# Unlocking Practical Stability in Smart Microgrid Economic Dispatch

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***Abstract*—In the rapidly transforming domain of microgrids, the role of Economic Dispatch transcends traditional paradigms of cost minimization. The pervasive integration of stochastic renewable resources, coupled with the technological heterogeneity of distributed assets, imposes multifaceted operational constraints that necessitate solutions simultaneously attuned to efficiency, resilience, and reliability. This work advances the state of the art by introducing a multidimensional ellipsoidal constraint that intrinsically incorporates the Practical Stability Region, where "practical" denotes stability limits imposed by protection relay settings rather than classical voltage stability notions, into the formulation of optimal setpoints. The proposed framework yields dispatch strategies that are not only economically optimal but also provably robust against uncertainties in demand and generation, while being inherently compliant with real-world protection constraints. These results establish a principled and implementable foundation for the next generation of intelligent control and strategic planning in smart microgrids.**

## I. Introduction

Economic Dispatch (ED) has become a cornerstone of modern power system operation and planning [1], [2]. At its core, ED seeks the optimal allocation of generating units and their outputs at each time interval to meet demand at minimal cost under system constraits. Early formulations emphasized the fuel and operational costs of thermal plants, but ED soon revealed a broader scope, incorporating investment and depreciation, technical limits, and, critically, system security and stability [3], [4]. In Italy, as in many other power systems worldwide, ED was historically coordinated within centralized, vertically integrated structures [5], [6]. Installed capacity was maintained above instantaneous demand, with reserve margins considered essential to guarantee reliability under contingencies and abrupt load variations. This operating philosophy highlighted the existence of multiple technically feasible solutions for the same demand scenario, reflecting different trade-offs between cost-efficiency and security. In systems dominated by large thermal units, ED ultimately converged toward marginal cost as the guiding criterion [7], [8]. However, the energy landscape is undergoing a fundamental transformation. Market liberalization and the rapid expansion of non-dispatchable renewable energy sources (RES) have fragmented generation across multiple actors [9]–[11]. Distribution networks, long passive conduits to the transmission system, now operate as active hubs of local generation and intelligent management. In this context, microgrids have emerged as a central paradigm for the coordinated integration of distributed energy resources (DER), controllable loads, and advanced SCADA (Supervisory Control and Data Acquisition) systems, redefining the foundations of ED [12]–[15]. ED in microgrids faces unique challenges: reduced system scale but high capacity-to-load ratios, intrinsic uncertainty in RES availability, technological heterogeneity with diverse cost functions and dynamic responses, and narrow operational margins that impose stringent stability and protection requirements [16]–[18]. Under these conditions, ED must be formulated as a constrained optimization problem. Pure cost minimization risks driving operations toward the boundaries of the Practical Stability Region (PSR) [19], the domain within which reliable static equilibrium is preserved, thereby exposing the microgrid to instability under ordinary fluctuations of load or generation.

Overcoming these limitations requires a paradigm shift from cost-centric ED strategies to robust, anticipatory frameworks. The integration of predictive models for RES availability, adaptive coordination of heterogeneous resources, and the evaluation of stability margins enables ED to balance efficiency, reliability, and resilience. The ultimate vision extends beyond optimization within predefined limits: it is to expand operational boundaries, transforming microgrids into intelligent, self-organizing systems capable of proactively adapting to stochastic conditions. To address these challenges, this work augments the ED formulation with an additional constraint that confines the optimal solution within a PSR. The PSR is approximated by a multidimensional ellipsoid in the hyperspace of state and control variables, providing a compact and tractable representation of the secure operating domain. Incorporating this constraint yields setpoints that are both economically efficient and robust in terms of practical stability. The feasible region is thus redefined from the set of purely economic solutions to the subset that ensures proactive stability, producing setpoints that are secure, reliable, and directly implementable, beyond the traditional cost–security trade-off.

The remainder of this article presents the mathematical formulation of the proposed PSR-constrained ED problem in Section II, followed by its application to a case study reproducing a subset of the microgrid experimentally implemented at the PrInCE laboratory of the Politecnico di Bari in Section III, providing a three-dimensional representation of the problem. Finally, Section IV reports the conclusions and discusses potential directions for future research.

979-8-3315-8138-1

## II. The Methodology

Effective operation of microgrids depends on a coordinated, multi-layer control architecture in which local regulation and central planning complement each other [20]. Primary and secondary control layers ensure rapid stabilization of frequency and voltage, responding instantaneously to load fluctuations and variations in distributed generation. Simultaneously, the central layer orchestrates all available resources, optimizing the dispatch of generators, energy storage systems, and controllable loads based on continuously updated information on demand, renewable output, and the network's operational state. Within this framework, ED defines the optimal operational setpoints. Typically executed over intra-day horizons with updates every fifteen minutes to one hour, ED continuously adapts operational decisions to real-time conditions and revised forecasts of load and generation. This rolling-horizon approach enables the system to maintain a continuous balance between supply and demand while preserving both economic efficiency and operational security.

### A. Decision Variables

The ED optimization problem is formally defined through the decision vector $\mathbf{x}$ in (1), which encompasses all controllable power setpoints, described as follows.

$$\mathbf{x}(t) = \Big[P_S(t)\;\overline{P}_{DG}(t)\;\overline{P}_{ESS}(t)\Big]^T \tag{1}$$

- When the microgrid is connected to the distribution network, the exchanged power $P_S$ becomes a decision variable, reflecting the interaction with the main grid.
- For a microgrid with $n_G$ generating units, of which $n_{DG}$ are controllable and $n_{RES}$ are non-dispatchable renewable sources, the outputs of dispatchable generators $\overline{P}_{DG}(t) = [P_{DG_1} \dots P_{DG_{n_{DG}}}]$, with $P_{DG_i}$, $i = 1, \dots, n_{DG}$, are included in the decision vector, representing the portion of generation that can be actively scheduled.
- For $n_{ESS}$ energy storage systems, the output powers $\overline{P}_{ESS}(t) = [P_{ESS_1} \dots P_{ESS_{n_{ESS}}}]$, with $P_{ESS_j}$, $j = 1, \dots, n_{ESS}$, complete the vector, capturing the operational flexibility provided by storage assets.

### B. Objective Function

The core objective of ED in a microgrid is to minimize the total operational cost, accounting for all controllable resources at each time step. Formally, this is expressed as the sum of individual cost contributions, as shown in (2). Each resource incurs a cost $C_k(t)$ that depends on its instantaneous power output $P_k(t)$. For dispatchable units, these costs are commonly modeled with a quadratic function, reflecting both linear and nonlinear contributions from fuel consumption, maintenance, and operational efficiency, as in (3). The coefficients $\alpha_k$, $\beta_k$, and $\gamma_k$ encode the techno-economic characteristics of resource $k$, yielding a heterogeneous cost structure across generation, storage, and grid-interfaced assets. They can be extracted from technical specifications or estimated from operational data, including energy costs, capital expenditures, and operational expenses.

$$\min_{\mathbf{x}} \sum_t \Big(\sum_k C_k(t)\Big) \tag{2}$$

$$C_k(t) = \alpha_k + \beta_k \cdot P_k(t) + \gamma_k \cdot P_k(t)^2 \tag{3}$$

For energy exchanged with the main grid, the cost reflects both fixed network charges and dynamic market prices. At each time step, a fixed component $\alpha_S$ accounts for tariffs and network fees, while a variable term $\beta_S(t)$ scales with the instantaneous energy price from energy markets:

$$C_S(t) = \alpha_S + \beta_S(t) \cdot P_S(t), \tag{4}$$

Dispatchable generators are primarily constrained by operational expenditures linked to fuel usage and mechanical wear. Quadratic cost functions effectively capture this behavior, as in (5). Energy storage systems, on the other hand, incur costs mainly due to battery degradation and conversion losses. Their economic impact is modeled linearly with respect to exchanged power, taking positive values when discharging and negative when charging, thereby encouraging operations that extend device lifetime while adhering to the intra-day schedule, as illustrated in (6).

$$C_{DG_i}(t) = \alpha_{DG_i} + \beta_{DG_i} \cdot P_{DG_i}(t) + \gamma_{DG_i} \cdot P_{DG_i}(t)^2 \tag{5}$$

$$C_{ESS_j}(t) = \beta_{ESS_j} \cdot |P_{ESS_j}(t)| \tag{6}$$

### C. Traditional Constraints

The ED optimization problem is shaped by constraints that rigorously define the feasible operating space and ensure secure, reliable operation. These constraints can be broadly classified into equality and inequality types.

The equality constraint, as expressed in (7), enforces instantaneous power balance between generation and demand $\overline{P}_L(t)$, thereby guaranteeing system stability at all times. Inequality constraints, compactly represented in (8), restrict decision variables to allowable operational ranges dictated by device capabilities and network security requirements. These include minimum and maximum power limits, which protect the microgrid from operational violations and safeguard continuity of service.

$$P_S(t) + \overline{P}_{DG}(t) + \overline{P}_{RES}(t) + \overline{P}_{ESS}(t) = \overline{P}_L(t), \quad \forall t \tag{7}$$

$$\mathbf{x}^{\min} \le \mathbf{x}(t) \le \mathbf{x}^{\max}, \quad \forall t \tag{8}$$

Together, equality and inequality constraints define a precise and realistic feasible space that mirrors the true operational capabilities of the microgrid. Within this structured framework, the ED algorithm can identify setpoints that optimize economic efficiency while ensuring all decisions remain fully consistent with the system's physical and technical limits.

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### D. Practical Stability Constraints

While traditional constraints ensure feasibility and instantaneous balance between generation and demand, they do not fully capture the most critical aspect of microgrid operation: the ability to maintain stable and secure operation under real conditions. To address this gap, we introduce a constraint based on the PSR in [19], which practically refines the feasible space defined by conventional limits. The PSR is precomputed offline for each possible operating scenario, providing a secure operating envelope tailored to expected conditions. During the online phase, the current operating condition is identified and the corresponding PSR is selected for dispatch, ensuring that the resulting ED setpoints are economically optimal, operationally implementable, and compliant with system stability and security requirements.

The PSR can be envisioned as a well-defined, multidimensional secure operating envelope. It is represented by a hyper-ellipsoid in the space of control variables, encompassing all configurations that satisfy the stability limits imposed by protection relays against voltage deviations. The core of this ellipsoid is defined by the Minimum Volume Enclosing Ellipsoid (MVEE), characterized by the pair $(\mathbf{A}, \mathbf{c})$, where $\mathbf{c}$ is the centroid, with coordinates corresponding to the nodal power setpoints, and $\mathbf{A}$ is the characteristic matrix encoding the ellipsoid's shape and orientation. Starting from a predefined set of random operating points preliminarily verified as stable through load flow analysis, the Khachiyan's algorithm computes the MVEE enclosing them, yielding the parameters $(\mathbf{A}, \mathbf{c})$. Because the hyper-ellipsoid is a regular geometric figure, some points within it may still be unstable. These points are initially grouped using the k-means method to determine an optimal number $w$ of cluster and to assign each unstable point to a specific group. The $z$-th cluster, with $z = 1, \ldots, w$, is then enclosed in a secondary ellipsoid, computed as before, and defined by its pair $(\mathbf{A}_z,\ \mathbf{c}_z)$. Each secondary ellipsoid is then expanded according to a predefined security margin $sm$, yielding the pair $(\mathbf{A}'_z, \mathbf{c}_z)$, with $\mathbf{A}'_z$ obtained by scaling $\mathbf{A}_z$ according to $sm$. The choice of $sm$ depends on the considered network, the number of operating points used in the building phase of the PSR (which affects its accuracy), and the technical application of the PSR. The resulting secondary ellipsoids are subtracted from the main volume, providing a conservative representation of the feasible operational space. The resulting PSR is therefore compact and filtered: only points lying inside the main ellipsoid and simultaneously outside the expanded secondary ellipsoids are considered stable and secure. While this work focuses on the application of the PSR to ED, readers interested in a detailed treatment of the region's geometric construction, the operational aspects of the method, and comparisons with similar approaches are referred to [19], [21].

The practical advantage of this formulation is immediacy: the stability of any operating point $\mathbf{p}$, whose components represent the power levels at each node under the considered operating condition as in (9), can be verified with a small number of quadratic checks Equations (10) and (11), avoiding complex iterative simulations.

$$\mathbf{p} = \left[ P_S \; \overline{P}_{DG} \; \overline{P}_{RES} \; \overline{P}_{ESS} \; \overline{P}_{L}) \right]^T \tag{9}$$

$$(\mathbf{p} - \mathbf{c})^T \cdot \mathbf{A} \cdot (\mathbf{p} - \mathbf{c}) \leq 1 \tag{10}$$

$$(\mathbf{p} - \mathbf{c}_z)^T \cdot \mathbf{A}'_z \cdot (\mathbf{p} - \mathbf{c}_z) > 1, \quad \forall z = 1, \ldots, w \tag{11}$$

Although deceptively simple in appearance, this formulation ensures that each identified solution is not only theoretically optimal from an economic perspective but also practically implementable, fully complying with the system's security margins. In this sense, the PSR serves as a bridge between optimization theory and operational reality, enabling the ED formulation in (12) to generate setpoints that are not only economically advantageous but also resilient and secure.

$$\min_{\mathbf{x}} \left( C_S + \sum_{i=1}^{n_{DG}} C_{DG_i} + \sum_{j=1}^{n_{ESS}} C_{ESS_j} \right)$$

subject to

$$\begin{cases} P_S + \overline{P}_{DG} + \overline{P}_{RES} + \overline{P}_{ESS} = \overline{P}_L, \\ P_S^{\min} \leq P_S \leq P_S^{\max}, \\ P_{DG_i}^{\min} \leq P_{DG_i} \leq P_{DG_i}^{\max},\ \forall i = 1, \ldots, n_{DG} \\ P_{ESS_j}^{\min} \leq P_{ESS_j} \leq P_{ESS_j}^{\max},\ \forall j = 1, \ldots, n_{ESS} \\ (\mathbf{p} - \mathbf{c})^T \cdot \mathbf{A} \cdot (\mathbf{p} - \mathbf{c}) \leq 1, \\ (\mathbf{p} - \mathbf{c}_z)^T \cdot \mathbf{A}'_z \cdot (\mathbf{p} - \mathbf{c}_z) > 1,\ \forall z = 1, \ldots, w \end{cases} \tag{12}$$

## III. Case Study: the PrInCE Microgrid

The proposed method was applied to a real-world case study, corresponding to a subset of the microgrid installed at the PrInCe Lab of Politecnico di Bari, Fig. 1. This, highlighted with a dashed outline, comprises the Combined Heat and Power (CHP) unit, the Microturbine (MT), and Programmable Load 1 (L). Their capability limits, along with the allowable power exchange with the distribution network via the tie line (S), are summarized in Table I.

Prior to executing the ED algorithm presented in Section II, the methodology outlined in [19] was employed to derive the PSR associated with the given configuration. To facilitate visualization, the axes of the multidimensional hyperspace were mapped to the CHP, the MT, and the load, as the power exchanged with the main grid inherently depends on these quantities. As depicted in Fig. 2, the PSR is represented by the volume enclosed by the main ellipsoid while excluding

TABLE I
Capability limits of the considered devices

| | *CHP* | *MT* | *L* | *S* |
|---|---|---|---|---|
| $P^{min}$ [kW] | 0 | 0 | -120 | -250 |
| $P^{max}$ [kW] | 120 | 30 | 0 | 250 |

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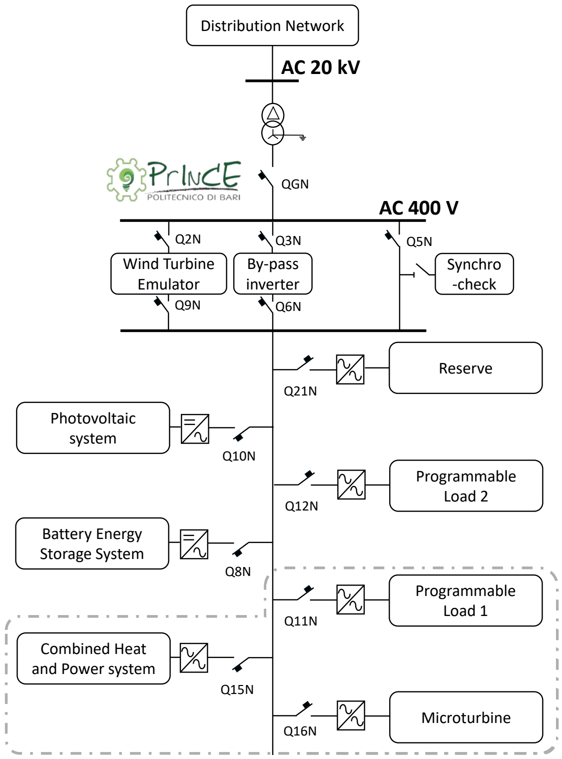


Fig. 1. PrInCE microgrid layout.

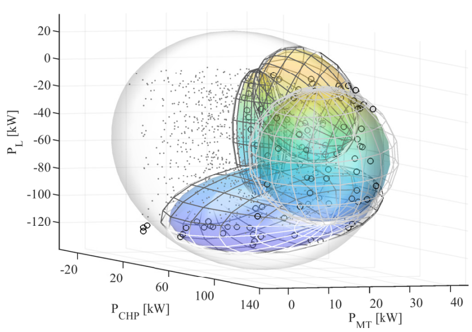


Fig. 2. PSR related to the considered subsystem.

four secondary clusters. These secondary ellipsoids correspond to technically feasible points that, however, violate practical stability requirements, exposing nodal voltages beyond the thresholds enforced by protection relays.

By integrating the PSR into the ED formulation, as formalized in (13), the optimization ensures setpoints that are both operationally feasible and economically informed. Here, $\mathbf{C_S}$, $\mathbf{C_{CHP}}$, and $\mathbf{C_{MT}}$ denote the costs of the state variables $\mathbf{x}$, and the constraints include energy balance, capability limits, and practical stability, as described in Section II. Load forecasts $\mathbf{P}_L$ and Day-Ahead Market prices across the 96 fifteen-minute intervals of the day were used to compare the classical ED with the PSR-constrained approach. Each solution $\mathbf{x}$ was computed with MATLAB's *fmincon*, defining 96 setpoints per controllable variable to minimize the daily operational cost. As illustrated in Fig. 3, the classical ED model, unconstrained by practical stability, occasionally generates points outside the PSR. Several points, shown in black, fall within the secondary ellipsoids and are therefore classified as insecure. In contrast, the PSR-based formulation systematically adjusts these points to lie within the admissible region, while keeping deviations from the original economic optimum minimal.

$$
\begin{aligned}
&\min_{\mathbf{x}} \left( \mathbf{C_S} + \mathbf{C_{CHP}} + \mathbf{C_{MT}} \right) \\
&\text{subject to} \\
&\begin{cases}
\mathbf{P}_S + \mathbf{P}_{CHP} + \mathbf{P}_{MT} = \mathbf{P}_L, \\
P_S^{min} \leq \mathbf{P}_S \leq P_S^{max}, \\
P_{CHP}^{min} \leq \mathbf{P}_{CHP} \leq P_{CHP}^{max}, \\
P_{MT}^{min} \leq \mathbf{P}_{MT} \leq P_{MT}^{max}, \\
(\mathbf{p} - \mathbf{c})^T \cdot \mathbf{A} \cdot (\mathbf{p} - \mathbf{c}) \leq 1, \\
(\mathbf{p} - \mathbf{c}_z)^T \cdot \mathbf{A}'_z \cdot (\mathbf{p} - \mathbf{c}_z) > 1, \ \forall z = 1, \ldots, 4
\end{cases} \\
&\text{with} \\
&\mathbf{x} = \begin{bmatrix} \mathbf{P}_S & \mathbf{P}_{CHP} & \mathbf{P}_{MT} \end{bmatrix}^T \\
&\mathbf{p} = \begin{bmatrix} \mathbf{P}_{CHP} & \mathbf{P}_{MT} & \mathbf{P}_L \end{bmatrix}^T
\end{aligned}
\tag{13}
$$

Constraining generator outputs in this manner has a limited economic impact. Over the analyzed 24-hour horizon, the total daily cost under the proposed approach amounts to €182.89, marginally above the €177.97 recorded with classical ED. This slight increase is predominantly driven by adjustments in network exchange power, $\mathbf{P}_S$: to uphold practical stability while controlling costs, the algorithm curtails MT output and

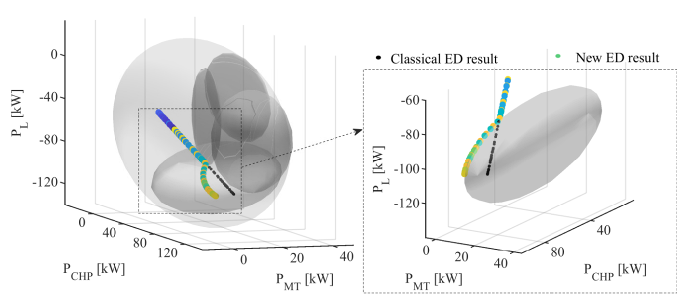


Fig. 3. Geometrical comparison between the results from two ED algorithms.

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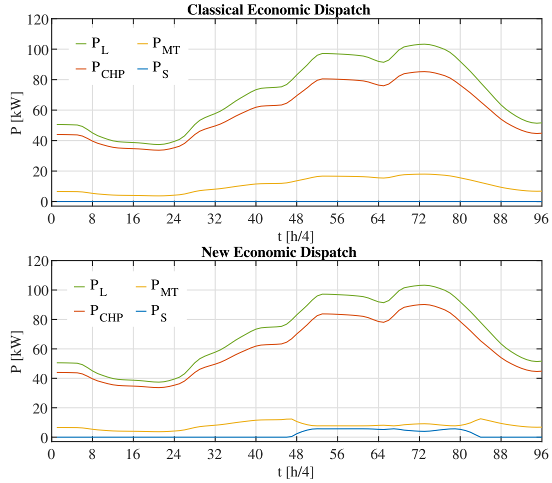


Fig. 4. Comparison between two ED algorithms.

compensates with increased imports from the grid, as shown in Fig. 4. The observed cost increase results from the infeasibility of the classical ED solution due to elevated nodal voltages at the MT bus. To comply with local network constraints and prevent violations, MT generation must be reduced, shifting a portion of the supply burden onto grid imports. Importantly, this allocation shows that a stability-aware ED can successfully reconcile cost efficiency with the practical security constraints inherent to microgrid operation, delivering setpoints that are simultaneously economically rational, technically feasible, and resilient. Evaluating all operating points took only 1.06 seconds on a 13th Gen Intel® Core™ i7-1355U processor, demonstrating the efficiency of the proposed approach.

## IV. Conclusions

This work shows that embedding the PSR within the ED framework enhances the dispatch process, producing generation setpoints that are both cost-optimal and inherently secure. Using an ellipsoidal representation, the method provides a mathematically rigorous yet compact mechanism to enforce robustness against practical network constraints, ensuring operational stability without compromising economic efficiency. The case study confirms that the approach matches classical ED performance while systematically excluding insecure or infeasible operating points. This framework bridges theoretical optimization and practical implementation, enabling stability-aware dispatch in complex power systems and supporting extensions to multi-microgrid coordination, longer-term planning, and adaptive control. By reconciling cost efficiency with robust stability guarantees, it establishes a benchmark for secure and economically efficient microgrid management.

## Acknowledgment

This work was conducted within the NEST - Network 4 Energy Sustainable Transition (D.D. 1243 02/08/2022, PE00000021) and supported by National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3, funded from the European Union – NextGenerationEU.

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