Journal of Applied Technology and Innovation
Vol. 09, Issue 4, 2025, pp. 01-24
e-ISSN:2600-7304-ISSN
DOI: https://doi.org/10.65136/jati.v9i4.5

Mitigation Technique Using a Hybrid Energy Storage and Time of Use (TOU) Approach in Solar Grid Connection.

Alireza Maghoul [1], Mohammad Reza Maghami [2*], Elnaz Yaghoubi [3], Mehdi Soltanzadeh [4], Elahe Yaghoubi [3]

[1] Faculty of Art and Architecture, Azad University, Ghiamdasht, Tehran, Iran
[2] Institute for the Future of Knowledge, University of Johannesburg, South Africa
[3.] Département of Mechanical Engineering, Faculty of Engineering, Alzahra University, Dehvanak, Tehran, Iran
[4] Academy of Malay Studies, University of Malaya, Kuala Lumpur, Malaysia
*Corresponding Author: mrmohammad@uj.ac.za

Abstract

A power system can experience voltage failure if the voltage drops below a certain level, leading to equipment damage, power outages, and other issues. In the context of large-scale solar power systems, voltage failures can occur due to various factors, such as the intermittent nature of solar power generation and the variability of solar irradiance. This study investigates the impact of large-scale solar PV penetration on typical power systems in South Africa and proposes a novel hybrid mitigation technique using Time of Use (TOU) and Community Battery Energy Storage (CBES) to minimize lower limit voltage violation. The network considered in this study includes two parallel 132/11kV transformers, four feeders, and 81 loads connected to the 11kV busbar, with a 150kW solar PV added to every single node. Four case studies were conducted to compare impact of different the mitigation technique including: the base network without any mitigation, the network with TOU mitigation, the network with CBES mitigation, and the network with hybrid TOU and CBES mitigation. The location and size of the CBES were determined using the Power Factory Cbc algorithm to address weaknesses in the network. TOU was used for peak shifting, and different levels of TOU were applied. The results from Power Factory dynamic simulations show that both mitigation techniques applied to the network significantly reduce the lower limit voltage violation, but a few nodes still remain. In addition, the findings shows that the hybrid mitigation using TOU and CBES dramatically solves the voltage violation in the network and minimizes the loss of network as well as power from the grid.

Keywords: *Dynamic Simulation, Large-scale Solar, Demand Response, Energy Storage, TOU.*

1. Introduction

Voltage failure, In the realm of power systems, voltage failure, or voltage collapse, arises when the voltage levels drop below a specific threshold, leading to equipment damage, power outages, and other related issues(Jafarzadeh-Ghoushchi et al., 2017; Maghami, 2025). The intermittent nature of solar power generation in large-scale solar PV power systems can also result in voltage failure. With the growing number of solar PV systems integrated into power systems, voltage fluctuations may arise, ultimately leading to voltage failure. To mitigate the effects of voltage failure in large-scale solar PV power systems, various methods can be employed. (Mansouri et al., 2019). One commonly used technique is reactive power control, which involves adjusting the reactive power output of generators and compensating devices to regulate the voltage levels. Reactive power control can be achieved through the use of voltage regulators, capacitors, and other reactive power compensation devices. Another technique is voltage control, which involves adjusting the voltage set-points of generators and compensating devices to regulate the voltage levels.

Voltage control can be achieved through the use of automatic voltage regulators (AVRs) and other voltage control devices. Demand response is another technique that can be used to mitigate voltage failure. It involves reducing the load demand during periods of high solar power generation to balance the power supply and demand and maintain voltage stability. Demand response can be achieved through the use of TOU, where the load demand is controlled by switching off non-essential loads during periods of high solar power generation. Battery energy storage (BES) is another technique that can be used to mitigate voltage failure. BES involves storing excess solar power during periods of low load demand and releasing it during periods of high load demand to balance the power supply and demand and maintain voltage stability.

Several studies have been conducted to investigate the impact of large-scale solar PV penetration on power systems and to propose solutions to mitigate voltage failure. For instance, a study by (Li et al., 2023)proposed an adaptive voltage control strategy to maintain voltage stability in a power system with high solar PV penetration. The strategy involved adjusting the voltage set-points of the power system based on the solar irradiance forecast and the load demand forecast. Another study by (Ariyaratna et al., 2018)proposed a coordinated control strategy for a hybrid energy storage system and reactive power compensation devices to mitigate voltage fluctuations in a power system with high solar PV penetration. The strategy involved using the energy storage system to absorb excess solar power during high irradiance periods and release stored energy during low irradiance periods to maintain voltage stability. In a study (Nguyen-Duc et al., 2022)a hybrid mitigation technique using demand response and battery energy storage was proposed to mitigate voltage failure in a power system with high solar PV penetration. The technique involved using demand response to reduce the load demand during periods of high solar power generation and using battery energy storage to store excess solar power during periods of low load demand and release it during periods of high load demand(Maghami et al., 2023a).

Hybrid mitigation techniques, which combine multiple techniques such as demand response and BES, can also be used to mitigate voltage failure in large-scale solar PV power systems. These techniques involve integrating different mitigation strategies to achieve optimal voltage stability and reliability. For example, a hybrid mitigation technique involving the use of reactive power control and BES can be used to mitigate voltage fluctuations in power systems with high PV penetration. This technique involves using reactive power control to regulate the voltage levels and using BES to store excess PV energy during periods of low load demand and release it during periods of high load demand. In a study (Zhang et al., 2019), a hybrid mitigation technique was proposed for voltage regulation in a power system with high PV penetration. The technique involved using a combination of reactive power control, BES, and demand response to maintain voltage stability and avoid voltage collapse. The study demonstrated that the hybrid mitigation technique was effective in reducing voltage fluctuations and maintaining voltage stability in the power system. In another study by (El-Bahay et al., 2023)a hybrid mitigation technique was proposed for frequency regulation in a power system with high PV penetration. The technique involved using a combination of BES and demand response to balance the power supply and demand and maintain frequency stability. The study demonstrated that the hybrid mitigation technique was effective in reducing frequency deviations and maintaining frequency stability in the power system. Table 1. aim is to review the recent mitigation technique in field of solar PV penetration.

Table 1. Overview of recent study on solar PV penetration and mitigation technique

Ref	**Method**	**Voltage Level**	**PV P**	**Simulation**	**Result**
(Almeida et al., 2020)	Volt/Var control	11kV/400V	2-7kWh	OPENDSS-	Voltage violations are not observed up to 80% PVP level without any voltage control. At 100%, 120%, & 140% of PVP levels, voltage violations were

					recorded for 2, 44, and 68 nodes, respectively.
(Nousdilis et al., 2018)	Active power management, BESS,	11kV/400V	7.5-10kWh	IEEE European LV Test -OPENDSS-	PVP with high self-consumption causes less impact on the feeder; conversely, prosumers with low self-consumption need to contribute to the proposed power management scheme to a larger extent.
(Rasheed et al., 2020)	Active power control	132kV	2MGW	IEEE 13& 14 Digsilent	The optimal location, optimal size, and proper power factor for PVP can considerably reduce the system's power losses while enhancing the voltage profile.
(Tantrapon et al., 2020)	BESS Active & Reactive	22kV	3.5MGW	PSO-Matlab-Digsilent	Results demonstrate that the BESS with the PSO is efficient in controlling the microgrid voltage fluctuation
(Ramli et al., 2021)	BESS	400V	20kW	Matlab/Simulink	When the PVP is high, the voltage rises from 1.11 p.u. to 1.13 p.u., but the BESS can keep the voltage at an acceptable level of 1.01 p.u,
(Raval & Pandya, 2021)	Load Shifting Strategy(PSS)	400V	5kW Roof top	IEEE 906 EU Network OPENDSS	The result from three scenarios, including Network with/without PVP and Network with PSS, shows and indicates that the voltage violation in the Network with PV/PSS in minimized.
(Atmaja & Putranto, 2021)	BESS	11kV	100KW	IEEE 123 MATLAB	The result shows that there are buses that are voltage violated, which BESS injected to that particular place to minimize violation.
(Sanni et al., 2020)	APC & RPC	11KV	15kW	IEEE 30BUS 284 MW & 127 MVAr.	Three different techniques were determined, including RPC (Suitable for Low PV), Power factor control(Medium PV), and APC (High PV)
(Shi et al., 2020)	volt-var	11kV	2990kW	IEEE 33BUS MATLAB Peak Load is 3715kW	Three cases were designed: No PVP, PVP, and PV and volt-var control. The result shows the number of power losses and voltage among different case studies. Vol-var has better performance. Power loss can be reduced using Volt-VAR regulation. 12-1 pm by 10%.
(Vergara et al., 2020)	APC RPC-APC	11kV/400V	20kWp Rooftop	Open DSS IEEE European Ave Load =3381kWh	The impact of curtained energy on annual energy bills is 372 % and 105 % for Scenario 2 and Scenario 3, respectively. Case 3 has a better performance by reducing SAB up to 37%.
(Ciocia et al., 2020)	PV & OLTC	20kV/400V	75KW	IEEE LV MATLAB 22NODE	Due to PV converter reactive power injection, Thelosses rise from about 20 percent rise. With OLTC, PV converter losses remain significant, with low fluctuation. Regarding the voltage profile, Installing an OLTC improves the voltage profile compared to using only PV converters(21% improvement)

One significant gap in this research is the lack of adequate assessment techniques for large-scale photovoltaic (PV) systems that are dispersed over a wide area. Although much research has been done on assessing single-point PV systems, larger systems with multiple PV units spread over a large area have not been studied as extensively as systems with several PV units dispersed over a small space. Additionally, there has been limited research into integrating PV systems with high grid penetration, making it challenging to plan the distribution network when PV systems become widespread. Battery storage is one solution to this problem, but there is a lack of studies on the optimal sizing and placement of battery storage systems for large-scale solar PV integration. Additionally, there is a need for studies on the integration of battery storage with demand response to achieve optimal load balancing and peak shaving. Another gap in this research is that most references refer to loads and PV systems as PQ nodes without considering that they are time-varying systems that interact continuously with each other and the grid. In reality, the power consumed by a load depends on the voltage level applied to the connected bus bar, making calculated results incomplete. Demand Response Program (DR) is another mitigation technique that has recently gained attention from many researchers. However, few studies have considered hybrid DR programs and other mitigation techniques.

This paper employs a novel hybrid mitigation technique using CBES and DR to improve the voltage profile of the network. This study identifies technical barriers related to high penetration PV scenarios in order to facilitate integrating PV into the grid and securing it against failure. Figure 1 shows the single-line diagram of the proposed network for 132/11 kV voltage transmission using Power Factory. We performed dynamic power flow simulation based on two worst-case scenarios: no load and peak load, in order to identify weak points in the network. This study aimed to achieve the following objectives:

(i) To examine the voltage failure analysis, power loss, and grid power based on both worst-case scenarios (no-load and peak load) using Powe Factory dynamic simulation.
(ii) To find the best placements as capacity of CBES on the network to mitigate voltage failure.
(iii) To Investigate the impact of TOU mitigation during peak load on network.
(iv) To investigate the hybrid mitigation technique using TOU and CBES on power network.

2. Methods

The methodology of the study is divided into four sections: network topology and data, PV penetration modeling and analysis, hybrid mitigation techniques, and evaluation. The study collected network data, such as transformer rates, line information, bus information, and solar irradiation, from the power supply company. Dynamic analysis techniques, such as voltage profiles, power loss, and transformer loading, were employed in the network evaluation phase to identify areas vulnerable to voltage failure. Once vulnerable areas were identified, the Cbc algorithm was used to find the best placements and capacity of CBES. It will be combined with TOU strategy to improve voltage stability. Following Table 2, four case studies were determined to compare the results of each. Case Study 1 is without any mitigation. However, in Case Study 2 and 3, two mitigation techniques were separately integrated with the network to overcome the voltage failure. In Case Study 4, a hybrid mitigation technique using CBES and TOU was applied to the network and the results were reported. The following steps provide a detailed outline of the methodology:

- Data collection on the grid and solar systems, including load demand, PV output, and single-line diagrams.
- Calculating power flow in a time-series framework: Power flow after adding 150 kW to every single node will be calculated every minute to produce results using Quasi-Dynamic simulation.
- Overvoltage limits: If overvoltage limits are violated, it indicates that PVP has reached its maximum.
- Identification of the node with the highest voltage: Overvoltage violations are reported from the node/bus with the highest voltage.
- Integrating TOU to mitigate the voltage failed over the solar PV penetration.
- Running Cbc algorithm to find the most appropriate CBES size and location.
- Integrating two mitigation techniques including CBES and TOU to overcome the voltage failure.

Table 2. Case study definitions

Case Studies	Without mitigation	TOU Mitigation	CBES Mitigation	Hybrid Mitigation
Case 1	X			
Case 2	X	X		
Case 3	X		X	
Case 4	X	X	X	X

Network Topology Description

The smart grid has grown in South Africa, and the government plans to increase distributed generation (DG) to the grid in the next decade. Figure 1 shows the single-line diagram of a typical South African MV distribution network integrated with solar PV. The network is connected to two 132/11kV, 30MVA transformers that are parallel connected to the an 11kV busbar. Four feeders are used to service the 81 nodes on the 11kV bus. Table 3 shows the total loads for all four feeders. The 11kV bus bar has a total load of 20892MVA, of which 13929MW are active loads, and 6963MVAR are reactive loads.

Table 3: Load specification among feeders

Lines	Active	Reactive	Bus No
Trans			1
Feeder 1	5976	2988	2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
Feeder 2	2362	1180	27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43
Feeder 3	2024	1012	44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63
Feeder 4	3567	1783	64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81
Total	13929	6963	81 Bus

Dynamic Power Flow Analysis

According to the South Africa distribution code, V_{min} and V_{max} equal 0.95p.u and 1.05p.u, respectively. The amount of power lost depends on the current flow through the lines and its line resistance. Solar PVP will decrease the amount of current flowing through the lines, reducing network losses and conventional generation currents. When solar PV penetration rises to a certain level, the real power loss increases as the current generated by solar PV reverses flow into the system. PV generation and load profiles are analyzed dynamically to take into account real-time variations. Following the designed case study in the previous section, the impact of solar PV penetration has been examined under both worst-case conditions. Nodes are examined for voltage profiles at different levels of solar PVP to ensure that statutory voltage limits of ±5% are met. Low voltage conditions may result in equipment malfunctions, such as motor stalling or generating units tripping. In contrast, high voltage situations may damage major equipment, cause insulation failure, or trip major transmission lines. As a part of this study, a distribution network was examined at various levels of solar during peak load to identify voltage limit violations that occurred during the integration of high solar PVP. Appendix A shows the load flow DPL code where was used to calculate network the simulation.

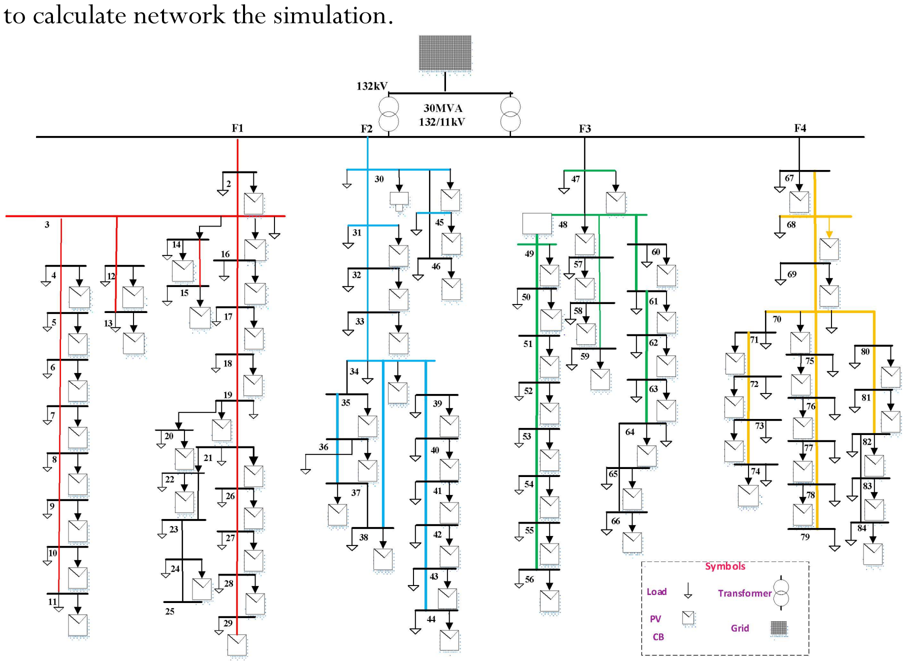


Figure 1. Typical MV network consist of 81 nodes across 4 feeders connected to 11kV bus bar through two 132/11kV, 30MVA transformers connected in parallel.

Network Mathematical Modeling and Mitigation

Kirchhoff's equations (Equations 1-3) describe the voltage at the beginning and end points of a 2-busbar network. In these equations, V_{PCC} represents the voltage at the connection point, I denotes the current flowing through the lines, V_G refers to the voltage of the transformer, and RL+jXL represents the impedance of the lines. S denotes the apparent power flowing from the grid network to the busbars, S_{PV} represents the apparent power generated by the solar system, and S_{LD} represents the power being consumed by the load. If the amount of power generated by the solar system at the PCC exceeds the consumption load, the excess power will be fed into the grid. However, if the PV power generation is lowered below the consumption load, the PCC will provide power to the load(See figure 2).

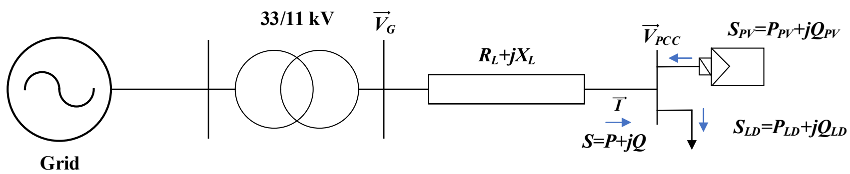


Figure 2, 2 busbars network system model

$$S = VI^* \tag{1}$$

$$\vec{I} = \frac{P - jQ}{\vec{V}_{PCC}^*} \tag{2}$$

$$\vec{V}_G = \vec{V}_{PCC} + \vec{I}(R_L + \mathrm{j}X_L) \tag{3}$$

$$\vec{V}_{PCC} = \vec{V}_G - \left[\frac{PR_L + QX_L}{\vec{V}_{PCC}^*} - j\,\frac{R_L Q - PX_L}{\vec{V}_{PCC}^*}\right] \tag{4}$$

The power flow at the point of connection (PCC) is described by Equation (4). Based on active and reactive power, we can get this power flow (Equation (5).

$$\vec{V}_{PCC} = \vec{V}_G - \left[\frac{(P_{LD} - P_{PV})R_L + (Q_{LD} - Q_{PV})X_L}{\vec{V}_{PCC}^*}\right] \tag{5}$$

PV Penetration (PVP) Level

The PVP rate is the ratio between the total coupled PV capacity and the permitted maximum PV capacity. To evaluate the efficiency of a PV system, its energy levels are measured by determining the percentage of the highest possible energy output that the system can generate at different stages of operation. Based on the Digsilent power factory simulation software, Figure 1 shows a model of the MV distribution network from the substation to the node. As part of this study, a distribution network was tested under two worse conditions under various levels of solar power (PVP): low (50kW), medium (100kW), and high (150kW). According to Eskom's electric utility standards, a statutory tolerance limit for voltage variations in the distribution networks should be in the range of +5% and -5%. Based on the grid voltage limits imposed on the grid, PVP levels are determined. In addition, the maximum PVP level was also examined from a voltage failure perspective to evaluate the potential PV generations. Appendix B shows the Solar PV Specifications where use for the current study such as solar module power, Vsc, Short Circuit Current and etc. The PV generation can be calculated by Eq:

$$P_{pv}(t) = R_{pv} D_{pv} \left(\frac{G_T(t)}{G_{T,STC}}\right) [1 + \alpha_p \left(T_{cell}(t) - T_{cell,STC}\right) \tag{6}$$

Where $P_{pv}(t)$ is the output power of the PV penetration during hour *t* of the year , R_{pv} donates rated capacity (kW), D_{pv} is the PV derating factor (%), G_T refer to incident solar radiation (kW/m^2), $G_{T,STC}$equal to incident radiation in STC (standard test conditions), $\alpha_p$is power temperature coefficient (%/˚C), and T_{cell} and $T_{cell,STC}$ are the cell temperature (˚C) at operating and STC condition, respectively.

Mitigation Technique

Two mitigation techniques were applied to this network to minimize voltage failure during two worst-case scenarios (peak load and no-load conditions). CBES was used to store surplus power generation, and TOU was used to shift load demand. In Power Factory, the Cbc algorithm can be applied to perform parameter tuning and optimization in power system studies. This involves defining the problem objective and constraints, selecting the variables to be optimized, and setting up the Cbc parameters such as voltage limit, minimum and maximum number of storage units, minimum and maximum battery capacity, and time sweep. The solutions are evaluated using the objective function and constraints, and the best solutions are selected for the next generation. This process is repeated until a satisfactory solution is obtained. In the following, we will discuss the details of these two mitigation techniques and the Cbc algorithm.

CBES Integration Strategy

CBES charging and discharging depends on the topology of network as well as size and location. This network has 81 nodes and the location of CBES should be determined to minimize the voltage failure. Appendix C shows the CBES specification and charging and discharging DPL code. Several factors determine the battery's state of charge (SOC) at any particular time of day, including:

$$SOC_{(t)} = SOC_{(0)} + \eta_c * \sum_{k=0}^{t} P_{CB}\,(k) + \eta_d \sum_{k=0}^{t} P_{DB}\,(K) \qquad (7)$$

Where, $SOC_{(0)}$ refer to the Batteries state of charge of the battery, P_{CB} represents the charging rate of the battery, P_{DB} reparent the discharge rate, η_c and η_d are referred to the charging and discharge efficiencies of the battery, respectively. The constraints for the available battery capacity are given by:

$$\begin{aligned} B_{min} &\le SOC \le B_{max} \\ B_{min} &= (1 - DOD)B_{max} \end{aligned} \qquad (8)$$

B_{min} and B_{max} are the battery's minimum and maximum capacities, and DOD is the depth of discharge. Batteries can discharge their power only if they meet the following conditions:

$$0 \le P_{DB}(K) \le P_{max} \qquad (9)$$

In this case, Pmax represents the maximum hourly discharging power that can be achieved. Optimum equipment location is selected in PF to be determined using Cbc algorithm through the Power Factory. Figure 4 shows the algorithm flow chart to find the optimum CBES placments to mitigate the network's lower limit voltage violation by minimizing nodes voltage deviation and power losses:

A: Minimizing Power losses

$$F_1 = Min\ Ploss = min\left\{\sum_{j=1}^{N_n-1}\left(\frac{P_j^h + Q_j^h}{Vj^h} \times r_{j,j+1}\right)\right. \qquad (10)$$

Where the P_j^h, Q_j^h, Vj^h *and* $r_{j,j+1}$ are representing active and reactive power, voltage magnitude and angel at i^{th} node in h^{th} hour and resistance of branch connecting nodes *i* and *j* respectively.

B: Minimizing of node voltage deviation

$$F_2 = Min\,Voltage\,Deviation = 1 + \{\textstyle\sum_t \left|(V^{traget} - V_1^h)\right| \quad (11)$$

Where V^{traget} refer to the substation voltage(p.u). Subjected to the following constraints

$$P_{PV}^h \mp P_{dis}^h/P_{ch}^h - P_{Load}^h = V_j^h \textstyle\sum_{j=1}^N V_j^h \cos\theta_{ij} + \delta_j^h - \delta_i^h \quad (12)$$

$$0 - Q_{load}^h = -V_i^h \textstyle\sum_{j=1}^N V_j^h \sin\theta_{ij} + \delta_j^h - \delta_i^h \quad (13)$$

Subject to constraint

$$V_{min} \le \left|V_j\right| \le V_{max}, \forall\, j\, \in\, B, \quad (14)$$

Where I_b is the current flowing through line b and I^{rated} is its rated current b .

$$I_{ij}^h \le I_{ij}^{Max};\ \forall i,j\ \in {}'\Omega, h \in T \quad (15)$$

$$0 \le P_{PV} \le P_{PV}^{Max}; \forall i\ \in {}'\Omega \quad (16)$$

$$0 \le P_{CBES} \le P_{CBES}^{Max}; \forall i\ \in {}'\Omega \quad (10)$$

$$P_{CBES}^{min} \le P_{ch/dis}^h \le P_{CBES}^{max};\ \forall i,j\ \in {}'\Omega, h \in T \quad (17)$$

$$SOC_{min} \le SOC_i^h \le SOC_{max};\ \forall i,j\ \in {}'\Omega, h \in T \quad (18)$$

$$SOC_i^h = SOC_i^{h-1} + \left\{\frac{\eta_c P_{ch}^h}{P_{CBES}^R} - \frac{P_{dic}^h}{\eta_d P_{CBES}^R}\right\};\ \forall i,j\ \in {}'\Omega, h \in T \quad (19)$$

Where eq 10 and 11 are the power balance, Eq 13,14 refers to the PV and CBES generation limits. CBES Charging and discharging using the Eq 1,2 and SOC represented by Eq 16 and 17. P_{CBES}^R , P_{PV}^{Max} , P_{CBES}^{max} are represents Power dispatch of CBES and Maximum PV generation, and CBES, Respectively.

Battery Frame Control in Power Factory

Before a controller can be implemented, it is important to understand the task of the controller. In the case of a battery energy storage system (BESS) with an IGBT-based converter, there are two current parameters to control: one in the d-axis and one in the q-axis. The PI controller will receive feedback from the BESS current and voltage, and use this feedback to adjust the output of the BESS converter. The goal of the PI controller is to keep the output power of the BESS within a predetermined range. Figure 3, shows the general BESS frame control in PF and each box has it own responsibility which is added in appendix F. To control active power, the PI controller will be set to track a reference signal for the real power output of the BESS. The reference signal can be set to a constant value, or it can be varied to simulate changes in load demand. To control voltage, the PI controller will be set to track a reference signal for the reactive power output of the BESS. The reference signal can be set to a constant value, or it can be varied to simulate changes in voltage imbalance. The BESS frame control in PF can be used to control both the real and reactive power output of the BESS. It can also be used to optimize the operation of the grid, such as by reducing the amount of energy that is wasted. The details of each frame were added in appendix F. The frequency control is deactivated as far as it is not in scope of this study.

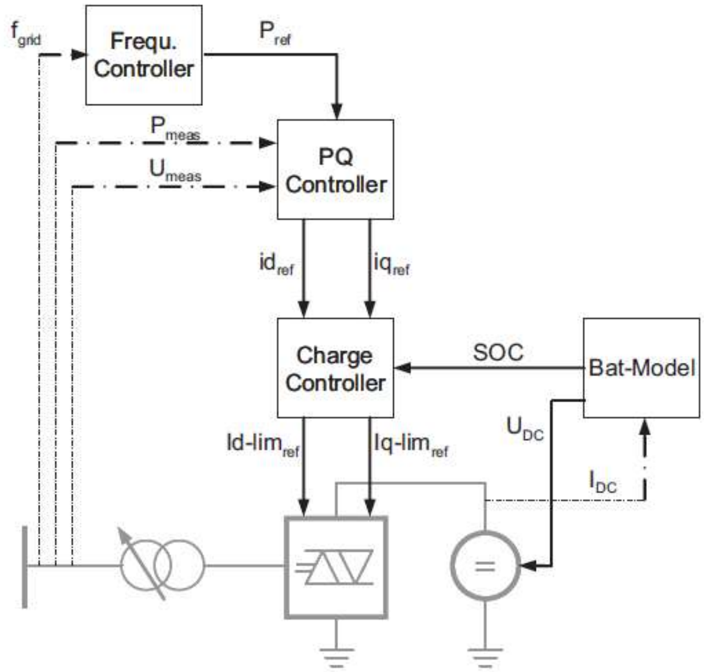


Figure 3, The frame control of CBES

TOU Integration Strategy

TOU is a valuable tool that can be used to mitigate the impact of solar grid connection. By reducing peak demand, regulating voltage levels, and providing spinning reserve, it can help to improve the overall performance of the grid and ensure that it is able to safely and reliably integrate increasing amounts of solar generation. TOU can be used in conjunction with other mitigation techniques, such as BES, to improve the overall performance of the grid and mitigate the impact of solar grid connection. In this study, TOU was applied to the network with different levels from 10% to 30% load reduction. Figure 4 shows the TOU program, which was applied only during the second peak load for 3 hours from 6pm to 9pm. The TOU increased during the peak load to evaluate the minimum TOU requirement to overcome the voltage mitigation.

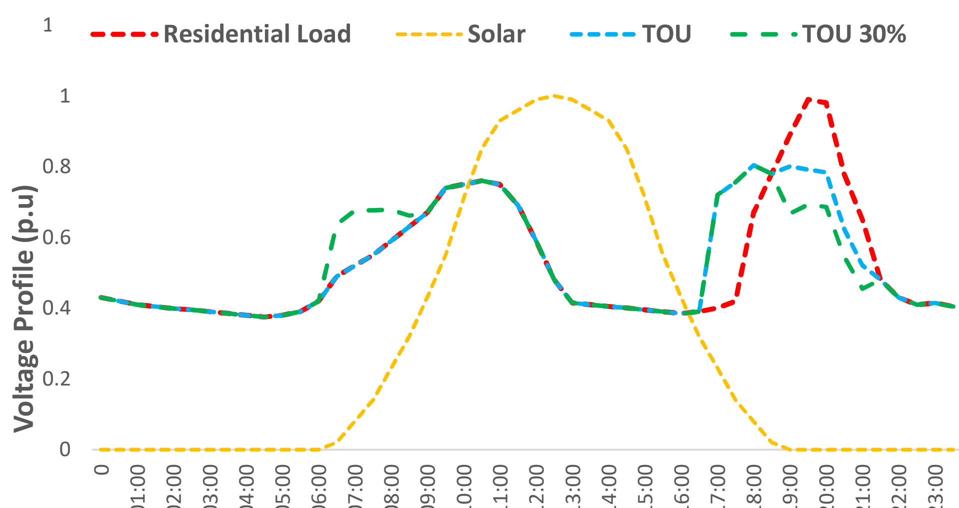


Figure 4. Different level of TOU applied on the network during the second peak load. including 10% and 30%.

Hybrid mitigation techniques

The third step was to develop hybrid mitigation techniques to address the challenges of high PV penetration. These techniques included TOU and CBES. The hybrid mitigation techniques were designed to ensure the stability and reliability of the power grid even with high levels of PV penetration. Figure 5 shows the strategy of hybrid mitigation technique using TOU and CBES to control voltage failure in the system for pre-contingency. As shown in the figure, there is a gap between the load profile and solar irradiation, which is shown by orange color in the figure. This is the peak sun hours and the best time to store and employ the CBES system and to use it during the two peak loads. There have been many studies conducted in the past about mitigation, but only a few studies have been conducted that combine battery and demand response programs. Additionally, these studies have only considered solar PV for single point connection.

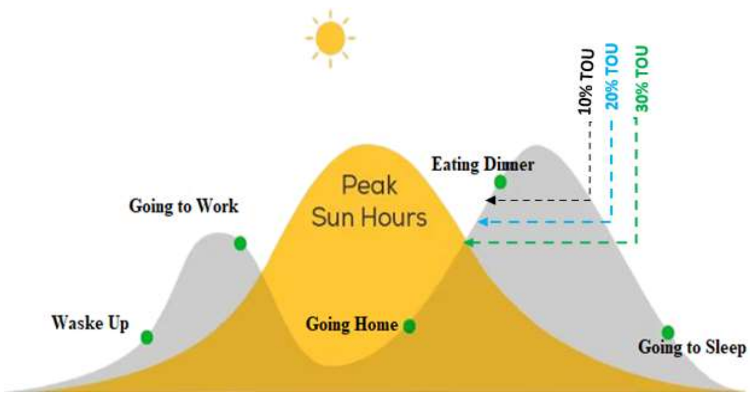


Figure 5. Hybrid mitigation technique using TOU and CBES to solve the lower voltage limit

3. Result and Discussion

This section discusses the findings based on the research objective and shows the dynamic simulation of PV grid connection and possible solutions using energy storage and demand response for a typical network in South Africa. This section is divided into three sections. The first section shows the impact of solar PV penetration without any mitigation at different PV penetration levels and identifies weak areas in the network. In the second step, the location and sizing of the CBES are determined to store surplus power generation from the solar system during the day and inject it into the grid during peak times. In the last section, TOU (demand response) is integrated with the CBES to optimize system mitigations. Figure 6 shows the load demand profile as well as solar PV generation during a day. Two areas are very important and need to consider, firstly the surplus power generation area, where the load is lower than PV generation and can be stored. Secondly the load demand area, where the load demand is peak and it is the place to apply demand response program to minimize the voltage violations. In this grid, each busbar has a different size and characteristics, which is reported in table 2. In the following part, the result from the impact of Battery energy storage and Demand response on voltage profile as well as transformer loading will be investigated. At the end, the hybrid mitigation using BES and DR will be used and the result will be discussed.

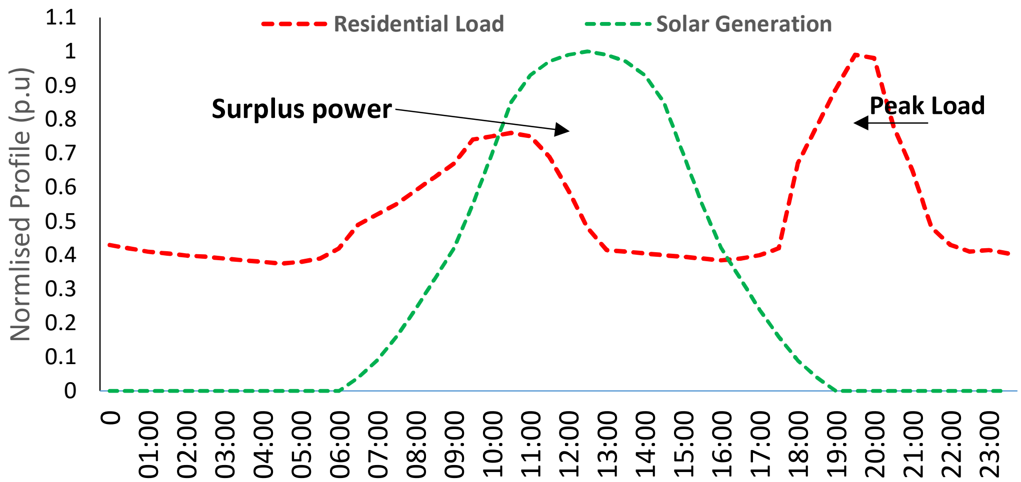
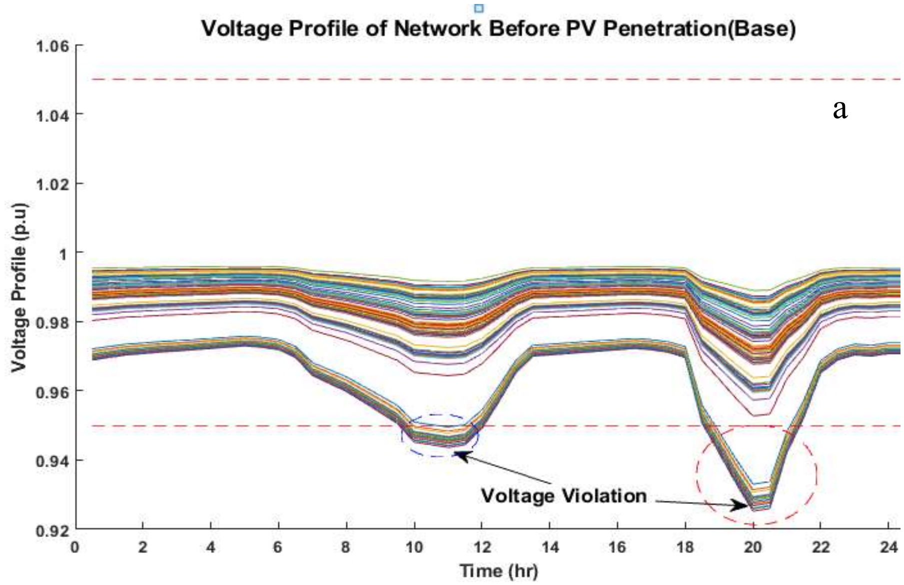


Figure 6. Normalized profile of residential and solar generation

As shown in Figure 7(a), the voltage profile of the network before PV penetration into the grid. It is observed that the network violated twice: first, in the morning from 10am to 12pm, and second, at night from 6:30pm to 9pm. Solar PV penetration is intended to be integrated into the network to improve the voltage profile. In this study, 150kW of solar PV was added to every single node of the network. Different PV penetration levels were applied to the network to find the optimum size of PV penetration during no-load and peak load conditions, based on previous research calculations (Maghami et al., 2023b). Figure 7(b) shows the voltage profile of all the nodes with 150kW solar PV penetration. It is clear that during the day, the voltage profile rises up to 1.03 p.u., and during the night, from 6:30 PM to 9 PM, the network experiences a lower limit violation. By comparing this figure with Figure 6(a), it is clear that the morning voltage violation is overcome due to solar generation, but the violation at night still remains. To solve these challenges, we need to shift the surplus power generation from the solar system to the time with peak demand. Appendix D shows the heatmap of the network before and after the mitigation technique.



.

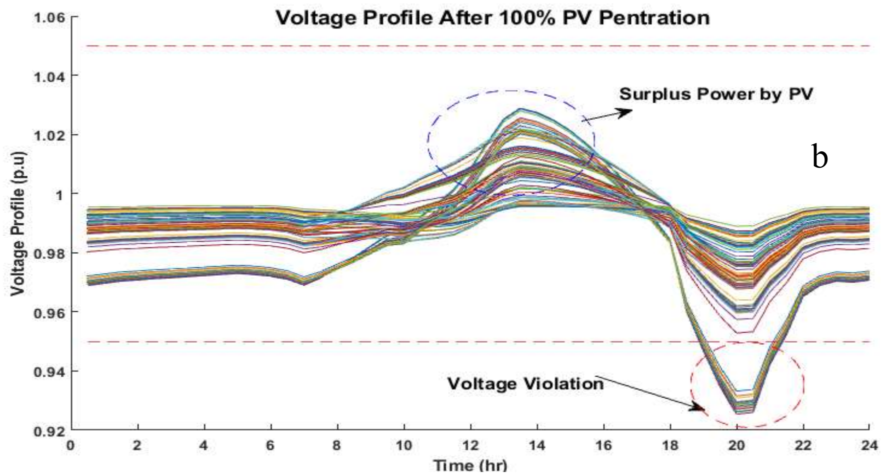


Figure 7. Voltage profile for all the nods before PV penetration (a) and after that (b).

Increasing solar PV penetration can increase power loss in the system. Figure 8 shows that feeder 4 experiences the highest power losses in the network. This is because it has a large number of nodes and is a longer feeder than the others. The figure also shows the accumulated power loss of the network by time per feeder, which was calculated based on Equation 10. The peak power losses occur between 7 and 8 PM, with 300 kW of loss. This is followed by a peak in the morning between 11 and 12 AM, with an accumulated power loss of 180 kW. Feeder 4 is shown in yellow color, and the highest number of losses occur during the second peak load. There are a number of things that can be done to reduce power losses in feeder 4. One option is to upgrade the feeder to thicker wires. This would reduce the resistance in the wires and therefore the amount of power that is lost. Another option is to install energy storage at the substation that feeds feeder 4. This would allow excess solar PV generation to be stored and used later, when demand is higher. Finally, demand-side management programs can be used to encourage customers to shift their energy usage to times when the network is less congested.

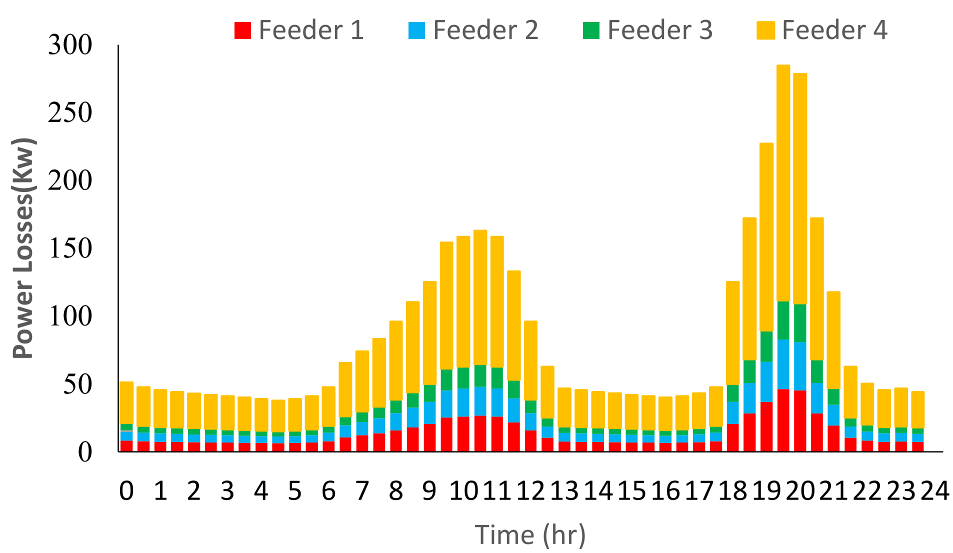


Figure 8. Accumulated power losses among different feeders

The transformer loading is dependent on the load demand. Figure 9 displays the transformer loading before and after PV penetration into the grid. It is observed that in the base network without PV penetration, the transformer loading reaches a maximum of 33% in the morning around 11:30 AM and

41% at night around 8 PM. The transformer loading after 100% PV penetration is also displayed in green color. It is clear that during the day, when the sun is up, the generation rises and reduces the transformer loading. In other words, the network is using solar generation rather than getting power from the upper grid. However, as the figure shows, the maximum amount of loading still occurs at 8 PM. This is because even though there is more solar generation during the day, the load demand is also higher during this time. As a result, the transformer loading can still reach high levels, even with PV penetration.

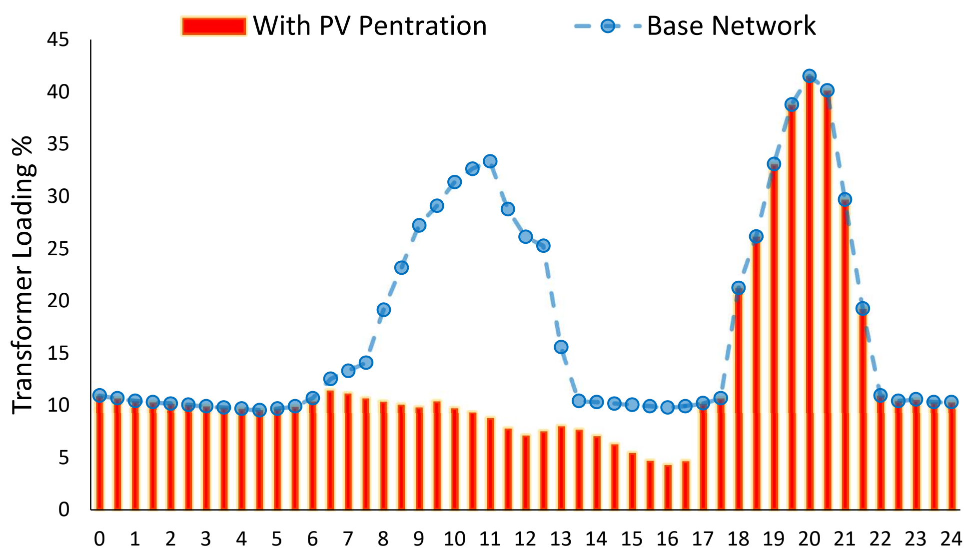


Figure 9. Transformer Loading before and after PV penetration into grid

The first mitigation technique used in this study was to integrate a DR program with solar PV penetration to overcome the voltage violation that occurred during the night for the network. As discussed in the last section, DR is a way to request customers to reduce their load demand during peak load. In this section, the impact of different levels of DR (5%, 10%, 20%, 30%, and 40%) were reported in the following table and compared. The solar PV penetration level was divided into 4 levels (0, 50, 100, and 150 kW). Based on the voltage profile in Table 4, the minimum DR program required to overcome the lower limit voltage violation is 30%, with a minimum of 50 kW of PV penetration. It also shows that increasing the DR program will lead to reducing the PV penetration level. The results from this network show that with a 40% DR program, even without PV penetration, the voltage violation can be overcome.

Table 4, Comparing the TOU integration with different PV penetration level.

PV Penetrations	TOU 5%	TOU10%	TOU 20%	TOU30%	TOU40%
150 kW	Violation	Violation	Violation	No Violation	No Violation
100kW	Violation	Violation	Violation	Violation	No Violation
50kW	Violation	Violation	Violation	Violation	No Violation
0kW	Violation	Violation	Violation	Violation	Violation

The following figure shows mitigation techniques using TOU and CBES. Figure 10(a) shows the voltage profile of the network after 30% TOU. It is observed that TOU alone, in combination with PV penetration, can almost mitigate voltage violations. However, the graph also shows that even after 30% TOU, the network touches the lower limit value between 7:30 PM and 8:30 PM and only few node violate. To overcome this issue, one way is to increase the TOU program to 35%, or to integrate energy storage to mitigate any violation. Figure 10(b) shows the CBES which is applied to the network during

100% PV penetration level. In addition, the graph clearly shows that during the morning, when PV generates power, there is excess power generation in the grid. This surplus power generation can be stored and injected into the grid during peak times, not only reducing the need for TOU programs, but also improving voltage stability. However, the network faces with violation again during the night. To overcome this issue with CBES integration, one way is to increase the CBES capacity, which would increase the cost of the system. Another way is to combine it with TOU program.

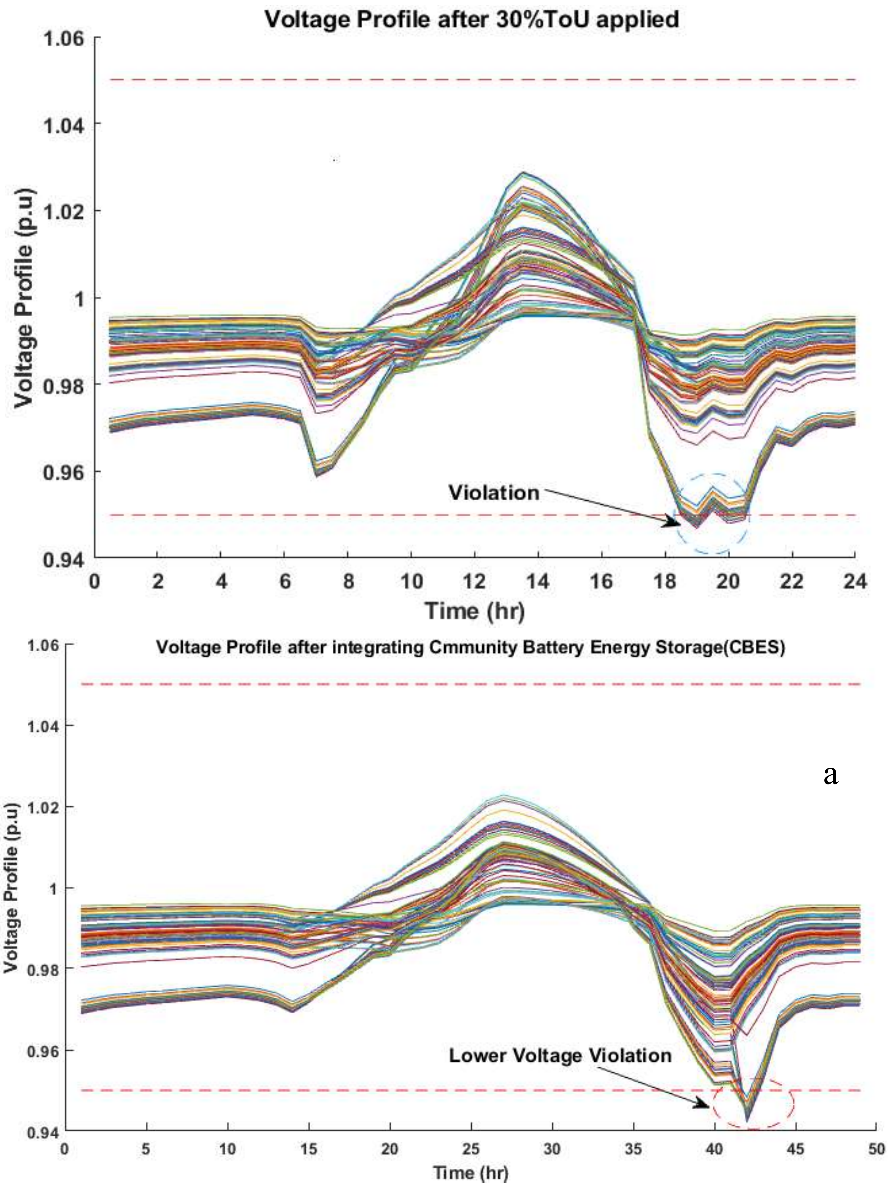


Figure 10. Mitigation technique using TOU program (a) and CBES (b)

Based on Equations 10 and 11, a multi-objective optimization problem was formulated using the Cbc algorithm to determine the optimal placement and capacity of CBES according to the constraints of the study. The goal of this section was to minimize both the loss and the number of nodes with violations. Table 5 shows the optimal placements and capacities of CBES based on the two objectives. It is clear that CBES with a capacity of 6MWh has the best performance compared to the other suggestions. Oversizing CBES, such as to 8MWh, as shown in the table, increases the number of nodes with violations and also the losses of the network. Undersizing CBES also increases the losses of the system and the number of nodes with violations in the network.

Table 5. Optimum placement and capacity of CBES

Capacity	Objective Function	Best Optimum Place		
		Bus 10	**Bus 2**	**Bus 81**
CBES 8MWh	Number of nodes violate	5	6	6
	Power Losses (kW)	541kW	515kW	531kW
CBES 6MWh	Number of nodes violate	5	5	7
	Power Losses (kW)	479 kW	491 kW	529kW
CBES 5MWh	Number of nodes violate	9	12	19
	Power Losses (kW)	514 kW	658 kW	598 kW

The critical point of voltage instability is an important parameter for assessing the voltage stability of a system. The critical point can be used to identify the weak points in the system, and to determine the operating limits of the system. The critical point is the point on the PV curve where the system becomes unstable. This can happen when the voltage drops below a certain threshold, or when the reactive power demand exceeds the available reactive power. Following figure shows the PV curve for current study for feeder 1 which is critical feeder. This figure plots the PV curves for all the busbars in this feeder. The upper busbar in this feeder shows with green line as well as the latest node at end of feeder (figure 11).

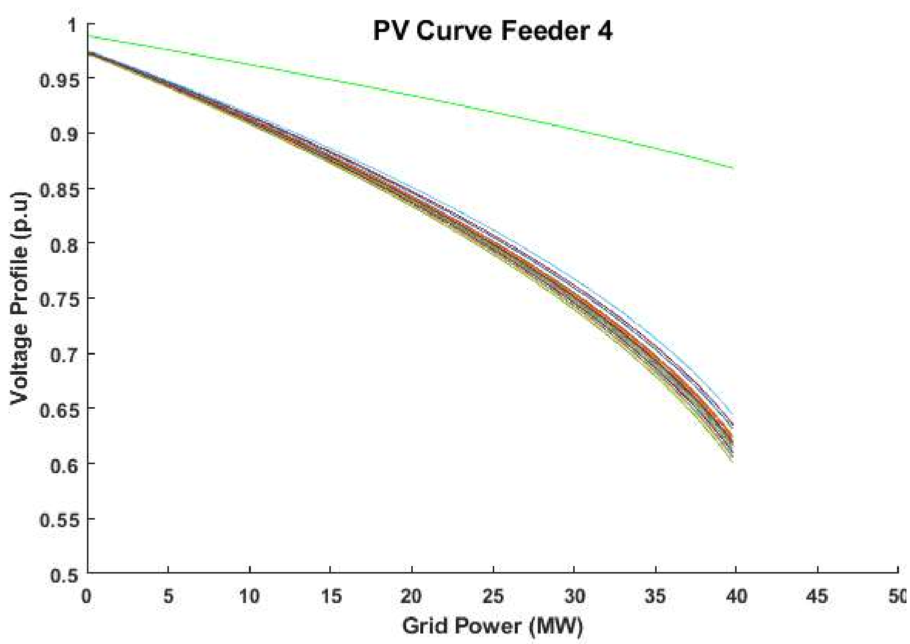


Figure 11. PV Curve of network for feeder 4 with high lower limit violations

Sensitive analysis was conducted on different CBES and TOU levels at a 100% solar PV penetration level. Table 6 shows the results of the analysis, which indicate the levels at which voltage profile violations occur. It is clear that increasing the TOU minimizes voltage violations as well as the required CBES capacity. For example, a system with a 40% TOU load reduction can mitigate voltage violations without the need for any CBES. Additionally, the table shows that a 10% TOU with 4MWh of CBES can overcome lower limit violations. On the other hand, Increasing CBES up to 8MWh shows that the network still violated this due to limited solar PV generation. Therefore, it is clear that hybrid mitigation can minimize the size and cost of network energy storage systems.

Table 6. Sensitive analysis for determining the optimum mitigation using TOU and CBES

PV Penetrations	TOU 5%	TOU10%	TOU 20%	TOU30%	TOU40%
CBES 8 Mwh	Violation	No Violation	No Violation	No Violation	No Violation
CBES 6 Mwh	Violation	No Violation	No Violation	No Violation	No Violation
CBES 5 Mwh	Violation	Violation	No Violation	No Violation	No Violation
CBES 4 Mwh	Violation	Violation	Violation	No Violation	No Violation
CBES 3 Mwh	Violation	Violation	Violation	Violation	No Violation
CBES 2 Mwh	Violation	Violation	Violation	Violation	No Violation
CBES 1 Mwh	Violation	Violation	Violation	Violation	No Violation
Without CBES	Violation	Violation	Violation	Violation	No Violation

The results in the last section showed that a single mitigation technique was unable to mitigate voltage violations in the grid. This section aims to combine these two techniques and investigate the impact of hybrid mitigation on voltage stability. Figure 12 shows the voltage profile of the network after integrating the two mitigation techniques. It is observed that the lower voltage violations have been overcome. This is because TOU can reduce load demand during peak times, which helps to balance the load and generation in the grid. This, in turn, helps to maintain voltage stability.

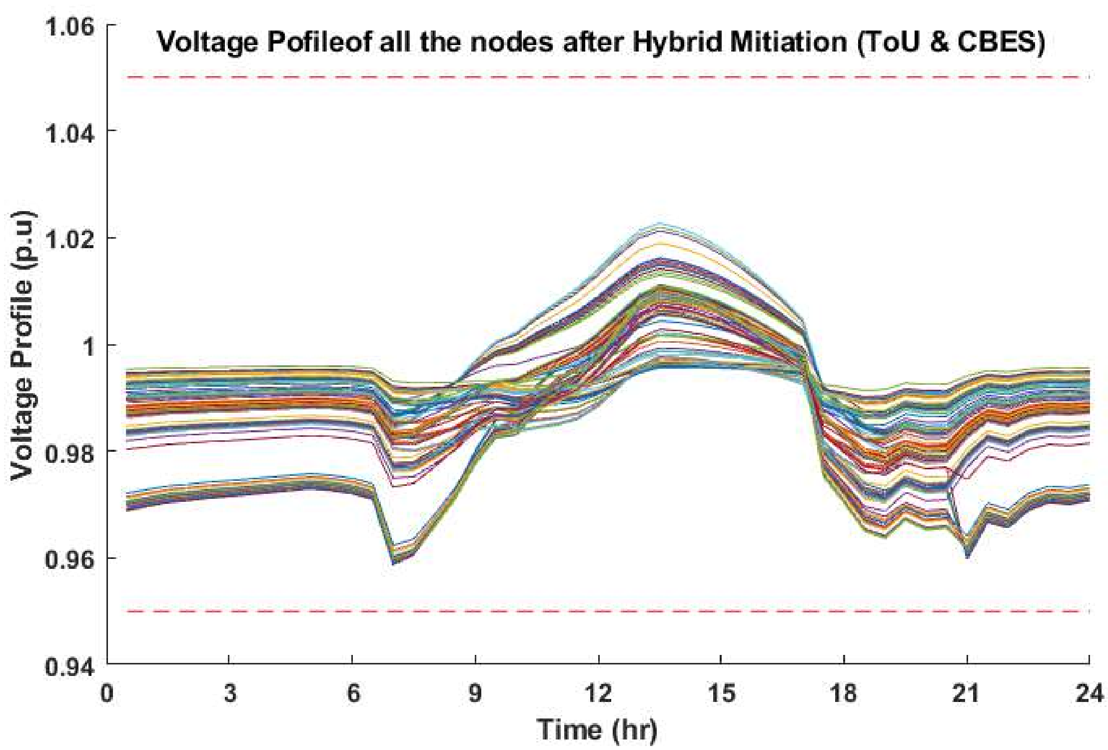


Figure 12. Voltage profile of all nodes after hybrid mitigation technique applied.

The charging and discharging of the battery in this case study depends on the variations in load and solar generation. As shown in Figure 13, the load has two peaks, one in the morning and one in the evening. The size of the battery is determined by Equations 10 and 11. The surplus power generated from solar PV penetration should be stored and fed back to the load during the second peak. The following figure shows the charging and discharging time periods of the CBES throughout the day. It is observed that the

CBES mostly charges after 11:30 PM due to the first peak load being in the morning from 9 to 11:30 AM. The battery reaches full charge by 4 PM. The total capacity of CBES after finding the optimum location was 5MWh. During the second peak (from 6PM till 8:30), the battery fully discharges. This is why the voltage violation rises up in Figure 10.b.

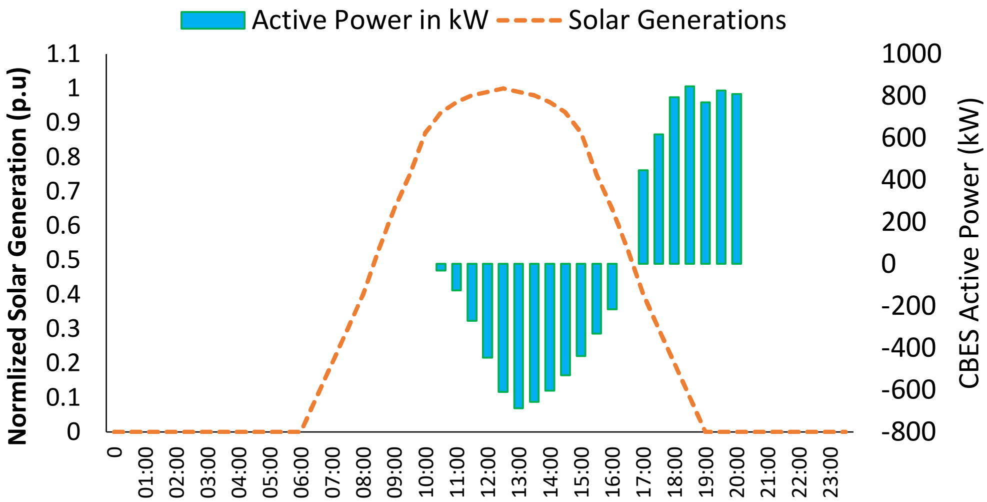


Figure 13. Charging and discharging of CBES during the day

The power of the grid is one of the key parameters that must be considered when connecting a solar PV system to the grid. The grid must be able to handle the additional power generated by the solar PV system, and the solar PV system must be able to safely interact with the grid. This study, as reported in the last section, aims to use a hybrid mitigation technique, such as battery and TOU, to control voltage stability. Figure 14 shows the power of the grid in different scenarios, such as the base system (with PV penetration), with TOU program, and with hybrid CBES and TOU program. It is observed that integrating CBES and TOU programs minimizes the power of the grid, as shown by the green line. This is because CBES can store excess power generated by solar PV systems during the day and release it back into the grid during peak demand times, while TOU can reduce load demand during peak times and add in another time during a day. The results of this study suggest that hybrid CBES and TOU programs can be an effective way to control voltage stability of the grid and improve the integration of solar PV systems. However, it is important to note that the effectiveness of these programs will depend on the specific characteristics of the grid and the solar PV system.

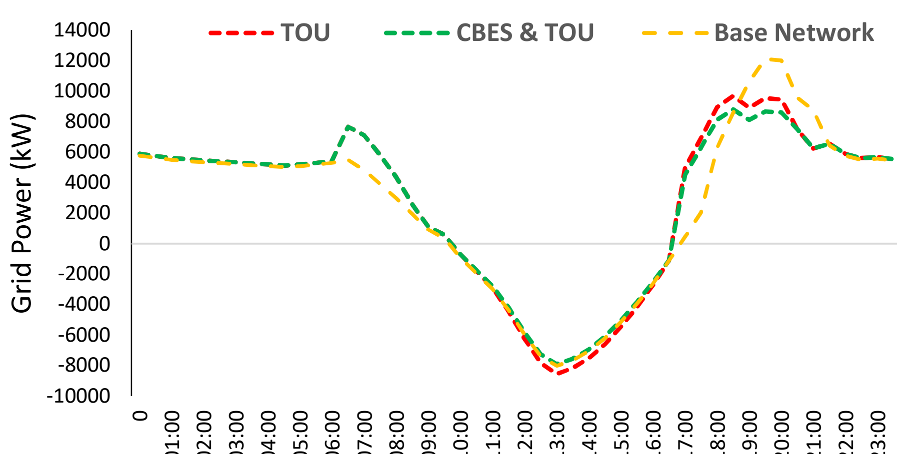


Figure 14. Grid power among different case study.

4. Conclusion

Currently, as distributed generation (DG) becomes more prevalent worldwide, the challenges faced by power grids are increasing. To address these challenges, researchers have investigated various mitigation techniques, including voltage control, harmonic and frequency control, and islanding. These techniques include tap changer control, Active power control (APC), Reactive-control (RPC), and battery energy storage (BES). This study aims to investigate the impact of solar PV penetration on a typical network in South Africa. The network consists of 81 nodes connected to 11-busbar through four feeders. In this study, 150 kW of solar PV was integrated into each node, and dynamic simulations were conducted to consider the impact of 100% PV penetration throughout a day.

Dynamic load flow analysis showed that even after 100% PV penetration to every node, there were still voltage violations below the lower limit in the grid. To overcome this challenge, two mitigation techniques were separately applied to the grid to investigate the impact of each. This study used demand response control (TOU) and CBES as mitigation techniques to control voltage. Different levels of TOU were applied to the network, and the results showed that with a 30% TOU program, most of the lower limit violations were overcome, but a few nodes still remained. Increasing the TOU program to 35% or 40% is one way to overcome these violations, but it is not easy to ask customers to reduce their load by 40% during peak times. CBES is another mitigation technique that has been used by many researchers around the world. In this study, the optimal placement and capacity of CBES were determined using the power flow Cbc algorithm. The results showed that with a 6MWh CBES capacity, most of the nodes with violations were shifted to an acceptable level, but again, a few nodes had violations during peak times. In the last step, and as the main contribution of this study, a hybrid TOU and CBES mitigation technique was applied to overcome voltage violations as well as reduce grid power.

The results of this study show that using TOU has a significant impact on voltage stability. This is because TOU can be used to reduce load demand during peak times, which helps to balance the load and generation in the grid. This, in turn, helps to maintain voltage stability. For future study is highly recommended following studies:

- Assessing the impact of TOU pricing and energy storage on renewable energy integration,
- Evaluating the effectiveness of demand response programs in conjunction with TOU pricing.
- Investigating the potential of electric vehicles as flexible loads in a TOU pricing.
- Examining the role of distributed energy resources in a TOU pricing and microgrid system. It would examine how different DER configurations and ownership models can support grid resilience and energy independence, and how TOU pricing can incentivize customers to participate in the system. It would also investigate the potential impact on utility business models and regulatory frameworks.

Nomenclature and Abbreviations

Nomenclature		**Abbreviation**	
D_{pv}	PV derating factor	**TOU**	**Time of Use**
G_T	incident solar radiation (kW/m^2)	**CBES**	Community Battery Energy Storage
α_p	power temperature coefficient (%/˚C),	**AVRs**	automatic voltage regulators
η_c	charging efficiencies	**BES**	Battery energy storage
η_d	Discharge efficiencies	**PV**	Photovoltaic
P_{DB}	discharge rate	**DR**	Demand Response Program
B_{min}	battery's minimum capacities	**DG**	distributed generation
B_{max}	battery's maximum capacities	**PVP**	PV Penetration
P_j^h	active power	**PCC**	point of connection

Q_j^h	Reactive power	**SOC**	state of charge
Vj^h	voltage magnitude	RPC	Reactive Power control
P_{max}	maximum hourly discharging power	APC	Active Power Control

Acknowledgments

This study was supported by Institute Future Knowledge (IFK) University of Johannesburg, South Africa.

References

Almeida, D., Pasupuleti, J., Ekanayake, J., & Karunarathne, E. (2020). Mitigation of overvoltage due to high penetration of solar photovoltaics using smart inverters volt/var control. *Indones. J. Electr. Eng. Comput. Sci*, *19*(3), 1259-1266.

Ariyaratna, P., Muttaqi, K. M., & Sutanto, D. (2018). A novel control strategy to mitigate slow and fast fluctuations of the voltage profile at common coupling Point of rooftop solar PV unit with an integrated hybrid energy storage system. *Journal of Energy Storage*, *20*, 409-417.

Atmaja, W. Y., & Putranto, L. M. (2021). A Voltage Rise Mitigation Control Scheme of Utility-Scale Battery in High PV Penetration. 2021 3rd International Conference on High Voltage Engineering and Power Systems (ICHVEPS),

Ciocia, A., Chicco, G., & Spertino, F. (2020). Benefits of On-Load Tap Changers Coordinated Operation for Voltage Control in Low Voltage Grids with High Photovoltaic Penetration. 2020 International Conference on Smart Energy Systems and Technologies (SEST),

El-Bahay, M. H., Lotfy, M. E., & El-Hameed, M. A. (2023). Computational methods to mitigate the effect of high penetration of renewable energy sources on power system frequency regulation: a comprehensive review. *Archives of Computational Methods in Engineering*, *30*(1), 703-726.

Jafarzadeh-Ghoushchi, S., Sharifi, A., Ahmadi, M., & Maghami, M. (2017). Statistical study of seasonal storage solar system usage in Iran. *Journal of Solar Energy Research*, *2*(3), 39-44.

Li, S., Wu, H., Zhou, Y., Bi, R., Qi, X., Sun, M., & Xu, B. (2023). Two-stage voltage control strategy in distribution networks with coordinated multimode operation of PV inverters. *IET Renewable Power Generation*, *17*(1), 66-82.

Maghami, M. R. (2025). The Role of Solar Energy in Mitigating the Impact of EV Charging Modes on Distribution Networks. *Results in Engineering*, 106009.

Maghami, M. R., Pasupuleti, J., & Ling, C. M. (2023a). Comparative analysis of smart grid solar integration in urban and rural networks. *Smart Cities*, *6*(5), 2593-2618.

Maghami, M. R., Pasupuleti, J., & Ling, C. M. (2023b). Impact of Photovoltaic Penetration on Medium Voltage Distribution Network. *Sustainability*, *15*(7), 5613.

Mansouri, N., Lashab, A., Sera, D., Guerrero, J. M., & Cherif, A. (2019). Large photovoltaic power plants integration: A review of challenges and solutions. *Energies*, *12*(19), 3798.

Nguyen-Duc, T., Hoang-Tuan, L., Ta-Xuan, H., Do-Van, L., & Takano, H. (2022). A Mixed-Integer Programming Approach for Unit Commitment in Micro-Grid with Incentive-Based Demand Response and Battery Energy Storage System. *Energies*, *15*(19), 7192.

Nousdilis, A. I., Christoforidis, G. C., & Papagiannis, G. K. (2018). Active power management in low voltage networks with high photovoltaics penetration based on prosumers' self-consumption. *Applied energy*, *229*, 614-624.

Ramli, N. M. A., Hussin, S. M., Said, D. M., Rosmin, N., & Nawabjan, A. (2021). VOLTAGE REGULATION CONTROL USING BATTERY ENERGY STORAGE SYSTEM IN DISTRIBUTION NETWORK WITH HIGH PV PENETRATION STRENGTH. *Jurnal Teknologi*, *83*(6), 203-209.

Rasheed, M. A., Verayiah, R., & Saleh, B.-s. (2020). Optimal Placement, Sizing and Operating Power Factor of PV for Loss Minimization and Voltage Improvement in Distribution Network via DigSilent. 2020 2nd International Conference on Smart Power & Internet Energy Systems (SPIES),

Raval, D. Y., & Pandya, S. N. (2021). Phase Shifting Strategy for Mitigation of Local Voltage Rise in Highly PV Penetrated Distribution Network. 2021 9th IEEE International Conference on Power Systems (ICPS),

Sanni, M. T., Pota, H., Mo, H., & Dong, D. (2020). Voltage-violation mitigation in power system networks with photo-voltaic penetration. 2020 IEEE Symposium Series on Computational Intelligence (SSCI),

Shi, Q., Feng, W., Zhang, Q., Wang, X., & Li, F. (2020). Overvoltage mitigation through Volt-VAR control of distributed PV systems. 2020 IEEE/PES Transmission and Distribution Conference and Exposition (T&D),

Tantrapon, K., Jirapong, P., & Thararak, P. (2020). Mitigating microgrid voltage fluctuation using battery energy storage system with improved particle swarm optimization. *Energy Reports*, *6*, 724-730.

Vergara, P. P., Salazar, M., Mai, T. T., Nguyen, P. H., & Slootweg, H. (2020). A comprehensive assessment of PV inverters operating with droop control for overvoltage mitigation in LV distribution networks. *Renewable Energy*, *159*, 172-183.

Zhang, Y., Meng, K., Luo, F., Yang, H., Zhu, J., & Dong, Z. Y. (2019). Multi-agent-based voltage regulation scheme for high photovoltaic penetrated active distribution networks using battery energy storage systems. *IEEE Access*, *8*, 7323-7333.

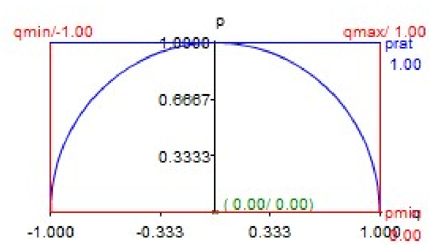
Appendices

Appendix A: Load Flow DPL Code

```
double Pgen,
        Qgen,
          redFac;
redFac = 1.0;
if ({chargeU = 3}.and.{chargeE >= 2}.and.{chargeE > 0}) {
          if (uGen > uFullFeed) {
                    redFac = 1 - ((uGen - uFullFeed)/(uStartFeed - uFullFeed));
          }
          Pgen = Pfeed * redFac; ! discharge = GEN, feeding
          Qgen = Qfeed * redFac; ! discharge = GEN, feeding
}
else if ({chargeU = 1}.and.{chargeE <= 2}.and.{chargeE > 0}) {
          if (uGen < uFullStore) {
                    redFac = 1 - ((uFullStore - uGen)/(uFullStore - uStartStore));
          }
          Pgen = -Pstore * redFac; ! charge = LOAD, storing
          Qgen = -Qstore * redFac; ! charge = LOAD, storing
}
else {
          Pgen = 0.;
          Qgen = 0.;
}
SetEquation(0, Pset - Pgen);
SetEquation(1, Qset - Qgen);
```

Appendix B: Solar PV Specifications

Solar PV Specifications:	
Peak Power (MPP)	500W
Rated Voltage (MPP)	80V
Rated Current (MPP)	6A
Open Circuit Voltage	90V
Short Circuit Current	7A
Model	Single crystalline silicon (Mono-Si)
Penetration Level	150kW
Number of Panel per inverter	18
Number of Inverter	15



Appendix C: Battery Energy Storage (CBES) Specifications

Battery Energy Storage (CBES) Specifications:	
Energy Storage Size MWh	500W
Initial state of charge%	100
Minimal state of charge %	6A
Maximal state of charge%	90V
Charging rate MW	2
Discharging rate MW	2 (Mono-Si)

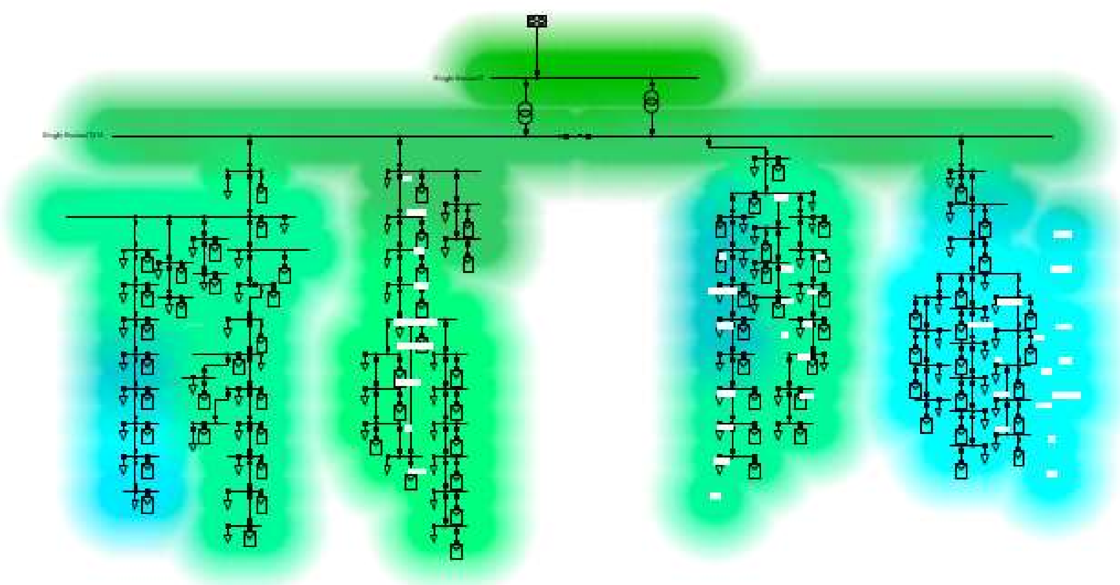
Battery Charging and Discharging DPL Code

```
double u;
SOC = SOCini;
u = 1.;
! voltage operation area
if ({uFullStore <= uStartStore}.or.{uStartFeed <= uFullFeed}) {
chargeU = 0; ! Error
Warn('uFullStore must be > than uStartStore and uStartFeed > than uFullFeed');
}
else if (u < uStartFeed) {
        chargeU = 3;
}
else if (u > uStartStore) {
        chargeU = 1;
}
else {
        chargeU = 2;
}
! energy operation area
iniSOCoob = 0; ! Inside bounds
if (SOCmin >= SOCmax) {
        chargeE = 0; ! Error
        Warn('SOCmin must be < than SOCmax.');
}
else if (SOC > SOCmax) {
        chargeE = 3;
        iniSOCoob = 1;
}
else if (SOC = SOCmax) {
        chargeE = 3;
}
else if (SOC = SOCmin) {
        chargeE = 1;
}
else if (SOC < SOCmin) {
        chargeE = 1;
        iniSOCoob = 1;
}
else {
        chargeE = 2;
}
```

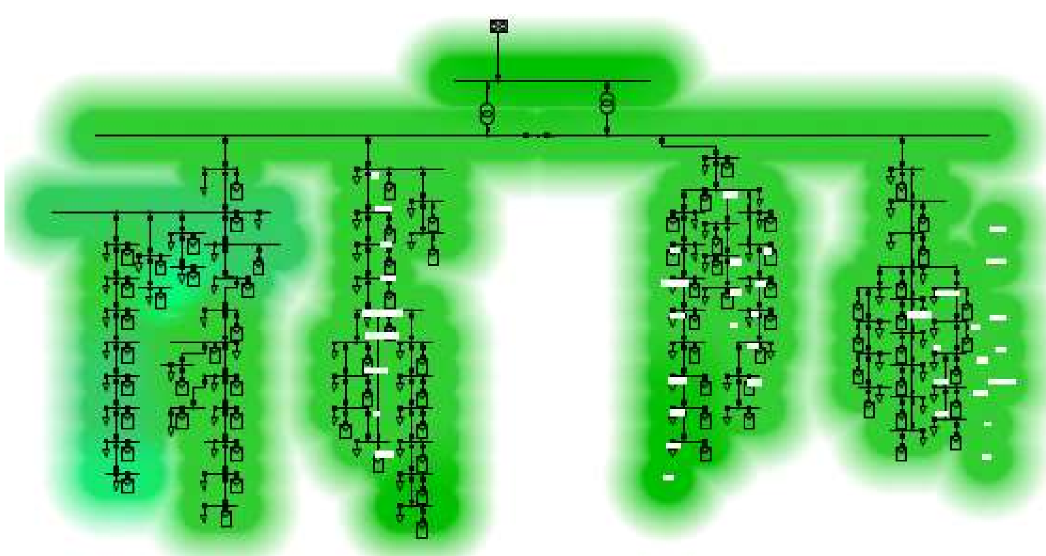
Appendix D: Heatmap of Network Before and After Mitigation

Heatmap of network before mitigation and after the mitigation shows in the following figure. Feeder 4 and 1 are critical feeders as it is shows by blue colors in the heatmap. The heatmap is shows after hybrid mitigation technique applied to the network.

Before mitigations

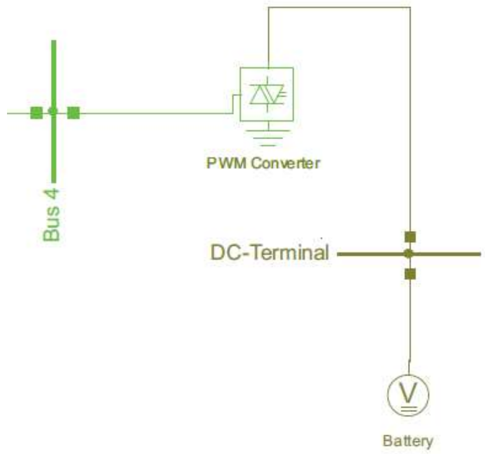


After Mitigation technique applied

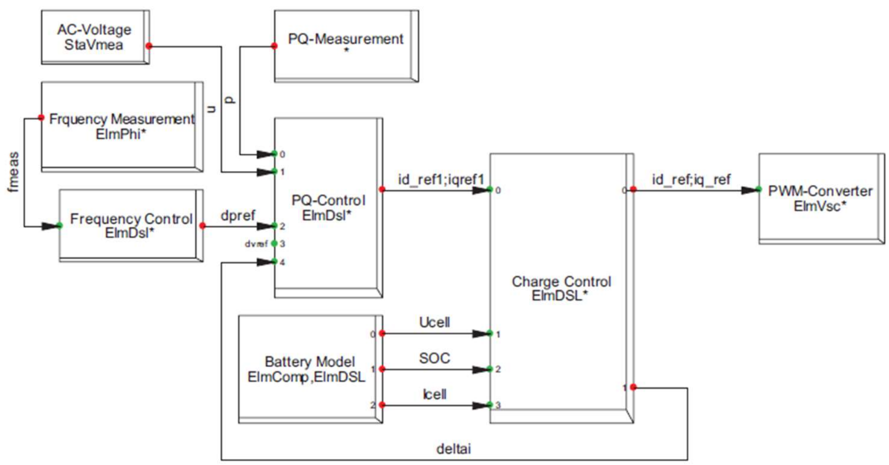


Appendix F: Controls

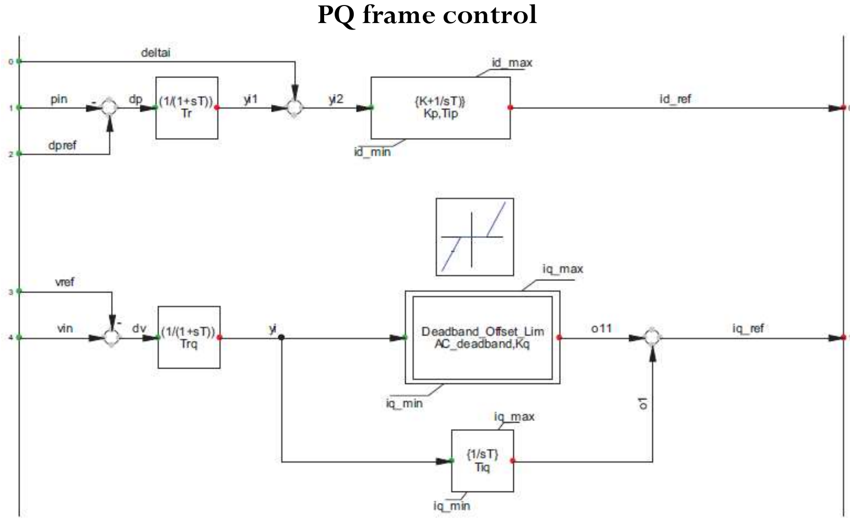
BESS Single Line Diagram

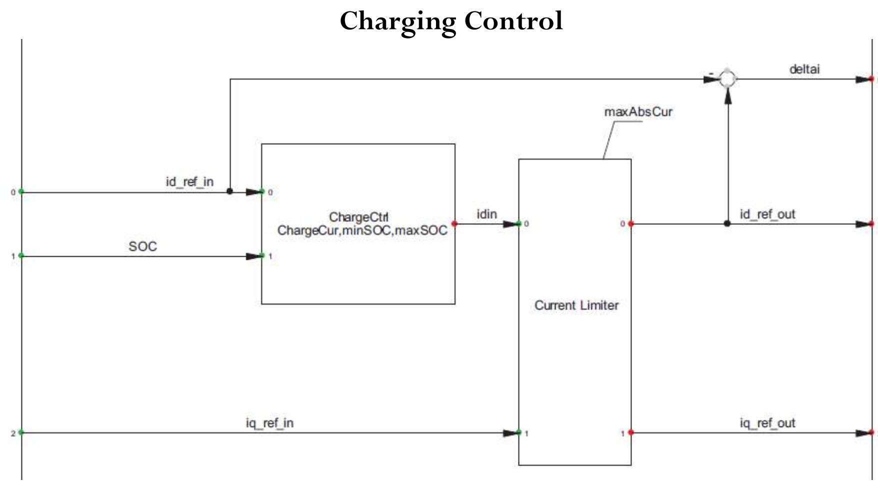


BESS Control Structure



PQ frame control




Charging Control
deltai
maxAbsCur
id_ref_in
ChargeCtrl
ChargeCur,minSOC,maxSOC
idin
id_ref_out
SOC
Current Limiter
iq_ref_in
iq_ref_out