CHAPTER II

LITERATURE REVIEWS

2.1 Introduction

In recent years, the enormous increase in renewable energy integration has had a significant impact on power system stability. As a result, it is critical to emphasize the design and control of system stability, particularly voltage stability. This chapter discusses voltage stability and its assessment methodologies, as well as the research of BESS, which improves the system's voltage stability. Finally, the main points of the content and research are summarized.

This research is divided into 8 sections that address the following themes. An overview of voltage stability and the implications of incorporating renewable energy into the system, a study of voltage stability indices for evaluating system stability, with a focus on the L-index as a critical measure for identifying weak buses, an analysis of traditional voltage control methods, their implementation and benefits, an exploration of the applications of batteries and Examine the management of BESS for energy supply or absorption with the goal to resolve system stability issues. The entire study emphasizes maintaining system stability, from assessment to control, to enhance system reliability. The various research efforts are presented in the following sections: 2.2 presents research relating to Voltage Stability in Modern Power Systems, 2.3 presents Power Flow Analysis Fundamentals: Newton-Raphson Method , 2.4 presents research on Voltage Stability Indices: L-index and Others (Comparison), 2.5 presents research on Conventional Voltage Control Methods (STATCOM, Capacitor, Tap Changer), 2.6 presents research on Battery Energy Storage System (BESS) for Voltage Regulation, 2.7 presents research on Voltage Droop Control and Its Variants (Adaptive, Fuzzy, etc.), 2.8 presents research on State of Charge (SoC) Management in BESS, 2.9

Optimization Techniques for BESS Control (PSO, Fuzzy, Multi-objective), 2.10 present Research Gap and Motivation and 2.11 Summary and Research Contribution

2.2 Voltage Stability in Modern Power Systems

Due to increased demand loads and renewable energy integration, electrical systems are becoming more complicated and difficult to operate and plan effectively. VS is an important concern for electrical systems since it indicates efficiency and reliability. Several research studies investigated into systems that integrate renewable energy sources.

Table 2.1 Key Research on Voltage Stability and Renewable Integration

Year	Author	Objective	Description
2018	(Xu et al., 2018)	To evaluate the impact of renewable energy variabilities on power system voltage stability.	Renewable power variabilities significantly impact the probability distributions of load margins.
2018	(Adnan et al., 2018)	To investigate the impact of installing Distributed Generation (DG), specifically solar photovoltaic (PV) systems.	Use the IEEE 30 bus test system and carefully selecting DG locations and penetration levels.
2021	(Dondariya & Sakravdia, 2021)	To assess and improve voltage stability in power systems with the integration of solar photovoltaic (PV) generation.	The integration of solar PV generators at suitable locations significantly increases the critical load ability limit of the system. If installed PV at weak buses, it can improve voltage stability.

Table 2.1 Key Research on Voltage Stability and Renewable Integration (Continued)

Year	Author	Objective	Description
2024	(Malik et al., 2024)	To provide a comprehensive review of voltage stability issues in power systems with integrated wind energy.	To address the challenges associated with voltage instability and its implications for wind power integration and Various voltage stability indices have been developed to identify weak buses and assess overall system stability.
2024	(Wang et al., 2024)	To develop a method for analyzing static voltage stability in distribution power systems with integrated renewable energy sources.	-The study aims to address the challenges posed by large-scale renewable energy integration on static voltage stability and propose a simpler, more effective analysis method compared to traditional approaches.

2.3 Power System Analysis Overview

Power system analysis is a key tool for electrical engineers to ensure the grid we rely on is reliable, safe, and efficient. This analysis looks at the grid under two main conditions: normal operation and abnormal operation. Normal Operation is when the power system is running smoothly, just as it was designed to. Key values like voltage and frequency stay within their standard limits. Analysis in this state focuses on routine planning to keep the system running at its best. Abnormal Operation refers to unexpected events that disturb the system, like a lightning strike, a downed power line, or a power plant suddenly going offline. These events can lead to major issues like blackouts.

Beyond these conditions, the analysis can also be classified by its timeframe into two types: Steady-State Analysis and Transient-State Analysis. Steady-State Analysis looks at the system's condition after things have settled down and become stable. It's like taking a snapshot of the grid to see if everything is balanced. The study of Voltage Stability, which is the focus of this thesis, is a type of steady-state analysis. It deals with the system's ability to maintain a steady voltage under changing load conditions. The primary tool for this is Power Flow Analysis, which calculates voltage levels and power flows in the network. The results are used to calculate a Voltage Stability Index (VSI), an indicator that helps gauge how close the system might be to a voltage collapse. Transient-State Analysis studies what happens in the brief moments right after a disturbance. This helps understand the rapid changes and design protective systems that can react in time.

Therefore, this research focuses exclusively on steady-state analysis to understand and solve voltage stability problems. It uses data from power flow analysis as a critical foundation, providing a clearer and more complete picture of the underlying theories involved.

2.4 Power Flow Analysis Fundamentals: Newton-Raphson Method

In power system engineering, power flow analysis, often called a load flow study, is one of the most essential and widely used computational tools. It plays a crucial role in system planning, operation, economic dispatch, and overall control. The main goal of a power flow study is to numerically analyze how electric power flows through an interconnected network under steady-state conditions. This analysis provides the voltage magnitude and phase angle at each bus in the system, which are then used to calculate the real and reactive power flowing through transmission lines and transformers, as well as overall system losses. By offering a detailed snapshot of issues and a system's operating status under specific load and generation scenarios, power flow analysis helps engineers ensure the system is running safely and efficiently, detect potential overload or voltage issues and make informed decisions for future system upgrades and expansions.

2.4.1 System Variables and Bus Classifications

In power system analysis, the steady-state condition of any bus i within a network is fully characterized by four fundamental variables: the real power injection (P_i), the reactive power injection (Q_i), the voltage magnitude ($|V_i|$), and the voltage phase angle (δ_i). For the power flow problem to be mathematically well-posed and solvable, exactly two of these four variables must be specified for each bus, leaving the remaining two to be determined through computation. This requirement underpins the standard classification of buses into three distinct types, which consequently defines the structure of the system of nonlinear algebraic equations to be solved. The standard bus classifications are presented in Table 2.2.

The designation of a slack bus is not merely a matter of computational convenience but represents a fundamental necessity within the power flow formulation. The analysis is governed by power balance equations, which require that total power generation equals the sum of total system load and transmission losses. However, real power losses primarily resulting from I^2R losses in transmission lines are a function of the current flow, which itself depends on bus voltage magnitudes and phase angles. Since these quantities are initially unknown, the total system losses cannot be determined a priori, thereby making it infeasible to predefine the exact real power output of every generator in the system.

To resolve this issue, a single bus referred to as the slack (or swing) bus is designated to absorb the mismatch between the specified generation and the total system demand plus losses. The real and reactive power injections at the slack bus are treated as unknowns, allowing it to adjust dynamically during the solution process. This ensures that the power balance equations are satisfied upon convergence of the power flow algorithm, thereby maintaining consistency with physical and operational constraints.

Table 2.2 Power System Bus Classifications and Variables

Bus Type	Description	Specified (Known) Variables	Unknown Variables to be Solved
Slack Bus (Swing or Reference Bus)	A single reference bus, typically connected to a large generator, that compensates for system power losses and provides the angle reference for all other buses.	Voltage Magnitude and voltage phase angle	Real Power (P) and Reactive Power (Q).
Load Bus (PQ Bus)	Represents a point of consumption in the network where real and reactive power are drawn from the system. Most buses in a power system fall into this category.	Real Power (P) and Reactive Power (Q).	Voltage Magnitude and voltage phase angle
Generator Bus (PV Bus)	Represents a bus where a generator is connected. The real power output is controlled via the prime mover, and the voltage magnitude is maintained by the generator's excitation system.	Real Power (P) and Voltage Magnitude	Reactive Power (Q) and voltage phase angle

2.4.2 Mathematical Formulation of Power Flow Equations

The mathematical model for the power flow problem is derived from fundamental circuit theory, specifically Kirchhoff's Current Law applied at each node of the power system. For a multi-bus network, this relationship is systematically expressed using the bus admittance matrix ($\mathbf{Y_{BUS}}$), which relates the vector of bus current injections ($\mathbf{I}$) to the vector of bus voltages ($\mathbf{V}$).

$$\mathbf{I} = \mathbf{Y_{BUS}}\mathbf{V} \tag{2.1}$$

For any given bus i in an n-bus system, the injected current I_i is the sum of the currents flowing from that bus into the connected branches:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \tag{2.2}$$

However, in power flow studies, the specified quantities are typically real and reactive power injections, not currents. The complex power injected into bus *i* is defined as:

$$S_i = P_i + jQ_i = V_i I_i^* \tag{2.3}$$

where I_i^* is the complex conjugate of the injected current I_i. Rearranging this equation yields an expression for the current injection in terms of power and voltage:

$$I_i = \frac{P_i - jQ_i}{V_i^*} \tag{2.4}$$

By substituting this expression for current back into the nodal admittance equation, we formulate the fundamental power flow equations. These equations relate the specified powers at each bus to the bus voltages throughout the network.

$$\frac{P_i - jQ_i}{V_i^*} = \sum_{j=1}^{n} Y_{ij} V_j \tag{2.5}$$

To facilitate an iterative solution, these complex equations are typically expressed in polar coordinates. Let the voltage at bus i be $V_i = |V_i| \angle \delta_i$ and the element of the admittance matrix between bus i and bus j be $Y_{ij} = |Y_{ij}| \angle \theta_{ij}$. By substituting these polar forms into the power flow equation and separating the real and imaginary parts, we arrive at the final set of non-linear, coupled algebraic equations that must be solved:

Real Power Injection Equation:

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \tag{2.6}$$

Reactive Power Injection Equation:

$$Q_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\delta_i - \delta_j - \theta_{ij}) \tag{2.7}$$

This system of non-linear equations forms the core of the power flow problem. Due to their non-linearity and the coupling between variables, an analytical solution is not feasible for any practical power system. Therefore, iterative numerical methods are required to find the unknown voltage magnitudes $|V|$ and angles δ that satisfy these equations within a specified tolerance.

2.4.3 Computational Algorithm of the Newton-Raphson Load Flow

The implementation of the Newton-Raphson method follows a structured, iterative procedure. The algorithm begins with an initial guess and repeatedly refines the solution until the power mismatches at all buses fall below a specified convergence tolerance. The detailed computational steps are as follows:

Step 1: Initialization

- Construct the system's bus admittance matrix, Y_{bus}, from the line and transform impedance data.
- Assume an initial voltage profile for all buses. A "flat start" is commonly used, where the voltage magnitude is set to 1.0 p.u. and the phase angle is set to 0° for all PQ and PV buses. The slack bus voltage is fixed at its specified value.
- Set the iteration counter, k, to 0 and define the convergence tolerance, ε.

Step 2: Calculate Power Mismatches

- Using the bus voltage values from the current iteration, $|V|^{(k)}$ and $\delta^{(k)}$, calculate the real power injection ($P_i^{(k)}$) for all buses except the slack bus, and the reactive power injection ($Q_i^{(k)}$) for all PQ buses using the power flow equations.
- Compute the power mismatch vectors by subtracting the calculated powers from the specified (scheduled) powers:

$$\Delta P_i^{(k)} = P_i^{spec} - P_i^{(k)} \tag{2.8}$$

$$\Delta Q_i^{(k)} = Q_i^{spec} - Q_i^{(k)} \tag{2.9}$$

Step 3: Check for Convergence

- Find the maximum absolute value among all elements of the power mismatch vectors.
- If max $\max(|\Delta P|, |\Delta Q|) < \varepsilon$ the solution has converged. The algorithm terminates the iterative loop and proceeds to Step 7. Otherwise, continue to the next step.

Step 4: Compute the Jacobian Matrix

- Calculate the elements of the four sub-matrices of the Jacobian, $j^{(k)}$, using the partial derivative formulas and the voltage values from the current iteration, $|V|^{(k)}$ and $\delta^{(k)}$.

$$\begin{bmatrix} \Delta P^{(k)} \\ \Delta Q^{(k)} \end{bmatrix} = \begin{bmatrix} J_{11}^{(k)} & J_{12}^{(k)} \\ J_{21}^{(k)} & J_{22}^{(k)} \end{bmatrix} \begin{bmatrix} \Delta \delta^{(k)} \\ \Delta |V|^{(k)} \end{bmatrix} \tag{2.10}$$

  - $J_{11} = \dfrac{\partial P}{\partial \delta}$: This sub-matrix relates changes in real power injections to changes in bus voltage angles. The diagonal and off-diagonal elements are given by:
    - Off-diagonal ($i \neq k$)

$$\frac{\partial P_i}{\partial \delta_k} = -|V_i||V_k||Y_{ik}|\sin(\theta_{ik} + \delta_k - \delta_i) \tag{2.11}$$

    - Diagonal ($i = k$)

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{\substack{j=1 \\ j \neq i}}^{n} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} + \delta_j - \delta_i) \tag{2.12}$$

  - $J_{12} = \dfrac{\partial P}{\partial |V|}$: This sub-matrix relates changes in real power injections to changes in bus voltage magnitudes. The diagonal and off-diagonal elements are:

- Off-diagonal ($i \neq k$)

$$\frac{\partial P_i}{\partial |V_k|} = |V_i||Y_{ik}|\cos(\theta_{ik} + \delta_k - \delta_i) \tag{2.13}$$

- Diagonal ($i = k$)

$$\frac{\partial P_i}{\partial \delta_i} = 2|V_i||Y_{ii}|\cos(\theta_{ii}) + \sum_{\substack{j=1 \\ j \neq i}}^{n} |V_j||Y_{ij}|\cos(\theta_{ij} + \delta_j - \delta i) \tag{2.14}$$

- $J_{21} = \dfrac{\partial Q}{\partial \delta}$: This sub-matrix relates changes in reactive power injections to changes in bus voltage angles. The diagonal and off-diagonal elements are:
  - Off-diagonal ($i \neq k$)

$$\frac{\partial Q_i}{\partial \delta_k} = -|V_i||V_k||Y_{ik}|\cos(\theta_{ik} + \delta_k - \delta_i) \tag{2.15}$$

  - Diagonal ($i = k$)

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{\substack{j=1 \\ j \neq i}}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} + \delta_j - \delta_i) \tag{2.16}$$

- $J_{22} = \dfrac{\partial Q}{\partial |V|}$: This sub-matrix relates changes in real power injections to changes in bus voltage magnitudes. The diagonal and off-diagonal elements are:
  - Off-diagonal ($i \neq k$)

$$\frac{\partial P_i}{\partial |V_k|} = -|V_i||Y_{ik}|\sin(\theta_{ik} + \delta_k - \delta_i) \tag{2.17}$$

  - Diagonal ($i = k$)

$$\frac{\partial Q_i}{\partial \delta_i} = -2|V_i||Y_{ii}|\sin(\theta_{ii}) - \sum_{\substack{j=1 \\ j \neq i}}^{n} |V_j||Y_{ij}|\sin(\theta_{ij} + \delta_j - \delta i) \tag{2.18}$$

Step 5: Solve for Voltage Corrections

- Solve the system of linear equations to find the voltage correction vector.

$$\begin{bmatrix} \Delta\delta^{(k)} \\ \Delta|V|^{(k)} \end{bmatrix} = \left[J^{(k)} \right]^{-1} \begin{bmatrix} \Delta P^{(k)} \\ \Delta Q^{(k)} \end{bmatrix} \tag{2.19}$$

Step 6: Update Voltages and Iterate

- Update the voltage magnitudes and angles for the next iteration:

$$\delta^{(k+1)} = \delta^{(k)} + \Delta\delta^{(k)} \tag{2.20}$$

$$\left|V\right|^{(k+1)} = \left|V\right|^{(k)} + \Delta\left|V\right|^{(k)} \tag{2.21}$$

- Increment the iteration counter, k = k+1, and return to Step 2 to begin the next iteration.

Step 7: Final Calculations

- Once convergence is achieved, use the final bus voltage solution to calculate the real and reactive power injections at the slack bus.
- Calculate the real and reactive power flows on all transmission lines and transformers, as well as the power losses in each component.

2.5 Voltage Stability Indices: L-index and Others (Comparison)

To address the many concerns with voltage stability (VS) that occur as a result of renewable energy integration, instruments for assessing system stability are required. Numerous research has looked into these techniques, one of which is the voltage stability indices (VSI). VSI is used to compare the current operating state of the system to the voltage collapse point; in other words, it indicates how close the system's voltage stability is to collapsing. VSI can also detect important buses and analyze the stability of transmission lines.

Voltage stability index is classified into three types based on the calculation method: system parameters (variable)-based, Jacobian matrix-based, and phasor measurement units (PMU)-based. Each type has characteristics. The Jacobian matrix-based approach can be used to calculate the voltage collapse point and load margin. The system parameters (variable)-based method is used to identify weak buses or places that need to be assessed, and it considers the line loadability limit. The PMU-based technique, which relies on local measurements and Thevenin impedance computations, is used to monitor voltage stability indices rather than to anticipate instability. Table 2.2 shows a comparison of various VSIs.

Table 2.3 Comparison of Voltage Stability Indices

Index	Advantages	Disadvantages	Example Application	References
L-index	The L-Index can be easily implemented in real-time monitoring systems. Identify strong/weak buses using L-index coeff.	Not suitable for dynamic analysis	IEEE 10, 14, 39, 118 test system., the WSCC 9 bus system	(Karn et al., 2023; Kessel & Glavitsch, 1986; Ram & M, 2016; Ramanareddy, 2011)

Table 2.3 Comparison of Voltage Stability Indices (Continued)

Index	Advantages	Disadvantages	Example Application	References
FSVI	The Fast Voltage Stability Index (FVSI) can identify "weak buses" that are close to voltage collapse based on index values approaching 1.00. The calculation is straightforward.	Low efficiency for large systems requires multiple power flow iterations.	IEEE 30-bus	(Isaiah et al., 2015)
Jacobian-based	It can accurately estimate the collapse point and Voltage Stability Margin (VSM).	The calculations are extensive and complex, making it unsuitable for real-time monitoring and not ideal for identifying weak buses/lines.	-	(Danish et al., 2019; Yadav et al., 2024)

Table 2.3 Comparison of Voltage Stability Indices (Continued)

Index	Advantages	Disadvantages	Example Application	References
PMU-based	It offers high accuracy, excellent real-time performance, and the ability to perform online monitoring, providing alerts before voltage collapse occurs.	The Thevenin-based (local) method has a drawback in that parameter changes between two measurement periods can lead to inaccurate estimations.	-	(Yadav et al., 2024; Zaheb et al., 2020)

Based on Table 2.3, the L-index is suitable for selecting buses for BESS installation due to its simplicity and ability to identify weak buses in the system. the L-index, introduced by (Kessel & Glavitsch, 1986) who investigated power system voltage stability and presented a novel analytical method based on the Indicator L, which assesses voltage stability on a scale from 0 (no load) to 1 (voltage collapse). The method reliably forecasts voltage stability limits and identifies important nodes prone to voltage collapse. Radial network designs provided the best voltage stability, whereas increasing transmission capacity and optimizing system topology increased the Indicator L and overall system stability. Furthermore, selecting node locations with higher Indicator L values helped to improve the voltage stability of the power distribution system. This study provides useful information for building and operating power systems to ensure voltage stability and avoid voltage collapse.

2.6 Conventional Voltage Control Methods (STATCOM, Capacitor, Tap Changer)

Once the weak bus has been identified through the L-index, enhancing the system's voltage stability (VS) requires system control to guarantee that it operates correctly. One way to accomplish this is by voltage regulation. Voltage levels in the electrical system can be maintained within acceptable limits by controlling the voltage, enhancing stability and reliability. Several approaches for voltage regulation have been investigated, including STATCOM, capacitor banks and tap-changing transformers. The primary premise of voltage regulation is to provide reactive power to the system in order to increase the voltage to normal levels. (Soni & Gaur, 2018)

Table 2.4 Comparison of Conventional Voltage Control Methods

Device	Principle	Advantages	Disadvantages	References
STATCOM	Reactive power compensation (VSC)	STATCOMs are better suited for short-term stability issues. effective voltage regulation and designing both linear and nonlinear controllers to manage load voltage effectively	It involves high costs and investment.	(Jain et al., 2006; Taylor, 2003; Xu & Li, 2014)
Capacitor Banks	Reactive power compensation	Mechanically switched capacitor banks are effective for long-term voltage stability	Slow response, not for transients	(Swe et al., 2011; Taylor, 2003)

Table 2.4 Comparison of Conventional Voltage Control Methods (Continued)

Device	Principle	Advantages	Disadvantages	References
Tap-Changing Transformer	Adjust transformer winding ratio	Continuous voltage adjustment	Slow, mechanical wear	(Swe et al., 2011; Taylor, 2003)

From the three presented methods of voltage control, each method has its own advantages and disadvantages. However, the aforementioned voltage control is still not suitable for power systems with high levels of renewable energy penetration. Therefore, in the next section, we will present a voltage control method using Battery Energy Storage Systems (BESS).

2.7 Battery Energy Storage System (BESS) for Voltage Regulation

Battery Energy Storage Systems (BESS) are devices that can store, or supply energy as needed. One of their key advantages is their ability to help manage load and fluctuating renewable energy, which gives BESS an edge over voltage control as mentioned in the previous section. The primary function of BESS is to store excess energy when electricity production exceeds demand. Conversely, if the system experiences an energy shortage, BESS can help supply energy and can respond quickly to changes. (Zhang & Srivastava, 2021)

Several studies have investigated methods to address voltage regulation issues in distribution networks with high PV penetration. (Wang et al., 2016) proposed a coordinated control strategy for distributed energy storage systems (ESS) to regulate voltages in low-voltage (LV) distribution networks with high PV penetration. Their approach involves coordinating the power outputs of ESS based on distributed control and localized state-of-charge (SoC) management. Simulation results demonstrated that the proposed method effectively maintains voltages within specified ranges during daily operations and enhances system stability.

In another approach, (Alam et al., 2013) addressed the impacts of rooftop solar PV on voltage profiles and proposed a new strategy for charging and discharging distributed energy storage systems to mitigate these effects. Their method utilizes the available capacity of storage devices to reduce voltage rise during peak PV generation, mitigate voltage fluctuations due to sudden changes in PV output, and support evening peak loads by discharging stored energy. Simulation results showed that this strategy effectively mitigates negative impacts of PV, supports peak-time load demand, and optimizes the utilization of storage capacity.

Furthermore, (Zeraati et al., 2016) proposed a coordinated control strategy for battery energy storage systems (BESS) to address voltage rise and drop issues in low voltage distribution networks with high photovoltaic (PV) penetration. The research highlights the challenges of voltage regulation due to reverse power flow from PV systems. The proposed strategy combines local droop-based control with distributed consensus algorithms to manage the charge and discharge of BES. Two consensus algorithms are employed: the Weighted Consensus Control (WCC) algorithm, which allocates BES participation based on capacity, and the Dynamic Consensus Control (DCC) algorithm, which adjusts participation based on the state of charge (SoC) to prevent saturation or depletion. Simulation results using real data from a radial distribution feeder demonstrate the effectiveness of the approach in maintaining voltage within permissible limits and optimizing the use of storage capacity.

2.8 Voltage Droop Control and Its Variants (Adaptive, Fuzzy, etc.)

One method of controlling BESS is voltage droop control. This control method allows for the adjustment of the power supplied or received as needed. Adaptive droop control and fuzzy logic-based droop control have been developed to enhance performance, prevent battery saturation, and improve system resilience.

Table 2.5 Droop Control Methods for BESS

Method	Principle	Strengths	Example	References
Conventional Droop	Linear adjustment by deviation	Smooth power-sharing, no oscillations Keeps feeder voltages inside limits	The CIGRE B4 dc grid test system, A 6-bus distribution feeder and a 13-bus distribution network, a realistic 7-bus LV radial feeder modeled.	(Rouzbehi et al., 2015; Wang et al., 2016; Zeraati et al., 2016)
Adaptive Droop	Dynamic coefficient adjustment	Sustains SoC, eases generator burden	-	(Tan et al., 2020)
Fuzzy Droop	Fuzzy logic-based adaptation	Cuts voltage deviation, avoids overload Holds voltage band, prevents saturation	Test on a simplified LV microgrid simulated.	(Chen et al., 2017; Jamroen et al., 2018)

Therefore, voltage droop control is crucial for managing BESS to achieve maximum efficiency and is suitable for power systems with high renewable energy fluctuations, such as wind energy with its inherent uncertainty or solar energy, which also exhibits variability. The adaptability of droop control makes it the best and most appropriate choice.

2.9 State of Charge (SoC) Management in BESS

One important aspect of using BESS is considering the SoC. If neglected, it may result in the system's inability to control voltage effectively. There are several research studies that examine BESS with a focus on SoC. (Ota et al., 2012) investigated an autonomous distributed Vehicle-to-Grid (V2G) control scheme designed to integrate electric vehicles (EVs) into the power grid while satisfying users' scheduled charging requirements. They proposed a V2G control that utilizes frequency deviation at the plug-in terminal to provide distributed spinning reserves, enabling EVs to respond quickly and synchronously to grid fluctuations. The study examined the impact of SoC balance control, scheduled charging requests, and battery characteristics on V2G performance. Results showed that the proposed scheme effectively contributes to grid frequency regulation without compromising user convenience or interfering with traditional load frequency control by thermal power plants. The smart charging control ensures that EVs meet their scheduled charging demands while leveraging idle plug-in times for V2G operations.

(Jamroen et al., 2018) presented an adaptive droop-based control of BESS for voltage regulation in microgrids with high PV penetration. Their strategy aims to eliminate voltage rise caused by peak PV generation and voltage drop due to PV intermittency or high loading conditions. By employing fuzzy logic to adjust the droop coefficient based on allowable voltage deviation limits and the SoC of the BESS, the proposed control strategy enhances performance and avoids undesired battery saturation. Simulation studies demonstrated the effectiveness of the method in regulating voltages within allowable limits and improving system resilience.

In controlling BESS, the SoC should be managed to ensure continued operation. These research studies have explored methods for restoring the SoC to enable efficient continued use. (Liu et al., 2013) explored decentralized Vehicle-to-Grid (V2G) control systems for primary frequency regulation, emphasizing charging demands of electric vehicles (EVs). They proposed two strategies: the Battery SoC Holder (BSH) and Charging with Frequency Regulation (CFR). The BSH maintains the battery SOC while participating in frequency regulation, while CFR combines scheduled charging and frequency regulation. Simulation results on a two-area interconnected system, including wind power integration, demonstrated that these methods effectively enhance frequency stability and meet charging demands. The study concluded that decentralized control offers greater flexibility and efficiency compared to centralized approaches, improving both system stability and EV battery management.

(Jamroen & Sirisukprasert, 2022) proposed a voltage regulation strategy using BESS with SoC management optimized by a self-learning particle swarm optimization (SLPSO) algorithm. The study addresses voltage deviations in distribution networks with high PV penetration. The proposed strategy employs an adaptive droop characteristic to manage voltage deviations while considering SoC constraints. SoC management is designed to restore SoC to nominal levels by compensating BES power based on restoring power and restriction coefficient characteristics. The SLPSO algorithm optimizes the operation of BES by balancing voltage regulation and SoC restoration. Simulation results demonstrate that the proposed strategy outperforms existing methods, achieving up to 12.09% improvement in performance by effectively maintaining voltage within permissible limits and optimizing SoC management.

2.10 Optimization Techniques for BESS Control (PSO, Fuzzy, Multi-objective)

Optimal control of BESS is essential for maximizing their benefits in voltage regulation. Optimization techniques such as PSO, fuzzy logic, and multi-objective optimization are commonly used to determine the best locations for BESS installation and to optimize their control strategies

Table 2.6 Optimization Techniques for BESS

Technique	Principle	Strengths	Example	References
PSO	Population-based search that updates particle "velocity" & "position" toward the global-best and personal-best solutions.	• Simple to code, few hyper-parameters • Fast convergence on nonlinear problems • Easily hybridised with other methods	PSO fine-tunes the V-P / V-Q droop-control slopes of BESS-equipped soft-open-points in a multi-time-scale voltage-control scheme for a 33-bus distribution network.	(Ding et al., 2024)
Fuzzy Logic	Rule-based inference using linguistic variables and membership functions; no precise mathematical model needed.	• Handles uncertainty and imprecise measurements • Can embed expert knowledge directly • Very fast real-time computation	Type-2 fuzzy-logic direct-power control of a PV–Battery inverter; provides voltage regulation and frequency support in a micro-grid prototype, outperforming classical PI.	(Maroua et al., 2024; Zainal Abidin & A. Danapalasingam, 2022)

Table 2.6 Optimization Techniques for BESS (Continued)

Technique	Principle	Strengths	Example	References
Multi-objective	Simultaneous optimizaation of conflicting goals (losses, voltage deviation, cost, risk) producing a Pareto front; selection via decision criteria (CVaR, fuzzy ranking, etc.).	• Yields trade-off solutions instead of a single point • Can incorporate uncertainty (stochastic, robust, DRO)	Distributionally-robust model-predictive control allocates BESS capacity while minimising operating cost and CVaR-based voltage-violation risk on an IEEE-37 feeder.	(Duan et al., 2024; Li et al., 2024; Wang et al., 2024)

2.11 Research Gap and Motivation

Despite the extensive research on voltage stability assessment and control, several gaps remain in the literature, particularly in the context of distribution networks with high renewable energy penetration:

- Limitations of Traditional Voltage Control Methods: Traditional methods such as capacitor banks and tap-changing transformers may not be sufficient to address the voltage fluctuations caused by intermittent renewable energy sources.
- Application for BESS for Voltage Control: While BESS has been shown to be effective for voltage regulation, there is a need for more research on the optimal control strategies for BESS in distribution networks with high renewable penetration.

- BESS Siting Considerations: The optimal placement of BESS in distribution networks is a complex problem that depends on various factors, including network topology, load profiles, and renewable energy generation patterns.
- Joint SoC Restoration and Voltage Deviation: Most studies focus on either voltage regulation or SoC management, but there is a need for integrated control strategies that consider both objectives simultaneously.
- Multi-Objective Optimization Frameworks: Multi-objective optimization techniques can be used to balance competing objectives such as voltage regulation and SoC management but there is a need for more research on the application of these techniques to BESS control in distribution networks.
- Test Cases and Validation: Many studies rely on small test systems or simplified models, but there is a need for more research on the validation of BESS control strategies in large distribution networks with high renewable penetration.

Therefore, there is a need for a comprehensive framework that:

a) Utilizes the L-index for optimal BESS placement, considering the specific characteristics of distribution networks with high renewable penetration.

b) Employs an adaptive droop control strategy that adjusts the BESS output based on the SoC and voltage deviation.

c) Integrates SoC restoration as a primary objective alongside voltage deviation minimization.

d) Evaluates the performance of the proposed framework on standard distribution networks over a 24-hour period under high renewable energy penetration scenarios.

This research proposes an integrated approach combining L-index, BESS Adaptive Droop, and FMOO-PSO to address these gaps and provide a comprehensive solution for voltage stability enhancement in distribution networks with high renewable energy penetration.

2.12 Summary and Research Contribution

This chapter has provided a comprehensive review of the literature on voltage stability assessment and control, highlighting the challenges posed by renewable energy integration and the potential of BESS for voltage regulation. The review has identified several gaps in the literature, including the need for more research on optimal BESS control strategies, BESS sitting considerations, joint SoC restoration and voltage deviation, multi-objective optimization frameworks, and test cases and validation. The following chapters will present the proposed framework for voltage stability enhancement in distribution networks with high renewable energy penetration, which aims to address these gaps and provide a comprehensive solution for voltage stability management.