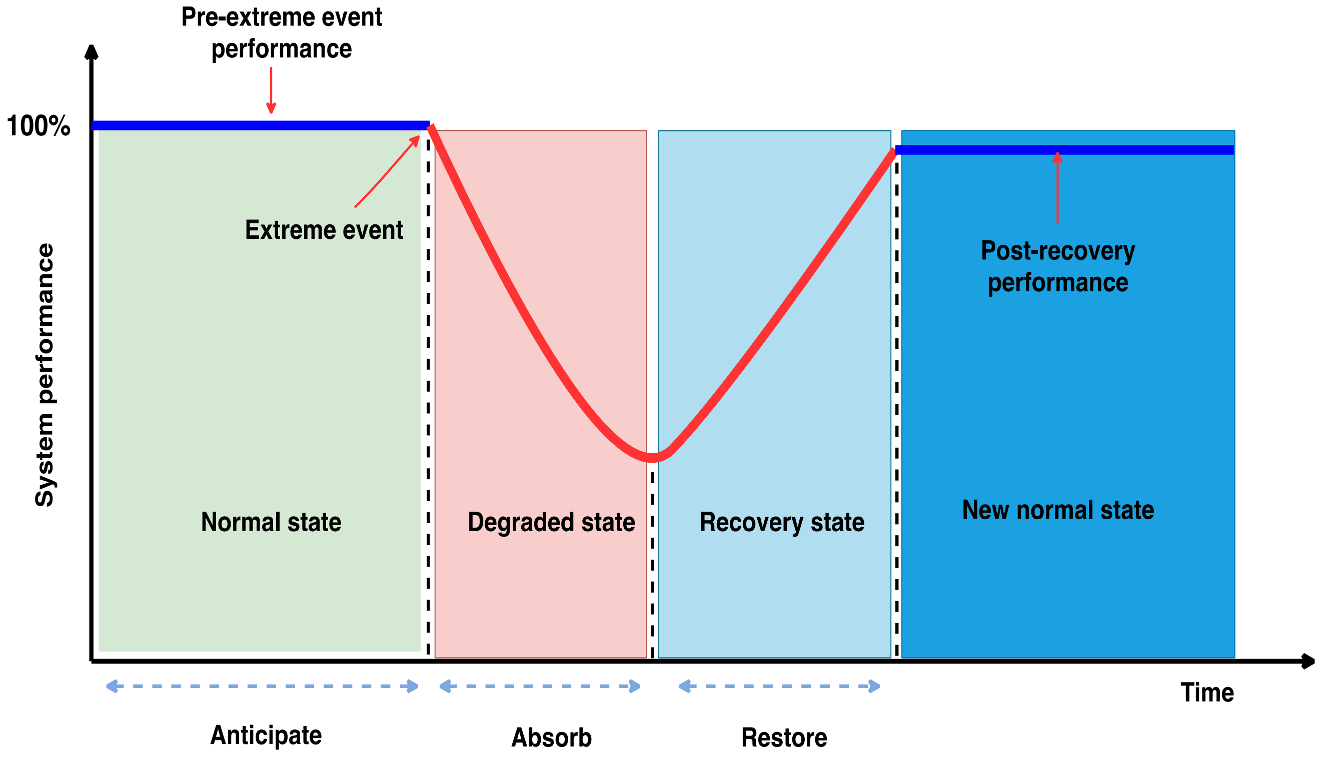
Contents

Background

- Incidence of extreme events (natural disasters, cyber and terrorist attacks) is rising globally due to the changes in weather conditions and socio-political threats.
- Standard definition and metrics for resilience are not available yet.
- Resilience - "the ability to anticipate and adapt to changing conditions and withstand and recover rapidly from disruptions," according to the U.S. PPD-21.



Resiliency curve

- Resilient power system should be able to anticipate, absorb and recover from extreme events.

Background

- Data collected by power utilities show that about 90% of power outages in the U.S. initiated from distribution grids.
- Load restoration is an important method to enhance the resilience of distribution grids during extreme events.
- Model predictive control (MPC) has become a popular control paradigm for sequential multi-period control problems with variable/uncertain parameters and variables.

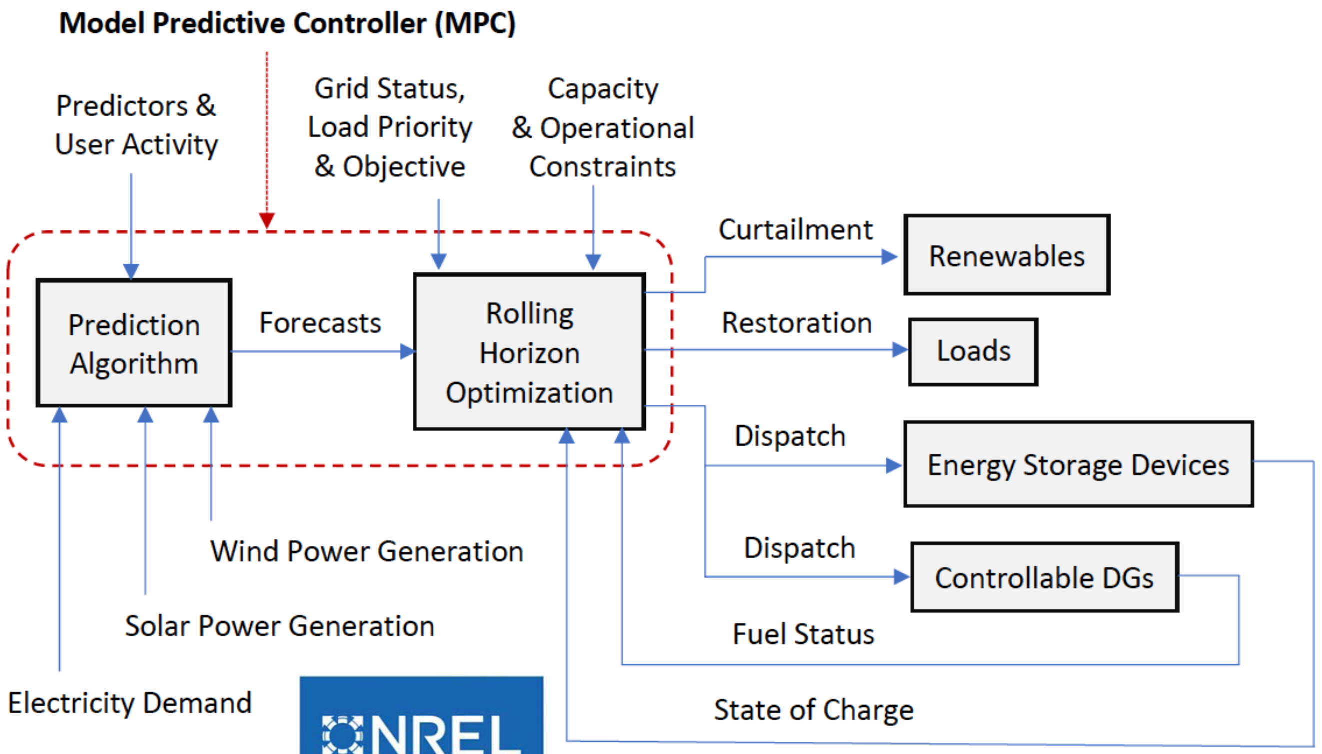
This study proposes MPC-enabled prioritized load restoration strategy for distribution grids to improve the grid resilience through the control of dispatchable distributed energy resources (DERs).

Problem Statement

Objective:

We plan to leverage MPC for prioritized load restoration problem during extreme event-caused sub-station outage in distribution feeders through the control of DERs.

Control Framework:



Problem Formulation

- The load restoration problem is formulated as a multi-step sequential decision process that uses predicted power values of distributed renewables in the distribution system.
- **Objective function:**

$$Maximize: \Big\{ \sum_{i \in N} \sum_{t \in T} \omega_i . P^l_{i,t}$$

Prioritized restored load

$$- \psi \sum_{i \in N} \sum_{t \in T \setminus \{1\}} \omega_i . max\left(\left(P^l_{i,t-1} - P^l_{i,t} \right), 0 \right)$$

Penalty for shedding prior restored load

$$- \alpha \sum_{t \in T} P^{wt,cut}_t - \beta \sum_{t \in T} P^{pv,cut}_t \Big\}$$

Penalty for renewable curtailment

Notations:

N	number of nodes
T	control horizon (shrinks over time)
i	node index
t	control interval (time) index
ω	load priority weight
ψ	penalty for shedding prior restored load
α/β	penalties for wind and solar power curtailments
$P^l_{i,t}$	restored load i at time t
$P^{wt,cut}_t$	wind power curtailed
$P^{pv,cut}_t$	PV power curtailed

Problem Formulation

- **Constraints**

1

$$P_t^{wt} + P_t^{pv} + P_t^{mt} + P_t^{es,dch} = P_t^{wt,cut} + P_t^{pv,cut} + P_t^{es,ch} + \sum_{i \in N} P_{i,t}^{l}$$

Power balance constraint

2

$$0 \le P_t^{mt} \le P_{max}^{mt}$$

$$\sum_{t \in T} P_t^{mt} . \Delta t \le E_{max}^{mt}$$

Generator power limits and fuel usage constraint

3

$$0 \le P_{i,t}^{l} \le P_{i,t}^{l,demand}$$

Restored load limits

4

$$0 \le P_t^{wt,cut} \le P_t^{wt}$$

$$0 \le P_t^{pv,cut} \le P_t^{pv}$$

5

$$0 \le P_t^{es,ch} \le b_t^{es,ch} P_{max}^{es,ch}$$

$$0 \le P_t^{es,dch} \le b_t^{es,dch} P_{max}^{es,dch}$$

$$b_t^{es,ch} + b_t^{es,dch} \le 1 \,, b_t^{es,ch}, b_t^{es,dch} \in \{0,1\}$$

$$SOC_{min}^{es} \le SOC_t^{es} \le SOC_{max}^{es}$$

Energy storage charge/discharge power limits and SOC constraints

6

$$SOC_t^{es} = SOC_{t-1}^{es} + \left(\frac{\eta^{es,ch} P_t^{es,ch}}{C_{es}} - \frac{P_t^{es,dch}}{\eta^{es,dch} C_{es}} \right) \Delta t$$

Energy storage SOC dynamics

c

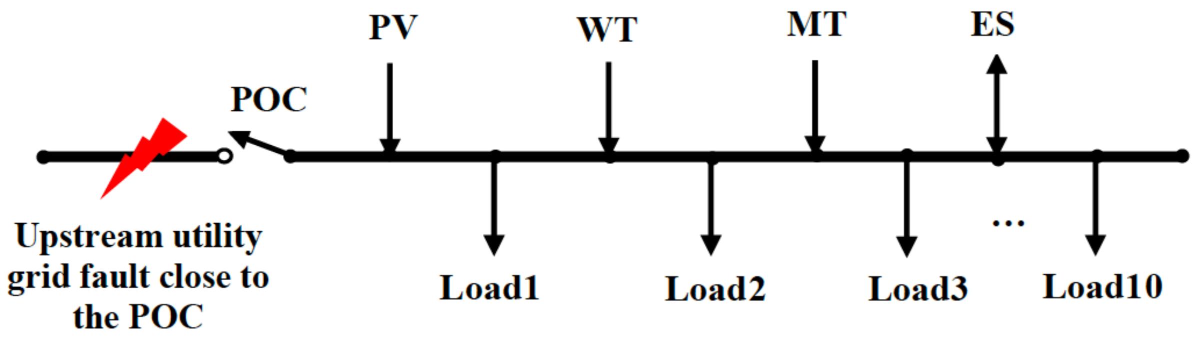
Problem Formulation

- **Decision Variables:**

$P_{i,t}^{l}$	restored load
P_t^{mt}	microturbine generator power
P_t^{es}	storage power
SOC_t^{es}	storage state of charge
$b_t^{es,ch}/b_t^{es,dch}$	storage charge/discharge status indicator
$P_t^{wt,cut}$	wind power curtailment
$P_t^{pv,cut}$	solar power curtailment, at time t

Results and Discussion - Simulation Details

- We apply the devised load restoration technique to a simplified single-bus equivalent of the IEEE 13-bus system with WT, PV, MT, and ES.



- We consider 10 spot loads (Load1 – Load10) with constant power load models.
- We assume an extreme event-caused substation outage occurred at 12:00.
- The utility outage time is set as 6 hours and the control step is 5min.
- We implemented the MPC using JuMP in Julia v1.5.
- The renewable power forecasting, data analytics and the MPC execution are performed in Python 3.7.
- The problem is MILP and solved by leveraging GLPK OS solver.

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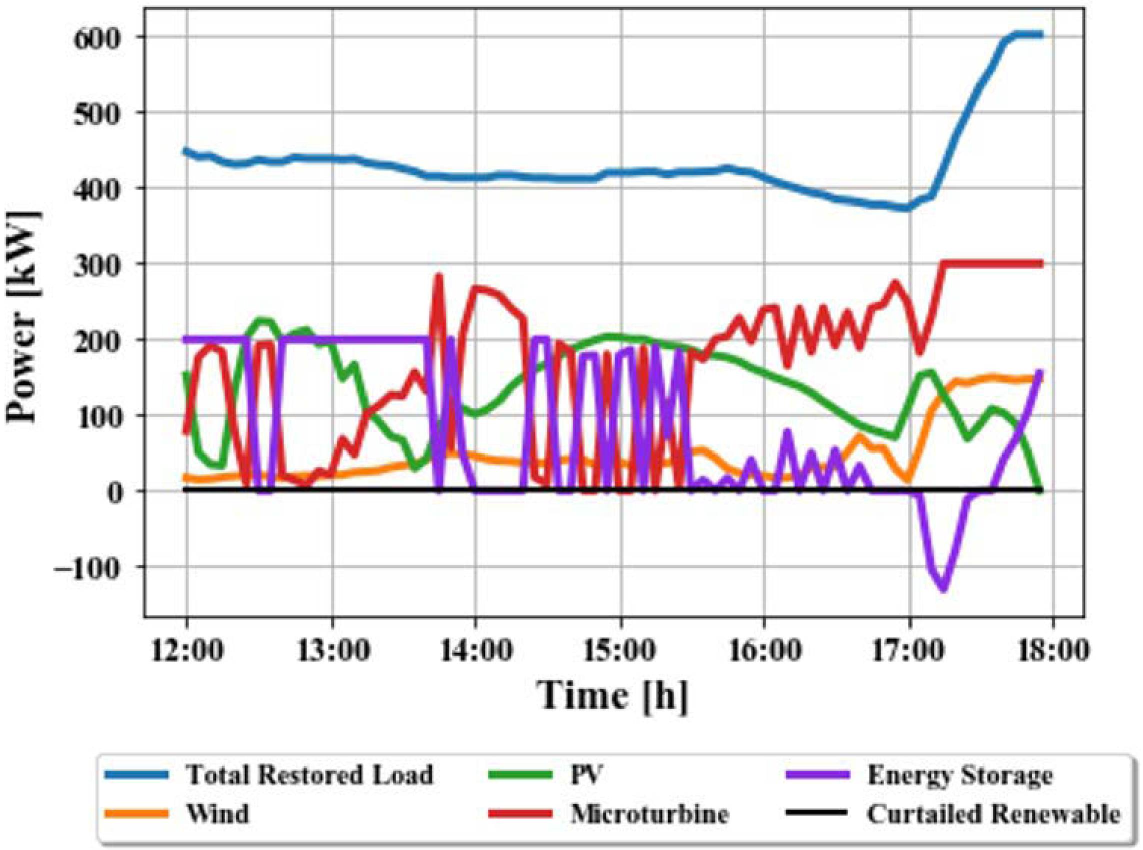
Results and Discussion – System Parameters

Parameter	Unit	Value	Parameter	Unit	Value
Load priority weight (ω)	-	[1.0, 1.0, 0.9, 0.85, 0.8, 0.65, 0.45, 0.4, 0.3, 0.3]	Penalty factor for shedding restored load (ψ)	-	100
Demanded spot loads ($P^{l,demand}$)	kW	[33, 34, 8.5, 85, 60, 60, 58, 115, 64, 85]	MT rated power (P_{max}^{mt})	kW	300
Initial control horizon (T_0)	hour	6	MT allowable total energy production (E_{max}^{mt})	kWh	1000
Control steps (t)	-	[1, 2, ..., 72]	Length of one control step (Δt)	hour	1/12
WT rating	kW	150	ES peak charging and discharging powers ($P_{max}^{es,ch}$,$P_{max}^{es,dch}$)	kW	200
PV array rating	kW	300	ES initial SOC (SOC_0^{es})	%	90
Penalty factors for WT and PV curtailment (α, β)	-	0.2	ES charging and discharging efficiencies ($\eta^{es,ch}, \eta^{es,dch}$)	%	95, 90
ES min and max SOCs (SOC_{min}^{es}, SOC_{max}^{es})	%	20, 90	ES rated capacity (C_{es})	kWh	800

Results and Discussion

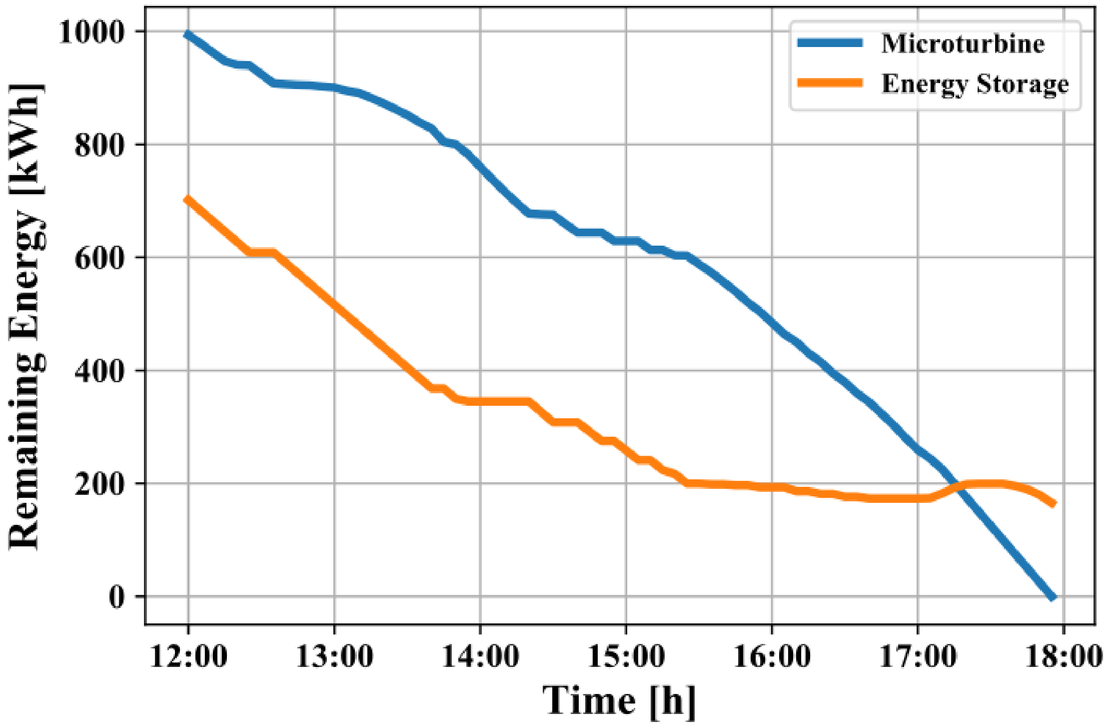
- We tested the MPC over 50 scenarios (different fault occurrence times and renewable generation profiles).
- For the purpose of demonstration, the MPC actions for a single scenario (fault occurrence time = 12:00) on a specific day (August 3, 2019) will be shown in the next slides.

Results and Discussion – Resource Dispatch & Load Restoration



- The MPC operates the microturbine and storage complimentary to serve the loads together with the wind and PV.
- The storage charges and stores energy in some of the control steps (17:00 – 17:30) to serve more loads in the future times.
- The total load was restored to full demand (600kW) during the last control steps (17:45 – 18:00).

Results and Discussion – Energy/Fuel Utilization



- The MPC was able to effectively utilize the controllable resources to serve the loads following the occurrence of the extreme event.
- At the end of the control horizon (18:00), the microturbine was out of fuel (zero remaining energy) and the energy storage reached its minimum SOC (160kWh).

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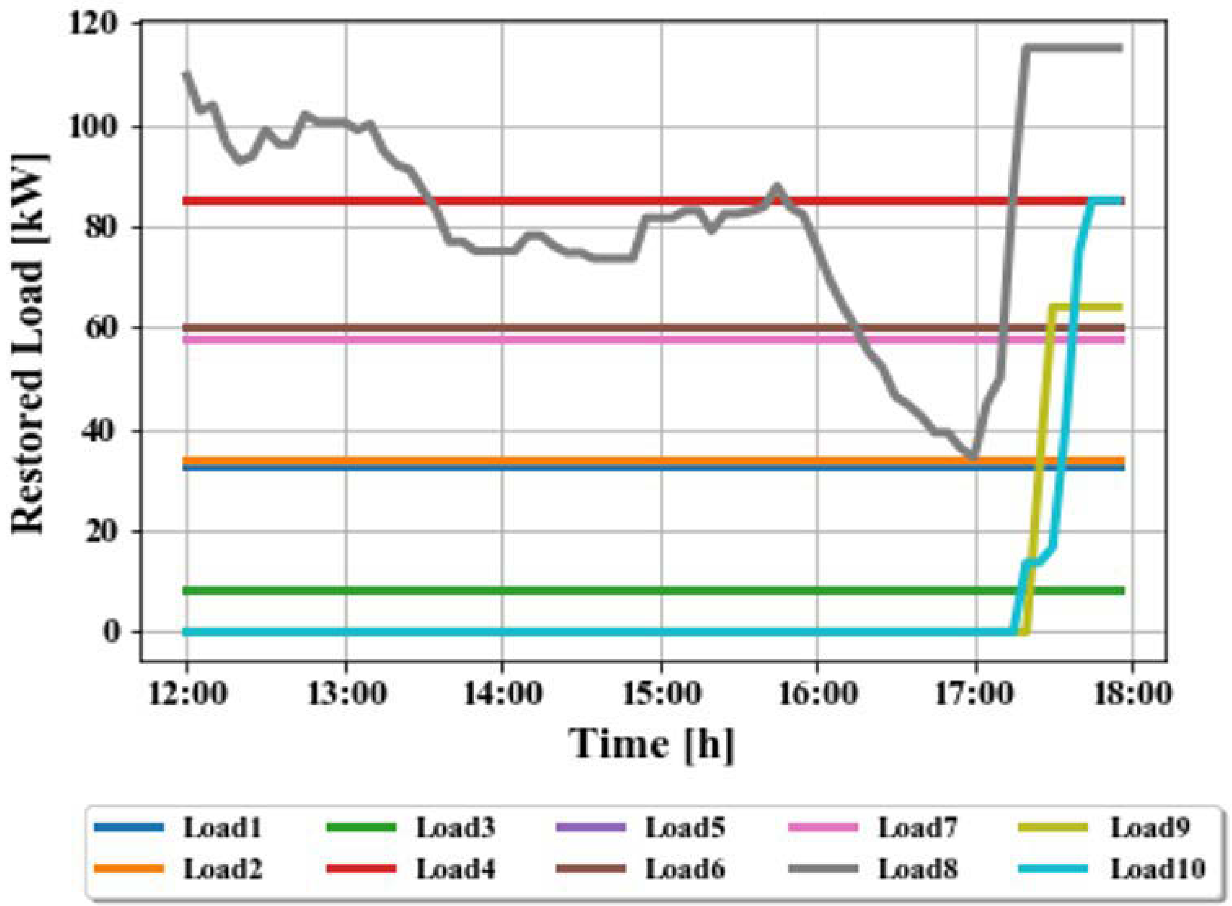
Results and Discussion – Individual Restored Loads



- The first 7 higher priority loads (Load1 – Load7) were restored with their full demand (100%) throughout the control horizon.
- The lower priority load (Load8) was served less than its full demand except in the control steps (17:20 – 18:00).
- The lowest priority loads (Load9 – Load10) were not served at all throughout the control horizon except during (17:40 – 18:00) and (17:45 – 18:00), respectively.
- This reveals the effectiveness of the devised MPC approach for the prioritized load restoration problem.

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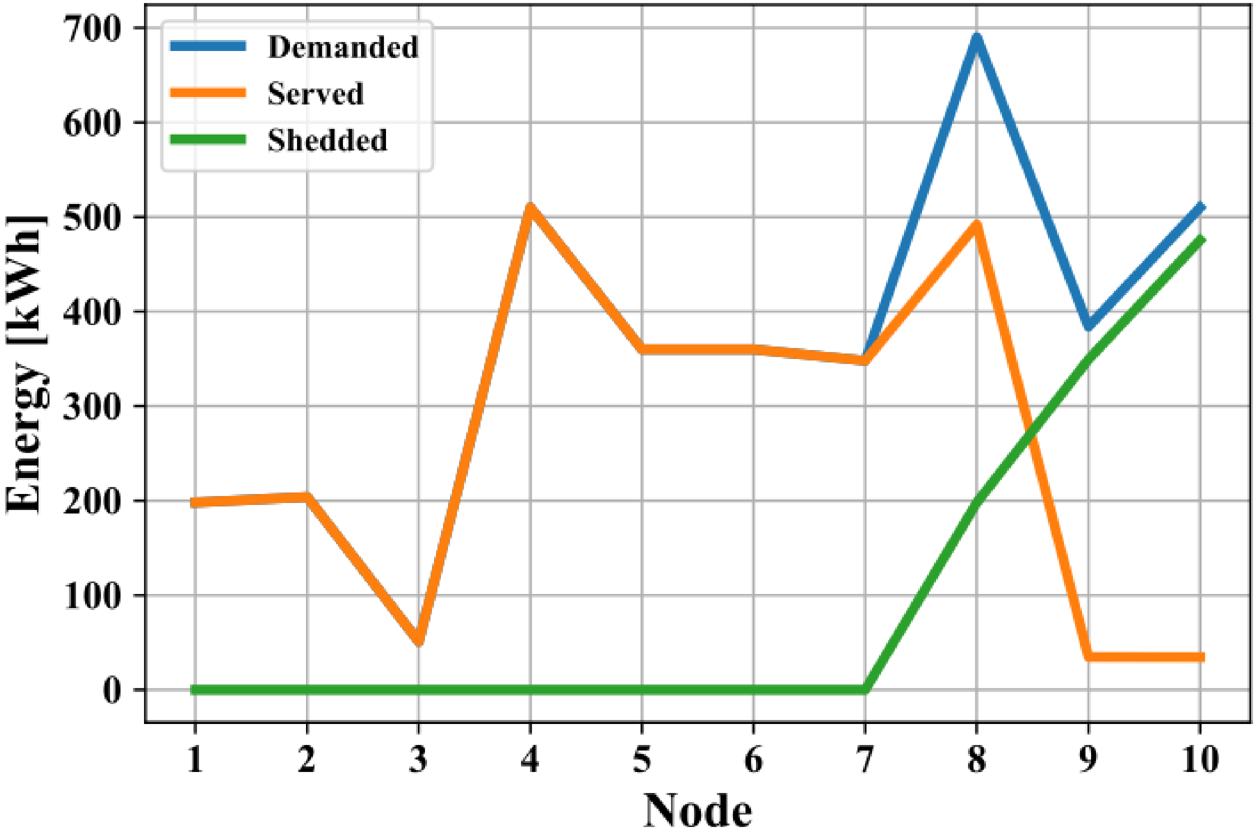
Results and Discussion – Demanded vs Restored Energy



- The total served energy over the control horizon is equal to the total demanded energy for the first seven higher priority nodes (loads) and hence zero shedded energy for these nodes.
- The served energy for the lower priority nodes (last three loads) is less than their demanded energy and thus their unserved energy was higher.
- This further shows the efficacy of the devised MPC in prioritizing critical loads during resource inadequacy.

Conclusion and Future Work

- The formation of resilient systems and the enhancement of operational resilience have become basic needs for energy systems.
- We devised an optimal and efficient MPC-based load restoration technique and demonstrated its effectiveness.
- We revealed that DERs and robust distribution grid automations (such as optimal restoration algorithms) are vital for enhancing the resilience of power systems.
- The current research findings and capabilities have continued in the other phases of our research such as incorporating the distribution network flows and voltage constraints in the MPC formulations.

Thank you! Questions?

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