Spatially Distributed Multi-Period Optimal Power Flow with Batteries

Aryan Ritwajeet Jha*, *SIEEE*, Subho Paul#, *MIEEE* and Anamika Dubey*, *SMIEEE*
*School of Electrical Engineering & Computer Sciences, Washington State University, Pullman, WA, USA
#Department of Electrical Engineering, Indian Institute of Technology (BHU) Varanasi, Varanasi, UP, India

KEY POINTS

A **Substation Operator's** key **objective** when operating a Power Distribution System is **minimizing Cost of Operation**, subject to safety and reliability limits. **This problem** of determining an Optimal Control Schedule to achieve the same **is called** the **Optimal Power Flow** (**OPF**) problem. **When** the **problem extends across** a horizon of **multiple time-steps**, it **is** called the **Multi-Period OPF (MPOPF)** problem.

As generation share of Distributed Energy Resources (**DER**) **and** Battery Energy Storage Systems (**BESS**) **increases**, **Complexity of solving MPOPF increases** as well.

We propose an **efficient MPDOPF (Multi-Period Distributed OPF) algorithm to solve** for the **MPOPF problem** by spatially furcating the problem into manageable subproblems which may be solved in parallel.

Substantial speedup (10x) in computation speed with virtually **no loss in solution optimality or feasibility**.

TEST SYSTEM

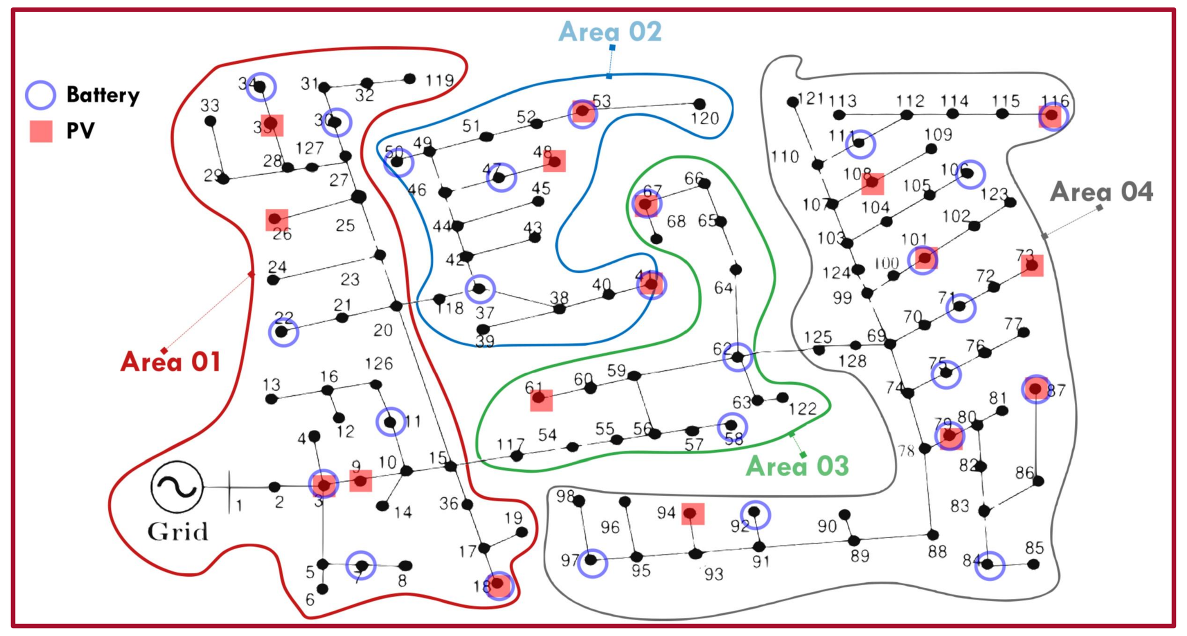

Fig. 1: IEEE 123 Node System Divided into Four Areas

As seen in Fig. 1, A Balanced Three-Phase IEEE 123 Node System with 85 Load Nodes, with 20% (17) PVs and 30% (26) Batteries is used.

Horizon Duration for Comparison: 10 Hours

For the centralized OPF approach (MPCOPF), the entire system is solved for at once.

For the proposed distributed OPF approach (MPDOPF) based on the ENApp algorithm [1], the system is divided into four areas, between which boundary variables will be exchanged.

OPTIMIZATION MODEL

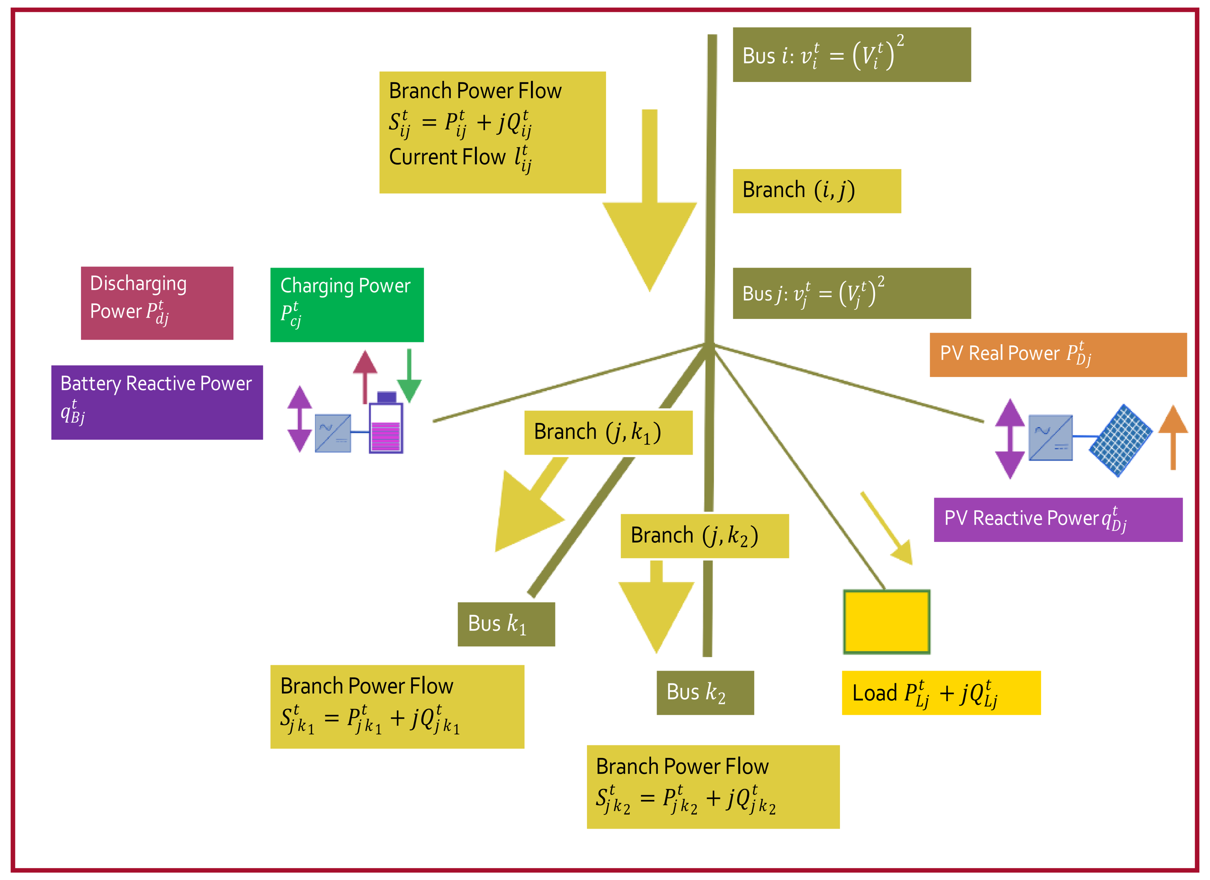

Fig. 2: A Schematic Representing all the Components in the System

Fig. 2 and (1) to (12) describe the entire system including the DER and BESS Components.

The Battery Loss Term in (1) helps us avoid Integer Constraints, avoiding solution complexity [2]

Cost of Substation Power and losses due to Battery Actions

$$\min \sum_{t=1}^{T} \left[C^t P_{Subs}^t \Delta t + \alpha \sum_{j \in \mathcal{B}} \left\{ (1-\eta_C) P_{C_j}^t + \left(\frac{1}{\eta_D} - 1 \right) P_{D_j}^t \right\} \right] \quad (1)$$

Subject to the constraints

Node j Real Power Balance

$$\sum_{(j,k)\in\mathcal{L}} \{P_{jk}^t\} - (P_{ij}^t - r_{ij} l_{ij}^t) = \left(P_{d_j}^t - P_{c_j}^t \right) + p_{D_j}^t - p_{L_j}^t \quad (2)$$

Node j Reactive Power Balance

$$\sum_{(j,k)\in\mathcal{L}} \{Q_{jk}^t\} - (Q_{ij}^t - x_{ij} l_{ij}^t) = q_{D_j}^t + q_{B_j}^t - q_{L_j}^t \quad (3)$$

$$v_j^t = v_i^t - 2(r_{ij} P_{ij}^t + x_{ij} Q_{ij}^t) + \{ r_{ij}^2 + x_{ij}^2 \} l_{ij}^t \quad (4)$$

KVL across branch (i,j)

$$(P_{ij}^t)^2 + (Q_{ij}^t)^2 = l_{ij}^t v_i^t \quad (5)$$

Current Magnitude across branch (i,j)

$$P_{Subs}^t \geq 0 \quad (6)$$

$$v_j^t \in [V_{min}^2, V_{max}^2] \quad (7)$$

Voltage Limits

$$q_{D_j}^t \in \left[-\sqrt{{S_{D_{R,j}}}^2 - {p_{D_j}^t}^2}, \sqrt{{S_{D_{R,j}}}^2 - {p_{D_j}^t}^2} \right] \quad (8)$$

DER Reactive Power Limits

$$B_j^t = B_j^{t-1} + \Delta t \eta_c P_{c_j}^t - \Delta t \frac{1}{\eta_d} P_{d_j}^t \quad (9)$$

Battery SOC Trajectory

$$P_{c_j}^t, P_{d_j}^t \in \left[0, P_{B_{R_j}} \right], \quad B_j^0 = B_j^T \quad (10)$$

Battery Power Limits

$$q_{B_j}^t \in \left[-0.44 P_{B_{R,j}}, 0.44 P_{B_{R,j}} \right] \quad (11)$$

Battery Reactive Power Limits

$$B_j^t \in [soc_{min} B_{R,j}, soc_{max} B_{R,j}] \quad (12)$$

Battery SOC Limits

RESULTS

The proposed MPDOPF algorithm and the benchmark MPCOPF algorithm were simulated for a 10 hour horizon represented by Fig. 3 [3]. Table 1 describes the size of the biggest subproblems solved as part of either algorithm, their output results and their computational performances.

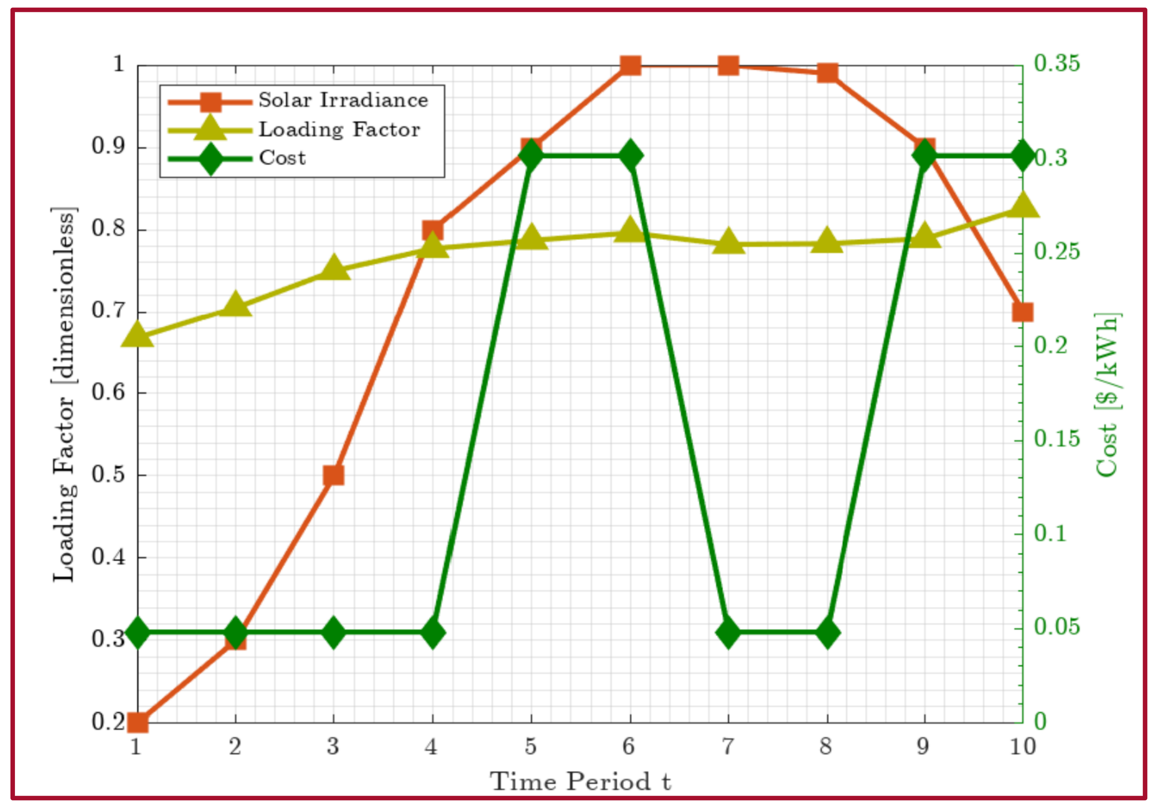

Fig. 3: Forecast of Demand, Solar and Cost of Substation Power

From Table 1, It may be seen that the **proposed MPDOPF significantly cuts down on** the **computation time**, by reducing the primary computational bottleneck encountered when solving for the OPF for a subproblem. It does so by reducing the size of the largest subproblem solved at any single instance.

The **proposed MPDOPF solution reaches** virtually the **same** level of **optimality** (Substation Power Cost) **as** the **benchmark MPCOPF, in a fraction of the time.**

Table 1: Comparison between MPCOPF and MPDOPF Results – 10 hour horizon

Metric	MPCOPF	MPDOPF
Largest subproblem		
Decision variables	6300	2640
Linear constraints	11636	4891
Nonlinear constraints	1270	530
Simulation results		
Substation power cost ($)	1197.87	1197.87
Substation real power (kW)	8544.28	8544.04
Line loss (kW)	148.67	148.94
Substation reactive power (kVAR)	1092.39	1252.03
PV reactive power (kVAR)	222.59	139.81
Battery reactive power (kVAR)	388.52	310.94
Computation		
Number of Iterations	-	5
Total Simulation Time (s)	4620.73	358.69

Table 2: ACOPF Feasibility Analysis against OpenDSS – 10 hour horizon

Metric	MPDOPF	OpenDSS
Full horizon		
Substation real power (kW)	8544.04	8544.40
Line loss (kW)	148.94	148.87
Substation reactive power (kVAR)	1252.03	1243.36
Max. all-time discrepancy		
Voltage (pu)	0.0002	
Line loss (kW)	0.0132	
Substation power (kW)	0.4002	

Table 2 confirms the feasibility of the solution against OpenDSS, while Fig. 4 validates the effectiveness of the extra battery loss term in its goal of ensuring complementarity of charging and discharging actions.

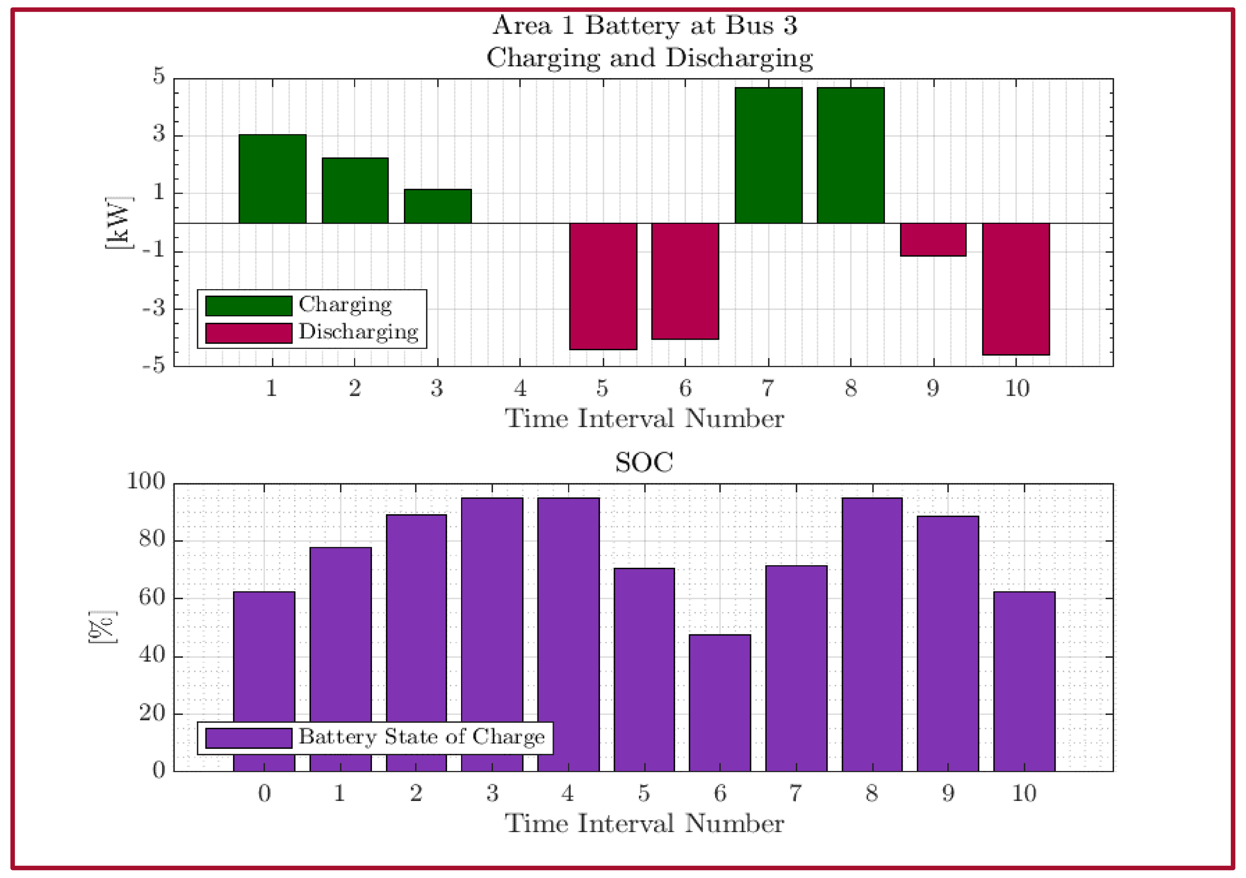

Fig. 4: Optimal Schedule for one of the BESS in the test system.

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ACKNOWLEDGEMENT

The authors acknowledge the financial support provided by the Department of Energy (DOE) for the project named 'Spokane Connected Communities' under contract number DE-EE0099775