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Accelerating energy transition through battery energy storage systems deployment: A review on current status, potential and challenges in Malaysia

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ABSTRACT

This paper examines the present status and challenges associated with Battery Energy Storage Systems (BESS) as a promising solution for accelerating energy transition, improving grid stability and reducing the greenhouse gas emissions. Serving as a key facilitator, BESS aids in integrating and balancing variable renewable energy sources to maintain a stable energy supply by storing excess energy and releasing it as needed. While global BESS deployment is on the rise, it falls short of aligning with storage capacity projections for a net-zero scenario, necessitating heightened efforts. In Malaysia, BESS is recognized as vital for system stability, prompting the government's plan to install 5 units of 100 MW BESS capacity by 2034. The establishment of grid codes and regulations is critical for the safe and reliable integration of BESS. Although specific guidelines for BESS grid integration are limited, certain sections from existing guidelines for Large Scale Solar (LSS) connections can be adapted. To enable widespread BESS implementation, challenges such as scalability, grid integration, and cost need to be addressed. Robust guidelines and regulations must be developed to successfully integrate BESS into the grid and pave the way for a sustainable energy future. The motivation behind this study is to assess the current state of research on BESS and its integration into power systems, identifying challenges and opportunities associated with this technology. Additionally, the paper aims to shed light on the role of grid codes in governing the connection and operation of BESS and other energy storage systems within the grid.

1. Introduction

Countries around the world are recognizing the need to shift towards a low-carbon energy system, therefore undergoing energy transition towards more sustainable and renewable energy sources. The Paris Agreement, coordinated by the United Nations Framework Convention on Climate Change (UNFCCC), has received commitments from many nations, to decrease their greenhouse gas (GHG) emissions to levels that would prevent global temperatures from rising beyond 2 °C [1,2]. To achieve this goal, all participating countries have committed to reducing their greenhouse gas emissions, including carbon dioxide, methane, and nitrous oxide, which are the main contributors to climate change.

According to the Intergovernmental Panel on Climate Change (IPCC), energy industry is the largest contributor to global greenhouse gas emissions, accounting for approximately 75% of emissions [3]. This includes emissions from the production, transportation, and consumption of fossil fuels such as coal, oil, and gas. Therefore, to accelerate energy transition, it is important to reduce greenhouse gas emissions from energy industry by transitioning to cleaner energy sources such as renewable energy and electric vehicles [4]. The adoption of cleaner energy sources will not only help to reduce greenhouse gas emissions but also promote sustainable development and create new employment opportunities in the clean energy sector.

Decarbonizing energy sector is a challenging task that requires significant effort. The existing fossil fuel-based technologies cannot achieve

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List of abbreviations

BESS	Battery Energy Storage Systems
UNFCCC	United Nations Framework Convention on Climate Change
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
RE	Renewable Energy
GAO	Government Accountability Office
IEA	International Energy Agency
EERA	European Energy Research Alliance
REC	Renewable Energy Certificate
CAGR	Compounded Annual Growth Rate
GDP	Gross Domestic Product
EC	Energy Commission
GSO	Grid System Operator
FiT	Feed in Tariff
NEM	Net Energy Metering
CGPP	Corporate Green Power Programme
VPP	Virtual Power Plant
TSO	Transmission System Operator
NER	National Electricity Rules
DMAT	Dynamic Model Acceptance Test
AEMO	Australia Energy Market Operator
PSS	Power System Studies
MGC	Malaysia Grid Code
TSRS	Transmission System Reliability Standards
SOC	State of Charge
BMS	Battery Management System

decarbonization without incurring significant additional costs, such as those associated with carbon capture, utilization, and sequestration. Therefore, there is an urgent need to explore and invest in emerging technologies such as renewable energy and energy storage, which can help to reduce greenhouse gas emissions and support the transition towards a low-carbon energy system [5]. These emerging technologies present a significant opportunity to create a more sustainable and resilient energy system that can mitigate the impacts of climate change and reduce dependence on fossil fuels.

Energy storage plays an important role in addressing decarbonization in energy sector by helping to integrate and balance variable renewable energy (RE) sources such as wind and solar. These sources can produce energy intermittently, depending on weather conditions, so energy storage technologies can help to store excess energy when it is available and release it back into the grid when it is needed [6,7]. This helps to ensure that renewable energy is available when demand for energy is high, without relying on fossil fuel-based energy sources to fill in the gaps [8]. Since more renewable energy (RE) sources such as wind and solar with intermittent nature will be connected to the grid, excess of energy can be stored and used later. Other multiple energy storage system functions, such as short-term balancing and operating reserves, ancillary services for grid stability, frequency regulation in microgrid system [9], delaying the investment in new transmission and distribution lines, long-term energy storage, and restarting the grid after a blackout, are required.

Current research is lacking on the role of Battery Energy Storage Systems (BESS) in the process of energy transition [10]. Energy transition typically refers to the shift from conventional, fossil fuel-based energy sources to cleaner and more sustainable alternatives. BESS, which involves storing energy for later use, can play a crucial role in this transition by providing a means to store and use renewable energy when needed. Despite the progress being made, the predicted increase in grid-scale storage capacity is now out of step with the net-zero scenario and calls for more work [11]. BESS is a type of electrochemical energy storage system (ESS) that has seen the most growth in recent years out of all other energy storage types. This is mostly because BESS has the following benefits [12].

- Flexible in its ability to be built into different sizes and shapes as needed for the ESS application.
- Unlike some ESS types, where special location of installation is necessary (e.g. subterranean caverns, water dam, etc.), BESS may be built practically everywhere.
- Along with the increase in battery demand, the technology development has gotten more advanced. Energy and power density of BESS is among the greatest available solutions at a reasonable cost.

Therefore, this paper aims to highlight the status, challenges, and benefits of BESS in accelerating energy transition and emphasizes the effort required to successfully decarbonize the energy sector. It implies that more attention and investigation are needed in understanding how BESS can contribute to the broader goal of transitioning to cleaner and more sustainable energy sources. This paper provides a comprehensive review of the current status, challenges and benefits of BESS application in accelerating energy transition in Malaysia, taking into account the current landscape of BESS installation globally by emphasizing the increasing importance of BESS as a promising solution for integrating renewable energy sources, reducing greenhouse gas emissions and integration into the grid power system.

2. Current status of BESS around the world

According to United States of Government Accountability Office (GAO) [13], climate change is anticipated to have extensive consequences on the electricity grid that might cost billions and affect every component of the grid, including generation, transmission, and distribution as well as power demand. Energy storage would be one of the potential solutions to mitigate these adverse effects with the advantages it can offer.

International Energy Agency (IEA) has developed a roadmap which outlines a comprehensive plan to achieve global net-zero emissions by 2050 [14]. The roadmap stresses the urgency of action, emphasizing that immediate and bold steps are required to limit global warming to 1.5 °C above pre-industrial levels. It highlights that a rapid transformation of energy sector is crucial, as it is responsible for the majority of greenhouse gas emissions. Fig. 1 demonstrates the installed BESS worldwide in the net-zero scenario target from Year 2015–2030 where it shows that actions need to be taken to install BESS with dramatic amount, to achieve 680 MW capacity by 2030.

Research from International Energy Agency (IEA) stated that the deployed grid-scale battery storage (BESS) capacity should increase 44-fold to 680 GW in the Net Zero Scenario target between 2021 and 2030 [11]. Up from 6 GW in 2021, about 140 GW of capacity is created in just 2030. Annual additions must increase dramatically, reaching an average of over 80 GW per year over the years 2022–2030, in order to stay on pace with the Net Zero Scenario target.

BESS integrated into the power system have different specifications and integration methodologies. A summary of 11 demonstration projects for BESS integration from various European nations is provided in Ref. [2]. Members of the European Energy Research Alliance (EERA) Joint Program on Smart Grids, Sub-program 2, Storage Integration, are responsible for carrying out these projects. To coordinate and synchronise their research and carry out the European Union's 2008 strategic technology strategy, EERA fosters collaboration among universities and public research centres across all of Europe [15]. One country with a significant deployment of BESS projects is South Korea. The Korean

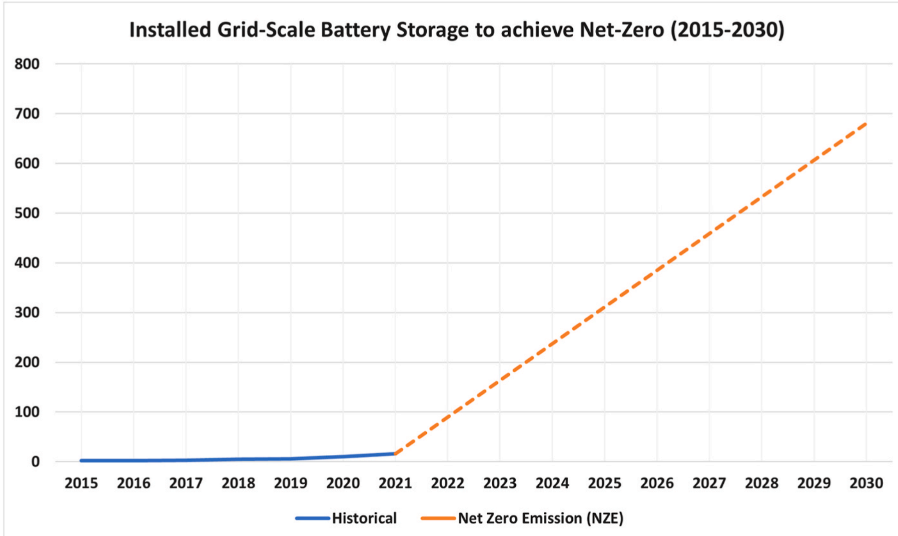

Fig. 1. Installed grid-scale BESS in the net-zero scenario (2015–2030) (Source:IEA).

government has been using BESS for 500 MW of frequency regulation since 2011. This is reinforced by generous multiples of issued Renewable Energy Certificate (REC) [16].

Fig. 2 describes the historical worldwide annual grid-scale BESS addition from Year 2015–2021. United States is the biggest contributor to BESS deployment with 2.9 GW capacity in 2021, followed by China 1.9 GW, Europe 1 GW, South Korea 0.1 GW and the rest of the world 0.5 GW which the numbers are gradually increasing over the time period. The BESS adoption originates from factors due to the evolving energy landscape and the need for more sustainable and reliable power system. The main factors that are driving its adoption includes renewable energy integration, grid stability and reliability, peak shaving and load management, energy arbitrage, policy and regulatory support, environmental concerns and resilience and emergency preparedness.

As the end of 2021, the total installed grid-scale battery storage capacity was close to 16 GW, with the majority of which had been added in the preceding five years. In 2021, more than 6 GW (GW) of storage capacity are built, representing a 60 percent increase over the previous year. The United States, China, and Europe lead the market with gigawatt-scale additions, respectively.

Another important aspect before deciding to invest in BESS is the projection of compounded annual growth rate (CAGR) which is a crucial metric indicating the potential of the BESS market in the coming years. CAGR would depend on several factors such as the initial investment cost, the cost of maintenance and operations, and the revenue generated

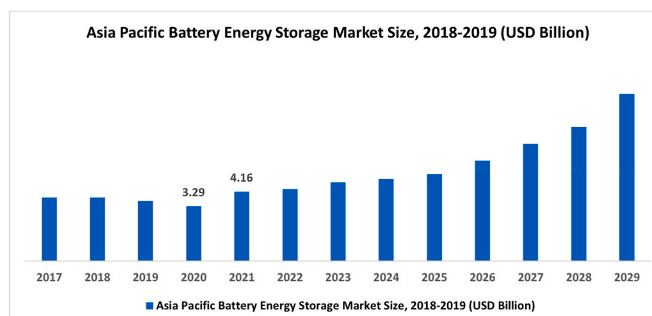

Fig. 3. Asia Pacific energy storage market size (USD billion) [17].

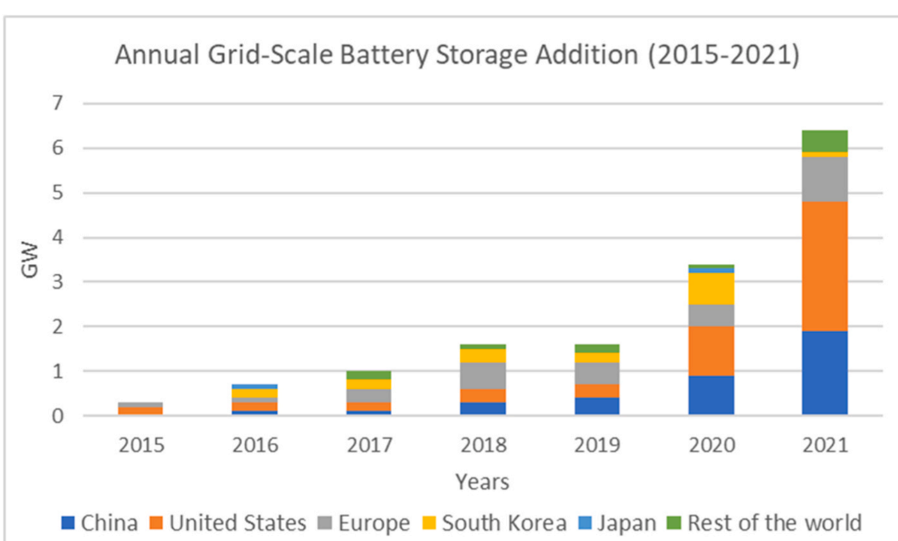

Fig. 2. Annual grid-scale BESS addition for 2015–2021 (source: IEA).

from selling the stored energy.

Fig. 3 demonstrates the Asia Pacific CAGR of 16.3% over the projection period, it is expected that the global market for battery energy storage would increase from $10.88 billion in 2022 to $31.20 billion by 2029 [17]. Therefore, it is projected that more BESS will be installed progressively in the Asia Pacific region.

3. Current status and potential of BESS deployment in Malaysia

Malaysia, as a signatory to the Paris Agreement, is committed to reducing its greenhouse gas emissions. The country aims to decrease the emissions intensity of its GDP by 45% by 2030 compared to the levels in 2005. To achieve this goal, Malaysia plans to increase the proportion of renewable energy sources, including solar, wind, hydro, and biomass, in its energy mix [18]. By 2035, it is expected that solar energy penetration will reach 30% of the anticipated peak demand. However, the rise in renewables poses challenges to system stability. To address this concern, critical technical enablers, such as the implementation of battery energy storage systems (BESS), play a crucial role in meeting the strategic goal [19].

In August 2023, the Malaysian government introduced the National Energy Transition Roadmap (NETR) to expedite and guide the national energy transition. The roadmap includes a substantial reduction in coal usage, with a target of increasing renewable energy (RE) from 4% in 2023 to 22% in 2050. Recognizing the intermittent nature of renewable energy, particularly in Malaysia, the development of energy storage, especially BESS, is considered essential, and NETR identifies BESS as a key initiative [20]. Incentives and subsidies for development and deployment of BESS are also included NETR due to the fact that it is a critical enabler in order to attain higher RE penetration in the country.

The country's generation master plan outlines the deployment of BESS, as planned by the government. The Energy Commission (EC) of Malaysia, as reported by Ref. [21], has scheduled the installation of five units of BESS with a capacity of 100 MW each year between 2030 and 2034. This initiative aims to address system stability issues arising from the increasing use of RE and aligns with the country's 2021–2039 energy transformation plan. The Malaysian Grid System Operator (GSO) will conduct a trial project for BESS connected to the grid before the full implementation into the grid system begins in 2030. The global and Malaysian transition to renewable energy heavily relies on expanding battery usage to balance the grid, enhance the adaptability of low-carbon power, and foster a more sustainable power ecology.

The transition to renewable energy in Malaysia and around the world will depend heavily on expanding the usage of batteries which help to balance the grid, enhancing low-carbon power's adaptability, and fostering a more sustainable power ecology [22].

Fig. 4 shows the BESS deployment plan in Malaysia which 1 unit of 100 MW BESS capacity will be installed starting from Year 2030 and addition of 100 MW in the subsequent four years. By end of 2034, 500 MW of BESS will be installed various locations in the country to support the renewable energy integration and the transmission grid. By 2035, it is anticipated that Malaysia's RE capacity mix will reach a level of 40%. In order to support such strategic aim, the grid infrastructure would be significantly improved and strengthen with the help of crucial technical enablers like BESS technologies. In light of this, the Malaysian government has put in place a number of programmes to enhance the production of solar PV. The Feed in Tariff (FiT), Large Scale Solar (LSS), and Net Energy Metering (NEM) and Corporate Green Power Programme (CGPP) are examples of these programmes [23].

Presently in Malaysia, there are five units of BESS deployed as research projects at distribution level positioned in various locations such as research centre, education campus, commercial centre and university which the purpose is for peak demand reduction, energy arbitrage and grid ancillary services [24].

BESS for behind-the-meter and the virtual power plant (VPP) project have been implemented in Malaysia as part of research initiatives.

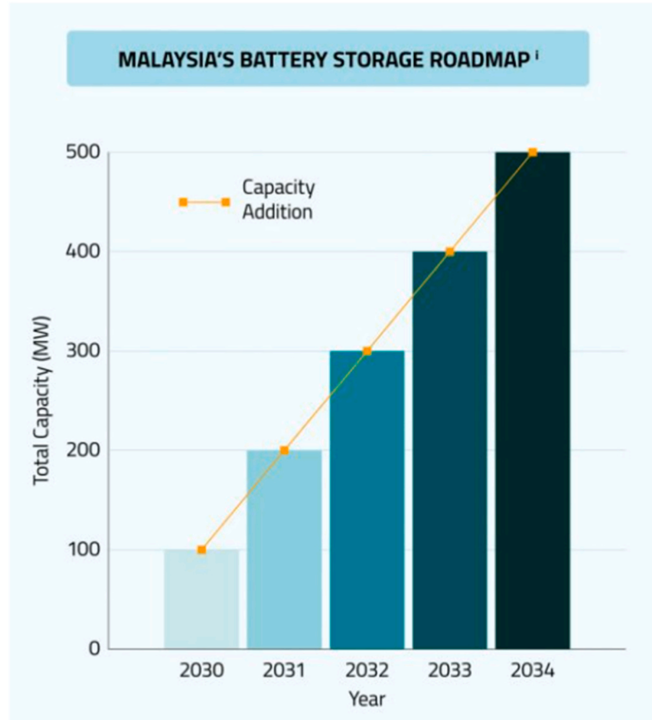

Fig. 4. BESS roadmap in Malaysia (2030–2034) [21], [22].

However, there has not been any deployment of utility-scale BESS which are connected to transmission level thus far [25]. The large capital expense is the key obstacle to implementing such initiatives. According to Ref. [26], increased mass production of battery packs will result in a 50% drop in battery prices from 2018 levels by 2030. However, commercial projects like BESS will continue to be difficult to complete without enough government incentives and restrictions. Ref [19] stated there will be increased deployment of RE with a 40% RE target by 2035, when solar penetration hits 30% during peak demand. As a result, particular actions must be taken to ensure system stability, such as the introduction of energy storage technology and increased system flexibility after 2025.

4. BESS grid interconnection

Grid interconnection for BESS is a vital component in the transition to a more sustainable and resilient energy system. This integration allows BESS to interact with the grid, providing a range of services that contribute to grid stability, reliability, and efficiency. The following subsections describe some considerations to guarantee the safety and reliability of BESS grid interconnection.

4.1. Standards and guidelines

Grid codes are a set of technical and operational requirements that govern the connection and operation of electricity generation and storage systems to the grid. Grid codes employed for BESS ensure the safety and reliability of the grid, while also enabling the integration of renewable energy sources and energy storage systems. It is used to establish the technical requirements for interconnecting BESS and other energy storage systems to the grid, including voltage and frequency regulation, power quality, and other technical parameters. Grid codes play a critical role in establishing the line between the demands of safe grid operation and obtaining the largest feasible proportion of Renewable Energy Sources (RES) including BESS in order to produce a cost-effective energy mix. Table 1 describes the existing guidelines and

Table 1
Standard and grid codes for BESS integration in power system.

Standards/Grid Codes	Purpose	Countries which have implemented the standard
National Electricity Rules (NER) [27]	Regulations that govern the National Electricity Market (NEM) mainly on the market operation, grid connection and access, reliability and security of power system, network planning and investment, market conduct and competition.	Australia
Dynamic Model Acceptance Test (DMAT) Guideline [28]	A guideline used in the power systems domain to validate and accept dynamic models used for simulations and control system. These tests are essential to ensure that the dynamic models accurately represent the behaviour of the actual systems they are intended to simulate or control.	Australia
Malaysia Grid Code (MGC) [29]	Standards established by the Malaysian Energy Commission to regulate the operation and planning of the electric power system in Malaysia.	Malaysia
Transmission System Reliability Standards (TSRS) [30]	Requirements established by system operator to ensure the reliable and secure operation of the electric transmission system. The standard covers various aspects of the transmission network, including planning, operation, maintenance, and contingency management.	Malaysia
Guidelines on LSSPV for Connection to Electricity Networks [31]	A guideline which consists of the technical standard for LSSPV plant such as design, installation, and operation. It also includes the connection process and details on grid code compliance and power quality.	Malaysia
IEEE 1547 [32]	Standard for interconnecting distributed energy sources to the power system which covers the aspects on interconnection, safety, power quality and testing requirements.	United States
UL 9540 [33]	Safety standard for energy storage systems including battery. It covers safety aspects such as thermal runaway, fire safety and electrical safety.	United States
IEC 61850 [34]	International standard for the design and integration of communication networks within substations. It is relevant for the communication infrastructure needed for smart grid applications, including the integration of energy storage.	International
Australian Grid Connection Standard AS/NZS 4777 [35]	Standard for grid connection of energy system including energy storage.	Australia and New Zealand

regulations for BESS interconnections to the grid.

Prior to any BESS integration to the grid, power system studies need to be conducted to assess the capability of the BESS during various operating conditions. In United Kingdom (UK), the grid code requirements [36] have been released by Transmission System Operator (TSO) for BESS interconnection with wind plants as discussed in Ref. [37] which includes reactive power capability, load flow studies, short circuit levels, fault ride-through capability, voltage and frequency control regulation. Grid codes differ greatly from one country to another due to their close relationship to the type of generation characteristics and requirements set by the network operator. For example, in contrast to a large and strongly interconnected system, such as the French transmission system, the frequency response requirement is typically stricter in Great Britain and Ireland since the grid is a relatively isolated system [38].

In Australia, any generator and customers connection applications to the grid need to comply with the National Electricity Rules (NER) [27] which has rigorous and thorough technical requirements on power system studies of the overall transmission network. Other than that, there is also a Dynamic Model Acceptance Test (DMAT) guideline [28] which has been set by Australia Energy Market Operator (AEMO) prior to accept any new or updated plant models from equipment manufacturers to use in system studies and due diligence assessments for connection applications, registrations and plant alterations.

As of 2022, the Energy Commission (EC) of Malaysia has not issued any guidelines for the interconnection of Battery Energy Storage Systems (BESS) to the electricity network. This absence is attributed to the lack of immediate plans to install a BESS at the transmission level until 2030. However, it is noteworthy that in 2016, the EC released guidelines for Large Scale Solar (LSS) connections to the electricity network [31]. These guidelines encompass the scope of Power System Studies (PSS) and can be inferred to be applicable to various types of generation interconnections, including BESS.

These guidelines entail specific requirements such as power plant modelling, power flow and contingency analysis, short circuit analysis, and assessment of reactive power capability when integrated with the grid. The detailed criteria for benchmarking in Power System Studies are outlined in the Malaysia Grid Code (MGC) [29] and the Transmission System Reliability Standards (TSRS) [30].

4.2. Adaptation in regulatory evolution and technological advancements

As technology continues to evolve, it is crucial for interconnection standards to adapt and keep pace with these advancements. Regulatory bodies play a vital role in ensuring that these standards are updated to accommodate new technologies and to promote seamless integration of renewable energy sources into the grid [39]. These standards are continuously evolving to keep up with the pace of technological advancements in the field of energy storage. The evolution of BESS interconnection standards not only reflects the advancements in technology, but also the changing landscape of the energy industry as a whole.

There is a need for greater collaboration between stakeholders including utilities, equipment manufacturers, and regulatory bodies to develop comprehensive and consistent interconnection standards that can support the reliable and efficient integration of BESS into the grid.

Standards organizations such as the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) play a critical role in shaping the development of interconnection standards [40]. These organizations bring together experts from various fields to establish consensus-based standards that are essential for ensuring the reliability, safety, and interoperability of interconnected systems.

Furthermore, the involvement of standards organizations is crucial in addressing the technical complexities associated with the integration of battery energy storage systems into the grid. Standardized testing procedures developed in conjunction with these organizations can help validate the performance and safety of BESS technologies, thereby instilling confidence in their seamless integration with the grid [41].

In addition to technical specifications, standards organizations also contribute to the establishment of cybersecurity measures for interconnected systems [42]. By providing guidelines for secure communication protocols and data protection, these organizations help fortify the resilience of interconnected energy infrastructure against potential cyber threats.

The collaborative efforts of standards organizations, along with industry stakeholders and regulatory bodies, will be instrumental in driving the continued evolution of BESS interconnection standards. By staying abreast of technological advancements and industry best practices, these organizations can ensure that interconnection standards remain adaptive and responsive to the dynamic landscape of grid modernization.

5. BESS benefits, applications and recent advances

The integration of BESS in power systems brings a multitude of benefits and applications. It has showcased its pivotal role in diverse applications, from energy arbitrage to frequency regulation. Recent advances include grid-forming technology and second-life batteries, while there are various breakthroughs such as Li-Ion BESS cost reduction, battery technology and innovative control systems which promises a positive environmental impact.

5.1. BESS benefits and applications

BESS offer a myriad of advantages and find diverse applications in power systems. They enhance the reliability, efficiency, and resilience of power systems, simultaneously lowering costs and emissions. BESS plays a crucial role in facilitating the integration of renewable energy sources, aligning with grid code requirements to improve grid stability and reduce carbon emissions. Moreover, BESS contributes ancillary services to the grid, including frequency regulation, voltage control, and black start capability. In instances of grid disruptions, BESS can serve as a reliable backup power source for critical loads, expediting power restoration. Additionally, there is the potential for reduced electricity bills when BESS is utilized for activities such as peak shaving or participation in time-of-use pricing programs.

On the other hand, BESS is essential to the grid resilience because of its ability to support the renewable energy sources plant so that it complies with grid code requirements. At the point of interconnection, the overall power output is less variable since all dips and peaks can be filled in and eliminated using the BESS, resulting in a perfectly flat composite output. BESS also offers assistance during grid disruptions, such as frequency and voltage changes. Various benefits can be attained by utility, environment and communities with BESS installation. Utilities can achieve better grid stability and resiliency, while simultaneously releasing fewer carbon emissions into the air, preserving the environment. Table 2 summarizes the direct, indirect and intangible benefits of BESS integration in power systems [43].

Some of the applications of BESS in power systems applications include energy arbitrage, frequency regulation, spinning reserve and black start [44]. These applications help utilities optimize their energy supply and demand, provide grid support, and integrate renewable energy sources. Table 3 summarizes the categories and definition of various BESS applications in power systems. In Ref. [45], a distributed and mobile energy storage system is installed at the power distribution side to reduce power output fluctuations, agreement to the output plan at the renewable energy generation side and frequency adjustment at the power grid.

Voltage regulation and frequency control in power systems are inherently dependent on the pivotal role played by BESS, ensuring the stability of the grid. Table 4 describes the its impact and the optimization techniques that would enable BESS to efficiently manage voltage and frequency, enhancing overall system performance.

5.2. Recent advances and development of BESS

Innovations in BESS are reshaping the energy landscape. Recent advances such grid-forming BESS offers autonomy by independently establishing and maintaining voltage and frequency, crucial during grid disturbances. Second-life batteries could be used as grid storage, backup power, and renewables integration, driven by cost advantages and substantial capacities post-automotive use. BESS efficiency improvement is crucial and addressed by advanced Battery Management Systems (BMS) and accurate SOC estimation models.

Table 2
Benefits of BESS integration in power systems.

Direct Benefits	Indirect Benefits	Intangible Benefits
Improve grid resiliency	Less NOx, Co2 emissions	Fast deployment is possible even on MW scale compared to conventional power plant
Better spinning reserve management	No fuel cost as like conventional plants	Lower operation and maintenance cost
Immediate power production without any startup time	Increase system efficiency and makes system more economic	High reliability
Grid stability can be improved for load variations	Black start is possible	Redundancy is possible by paralleling
Reduces the power quality issues at PCC	Without the Grid islanded operation is possible	Simple installation
Frequency support capabilities	Transient smoothing	Technological innovation and research
Steady state and Dynamic voltage support	Reduce transmission and distribution losses	Avoided environmental and social costs
Peak demand reduction	Increase utilization of renewable energy resources	Grid modernization and future-proofing

Table 3
BESS application categories and definition.

Category	Description	Definition	References
Services for Bulk Energy	Electric Energy Time-shift (Arbitrage) Electric Supply Capacity Avoided Renewable Curtailment	Energy storage that charges or discharges over a long period of time and has a high energy capacity [46].	[47–50] [51–57]
Ancillary Services	Frequency Regulation Spinning, Non-spinning and supplemental Reserves Voltage Support Black Start	The aid in keeping the grid's electrical system reliable. Ancillary services ensure the right direction and flow of electricity, deal with supply and demand imbalances, and aid in the system's recovery following a power system event [58].	[59–62] [63–68] [69–72] [73–76]
Services for Transmission Infrastructure	Transmission Upgrade Deferral Transmission Congestion Relief	Alternatives and complements to conventional transmission infrastructure assets [77]	[78–81] [82–85]
Services for Distribution Infrastructure	Distribution Upgrade Deferral Voltage Support Outage Mitigation	Alternatives and complements to conventional transmission infrastructure assets at distribution level [86]	[87,88] [89–91] [92–94]
Services for Customer Energy Management	Power Quality Power Reliability Retail Electric Energy Time-shift Demand Charge Management	Help end customers control their energy expenditures and/or supply [95].	[96–100] [101–104] [105–107] [108–111]

Table 4
BESS impacts in voltage regulation, frequency control and optimization techniques.

BESS Impact	Type	Impact Description	Optimization Techniques
Voltage Regulation	Voltage Support	BESS is able to provide voltage support by injecting or absorbing reactive power as needed, helping to maintain voltage within acceptable limits [70,89,90].	Reactive Power Control: Simulation tools can be used to optimize the control algorithms for reactive power injection or absorption by the BESS, ensuring voltage stability.
	Voltage Flicker	Rapid charging or discharging of BESS may lead to voltage flicker, impacting the quality of power supply [112].	Voltage Control Setpoints: Setting appropriate voltage control setpoints based on grid conditions can help avoid over-voltage or under-voltage situations.
Frequency Control	Frequency Regulation	BESS can provide fast response frequency regulation by absorbing or injecting active power to stabilize the grid frequency [59–61].	Frequency Control Algorithms: Simulation tools allow testing and refining control algorithms for BESS to respond effectively to frequency deviations [113].
	Frequency Deviation	Rapid charge or discharge cycles of BESS can lead to frequency deviations if not properly controlled. [114]	Coordination with Other Resources: Optimal coordination with other grid resources, such as conventional generators or demand response, can enhance frequency control.
Active Power Injection and Absorption	Active Power Support	BESS can inject or absorb active power to mitigate grid imbalances and enhance overall system stability [115].	Predictive Control: Simulation tools can help develop predictive control strategies, allowing BESS to anticipate and respond to changes in power demand or generation.
	Power Quality	Rapid changes in active power flow may impact power quality, leading to voltage and frequency fluctuations.	Smooth Power Transitions: Implementing smooth power transitions during charge and discharge cycles can minimize power quality issues [116,117].

i) Grid-forming BESS

One of the recent advances of BESS is the grid-forming technology where it has the capability to independently establish and maintain voltage and frequency levels without relying on the grid. The key feature of this technology is that it gains independence from grid and able generate power and maintain grid stability even when disconnected from the main grid. This is crucial for scenarios where the main grid is unreliable or during grid disturbances. Ref [118] has proposed a grid-forming (GFM) control strategy in order to enhance the low voltage ride through capability by modifying the active power and reactive power loop to achieve the reactive power support and current limiting during the grid faults and verified by using PSCAD simulation.

The GFM-BESS technology is also used with offshore wind power plant and the controlled interaction between the two plants modelling is described in Ref. [119] using frequency-domain model of GFM-BESS. The long power transmission cables in offshore wind power results in a low short-circuit ratio (SCR) at the WT terminals and destabilize the system, which then GFM-BESS is able to mitigate the weak grid issue due to the low SCR.

ii) Second-Life Batteries in Grid

Used batteries are repurposed as stationary energy storage applications such as such as grid storage, backup power, or integration with renewable energy systems. These applications can benefit from the lower cost of second-life batteries compared to new ones. Ref [120] demonstrated a second-life BESS project in Lünen, Germany that had been built from 1000 used battery modules from *Smart for Two* electric vehicles. These batteries are used for second-life application is due to battery degradation which made the traction batteries lost a certain part of their capacity after several years of use in electric vehicles and no longer meet the requirements for automotive applications. Due to the high standards for battery performance, security (such as crash test), and robustness in automotive applications, the available storage capacities for second-life use in stationary systems are notably substantial once the automotive usage phase ends.

Distribution grids also benefits from the of second life batteries application, for instance Ref. [121] reviews the usage of second life batteries which can provide auxiliary services for voltage and frequency regulation and easier integration of RE in the grid. Since the battery life capacity has about 80% from its primary usage, there second life usage can be utilized for a couple of years. Manufactures would normally declare the duration of first life. Typically, eight years warranty would be provided by manufacturers for most battery packs. Cost, environment and aging are the main factors that contribute to determining the time of the first life and the point of entering the second life [122].

iii) BESS State of Charge (SOC) Efficiency

There is various research has been done to improve on the BESS SOC efficiency. Since it is subject to frequent charging/discharging cycles, the operational life of the battery decreases and system reliability reduces in the long run. Various battery management system (BMS) has been developed to maintain system reliability and improve the battery's operative life. Accurate estimation of the BESS SOC is a key challenge in the BMS due to its non-linear behaviour. Ref. [123] presents the most recent classifications and mathematical models for SOC estimation and future trends for SOC estimation methods.

Additionally, a modelling framework that has been validated is proposed in Ref. [124] that can be applied during or after BESS commissioning to identify and derive the useful parameters to characterize BESS performances. Three different modelling approaches were discussed that optimizes BESS operation, with each providing a different balance between modelling accuracy and computational effort. These three mathematical models were validated against a numerical simulation model based on performance data on site, and then it was tested on a reference case study. It is possible the average error can be restricted in estimating BESS efficiency, and at the same time limiting the model computational effort by applying the method.

5.3. BESS research and development breakthroughs forecast

Breakthroughs in research and development efforts at BESS can be expected in the next few years. These developments will not only drive progress but also contribute to positive environmental impact on a global scale. Some potential breakthroughs include.

i) **Cost** reduction **in Li-Ion BESS**

Significant reductions in the cost of Lithium-Ion (Li-Ion) BESS over the past decade have made the economics of such systems viable for a wide variety of applications [125]. This has led to increased adoption across industries, ranging from residential and commercial use to large-scale utility projects and mobile electric vehicles.

ii) **Advancements in Battery Technology**

Advancements in battery technology, such as higher energy density and longer lifespan, are leading to improved performance and efficiency of BESS [126]. These advancements have the potential to revolutionize various industries by providing more reliable and long-lasting energy storage solutions.

iii) Frugal Engineering and Modular Design

Ref [127] proves that implementation of frugal engineering and modular design approaches can further reduce the costs of non-battery BESS components and significantly impact the affordability and accessibility of energy storage solutions. For example, adopting standardized interfaces for different components within a battery energy storage system can streamline manufacturing processes and increase economies of scale, ultimately driving down production costs. Similarly, leveraging frugal engineering principles in the design phase by prioritizing simplicity, durability, and cost-effectiveness can lead to innovative solutions that are more accessible to a wider range of users.

iv) Innovative Software and Control Systems

The development of innovative software and control systems is crucial for optimizing the operation and management of BESS, ultimately improving their overall performance and integration with the grid [128]. By implementing advanced algorithms and real-time monitoring, these systems can effectively balance supply and demand, enhance grid stability, and support renewable energy integration.

6. Incorporation of BESS in emerging economies and developed nations

BESS are becoming increasingly essential in global energy infrastructure, catering to diverse needs across both emerging and developed economies. In emerging markets, BESS addresses energy access challenge and in developed nations, it plays an important role in grid stability and renewable energy integration. From facilitating rural electrification to supporting large-scale grid systems, BESS deployment has proven a worldwide shift towards sustainable energy solution.

6.1. BESS incorporation in emerging economies and lessons learnt

Incorporation of BESS in developing countries is gaining momentum as these countries strive for improved access to electricity and sustainable energy solutions [129]. Studying successful instances and insights from developing economies helps us to better comprehend the importance of integrating BESS and the essential factors for its successful implementation. Various emerging countries that have successfully incorporated BESS into their energy infrastructure, a few listed below.

6.1.1. India

India has made significant progress in incorporating BESS into its energy infrastructure. The government has launched various schemes to promote distributed generation and non-conventional energy resources in the country. These initiatives have created opportunities for the deployment of BESS, particularly in areas such as rural electrification and power backup for telecom towers and rooftop solar installations [130]. Lessons learned from India's experience with BESS incorporation include the importance of differential tariffs and financial incentives to drive economic viability, as well as the need for strong government commitment and supportive policies to encourage the adoption of BESS [131].

6.1.2. Brazil

Brazil has been incorporating BESS into its energy infrastructure to address challenges such as grid stability and intermittent renewable energy sources. The country has implemented pilot projects and demonstration sites to test the integration of BESS into the grid, with a focus on utilizing storage systems in combination with renewable energy sources [132]. Lessons learned from Brazil's experience include the need for regulatory frameworks and market mechanisms to support BESS deployment, the importance of addressing specific consumer and company needs in the design and implementation of BESS projects, and the potential for BESS to promote the decarbonization of the energy sector [133].

6.1.3. Nigeria

Nigeria has successfully incorporated BESS to improve energy access in rural areas and enhance grid reliability. This includes deploying microgrids powered by BESS in off-grid communities to extend electricity access, along with supportive policies promoting the adoption of BESS in rural electrification projects [134]. Nigeria's example emphasizes the importance of tailoring BESS projects to address specific energy challenges within a country and leveraging them to meet unique energy needs, showcasing the potential for addressing sustainable development goals effectively and sustainably [135].

The case studies of India, China, Brazil, South Africa, and Nigeria provide valuable insights into the successful incorporation of BESS into energy infrastructure. These experiences highlight the importance of regulatory frameworks and market mechanisms to support BESS deployment, collaboration between government, private sector, and research institutions, and addressing specific local energy challenges in the design of BESS projects.

Lessons can be learned from emerging economies on the importance of stakeholder engagement and participation in the planning and implementation of BESS projects. Localizing manufacturing capabilities to boost the demand for BESS and promote domestic industries is also important. In addition, the experiences of these emerging economies highlight the need for supportive policies and incentives to encourage the deployment of BESS.

6.2. BESS deployment in developed nations

Global deployment of BESS has paved the way of transformative era in energy management. These advanced systems are crucial for creating sustainable power grids, seamlessly integrating renewable sources while ensuring grid stability. BESS becomes a cornerstone by efficiently storing and distributing renewable power as the world is undergoing energy transition. Several countries that are listed here have successfully deployed BESS for various purposes to meet the grid demand.

6.2.1. Australia

The South Australia government built the Hornsdale power reserve, the largest Li-ion battery in the world (100 MW/129 MWh), to offer the necessary grid support services. The BESS plant main function is to provide premium contingency frequency control ancillary service using its fast frequency response features [136].

A 25 MW/50 MWh BESS was installed as part of the Gannawarra project in Victoria, Australia, in 2019 to promote the maximum integration of renewable energy sources and control frequency in the Victorian electricity networks [137].

6.2.2. China

In Ningxia, China, the largest 200MW/400 MWh battery energy storage system (BESS) containing lithium iron phosphate (LFP) cells have started operating since December 2022. This BESS plant offers to store energy so it may be released into the grid when demand is at its highest. It will also assist in controlling grid frequency [138].

Another constructed project example is a BESS project in Golmud with multi-mix power station which is the first of its kind in China to integrate wind (400 MW), photovoltaic (200 MW), concentrated solar power (50 MW), and energy storage system (ESS) (100 MWh) into a single integrated grid system. These three distinct renewable energy sources, each of which fluctuates and is notably unstable, and is expected to continuously respond to shifting demand, making its batteries and battery management system essential to the system's dependability [139].

6.2.3. United Kingdom

In United Kingdom, the largest BESS which has the ability to store up to 196 MWh of electricity, has gone online, paving the door for increased use of the technology to replace fossil fuels with renewable energy [140].

The Pillswood BESS project in Hull by Harmony Energy Limited hopes to offer load balancing services to the electrical system. It can reportedly hold enough energy to supply almost 300,000 houses with power for 2 h. Tesla battery technology was implied to makes use of the Megapack system from the business. Each unit can store more than 3 MWh of energy and is about the size of a shipping container.

6.2.4. United States

A 200 MWh battery energy storage system (BESS) in Texas has been made operational by energy storage developer Jupiter Power, and the company anticipates having over 650 MWh operating by The Electric Reliability Council of Texas (ERCOT) summer peak season [141]. Reeves County's Flower Valley II BESS plant with capacity of 100 MW/200 MWh BESS is one of Texas's largest commercially running projects and Jupiter's first transmission-connected plant.

It will provide energy capacity and grid-firming ancillary services to the ERCOT system. Fast frequency response (FFR), a component of the regulatory reserve service (RRS), is the primary auxiliary service that energy storage uses on the Texas grid. These two services combined generate the majority of revenue for energy storage assets.

7. BESS infrastructure, operations, and grid integration strategies

The integration of BESS into utility infrastructure becomes important as the demand of energy storage grows. Careful planning is required to adapt utility infrastructure and operations for BESS integration. Utilities and grid operators has employed strategies including substation upgrades and grid planning, to ensure efficient BESS integration while maintaining grid stability and reliability.

7.1. BESS infrastructure and operations adaptation

The integration of BESS into existing utility infrastructure has become important to many stakeholders as the demand of energy storage grows. The adaptation of utility infrastructure for BESS integration requires careful planning and consideration of various technical, operational, and regulatory factors. Utilities and grid operators are adapting their infrastructure and operations in several ways to accommodate BESS which includes.

- **Upgrading and Expanding Substations**

Increasing capacity and demands of BESS integration may require upgrading and expanding of substations. The capacity of the substation needs to be assessed to ensure it can accommodate the additional power output from the BESS. This assessment should take into account the BESS maximum power output and the existing power demand in the area. The expansion involved increasing the capacity of the transformers in the substation, adding new protection and control systems to manage the demands of the BESS. Ref [142] highlighted that proper sizing methods for the capacity of the substation can help reduce the cost of building new facilities.

- **Implementing Advanced Control and Monitoring Systems**

The integration of advanced control and monitoring systems with BESS in the grid is essential for efficient and reliable operation [128]. These systems enable real-time monitoring and control of the BESS, allowing grid operators to optimize its performance and ensure seamless integration with the overall power system [143]. Additionally, utilities are integrating advanced control algorithms and predictive analytics to optimize the operation of BESS units. These algorithms can forecast energy demand and generation patterns [144], allowing utilities to schedule the charging and discharging of BESS units to maximize their efficiency and grid stability while minimizing costs.

- **Integrating BESS into Grid Planning and Operation Process**

Utilities and grid operators are actively including BESS in their long-term planning and operation processes [145]. This includes conducting studies to assess the full potential benefits and impacts of BESS integration, such as voltage support, peak load shaving, and grid stability. Furthermore, utilities are collaborating with battery manufacturers and technology providers to identify suitable locations for BESS installations and develop strategies for optimal grid integration [146].

7.2. BESS grid integration strategies and stability maintenance

Grid operators are facing challenges of integrating BESS with various technologies, sizes, and applications while maintaining grid stability, quality of service and mitigating grid congestion [136]. In order to address the challenges, the following strategies in Table 5 below are implemented by grid operators.

8. BESS modelling and impacts in power system simulation software tools

Modelling and simulation are crucial in analyzing the integration of BESS into power systems. Steady-state and dynamic simulations are able to provide insights into system behaviour, and accurate modelling of BESS components is essential for reliable assessments. Additionally, suitable BESS modelling techniques, computational requirements, data quality considerations and software adaptability should be considered.

8.1. BESS steady state and dynamic modelling

Steady-state and dynamic simulations serve different purposes in the analysis of power systems, and they provide insights into different aspects of system behaviour. When integrating BESS into power systems, both types of simulations are crucial for assessing the system's stability, reliability, and performance [153].

i) Steady-State Simulations:

Steady-state simulations provide a snapshot of the power system under balanced and steady-state conditions. The purpose is to assess the power flow, voltage profiles, and overall system loading at a specific point in time. The simulation includes load flow analysis which assesses the impact of BESS on system loading, voltage profiles, and power flows under normal operating conditions. It is also applied in system planning to determine the optimal configuration and operation of BESS.

ii) Dynamic Simulations:

Dynamic simulations assess the system's response to disturbances, capturing the transient behaviour during and after a disturbance. The purpose is to evaluate the system's ability to maintain stability and

Table 5
BESS grid integration strategies.

Strategies	Description
Implementing advanced control and monitoring systems	Grid operators are investing in advanced control and monitoring systems to efficiently manage the integration of BESS with different technologies and applications [128]. These systems enable real-time monitoring of the grid and the BESS performance, allowing operators to make necessary adjustments to maintain stability and quality of service.
Coordinating power flow	Coordination strategies to manage the power flow between the grid and the BESS are implemented by grid operators. This includes ensuring the smooth transfer of power during grid-connected operation and managing the bidirectional power flow during islanded or off-grid operation [147].
Establishing grid codes and standards	Grid operators are developing and implementing comprehensive grid codes and standards that outline the technical requirements for integrating BESS with the grid. These codes and standards a wide range of parameters such as voltage and frequency regulations, response to grid disturbances, and overall system performance [38]to ensure the safe and efficient operation of the grid and the BESS.
Implementing proper communication and coordination protocols	Communication and coordination protocols are established between the BESS, other grid-connected devices, and control systems [148]. These protocols facilitate the exchange of information and commands which allows for effective coordination, response, and control of the BESS and other grid assets to maintain stability and quality of service [149].
Implementing grid resilience strategies	Strategies to ensure the resilience of the grid in case of disruptions or failures are implemented by grid operator. These include backup power systems such as standby generators or energy storage systems [150], establishing redundancy in the grid infrastructure [151], and developing contingency plans [152] to quickly restore power in the event of a failure or emergency.

recover from disturbances. Dynamic simulation includes transient stability analysis which assesses the BESS contribution to system stability during and after disturbances, such as faults or sudden changes in load or generation. In addition, dynamic simulations help design and optimize control systems for BESS, ensuring effective responses to transient events.

In order to assess the grid condition with BESS integration using power system simulation tool, accurate model representing BESS characteristics need to be used in power system studies. Western Electricity Coordinating Council (WECC) has created and approved new generic models of the plant controller and battery storage electrical control in order to suit the growing industry needs [154].

In dynamic stability analysis, a BESS is modelled using three WECC generic model modules focusing on grid frequency regulation and voltage support [155,156].

The models are REGC_A, REEC_C and REPC_A which interacts with each other to demonstrate BESS functions. The details of each module are described as follows [154].

1) Generator/converter Module (REGC_A):

Using the feedback from terminal voltages for low voltage active current and high voltage reactive current management systems, this module accepts and processes real and reactive current commands from the electrical control module. It also dispatches real and reactive current injections into the network model. Fig. 5 illustrates the WECC generic generator/converter model for REGC_A [97].

2) Electrical Control Module (REEC_C):

In order to establish a prescribed reactive control response during dynamic system events, this module operates on active and reactive power references from the plant controller module by using a terminal voltage feedback signal. This block additionally uses feedback from the generator power output to monitor the BESS's state of charge (SOC) and establish the suitable active current limitations. Real or reactive power control priority can be selected, which allows this module to send real and reactive current directives to the generator/converter module.

3) Plant Controller Module (REPC_A):

In order to simulate frequency/active power regulation, this module obtains the measurements for frequency and power and computes the BESS's active power output. In order to simulate volt/var control at the plant level, it also processes the measurement of voltage and reactive power and calculates BESS reactive power output. The electrical control module receives references to both active and reactive power from this module.

Figs. 5 and 6 show the WECC generic generator/converter model for REGC_A [155]and WECC generic electrical control model REEC_C [156], respectively.

Whilst Figs. 7 and 8 depicts the WECC generic plant controller model REPC_A [155] and a schematic diagram that shows the main components of typical BESS, respectively, which includes a battery and insulated-gate bipolar transistor (IGBT) in Power Conversion System (PCS) which inverts DC power from battery to AC power to the grid (battery discharging) or rectifies the AC power from the grid to DC power to charge the battery.

In the PCS, Pulse Width Modulation (PWS) is implemented which requires the L-C filter to reduce the high frequency harmonics [157].

Several popular power system analysis software applications, including PSS®E [158], PSLF™ [159] and PowerWorld Simulator [160] have implemented and validated the new general plant controller and battery energy storage electrical control models.

In [161], The steady state load flow for BESS interconnection at 415V level in Malaysian system has been analysed using DigSILENT Powerfactory modelling software which performs over several range of operation conditions as recommended by Ref. [162].

DigSILENT Powerfactory software is also capable to demonstrate dynamic response of BESS in a distribution network using a modelling method proposed in Ref. [163] which directly controls the output of the static generator by adjusting the dq axis current.

b) Data Quality in BESS Modelling

Data is crucial for accurately representing the behaviour, performance, and interactions of BESS components within a simulation environment. Poor data quality can lead to inaccurate predictions, suboptimal performance, and unreliable assessments [124]. Data quality affects BESS simulation results as described below.

i) Accuracy of Performance Predictions

Precise knowledge of BESS attributes, such as battery efficiency, charge and discharge rates, self-discharge rates, and thermal behaviour, enhances the accuracy of performance predictions across diverse operational scenarios. Incomplete or inaccurate data can yield unreliable simulation results, deviating from actual system behaviour. Consistent validation and calibration of simulation models with actual performance

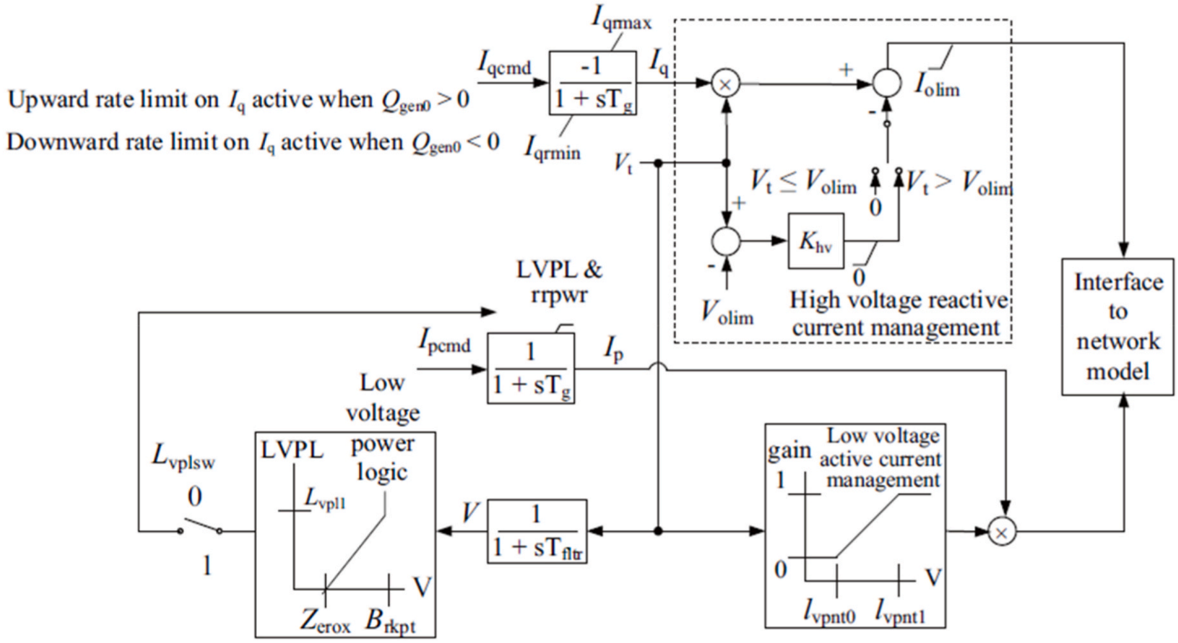

Fig. 5. REGC_A generic generator/converter model block diagram.

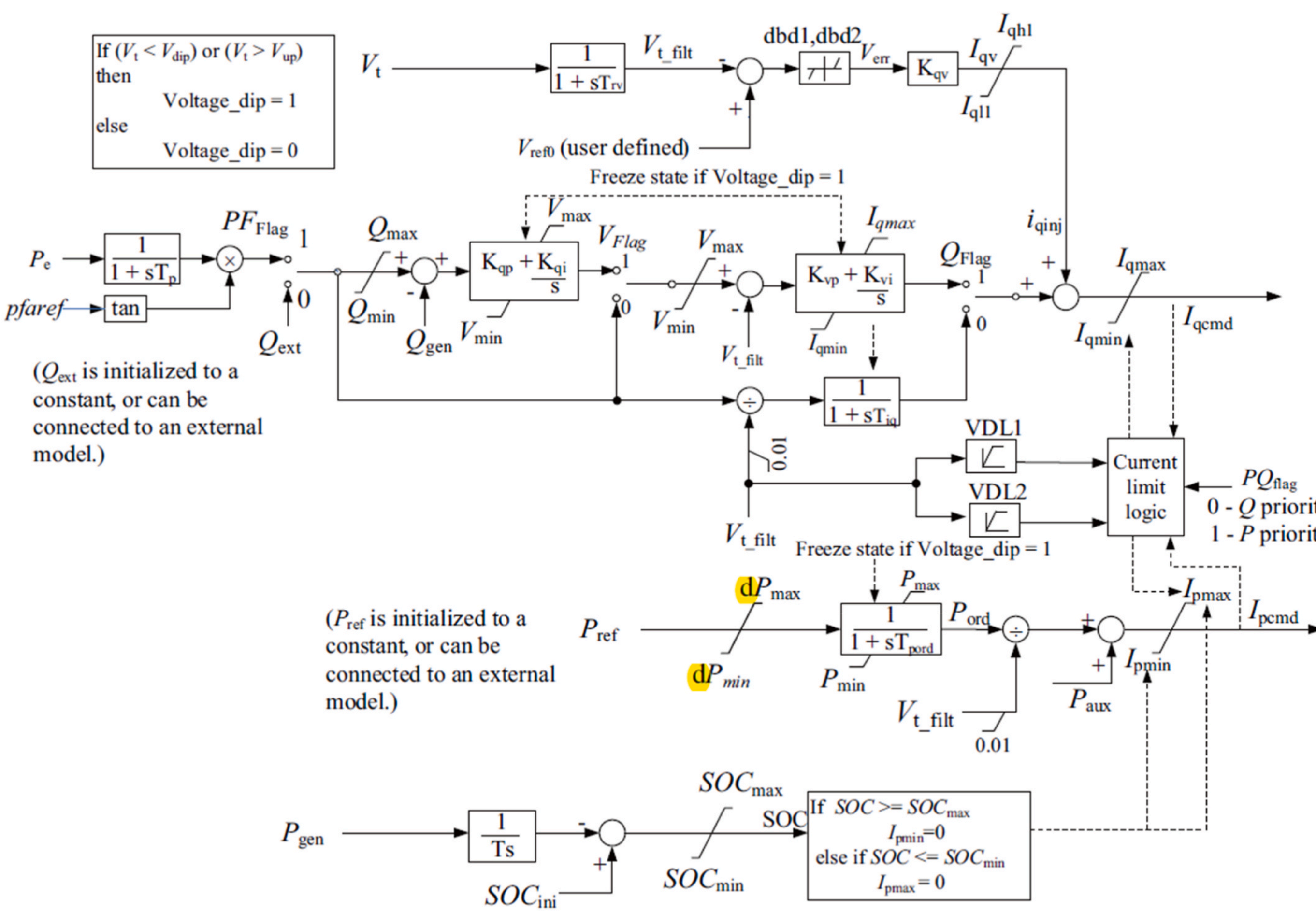

Fig. 6. REEC_C generic electric control model block diagram.

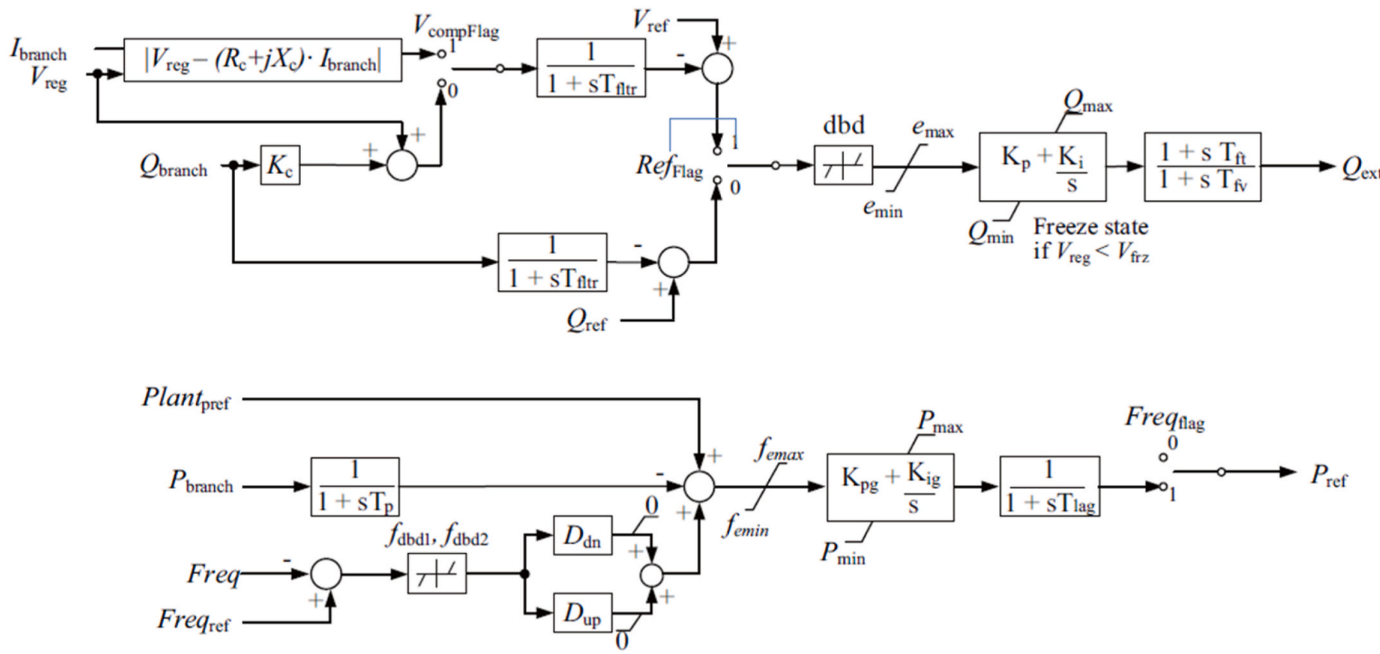

Fig. 7. REPC_A generic plant controller model block diagram.

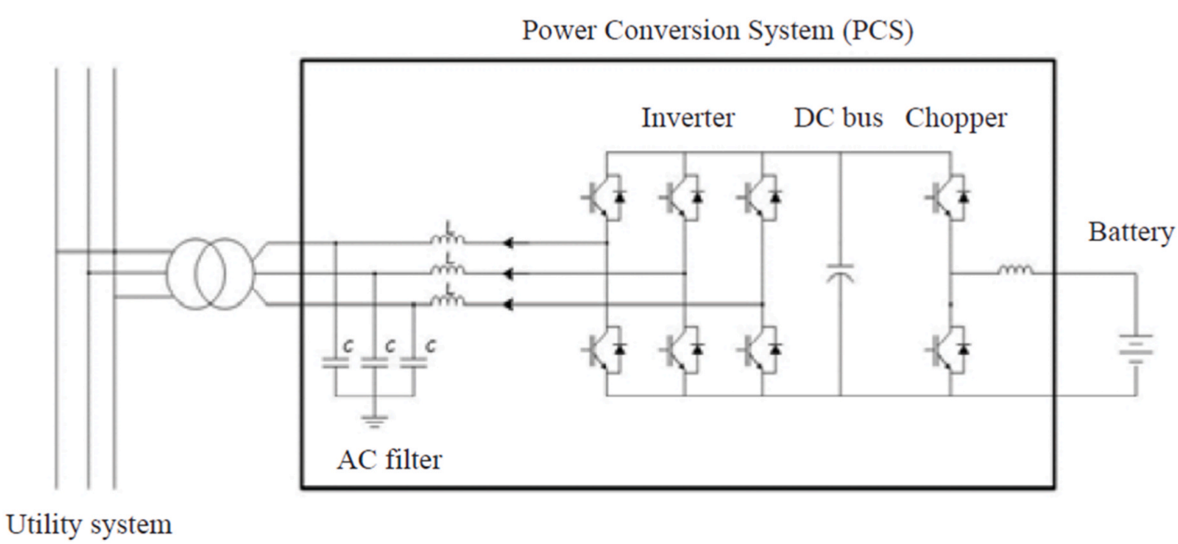

Fig. 8. Typical BESS schematic diagram.

data are essential for ensuring accurate reflection of BESS behaviour [164]. Robust validation processes must be implemented to confirm input data accuracy, minimizing potential errors in simulation outcomes.

ii) Reliability of System Control Strategies

Control strategies for BESS requires precision in input data for BESS operation which includes charge and discharge algorithms, voltage control, and frequency response. Subpar data quality can result in control strategies [113] that misrepresent actual system behaviour, jeopardizing BESS reliability. By iteratively refining strategies with actual data, simulations can faithfully capture the system's dynamic response, thereby boosting reliability. Rigorous evaluation of control strategies across diverse scenarios and operating conditions, supported by high-quality data, facilitates issue identification and performance optimization.

iii) Grid Interaction and Stability Analysis

Grid parameters including voltage profiles, frequency variations, and constraints which are accurate is essential for a dependable assessment of the BESS influence on grid stability and interactions. Misleading analyses can arise from inaccurate grid data, skewing evaluations of the BESS's impact on grid stability. Validating simulated grid data against real measurements guarantees an accurate representation of grid characteristics. Performing sensitivity analyses on grid parameter variations aids in pinpointing crucial factors, facilitating optimized system design based on a comprehensive understanding of BESS performance.

Ensuring the accuracy of BESS simulations require regular validation against actual performance data, manufacturer specifications, and industry standards. Continuous calibration, informed by actual data, enhances prediction accuracy and control strategies. Rigorous data validation, continuous calibration, and scenario testing collectively optimize BESS impact on grid parameters, aligning simulation results with actual performance.

8.2. BESS impacts and optimization in power system simulation software

BESS significantly impact the grid power systems parameters, influencing stability and reliability. Optimizing their integration within power system simulation software enhances grid performance. Simulations help analyse BESS behaviour, offering insights into efficient deployment and utilization. Table 6 below describes the BESS impact in power system software tools and the optimization techniques.

8.3. BESS interoperability with grid assets in simulation software tool

Simulation software packages are designed for power system analysis often include features to address the interoperability of BESS with other grid assets integration such as solar, wind farms and conventional generators. These software packages aim to model and simulate the interactions between various grid components that helps users to assess the overall system performance. The interoperability are addressed by simulation software as below.

i) The capability to model diverse grid assets

BESS Models:

Simulation software packages include detailed models for BESS components, allowing users to represent the electrochemical characteristics, control systems, and performance parameters of batteries accurately [154,158].

Renewable Generator Models:

These software packages come with built-in models in the library for renewable generators, such as solar photovoltaic (PV) systems and wind turbines [165], which enables the simulation of their power generation profiles [164].

Conventional Power Plant Models:

Models for conventional power plants, including thermal generators, gas turbines, and their stabilizers are commonly integrated into simulation software to capture the behaviour of traditional power generation units [160,166].

Demand-Side Management Models:

Some simulation tools [158,167]incorporate models for demand-side management systems in the library, which enables the representation of load profiles, complex loads dynamic models and demand response strategies.

ii) The capability to perform interconnection and grid integration studies:

Voltage and Frequency Coordination:

Simulation software allows users to study the impact of BESS on voltage and frequency coordination with other grid assets, ensuring proper integration without compromising stability.

Grid Code Compliance:

Simulation tools can be used by users to assess whether BESS and other grid assets comply with grid codes and regulations, ensuring seamless interoperability.

Dynamic Response Analysis:

Dynamic simulations enable the evaluation of the dynamic response of BESS and other grid assets to disturbances, helping to identify potential issues and optimize control strategies.

iii) Communication and control systems:

Integration of Control Systems:

Simulation packages often provide tools to integrate control systems for BESS and other grid assets, allowing users to model and analyse the coordination of control actions.

Table 6
BESS impact in power system simulation software.

BESS Impacts	Type	Description	Optimization Techniques
Grid Parameter Monitoring	Grid Stability	BESS can enhance grid stability by actively monitoring and responding to grid parameters, such as voltage and frequency [153].	Advanced Monitoring Systems: Simulation tools can evaluate the effectiveness of advanced monitoring systems that enable real-time visibility into grid parameters [158].
	Fault Detection	Real-time monitoring helps detect faults or anomalies in the grid, enabling quick responses to maintain reliability [158].	Fault Ride-Through Capability: Ensure that BESS has the capability to ride through and support the grid during faults.
Grid Integration Challenges	Grid Congestion	Improper integration may contribute to grid congestion, especially if BESS is not strategically placed or controlled.	Grid Planning and Modelling: Simulation tools facilitate grid planning and modelling to identify optimal locations for BESS deployment and assess its impact on congestion.
	Interference with Other Resources	Unoptimized operation may interfere with the operation of other grid resources, affecting overall grid performance.	Coordinated Operation: Coordinating BESS operation with other grid resources ensures harmonious and efficient grid performance.
Regulatory Compliance	Grid Code Compliance	BESS must comply with grid codes and regulatory requirements related to voltage and frequency control	Regulatory Compliance Checks: Simulation tools can perform regulatory compliance checks, ensuring that BESS configurations and control strategies adhere to established standards.
	Interconnection Standards	Meeting interconnection standards ensures seamless integration without causing disruptions.	Interconnection studies using simulation tools can identify potential issues and optimize the integration process prior to deployment.
Computational Constraint	Large-scale BESS models	Simulating large-scale BESS deployments involves modelling numerous components, control systems, and interactions can increase the numerical complexity and computational requirements.	i) Simulation software offers the option to use aggregated or equivalent models for groups of batteries, simplifying the representation of large battery banks without compromising accuracy significantly [158]. ii) The models that

(continued on next page)

Table 6 (*continued*)

BESS Impacts	Type	Description	Optimization Techniques
			capture the essential dynamics over a reduced time span to be used, especially when focusing on specific events or transient responses.

iv) Scalability and Grid Planning:

System Scalability:

Simulation software allows users to assess the scalability of BESS and other assets, considering the impact of scaling up or down the capacity of various components.

Grid Planning Scenarios:

Different grid planning scenarios can be modelled by users, including the addition of new renewable generators, changes in demand patterns, and the integration of advanced control strategies for future grid expansion.

v) Data Exchange and Standards:

Interoperability Standards:

Some simulation software packages support industry standards for data exchange, enabling interoperability between different software tools used for various aspects of power system analysis. PSS/E allows the import and export of files from load flow cases (*.raw format) and dynamic data files (*.dyr format).

vi) User Interface and Visualization:

User-Friendly Interface: Simulation software often provides a user-friendly interface that allows engineers and planners to visualize the interoperability of BESS with other grid assets, making it easier to interpret results and make informed decisions.

Graphical Representation: The graphical representation of simulation results helps users understand the interactions between BESS and other components which supports effective analysis and communication.

Features and capabilities related to interoperability varies among different simulation software packages such as PSS/E, PowerWorld, DIgSILENT Powerfactory and PSCAD. A software tool that aligns with their specific needs and the complexity of the power system to be analysed should be selected. Additionally, ongoing advancements in simulation technology may lead to further improvements in addressing interoperability challenges in power system modelling and analysis.

8.4. Computational requirements and appropriate simulations timescale

Real-time simulations involving BESS demand stringent computational requirements to ensure that simulations are performed within appropriate timescales. Achieving a balance between model complexity and computational efficiency while maintaining real-time responsiveness is the key challenge. Considerations for computational requirements and methods software tools should be taken into account to ensure real-time performance in BESS simulations are described below.

i) Computational Requirements:

- Model Complexity: Complex models that include detailed electrochemical processes, thermal dynamics, and control algorithms can strain computational resources [167]. An appropriate level of model detail must be chosen based on the simulation objectives, ensuring that it strikes a balance between accuracy and computational efficiency.
- Control System Dynamics: The dynamic response of BESS control systems, especially in real-time applications, requires high-frequency simulations to capture rapid changes [45]. The control system models for efficiency should be optimized, potentially using simplified representations while maintaining main dynamic characteristics.
- Communication Delays: In real-time simulations, communication delays between components (e.g., sensors and controllers) can impact the overall system response time since it allows real-time monitoring coordination [168]. Communication models that reflect actual latencies must be implemented and optimize simulation time steps to account for delays in control signals and sensor feedback.
- Hardware Acceleration: Achieving real-time performance may require leveraging specialized hardware, such as graphics processing units (GPUs), for certain computational tasks. Hardware acceleration techniques should be integrated to optimize specific computations for faster execution.

2. Real-Time Performance in Software Tools:
- Time-Step Adaptation: Adaptive time-step techniques that automatically adjust the simulation time step based on the dynamics of the system can be implemented [169]. This ensures that the simulation captures fast transients without unnecessary computational burden during stable periods.
- Fixed-Step Solver Optimization: Fixed-step solvers can be optimized to reduce computational overhead. Efficient solvers can significantly improve simulation speed while maintaining accuracy.
- Parallel Computing: Software tools should support parallel computing to distribute computational tasks across multiple processors or nodes, enabling faster simulation times. It allows the simulation to run even faster than real time, which gives future projection capability to study possible stability problems in the power grid [170].
- Code Generation and Compilation: Some simulation platforms offer code generation capabilities such as Python and C++ [158,171], allowing users to generate optimized executable code. Compiled code can often achieve higher computational efficiency compared to interpreted code.
- Real-Time Simulation Platforms: Consider using simulation platforms explicitly designed for real-time applications. These platforms are engineered to meet the specific computational demands of real-time systems, including hardware-in-the-loop (HIL) and power hardware-in-the-loop (PHIL) simulations [70,166].
- Hardware Compatibility: Ensure that the simulation software is compatible with the hardware infrastructure, including processors, GPUs, and communication interfaces. This alignment enhances overall system performance.
- Reduced-Order Models: For real-time applications where speed is critical, employ reduced-order models that only capture essential system dynamics while minimizing computational complexity.
- Model Simplification Techniques: Apply model simplification techniques, such as aggregated or reduced-order models, to streamline computations without sacrificing critical system behaviours [172].

Benchmarking and Profiling: Perform benchmarking and profiling of simulation models [173] to identify computational bottlenecks. This allows for targeted optimization efforts to enhance real-time performance.

8.5. Software adaptability with evolving grid integration standards, regulatory and policy

The ability of simulation software to adapt to evolving grid integration standards based on regulatory and policy changes depends on the flexibility and update mechanisms built into the software. The adaptability of simulation software to changes in grid integration standards should be considered, as described below.

1. Open Standards and Modularity:
   - Simulation software that supports open standards and interoperability protocols is more adaptable to changes in grid integration standards. Open standards facilitate seamless integration of new requirements and functionalities [171,174].
   - Software with a modular architecture allows users to update or replace specific components related to grid integration standards without overhauling the entire simulation environment. This modularity supports adaptability to changing standards [175].
2. Frequent Updates and Releases:
   - Vendor Commitment: Software vendors committed to staying current with industry standards regularly release updates [158,160] that incorporate changes in regulations and policies. Users benefit from these updates to ensure compliance and accuracy in simulation models.
   - Version Control: Version control features in simulation software enable users to switch between different versions of standards, accommodating transitional periods during the implementation of new regulations.
3. Customization and Extension:
   - Simulation tools that allow users to customize models, algorithms, and interfaces can be adapted to specific grid integration standards as they evolve. Extensible software architectures permit users to add new features or adapt existing ones in response to changes in standards [165,171]. This adaptability is crucial for staying compliant with evolving regulatory requirements.
4. Compliance Verification Tools:
   - Simulation software that includes built-in tools for verifying compliance with grid integration [176]standards simplify the process of ensuring that simulations adhere to the latest regulatory and policy requirements. Automated reporting features that highlight areas where a simulation model may not comply with current standards aid users in identifying necessary updates.
5. Compatibility with External Tools:
   - Simulation software that integrates with external platforms for data exchange and compliance checking can streamline the process of adapting to new grid integration standards. Application Programming Interfaces (APIs) and standardized interfaces facilitate communication between simulation software and external tools, enabling seamless updates to reflect changes in standards [174].
6. Training and Support
   - Simulation software vendors offering training programs and documentation on updates related to evolving grid integration standards empower users to make informed adjustments to their models [177]. Efficient and responsive customer support services provided by software vendors [178] assist users in addressing challenges and updating simulation models according to the latest standards.

The adaptability of simulation software is crucial to the evolving grid integration standards. Users should choose simulation tools that align with their needs for flexibility and responsiveness to changes in regulatory and policy frameworks affecting grid integration. Ongoing communication and collaboration between software vendors, users, and regulatory bodies contribute to the continued evolution and adaptability of simulation tools in the context of changing standards.

9. Challenges of BESS deployment in Malaysia

Regardless of the advantages and benefits that BESS can offer, there are several key challenges to implement BESS in the existing system. Due to a lack of digital platforms or solutions, many types of expertise and solutions are required, which are not limited to commercial level. Below are a few key challenges that were found during the research.

- **Ensuring grid compatibility**

BESS systems need to be compatible with the existing grid infrastructure, which may require reinforcement or modifications to the grid. Preliminary grid studies need to be conducted to foresee the potential compatibility issues and needs to ensure seamless BESS integration.

- High **investment costs for BESS**

Since BESS new technology that yet to be implemented in Malaysia on a large-scale, initial investments cost would be high [179] and require financial support from government incentives.

- **Clear guidelines from policy makers and grid operators**

Relevant authorities in Malaysia needs to establish a dedicated guideline for BESS connections as previously done for LSS connections so that it can be a good reference for service providers to participate in the electricity market.

- **Access provision of the load demand data and grid data to service providers.**

Before making an investment, the BESS service provider should research the system's economic and technical viability. In Finland for instance, the DSO is in charge of metering and data transmission for other players in energy market, although this may not be the case in all of Europe and other countries [180].

- **Optimizing the management and control of the BESS operation under uncertain situations.**

The General Energy Management System (GEMS) platform must take a number of uncertain elements, including generation, load, and electricity market price profiles, peak power, and tariffs, into account in order to reduce the overall cost of the BESS. Day-ahead scheduling can be challenging, particularly for managing peak demand, since the charging and discharging of BESS are normally scheduled one day in advance [181]. Each installation is unique and has its own set of uncertainties that must be modelled, handled, and controlled.

- **Environmental impacts associated with the BESS manufacturing and disposal**

The main environmental concerns are associated with BESS raw materials extraction, manufacturing process and disposal of batteries. It is important to implement and enforce regulations to minimize the environmental impact. Additionally, developers need to have a sense of awareness and be responsible of end-of-life practice, to attain a sustainable approach while deploying BESS.

- **Land acquisition for BESS plants**

Other than technical and commercial constraints, BESS plants are typically requiring large land sizes therefore specific locations will be chosen as site. Local communities should give full support for BESS construction in their areas to help pave the way for a clean energy transition.

These challenges require collaboration between industry stakeholders, policymakers, researchers, and the public to be addressed. A successful and sustainable deployment of BESS in diverse energy landscape can be attained if these obstacles are overcome.

10. Conclusion

In conclusion, as the world urgently transitioning to sustainable energy, BESS emerge as a key driver for change. Global commitments, exemplified by the Paris Agreement, drive nations to reduce greenhouse gas emissions and embrace cleaner energy sources.

The contribution of the paper can be summarized as follows.

- The paper reviews the worldwide scenario of BESS installation. Across the globe, BESS deployment is surging, particularly in countries like the United States, China, and Europe. This global perspective provides context to the discussion on BESS in Malaysia, offering insights into how other regions are adopting or facing challenges in integrating BESS into their energy systems.
- The review covers various aspects, including the present state of BESS implementation in Malaysia and the challenges faced in its application. Malaysia aims to deploy 500 MW of BESS between 2030 and 2034 to support its renewable energy goals. Despite this momentum, challenges persist. High initial costs, unclear guidelines, data access issues, uncertain operational management, and environmental impacts making things difficult. Overcoming these challenges demands collaborative effort from policymakers, grid operators, and industry stakeholders.
- The review emphasizes the significance of grid interconnection for BESS in advancing sustainable energy systems. Standards and guidelines governing BESS integration globally is discussed, highlighting technical considerations and country-specific regulations. Additionally, the need for regulatory evolution to accommodate technological advancements is emphasized, advocating for collaboration among stakeholders and standards organizations.
- The importance of BESS in enhancing grid reliability, efficiency, and resilience while lowering costs and emissions is included in the review. Diverse applications and benefits of BESS integration, including grid stability, ancillary services provision, and peak demand reduction are discussed. Recent advances like grid-forming technology and second-life batteries are highlighted, along with the forecast of breakthroughs in Li-Ion BESS cost reduction, battery technology, and innovative control systems
- The review highlights the increasing importance of BESS in both emerging and developed economies, addressing energy access, grid stability, and renewable energy integration. Case studies from India, Brazil, and Nigeria illustrate successful BESS incorporation in emerging economies, emphasizing regulatory frameworks and tailored solutions. In developed nations like Australia, China, UK, and the US, BESS deployment supports renewable energy integration and grid stability, driving the global energy transition.
- The review includes the critical role of modelling and simulation in integrating BESS into power systems. Simulations are able to provide insights into system behaviour, while accurate BESS modelling ensures reliable assessments. Considerations include BESS modelling techniques, computational requirements, data quality, and software adaptability.

BESS offers a range of benefits, from improved grid resiliency to reduced emissions and support for renewable energy integration. Applications of BESS has proven its versatility in power systems. Overcoming challenges, establishing comprehensive guidelines, and fostering international collaboration are crucial steps toward unlocking the full potential of BESS in shaping a sustainable energy future.

CRediT authorship contribution statement

Amani Syafiqah Mohd Razif: Conceptualization, Methodology, Resources, Writing – original draft, Visualization. **Nur Fadilah Ab Aziz:** and. **Mohd Zainal Abidin Ab Kadir:** and. **Karmila Kamil:** Validation, Supervision, Resources, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] The Paris Agreement," United Nations. Accessed: Dec. 30, 2022. [Online]. Available: https://www.un.org/en/climatechange/paris-agreement.
[2] C. Bertram, et al., Energy system developments and investments in the decisive decade for the Paris Agreement goals, Environ. Res. Lett. 16 (7) (Jul. 2021), https://doi.org/10.1088/1748-9326/ac09ae.
[3] Priyadarshi R. Shukla, Jim Skea, Andy Reisinger, Climate Change 2022 Mitigation of Climate Change, 2022.
[4] Climate change puts energy security at risk, World Meteorological Organization, 2023. https://wmo.int/media/news/climate-change-puts-energy-security-risk#:~:text=Otherwise%2C%20there%20is%20a%20risk,World%20Meteorological%20Organization%20(WMO). (Accessed 1 January 2023).
[5] L. Trahey, et al., Energy storage emerging: a perspective from the Joint center for energy storage research, Proc. Natl. Acad. Sci. U. S. A. 117 (23) (Jun. 2020) 12550–12557, https://doi.org/10.1073/pnas.1821672117.
[6] S. Asiaban, et al., Wind and solar intermittency and the associated integration challenges: a comprehensive review including the status in the belgian power system, Energies 14 (9) (May 01, 2021), https://doi.org/10.3390/en14092630. MDPI AG.
[7] G.L. Guizzi, L. Iacovella, M. Manno, Intermittent non-dispatchable renewable generation and reserve requirements: historical analysis and preliminary evaluations on the Italian electric grid, in: Energy Procedia, Elsevier Ltd, Dec. 2015, pp. 339–344, https://doi.org/10.1016/j.egypro.2015.12.103.
[8] S. Impram, S. Varbak Nese, B. Oral, Challenges of renewable energy penetration on power system flexibility: a survey, in: Energy Strategy Reviews, vol. 31, Elsevier Ltd, Sep. 01, 2020, https://doi.org/10.1016/j.esr.2020.100539.
[9] H.H. Coban, A. Rehman, M. Mousa, Load frequency control of microgrid system by battery and Pumped-hydro energy storage, Water (Switzerland) 14 (11) (Jun. 2022), https://doi.org/10.3390/w14111818.
[10] A. Kalair, N. Abas, M.S. Saleem, A.R. Kalair, N. Khan, Role of energy storage systems in energy transition from fossil fuels to renewables, Energy Storage 3 (1) (Feb. 2021), https://doi.org/10.1002/est2.135.
[11] IEA, "Grid-Scale Storage." Accessed: Dec. 11, 2022. [Online]. Available: iea.org/reports/grid-scale-storage.
[12] K.M. Tan, T.S. Babu, V.K. Ramachandaramurthy, P. Kasinathan, S.G. Solanki, S. K. Raveendran, Empowering smart grid: a comprehensive review of energy storage technology and application with renewable energy integration, J. Energy Storage 39 (Jul. 01, 2021), https://doi.org/10.1016/j.est.2021.102591. Elsevier Ltd.
[13] United States Government Accountability Office, ELECTRICITY GRID RESILIENCE Climate Change Is Expected to Have Far-Reaching Effects and DOE and FERC Should Take Actions Report to Congressional Requesters United States Government Accountability Office, 2021.
[14] International Energy Agency, Net Zero by 2050 A Roadmap for the Global Energy Sector, 2021 [Online]. Available: www.iea.org/t&c/.
[15] P.H. Divshali, et al., Battery storage demonstration projects an overview across Europe, in: Proceedings of 2021 IEEE PES Innovative Smart Grid Technologies Europe: Smart Grids: toward a Carbon-free Future, ISGT Europe 2021, Institute of Electrical and Electronics Engineers Inc., 2021, https://doi.org/10.1109/ISGTEurope52324.2021.9640073.
[16] Bloomberg New Energy Finance, Global Energy Storage Policy Review Part 2—Case Studies, Manhattan, NY, USA, 2019.

[17] "Battery Energy Storage Market," Fortune Business Insights. Accessed: Jan. 02, 2023. [Online]. Available: https://www.fortunebusinessinsights.com/industry-reports/battery-energy-storage-market-100489.
[18] Malaysia energy transition Outlook 2023 Accessed: Jun. 07, 2023. [Online]. Available:https://www.irena.org/Publications/2023/Mar/Malaysia-energy-transition-outlook.
[19] SEDA Malaysia, *MyRER*. 2021. [Online]. Available: www.seda.gov.my.
[20] M. Ministry, Of Economy, "national energy transition roadmap (NETR),", Aug. 2023. Accessed: Dec. 28, 2023. [Online]. Available: https://www.seda.gov.my/.
[21] Report_on_Peninsular_Malaysia_Generation_Development_Plan_2020_, FINAL", 2021-2039.
[22] Energy Watch, "Infographic: A Better Future with Battery Storage in Malaysia." Accessed: Jan. 02, 2023. [Online]. Available: https://www.energywatch.com.my/blog/2021/06/01/battery-storage-in-malaysia/.
[23] SEDA - Renewable Energy in Malaysia," SEDA Malaysia. Accessed: Jan. 02, 2023. [Online]. Available: https://www.seda.gov.my/reportal/re-incentive/.
[24] W.S.W. Abdullah, M. Osman, M.Z.A.A. Kadir, R. Verayiah, Battery energy storage system (BESS) design for peak demand reduction, energy arbitrage and grid ancillary services, Int. J. Power Electron. Drive Syst. 11 (1) (Mar. 2020) 398–408, https://doi.org/10.11591/ijpeds.v11.i1.pp398-408.
[25] W.S.W. Abdullah, M. Osman, M.Z.A.A. Kadir, R. Verayiah, The potential and status of renewable energy development in Malaysia, Energies 12 (2019) 12, https://doi.org/10.3390/en12122437.
[26] B. Wrålsen, B. Faessler, Multiple scenario analysis of battery energy storage system investment: Measuring economic and circular viability, Batteries 8 (2) (Feb. 2022), https://doi.org/10.3390/batteries8020007.
[27] Australian Energy Market Commission, National Electricity Rules ver 193 (Dec. 2022).
[28] Australia Energy Market Operator (AEMO), Dynamic Model Acceptance Test Guideline, 2021.
[29] Energy Commission Malaysia, Grid Code for Peninsular Malaysia, 2020.
[30] Tenaga Nasional Berhad, Transmission System Reliability Standards, 2006.
[31] Malaysia Energy Commission, Guidelines on Large Scale Photovoltaic Plant for Connection to Electricity Networks, 2018.
[32] 1547-2018, IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE, 2018.
[33] Petovarga, "For Operational Safety of Battery Energy Storage Systems Current Recommendations and Standards for Energy Storage Safety.".
[34] N. Liu, M. Panteli, and P. A. Crossley, "Reliability Evaluation of a Substation Automation System Communication Network Based on IEC 61850.".
[35] "AS/NZS 4777.2 – Inverter Requirements standard." Accessed: Jan. 01, 2024. [Online]. Available: https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/as-nzs-4777-2-inverter-requirements-standard.
[36] National Grid Electricity System Operator Limited, THE GRID CODE ISSUE 6 REVISION 15 THE GRID CODE, 2022.
[37] A.W. Briceno, V.-M. Macdonald, Grid Code Requirements in the UK for the Connection of BESS in Wind Systems, 2022.
[38] X. Luo, et al., Review of voltage and frequency grid code specifications for electrical energy storage applications, Energies 11 (5) (2018), https://doi.org/10.3390/en11051070. MDPI AG.
[39] Institute of Electrical and Electronics Engineers, Fla. IEEE photovoltaic specialist conference 42 2015.06.14-19 Tampa, Fla. IEEE Photovoltaic Specialists Conference 42 2015.06.14-19 Tampa, and Fla. PVSC 42 2015.06.14-19 Tampa, IEEE 1547 Standards advancing grid modernization.
[40] W. Wei, Z. Zhou, Architecture and roadmap of standard system for global energy interconnection, in: 2020 IEEE Student Conference on Electric Machines and Systems, SCEMS 2020, Institute of Electrical and Electronics Engineers Inc., Dec. 2020, pp. 298–305, https://doi.org/10.1109/SCEMS48876.2020.9352417.
[41] Z. Zhou, W. Wang, Standardization of smart grid technology for the development of global energy interconnection, in: 2020 IEEE Student Conference on Electric Machines and Systems, SCEMS 2020, Institute of Electrical and Electronics Engineers Inc., Dec. 2020, pp. 569–573, https://doi.org/10.1109/SCEMS48876.2020.9352385.
[42] R. Leszczyna, A review of standards with cybersecurity requirements for smart grid, Comput. Secur. 77 (Aug. 01, 2018) 262–276, https://doi.org/10.1016/j.cose.2018.03.011. Elsevier Ltd.
[43] K. Shanmugam, G. Pitto, L. Barbato, Gridcode compliances and operational requirements of grid connected BESS-Reneweable power plants, in: 2020 IEEE International Conference on Power Systems Technology, Institute of Electrical and Electronics Engineers Inc., Sep. 2020, https://doi.org/10.1109/POWERCON48463.2020.9230534. *POWERCON 2020*.
[44] Abbas A. Akhir, et al., DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA, 2015.
[45] X. Li, S. Wang, Energy management and operational control methods for grid battery energy storage systems, CSEE Journal of Power and Energy Systems 7 (5) (Sep. 2021) 1026–1040, https://doi.org/10.17775/CSEEJPES.2019.00160.
[46] S. Eric, M.L. Inês, Bulk Energy Storage Increases United States Electricity System Emissions, Environment, Science and Technology, Jan. 2015, pp. 3203–3210.
[47] B. Gundogdu, D.T. Gladwin, D.A. Stone, Battery SOC Management Strategy for Enhanced Frequency Response and Day-Ahead Energy Scheduling of BESS for Energy Arbitrage, 2017.
[48] A. Chen, P.K. Sen, Deployment of battery energy storage system for energy arbitrage applications, in: NAPS 2016 - 48th North American Power Symposium, Proceedings, Institute of Electrical and Electronics Engineers Inc., Nov, 2016, https://doi.org/10.1109/NAPS.2016.7747920.
[49] S. Nair, K. Rahbar, P. Peng, A. Albert, Multi-application battery energy storage systems for energy arbitrage and frequency regulation: Singapore context analysis, in: 2022 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia), IEEE, Nov., 2022, pp. 26–30, https://doi.org/10.1109/ISGTAsia54193.2022.10003510.
[50] S.G. Sadegh Vejdan, The Value of Real Time Energy Arbitrage with Energy Storage Systems, 2018.
[51] F.G. Tay, M. Tudzi, J. Wobil, F.B. Effah, Improved Voltage Control in LV Grid-Connected PV System Using Active Power Curtailment with Battery Energy Storage System, Institute of Electrical and Electronics Engineers (IEEE), Oct. 2022, pp. 1–5, https://doi.org/10.1109/powerafrica53997.2022.9905329.
[52] I. Latin, A. Transactions, PV Power Curtailment and BESS Management for Distribution Networks: A Practical Approach; PV Power Curtailment and BESS Management for Distribution Networks, A Practical Approach, 2023.
[53] A. Nikoobakht, J. Aghaei, M. Shafie-Khah, J.P.S. Catalao, Minimizing wind power curtailment using a continuous-time risk-based model of generating units and bulk energy storage, IEEE Trans. Smart Grid 11 (6) (Nov. 2020) 4833–4846, https://doi.org/10.1109/TSG.2020.3004488.
[54] M. Andrychowicz, B. Olek, Energy storing vs. generation curtailment - the measures for controlling renewable generation, in: International Conference on the European Energy Market, EEM, IEEE Computer Society, Jul. 2017, https://doi.org/10.1109/EEM.2017.7982004.
[55] Z. Shi, W. Wang, Y. Huang, P. Li, L. Dong, Simultaneous optimization of renewable energy and energy storage capacity with the hierarchical control, CSEE Journal of Power and Energy Systems 8 (1) (Jan. 2022) 95–104, https://doi.org/10.17775/CSEEJPES.2019.01470.
[56] U. Chrisrootandhantzpresume, Using Battery Energy Storage to Reduce Renewable Resource Curtailment, 2017.
[57] X. Dui, G. Zhu, L. Yao, Two-stage optimization of battery energy storage capacity to decrease wind power curtailment in grid-connected wind farms, IEEE Trans. Power Syst. 33 (3) (May 2018) 3296–3305, https://doi.org/10.1109/TPWRS.2017.2779134.
[58] Ancillary Services." Accessed: Feb. 15, 2023. [Online]. Available: https://greeningthegrid.org/integration-in-depth/ancillary-services.
[59] Y. Ma, Z. Hu, Y. Song, Hour-ahead optimization strategy for shared energy storage of renewable energy power stations to provide frequency regulation service, IEEE Trans. Sustain. Energy 13 (4) (Oct. 2022) 2331–2342, https://doi.org/10.1109/TSTE.2022.3194718.
[60] K. Doenges, I. Egido, L. Sigrist, E. Lobato Miguelez, L. Rouco, Improving AGC performance in power systems with regulation response accuracy margins using battery energy storage system (BESS), IEEE Trans. Power Syst. 35 (4) (Jul. 2020) 2816–2825, https://doi.org/10.1109/TPWRS.2019.2960450.
[61] N.S.E. Guzman, C.A. Canizares, K. Bhattacharya, D. Sohm, Frequency regulation model of bulk power systems with energy storage, IEEE Trans. Power Syst. 37 (2) (Mar. 2022) 913–926, https://doi.org/10.1109/TPWRS.2021.3108728.
[62] H. Zhao, M. Hong, W. Lin, K.A. Loparo, Voltage and frequency regulation of microgrid with battery energy storage systems, IEEE Trans. Smart Grid 10 (1) (Jan. 2019) 414–424, https://doi.org/10.1109/TSG.2017.2741668.
[63] N. Padmanabhan, M. Ahmed, K. Bhattacharya, Battery energy storage systems in energy and reserve markets, IEEE Trans. Power Syst. 35 (1) (Jan. 2020) 215–226, https://doi.org/10.1109/TPWRS.2019.2936131.
[64] A. Gupta, S.R. Vaishya, M. Gupta, A.R. Abhyankar, Participation of battery energy storage technologies in co-optimized energy and reserve markets, in: 2020 21st National Power Systems Conference, NPSC 2020, Institute of Electrical and Electronics Engineers Inc., Dec. 2020, https://doi.org/10.1109/NPSC49263.2020.9331865.
[65] R. Hollinger, A.M. Cortes, T. Erge, Fast frequency response with BESS: a comparative analysis of Germany, Great Britain and Sweden, in: International Conference on the European Energy Market, EEM, IEEE Computer Society, Sep. 2018, https://doi.org/10.1109/EEM.2018.8469998.
[66] H. Shafique, L.B. Tjernberg, D.E. Archer, S. Wingstedt, Energy management system (EMS) of battery energy storage system (BESS) - providing ancillary services, in: 2021 IEEE Madrid PowerTech, PowerTech 2021 - Conference Proceedings, Institute of Electrical and Electronics Engineers Inc., Jun, 2021, https://doi.org/10.1109/PowerTech46648.2021.9494781.
[67] R. Kurniawan Subroto, D. Gebbran, A. Barragan Moreno, T. Dragicevic, BESS optimal sizing and scheduling for energy arbitrage and frequency containment reserve via dual-loop optimization, in: 2022 IEEE Transportation Electrification Conference and Expo, ITEC 2022, Institute of Electrical and Electronics Engineers Inc., 2022, pp. 941–946, https://doi.org/10.1109/ITEC53557.2022.9813993.
[68] N. Pattana-Ew, S. Sangwongwanich, Unit management of a BESS-integrated hydro power plant for spinning reserve enhancement, in: Proceeding of the 2021 9th International Electrical Engineering Congress, iEECON 2021, Institute of Electrical and Electronics Engineers Inc., Mar., 2021, pp. 33–36, https://doi.org/10.1109/iEECON51072.2021.9440278.
[69] S.S. Al-Maaitah, H.D. Al-Majali, Particle swarm optimizer for BESS operation to mitigate voltage deviation of the modified IEEE 9-bus power system, in: 2021 IEEE Jordan International Joint Conference on Electrical Engineering and Information Technology, JEEIT 2021 - Proceedings, Institute of Electrical and Electronics Engineers Inc., 2021, pp. 31–36, https://doi.org/10.1109/JEEIT53412.2021.9634129.
[70] J. Krata, T.K. Saha, Real-time coordinated voltage support with battery energy storage in a distribution grid equipped with medium-scale PV generation, IEEE Trans. Smart Grid 10 (3) (May 2019) 3486–3497, https://doi.org/10.1109/TSG.2018.2828991.

[71] M.K.M.B. Best, R and Institute of Electrical and Electronics Engineers, "Reactive Power Injection from Battery Energy Storage during Voltage Dips at a Thermal Power Plant,", IEEE Power & Energy Society. General Meeting, Portland, 2018. Or.), 2018.
[72] J. Krata, T.K. Saha, Real-time coordinated voltage support with battery energy storage in a distribution grid equipped with medium-scale PV generation, IEEE Trans. Smart Grid 10 (3) (May 2019) 3486–3497, https://doi.org/10.1109/TSG.2018.2828991.
[73] M. Shahparasti, H. Laaksonen, K. Kauhaniemi, P. Lauttamus, S. Strandberg, J. Strandberg, Inrush current management during medium voltage microgrid black start with battery energy storage system, IEEE Access 10 (2022) 42273–42282, https://doi.org/10.1109/ACCESS.2022.3167701.
[74] A. Wang, H. Gang, P. Qiu, X. Luo, X. Pang, C. Zhang, Self-Starting Analysis of New Energy System with Wind Power and Energy Storage, in: Proceedings of the 37th Chinese Control Conference, Wuhan, China, 2018, pp. 7422–7427.
[75] B.S.G.L. Hongfen C, Research on Method of Photovoltaic Power Station Assisting Power Grid Black Start Based on Energy Storage, IEEE, 2018.
[76] J. Li, H. You, J. Qi, M. Kong, S. Zhang, H. Zhang, Stratified optimization strategy used for restoration with photovoltaic-battery energy storage systems as black-start resources, IEEE Access 7 (2019) 127339–127352, https://doi.org/10.1109/ACCESS.2019.2937833.
[77] E. A. for S. of E. Jean-Michel D, Services to Support Transmission Infrastructure Energy Storage Applications Forms, Aug. 2021. Brussels.
[78] C. Macrae, M. Ozlen, A. Ernst, Transmission expansion planning considering energy storage, in: 2014 IEEE International Autumn Meeting on Power, Electronics and Computing, ROPEC 2014, Institute of Electrical and Electronics Engineers Inc., Feb. 2014, https://doi.org/10.1109/ROPEC.2014.7036327.
[79] darrenbarnes, Assessment of Battery Energy Storage for Distribution Capacity Upgrade Deferral, 2017.
[80] A. Bhandari, D. Ramasubramanian, V. Singhvi, A. Gaikwad, Considerations for electric utilities to determine energy storage size for transmission deferral to increase hosting capacity, in: 2020 52nd North American Power Symposium, NAPS 2020, Institute of Electrical and Electronics Engineers Inc., Apr, 2021, https://doi.org/10.1109/NAPS50074.2021.9449689.
[81] H. Abdeltawab, Y.A.R.I. Mohamed, Energy storage planning for profitability maximization by power trading and ancillary services participation, IEEE Syst. J. 16 (2) (Jun. 2022) 1909–1920, https://doi.org/10.1109/JSYST.2021.3069671.
[82] Z. Leonowicz, Institute of electrical and Electronics engineers, IEEE electromagnetic compatibility society, in: IEEE Power & Energy Society, IEEE Industry Applications Society, and Industrial and Commercial Power Systems Europe, Stationary and Transportable Storage Systems for Transmission Networks with High RES Penetration Spain, 2020, 4th : 2020 : Online), *Expansion Planning Model Coordinated with both*.
[83] J. Arteaga, H. Zareipour, N. Amjady, Energy storage as a service: optimal pricing for transmission congestion relief, IEEE Open Access Journal of Power and Energy 7 (2020) 514–523, https://doi.org/10.1109/OAJPE.2020.3031526.
[84] Ga, IEEE Power & Energy Society, General Meeting (2019 : Atlanta and Institute of Electrical and Electronics Engineers, 2019. *Spatiotemporal Arbitrage of Large-Scale Portable Energy Storage for Grid Congestion Relief*.
[85] G. Pulazza, N. Zhang, C. Kang, C.A. Nucci, Transmission planning with battery-based energy storage transportation for power systems with high penetration of renewable energy, IEEE Trans. Power Syst. 36 (6) (Nov. 2021) 4928–4940, https://doi.org/10.1109/TPWRS.2021.3069649.
[86] E. A. for S. of E. Jean-Michel D, Services to Support Distribution Infrastructure Energy Storage Applications Forms, Aug. 2021. Brussels.
[87] O. Unigwe, D. Okekunle, A. Kiprakis, Towards Benefit-Stacking for Grid-Connected Battery Energy Storage in Distribution Networks with High Photovoltaic Penetration, APSCOM, 2018.
[88] Ga, IEEE Power & Energy Society, General Meeting (2019 : Atlanta and Institute of Electrical and Electronics Engineers, 2019. Stacking Revenue from Energy Storage Providing Resilience, T&D Deferral and Arbitrage.
[89] J. Liu, P. Zeng, Z. He, Y. Li, Q. Wu, N-1 security-constrained integration of distributed generators in active distribution grids with energy storage support, in: 2020 IEEE 4th Conference on Energy Internet and Energy System Integration: Connecting the Grids towards a Low-Carbon High-Efficiency Energy System, EI2 2020, Institute of Electrical and Electronics Engineers Inc., Oct. 2020, pp. 2528–2533, https://doi.org/10.1109/EI250167.2020.9346745.
[90] O. Alahmad, M. Aldahmi, Enhancing security of supply using battery energy storage systems in distribution networks in UAE, in: 2021 11th International Conference on Power and Energy Systems, ICPES 2021, Institute of Electrical and Electronics Engineers Inc., 2021, pp. 168–171, https://doi.org/10.1109/ICPES53652.2021.9683958.
[91] J. Krata, T.K. Saha, Real-time coordinated voltage support with battery energy storage in a distribution grid equipped with medium-scale PV generation, IEEE Trans. Smart Grid 10 (3) (May 2019) 3486–3497, https://doi.org/10.1109/TSG.2018.2828991.
[92] L. Sun, W. Liu, C.Y. Chung, M. Ding, R. Bi, L. Wang, Improving the restorability of bulk power systems with the implementation of a wf-bess system, IEEE Trans. Power Syst. 34 (3) (May 2019) 2366–2377, https://doi.org/10.1109/TPWRS.2018.2889990.
[93] Kurukshetra. D. of E. E. National Institute of Technology, Institute of Electrical and Electronics Engineers. Delhi Section. PELS/IES Joint Chapter, Institute of Electrical and Electronics Engineers. Delhi Section. PES/IAS Joint Chapter, and Institute of Electrical and Electronics Engineers vol. 2018, Study Results for Preventing Power Outages utilizing Battery Energy Storage Systems, 2018, 8th IEEE Power India International Conference : PIICON.
[94] A. Hussain, V.H. Bui, H.M. Kim, Optimal sizing of battery energy storage system in a fast EV charging station considering power outages, IEEE Transactions on Transportation Electrification 6 (2) (Jun. 2020) 453–463, https://doi.org/10.1109/TTE.2020.2980744.
[95] E. A. for S. of E. Jean-Michel D, Services to Support behind the Meter Customer Energy Management Energy Storage Applications Forms, Aug. 2021. Brussels.
[96] M.A. Rajabinezhad, A.G. Baayeh, J.M. Guerrero, Fuzzy-based power management and power quality improvement in microgrid using battery energy storage system, in: 2020 10th Smart Grid Conference, SGC 2020, Institute of Electrical and Electronics Engineers Inc., Dec. 2020, https://doi.org/10.1109/SGC52076.2020.9335758.
[97] R.N. Shaw, P. Walde, P, C T, GUCON) International Conference on Computing, *Power Quality Improvement in Hybrid Power System Using Synchronous Reference Frame Theory Based Distribution Static Compensator with Battery Energy Storage System*, 2019.
[98] M. Xun, W. Zhen, G. Li, Z. Yong, Research on grid power quality control strategy based on energy storage capacity, in: 2021 IEEE International Conference on Advances in Electrical Engineering and Computer Applications, Institute of Electrical and Electronics Engineers Inc., Aug. 2021, pp. 1136–1139, https://doi.org/10.1109/AEECA52519.2021.9574335. ***AEECA 2021***.
[99] 2019 IEEE 2nd International Conference on Power and Energy Applications, *Harmonics Measurements And Analysis Of Battery Energy Storage Systems In Microgrids*, 2019.
[100] L. Dexin, W. Jiarui, Z. Guanqun, C. Chaohao, J. Longfei, Research on the method of using APF to improve the power quality of microgrid based on the control of energy storage, in: 2020 4th International Conference on Power and Energy Engineering, ICPEE 2020, Institute of Electrical and Electronics Engineers Inc., Nov. 2020, pp. 48–52, https://doi.org/10.1109/ICPEE51316.2020.9311092.
[101] D. Mei, et al., Study on different time level control methods of energy storage system considering the reliability of microgrid cluster power supply, in: 2020 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices, Institute of Electrical and Electronics Engineers Inc., Oct. 2020, https://doi.org/10.1109/ASEMD49065.2020.9276331. ***ASEMD 2020***.
[102] H. Jia, R. Peng, L. Yang, Y. Li, Reliability assessment of power systems with warm standby and energy storage, in: 2021 Global Reliability and Prognostics and Health Management, PHM-Nanjing 2021, Institute of Electrical and Electronics Engineers Inc., 2021, https://doi.org/10.1109/PHM-Nanjing52125.2021.9613081.
[103] J. Han, et al., Reliability evaluation of regional integrated energy system considering multiple energy storage resources, in: IEEE International Conference on Control and Automation, ICCA, IEEE Computer Society, Oct. 2020, pp. 436–441, https://doi.org/10.1109/ICCA51439.2020.9264508.
[104] M.R. Tur, Reliability assessment of distribution power system when considering energy storage configuration technique, IEEE Access 8 (2020) 77962–77971, https://doi.org/10.1109/ACCESS.2020.2990345.
[105] R. Karandeh, T. Lawanson, V. Cecchi, A multi-application energy management of behind-the-meter battery energy storage system, in: 2020 52nd North American Power Symposium, NAPS 2020, Institute of Electrical and Electronics Engineers Inc., Apr, 2021, https://doi.org/10.1109/NAPS50074.2021.9449803.
[106] F.O. Ramos, A.L. Pinheiro, R.N. Lima, M.M.B. Neto, W.A.S. Junior, L.G.S. Bezerra, A real case analysis of a battery energy storage system for energy time shift, demand management, and reactive control, in: 2021 IEEE PES Innovative Smart Grid Technologies Conference - Latin America, ISGT Latin America 2021, Institute of Electrical and Electronics Engineers Inc., Sep. 2021, https://doi.org/10.1109/ISGTLatinAmerica52371.2021.9543069.
[107] J.S. Guzmán-Feria, L.M. Castro, J.H. Tovar-Hernández, N. González-Cabrera, G. Gutiérrez-Alcaraz, Unit commitment for multi-terminal VSC-connected AC systems including BESS facilities with energy time-shifting strategy, Int. J. Electr. Power Energy Syst. 134 (Jan. 2022), https://doi.org/10.1016/j.ijepes.2021.107367.
[108] F.O. Ramos, A.L. Pinheiro, R.N. Lima, M.M.B. Neto, W.A.S. Junior, L.G.S. Bezerra, A real case analysis of a battery energy storage system for energy time shift, demand management, and reactive control, in: 2021 IEEE PES Innovative Smart Grid Technologies Conference - Latin America, ISGT Latin America 2021, Institute of Electrical and Electronics Engineers Inc., Sep. 2021, https://doi.org/10.1109/ISGTLatinAmerica52371.2021.9543069.
[109] A.C. Duman, H.S. Erden, Ö. Gönül, Ö. Güler, Optimal sizing of PV-BESS units for home energy management system-equipped households considering day-ahead load scheduling for demand response and self-consumption, Energy Build. 267 (Jul. 2022), https://doi.org/10.1016/j.enbuild.2022.112164.
[110] M.E. Raoufat, B. Asghari, R. Sharma, Model predictive BESS control for demand charge management and PV-utilization improvement, in: 2018 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2018, Institute of Electrical and Electronics Engineers Inc., Jul. 2018, pp. 1–5, https://doi.org/10.1109/ISGT.2018.8403403.
[111] W. Kong, F. Luo, Y. Jia, Z.Y. Dong, J. Liu, Benefits of home energy storage utilization: an Australian case study of demand charge practices in residential sector, IEEE Trans. Smart Grid 12 (4) (Jul. 2021) 3086–3096, https://doi.org/10.1109/TSG.2021.3054126.
[112] M. Abou Houran, K. Sabzevari, A. Hassan, A. Oubelaid, M. Tostado-Véliz, N. Khosravi, Active power filter module function to improve power quality conditions using GWO and PSO techniques for solar photovoltaic arrays and battery energy storage systems, J. Energy Storage 72 (Nov. 2023), https://doi.org/10.1016/j.est.2023.108552.
[113] B. Xu, A. Oudalov, J. Poland, A. Ulbig, G. Andersson, BESS control strategies for participating in grid frequency regulation, in: IFAC Proceedings Volumes (IFAC-

PapersOnline), IFAC Secretariat, 2014, pp. 4024–4029, https://doi.org/10.3182/20140824-6-za-1003.02148.
[114] Z. Tan, X. Li, L. He, Y. Li, J. Huang, Primary frequency control with BESS considering adaptive SoC recovery, Int. J. Electr. Power Energy Syst. 117 (May 2020), https://doi.org/10.1016/j.ijepes.2019.105588.
[115] C.E. Okafor, K.A. Folly, Provision of additional inertia support for a power system network using battery energy storage system, IEEE Access 11 (2023) 74936–74952, https://doi.org/10.1109/ACCESS.2023.3295333.
[116] M. Siddique, M. Hussain, J. Hussain, S. Raza, Power Quality Improvement of Grid Connected Wind Energy System Using DSTATCOM-BESS, 2019 [Online]. Available: https://www.researchgate.net/publication/351067111.
[117] X. Li, D. Hui, X. Lai, Battery energy storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations, IEEE Trans. Sustain. Energy 4 (2) (2013) 464–473, https://doi.org/10.1109/TSTE.2013.2247428.
[118] C. Wang, Y. Yu, W. Xu, S. Liu, An improved grid-forming control strategy of energy storage system for enhancing low-voltage ride through capability, in: 2023 IEEE International Conference on Advanced Power System Automation and Protection (APAP), IEEE, Oct. 2023, pp. 101–105, https://doi.org/10.1109/APAP59666.2023.10348485.
[119] F. Zhao, et al., Control interaction modeling and analysis of grid-forming battery energy storage system for offshore wind power plant, IEEE Trans. Power Syst. 37 (1) (Jan. 2022) 497–507, https://doi.org/10.1109/TPWRS.2021.3096850.
[120] J. Figgener, et al., The development of stationary battery storage systems in Germany – a market review, J. Energy Storage 29 (Jun. 2020), https://doi.org/10.1016/j.est.2019.101153.
[121] M. Rybarik, P. Bracinik, M. Kajanova, Overview of the usability of second-life batteries in smart distribution grids, in: 14th International Conference ELEKTRO, ELEKTRO 2022 - Proceedings, Institute of Electrical and Electronics Engineers Inc., 2022, https://doi.org/10.1109/ELEKTRO53996.2022.9803780.
[122] J. Neubauer, K. Smith, E. Wood, A. Pesaran, Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries, 2015 [Online]. Available: www.nrel.gov/publications.
[123] M.O. Qays, Y. Buswig, M.L. Hossain, A. Abu-Siada, Recent progress and future trends on the state of charge estimation methods to improve battery-storage efficiency: a review, CSEE Journal of Power and Energy Systems 8 (1) (Jan. 01, 2022) 105–114, https://doi.org/10.17775/CSEEJPES.2019.03060. Institute of Electrical and Electronics Engineers Inc.
[124] F. Bovera, M. Spiller, M. Zatti, G. Rancilio, M. Merlo, Development, validation, and testing of advanced mathematical models for the optimization of BESS operation, Sustainable Energy, Grids and Networks 36 (Dec. 2023), https://doi.org/10.1016/j.segan.2023.101152.
[125] J. Liu, C. Hu, A. Kimber, Z. Wang, Uses, cost-benefit analysis, and markets of energy storage systems for electric grid applications, J. Energy Storage 32 (Dec. 01, 2020), https://doi.org/10.1016/j.est.2020.101731. Elsevier Ltd.
[126] C. Zhang, Y.L. Wei, P.F. Cao, M.C. Lin, Energy storage system: current studies on batteries and power condition system, Renew. Sustain. Energy Rev. 82 (Feb. 01, 2018) 3091–3106, https://doi.org/10.1016/j.rser.2017.10.030. Elsevier Ltd.
[127] M. Chiang, L. Su, S. Pan, Z. Li, Lowering the Bar on Battery Cost, 2017 [Online]. Available: www.cell.com/joule/fulltext/S2542-4351.
[128] A. IEEE Industrial Electronics Society, Institute of Electrical and Electronics Engineers, IEEE Industrial Electronics Society, and Keisoku Jido Seigyo Gakkai (Japan), Recent advances on Energy Storage Systems, 2011. Conference (37th : 2011 : Melbourne (Vic.).
[129] S. Mandelli, M. Molinas, E. Park, M. Leonardi, E. Colombo, M. Merlo, The role of storage in emerging country scenarios, in: Energy Procedia, Elsevier Ltd, 2015, pp. 112–123, https://doi.org/10.1016/j.egypro.2015.07.657.
[130] T. Gandhok, P. Manthri, Economics of stationary energy storage systems: driving faster adoption for behind-the-meter applications in India, J. Clean. Prod. 330 (Jan. 2022), https://doi.org/10.1016/j.jclepro.2021.129610.
[131] Delhi Technological University, Delhi Technological University. Department of Electrical Engineering, Institute of Electrical and Electronics Engineers. Delhi Section, Institute of Electrical and Electronics Engineers. Delhi Section. PELS-IES Joint Chapter, Institute of Electrical and Electronics Engineers. Delhi Section. PES-IAS Joint Chapter, and Institute of Electrical and Electronics Engineers, "Potential of distributed generation resources in India.".
[132] L. Deotti, W. Guedes, B. Dias, T. Soares, Technical and economic analysis of battery storage for residential solar photovoltaic systems in the Brazilian regulatory context, Energies 13 (24) (Dec. 2020), https://doi.org/10.3390/en13246517.
[133] V.T. Nascimento, P.A. Gimenes, M.E.M. Udaeta, A.L.V. Gimenes, Energy storage systems issues looking for integrated distributed energy-resource planning, MDPI AG, Nov. (2020) 15, https://doi.org/10.3390/wef-06931.
[134] E.C. Nnaji, D. Adgidzi, M.O. Dioha, D.R.E. Ewim, Z. Huan, Modelling and management of smart microgrid for rural electrification in sub-saharan Africa: the case of Nigeria, Electr. J. 32 (10) (Dec. 2019), https://doi.org/10.1016/j.tej.2019.106672.
[135] S. Mandelli, et al., The role of electrical energy storage in sub-Saharan Africa, J. Energy Storage 8 (Nov. 01, 2016) 287–299, https://doi.org/10.1016/j.est.2015.11.006. Elsevier Ltd.
[136] K. Prakash, et al., A review of battery energy storage systems for ancillary services in distribution grids: current status, challenges and future directions, Front. Energy Res. 10 (Sep. 16, 2022), https://doi.org/10.3389/fenrg.2022.971704. Frontiers Media S.A.
[137] E. Energy, "Gannawarra Energy Storage System Operational Report #3 and #4.".
[138] Andy Colthorpe, "China's largest stand-alone battery storage project begins commercial operation," Energy Storage News. Accessed: Apr. 06, 2023. [Online]. Available: https://ieefa.org/articles/chinas-largest-stand-alone-battery-storage-project-begins-commercial-operation.
[139] CATL Connects World's First and China's Largest BESS Multi-Mixed Energy Power Station (100MWh) to the Grid," Contemporary Amperex Technology Co., Limited. Accessed: Apr. 06, 2023. [Online]. Available: https://www.prnewswire.com/news-releases/catl-connects-worlds-first-and-chinas-largest-bess-multi-mixed-energy-power-station-100mwh-to-the-grid-300786663.html.
[140] Dan Robinson, "Massive energy storage system goes online in UK." Accessed: Feb. 15, 2023. [Online]. Available: https://www.theregister.com/2022/11/24/uk_battery_energy_storage/.
[141] Cameron M, "200MWh BESS in Texas begins commercial operations." Accessed: Feb. 15, 2023. [Online]. Available: https://www.energy-storage.news/200mwh-bess-in-texas-begins-commercial-operations/.
[142] Y. Yoo, G. Jang, S. Jung, A study on sizing of substation for PV with optimized operation of BESS, IEEE Access 8 (2020) 214577–214585, https://doi.org/10.1109/ACCESS.2020.3040646.
[143] S.W. Xiangjun Li, A Review on Energy Management, Operation Control and Application Methods for Grid Battery Energy Storage Systems, CSEE Journal of Power and Energy Systems, Jun. 2019.
[144] Y. Liu, W. Huang, N. Sifang Epower, Information Modeling and Implementation of Monitoring and Control System in Large Scale Battery Energy Storage System, 9th IET International Conference, 2012, https://doi.org/10.1049/cp.2012.2115.
[145] Y. Yoo, G. Jang, S. Jung, A study on sizing of substation for PV with optimized operation of BESS, IEEE Access 8 (2020) 214577–214585, https://doi.org/10.1109/ACCESS.2020.3040646.
[146] C. Jankowiak, A. Zacharopoulos, C. Brandoni, P. Keatley, P. MacArtain, N. Hewitt, The role of domestic integrated battery energy storage systems for electricity network performance enhancement, Energies 12 (Oct. 2019), https://doi.org/10.3390/en12203954, 20.
[147] X. Li, D. Hui, X. Lai, Battery energy storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations, IEEE Trans. Sustain. Energy 4 (2) (2013) 464–473, https://doi.org/10.1109/TSTE.2013.2247428.
[148] K.C. Budka, J.G. Deshpande, T.L. Doumi, M. Madden, T. Mew, Communication network architecture and design principles for smart grids, Bell Labs Tech. J. 15 (2) (Sep. 2010) 205–227, https://doi.org/10.1002/bltj.20450.
[149] D. Muyizere, L.K. Letting, B.B. Munyazikwiye, Effects of communication signal delay on the power grid: a review, Electronics 11 (Mar. 01, 2022) 6, https://doi.org/10.3390/electronics11060874. MDPI.
[150] J.W. Feltes, et al., Some considerations in the development of restoration plans for electric utilities serving large metropolitan areas, IEEE Trans. Power Syst. 21 (2) (May 2006) 909–915, https://doi.org/10.1109/TPWRS.2006.873128.
[151] S. Mishra, K. Anderson, B. Miller, K. Boyer, A. Warren, Microgrid resilience: a holistic approach for assessing threats, identifying vulnerabilities, and designing corresponding mitigation strategies, Appl. Energy 264 (Apr. 2020), https://doi.org/10.1016/j.apenergy.2020.114726.
[152] Y. Lin, Z. Bie, A. Qiu, A review of key strategies in realizing power system resilience, Global Energy Interconnection 1 (1) (Jan. 2018) 70–78, https://doi.org/10.14171/j.2096-5117.gei.2018.01.009.
[153] A. Ameur, K. Loudiyi, M. Aggour, Steady state and dynamic analysis of renewable energy integration into the grid using PSS/E software, in: Energy Procedia, Elsevier Ltd, 2017, pp. 119–125, https://doi.org/10.1016/j.egypro.2017.11.023.
[154] X. Xu, M. Bishop, O. Donna G, H. Chen, Application and modeling of battery energy storage in power systems, CSEE Journal of Power and Energy Systems 2 (3) (Sep. 2016) 82–90, https://doi.org/10.17775/CSEEJPES.2016.00039.
[155] W.E.C.C. Modelling, Validation Work Group, "WECC Wind Plant Dynamic Modelling Guidelines," Salt Lake City, UT, Apr. 2014. Accessed: Dec. 15, 2022. [Online]. Available: https://www.wecc.biz/Reliability/WECC%20Wind%20Plant%20Dynamic%20Modeling%20Guidelines.pdf.
[156] W.E.C.C. Modelling, Validation Work Group, Adhoc group on BESS modelling, WECC Energy Storage System Model (2015). Accessed: Dec. 15, 2022. [Online]. Available: https://www.wecc.biz/Reliability/WECC%20Approved%20Energy%20Storage%20System%20Model%20-%20Phase%20II.pdf.
[157] xiaokangxu, Application of New Generic Models for Master Plant Controller and Auxilliary PV and BESS, 2017.
[158] "PSS/E Version 33.8 Program Operational Manual and Model Library." Siemens Power Technologies (PTI), May 2016. Schenectady, NY.
[159] PSLF User's Manual Version 19.0_02, General Electric International Inc., Shenectady, NY, Apr. 2016.
[160] PowerWorld Simulator Program Manual Version 18, PowerWorld Corporation, Champaign, IL, Sep. 2015.
[161] W.S.W. Abdullah, M. Osman, M.Z.A.A. Kadir, R. Verayiah, N.F.A. Aziz, M. A. Rasheed, Techno-economics analysis of battery energy storage system (bess) design for virtual power plant (VPP)–A case study in Malaysia, J. Energy Storage 38 (Jun. 2021), https://doi.org/10.1016/j.est.2021.102568.
[162] 3002.2-2018, IEEE Recommended Practice for Conducting Load-Flow Studies and Analysis of Industrial and Commercial Power Systems, IEEE, 2018.
[163] Q. Li, Y. Tao, Z. Li, Y. Zhang, Z. Zhang, Simulation and modeling for active distribution network BESS system in DIgSILENT, Energy Rep. 8 (Jul. 2022) 97–102, https://doi.org/10.1016/j.egyr.2022.01.113.
[164] G. Rancilio, et al., Modeling a large-scale battery energy storage system for power grid application analysis, Energies 12 (17) (Aug. 2019), https://doi.org/10.3390/en12173312.

[165] A.D. Hansen, Dynamic Wind Turbine Models in Power System Simulation Tool, DIgSILENT. Risø National Laboratory, 2007.
[166] IEEE Power & Energy Society and B. C. IEEE Power and Energy Society (PES) General Meeting 2013.07.21-25 Vancouver, *A Real-Time Dynamic Simulation Tool For Transmission And Distribution Power Systems*.
[167] X. Jiang, X. Han, L. Liu, G. Chen, H. Wang, Transient stability analysis of power system considering traction load, in: 2023 IEEE International Conference on Advanced Power System Automation and Protection (APAP), IEEE, Oct. 2023, pp. 339–344, https://doi.org/10.1109/APAP59666.2023.10348404.
[168] D. Muyizere, L.K. Letting, B.B. Munyazikwiye, Effects of communication signal delay on the power grid: a review, Electronics 11 (Mar. 01, 2022) 6, https://doi.org/10.3390/electronics11060874. MDPI.
[169] F. Gao, K. Strunz, Frequency-adaptive power system modeling for multiscale simulation of transients, IEEE Trans. Power Syst. 24 (2) (2009) 561–571, https://doi.org/10.1109/TPWRS.2009.2016587.
[170] IEEE Power & Energy Society and B. C. IEEE Power and Energy Society (PES) General Meeting 2013.07.21-25 Vancouver, *Parallel Implementation Of Power System Dynamic Simulation*.
[171] F. Milano, An open source power system analysis toolbox, IEEE Trans. Power Syst. 20 (3) (Aug. 2005) 1199–1206, https://doi.org/10.1109/TPWRS.2005.851911.
[172] F. Calero, C.A. Canizares, K. Bhattacharya, Aggregated BESS dynamic models for active distribution network studies, IEEE Trans. Smart Grid 12 (3) (May 2021) 2077–2088, https://doi.org/10.1109/TSG.2020.3048648.
[173] S. Meinecke, et al., SimBench-A benchmark dataset of electric power systems to compare innovative solutions based on power flow analysis, Energies 13 (12) (Jun. 2020), https://doi.org/10.3390/en13123290.
[174] L. Thurner, et al., Pandapower - an open-source Python tool for convenient modeling, analysis, and optimization of electric power systems, IEEE Trans. Power Syst. 33 (6) (Nov. 2018) 6510–6521, https://doi.org/10.1109/TPWRS.2018.2829021.
[175] European Power ElectronicsandDrives Association, Politechnika Poznańska, Modular architecture for decentralized Hybrid Power Systems, in: 13th International Power Electronics and Motion Control Conference (EPE-PEMC), 2008, pp. 2134–2141.
[176] A. Etxegarai, P. Eguia, E. Torres, G. Buigues, A. Iturregi, Current procedures and practices on grid code compliance verification of renewable power generation, Renew. Sustain. Energy Rev. 71 (2017) 191–202, https://doi.org/10.1016/j.rser.2016.12.051. Elsevier Ltd.
[177] DIgSILENT PowerFactory Training Courses." Accessed: Jan. 01, 2024. [Online]. Available: https://www.digsilent.de/en/training-courses.html.
[178] PSS/E Global User Support." Accessed: Jan. 01, 2024. [Online]. Available: https://www.siemens.com/global/en/products/energy/grid-software/planning/pss-software/pss-contact.html.
[179] D. Mejía-Giraldo, G. Velásquez-Gomez, N. Muñoz-Galeano, J.B. Cano-Quintero, S. Lemos-Cano, A BESS sizing strategy for primary frequency regulation support of solar photovoltaic plants, Energies 12 (2) (Jan. 2019), https://doi.org/10.3390/en12020317.
[180] A. Ramos, M. Tuovinen, M. Ala-Juusela, Battery energy storage system (BESS) as a service in Finland: business model and regulatory challenges, J. Energy Storage 40 (Aug. 2021), https://doi.org/10.1016/j.est.2021.102720.
[181] M. Kim, K. Kim, H. Choi, S. Lee, H. Kim, Practical operation strategies for energy storage system under uncertainty, Energies 12 (2019) 6, https://doi.org/10.3390/en12061098.