Scientific Research Publishing

**Journal of Power and Energy Engineering, 2025, 13(9), 402-421**
https://www.scirp.org/journal/jpee
ISSN Online: 2327-5901
ISSN Print: 2327-588X

# Rule-Based Energy Storage Deployment Strategy for Enhancing the Performance of Distribution Network with Photovoltaic and Electric Vehicle

**Mirza Danish Mohd Rosli[1], Junainah Sardi[2], Surina Mat Suboh[3]**

[1]eLeaps Sdn Bhd, Selangor, Malaysia
[2]Faculty of Electrical Engineering and Technology, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[3]Faculty of Electrical Engineering and Technology, Universiti Malaysia Perlis, Perlis, Malaysia
Email: junainah@utem.edu.my

**How to cite this paper:** Rosli, M.D.M., Sardi, J. and Suboh, S.M. (2025) Rule-Based Energy Storage Deployment Strategy for Enhancing the Performance of Distribution Network with Photovoltaic and Electric Vehicle. *Journal of Power and Energy Engineering*, **13**, 402-421.
https://doi.org/10.4236/jpee.2025.139025

**Received:** August 13, 2025
**Accepted:** September 23, 2025
**Published:** September 26, 2025

## Abstract

The increasing integration of photovoltaic (PV) systems and electric vehicles (EVs) into distribution networks (DNs) presents significant operational challenges, including voltage fluctuations, reverse power flow, and rapid PV ramp rates. This paper proposes a rule-based strategy for deploying battery energy storage systems (BESS) to mitigate these issues and enhance the overall performance of the DN. The study evaluates the impacts of high PV and EV penetration on distribution network, performance using simulation models in OpenDSS, an open-source electric power distribution system simulator. A rule-based approach is then developed to determine strategic BESS dispatch strategies and sizing, targeting improvements in voltage stability, power quality, and system reliability. The proposed methodology is validated on a modified IEEE 33-bus radial distribution system comprising mixed loads (residential, industrial, and commercial) under PV penetration levels of 25% and 50%, with an EV penetration level of 10%. The optimal BESS allocations are identified at buses 18 and 33, with capacities of 1436 kW/5526 kWh and 1816 kW/10,854 kWh, respectively. Results indicate that higher PV penetration (50%) necessitates larger BESS capacities to sustain network reliability. The proposed allocation strategy ensures that bus voltages and PV ramp rates remain within permissible limits, while reverse power flow (RPF) is substantially mitigated. The proposed method offers a practical framework for grid operators to manage distributed energy resources efficiently, contributing to a more resilient and sustainable power system.

**Keywords**

Photovoltaic, Electric Vehicle, Energy Storage System, Voltage Profile, PV Ramp Rate

## 1. Introduction

The increment of energy consumption resulting from economic development, rising population and technological developments. International Energy Agency (IEA) shows the rising of energy demand as much as 4.5% or over 1000 TWh in 2021 [1]. The world's target to achieve net zero carbon by 2050 and to keep global warming less than 1.5˚C (Paris Agreement) [2]. Global warming is a concerning issue that must be addressed to tackle the greenhouse effects. One of the solutions to reduce greenhouse gas emissions and mitigate climate change is by replacing traditional power generation with renewable energy resources such as solar energy. Another way to reduce carbon emissions is by utilizing EV in transportation.

The intermittent characteristics of PV could lead to another issues. High penetration level of PV into the grid contributes to several issues including voltage and power fluctuations as well as reverse power flow (RPF) [3]. The increment of EV chargers could lead to an increment of load demand. The load demand could be unstable because it completely depends on the EV users charging rates and patterns. The negative impacts of the high EV penetration can be observed in power quality and grid stability [4]. To overcome these problems, BESS implementation should be considered.

Many studies have explored the challenges brought by the increasing integration of photovoltaic (PV) systems and electric vehicles (EVs) into distribution networks (DNs). Common issues include voltage fluctuations due to intermittent solar generation, reverse power flow during periods of high PV output and low demand, and rapid PV ramp rates caused by sudden changes in weather conditions. These challenges can negatively affect voltage stability, power quality, and overall system reliability [4] [5].

To address these issues, battery energy storage systems (BESS) have been widely proposed. Existing approaches to BESS control include optimization-based strategies, which require extensive computation and forecasting; and artificial intelligence (AI) or heuristic-based methods, such as fuzzy logic or machine learning, which offer flexible solutions but are often complex and challenging to implement in real-time operation [6]. While rule-based BESS control offers a simpler and more practical alternative, lack of studies is conducted with respect to high PV and EV penetration scenarios. Furthermore, most existing studies tend to focus on either PV or EV impacts in isolation rather than addressing their combined effects on the distribution network.

This highlights a clear research gap: the need for a practical, rule-based BESS control strategy that can effectively manage both PV and EV integration while improving voltage stability, mitigating reverse power flow, and reducing PV ramp rates.

This study aims to address the identified research gap through the following key contributions:

1) Quantifying the impact of PV and EV integration on distribution network performance.

2) Developing a rule-based methodology for the strategic allocation of BESS to mitigate issues arising from PV and EV adoption, specifically voltage limit violations, reverse power flow, and high PV ramp rates.

3) Evaluating the effectiveness of the proposed BESS allocation strategy under 25% and 50% PV penetration levels with EV integration, using OpenDSS simulations.

The remainder of this paper is as follows: Section 2 describes the methodology and mathematical formulation used in the proposed allocation strategy including the modelling of loads, PV, EV and BESS. Section 3 presents a case study description, numerical results and discussions. Finally, Section 4 concludes the paper by highlighting major conclusions and contribution of the work.

## 2. Methodology

### 2.1. Overview

This section outlines a methodology proposed for the strategic deployment of BESS in distribution network aiming on improving the performance of distribution grid with respect to reverse power flow avoidance, voltage profile improvement and power ramp rate mitigation. **Figure 1** illustrates the general framework of the proposed BESS allocation strategy. BESS allocation is defined in this work as the BESS location, dispatch power and size. The inputs of the BESS allocation strategy include a year of hourly historical or forecasted load power, EV charging power and solar PV generation of the network. A rule-based BESS dispatch scheduling approach is used to identify the hourly BESS dispatch power aiming to reduce reverse power flow, improve voltage profile and mitigate high PV ramp rate. The rated size of BESS in kW and kWh is identified based on the total utilized capacity of BESS daily for discharge/charge and the technical characteristics of BESS technology such as its round-trip efficiency, degradation rate, allowable SOC and Depth of Discharge (DOD).

### 2.2. Load Model

Mixed residential, industrial and commercial end-user load, which is considered as AC load demand, are connected at the AC bus of the system. The load power is represented as a time-varying PQ model. The load power at nominal voltage is assumed to follow an hourly residential, commercial and industrial load curves, which was generated from historical data found in [7] and [8]. The daily profiles of the power demand are shown in **Figure 2**. For the purposes of practical application, forecasted of load power should be used to accurately determine the BESS dispatch power.

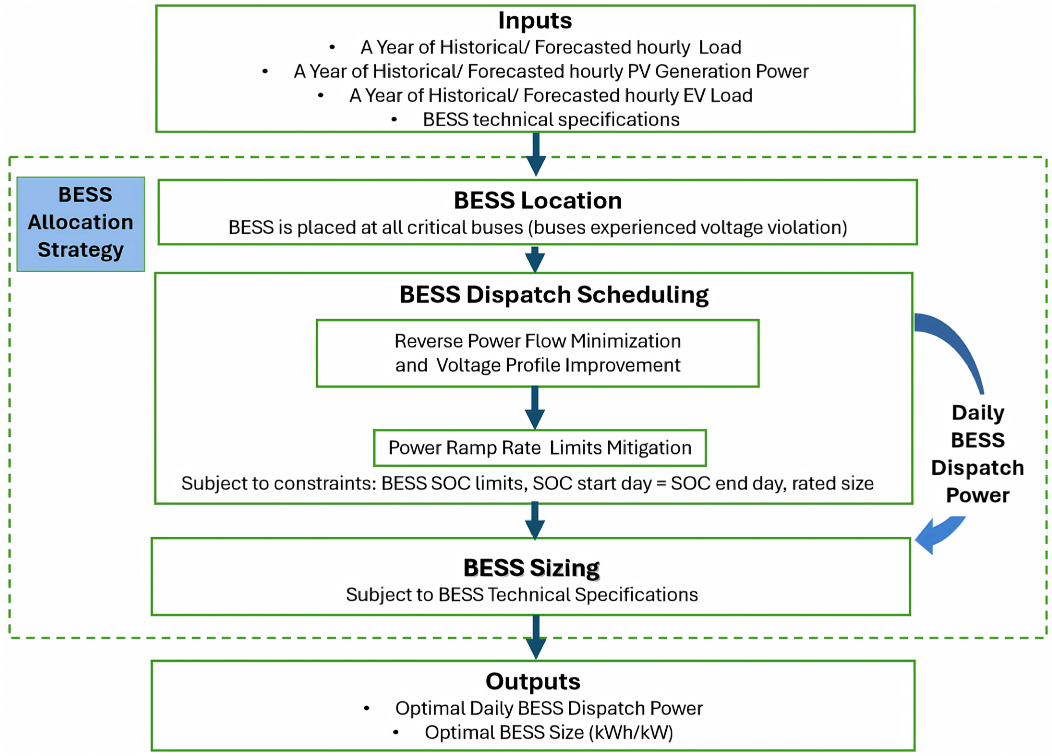


**Figure 1.** General framework of BESS allocation for distribution network with Solar PV and EV in Malaysia.

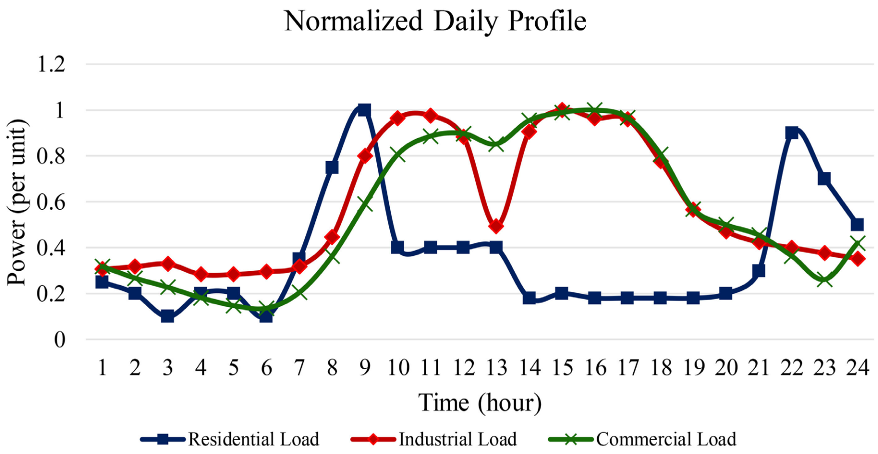


**Figure 2.** Normalized daily load profile [7] [8].

## 2.3. PV Model

In this study, PV power generation is represented using historical PV output data, which inherently captures the variability due to irradiance and temperature conditions. Since the analysis relies on actual generation profiles, maximum power point tracking (MPPT) mechanisms are not explicitly modeled, and the recorded PV data is directly applied as the generation input in the simulations. Normalized PV generations are obtained from historical data and used in this work to represent much higher size of solar PV that can be integrated to commercial building. With that, the PV penetration level can be varied. Normalized PV profile is shown in **Figure 3**. Percentage of PV penetration level in this paper is defined as follows:

$$PV_{pen} = \frac{E_{pv}}{E_{load}} * 100\% \tag{1}$$

where $E_{pv}$ is the annual energy generated by solar PV in kWh and $E_{load}$ is the annual energy consumption of the network in kWh [9].

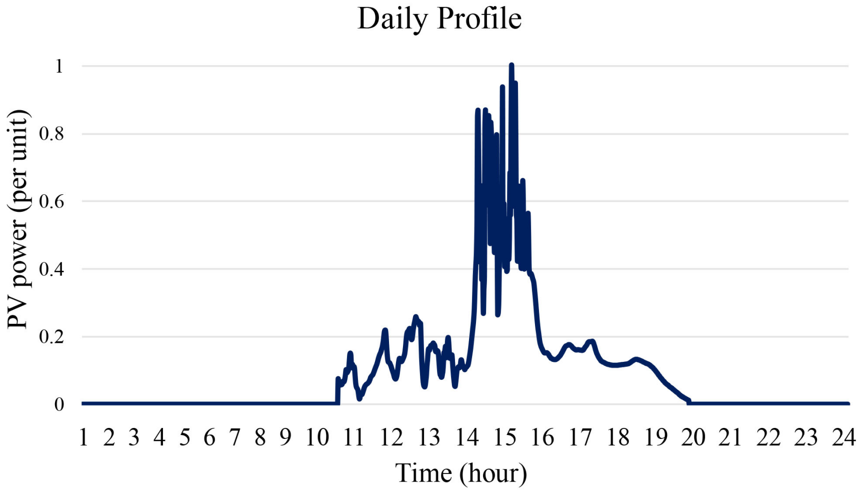


**Figure 3.** Normalized PV profile.

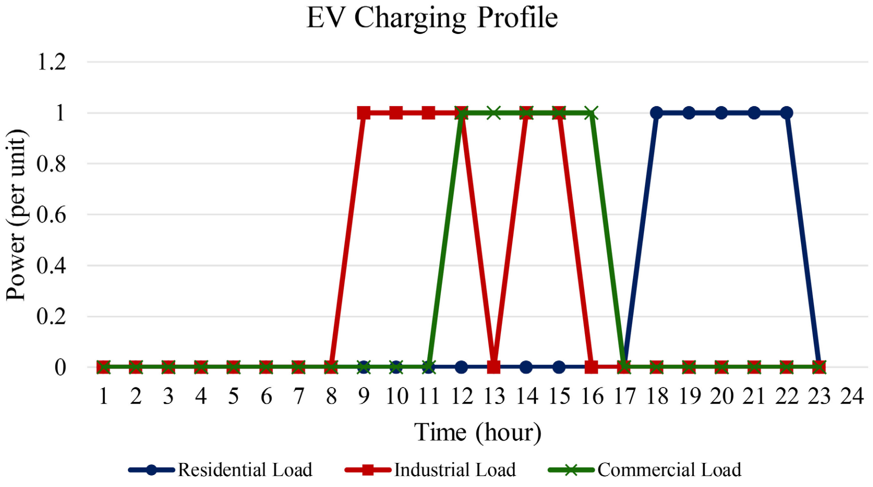


**Figure 4.** EV charging profile for residential, industrial and commercial load.

## 2.4. EV Model

EV is modelled as hourly PQ time-varying load demand based on the charging rate and pattern of consumers. It is assumed that EV cars users start charging their EV cars at 6 pm or 7 pm in residential areas. Meanwhile, EV users in industrial areas are estimated to charge their vehicles when they are working, especially around 9 am. For commercial areas, EV users are predicted to start charging their vehicles at 12 pm. The time taken for the charging period is 5 hours, which is during the peak hours. Figure 4 shows the charging profile for each area. Percentage of EV penetration level is defined as follows:

$$EV_{pen} = \frac{E_{ev}}{E_{load}} * 100\% \tag{2}$$

where $E_{ev}$ is the annual energy consumed by EV charging in kWh.

Given any PV capacity and EV installed at the particular feeder, net demand power of the feeder for each hourly time segments, $t$ is expressed as

$$P_D(t) = P_L(t) - P_{PV}(t) + P_{EV}(t) \tag{3}$$

## 2.5. BESS Model

There are three important elements in designing BESS which are location sizing, and dispatch strategy. This section presents the methodology to identify the strategic location, dispatch strategy and size of BESS.

### 2.5.1. Location

BESS placement in this study is considered at all critical buses, defined as the buses where voltage violations occur (*i.e.*, voltages exceeding the permissible limits).

### 2.5.2. Dispatch Power

BESS dispatch power is determined with the aim of minimizing RPF and improving voltage profile. Figure 5 shows the flowchart of BESS dispatch strategy for this purpose. The amount of power needed to charge is according to the amount of reverse power flow (RPF) whereas the discharge power is based on the undervoltage. This can be done by calculating using (4) and (5) to determine charging power and discharging power respectively.

$$P_C(t) = \begin{cases} P_C(t) = \dfrac{P_D(t)\left(V_{c1}(t) - V_{lim\_low}\right)}{V_{c1}(t) - V_R(t)} & \in P_D(t) < 0 \\ P_C(t) = 0 & \in P_D(t) \geq 0 \end{cases} \tag{4}$$

where $P_C$ is the charging power, $V_{c1}$ is the voltage at critical bus for case with PV and EV (Case 1), and $V_R$ is the voltage at critical bus during reverse power flow occurred. All power and voltage are in units of kW and pu respectively.

$$P_D(t) = \begin{cases} P_D(t) = P_{set}(t)\left(1 - \dfrac{V_{set}(t) - V_D(t)}{V_{set}(t) - V_{C1}(t)}\right) & \in V_D(t) < V_{set}(t) \\ P_D(t) = P_{set}(t)\left(\dfrac{V_D(t) - V_{C1}(t)}{V_{set}(t) - V_{C1}(t)}\right) & \in V_D(t) > V_{set}(t) \end{cases} \tag{5}$$

where $P_D$ = discharging power, $V_{set}$ = setting voltage, $V_D$ = desired voltage, $P_{set}$ = setting power, $V_D$ = desired voltage and $V_{C1}$ = voltage at the critical bus for Case 1. All power and voltage are in units of kW and pu respectively.

To ensure realistic operation of the BESS, the state of charge (SOC) is constrained such that the SOC at the beginning of the day equals the SOC at the end of the day. This balance condition guarantees that the total daily charging energy equals the total daily discharging energy, thereby preventing the battery from being fully depleted or overcharged at any time.

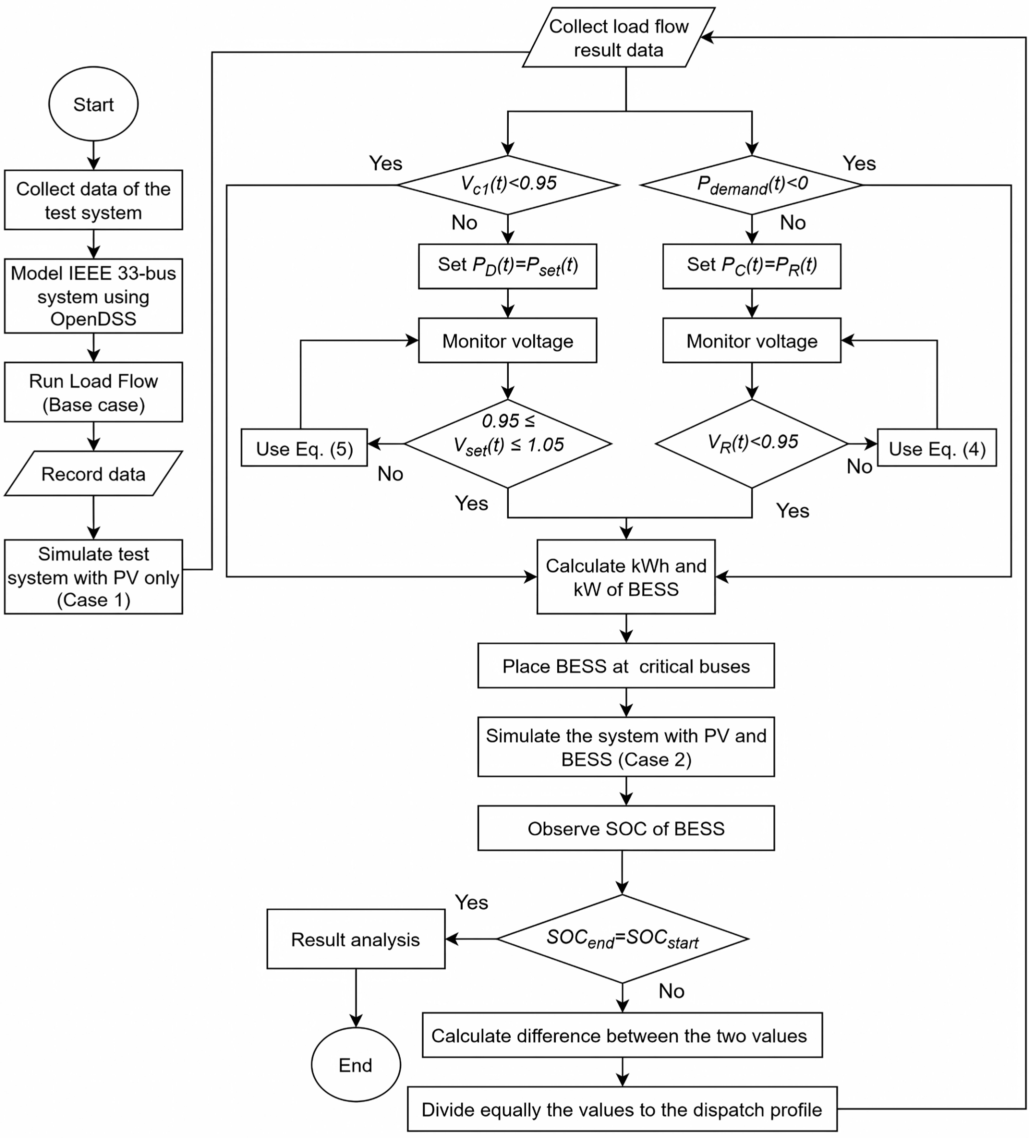


**Figure 5.** Flowchart of BESS dispatch strategy for RPF minimization and voltage profile improvement.

The SOC evolution is modeled as:

$$\mathrm{SOC}(t)=\mathrm{SOC}(t-1)+\left(P_{ch}(t)*\eta-\frac{P_{dis}(t)}{\eta}\right)\Delta t \tag{6}$$

where $\mathrm{SOC}(t)$ is the SOC at hour $t$, $P_{ch}(t)$ and $P_{dis}(t)$ denote charging and discharging power, $\eta$ is BESS efficiencies, and $\Delta t$ is the time step (1 hour in this study) [10] [11].

The daily SOC balance constraint is expressed as:

$$\text{SOC}_{\text{end}} = \text{SOC}_{\text{start}} \tag{7}$$

$$\sum_{t=1}^{24} P_{ch}(t) * \eta = \sum_{t=1}^{24} \frac{P_{dis}(t)}{\eta} \tag{8}$$

This condition ensures that the BESS operates in a sustainable cycle across the 24-hour simulation horizon, maintaining its energy neutrality while still supporting the network in mitigating voltage violations, reverse power flow, and PV ramp rate issues.

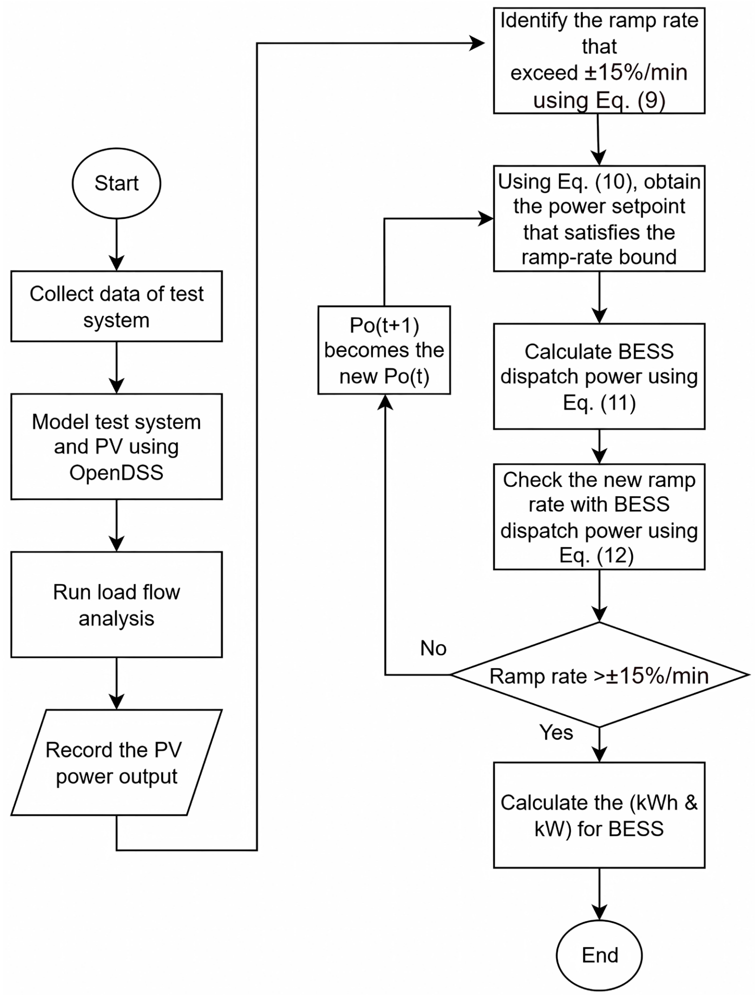


**Figure 6.** Flowchart of BESS dispatch strategy for PV ramp rate improvement.

The allowable PV ramp rate is based on the standard set by Energy Commission (EC) which is 15%/minute [12]. The EC standard refers to the transmission-connected Large Scale Solar (LSS), but in this project the PV solar is connected in the distribution level. Although individual rooftop PV systems produce relatively small fluctuations, their cumulative ramping effect at points of common coupling (e.g., substations) can be significant and may propagate upstream, potentially causing critical challenges at the transmission level. Therefore, this project uses the standard ramp rate limit of ±15%/minute. Figure 6 shows the flowchart of rule-based strategy to identify BESS dispatch power for PV ramp rate improvement. The equations of this process are as follows.

$$Ramp(t) = \frac{P_O(t-1) - P_O(t)}{P_{PV}} \times 100\% \tag{9}$$

where $P_O(t-1)$ is the output PV power at minute $(t-1)$, $P_O(t)$ is output PV power at minute $t$ and $P_{PV}$ is the rated PV capacity power. All power and voltage are in units of kW and pu respectively.

$$P_N(t) = \begin{cases} P_N(t) = \left(\frac{P_{PV}}{100} \times 14\right) + P_O(t-1) & \text{if } P_O(t) > P_O(t-1) \\ P_N(t) = P_O(t-1) - \left(\frac{P_{PV}}{100} \times 14\right) & \text{if } P_O(t) < P_O(t-1) \end{cases} \tag{10}$$

where $P_N(t)$ is the necessary power. All power and voltage are in units of kW and pu respectively.

$$P_{Dispatch}(t) = P_N(t) - P_O(t) \tag{11}$$

where $P_{Dispatch}(t)$ is the dispatch power at minute $t$. All power and voltage are in units of kW and pu respectively. With the dispatch power from BESS, the new PV ramp rate in the network is as follows:

$$Ramp_{BESS}(t) = \frac{P_N(t) - P_O(t)}{P_{PV}} \times 100\% \tag{12}$$

### 2.5.3. Sizing

BESS size is computed using Equation (13) and (14). The formulations considered BESS utilized capacity identified in the previous section and specific technical characteristics of BESS technology, which are round-trip efficiency $\eta$, the maximum depth of discharge $\gamma$ and self-discharge rate $\kappa$.

$$E_{ESR} = (1+\kappa) \times \left(\frac{E_{ES}}{\eta} + (1-\gamma) \times E_{ES}\right) \tag{13}$$

$$P_{ESR} = \frac{\max\left(\left|P_{ES,m,t}\right|\right)}{\eta} \tag{14}$$

## 3. Result and Discussion

### 3.1. Test System Description

A modified 12.66 kV, IEEE 33 bus radial distribution system shown in **Figure 7** is used in this study to test the proposed strategy. Distribution of load types is shown in **Figure 8**. Historical data of PV generation for 28 kWp PV modules located at Solar PV System and Smart Grid Laboratory, Faculty of Electrical Technology and Engineering, UTeM is utilized in this study [13]. Generation data are normalized to be used for higher capacity of PV. Voltage limitation is based on the standard set by Energy Commission, Malaysia which is between 0.95 pu and 1.05 pu [14]. The PV systems are located on 17 different buses that have low voltage profile (below 0.95 pu). Meanwhile, the EV chargers are placed randomly on 15 buses. As for BESS, Lithium-ion battery is chosen as the preferred technology due to its maturity for grid applications, high efficiency, and cost-effectiveness. Its degradation loss, $\kappa$ is 0.1, round trip efficiency, $\eta$ is 0.9 and maximum Depth of Discharge of BESS, $\gamma$ is 0.9.

To evaluate the performance of distribution network with the adoption of PV, EV and BESS considering the proposed allocation strategy, 3 cases are modelled and simulated using OpenDSS that are Base Case that is case without PV, EV and BESS, Case 1 that is the network with PV and EV only and Case 2 that is network with PV, EV and BESS. For all three cases, two scenarios are considered, that are the network under 25% and 50% PV penetration levels.

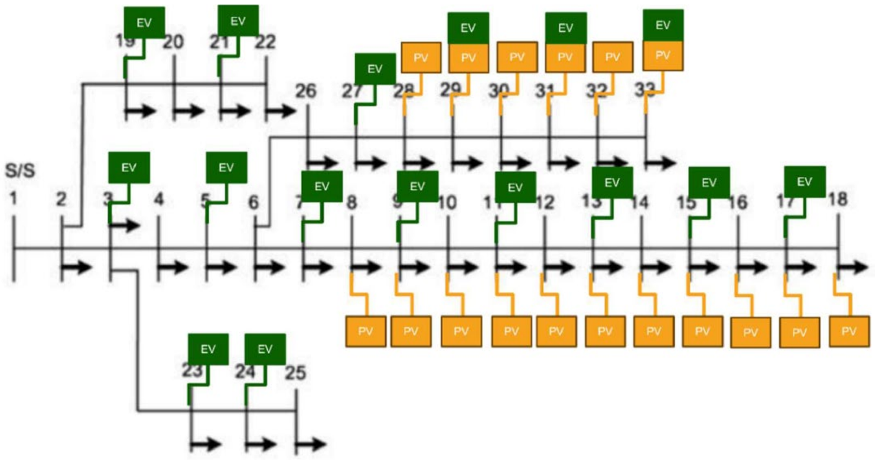


Figure 7. The modified IEEE 33-bus distribution network.

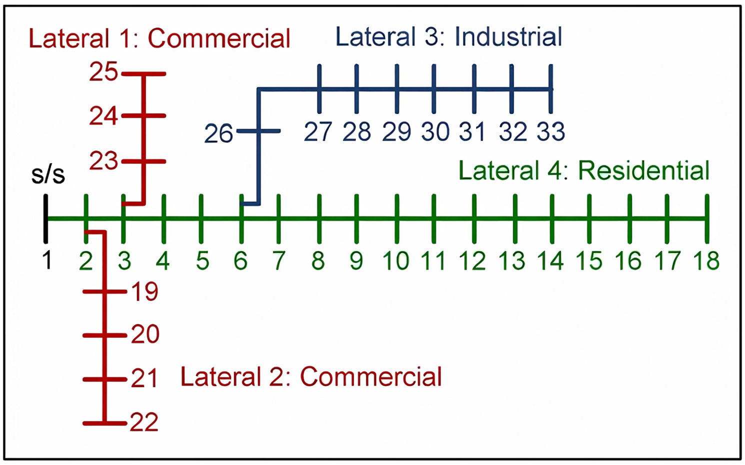
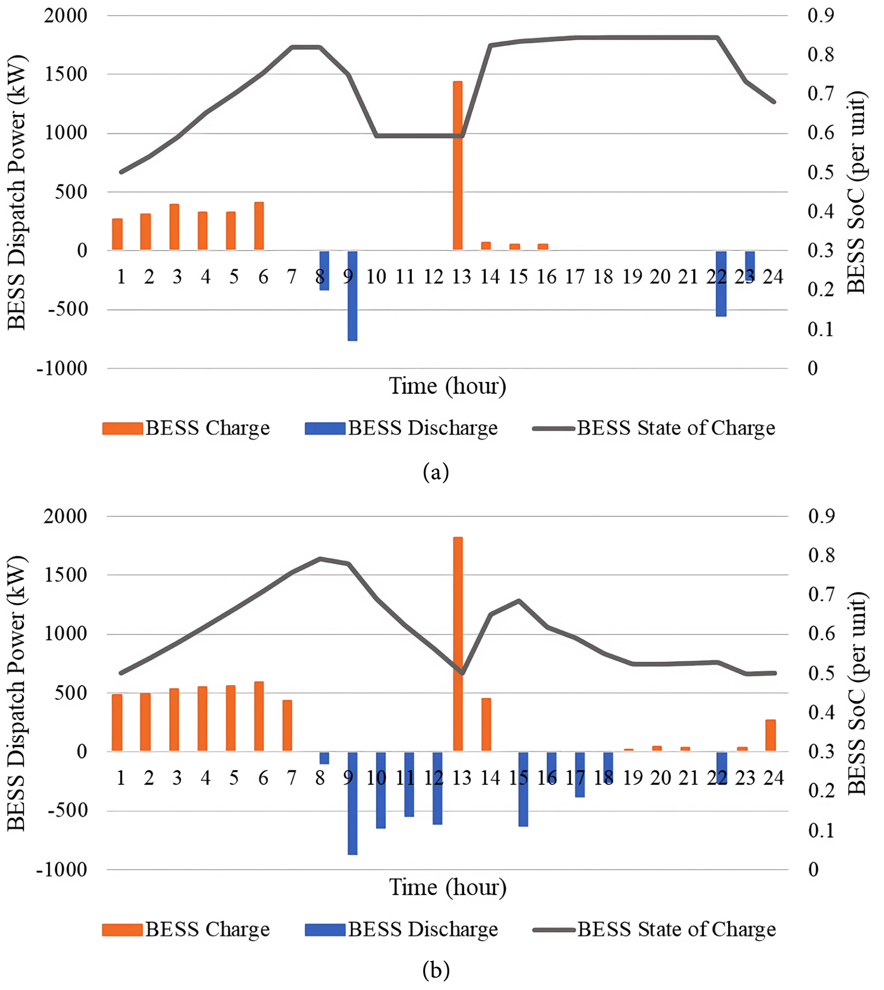


Figure 8. Mixed load in IEEE33-bus system.

### 3.2. BESS Dispatch Strategy

Based on the simulation without BESS (Case 1), there are two buses that experienced voltage limits violation which are Bus 18 and Bus 33. The strategy is to place BESS on the two mentioned buses. The initial energy stored in BESS is set at 50%

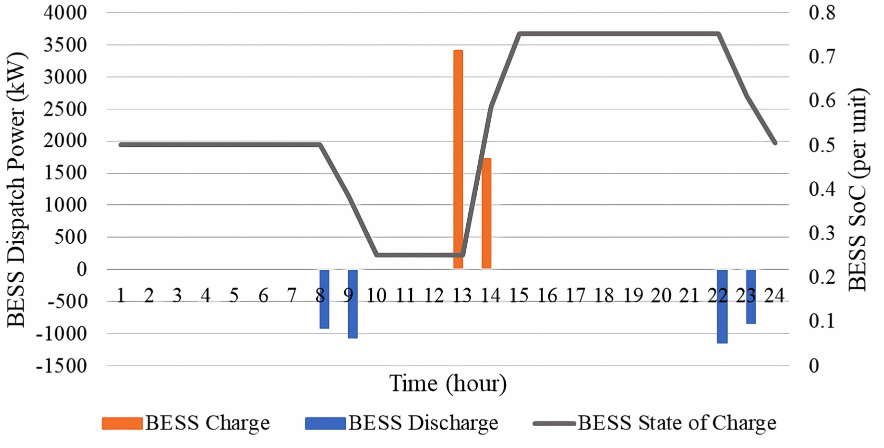
of its full capacity and the minimum allowable battery capacity is 20% of its full capacity. **Figure 9** and **Figure 10** depict the power of BESS as well as its SoC for Case 2 with 25% and 50% PV penetration levels respectively.



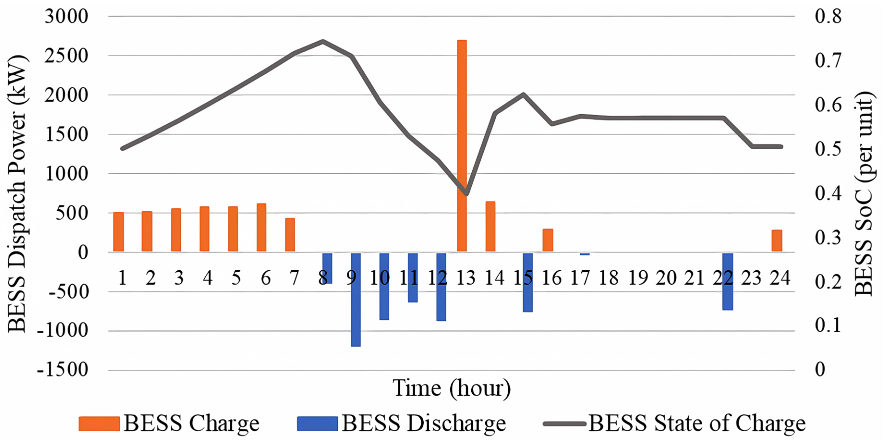
(a)

(b)

**Figure 9.** Dispatch power profile of Case 1 with 25% PV penetration at bus (a) 18 and (b) 33.



(a)



(b)

**Figure 10.** Dispatch power profile of 50% PV penetration at bus (a) 18 and (b) 33.

### 3.3. BESS Sizing

**Table 1** and **Table 2** list the description of cases studies and the computed BESS size for 25% and 50% PV penetration level respectively, using the proposed allocation strategy. The result shows that with the increment of PV penetration level, BESS size required to mitigate the voltage profile, reverse power flow and high PV ramp rate issues are increased.

**Table 1.** Description of case studies (25% PV penetration).

| Case | PV capacity (kWh) | EV capacity (kWh) | BESS size (kW/kWh) | |
|---|---|---|---|---|
| | | | BESS 18 | BESS 33 |
| Base | 0 | 0 | 0 | 0 |
| Case 1 | 3658 | 1553 | 0 | 0 |
| Case 2 | 3658 | 1553 | 1436/5526 | 1816/10,854 |

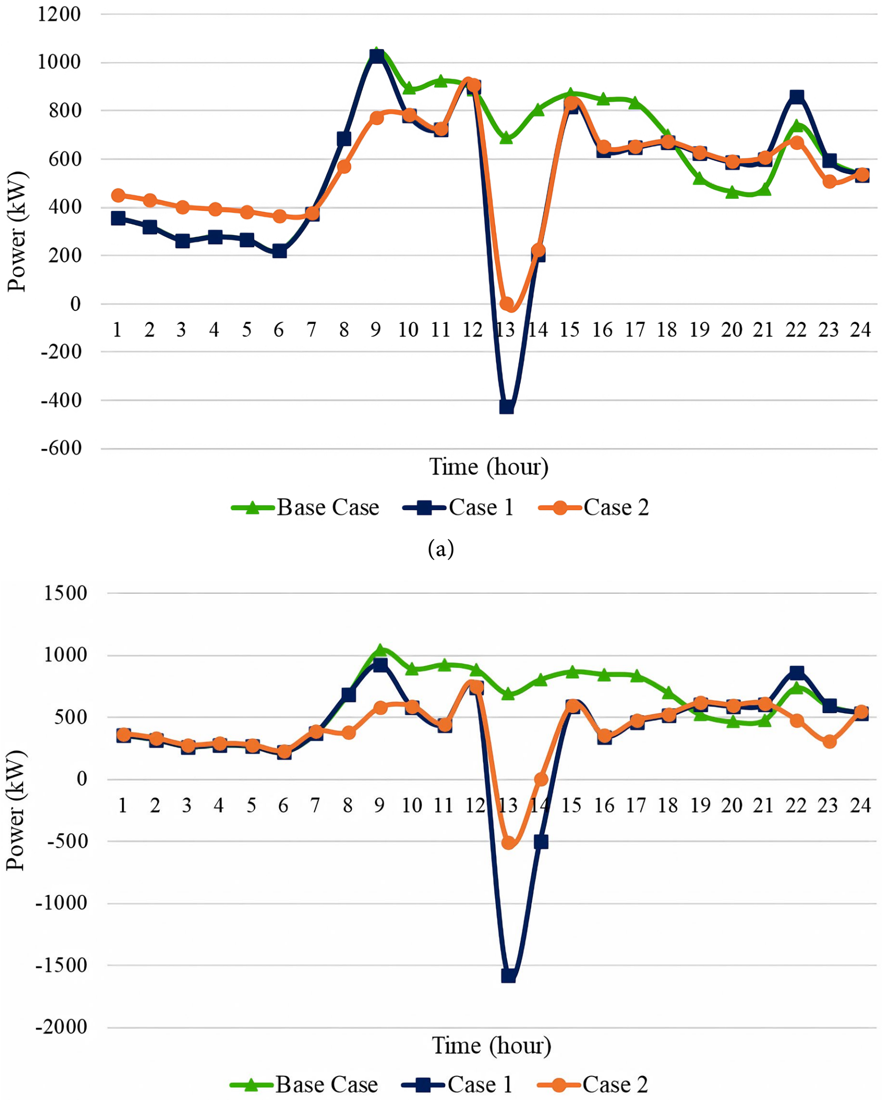
**Table 2.** Description of case studies (50% PV penetration).

| Case | PV capacity (kWh) | EV capacity (kWh) | BESS size (kW/kWh) | |
|---|---|---|---|---|
| | | | BESS 18 | BESS 33 |
| Base | 0 | 0 | 0 | 0 |
| Case 1 | 7316 | 1553 | 0 | 0 |
| Case 2 | 7316 | 1553 | 3404/9035 | 2685/13,041 |

### 3.4. Distribution Network Performance

#### 3.4.1. Demand Profile

Three cases of demand profile are presented graphically in **Figure 11** to observe the impact of PV, EV and BESS integration on the network demand in a day. For the Base Case, the total power demand over 24 hours is recorded at 14599.49 kWh. Demand increases between 7 am and 9 am. Peak electricity usage by consumers occurs at 9 am, with consumption at 1041.42 kW. In Case 1, with PV installation, the network experiences RPF at 1 pm due to excess PV generation, resulting in 425.173 kWh of RPF as shown in **Figure 11(a)**. The maximum demand occurs at two different times, which are at 9 am and 10 pm as it is recorded to peak at 860.473 kW. Implementing BESS reduces RPF and successfully lowers peak demand compared to Case 1, with a reduction of 251.797 kW. **Figure 11(b)** shows the demand for 50% PV penetration also highlighted the same trend.



(a)

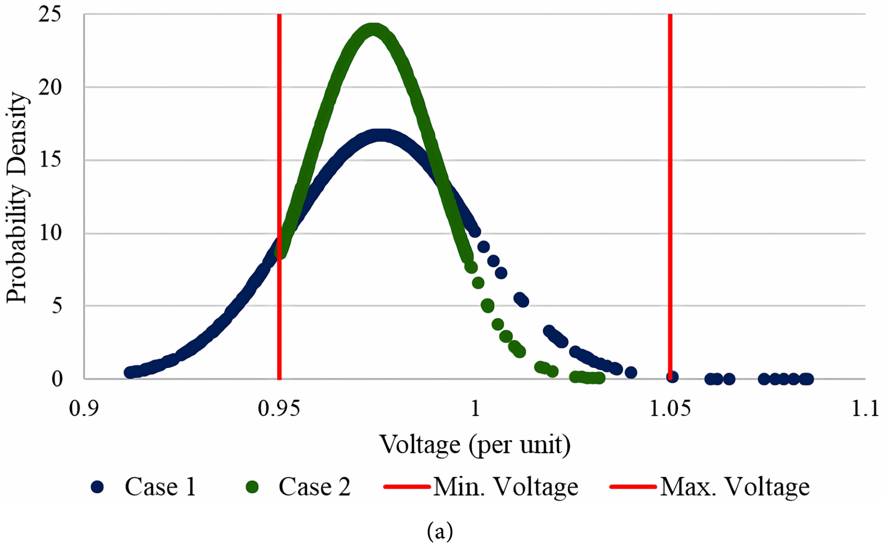
(b)

**Figure 11.** Load demand of three cases for (a) 25% and (b) 50% PV penetration.

### 3.4.2. Voltage Profile

**Figure 12** illustrates voltage distribution of Case 1 and 2 with (a) 25% PV penetration and (b) 50% PV penetration. The result shows that without BESS implementation, approximately 14% of the voltage falls outside the acceptable range. The observed minimum and maximum voltages are 0.912 pu and 1.085 pu, respectively. With BESS implementation, all voltages are within range, with the minimum at 0.950 pu and the maximum at 1.032 pu.

Additionally, Figure 12(b) shows that around 20% of the voltage is outside the acceptable range without BESS. The voltage ranges from a minimum of 0.915 pu to a maximum of 1.213 pu. However, integrating BESS in Case 2 has improved the overall voltage profile, resulting in a minimum voltage of 0.950 pu and a maximum of 1.032 pu.



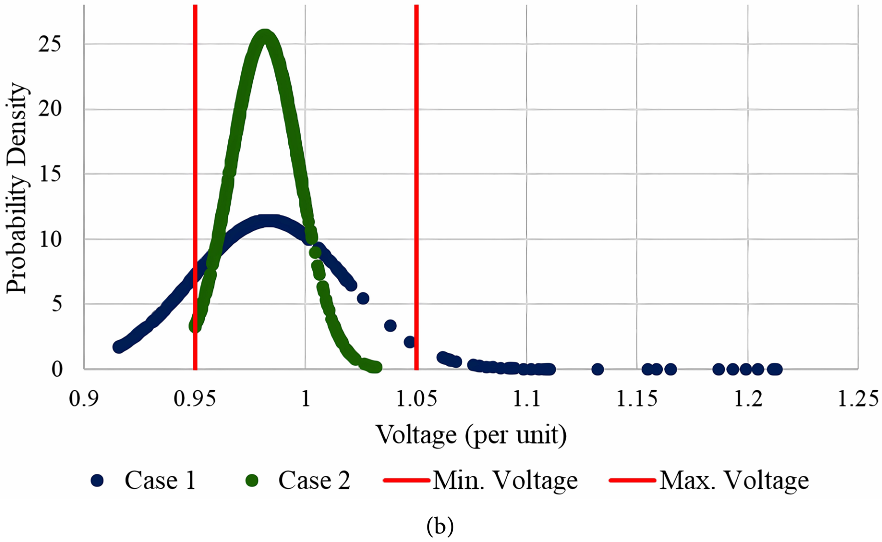


Figure 12. Distribution of bus voltage values (in p.u.) across the test system for each hour of the day of Case 1 and 2 with (a) 25% PV penetration and (b) 50% PV penetration.

### 3.4.3. Load Factor

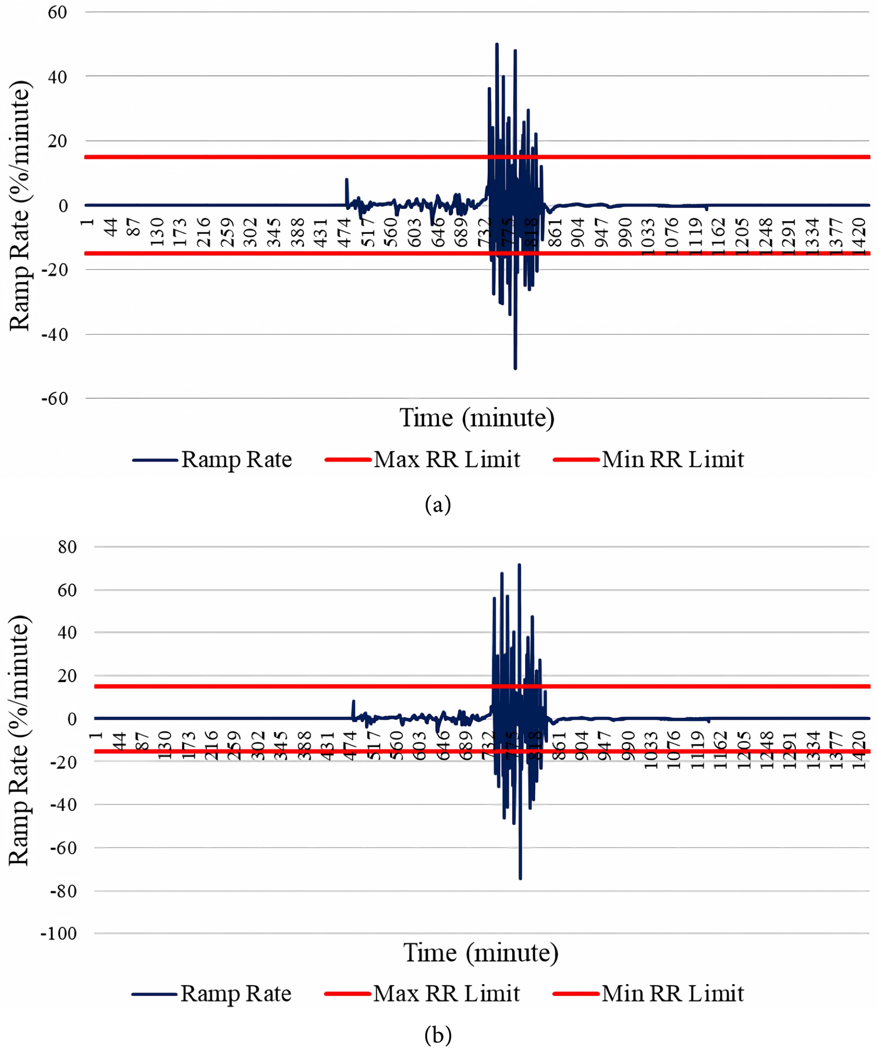
Table 3 shows the load factor for mixed load network with EV and different percentages of PV penetration. The result highlights that for both scenarios, implementing BESS with the proposed allocation strategy able to improve the load factor of the network.

**Table 3.** Load factor for all cases under 25% ad 50% PV penetration levels.

| Case | PV penetration level (%) | |
|---|---|---|
| | 25 | 50 |
| Base case | 0.58 | |
| Case 1 | 0.51 | 0.41 |
| Case 2 | 0.61 | 0.53 |

### 3.4.4. PV Ramp Rate

The PV ramp rate is experimented on two different penetration levels which are 25% and 50%. Figure 13(a) and Figure 13(b) show the PV ramp rate for the network with 25% and 50% PV penetration level respectively. There are two types of power fluctuations, upward fluctuation and downward fluctuation. From Figure 13(a), the maximum upward fluctuation is 50% while the maximum downward fluctuation is 50.7%. Meanwhile for the case with 50% PV penetration, the



(a)

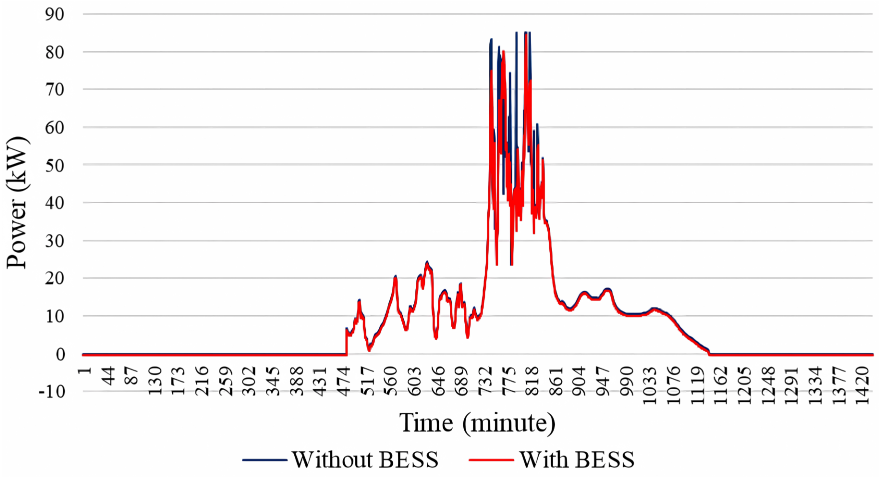
(b)

**Figure 13.** PV power fluctuation on (a) 25% PV penetration level and (b) 50% PV penetration level.

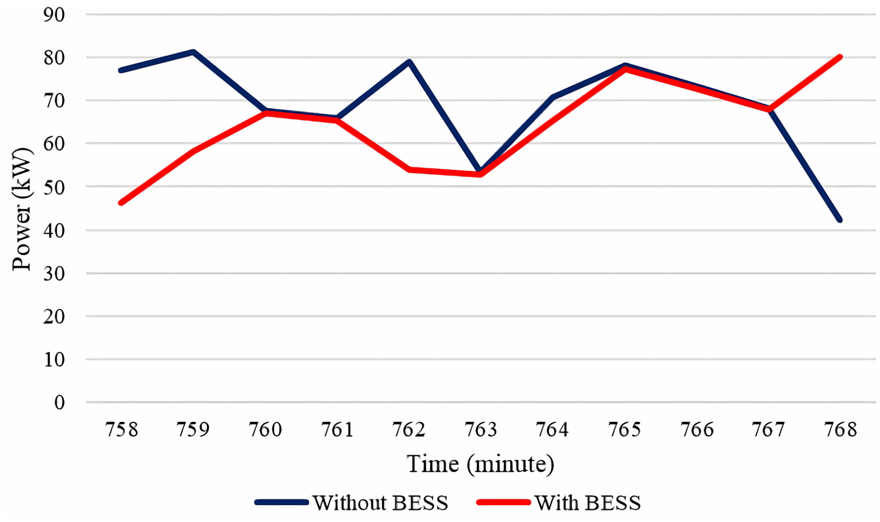
maximum upward fluctuation is 71.6% while the maximum downward fluctuation is 74.5%. This demonstrates that the greater the PV capacity, the higher the power fluctuation.

Figure 14(a) shows the difference between without and with BESS implementation on PV output power. The zoom in graph on Figure 14(b) shows that the output power has less power fluctuation with BESS than without BESS. Figure 14(c) shows that the BESS manages to improve the ramp rate to be within ±15%/minute. Meanwhile for 50% PV penetration level, Figure 15(a) compares the PV output power before and after BESS adoption. The zoom in graph in Figure 15(b) demonstrates that the output power fluctuates less with BESS than without BESS. Figure 15(c) demonstrates that the BESS improves the ramp rate to within ±15%/minute.

In this study, the PV ramp rate limit of ±15%/minute, commonly applied to transmission-level solar farms, was adopted as a conservative benchmark. While this value ensures a stringent requirement for grid stability, it is acknowledged



(a)



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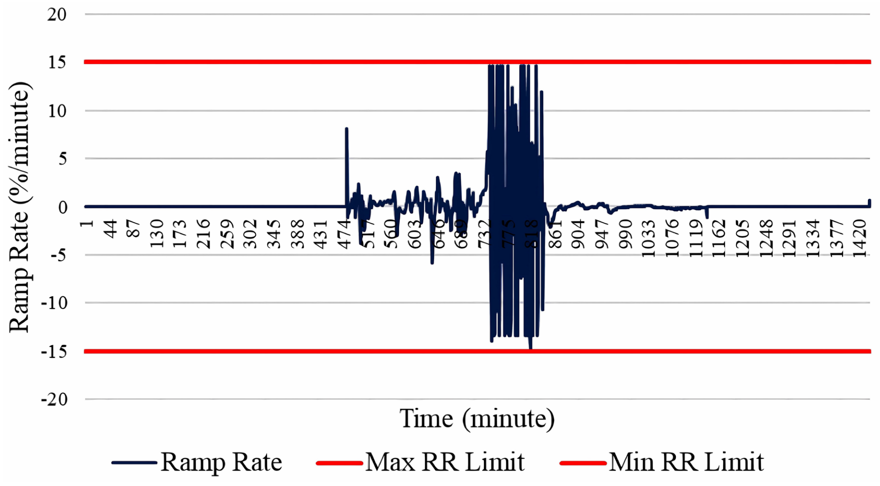
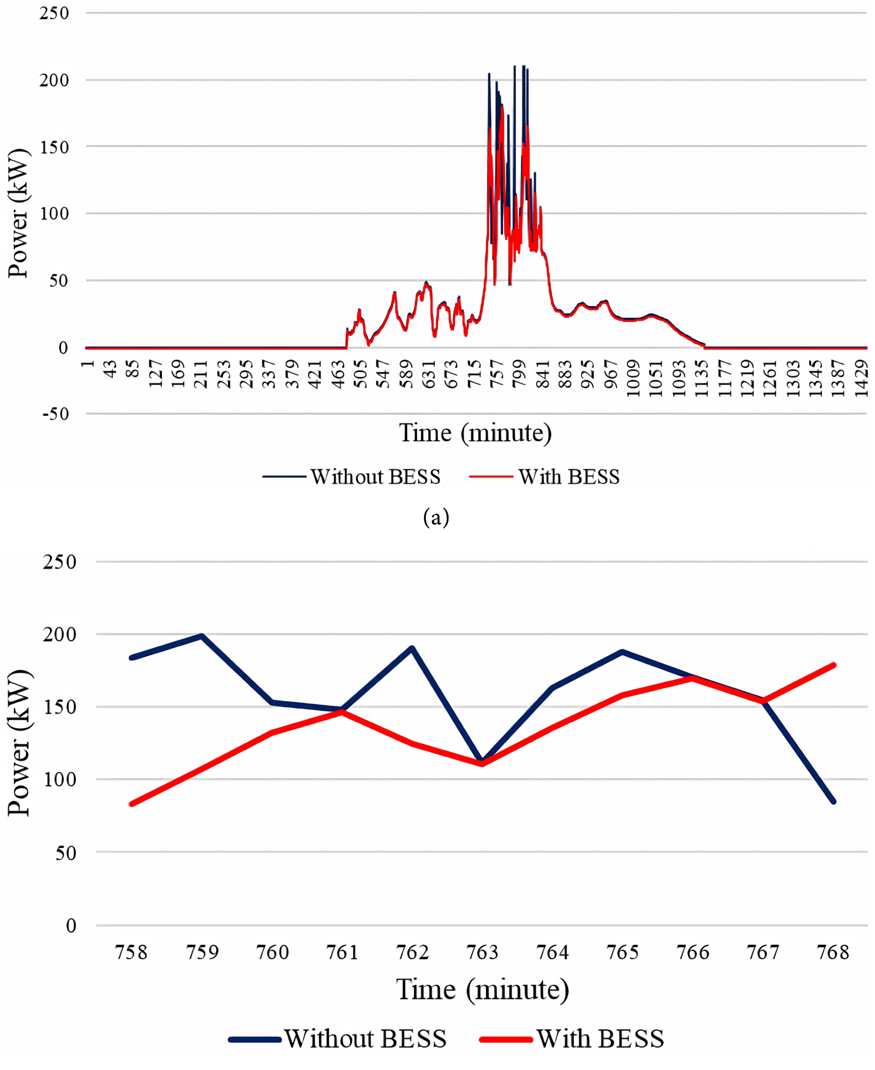


(c)

**Figure 14.** (a) PV power fluctuation, (b) Zoom in graph from 758th to 768th minute and (c) Ramp rate after BESS adoption for network with 25% PV penetration level.



(a)

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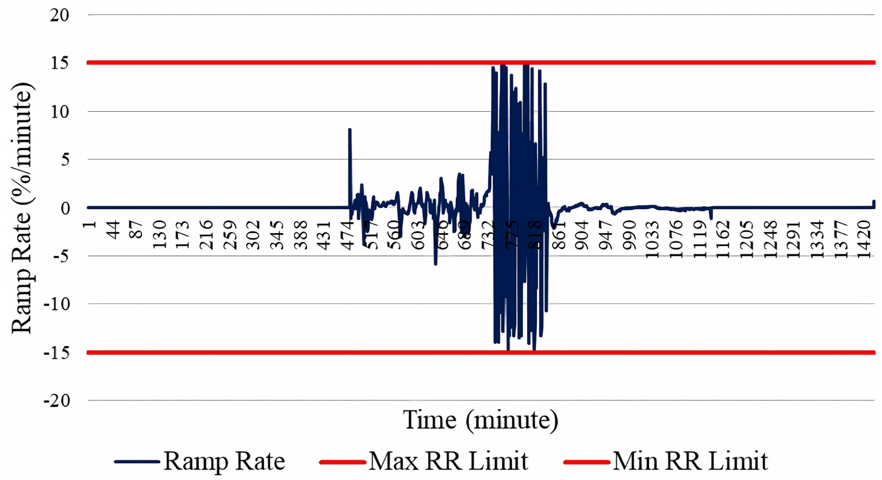

(c)

**Figure 15.** (a) PV power fluctuation, (b) Zoom in graph from 758th to 768th minute and (c) Ramp rate after BESS adoption for network with 50% PV penetration level.

that the required BESS size is sensitive to the ramp rate threshold. A tighter limit would increase the BESS capacity needed for smoothing, whereas a more relaxed limit would reduce the capacity requirement.

## 4. Conclusion

The modified IEEE 33-bus system is successfully modelled using OpenDSS with high PV and EV penetration. The PV penetration level of 25% and 50% is determined by taking the ratio of the energy of PV to the energy of load demand of Base Case. This aligns with the case of EV penetration level of 10%. After the integration of PV and EV chargers into the power system, the difference from the Base Case can be noticed in the increased peak demand and also the RPF. PV integration contributes to the RPF whereas EV integration triggers the load demand to increase. In accordance with that, the impact of PV and EV integration causes the power and voltage to fluctuate more as seen in voltage profile and PV ramp rate chapter. To overcome this issue, BESS is taken into action. With the suitable sizing, location and dispatch strategy of BESS, the RPF and the peak demand problems can be mitigated. The dispatch strategy of BESS is planned thoroughly using the related equations for the improvement of voltage profile, increased power demand and PV ramp rate. According to the result, BESS is able to improve voltage profile, reduce peak demand and reduce RPF simultaneously. BESS also plays a significant role in enhancing the PV ramp rate. As a result, the PV ramp rate is smoothened within the allowable limit of 15%/minute. The findings demonstrate that the proposed BESS allocation enhances distribution network performance under PV and EV integration. As EV charging model in this study is based on deterministic assumptions, future research could adopt stochastic or data-driven charging profiles to better reflect real EV scenarios. Beyond the technical benefits presented in the paper, the economic feasibility of BESS deployment remains a critical factor for practical implementation. Hence, incorporating cost–benefit analysis into future studies on BESS sizing and placement would provide valuable insights for real-world applications.

## Acknowledgements

This study is funded by Ministry of Higher Education (MOHE) of Malaysia through the Fundamental Research Grant Scheme (FRGS), No. FRGS/1/2023/TK07/UTEM/02/4. The authors also would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for all the supports.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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