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Research Article

Simultaneous Optimization of Energy Storage Performance and Load Unbalance Reduction in Renewable-Based Microgrids Using Single-Phase Electric Vehicles

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Abstract:
The integration of renewable energy sources—particularly wind turbines—into microgrids (MGs) offers a sustainable pathway toward decarbonized power systems. However, the inherent intermittency and stochastic nature of wind power introduce significant challenges, including **power fluctuations**, **voltage instability**, and **reduced power quality**. Concurrently, in low-voltage distribution networks and residential MGs, **single-phase loads** are typically distributed unevenly across phases, leading to **load unbalance**, elevated **neutral currents**, increased **network losses**, and potential **equipment derating or damage**. These two issues—power variability and phase imbalance—often coexist in real-world MGs, yet are rarely addressed in an integrated framework.

This paper proposes a **novel, two-stage optimization strategy** that simultaneously enhances the **smoothing performance of an energy storage system (ESS)** and mitigates **load unbalance** by intelligently leveraging **single-phase electric vehicles (EVs)** as dynamic, controllable loads. The core innovation lies in the development of a **quantitative smoothness index (SI)** for performance evaluation, the systematic analysis of **State of Charge (SoC)** operating ranges for battery longevity, and the design of an **adaptive EV assignment algorithm** for real-time phase balancing.

In the first stage, a detailed dynamic model of a battery-based ESS is integrated with a 50-kW wind turbine within a simulated MG. To determine the optimal battery capacity, a stepwise sizing algorithm is employed, which calculates the energy required to cover peak demand surges over a 10-second window, while respecting practical constraints such as **Depth of Discharge (DoD)** and **round-trip efficiency**. The battery is then operated under seven distinct scenarios, each defining a unique SoC operating window—from the full range (0–100%) to constrained bands (e.g., 20–80%, 30–70%) and half-capacity modes (0–50%, 50–100%). A **baseline scenario** with no storage is also included for reference.

To quantitatively assess the effectiveness of each scenario in smoothing wind power output, a **novel smoothness index (SI)** is introduced. This index is derived from a complementary **Roughness Index (RI)**, which measures the total absolute deviation of local power peaks and valleys from the mean output. The SI is then defined as:

$$SI = \left(1 - \frac{RI_i}{\max(\mathrm{RI}_i)}\right) \times 100\% \;\;,\;\; i = number\ of\ scenario$$

where max(RI_i) is the highest roughness observed across all scenarios. The SI provides a normalized, intuitive metric (0–100%) where a higher value indicates a smoother, more stable power output. This metric enables a fair, quantitative comparison of scenarios that balance **technical performance (smoothing)** against **battery health (SoC constraints)**.

Simulation results over a 100-second wind profile—sourced from real-world Australian data—reveal that operating the battery in the **20–80% SoC range (Scenario 3)** provides the optimal trade-off. This scenario achieves an **SI of 65.16%**, only slightly lower than the 72.12% achieved in the full 0–100% range (Scenario 1), but crucially **preserves battery lifespan** by avoiding deep discharges and overcharging, which accelerate degradation in lithium-ion chemistries. Moreover, a novel **decision-making criterion** is proposed: the product of SI and the normalized SoC span ($SI \times SSoC$). **Scenario 3 yields the highest value for this combined metric (48.70)**, formally confirming its superiority as a balanced solution.

In the second stage, the focus shifts to **load unbalance mitigation** in a three-phase MG with **inherently unbalanced single-phase residential loads**. The paper proposes an **adaptive decision-making algorithm** that exploits the **flexible, controllable nature of EVs**. The algorithm continuously monitors the instantaneous power on each phase and **dynamically assigns incoming single-phase EVs to the most underloaded phase**. This strategy turns EVs—often viewed as a source of grid stress—into a **distributed balancing resource**.

The impact of this intelligent EV allocation is profound. In a comparative simulation, the presence of strategically assigned EVs reduces the **neutral current from 16.25 A to 8.42 A**, a **48.2% decrease**, effectively suppressing the zero-sequence component that causes losses and neutral conductor overheating. Simultaneously, the **smoothness index (SI) increases from 55.91% to 68.34%**, a **12.43 percentage-point improvement**. This dual benefit arises because the EVs not only balance phase loading but also provide additional, distributed smoothing capacity through their aggregate charging/discharging actions.

Furthermore, the phase power distribution is significantly homogenized. Without EVs, the power on phases A, B, and C is 22.1 kW, 17.8 kW, and 20.3 kW, respectively—a maximum imbalance of 4.3 kW. With the proposed algorithm, this imbalance is reduced to less than 1.5 kW, demonstrating effective real-time load leveling.

The integrated strategy offers several practical advantages:

1. **Extended Battery Lifespan**: By constraining SoC to 20–80%, the number of deep cycles is minimized, directly enhancing the economic viability of the ESS.
2. **Enhanced Power Quality**: The combined effect of ESS smoothing and EV-based balancing significantly reduces both temporal (power fluctuations) and spatial (phase imbalance) power quality issues.
3. **Cost-Effectiveness**: The method leverages existing EV infrastructure as a virtual balancing asset, avoiding the need for expensive, dedicated hardware like STATCOMs.
4. **Scalability and Practicality**: The algorithm is simple to implement in a centralized or distributed energy management system, requiring only basic phase power measurements and flexible EV scheduling.

In conclusion, this paper presents a holistic and practical framework for managing the dual challenges of renewable intermittency and load unbalance in modern MGs. By introducing a rigorous performance metric (SI), identifying an optimal SoC operating window, and innovatively repurposing single-phase EVs as a grid-balancing tool, the proposed strategy delivers a significant, quantifiable improvement in both **technical performance and economic sustainability**. The results demonstrate that a well-coordinated, multi-resource approach can transform potential liabilities—wind variability and unbalanced EV loads—into assets for a more resilient and efficient power system. Future work will extend this framework to include uncertainty modeling for wind and EV behavior, and its application in multi-MG or distribution network-level coordination.

Keywords: Microgrid, Energy Storage System, State of Charge (SoC), Single-Phase Electric Vehicle, Power Fluctuation, Load Unbalance

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