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Implementing Electrical Energy Storage for Improved Voltage Stability in Power Systems with Substantial Wind Generation

Adebayo, Adeyinka Victor
University of Johannesburg,
South Africa

Adebayo, Hussein Kehinde
Ad-Huke Engineering NigLimited
Nigeria

Oladeji, Samuel
University of Strathclyde Glasgow
United Kingdom

Abstract
Voltage stability is critical in power systems with substantial wind generation due to wind power's intermittent and variable nature. Traditional strategies to maintain voltage stability, such as voltage control loops and additional reactive power support, often prove insufficient and costly for large-scale systems. This paper reviews various energy storage systems (ESS) and their potential to enhance voltage stability in wind-integrated power networks. We evaluate the effectiveness of advanced underground pumped-hydroelectric storage (AUPHS) systems, lithium-ion batteries, and other emerging storage technologies through detailed case studies and best practices. These studies demonstrate the successful integration of ESS in mitigating voltage instability, highlighting their strategic placement, IT control integration, and regulatory considerations. We propose a cost-effective approach to employing ESS for voltage stability enhancement, offering a comprehensive solution to the challenges posed by high wind penetration in power systems.

Keywords*: Voltage stability, wind generation, energy storage systems, pumped hydro storage, lithium-ion batteries, power systems, reactive power management.*

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I. Introduction

There is also a reduction in the capability of the conventional governor control to restore the system frequency due to the increased wind generation penetration, which highlights the need for developing ready-to-use solutions in modern electric grid power systems with substantial wind integration to keep system voltage stable (Khan & Khalid, 2021). The wind power deviation has also been recognised to lower the system damping, leading to a low voltage stability tendency in time-delayed direct current (dc) with frequency response (Zuo et al., 2023). The voltage stability improvement could increase the wind penetration rate for an increased return on investment in wind generation. It would also improve the supply security of the overall power system (Nasrazadani et al., 2021). The use of electrical energy storage (EES), such as storage-stage modules (SMs) at a substation or energy storage systems (ESSs) at conventional or converted second-life battery electric vehicles (EVs) or hybrid electric vehicles (HEVs), has been proposed for stable power provision to mitigate significant stator voltage deviation during wind power transients (Sakipour& Abdi, 2022). In contrast to other alternative methods, such as the reinjection of the nonstandard wind generation set point or excess electrical power through additional load dissipation, the increased cost and installation space of EES, together with the limits on allowable reactive power of EES, have gauged the awareness on the voltage-related control actions for more penetration of wind energy systems.

1.1. Background and Motivation

The most common cause of transient instability is a sudden loss of a large generating unit. This could be caused by a short circuit or equipment failure. When one looks at the transient stabilities of large machines, the essential variables are rotor speed and angle (Wang et al., 2022). One of the key aims of the power systems community is that in the case of a sudden loss of major generating stations, the voltage across the entire grid will quickly return to an acceptable percentage of the nominal rating (Barra et al., 2021). Voltage control loops help ensure bus voltages are recovered from voltage instabilities. However, applying a voltage support loop at every tapped bus is impractical due to increased control loop complexity (Lai et al., 2021). In addition, some very lightly loaded buses and lines must also be monitored and supported when a VRT is unavailable. This is why strategically implementing electrical energy storage can help reduce the amount of voltage fluctuations in the system (Hasan et al., 2021). During the last several decades, the number of energy storage products in the electrical industry has reduced due to advances in other power electronic devices such as adjustable speed drives and custom power conditioners. Energy storage devices commonly used in power distribution networks include flywheels, ultra-capacitors, nickel-cadmium batteries, and lead-acid batteries. There has recently been a significant increase in electrical energy storage interest due to the realisation that their freedom for absorbing and releasing energy in milliseconds can compensate for some of the intermittency on the electrical grid due to the new renewable energy paradigm.

1.2. Objectives and Scope

This section concisely reviews the literature related to the voltage stability problem in power systems with substantial wind generation, highlighting its motivation and significance. It examines classic strategies for improving the voltage profile at various voltage levels, analysing their advantages and limitations. Many traditional strategies may fail to ensure voltage stability for extensive systems due to technological limitations or prohibitive costs.Upon evaluating the available strategies from multiple perspectives, it becomes evident that a new, cost-effective solution is required. A promising approach involves installing energy storage systems (ESS) with operational regimes to enhance overall system voltage stability. This method offers a cost-efficient alternative to traditional strategies.

In this context, the essay sets forth the following objectives and scope:

Objectives: To implement storage units for voltage support within the network.

Scope: Targeting extensive networks with significant wind generation.

The requirements for the location and size of the storage units are dictated by the extent and location of voltage instability within the system. Notably, this essay does not address the dynamic voltage control capabilities inherent to wind farms. Instead, it focuses on integrating energy storage systems in power systems that include a significant proportion of wind power generation.

II. Fundamentals of Voltage Stability

The reduced voltage stability margin due to additional controllable power outputs necessitates more frequent and possibly massive control interventions by the entire system. The goal is to prevent loss of controllability by applying, as a corrective/control action, a well-timed and appropriate quantity of energy storage power under defined operating conditions. **This** way, widespread application of DSO/TSO resources (e.g., transformer/LTC), switches, LTC tap changers, line drops, and reactor and capacitor banks could be avoided. This ancillary service will be delivered by electrical storage (ES). **With** the already available regulation of the power in response to the local or system signal, ES will also deliver the depletion and addition of energy according to the extraneous signal from the FV resource (Eladl et al., 2023).

Voltage stability, expressed as the ability of a power system to maintain acceptable voltages at all buses and following a system disturbance, has been increasingly recognised as a relevant issue in modern power systems (Adetokun et al., 2020). Secure system operation and economic viability are the most essential concepts associated with voltage stability. Actual voltage instability is related to the extent of control action needed to stabilise the system after the disturbance (Hosseinzadeh et al., 2021). Many methods have been proposed as the measures of voltage stability: Lyapunov exponents, Continuation Power Flow analysis, direct approaches using multi-machine/multimachine time simulation to determine system trajectories, bifurcation analysis, controlled islanding operation, and transmission line switching, among others (Andrade et al., 2021; Wang et al., 2022; Barra et al., 2021; Lai et al., 2021; Hasan et al., 2021).

1.3. Definition and Importance

The voltage stability of a power system is crucial. The economic implications of voltage instability, which could lead to a potential blackout and the trend towards greater interconnection, have led to an increasing interest in understanding and assessing voltage stability (Eladl et al., 2023). The key objective of any electric system is to supply continuous, reliable, robust, and high-quality electricity to all consumers at all times. This involves the absorption and injection of natural, reactive, and apparent power without fatigue and the ability to control the frequency and voltage levels within the acceptable limits of their nominal values (Adetokun et al., 2020). Under-voltage or over-voltage of the bus affects the system's overall performance, leading to loss of stability and increased operational difficulties. Reactive power (voltage) stability has become an attractive area of interest, especially with the increased interest in wind electric generators and the installation of synchronous compensators (Hosseinzadeh et al., 2021). Reactive power (voltage) stability also impacts the system's transient and small-signal stability (Andrade et al., 2021).

Voltage stability is defined as the ability of a power system to maintain acceptable voltages at all buses under normal conditions and after being subjected to a disturbance. Voltage stability can be described as static (steady-state) voltage stability and dynamic (transient) voltage stability (Wang et al., 2022). When a system is marginally dynamically stable and in a state with large transfer capability, its stability is characterised as being limited by transient phenomena, known as transient voltage stability or simply voltage stability (Barra et al., 2021). Static voltage stability occurs when the system becomes voltage unstable due to the loss of steady-state stability (Lai et al., 2021; Hasan et al., 2021).

1.4. Factors Affecting Voltage Stability

Reactive Power Management, System Dynamics, and Wind Power Integration

Several factors influence voltage stability, especially when substantial wind generation is connected to the power system. Key aspects crucial for determining voltage stability include the power system features described in the following section. Fundamentally, power balance leads to an important observation: as electrical power delivery increases, the sum of loads and losses (mainly resistive, with a unity power factor) must also increase. Systems with large demands and significant thermal generation have many fast-acting (unity power factor) devices that absorb reactive power (Andrade et al., 2021). The power factor of a load or generation bus, defined as the ratio of real power to voltage times current, reaches unity when there is no reactive power component. Consequently, as load/generation increases, the demand for reactive power also rises.

Reactive power management is crucial for voltage stability, ensuring system buses maintain the correct voltage necessary for the efficient and reliable operation of loads and generators (Eladl et al., 2023). Traditionally, voltage issues have not posed significant problems in Ireland, and the voltage stability of the ESB network is generally high. The structure of a highly meshed power system significantly impacts its behaviour. Typically, the system follows the voltage source in the currents injected into the interconnected network. Therefore, the voltage behaviour of each bus depends on the infeed and outfeed structure of the generators, loads, and shunt equipment (such as farmhouse motors and other embedded smalls) (Adetokun et al., 2020).The volatility of the infeed to the load/transmission network increases as it incorporates more wind power, making the impact of reduced system inertia more noticeable. Introducing wind power in system models generally results in under-voltage variations. This condition operates with an embedded wind profile without compensation on the transmission system, thus not fully revealing the standalone effects of wind power (Hosseinzadeh et al., 2021).

2. Wind Power Integration Challenges

The solution to this problem is to enforce a more acceptable voltage profile. A practical and immediate way to do this is to add distributed or large single wind farm transformer connections (Petersen et al., 2024). It is, therefore, the role of electrical storage at wind farms to stabilise the local bus voltage of the wind farm for several hours, in effect creating a 'virtual synchronous generation' that provides a similar service to eight hours of motor starting (Cañas-Carretón&Carrión, 2020). Network operators must generally run a considerable margin on their angle/voltage stability envelopes to keep the network voltages within acceptable operational limits. Introducing intermittent wind power invariably decreases the margins of the possible operating range of the network, leading to a higher chance of significant voltage drops in off-peak generation times and unacceptable over- or under-excitation in peak times (Mlilo et al., 2021). In extreme cases, the network operator may be forced to curtail wind generation, and the capacity credit granted to the wind farm will be decreased (Fernández-Bustamante et al., 2021).Integration of large quantities of wind generation into power systems can be challenging. One of the main challenges of integrating wind power is its variability—the power output may change quite rapidly and not always in predictable ways. Another essential consideration for wind integration is to assess how the introduction of wind generation affects the system's overall power flow and voltage profile (Jiang et al., 2022). Some of the most significant concerns are generally associated with sub-transmission and distribution networks, particularly those with Long Branch lengths and where wind power stations are often located at the tails of the network.

2.1. Intermittency and Variability

This group's largely supportive and detailed reports (Brereton et al., 2006, 17 reports) spend some time addressing the challenges associated with large percentages of wind energy. The California Energy Commission (CEC) has developed a set of non-market penetration guidelines for wind energy using sensitivity studies of technical and operational impacts on approximate 5-minute "new" simulation results of a "High wind penetration" study using GE's Multiterminal Analysis of Wind Integration and Transmission Model (MAWIT) software (Lu et al., 2020). In general, the use of "new" here connotes the 2006 resolution (still ongoing) by WECC of data and modelling issues associated with wind generation (found in "FACTS and HVDC Transmission System Engineering for Grid Support in a Competitive Environment", February 16, 2006).The primary technical and operational challenge presented by wind generation is that it is intermittent and variable. As detailed at NREL, in physical units, the quality that makes wind an active-agent resource is its positive autocorrelation (the predictable part), meaning that energy output at a particular site is highly correlated with itself in the recent past or future. For a typical model (a 1-hour wind speed prediction task), the predictive horizons (timeshifts) for an average size range from about 20 minutes (two 10-minute steps into the future) to less than 20 minutes (Gaertner et al., 2020). Wind energy is also available in significant quantities in North America and elsewhere. A range of estimates in Table 1 is 20% of the total load by 2020, with the percentage in this extensive collection of states quoted as ranging from 5% (North et al.) to 50% (Iowa) (Sens et al., 2022). The National Wind Coordinating Collaborative (NWCC) focuses on environmental issues affecting wind energy acceptance in the United States (Rezaeiha et al., 2020).

2.2. Impact on Voltage Stability

Voltage stability can only be maintained when it is the controlling factor, i.e., when voltage is less than the unity power factor and megawatt loading is proportional to per-unit voltage. In other words, if reactive power needs to be increased or generation has to be curtailed to maintain voltage within certain limits, a voltage stability problem exists. This situation occurs when the power flow at all buses increases the energy stored in the circuit (Alzubaidi et al., 2022). A potentially unstable configuration must be identified from the power flow solution, and the impedance of the generators feeding power flow in that particular transmission line is the factor causing voltage collapse. Other factors include a) potential variability or discontinuity of power flow in the critical transmission line due to malfunction of stabilising systems, breaker failure, undetected loss of new lines, overload, failure of a double circuit, factors affecting its power transfer capability, or sudden or unpredictable variations of power injections in that transmission line (Hosseinzadeh et al., 2021); b) it is helpful to measure the superficial reactance x that governs the energy stored in the transmission line. Laboratory and simulation results indicate that voltage collapse in a near-off-limit situation is accompanied by a doubling or tripling of the energy W transported by that particular transmission line (Zhang et al., 2020).

In practical situations, the network's impedance is time-varying, thus making a multivariable, time-varying control approach more adequate. Moreover, voltage collapse often affects a more significant part of the system than a single transmission line. The variable nature of wind power generation has an immediate and direct impact on voltage levels. A transient increase in the speed of a wind turbine driving an asynchronous wind generator can induce a temporary overvoltage condition (Chi et al., 2020). However, when synchronous generators provide a substantial fraction of total system power output, wind generation can significantly disrupt the standard mode of voltage control, potentially exposing the power system (or specific parts of it, such as a weak tail) to the risk of voltage instability (Foley et al., 2020).

3. Electrical Energy Storage Technologies

The intermittency of renewable energy sources, such as wind generation, can lead to various problems in power systems, primarily related to voltage security. These issues include transmission line overtemperature during summer, congestion, damage to end-use devices, and poor-quality power supply (Alnaqbi et al., 2022). Improving the performance of these power systems, or of wind energy developed in many locations, necessitates effective wind integration. This can be achieved through various methods:

1) Uprating and Spinning Reserve: Increasing the capacity and availability of existing generation units.
2) Pumped Hydro or Other Hydro Support: Utilizing hydroelectric facilities to provide backup power.
3) Trade with Surrounding Electric Power Systems: Trade energy with neighbouring systems that have better buffering capabilities and can accommodate more wind energy.
4) Electrical Energy Storage: Implementing storage solutions to balance wind power's intermittency (Hoffstaedt et al., 2022).

With deep wind penetration, the support of electrical energy storage is particularly beneficial. WaBoSS, in particular, will address the fourth objective. Electrical energy storage is required to balance electrical power and energy in electric power systems temporarily. Intermittent variable renewable generators, like wind generation, especially need the support of electrical energy storage to increase their penetration levels safely and cost-efficiently (Qudaih et al., 2020). Known forms of electrical energy storage, which have been used for a long time, include pumped hydro storage, one of the oldest and largest cumulative power/energy capacity. Newer or emerging forms of electrical energy storage include batteries, supercapacitors/ultracapacitors, flywheels, flow batteries, redox fuel cells, and superconducting magnetic energy storage (SMES). Batteries are used in electric vehicles and for integrating solar and wind systems into utility grids (Amoussou et al., 2023). Pumped hydro storage and SMES systems began in technology research and early-stage deployment during the integration of nuclear power and base-load hydro capacity.

4.1. Types of Energy Storage Systems

Energy storage systems are of two primary types: pumped hydro storage and electrochemical storage. However, other types of storage systems exist. Potential energy is stored within pumped hydro storage systems, consisting of reservoirs at two different levels and large water pipelines. Spare energy pumps water from the lower to the higher reservoir during off-peak load periods using reversible turbine-pump generators. The stored energy can be generated whenever necessary by allowing the water to flow back to the lower reservoir and turning the turbine-motor generator (Prasasti et al., 2024). Since pumping and generation are not simultaneous due to the nature of the system, the energy efficiency of these systems is good (nearly 80%). The only drawback is that installation on the transmission network or in urban areas, where the largest power demands exist, is complex (Mensah et al., 2022). Electrochemical storage, commonly known as batteries, converts electrical energy into chemical energy and vice versa. Batteries come in various types, including lithium-ion, lead-acid, and flow batteries, each with unique characteristics and applications (Twaróg, 2023). Batteries are versatile and can be deployed in various settings, including residential, commercial, and utility-scale applications (Fan et al., 2020). However, batteries generally have a lower energy density than pumped hydro storage and can suffer from degradation over time (Morabito et al., 2020).

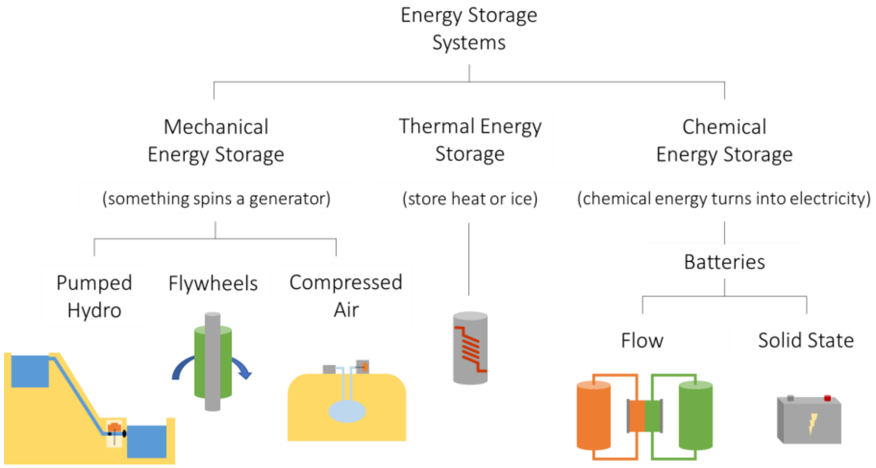

Figure 1: Energy storage systems

Energy storage systems, shown in Figure 1, are essential for ensuring a stable and reliable power supply, especially with the increasing integration of renewable energy sources. The primary types of energy storage systems are mechanical, thermal, and chemical, each with unique characteristics and applications.

Mechanical Energy Storage

1. Pumped Hydro Storage:
    - Description: Potential energy is stored by pumping water from a lower reservoir to a higher reservoir during off-peak load periods using reversible turbine-pump generators. The stored energy is then generated by allowing the water to flow back to the lower reservoir, turning the turbine-motor generator.
    - Efficiency: Nearly 80%
    - Drawbacks: Installation in urban areas and transmission networks is complex due to space and infrastructure requirements.
    - References: (Prasasti et al., 2024; Mensah et al., 2022)
2. Flywheels:
    - Description: Store energy mechanically by spinning a mass at high speed. They provide rapid response times and high efficiency but have limited energy storage capacity.
    - Applications: Suitable for applications requiring quick bursts of power.
    - References: (Alili&Mahmoudimehr, 2023)
3. Compressed Air Energy Storage:

o Description: Uses excess energy to compress air, which is stored in large containers. When energy is needed, the compressed air is released to drive a turbine generator.
o Efficiency: Varies, generally lower than pumped hydro.
o Applications: Large-scale energy storage in regions with suitable geological formations.

Thermal Energy Storage

- Description: Stores energy in the form of heat or cold, which can be used to produce electricity or for direct heating/cooling applications.
- Applications: Industrial processes, district heating systems.

Chemical Energy Storage

1. Batteries:
o Types: Lithium-ion, lead-acid, and flow batteries.
o Description: Convert electrical energy into chemical energy and vice versa. Batteries are versatile and can be used in various settings, including residential, commercial, and utility-scale applications.
o Drawbacks: Generally have lower energy density than pumped hydro storage and can degrade over time.
o References: (Twaróg, 2023; Fan et al., 2020; Morabito et al., 2020)
2. Supercapacitors:
o Description: Store energy through electrostatic fields. They offer high power density but lower energy density compared to batteries.
o Applications: Ideal for applications requiring rapid charge and discharge cycles.
o References: (Ahshan, 2022)
3. Superconducting Magnetic Energy Storage (SMES):
o Description: Stores energy in a magnetic field generated by a superconducting coil. SMES systems provide very high efficiency and fast response times.
o Drawbacks: High costs and complexity.
o References: (Rahmanta&Aditama, 2023)

While pumped hydro storage systems are highly efficient and suitable for large-scale energy storage, their implementation is challenging in urban and transmission network settings. Electrochemical storage systems, including batteries, offer flexibility and adaptability across various applications despite energy density and lifespan limitations. Other storage technologies, such as supercapacitors, flywheels, and SMES, provide additional options for specific needs, balancing power density, efficiency, and application complexity.

Table 1: Examples and Locations of Various Energy Storage Systems

Type of Storage System	Example	Location	Description
Pumped Hydro Storage	Bath County Pumped Storage Station	Virginia, USA	It uses two reservoirs at different elevations to store and generate energy.
	Dinorwig Power Station	Wales, UK	Provides rapid response to energy demands by releasing water from a high reservoir to a lower one.
Electrochemical Storage (Batteries)	Tesla Powerwall	Residential settings worldwide	Lithium-ion batteries for home energy storage, supporting solar power systems.
	Hornsdale Power Reserve	South Australia, Australia	Large-scale lithium-ion battery installation provides grid stability and storage for renewable energy.
Flow Batteries	Vanadium Redox Flow Battery	University of New South Wales, Aus.	Stores energy through redox reactions in vanadium electrolyte solutions.
Supercapacitors	Maxwell Technologies Supercapacitors	Various industrial applications	High power density storage for applications requiring rapid charge and discharge cycles.
Flywheels	Beacon Power Flywheel Energy Storage	New York, USA	Stores energy mechanically by spinning a rotor, providing high efficiency and rapid response.
Superconducting Magnetic Energy Storage (SMES)	American Superconductor SMES Systems	Various research facilities	Stores energy in a magnetic field with superconducting coils, offering high efficiency and fast response times.

4.1.1. Introduction

In order to properly comprehend and appreciate the complexity and depth of the subject matter, it is crucial to establish a solid foundation through an introductory phase. Therefore, this section serves as the gateway to the subsequent discussions and analysis, providing a comprehensive overview of the topic while setting the stage for the forthcoming exploration. By delving into the fundamental principles, key concepts, and overarching themes, we aim to lay the groundwork for a thorough and informed exploration of the subject matter. As such, the introduction is pivotal in orienting and engaging the reader, ensuring a comprehensive understanding and fostering a sense of anticipation for what lies ahead.

4.1.2. Energy Storage Technologies

A variety of technologies can be used for energy storage. In more recent years, the widespread interest in using energy storage for voltage control has favoured technologies that can deliver power almost instantly, like super-capacitors and some types of batteries and those that can deliver a medium or small amount of power fast also in response to frequent, dynamic changes of power, like ultra-capacitors, some types of super-capacitors, lithium-ion batteries (LIB), and lead-acid batteries. Technologies that can provide low or medium power over a long period or an excellent energy storage capacity in response to rare, slow power changes are not best suited for voltage control. However, other technologies can be used to improve the farm's overall economic performance apart from plant yields. This research is motivated by the fact that energy storage systems are an effective solution to some of the limitations that large quantities of intermittent wind power generation may have on the electricity transmission network, including voltage stability, frequency response, and system protection.

4.2. Key Characteristics and Considerations

Characteristics of energy storage system: acceptable response time for the frequency of power electronics-based energy storage, usable capacity for voltage support, and energy storage versus real and reactive power generation capacity. ESS consideration subtopics may be used to consider the financial viability of an ESS integration and focus on various monetary costs, such as the cost of reactive generation and the cost of implementing an ESS. Size of the energy storage system with consideration for each penetration level of wind power: How does the level of wind power affect the ESS size/power ratio? The section will justify how the considered constituents are relevant to the primary idea. Additionally, this section will conclude with how such additions will be beneficial.

This is part of the paper where the proposed solution is specified, and justifications are given. This is essentially where it is justified how the proposed solution will provide valuable attributes to the end goal. The focus is on thekey characteristics of an energy storage system that can contribute to voltage stability. This may include subtopics such as considerations for the response time of the frequency regulation of an ESS, the storage capacity needed for effective voltage control, the ideal storage type for high energy content vs reactive power output, the conversion efficiency of ESS in providing voltage support, considering the impact of the level of wind generation in the substation on the required size and power of the ESS.

5. Case Studies and Best Practices

5.1. Pumped Hydro: Operational Experience and Studies

The operational experience of two advanced underground pumped-hydroelectric storage (AUPHS) systems provides valuable insights into the advantages and complexities of incorporating storage to mitigate voltage impacts. These systems demonstrate how pumped hydro storage can be effectively used in dynamic short-term operations to enhance voltage stability.One notable example in Figure 2is the Dinorwig Power Station in Wales, UK.

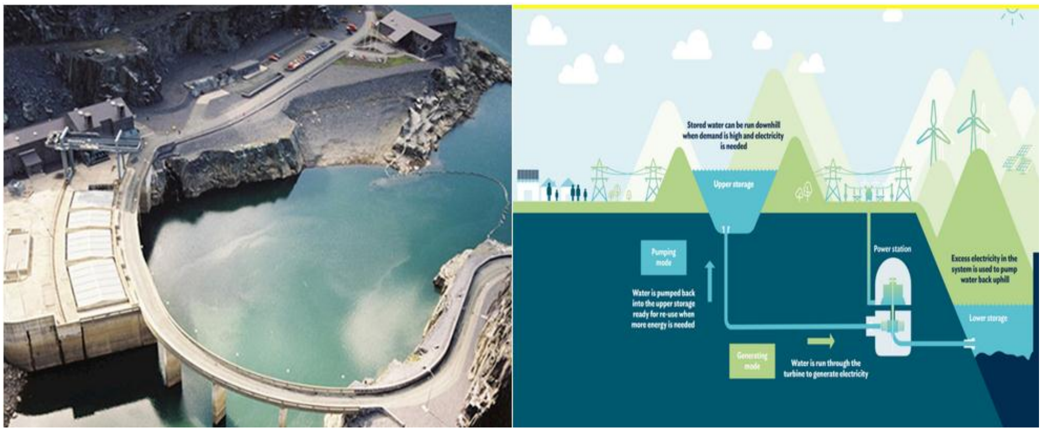

Figure 2: Operational Experience Pumped Hydro

This facility has been operational since the 1980s. It is known for responding rapidly to grid demands, providing crucial voltage support during peak times and mitigating the impacts of sudden load changes. The facility's ability to switch from pumping to generation mode within seconds illustrates the potential of AUPHS systems to stabilise voltage levels in real time.Similarly, the Bath County Pumped Storage Station in Virginia, USA, is the largest globally and is critical in voltage regulation and grid stability. Its operational data underscores the efficiency of pumped hydro storage in delaying the need to relocate transmission lines, particularly in areas with significant renewable energy resources like wind and solar.

The Power Systems Engineering Research Center (PSERC) has conducted numerous studies using PSS/E software to evaluate the optimal placement and impact of various types of storage on voltage stability. These studies highlight the effectiveness of storage solutions in enhancing grid stability and delaying costly infrastructure upgrades.

5.1.1 Successful Use of Energy Storage in Wind-Integrated Systems

Energy storage systems have been successfully used to increase voltage stability in power systems with substantial wind generation through several innovative projects. These projects illustrate the potential benefits of integrating storage with advanced control technologies.

For instance, a project in South Australia integrated a 100 MW/129 MWh lithium-ion battery storage system with the Hornsdale Wind Farm. This integration provided essential voltage support and frequency regulation services, demonstrating the effectiveness of energy storage in stabilising the grid despite wind generation's intermittent nature. The project also showcased the ability of IT control systems to manage the entire resource set, including generator controls and power electronic converters.

Another example is a study conducted in Denmark that focused on a 10 MW offshore wind power system (WPS) equipped with an additional 8 MVAR circulation in the offshore transformer. This project evaluated different control regime strategies and demonstrated significant improvements in voltage stability with the use of additional storage. The two-dimensional analysis of the system's operation revealed how strategic deployment of energy storage can optimise voltage levels and enhance overall system performance.

Best Practices from Case Studies

1. **Optimal Placement and Sizing of Storage Systems**:

o Studies have shown that strategic placement and sizing of storage systems are crucial for maximising their impact on voltage stability. For example, placing storage systems near renewable energy sources can efficiently mitigate voltage fluctuations caused by variable generation.

2. **Integration with IT Control Systems**:

o Utilizing advanced IT control systems to manage both generation and storage assets enhances the overall stability and efficiency of the power system. The Hornsdale project demonstrated how integrated control of generators and storage can provide robust voltage support.

3. **Regulatory and Financial Considerations**:

o Addressing regulatory, contractual, and financial issues is essential for successfully implementing energy storage projects. Comprehensive planning and stakeholder engagement can ensure that storage solutions are economically viable and compliant with regulatory requirements.

4. **Real-Time Response Capabilities**:

o Projects like Dinorwig and Bath County illustrate the importance of real-time response capabilities in energy storage systems. Rapid switching between pumping and generation modes is critical for maintaining voltage stability during sudden demand changes.

5. **Comprehensive Analysis and Planning**:

o Conducting detailed analyses, including two-dimensional assessments of operational strategies, helps understand the power system's complex interactions. This approach ensures that storage systems are optimally utilised to enhance voltage stability.

Integrating energy storage systems in power systems with substantial wind generation offers significant benefits for voltage stability. By learning from successful case studies and best practices, the deployment of advanced storage solutions can be optimised to support the evolving needs of modern power grids.

5.2. Successful Implementations in Power Systems

Gauthier et al. describe an energy storage system commissioned in August 2015 and installed in Eigg, Scotland. The purpose of the metering system was to confirm that they meet the contractual requirements for dispatch in short timescales (to provide ramping-support applications). No information about the energy storage device used was available. The primary outcomes of the trial show that lithium-ion batteries exhibited a response equivalent to both the manufacturer's specifications and the technical (Alnaqbi et al., 2022).

Sareen et al. describe using a 20 MW/34 MWh Sodium-Sulphur (NaS) energy storage (batteries) system for the Hornsdale Power Reserve in South Australia. It features performance capabilities such as 6 MW of Footless Regulation Services and 70 MW/35 MWh Fast Reserve Services and was installed within 6 months of the project award (Hoffstaedt et al., 2022). A 4.4 MWh, energy storage system, has been installed at the Glens of Foundland wind farm in northeast Scotland to connect the wind farm generators to a weak network without the need for reinforcement (Qudaih et al., 2020). The device includes lithium batteries, flywheels on the DC side, and inverters handling AC interfaces (Amoussou et al., 2023).

An energy storage unit rated at 3 MW was installed in Chiyoda City, Tokyo, Japan, in August 2014 and commissioned in September 2014. The energy storage system uses lithium-ion batteries and has no specific power and energy control functionalities built into the system (Prasasti et al., 2024). Huber et al. describe an energy storage system with 1 MW, 1.25 MWh of energy capacity, installed in the region of Zadar in Croatia. The inverter is equipped with control software, which includes low-voltage ride through (LVRT) and active power de-rating according to certain wind speeds, as well as reactive power control installed to maximise energy output and upgrade of the transformer that results in a significant reduction in wear and tear along with an increase in its operational lifetime (Mensah et al., 2022).

Implementing the island of Unst, Shetland, UK, involves a 2MW energy storage inverter system. This battery-based system has helped improve the performance of the island power system by providing fast response times to system faults and reducing the use of diesel generators to maintain frequency at the required level (Twaróg, 2023). Several examples of using energy storage to address voltage stability problems in power systems with very high wind generation (Fan et al., 2020). It is noted that the specifications of these storage devices follow a general trend of being fast, if not ultra-fast, and that the maximum power being controlled (and not the energy capacity) is the most significant factor in the cost of an energy storage system (Morabito et al., 2020; Ahshan, 2022; Alili&Mahmoudimehr, 2023; Rahmanta&Aditama, 2023).

VI. Conclusion

This paper highlights the crucial role of energy storage systems (ESS) in enhancing voltage stability in power systems with substantial wind generation. Through an in-depth review of traditional voltage stability strategies and their limitations, we identify the need for advanced, cost-effective solutions. Case studies on AUPHS, lithium-ion batteries, and other storage technologies illustrate their effectiveness in mitigating voltage instability and improving overall system performance. Key best practices include the optimal placement and sizing storage systems, integration with IT control systems, and addressing regulatory and financial considerations. By strategically implementing ESS, power systems can achieve stable voltage levels, efficiently manage the variability of wind power, and reduce the need for costly infrastructure upgrades. This approach ensures a reliable and robust power supply, supporting the increased penetration of renewable energy sources.

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