Heliyon 9 (2023) e22029

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Power quality enhancement for Thailand's wind farm using 5 MWh Li-ion battery energy storage system

Rattaporn Ngoenmeesri [a], Sirinuch Chidaruksa [a,b], Rabian Wangkeeree [c], Chatchai Sirisamphanwong [a,b,*]

[a] *Department of Physics, Faculty of Science, Naresuan University, 99 Moo 9. T.Ta Pho, A.Muang, Phitsanulok 65000, Thailand*
[b] *Smart Energy System Integration Research Unit, Department of Physics, Faculty of Science, Naresuan University, 99 Moo 9. T.Ta Pho, A.Muang, Phitsanulok 65000, Thailand*
[c] *Research Center for Academic Excellence in Mathematics, Department of Mathematics, Faculty of Science, Naresuan University, 99 Moo 9. T.Ta Pho, A.Muang, Phitsanulok 65000, Thailand*

ARTICLE INFO

Keywords:
Wind farm
Feeder trip
Over voltage
Power quality
Energy storage

ABSTRACT

Several studies have stated that an increase in wind power plants and unpredictable wind energy generation face several issues during over-voltage. In this study, an operational 8 MW wind farm in Nakhon Ratchasima province faced severe annual feeder trips 146 times, which is not permissible according to the manufacturers. The feeder trips are mainly attributed to high grid voltage caused by low load demand. This study developed a Battery Energy Storage System (BESS) to minimise feeder trips using DigiSILENT and utilized the higher feeder trip period of September to optimise BESS capacity with a 10 % grid load. Notably, a 5 MWh BESS maintained the grid voltage within an allowable range compared to the 1–4 MWh (increment of 1 MWh) throughout the operational period. Furthermore, a 5 MWh BESS was tested during low and high wind periods to assess the stability of over-voltage management. We found that the 5 MWh BESS controlled over-voltage and prevented feeder trips, resulting in enhanced power generation on selective days with high feeder trips, low wind speed, and high wind speed, generating 28.34 MWh, 0.33 MWh, and 76.67 MWh, respectively, compared to conditions without BESS. Additionally, we recommend that the 5 MWh BESS can enhance wind farm power stability and uphold the manufacturer's warranty.

1. Introduction

Wind energy is a promising renewable energy source abundant in resources. In recent years, Thailand has seen significant growth in the installation of new wind turbines, aimed at reducing reliance on conventional energy sources [1,2]. According to the Alternative Energy Development Plan (AEDP), the rapid growth in wind turbine installations is projected to reach 3002 MW as Thailand possesses excellent wind energy potential and other renewable energy sources. Especially in Thailand's coastal areas, there is significant potential to reduce the substantial share of non-renewable energy-based power production. Additionally, the western and eastern mountainous areas have the second-largest potential for wind energy [3–5]. Although the potential for wind energy is high in

---

* Corresponding author. Department of Physics, Faculty of Science, Naresuan University, 99 Moo 9. T.Ta Pho, A.Muang, Phitsanulok 65000, Thailand.

E-mail address: chatchaisi@nu.ac.th (C. Sirisamphanwong).

https://doi.org/10.1016/j.heliyon.2023.e22029
Received 2 July 2023; Received in revised form 20 October 2023; Accepted 2 November 2023

Thailand, the intermittency and seasonal variation in wind speed significantly impact energy production. Fluctuations in energy production create imbalances in the power distribution line, leading to issues such as overvoltage or undervoltage, which result in feeder trips or necessitate shutting down the wind power plants [6,7]. Due to the absence of an energy storage system, high-penetration wind power plants are disconnected from the distribution system to maintain grid stability and the Distribution System (DS) unless power quality issues such as harmonic distortion, voltage, and frequency variations arise [8–11]. In this study, a detailed review was conducted to understand the necessity of energy storage for wind power plants. Various aspects were explored, including wind turbine placement optimisation, renewable energy integration, potential wind assessment, optimal placement and sizing of wind turbines, energy storage systems, wind power prediction, and the impact of wind power on power systems.

Kheder-Haddouche and Saheb-Koussa assessed the wind potential in the Mecheria region of Algeria and evaluated the cost of energy production by a wind farm. They utilized ten years of wind data to identify the windiest areas, conducted various wind turbine configuration tests to determine an efficient system, and performed 40 MW grid optimisation using HOMER software to assess the economic and environmental impact [12]. Hashem et al. developed a multi-objective optimisation method to determine the optimal sizing of wind turbines and energy storage systems, aiming to reduce the high penetration of intermittent wind power. They utilized the Equilibrium Optimizer (EO) algorithm and a Loss Sensitivity Factor (LSF) as indices of distribution system performance. These methods were applied simultaneously to minimise energy loss and voltage deviation while enhancing voltage stability [13]. Various analytical and optimisation techniques are accessible for enhancing wind power system performance and energy storage efficiency. Moon et al. introduced a weighted evaluation method to identify appropriate wind farm locations, annual wind speed, power generation capacity, and system sizing aligned with the Korean government's initiative to install 17 GW. Additionally, they utilized discrete Fourier transform and probability density models to optimise Energy Storage Systems (ESS) and maintain grid stability [14]. Yan et al. developed an optimal method for sizing the ESS using a steady-state model. In this study, the prediction of wind power establishing the developed system for commercial-grade use includes further operation and maintenance to identify the economically suitable EES for local grid stability [15].

Numerous studies have conducted analyses on power forecasting, error mitigation, long-term variability of wind speed, and wind power resource assessment to optimise the EES [16–19]. Yi et al. examined different operating strategies to optimise the EES capacity, EES lifetime, wind curtailment, and profits. Comparatively, the dynamic control strategy extended the EES's lifetime to 13.39 years, achieving a notably higher profit of 717,207.44 USD. Optimised EES maintains zero overcharging or discharging, making operations 81.85 % efficient, cost-effective, reliable, extending profit, and storing energy [20]. Felix et al. [21] performed an EES optimisation in hourly intervals to meet the electricity bidding in Australia. This study simulates one year of GIS data to generate power through various renewable energy sources. Following the simulation findings, they developed 55 MW battery storage systems capable of discharging over 12 h (110 MWh). The assistance of EES significantly reduced the LCOE by 13–23 %.

Flexi et al., researchers in Portugal have developed Battery Energy Storage System (BESS) integration strategies to reduce power curtailment while harnessing various renewable energy sources. This study utilises unit commitment and economic dispatch algorithms to optimise the system. The total load demand for the selected location stands at 35 MW, with installed capacities from thermal power plants, wind, hydro-geothermal, and waste-to-energy sources amounting to 47.6 MW, 12.6 MW, 1.4 MW, 3 MW, and 1.7 MW, respectively. As mentioned earlier, renewable energy sources often face challenges in providing stable power production due to climate variability. By integrating BESS with non-conventional energy systems, this approach significantly reduces the annual consumption of 1500 tons of oil. Sensitivity analysis reveals that integrating a 1500 KW and 6300 kWh BESS is a cost-effective solution for the examined location, leading to a remarkable 59 % reduction in renewable energy curtailment [22].

Xin et al. [23] developed a Battery Energy Storage System (BESS) to mitigate the uncertainty of wind production in China's varying climatic conditions. They conducted a day-ahead simulation using a Model Predictive Control (MPC) method, validated the results with real-time data, and found that integrating BESS significantly enhances grid stability and accuracy compared to a myopic controller. Furthermore, they discovered that BESS is economically viable with a reserve State of Charge (SOC) of 0.1, as any increase beyond this threshold results in reduced profitability.

In a separate study, Chen et al. [24] addressed wind energy curtailment in China's unpredictable climate. Without BESS, wind energy curtailment reached 40.16 % due to the high variation and unpredictability of wind speeds. To tackle this issue, Chen et al. developed an optimisation technique using a CPLEX solver, aiming to reduce wind energy curtailment and enhance the efficiency of China's wind energy production. This study employs a sodium-sulfur battery as BESS and Phase Change Material (PCM) to reduce the battery operating temperature during peak charging/discharging [25–27]. Utilized the removed temperature from the battery for building thermal applications and enhanced the battery's performance by reducing thermal stress. BESS and PCM reduced wind energy curtailment to 13.70 % and reduced conventional combined heat and power plant operation by 5 %, respectively.

Watson et al. developed a 2 MWh Battery Energy Storage System (BESS) for Canada's 10 MW research and development wind energy institute to reduce their reliance on the conventional grid during periods of low wind. The wind farm's annual energy production was 40 GWh, which was primarily exported to the grid. However, during low wind periods, the wind farm had to draw approximately 13 MWh from the grid to power the institute. This practice not only increased the grid load consumption but also led to low grid voltage levels. By implementing the BESS, the wind farm was able to reduce its grid dependence significantly. Specifically, during a 339-h low wind speed period, which accounted for approximately 63 % of the energy consumption, the BESS played a crucial role in stabilizing the institute's power needs and alleviating stress on the grid [28]. Ikni et al. examined lithium-ion BESS with a 300 MW offshore wind farm to maintain the grid frequency stable during the power fluctuation caused by unaccounted wind speed. Within 600 s, wind turbine power generations widely oscillate between 130 and 180 MW, which causes a mismatch in the grid frequency code. Incorporating a 30 MW lithium-ion, BESS remarkably maintained the grid feeding voltage and frequency code, reducing the feeder trip and power curtailment [29].

Table 1

Recent literature study of wind farms associated with BESS.

Wind farm capacity	Location	Study platform	EES capacity	Description	Reference
481.5 MW	Spain	MATLAB/Simulink	50 MWh	BESS is used for wind turbine frequency matching to stabilise the grid voltage.	[33]
3.6 MW	Taiwan	Simulation	0.72 MW	Wind gusts, crescendos, and random wind strategies are employed to smooth wind power production.	[34]
3 MW	India/Korea	Simulation	500 Ah	A Neuro-fuzzy inference hybrid controller monitors the wind turbine and BESS for power filtering.	[35]
Two multi-MW	Greece	Simulation	94 Ah	Wind speed and related data are collected from the EUNICE ENERGY GROUP (EEG) to optimise the BESS using the discrete wavelet transform method.	[36]
160 MW	Iran	Analytical model (Simulation)	21–80 MWh	Optimal BESS is calculated based on the one-year wind farm data, and different scenarios such as optimum method, total compensation, and no compensation are considered in optimising the BESS.	[37]
5.950 MW	Cape Verde	Autoregressive Integrated Moving Average (ARIMA)	9 MWh	A combination of ARIMA forecasting with BESS improved the grid reliability.	[38]
60 MW and 45 MW	Mongolia and Sinkiang	Simulation	2.01 MW and 1.34 MW	The proposed wind power prediction model aims to reduce power production errors using a modified statistical distribution model.	[39]
9 MW	France	Simulation	36 MWh	Simulation is conducted for four cases to optimise BESS capacity, minimise wind power curtailment, and improve BESS lifetime.	[40]
100 kW	India	Simulation	24 kWh	The Inherited Competitive Swarm Optimisation (ICSO) algorithm improves the BESS performance with wind turbine and load regulation.	[41]
8 MW	Thailand	Power flow algorithm (DigSILENT simulation)	5 MWh (Li-ion)	We collect wind speed and other site data from the 8 MW wind farm SubPlu 1 in Nakhon Ratchasima province, Thailand, to optimise the BESS capacity using DigSILENT. Monthly prioritisation of feeder trips is conducted to determine the optimal solution for reducing overvoltage problems in the existing 8 MW wind farm. A comparative study is performed for an 8 MW wind farm using with and without 5 MWh BESS.	Present study

Dratsas et al. performed a feasibility study of incorporating the BESS for small islands to maintain grid stability and attain energy generation through non-conventional systems. The islands are primarily rich in wind energy, but the wind speed and power generation stability are not attractive compared to other renewable energy systems. During low wind periods, operators often compensate for power curtailments with diesel engines. Utilizing BESS as an auxiliary power generator reduces 42.75 % of the wind curtailments, amounting to 1442.8 MWh/year [30]. BESS are widely employed with wind turbines to avoid power curtailment and regulate the grid frequency. As mentioned earlier, wind power productions are unpredictable and fail to match the forecasted power generation, resulting in grid load mismatch and causing voltage flotation [31].

The wind farm maintained a power factor of unity for most of the period, depending on the availability of BESS capacity. The overall performance of the wind farm increased by 3.97 % compared to unsmoothed power feeding from the wind farm without BESS [32].

The above literature review and Table 1 emphasise the critical role of energy storage systems in enhancing the efficiency and reliability of wind power systems. The strategic placement and coordinated control of wind turbines and energy storage systems (ESS) in a distribution network are vital for maintaining stability and reliability during operation. Numerous studies have explored analytical and optimisation techniques to size and place energy storage systems effectively. These studies have demonstrated the efficacy of their approaches in reducing energy losses, managing congestion and voltage deviations, and enhancing the stability and controllability of wind power systems. Research findings consistently support the benefits of hybrid electricity generation systems, which combine wind energy and energy storage. Such systems prove advantageous for both the wind farm and the end-users within the distribution network. In the context of this study, a Battery Energy Storage System (BESS) was developed to mitigate fluctuations in electricity generation from an operational 8 MW commercial-scale onshore wind farm in Nakhon Ratchasima province, Thailand, as illustrated in Fig. 1 (a) and Fig. 1 (b). The primary purpose of developing the BESS is to reduce feeder trips by controlling the overvoltage and improving power quality through ramp control. The main objective of this study is as follows.

- Real-time data from an operational 8 MW commercial-scale onshore wind farm (Nakhon Ratchasima province, Thailand) is collected to analyse the nature of wind speed, wind directions and frequencies and the annual feeder trip.
- The high feeder trip period (September) is selected to optimise BESS capacity to simplify operations. DigSILENT simulation is performed with the lowest grid load of 10 %, varying BESS capacity from 1 to 5 MWh in 1 MWh increments.
- A comparative study is performed for wind turbine voltage and power productions using different BESS to optimise the suitable BESS for the operational wind farm.

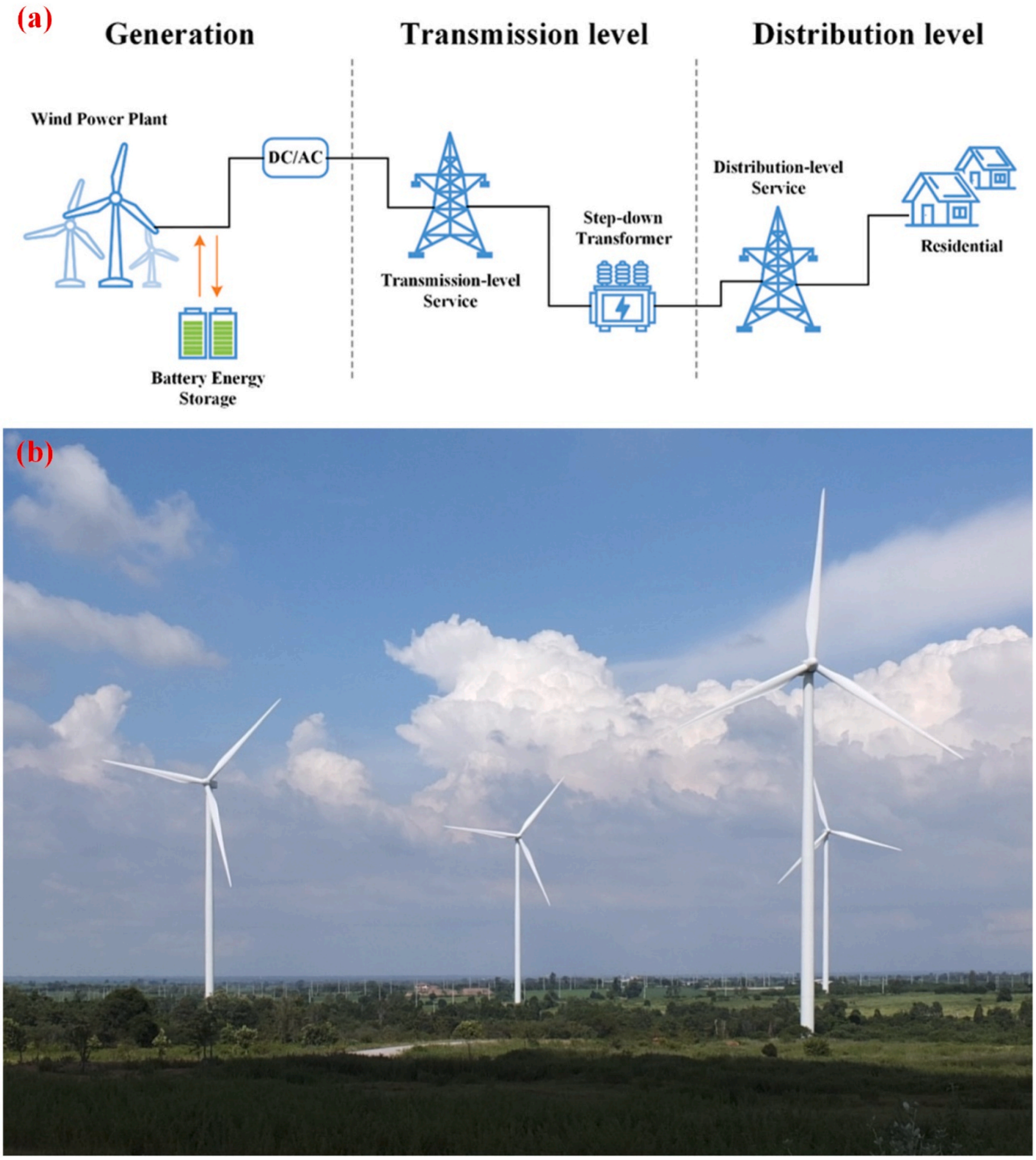

Fig. 1. (a) Conceptual diagram of BESS with wind power plant and (b) real-time view of 8 MW wind farm SubPlu 1, Nakhon Ratchasima province.

Table 2
Specification of wind turbine and BESS.

Description	Range
Wind turbine type	Doubly Fed Induction Generator
Rated power	2 MW
Cut-in wind speed	2.5 m/s
Rated wind speed	10 m/s
Cut-out wind speed	25 m/s
Survival wind speed	60 m/s
Battery type	Lithium Ion
BESS capacity	5 MWh/2 MW
Depth of Discharge (DOD)	90 %
State of Charge (SOC)	95 %

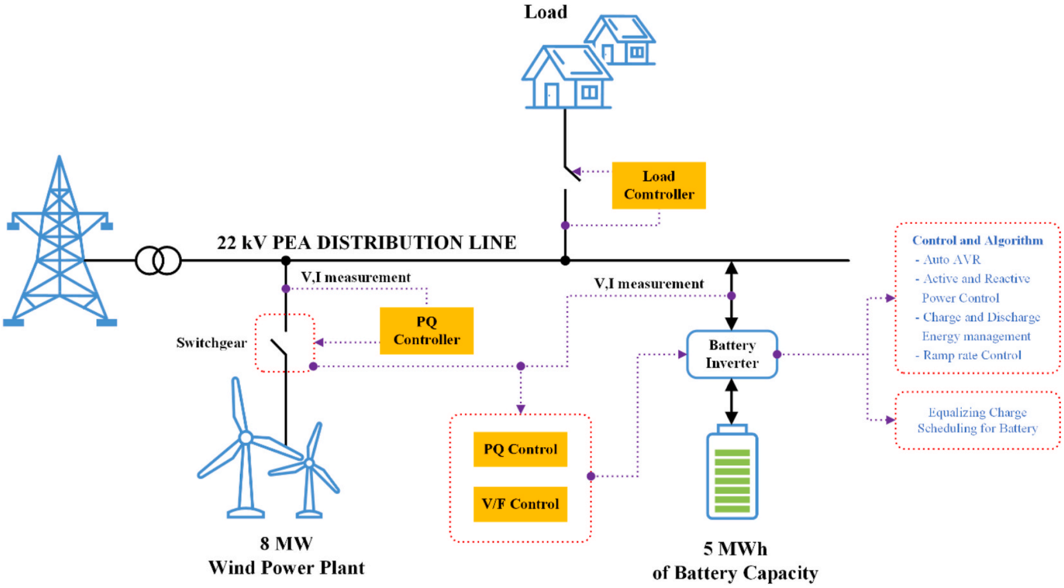

Fig. 2. Energy management system for BESS with a wind power plant.

- Further, the optimised BESS is performed for low and high wind speed periods to obtain the stability of the BESS in controlling the feeder trip and power generation.

2. Materials and methods

This study introduced a Battery Energy Storage System (BESS) for Wind Farm SubPlu 1, an operational 8 MW commercial-scale onshore wind farm located in Nakhon Ratchasima province, Thailand (refer to Table 2). The energy management system is designed to monitor the power production of the wind farm as well as the grid voltage. Over-voltage issues primarily arise under two conditions: when the wind turbine generates more power than expected and when there is a decrease in load demand. In both cases, the BESS effectively maintains the grid voltage within an allowable range, as specified by the Provincial Electricity Authority (PEA). By ensuring that the voltage fed into the grid remains within the permissible range, the stability of the power distribution system is preserved, and feeder trips are kept within the limits set by the wind turbine manufacturers. This integration of BESS with wind power plants not only enhances the stability of the system but also improves the overall power quality in the distribution network. For a visual representation, please refer to Fig. 2 for the schematic view of the wind farm with BESS and Fig. 3 for an overview of the research methodology.

2.1. Data collection and methods

Data collected from the wind farm and Provincial Electricity Authority (PEA) include wind speed, energy yield, downtime, fault descriptions and duration, forecasted energy production, grid outage time, customer stop time, grid regulator readings, and other relevant parameters. These data points are crucial for optimising the BESS, as illustrated in Fig. 3. Initially, key parameters such as wind power, wind speed, and various wind turbine specifications are fed into DigSILENT, considering different load scenarios of 100 %, 50 %, and 10 %. This analysis aims to understand the grid voltage under varying power consumption levels in the distribution system. Based on the grid voltage profiles obtained, further simulations are carried out with a negligible load of 10 %, varying the BESS capacity from 1 MWh to 5 MWh. This iterative process is crucial for optimising the BESS capacity and ensuring compliance with PEA regulations. A comparative study is conducted, analyzing grid voltage under different BESS capacities according to PEA regulations. Additionally, the optimised BESS configurations are tested under various operating conditions of wind turbines, including high feeder trips, low wind speeds, and high wind speeds. These tests assess the reliability of BESS in reducing annual feeder trips. The implementation of State of Charge (SOC) and Depth of Discharge (DOD) protocols is crucial for efficient BESS operation. When the grid voltage is high, BESS initiates charging to prevent overloading and reduce grid voltage, subsequently minimising feeder trips. Conversely, when BESS reaches 95 % capacity, it discharges power to the grid without causing voltage spikes, ensuring a stable power supply. This continuous charging and discharging process optimises power distribution, enhances wind turbine performance, and ultimately contributes to the overall efficiency and stability of the wind power plant. By breaking down the information into smaller, organized sections, the methodology becomes more digestible for readers.

2.1.1. Simulations of BESS

To develop a prototype wind farm assisted with BESS, DigSILENT Power Factory Software is used for grid voltage stability, as

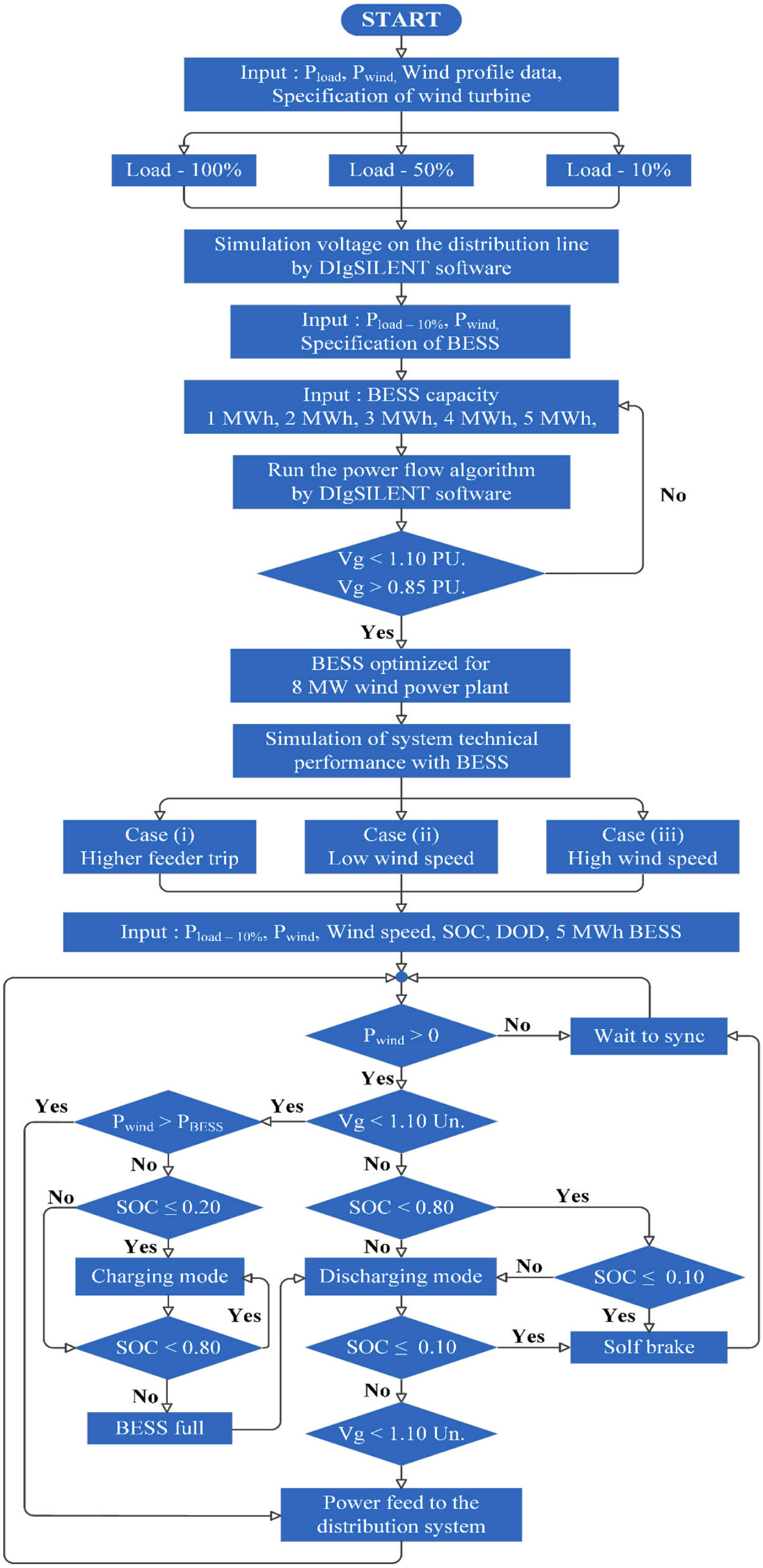

Fig. 3. Methodology of BESS optimisation for 8 MW wind farm.

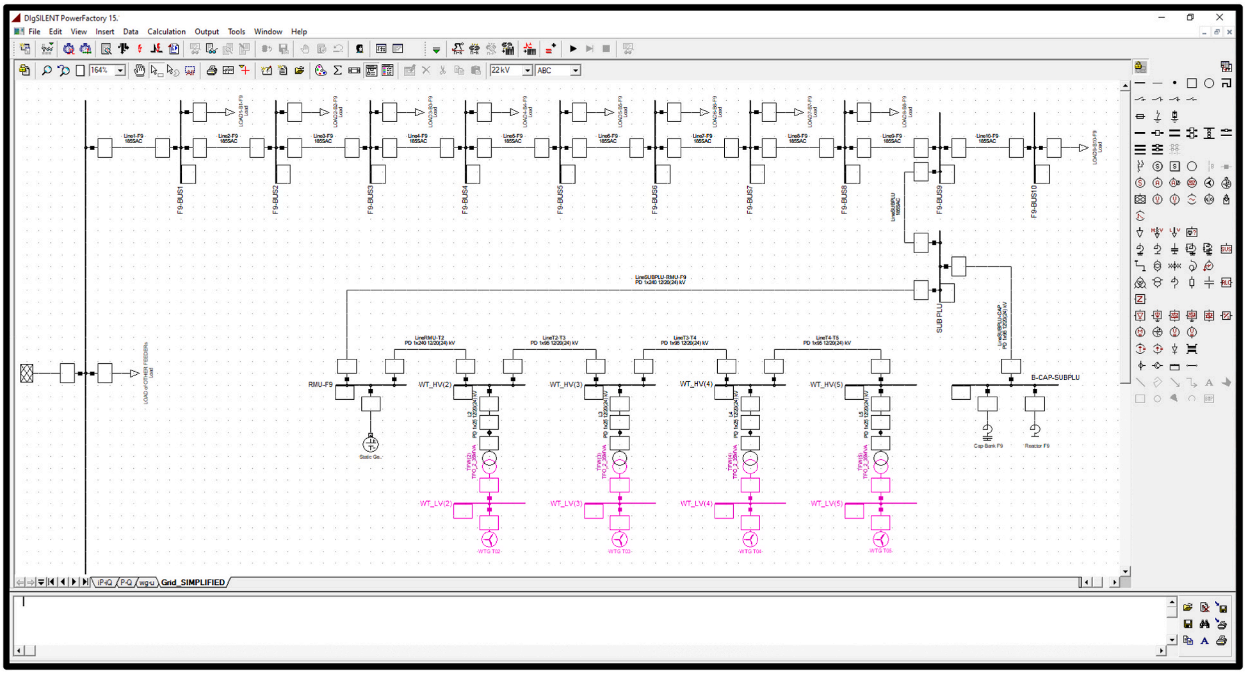

Fig. 4. Modelling of wind power plant with distribution network test system.

Table 3
The functions and details of BESS.

Function	Details
Installed in conjunction with existing wind power plant.	It can be connected to the electrical circuit of the existing wind power plant to stabilise the grid.
Complies with the Regulation for Very Small Power Producers (VSPP).	Managed under the Regulation for VSPP. If there is any non-compliance, it favours designing a plan with the least possible impact to propose an exemption from the Regulation for VSPP.
Complies with the grid connection code.	Overall, control complies with the grid connection code.
Prevents tripping.	BESS prevents tripping the wind power plant under various conditions within an acceptable range.

shown in Fig. 4. The proposed system's medium voltage distribution system is divided into two parts: a medium voltage distribution test system connected with a wind power plant without BESS and a distribution test system connected with a wind power plant with BESS. DIGSILENT Power Factory software version 15.1 (research license of Naresuan University, School of Renewable Energy Technology, Thailand) simulates the voltage profiles of both systems. Furthermore, the wind farm's technical performance is analysed using the distribution system's voltage profile. Simulation is carried out with and without BESS to perform a comparative analysis. Table 3 presents the functions of the BESS."

Feeder trip: In this study, we develop a power flow algorithm to reduce the feeder trip using BESS. During the regular operation of the wind turbine, wind farm operators monitor various aspects, including continuous monitoring of line voltage. If the line voltage is less than 0.85 PU for 0.5 s or greater than 1.10 PU for 0.1 s or 0.2 PU for 0.1 s, the monitoring system finds the status of BESS and synchronises it with a wind turbine. Whenever the line voltage is less than 0.85 PU, BESS can discharge to the grid to increase the line voltage, but in this study, line voltage does not face less than 0.85 PU and residual voltage. Therefore, simulations analyse line overvoltage. If the BESS capacity remains to charge, a soft brake will be applied to synchronise the wind turbine and BESS. This power flow algorithm regulates wind turbine operations and reduces the feeder trip. BESS system controls the power feeding according to the regulated plant's parameters to follow the grid connection code. During the wind farm operation, if the power quality of the wind power plant is abnormal, Battery Management System (BMS) will synchronise the BESS with wind turbines to regulate the power feeding to the grid by using a soft brake/emergency brake. After that, the wind turbine will wait to sync at the grid connection point again. Fig. 5 shows the protection model for feeder trip and plant shutdown. The same wind farm operation without BESS leads to a feeder trip and emergency brake applied to protect the wind turbine.

The wind power plant has a protection system to control the power quality according to the grid connection code. It is divided into three main parts, namely under-voltage protection, over-voltage protection, and residual over-voltage protection, as listed in Table 4. The protection control system monitors the line voltage in wind farms without BESS. Wind turbines are disconnected from the grid whenever the voltage exceeds the permissible range. BESS stores excess energy from the wind turbines, controlling feeder trips and

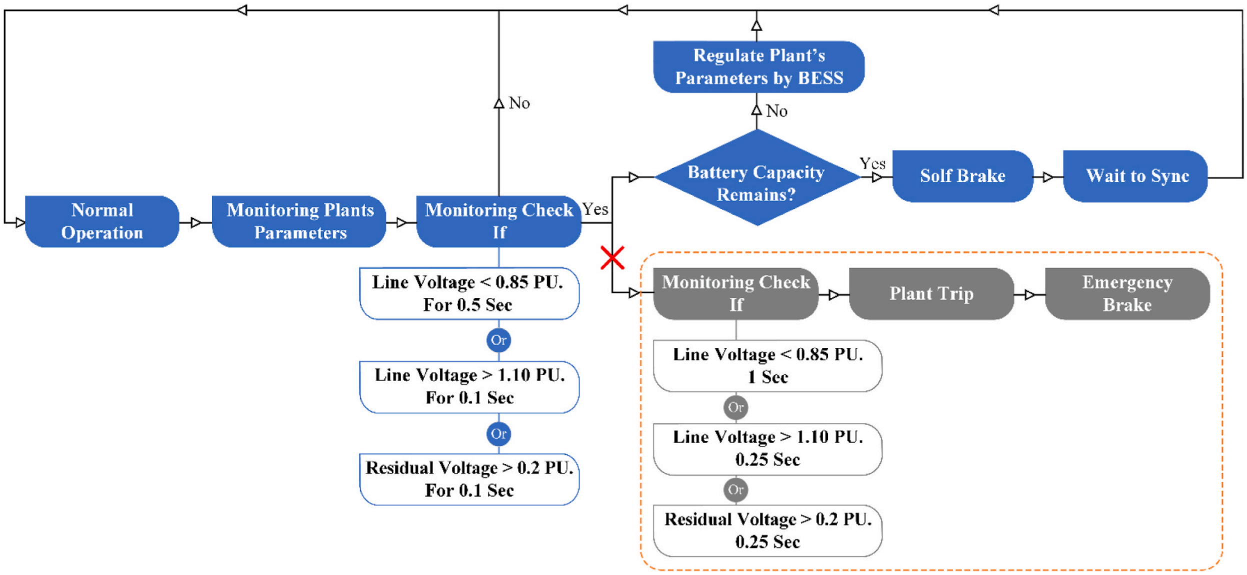

Fig. 5. Power flow algorithm to protect the feeder trip.

Table 4
The desired range of voltage for wind power plant.

Protection Relay	Parameter	Time
Under Voltage Protection (27)	Line Voltage <0.85 PU	1 Sec
Over Voltage Protection (59)	Line Voltage >1.10 PU	0.25 Sec
Residual Over Voltage Protection (59 N)	Residual Voltage >0.2 PU	0.25 Sec

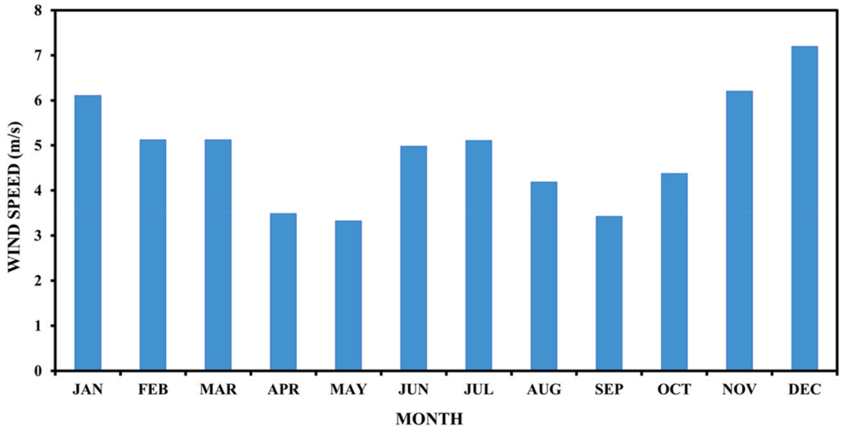

Fig. 6. Monthly wind speed distribution of Nakhon Ratchasima province, Thailand.

minimising wind power curtailments.

3. Results and discussions

The wind speed data from the 8 MW commercial-scale onshore wind farm were crucial for estimating the Battery Energy Storage System (BESS) capacity and conducting in-depth analyses, as depicted in Fig. 6. The monthly average wind speed analysis revealed the site's significant wind energy potential, with December registering the highest wind speed at 7.15 m/s. Conversely, May experienced the lowest wind speed at 3.3 m/s compared to other months. Notably, wind speeds in April, May, and September remained consistently below 4 m/s, marking these periods as low-wind seasons. In contrast, January, November, and December were identified as high-windy periods. The observed fluctuation in annual wind speeds necessitates the implementation of BESS to stabilise the

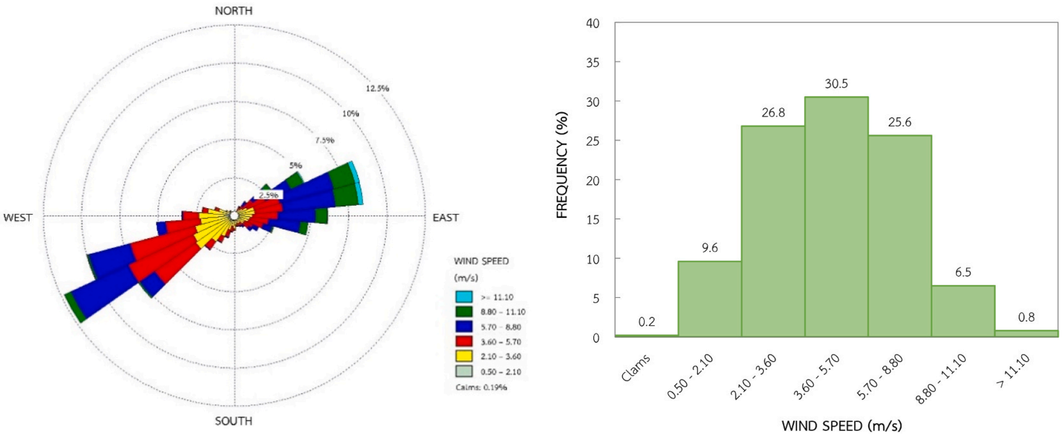

Fig. 7. Wind rose diagram and frequency of wind speed.

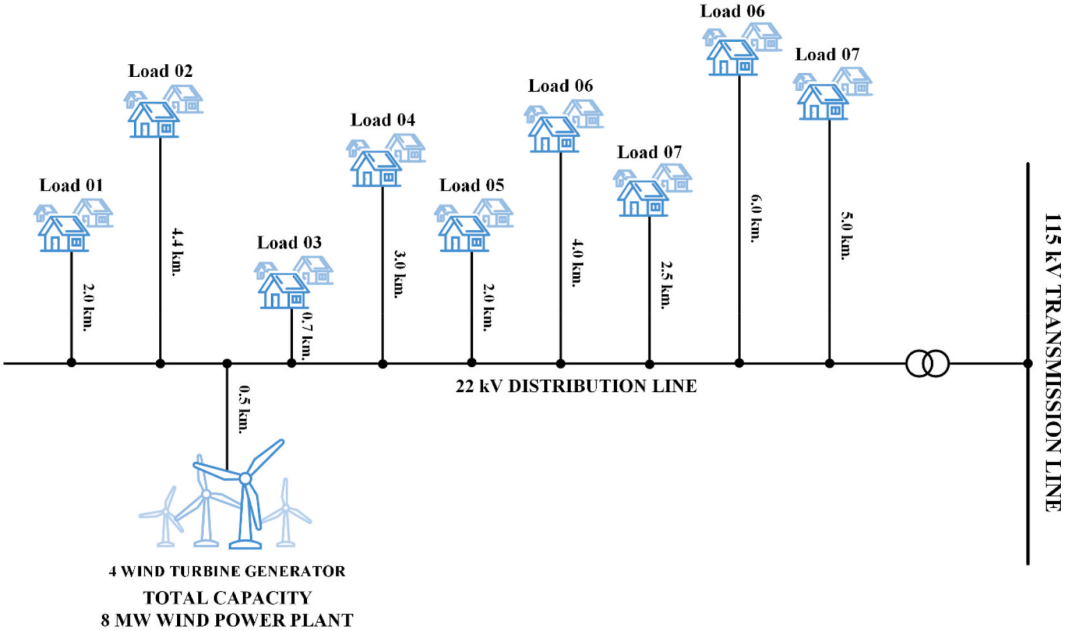

Fig. 8. Schematic view of 8 MW Windfarm distribution and transmission line.

distribution line without incurring penalties from the Provincial Electricity Authority (PEA) and grid authorities. The BESS system acts as a vital buffer, ensuring uninterrupted power supply during low-wind seasons and optimising energy distribution throughout the year.

Further, the annual wind speed is analysed using Lakes Environmental software to understand the nature and directions of wind flow, as shown in Fig. 7. The wind rose diagram in Fig. 7, displayed on the left-hand side, illustrates the annual wind speed directions. It is observed that winds predominantly blow from the south towards the west, indicating a higher frequency and extended periods in the north towards the east direction. Throughout most of the recorded period, wind directions were consistently in the southwest, surpassing other directions in frequency Fig. 6, right-hand side, represents the wind speed frequency; the higher frequency of 30.5 is achieved for 3.60–5.70 m/s, and the lowest frequency of 0.2 and 0.8, recorded for clams and wind speeds above 11.10 m/s, respectively. Apart from these, lower frequencies of 9.6 and 6.5 are achieved for 0.5–2.10 m/s and 8.80–11.10 m/s, respectively, and for the mid-high frequencies of 26.8 and 25.6 are achieved for 2.10–3.60 m/s and 5.70–8.80 m/s, respectively. Overall, it is found that for the selected location, the annual average wind speed is recorded to be 4.89 m/s, which shows that the eastern region of Thailand has a more significant potential for wind energy.

Fig. 8 shows the schematic view of an 8 MW wind farm on the 22 kV distribution and transmission line obtained from the Provincial Electricity Authority (PEA) since the Commercial Operation Date (COD). The wind farm is 0.5 km from the distribution line, and most loads are connected to the distribution line within the 0.7–6.0 km range before the transmission line.

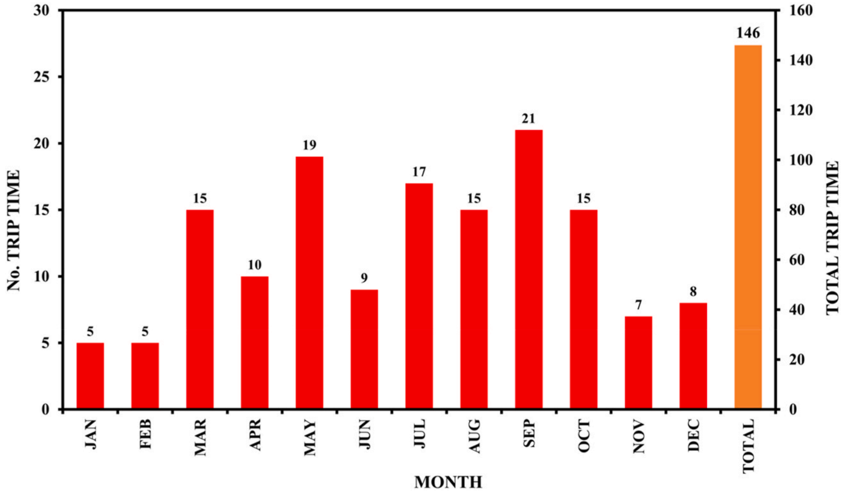

Fig. 9. Monthly feeder trip of 8 MW wind farm in 2021.

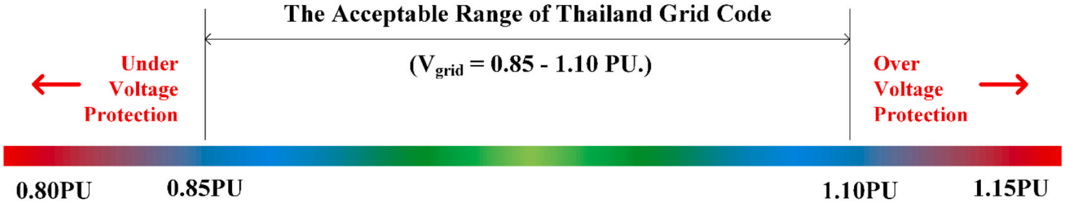

Fig. 10. Thailand's grid code for under, over, and acceptable voltage range.

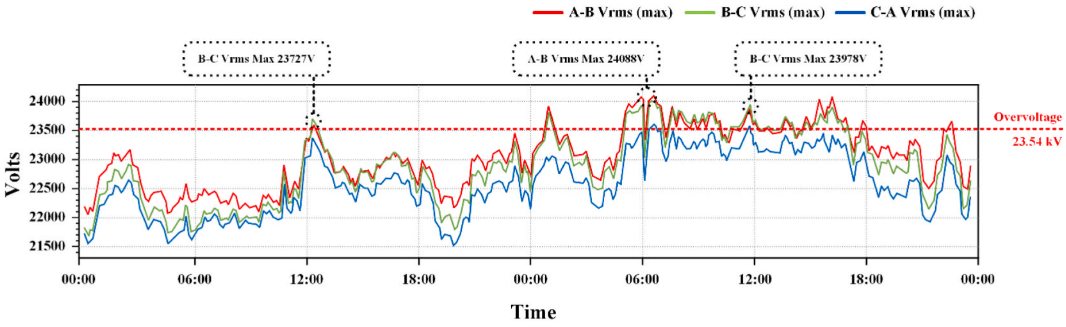

Fig. 11. Voltage profile of 8 MW wind farm (three phases) on 22 kV distribution line.

The primary challenge faced by the 8 MW wind farm is frequent feeder trips caused by unpredictable fluctuations in load demand and wind power production. These fluctuations lead to overvoltage and voltage dips, triggering feeder trips that halt the wind farm's operation. Unanticipated and increasingly frequent feeder trips render the entire system inefficient, especially considering that wind turbines come with a manufacturer's guarantee that feeder trips should not exceed 52 times per year. Based on the wind farm's operation data from 2021, the number of feeder trips exceeded the allowable limit. Fig. 9 illustrates the monthly variation in feeder trips recorded at the wind farm, providing crucial insights into the urgency of implementing a Battery Energy Storage System (BESS). The lowest number of feeder trips occurred in January and February, while the highest was observed in May and September, reaching 19 and 21 times, respectively. The total annual feeder trips amounted to 146 times, nearly double the permissible range, highlighting the pressing need for a solution to this issue. Fig. 10 shows the allowable voltage range of Thailand's grid code. The wind turbine's voltage feed is strictly monitored to maintain a stable frequency in the transmission and distribution system. Whenever the wind turbine voltage production is higher than 1.10 Vn, it is considered a harmful threat to the load, resulting in the protection control system automatically tripping the feeder, and the wind farm shuts until the grid voltages are within an allowable range. Due to massive disruption in feeder trips, wind farms faced several economic complications from grid authority and PEA.

In this study, the focus lies primarily on over-voltage faults as they are the predominant challenges encountered by the 8 MW wind

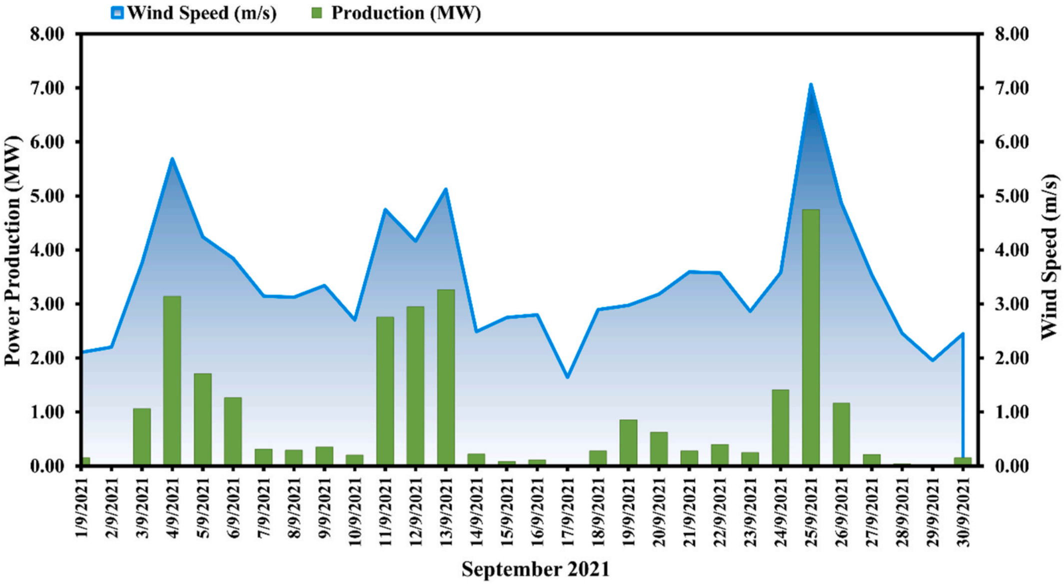

Fig. 12. Monthly average wind speed and power production (September 2021).

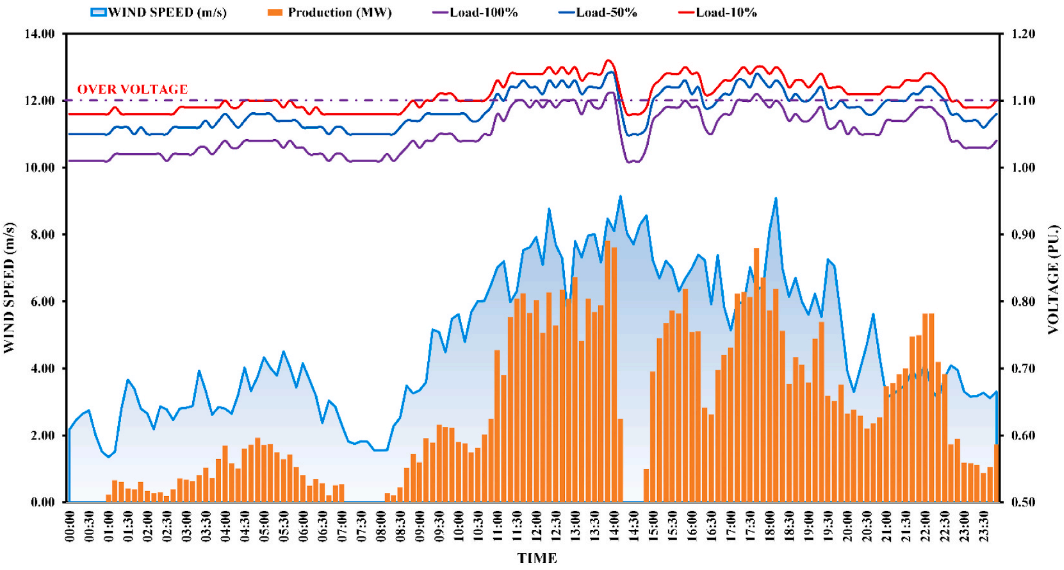

Fig. 13. Voltage profile on distribution system under different load conditions.

farm during its operational period. Over-voltage protection faults are prevalent, prompting an in-depth analysis compared to low and residual voltage faults. To gain a deeper understanding of the wind farm's characteristics, a specific day's three-phase voltage profile is presented in Fig. 11. Throughout the working day, slight oscillations were observed in all three phases. Notably, A-B Vrms and B–C Vrms experienced overvoltage conditions, peaking at 24088 V and 23978 V, respectively. In contrast, C-A Vrms maintained a stable voltage profile under overvoltage conditions throughout the day. Notably, whenever the other phases reached over-voltage levels, automatic feeder trips were triggered.

To address these over-voltage challenges, different Battery Energy Storage System (BESS) capacities were tested in real-time scenarios, focusing on three specific cases: periods of higher feeder trips, low wind speeds, and high wind speeds. These tests were conducted to develop effective strategies for controlling overvoltage faults and enhancing the wind farm's overall stability and performance.

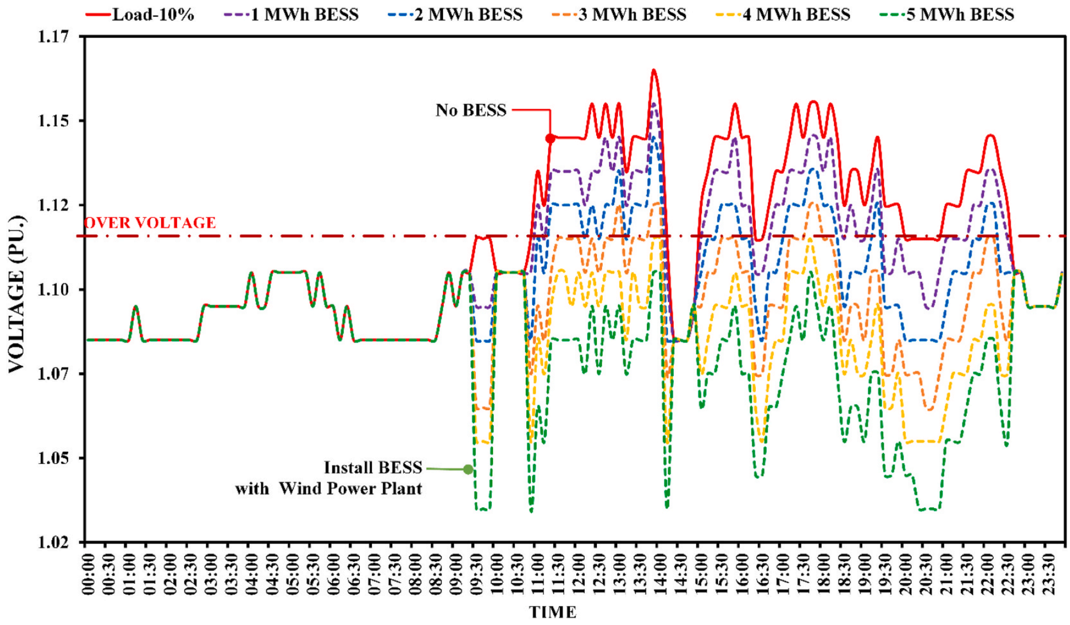

Fig. 14. Comparative analysis of grid voltage with different BESS.

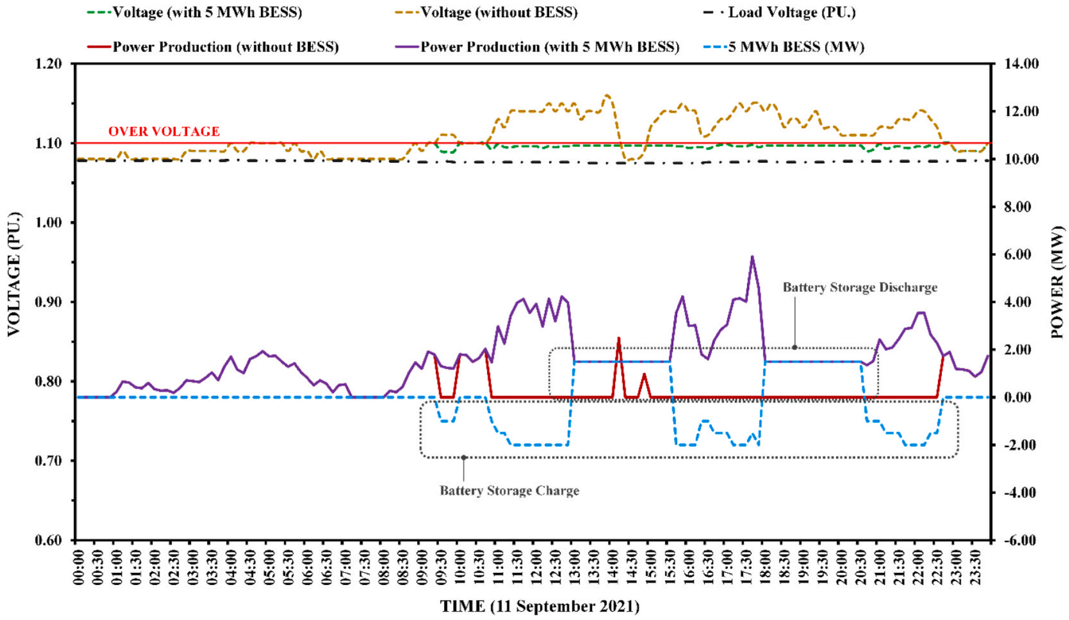

Fig. 15. The relationship between grid voltage and power production of 8 MW wind farm using with and without BESS (September 11, 2021).

3.1. *Case (i): higher feeder trip period*

In Fig. 12, the wind speed and power production data for September are depicted. On most days, power production remains below 1 MW due to low wind speeds. The highest wind speed recorded was 7.07 m/s, correlating with a power production of 4.75 MW. However, the wind turbine's power generation often falls below the permissible limit defined by the Provincial Electricity Authority (PEA). When this occurs, the wind farm experiences higher grid voltage, surpassing the acceptable range. Consequently, the wind turbine fails to feed power into the grid, leading to feeder trips and shutting down the entire wind power plant operation. To gain insights into the nature of these feeder trips, a specific day with a recorded feeder trip was selected for simulation using DigSILENT, as shown in Fig. 13. The simulation was conducted under different load operating conditions of 100 %, 50 %, and 10 %. During 100 % load, the wind farm's voltage profile remained within the acceptable overvoltage range for most of the period. However, in practical

Table 5

Summarised view of grid voltage, power production, BESS capacity and production for using BESS and without BESS.

Time	Grid voltage (PU.)						Power (MW)						BESS capacity (MW)			Energy production (MWh)					
	Without BESS			With BESS			Without BESS			With BESS						Without BESS			With BESS		
	Case (i)	Case (ii)	Case (iii)	Case (i)	Case (ii)	Case (iii)	Case (i)	Case (ii)	Case (iii)	Case (i)	Case (ii)	Case (iii)	Case (i)	Case (ii)	Case (iii)	Case (i)	Case (ii)	Case (iii)	Case (i)	Case (ii)	Case (iii)
00:00	1.08	1.08	1.16	1.08	1.08	1.10	0.00	0.33	0.00	0.00	0.33	6.12	0.00	0.00	−1.50	10.40	21.30	0.58	38.74	21.63	77.25
00:30	1.08	1.10	1.10	1.08	1.10	1.10	0.00	1.49	1.87	0.00	1.49	1.85	0.00	0.00	0.00						
01:00	1.08	1.10	1.13	1.08	1.10	1.10	0.22	2.01	0.00	0.22	2.01	2.81	0.00	0.00	−1.50						
00:30	1.08	1.08	1.15	1.08	1.08	1.10	0.42	0.51	0.00	0.42	0.51	4.57	0.00	0.00	−2.00						
02:00	1.08	1.09	1.16	1.08	1.09	1.10	0.34	0.90	0.00	0.34	0.90	6.18	0.00	0.00	−1.50						
00:30	1.08	1.10	1.15	1.08	1.10	1.10	0.19	1.58	0.00	0.19	1.58	4.79	0.00	0.00	−2.00						
03:00	1.09	1.09	1.14	1.09	1.09	1.10	0.68	1.14	0.00	0.68	1.14	1.49	0.00	0.00	1.50						
00:30	1.09	1.09	1.14	1.09	1.09	1.10	1.04	1.38	0.00	1.04	1.38	1.49	0.00	0.00	1.50						
04:00	1.10	1.09	1.16	1.10	1.09	1.10	1.70	1.12	0.00	1.70	1.12	1.49	0.00	0.00	1.50						
00:30	1.10	1.09	1.14	1.10	1.09	1.10	1.60	0.89	0.00	1.60	0.89	1.49	0.00	0.00	1.50						
05:00	1.10	1.08	1.15	1.10	1.08	1.10	1.71	0.40	0.00	1.71	0.40	1.49	0.00	0.00	1.50						
00:30	1.09	1.10	1.16	1.09	1.10	1.10	1.29	3.14	0.00	1.29	3.14	6.18	0.00	0.00	−1.50						
06:00	1.09	1.10	1.14	1.09	1.10	1.10	0.81	3.39	0.00	0.81	3.39	3.49	0.00	0.00	−2.00						
06:30	1.08	1.10	1.14	1.08	1.10	1.10	0.57	1.94	0.00	0.57	1.94	3.73	0.00	0.00	−2.00						
07:00	1.08	1.10	1.16	1.08	1.10	1.10	0.54	2.01	0.00	0.54	2.01	6.24	0.00	0.00	−1.50						
07:30	1.08	1.09	1.15	1.08	1.09	1.10	0.00	1.33	0.00	0.00	1.33	1.49	0.00	0.00	1.50						
08:00	1.08	1.11	1.15	1.08	1.08	1.10	0.00	0.00	0.00	0.00	0.06	1.49	0.00	−1.00	1.50						
08:30	1.08	1.10	1.16	1.08	1.10	1.10	0.44	0.95	0.00	0.44	0.95	1.49	0.00	0.00	1.50						
09:00	1.09	1.10	1.16	1.09	1.10	1.10	1.20	0.90	0.00	1.20	0.90	1.49	0.00	0.00	1.50						
09:30	1.11	1.08	1.10	1.09	1.08	1.10	0.00	0.00	1.62	1.31	0.00	1.49	−1.00	0.00	1.50						
10:00	1.10	1.08	1.16	1.10	1.08	1.10	1.80	0.00	0.00	1.80	0.00	1.49	0.00	0.00	1.50						
10:30	1.10	1.09	1.16	1.10	1.09	1.10	1.64	0.89	0.00	1.64	0.89	6.25	0.00	0.00	−1.50						
11:00	1.13	1.09	1.16	1.09	1.09	1.10	0.00	0.96	0.00	2.98	0.96	6.18	−1.50	0.00	−1.50						
11:30	1.14	1.10	1.16	1.09	1.10	1.10	0.00	1.45	0.00	3.97	1.45	6.20	−2.00	0.00	−1.50						
12:00	1.14	1.10	1.16	1.09	1.10	1.10	0.00	1.72	0.00	3.92	1.72	6.14	−2.00	0.00	−1.50						
12:30	1.14	1.09	1.15	1.09	1.09	1.10	0.00	1.37	0.00	3.19	1.37	6.01	−2.00	0.00	−1.50						
13:00	1.15	1.09	1.14	1.09	1.09	1.10	0.00	1.03	0.00	1.49	1.03	1.49	1.50	0.00	1.50						
13:30	1.14	1.09	1.14	1.09	1.09	1.10	0.00	0.84	0.00	1.49	0.84	1.49	1.50	0.00	1.50						
14:00	1.15	1.11	1.13	1.09	1.08	1.10	0.00	0.00	0.00	1.49	0.18	1.49	1.50	−1.00	1.50						
14:30	1.08	1.08	1.13	1.09	1.08	1.10	0.00	0.50	0.00	1.49	0.50	1.49	1.50	0.00	1.50						
15:00	1.12	1.08	1.12	1.09	1.08	1.10	0.00	0.00	0.00	1.49	0.00	1.49	1.50	0.00	1.50						
15:30	1.14	1.08	1.12	1.09	1.08	1.09	0.00	0.00	0.00	1.49	0.00	2.02	1.50	0.00	−1.50						
16:00	1.14	1.08	1.12	1.09	1.08	1.09	0.00	0.00	0.00	2.99	0.00	2.14	−2.00	0.00	−1.50						
16:30	1.11	1.08	1.12	1.09	1.08	1.10	0.00	0.05	0.00	1.60	0.05	2.32	−1.00	0.00	−1.00						
17:00	1.13	1.08	1.11	1.09	1.08	1.09	0.00	0.02	0.00	3.05	0.02	1.74	−1.50	0.00	−1.00						
17:30	1.14	1.08	1.11	1.09	1.08	1.09	0.00	0.43	0.00	4.02	0.43	1.53	−2.00	0.00	−1.00						
18:00	1.14	1.08	1.11	1.09	1.08	1.09	0.00	0.05	0.00	1.49	0.05	1.75	1.50	0.00	−1.00						
18:30	1.12	1.08	1.11	1.09	1.08	1.10	0.00	0.30	0.00	1.49	0.30	1.89	1.50	0.00	−1.00						
19:00	1.12	1.09	1.13	1.09	1.09	1.10	0.00	1.30	0.00	1.49	1.30	1.49	1.50	0.00	1.50						
19:30	1.12	1.08	1.13	1.09	1.08	1.10	0.00	0.49	0.00	1.49	0.49	1.49	1.50	0.00	1.50						
20:00	1.11	1.08	1.12	1.09	1.08	1.10	0.00	0.12	0.00	1.49	0.12	1.49	1.50	0.00	1.50						
20:30	1.11	1.08	1.13	1.09	1.08	1.10	0.00	0.41	0.00	1.49	0.41	1.49	1.50	0.00	1.50						
21:00	1.12	1.09	1.15	1.09	1.09	1.10	0.00	0.68	0.00	2.43	0.68	1.49	−1.00	0.00	1.50						
21:30	1.13	1.09	1.15	1.09	1.09	1.10	0.00	1.15	0.00	2.44	1.15	5.76	−1.50	0.00	−1.50						
22:00	1.14	1.10	1.16	1.09	1.10	1.10	0.00	1.58	0.00	3.54	1.58	6.19	−2.00	0.00	−1.50						
22:30	1.12	1.08	1.16	1.09	1.08	1.10	0.00	0.00	0.00	2.28	0.00	6.25	−1.50	0.00	−1.50						
23:00	1.09	1.09	1.16	1.09	1.09	1.10	1.19	1.12	0.00	1.19	1.12	6.25	0.00	0.00	−1.50						
23:30	1.09	1.09	1.16	1.09	1.09	1.10	0.87	0.90	0.00	0.87	0.90	6.25	0.00	0.00	−1.50						

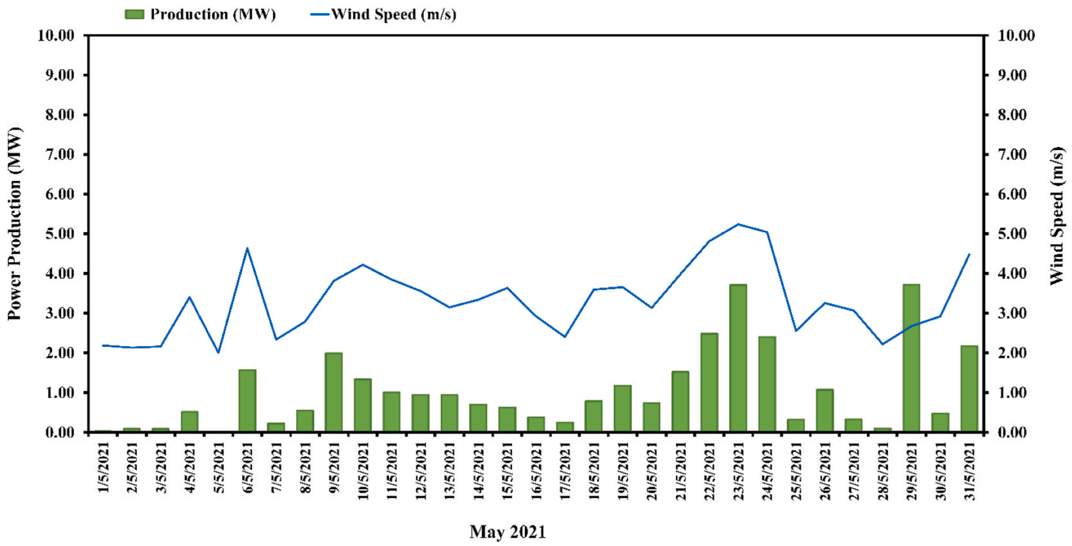

Fig. 16. Monthly average wind speed and power production (May 2021).

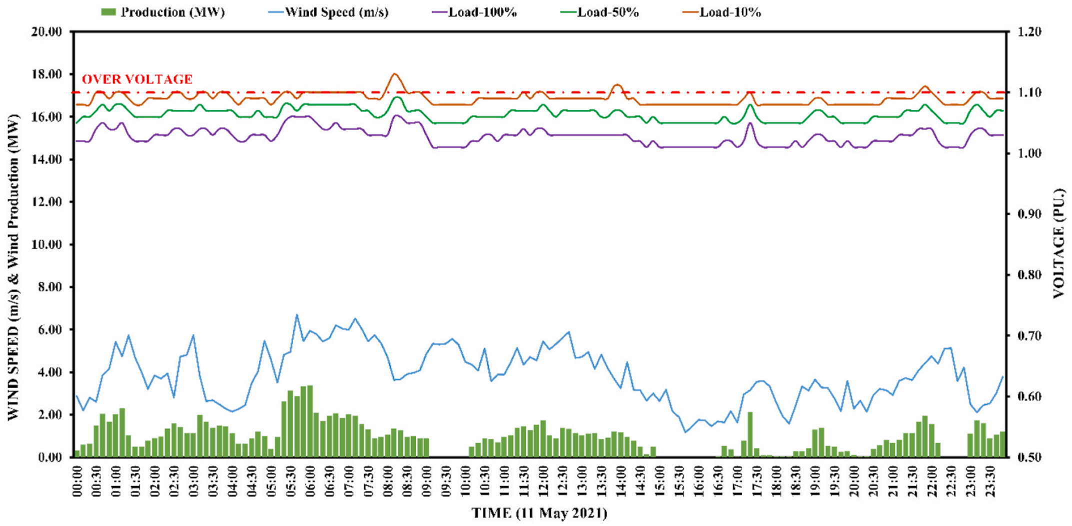

Fig. 17. Selected feeder trip day from May with different load conditions.

scenarios, maintaining a constant 100 % load on the distribution line is unfeasible. When the load is reduced to 50 % and 10 % on the distribution line, overvoltage issues arise as early as 09:30, leading to the wind farm being compelled to halt power production to prevent further grid instability.

Further, to optimise the BESS capacity, a 10 % load is considered the highest feeder trip for a wind farm, and the simulation is performed using a different capacity of BESS. At 09:25, over-voltage is identified, and the feeder starts tripling and isolating the wind power production. Implementation of BESS clearly shows that grid voltage is under the over-voltage range. However, 1 MWh, 2 MWh and 3 MWh BESS are not favouring throughout the working day, and they are not suitable for 10 % grid load consumption as the grid voltage is higher than 1.10 PU, as shown in Fig. 14. Notably, 4 MWh BESS controls the over-voltage protection better than 1–3 MWh BESS; however, during the 13:45 to 14:05 and 17:30 to 17:40 period, 4 MWh BESS failed to control the grid feed voltage. Considering complete protection against the feeder trip, a 5 MWh BESS is optimised to maintain the grid feeder voltage. Comparatively, a 5 MWh BESS controls the grid voltage within or under the 1.10 PU, resulting in the feeder trip being neglected throughout the working day.

In Fig. 15, an insightful comparison between an 8 MW wind farm with and without a 5 MWh Battery Energy Storage System (BESS) is presented. As previously mentioned, the 5 MWh BESS plays a crucial role in regulating power fed into the grid during over-voltage periods. The BESS system effectively stores excess power and maintains the grid voltage within an allowable range, preventing feeder trips and ensuring uninterrupted power supply. In the absence of BESS, the wind farm experiences multiple feeder trips, disrupting power supply from 09:30 to 10:00, 10:55 to 14:10, and 14:25 to 14:40. However, with the implementation of a 5 MWh BESS,

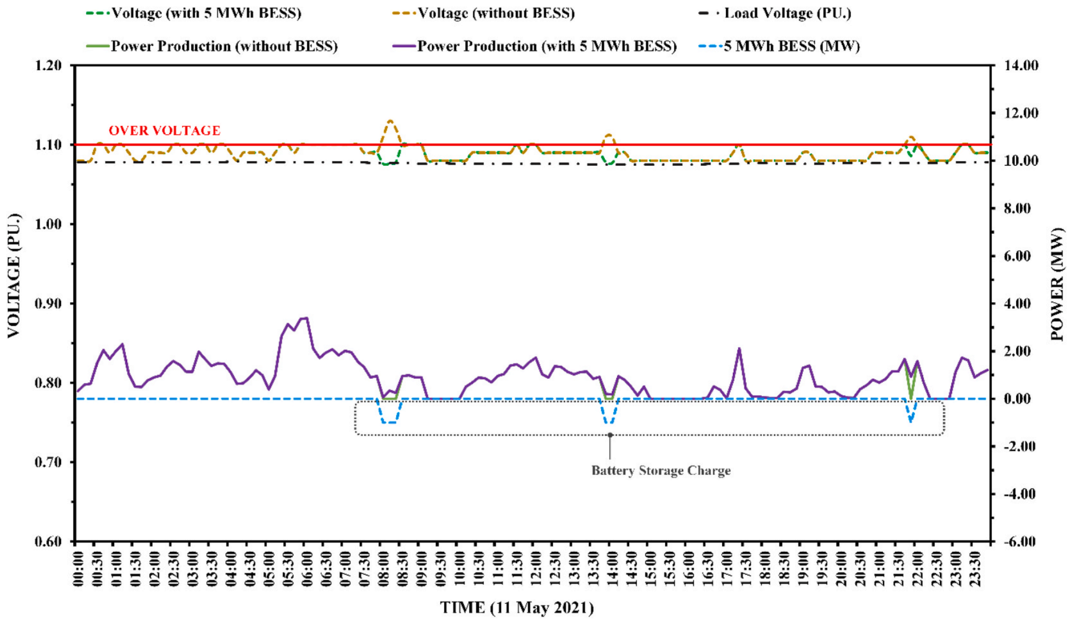

Fig. 18. The relationship between grid voltage and power production of 8 MW wind farm using with and without BESS (May 11, 2021).

continuous voltage feeding to the distribution line is achieved. This minimizes wind farm power curtailment, eliminates penalties from the Provincial Electricity Authority (PEA), enhances annual income, and ensures long-term system reliability. One of the significant advantages of the BESS is demonstrated during over-voltage periods. With BESS in operation, power production reaches 6 MW, effectively utilizing the excess power by initiating battery charging. Charging continues until the BESS reaches 90 % capacity. Between 13:00 and 15:40, the BESS discharges 1.5 MW to the grid, ensuring stable voltage levels. During the discharge period, wind farm operation is temporarily halted to maintain grid stability. In this study, BESS is optimised to control the feeder trip and not to store the entire overvoltage period of wind power production. BESS capacity needed to increase to store the entire wind power production, which could not be economically favorable. The second charging peak is noted between 15:30 and 18:00 and discharged from 18:00 to 20:30. Overall, it was found that BESS maintained the uninterrupted power feed to the grid and increased power production without tripping the feeder. Table 5 shows that with the help of BESS, a wind turbine can generate a power production of 38.74 MWh, whereas without BESS, it is 10.40 MWh and, comparatively, 3.7 times lower than with BESS. As mentioned earlier, wind power productions are unpredictable compared to other renewable energy systems, and it is found that when the wind turbine and BESS are not functioning, the grid voltage is nearly stable for the entire period of operations. As conventional energy generators can be easily optimised with the grid power consumption. The necessity of BESS in this study is to control the fluctuating wind power production and protect the wind turbine from feeder trips.

3.2. *Case (ii) low wind speed period*

The second-highest feeder trip occurred in May; on the other hand, the lowest wind speed occurred in the same month, as shown in Fig. 16. Due to low wind speed, the average power generation of the entire month is 1.04 MW, which is lower than other months, though the over-voltage causes the 19 times feeder trip. Low wind potential and higher feeder trip deteriorate the power feed during May to the grid. A selective feeder trip day from May shows the grid voltage is higher than the PEA allowable range, as shown in Fig. 17. Overall, three times overvoltage occurred during the operational hours of the wind turbines, and noticeably, it occurred during the low wind power production period. Secondly, the grid voltage is closer to the over-voltage range for most of the operating period. The over-voltage during the low wind potential period is due to low load consumption from the grid. Grid load consumption depends on the end-user, which cannot be modified, but incorporating a 5 MWh BESS can regulate the overvoltage during power production. It could reduce the feeder trip and harvest the energy produced by the wind turbine. Facing a higher feeder trip during the low wind period could minimise the economic benefit of the wind farm. It is found that a 5 MWh BESS initiates the charging mode when the grid voltage is high, resulting in the 8 MW wind farm producing the power without any interference, as shown in Fig. 18. However, in this case, BESS initiated only charging mode due to low wind speed and less power production, and the BESS did not reach the SOC (95 %) beneficial feeder trip is reduced three times. Noticeably, 0.33 MWh power production enhanced as compared to without BESS.

3.3. *Case (iii) high wind speed period*

As mentioned earlier, over-voltage occurs due to low load consumption and high-power production; for the selected location, December records to be the highest wind potential period with an average and peak wind speed of 7.2 m/s and 9.5 m/s, respectively, as

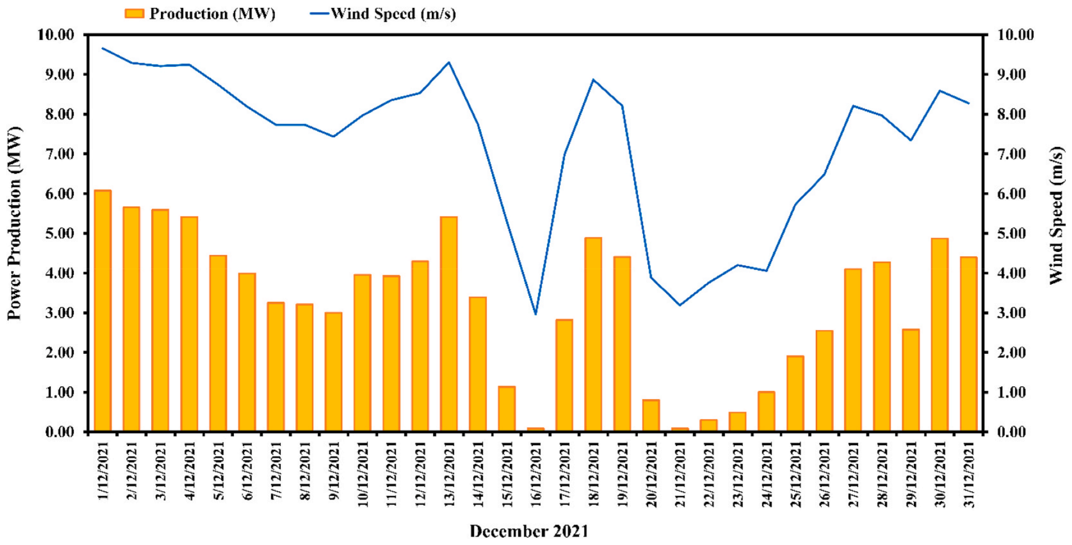

Fig. 19. Monthly average wind speed and power production (December 2021).

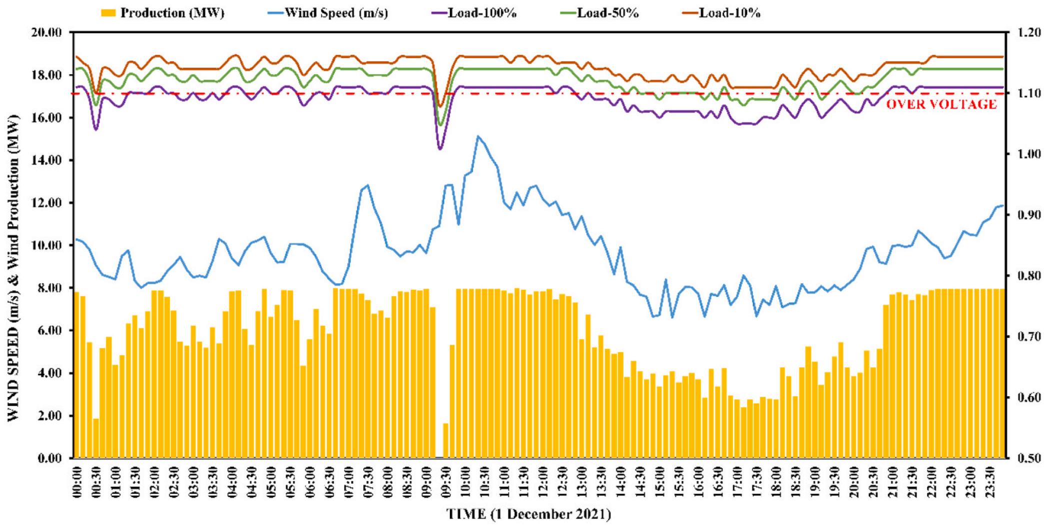

Fig. 20. Selected feeder trip day from December with different load conditions.

shown in Fig. 19. Furthermore, the study identified that the occurrence of feeder trips exhibits a strong negative correlation with wind speed and power production but a strong positive correlation with grid load. To delve deeper into this correlation, a specific day with selective feeder trips was chosen for analysis, as shown in Fig. 20. For instance, on December 1st, 2021, most of the wind farm's operational period power production hovering around 8 MW, corresponding to sustained wind speeds greater than or close to 10 m/s the rated wind speed of the selected wind turbine. However, even though high production was achieved on this day, the wind farm failed to feed power to the grid due to feeder trips, primarily caused by elevated grid voltage. Notably, despite the occurrence of feeder trips, the BESS played a pivotal role. During this specific day, the BESS was fully charged five times and discharged stored energy to the grid four times, as indicated in Fig. 21. During BESS discharge, stabilized power was seamlessly fed into the grid without increasing grid voltage. Consequently, the power generation of the 8 MW wind turbine increased to 77.25 MWh on this day, marking a staggering 133 times increase compared to scenarios without BESS. This illustrates the significant impact of BESS in enhancing power generation and system stability, even during challenging operational conditions. The above-mentioned three cases are summarised in Table 5 to understand the nature of the proposed study better. Integrating the 5 MWh BESS enhanced the wind farm operation by reducing the feeder trip. Overall, power generation increased for all cases, particularly for high-speed and high-feeder trip periods. This technique shows an excellent enhancement in power production and stabilized power feeding to the grid. It is concluded that a 5 MWh BESS is suitable for an 8 MW commercial-scale onshore wind farm in Nakhon Ratchasima province, Thailand, for all climatic conditions. Integrating BESS with the proposed wind farm will maintain the wind turbine manufacturer warranty, which could directly reduce the

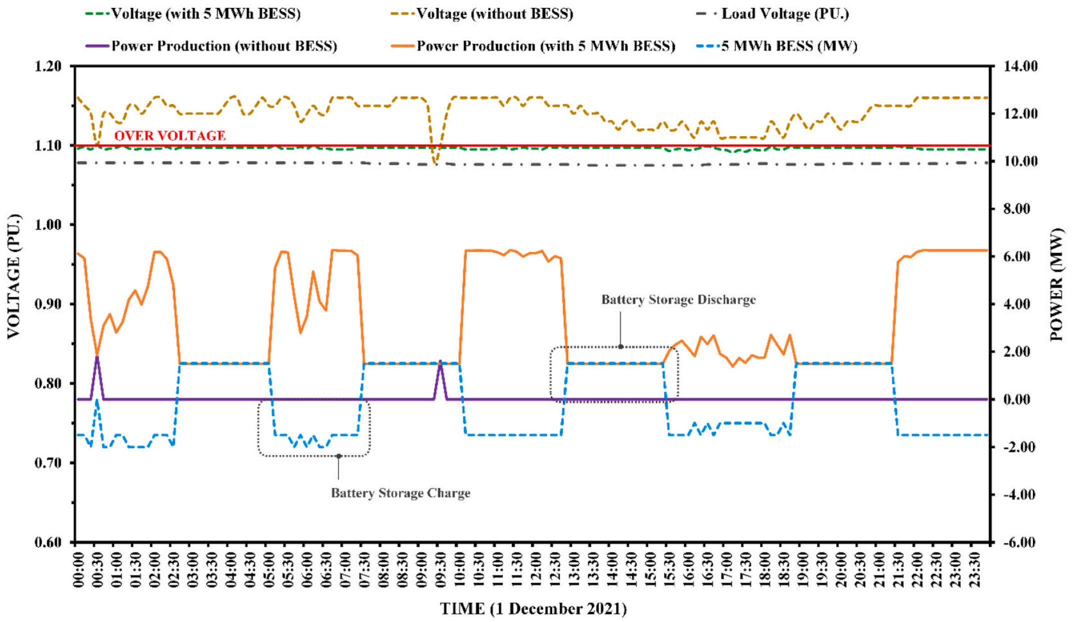

Fig. 21. The relationship between grid voltage and power production of 8 MW wind farm using with and without BESS (December 1, 2021).

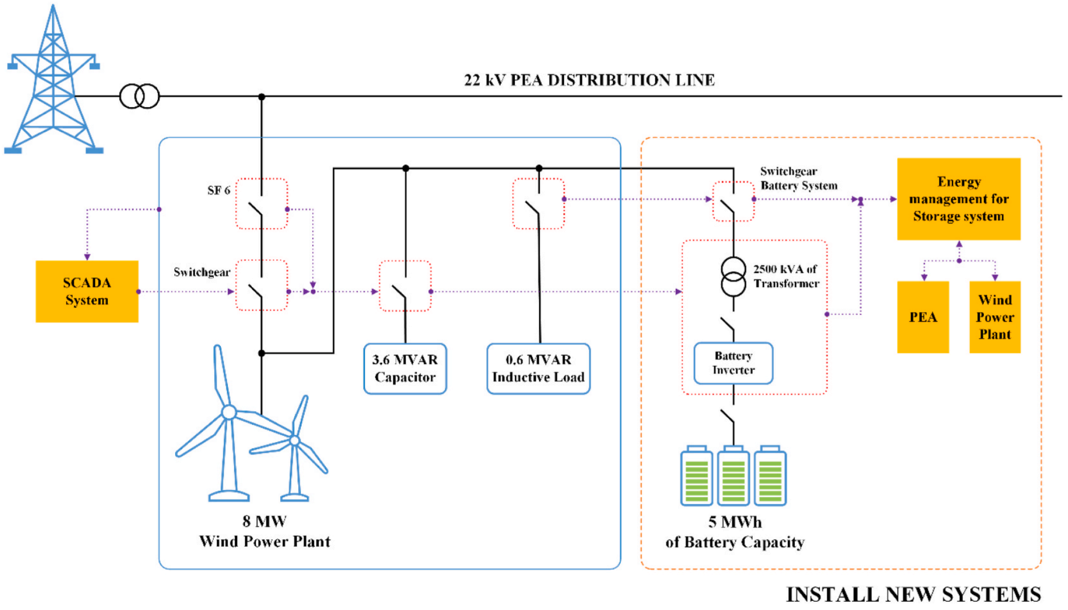

Fig. 22. Schematic view of 8 MW wind farm with 5 MWh BESS under real-time operation.

maintenance cost and increase the wind turbine's lifetime, resulting in economic favours for the wind farm. However, a detailed economic analysis did not perform in this study as the study's primary aim focuses on reducing the feeder trip. Further, it is recommended to implement the 5 MWh BESS with a battery inverter and energy management system to stabilise the power quality and manage the power production from the wind farm and BESS, as shown in Fig. 22.

4. Conclusion

The operational data from the 8 MW wind farm throughout the year highlights a significant issue: feeder trips, occurring 146 times annually, severely impacting power generation. The primary cause behind these feeder trips is overvoltage in the grid, resulting from unaccounted grid load and power production from the wind farm. Notably, in September alone, there were 21 instances of feeder trips, constituting nearly 50 % of the total annual occurrences and surpassing the limits set by the wind turbine manufacturers. To address this challenge, a Battery Energy Storage System (BESS) was integrated into the existing setup. The incorporation of BESS is not only vital for reducing feeder trips but also crucial for maintaining the warranty provided by the turbine manufacturers. In the optimisation process, this study considered a minimal grid load of 10 % and tested various BESS capacities ranging from 1 MWh to 5 MWh, with incremental steps of 1 MWh. Simulation results for a high feeder trip period revealed that BESS capacities of 1 MWh and 2 MWh managed to maintain voltage stability but failed during 24 h of selective day operations. Subsequently, BESS capacities of 3 MWh and 4 MWh exhibited improved stabilization compared to their smaller counterparts; however, feeder trips persisted despite these improvements. The simulation results conclude that the selected location is optimal for a 5 MWh BESS, demonstrating zero feeder trips. To ensure stable wind farm operation, the optimised BESS capacity is utilized during periods of low wind speed. This results in a 5 MWh BESS capable of supplying voltage to the grid without any feeder trips. However, optimising the BESS is for controlling the feeder trip and not for designing it to provide uninterrupted power to the grid during no wind power production periods. We recommend using a 5 MWh BESS to maintain grid stability with controlled voltage feed and to support wind turbine maintenance and service. A detailed economic analysis will be conducted in our future studies using with and without BESS.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Rattaporn Ngoenmeesri: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Sirinuch Chidaruksa:** Writing – original draft, Conceptualization. **Rabian Wangkeeree:** Writing – original draft, Conceptualization. **Chatchai Sirisamphanwong:** Writing – review & editing, Writing – original draft, Validation, Supervision, Conceptualization.

Declaration of competing interest

All authors declare no conflict of interest.

Acknowledgment

The authors would like to express their sincere gratitude to Wind Energy Development Company Limited for providing the necessary data to complete this research successfully. Also, the authors would like to thank the Faculty of Science, Naresuan University, Thailand, for providing the generous grant and laboratory facility.

References

[1] T. Khan, T. Theppaya, J. Taweekun, Wind resource assessment of northern part of Thailand, Ain Shams Eng. J. 14 (7) (2023), 102025.

[2] L. Niyomtham, J. Waewsak, C. Kongruang, S. Chiwamongkhonkarn, C. Chancham, Y. Gagnon, Wind power generation and appropriate feed-in-tariff under limited wind resource in central Thailand, Energy Rep. 8 (2022) 6220–6233.

[3] M. Ranthodsang, J. Waewsak, C. Kongruang, Y. Gagnon, Offshore wind power assessment on the western coast of Thailand, Energy Rep. 6 (2020) 1135–1146.

[4] P. Muangjai, W. Wongsapai, R. Bunchuaidee, N. Tridech, C. Ritkrerkkrai, D. Damrongsak, O. Bhuridej, Estimation of marginal abatement subsidisation cost of renewable energy for power generation in Thailand, Energy Rep. 8 (2022) 528–535.

[5] M.W. Rahman, K. Velmurugan, M.S. Mahmud, A.A. Mamun, P. Ravindran, Modeling of a stand-alone wind-PV hybrid generation system using (MATLAB/SIMULINK), in: 2021 International Conference on Computing, Communication, and Intelligent Systems, ICCCIS, 2021.

[6] G. Rediske, H.P. Burin, P.D. Rigo, C.B. Rosa, L. Michels, J.C.M. Siluk, Wind power plant site selection: a systematic review, Renew. Sustain. Energy Rev. 148 (2021), 111293.

[7] J. Yan, C. Möhrlen, T. Göçmen, M. Kelly, A. Wessel, G. Giebel, Uncovering wind power forecasting uncertainty sources and their propagation through the whole modelling chain, Renew. Sustain. Energy Rev. 165 (2022), 112519.

[8] M.J. Aziz, D.F. Gayme, K. Johnson, J. Knox-Hayes, P. Li, E. Loth, L.Y. Pao, D.R. Sadoway, J. Smith, S. Smith, A co-design framework for wind energy integrated with storage, Joule 6 (9) (2022) 1995–2015.

[9] P.H.A. Barra, W.C. de Carvalho, T.S. Menezes, R.A.S. Fernandes, D.V. Coury, A review on wind power smoothing using high-power energy storage systems, Renew. Sustain. Energy Rev. 137 (2021), 110455.

[10] J. Arockia Dhanraj, R.S. Alkhawaldeh, P. Van De, V. Sugumaran, N. Ali, N. Lakshmaiya, P.K. Chaurasiya, P.S.K. Velmurugan, M.S. Chowdhury, S. Channumsin, S. Sreesawet, H. Fayaz, Appraising machine learning classifiers for discriminating rotor condition in 50W–12V operational wind turbine for maximising wind energy production through feature extraction and selection process, Front. Energy Res. 10 (2022).

[11] M. Sethi, S. Sahoo, J. Arockia Dhanraj, V. Sugumaran, Vibration signal-based diagnosis of wind turbine blade conditions for improving energy extraction using machine learning approach, J. ASTM Int. (JAI) 7 (2023) 14–40.

[12] S. Kheder-Haddouche, S.M. Boudia, Feasibility study of a wind farm in el golea region in the Algerian sahara, in: 2018 6th International Renewable and Sustainable Energy Conference, IRSEC, 2018.

[13] M. Hashem, M. Abdel-Salam, M.T. El-Mohandes, M. Nayel, M. Ebeed, Optimal placement and sizing of wind turbine generators and superconducting magnetic energy storages in a distribution system, J. Energy Storage 38 (2021), 102497.

[14] M. Seung-Pil, K. Soo-Yeol, R. Labios, Y. Yong-Beum, Determining wind farm locations, allocation of wind farm capacity, and sizing of energy storage for 17 GW new wind power capacity in Korea, in: 2016 IEEE Power and Energy Society General Meeting, (PESGM), 2016.

[15] N. Yan, Z.X. Xing, W. Li, B. Zhang, Economic dispatch analysis of wind power integration into power system with energy storage systems, in: 2015 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices, ASEMD, 2015.

[16] J. Arockia Dhanraj, M. Prabhakar, C. Ramaian, M. Subramaniam, J. Muthiya, V. Nadanakumar, Increasing the Wind Energy Production by Identifying the State of Wind Turbine Blade, 2022, pp. 139–148.

[17] H.S. Sunil Kumar, K. Jagadeesh, A. r b, T. Rangaswamy, S. Salyan, J. Muthiya, J. Arockia Dhanraj, J. Lalvani, The impact of critical flutter velocity in composite wind turbine blade with prebend condition, Math. Probl Eng. (2022) 2022.

[18] K.S.R. Murthy, O.P. Rahi, P. Sonkar, S. Ram, Longterm analysis of wind speed and wind power resource assessment for the site Vijayawada, Andhra Pradesh, India, in: 2017 6th International Conference on Computer Applications in Electrical Engineering-Recent Advances, CERA, 2017.

[19] M.A. Jaikrishna, S. Nv, S. V, J.A. Dhanraj, K. Velmurugan, C. Sirisamphanwong, R. Ngoenmeesri, C. Sirisamphanwong, Transfer learning-based fault detection in wind turbine blades using radar plots and deep learning models, Energy Sources, Part A Recovery, Util. Environ. Eff. 45 (4) (2023) 10789–10801.

[20] T. Yi, H. Ye, Q. Li, C. Zhang, W. Ren, Z. Tao, Energy storage capacity optimisation of wind-energy storage hybrid power plant based on dynamic control strategy, J. Energy Storage 55 (2022), 105372.

[21] F. Keck, M. Lenzen, A. Vassallo, M. Li, The impact of battery energy storage for renewable energy power grids in Australia, Energy 173 (2019) 647–657.

[22] H. Branco, R. Castro, A. Setas Lopes, Battery energy storage systems as a way to integrate renewable energy in small isolated power systems, Energy for Sustainable Development 43 (2018) 90–99.

[23] X. Ai, Z. Wu, J. Hu, Y. Li, P. Hou, Robust operation strategy enabling a combined wind/battery power plant for providing energy and frequency ancillary services, Int. J. Electr. Power Energy Syst. 118 (2020), 105736.

[24] Q. Chen, T. Zhao, Heat recovery and storage installation in large-scale battery systems for effective integration of renewable energy sources into power systems, Appl. Therm. Eng. 122 (2017) 194–203.

[25] K. Velmurugan, C. Sirisamphanwong, S. Sukchai, Thermal investigation of paraffin wax for low-temperature application, Journal of Advanced Research in Dynamical and Control Systems 11 (2019) 1437–1443.

[26] V. Karthikeyan, C. Sirisamphanwong, S. Sukchai, Investigation on thermal absorptivity of PCM matrix material for photovoltaic module temperature reduction, Key Eng. Mater. 777 (2018) 97–101.

[27] K. Velmurugan, R.M. Elavarasan, P.V. De, V. Karthikeyan, T.B. Korukonda, J.A. Dhanraj, K. Emsaeng, M.S. Chowdhury, K. Techato, B.S.A. El Khier, E.-A. Attia, A review of heat batteries based PV module cooling—case studies on performance enhancement of large-scale solar PV system, Sustainability 14 (4) (2022) 1963.

[28] D. Watson, E. Rebello, N. Kii, T. Fincker, M. Rodgers, Demand and energy avoidance by a 2 MWh energy storage system in a 10 MW wind farm, J. Energy Storage 20 (2018) 371–379.

[29] D. Ikni, M.B. Camara, B. Dakyo, Offshore wind farms energy injection in the electrical grid - lithium battery to mitigate power fluctuations, International Journal of Renewable Energy Research 5 (2015) 1049–1061.

[30] P. Dratsas, G. Psarros, S. Papathanassiou, Feasibility of behind-the-meter battery storage in wind farms operating on small islands, Batteries 8 (2022) 275.

[31] A.T. Tadie, Z. Guo, Y. Xu, Hybrid model-based BESS sizing and control for wind energy ramp rate control, Energies 15 (23) (2022) 9244.

[32] N.K.L. Dantas, A.C.M. Souza, A.S.M. Vasconcelos, W.d.A.S. Junior, G. Rissi, C. Dall'Orto, A.M.A. Maciel, J.F.C. Castro, Y. Liu, P. Rosas, Impact analysis of a battery energy storage system connected in parallel to a wind farm, Energies 15 (13) (2022) 4586.

[33] A. Pokhriyal, J.L. Domínguez-García, P. Gómez-Romero, Impact of battery energy system integration in frequency control of an electrical grid with wind power, Cleanroom Technol. 4 (4) (2022) 972–986.

[34] F.-C. Gu, H.-C. Chen, Modelling and control of vanadium redox flow battery for smoothing wind power fluctuation, IET Renew. Power Gener. 15 (15) (2021) 3552–3563.

[35] S. Koganti, K.J. Koganti, S.R. Salkuti, Design of multi-objective-based artificial intelligence controller for wind/battery-connected shunt active power filter, Algorithms 15 (8) (2022) 256.

[36] G. Pechlivanoglou, A. Mannelli, F. Papi, G. Ferrara, A. Bianchini, Discrete wavelet transform for the real-time smoothing of wind turbine power using Li-ion batteries, Energies 14 (2021) 2184.

[37] M. Gholami, O. Shahryari, N. Rezaei, H. Bevrani, Optimum storage sizing in a hybrid wind-battery energy system considering power fluctuation characteristics, J. Energy Storage 52 (2022), 104634.

[38] S. Yuan, A.S. Kocaman, V. Modi, Benefits of forecasting and energy storage in isolated grids with large wind penetration – the case of Sao Vicente, Renew. Energy 105 (2017) 167–174.

[39] J. Wu, B. Zhang, H. Li, Z. Li, Y. Chen, X. Miao, Statistical distribution for wind power forecast error and its application to determine optimal size of energy storage system, Int. J. Electr. Power Energy Syst. 55 (2014) 100–107.

[40] A. Michiorri, J. Lugaro, N. Siebert, R. Girard, G. Kariniotakis, Storage sizing for grid connected hybrid wind and storage power plants taking into account forecast errors autocorrelation, Renew. Energy 117 (2018) 380–392.

[41] M.R. Nayak, D. Behura, K. Kasturi, Optimal allocation of energy storage system and its benefit analysis for unbalanced distribution network with wind generation, Journal of Computational Science 51 (2021), 101319.