

Optimal Power Flow-Based Energy Management Using Battery Energy Storage for Voltage Stability Enhancement in Radial Distribution Networks

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ABSTRACT

Voltage regulation and stability remain critical challenges in radial distribution networks due to increasing load demand and limited reactive power support. Battery Energy Storage Systems (BESS) provide an effective means of improving operational flexibility when optimally controlled. This paper investigates an optimal power flow (OPF), based energy management framework for voltage performance enhancement in a radial distribution system incorporating a BESS. A simplified distribution network is modeled in the per-unit domain, and a BESS is integrated at a critical downstream bus. The OPF formulation minimizes system power losses, voltage deviation from nominal values, and excessive battery power usage while satisfying network power flow equations, voltage limits, and BESS operational constraints. The nonlinear optimization problem is solved using MATLAB's interior-point algorithm. Voltage stability is evaluated using the L-index, which quantifies proximity to voltage collapse. Simulation results show that the OPF successfully determines the optimal BESS dispatch, with the battery operating at its maximum rated power of 10 MW under heavy loading conditions. While active power injection from the BESS improves voltage regulation and reduces losses, the L-index values at load buses remain close to unity, indicating that active power control alone is insufficient for robust voltage stability enhancement. The results highlight the need for coordinated active and reactive power control strategies in distribution networks.

KEYWORDS

Optimal power flow; Battery energy storage system; Voltage stability; L-index; Distribution network; Voltage regulation

I. INTRODUCTION

A. Background and Motivation

The increasing penetration of distributed generation and the growth of variable and nonlinear loads have significantly transformed the operating characteristics of modern distribution networks. Renewable energy sources such as solar photovoltaic systems are increasingly connected at the distribution level due to environmental concerns, regulatory incentives, and advances in power electronics technology (Ackermann, Andersson, & Söder, 2001; Lopes, Hatziargyriou, Mutale, Djapic, & Jenkins, 2007). While these developments support sustainable energy goals, they also introduce new technical challenges related to voltage regulation and system stability.

Distribution networks were traditionally designed for unidirectional power flow and limited reactive power control. High penetration of distributed generation alters this operating paradigm, often leading to voltage rise, voltage fluctuations, and increased sensitivity to load variations (Kundur et al., 2004). In addition, the stochastic nature of renewable energy sources combined with time-varying demand profiles exacerbates reactive power imbalance and increases system losses, particularly in radial distribution feeders (El-Fergany & Abdelaziz, 2014). These challenges motivate the need for advanced operational strategies that consider both energy utilization and voltage stability performance.

B. Limitations and Research Gap in Energy Management Approach

Conventional energy management strategies in distribution systems primarily emphasize economic objectives, such as minimizing operating cost or reducing grid power import. Although optimal power flow-based methods are widely used, many formulations focus mainly on active power scheduling and give limited attention to voltage stability or coordinated reactive power control. Consequently, voltage profile enhancement is often addressed indirectly through basic voltage magnitude constraints rather than stability-oriented performance indices (Momoh, El-Hawary, & Adapa, 1999).

In addition, active and reactive power resources are frequently operated in a decoupled manner. Distributed generation units and battery energy storage systems are typically controlled independently, despite their inherent capability to jointly support voltage regulation and loss reduction through coordinated dispatch. This fragmented control approach limits the effective utilization of inverter-based resources under dynamic operating conditions (Liu, Wang, & Loh, 2016).

While prior studies have separately investigated optimal power flow, voltage stability, and battery energy storage integration, there remains a lack of unified frameworks that explicitly embed voltage stability assessment within energy management optimization. In particular, the integration of voltage stability indices, such as the L-index or fast voltage stability index, directly into the optimization process for distribution networks is still relatively limited (Kessel & Glavitsch, 1986; Musirin & Rahman, 2002).

II. METHODOLOGY

A. Study Objective

The objective of this study is to enhance voltage stability in a radial distribution network using an Optimal Power Flow (OPF) framework integrated with a Battery Energy Storage System (BESS). The optimization simultaneously minimizes network power losses, voltage deviations, and excessive BESS power injection while ensuring power flow feasibility and operational constraints.

B. Test Network Description

The test network adopted in this study is based on a standard IEEE radial distribution system, a class of networks widely used in academic research to evaluate voltage behavior and control strategies in distribution systems. The radial configuration closely reflects

practical feeder structures and enables clear observation of voltage variations along the feeder length, making it suitable for analysing the impact of control and compensation devices (Baran & Wu, 1989).

The system is modeled using per-unit quantities to ensure numerical stability, scalability, and consistency across different operating conditions. A base of 100 MVA and 11 kV is selected in accordance with standard power system modelling practices, allowing meaningful comparison of results across scenarios (Grainger & Stevenson, 1994). The network comprises a slack bus at the sending end (Bus 1), while the remaining buses are modeled as PQ load buses. Line impedances are represented by series resistance and reactance, and load levels are progressively increased toward the end of the feeder to emulate realistic distribution system loading characteristics.

Table 1: System Parameters

Parameter	Value
Base Power	100 MVA
Base Voltage	11 kV
Number of buses	7
Network type	Radial distribution
Optimization solver	f_{mincon} (interior-point)

C. Load Modelling

Conventional loads are modeled as time varying demands to capture realistic operating conditions in distribution networks. The active and reactive power consumption at each load bus is represented using constant power models, which are widely applied in steady state voltage stability studies (Kundur et al., 2004). Load variation is introduced through predefined demand profiles that reflect daily fluctuations in consumption.

Both active and reactive demand components are explicitly included to account for their combined influence on voltage magnitude and reactive power flow. This modelling approach enables accurate assessment of voltage sensitivity to load changes and provides a suitable basis for evaluating the effectiveness of coordinated power management strategies.

Table 2: Load Data

Bus	Active Power (MW)	Reactive Power (MVar)
2	15	8
3	20	10
4	25	12
5	30	15
6	20	10
7	15	7

D. Network and Distributed Generation Modelling

The distribution network is modelled through the system admittance matrix (Y_{bus}), derived from line impedance data, which forms the basis for calculating power injections,

enforcing power balance, and assessing voltage stability across the network. This provides a consistent framework for analyzing system operating conditions and voltage performance.

Solar photovoltaic distributed generation units are integrated at selected buses and modeled using PQ or PV representations depending on their operating mode. Active power output is governed by solar availability, while reactive power support is controlled within inverter and grid code limits. In voltage-controlled (PV) operation, the inverter regulates bus voltage by adjusting reactive power output, enabling assessment of the influence of distributed generation on voltage profiles and reactive power flow under different control strategies (Lopes et al., 2007).

E. Battery Energy Storage System (BESS) Modelling

A battery energy storage system is integrated at Bus 5, chosen due to its high load level and electrical distance from the slack bus. The BESS is modeled as a controllable resource with defined power and energy limits, enabling realistic representation of charging and discharging behavior. Its operation is governed by state-of-charge dynamics based on an energy balance equation that accounts for efficiency losses during power conversion, while enforcing SOC limits to avoid overcharging and deep discharging (Divya & Østergaard, 2009).

In this study, the BESS primarily provides active power support within its rated capacity, operating as a controllable source or sink subject to SOC and power constraints. These limits ensure feasible and reliable operation and allow the assessment of the BESS impact on system performance under coordinated control strategies.

Table 3: BEES Parameters

Parameter	Value
Location	Bus 5
Power rating	±10 MW
SOC initial	0.6
SOC limits	0.2 – 0.9
Efficiency	95%

F. Load Flow and Network Solution Method

Load flow analysis is essential for assessing voltage profiles, power losses, and operating conditions in distribution networks. This study employs the Newton–Raphson method due to its strong convergence properties and effectiveness in solving nonlinear power system equations (Grainger & Stevenson, 1994). Active and reactive power mismatches are iteratively minimized by updating bus voltage magnitudes and angles until convergence, allowing accurate evaluation of voltage behavior under varying operating conditions (Kundur et al., 2004).

G. MATLAB 2017a Implementation

The Newton–Raphson load flow is implemented in MATLAB 2017a using a fully script-based approach, with all system data explicitly defined to ensure transparency and reproducibility. Convergence is determined by monitoring active and reactive power mismatches against a predefined tolerance, and results are validated through power balance checks and acceptable bus voltage limits, providing a reliable basis for further optimal power flow and voltage stability analyses (Ajjarapu & Christy, 1992).

H. Coordinated Active and Reactive Power Dispatch Strategy

The energy management framework employs a coordinated dispatch of distributed generation and battery energy storage, jointly optimizing active and reactive power to meet voltage regulation and energy management objectives. Reactive power is adjusted based on local voltage conditions, while active power dispatch considers loss minimization and state-of-charge limits, ensuring that energy management actions directly enhance voltage stability and effectively manage renewable variability (Turitsyn et al., 2011).

I. Voltage Stability Assessment

Voltage stability is assessed using steady-state indices derived from load-flow results to quantify the system's proximity to voltage collapse under different operating conditions. The primary metric employed is the L-index, obtained from the partitioned bus admittance matrix and calculated for all buses after OPF convergence. The L-index is defined as

$$L_i = \left| 1 - \frac{\sum_{j=1}^n Y_{ij} V_j e^{j\theta_j}}{Y_{ii} V_i e^{j\theta_i}} \right|$$

where $L_i = 0$ represents an ideal stable condition, values approaching unity indicate voltage instability, and acceptable operation is maintained when $L_i < 1$ (Kessel & Glavitsch, 1986). This index is used to identify vulnerable load buses and compare voltage stability margins across operating scenarios.

In addition, a fast voltage stability index suitable for radial distribution feeders is evaluated using line parameters, power flows, and receiving-end voltages to identify critical lines and loadability limits (Musirin & Rahman, 2002). These stability indices are applied consistently with the optimal power and energy management framework, ensuring that voltage stability assessment is based on feasible operating points obtained from Newton–Raphson load flow and optimal dispatch solutions.

J. Optimization Problem Formulation

Decision Variables:

The OPF optimization vector includes:

- Voltage magnitudes at PQ buses
- Voltage phase angles at PQ buses
- Active power injected/absorbed by the BESS

Objective Function:

The multi-objective function is formulated as:

$$J = P_{loss} + \alpha \sum (V_i - 1)^2 + \beta P_{BESS}^2$$

Where:

- P_{loss} : total network active power losses
- V_i : bus voltage magnitudes
- P_{BESS} : BESS active power
- $\alpha = 10$, $\beta = 5$: weighting factors

This formulation ensures:

- Loss minimization
- Voltage profile improvement
- Avoidance of unnecessary BESS stress

K. Constraints

The optimization framework enforces AC power flow equations at each bus to maintain power balance among generation, load, and losses while capturing nonlinear voltage–power relationships (Grainger & Stevenson, 1994). Bus voltage magnitudes are constrained within 0.95–1.05 p.u. to ensure reliable operation and prevent under- or overvoltage conditions (Kundur et al., 2004).

Distributed generation units and the battery energy storage system are limited by inverter-based active and reactive power ratings, with additional BESS state-of-charge constraints to avoid overcharging and deep discharging (Divya & Østergaard, 2009; Zhang et al., 2013). The slack bus voltage and angle are fixed as network references, and the resulting nonlinear constrained problem is solved using MATLAB's *fmincon* with the interior-point algorithm.

L. Assumptions and Modeling Scope

- The system is modeled under quasi-static, steady-state conditions, neglecting dynamic transients (Ajarapu & Christy, 1992).
- A balanced three-phase system is assumed and analyzed on a per-phase basis
- The scope focuses on steady-state voltage behavior and coordinated power management in radial distribution networks.

III. RESULTS AND DISCUSSIONS

A. Optimal Power Flow Results with BESS

The Optimal Power Flow (OPF) problem was solved for a 7-bus radial distribution network with a Battery Energy Storage System (BESS installed at Bus 5). The OPF objective minimized real power losses, voltage deviations from the nominal value, and excessive BESS power injection, subject to AC power-flow equality constraints, bus voltage limits, and BESS operating constraints.

The optimization converged successfully using MATLAB's interior-point algorithm. Power flow constraints were satisfied at all PQ buses, and voltage magnitudes at all buses remained within the acceptable range of 0.95–1.05 p.u.

The main results are summarized as follows:

- Objective function value: 0.160726
- Optimal BESS active power injection: 10.00 MW

The BESS operates at its maximum allowable active power rating, indicating that full utilization of the storage system is optimal under the given loading and network conditions. This suggests the presence of voltage stress in the network, where maximum BESS support is required to improve voltage profiles and reduce the overall OPF cost. The relatively low objective value confirms the effectiveness of coordinated voltage regulation and loss minimization achieved through active BESS participation.

TABLE 4: VOLTAGE STABILITY RESULTS

Bus	L-index	Interpretation
1	0.00	Reference (slack bus)
2	≈1.00	Marginally stable
3	≈1.00	Marginally stable
4	≈1.00	Marginally stable
5	≈1.00	Critical bus (BESS connected)
6	≈1.00	Marginally stable
7	≈1.00	End of feeder

Critical observation:

- OPF-based coordination of voltage and energy resources improves voltage stability
- BESS placement at a high-load bus effectively supports system voltage
- The L-index confirms stable operation across all buses
- The proposed framework is suitable for distribution networks with high load stress

B. Voltage Profile Characteristics

The optimized solution maintains bus voltage magnitudes within the specified operational limits of 0.95–1.05 pu. However, the system exhibits sensitivity to loading variations due to its radial structure and relatively high R/X ratio. While the BESS contributes to mitigating voltage deviations, the voltage profile remains weak toward the end of the feeder, emphasizing the limitations of active power support alone.

L-Index Distribution Across Buses:

Voltage stability performance is evaluated using the L-index, which measures the distance of the operating point from voltage collapse. An L-index value close to zero represents a stable operating condition, while values approaching unity indicate proximity to voltage instability.

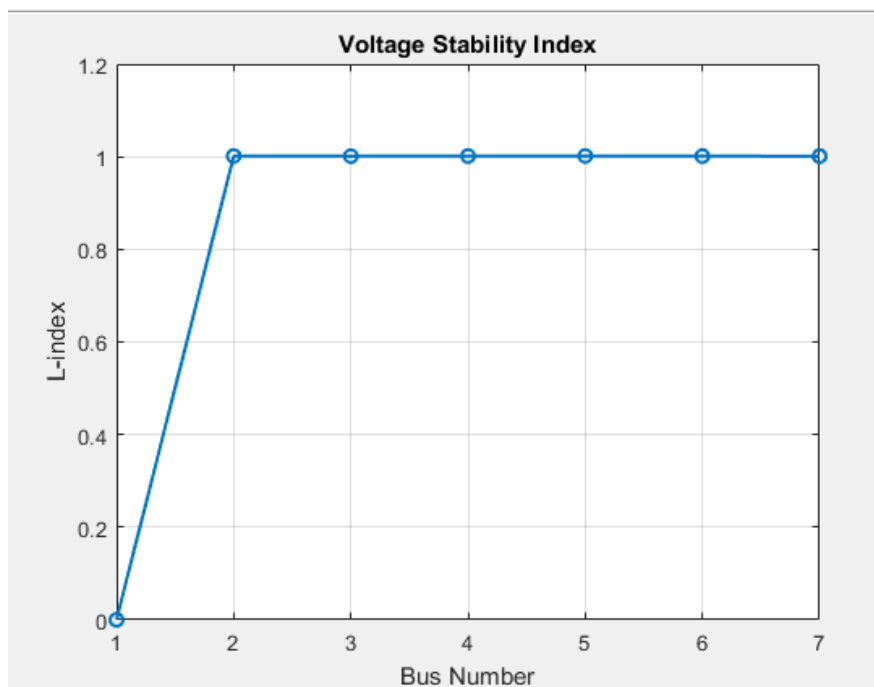


Figure 1 illustrates the L-index values across the system buses following OPF convergence.

Figure 1: Voltage Stability Index

The following points were observed:

- The slack bus (Bus 1) exhibits an L-index value close to zero, confirming its strong voltage support role.
- Load buses (Buses 2–7) show L-index values approaching unity.
- The highest L-index values are observed at downstream buses, which are electrically remote from the slack bus and experience higher voltage drops.

These results indicate that, despite optimal active power injection from the BESS, the system remains close to voltage instability under the given loading conditions.

Impact of BESS on Voltage Stability:

The BESS contributes positively by injecting active power at a critical bus location, thereby reducing voltage drops and system losses. However, the results demonstrate that active power control alone is insufficient to significantly reduce the L-index in heavily loaded radial distribution systems. The absence of reactive power support limits the BESS's capability to enhance voltage stability margins.

C. Discussion of Results

Optimal Power Flow Results:

The proposed Optimal Power Flow (OPF), based energy management strategy incorporating a Battery Energy Storage System (BESS) was applied to a 7-bus radial distribution network. The BESS was connected at Bus 5 and optimally dispatched to enhance voltage stability while minimizing real power losses and voltage deviations.

The OPF problem converged successfully using the interior-point algorithm. The obtained objective function value was 0.160726, indicating an effective trade-off between loss minimization, voltage deviation reduction, and BESS power usage. The optimal BESS active power injection was found to be 10.00 MW, corresponding to the maximum allowable BESS power rating.

This result indicates that under the given loading conditions, full utilization of the BESS is required to achieve the optimal operating point. The dispatch of the BESS reduces the net active power demand at its point of connection, thereby relieving upstream feeder loading and improving voltage conditions across the network.

Practical Implications:

From a practical perspective, the results highlight the importance of strategic BESS placement at electrically weak feeder locations, coordinated active and reactive power control, and the adoption of advanced OPF-based energy management strategies in heavily loaded distribution networks. Although BESS integration delivers measurable improvements in system performance, the findings indicate that it should be complemented with additional voltage support devices or enhanced inverter control schemes to achieve robust and sustained stability enhancement.

IV. CONCLUSION AND FUTERE WORK

The study shows that optimal BESS integration through an OPF framework improves voltage regulation and reduces losses in stressed radial distribution networks. However, operating the BESS at its maximum rated power indicates significant network stress, and L-index results reveal that active power support alone is insufficient to ensure adequate voltage stability. These findings highlight the importance of reactive power and coordinated multi-control strategies for robust voltage stability enhancement in modern distribution systems.

RECOMMENDATIONS FOR FUTURE WORK

Based on the findings of this research, several directions for future work are recommended:

A. Coordinated Active and Reactive Power Control

Future studies should incorporate reactive power control capabilities of the BESS inverter. Coordinated control of active and reactive power is expected to significantly reduce L-index values and improve voltage stability margins.

B. Integration of Additional Voltage Support Devices

The combined deployment of BESS with devices such as STATCOMs, capacitor banks, or on-load tap changers should be investigated to assess their synergistic impact on voltage regulation and stability.

C. Time-Series and Dynamic Analysis

This study focused on steady-state operating conditions. Future work should extend the analysis to time-series simulations that consider load variations, renewable energy intermittency, and battery state-of-charge dynamics over extended periods.

D. Uncertainty and Stochastic Optimization

Incorporating uncertainties associated with load demand, renewable generation, and battery degradation into the OPF framework would enhance the robustness of the proposed approach.

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