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# Smart Grid Voltage Mitigation Using a Direct Load Control and Battery Energy Storage Approach in Solar Integration.

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## 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. It proposes a novel hybrid mitigation technique using Direct Load Control (DLC) 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 150 kW solar PV added to every single node. Four case studies were conducted to compare the impact of different mitigation techniques: the base network without any mitigation, the network with DLC mitigation, the network with CBES mitigation, and the network with hybrid DLC and CBES mitigation. The location and size of the CBES were determined using the Power Factory Cbc algorithm to address weaknesses in the network. DLC was used for peak shifting, and different levels of DLC 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 show that hybrid mitigation using DLC and CBES dramatically solves the voltage violation in the network and minimizes the loss of network and power from the grid.

**Keywords:** *Voltage Failure, Demand Response, Dynamic Simulation, Large-scale Solar, Demand Response, Energy Storage, Direct Load Control.*

## 1. Introduction

Voltage failure, also known as voltage collapse, occurs when the voltage levels in a power system drop below a certain threshold, leading to equipment damage, power outages, and other issues. In the context of large-scale solar PV power systems, voltage failure can occur due to the intermittent nature of solar power generation in power systems(Jafarzadeh-Ghoushchi et al., 2017; Maghami, 2025; Mohammed & San, 2019). As solar PV penetration increases in power systems, voltage fluctuations can occur, leading to voltage failure. Various techniques can be employed to mitigate voltage failure in large-scale solar PV power systems (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 high solar power generation periods to balance the power supply and demand and maintain voltage stability. Demand response can be achieved through DLC, which controls the load demand by switching off non-essential loads during high solar power generation periods. 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(Maghami et al., 2023a; Salman et al., 2021). 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. A study [4] proposed a hybrid mitigation technique using demand response and battery energy storage 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 high solar power generation periods 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.

Hybrid mitigation techniques, combining multiple techniques such as demand response and BES, can also 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. A study [5] proposed a hybrid mitigation technique 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 effectively reduced voltage fluctuations and maintained 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 effectively reduced frequency deviations and maintained 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 | 3.5MG W | 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(Balakrishnan et al.). 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 viz. 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; find the best placements as the capacity of CBES on the network to mitigate voltage failure; investigate the impact of different DLC levels during peak load on the network and; investigate the hybrid mitigation technique using DLC and CBES on a power network.

## 2. Methods

This section will demonstrate the research techniques and tools used to reach the study's objectives. The study's methodology 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 the DLC 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 Studies 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 DLC 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: After adding 150 kW to every single node, power flow 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 DLC to mitigate the voltage failure over the solar PV penetration.
- Running Cbc algorithm to find the most appropriate CBES size and location.
- Integrating two mitigation techniques, including CBES and DLC, to overcome the voltage failure.

**Table 2**. Case study definitions

| Case Studies | Solar PV | DLC 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***

Digsilent power factory was used to model the network as discussed in (Gonzalez-Longatt & Rueda, 2014). 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 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***

To conduct a dynamic power flow analysis, the PV generation and load profiles must be considered to perform a proper analysis(Gonzalez-Longatt & Rueda, 2014). According to the South Africa distribution code, $V_{min}$ and $V_{max}$ equal 0.95p.u and 1.05p.u, respectively. The power lost depends on the lines' current flow and line resistance. Solar PVP will decrease the current flow 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 PV penetration 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 PV penetration. Appendix A shows the load flow DPL code used to calculate the network simulation.

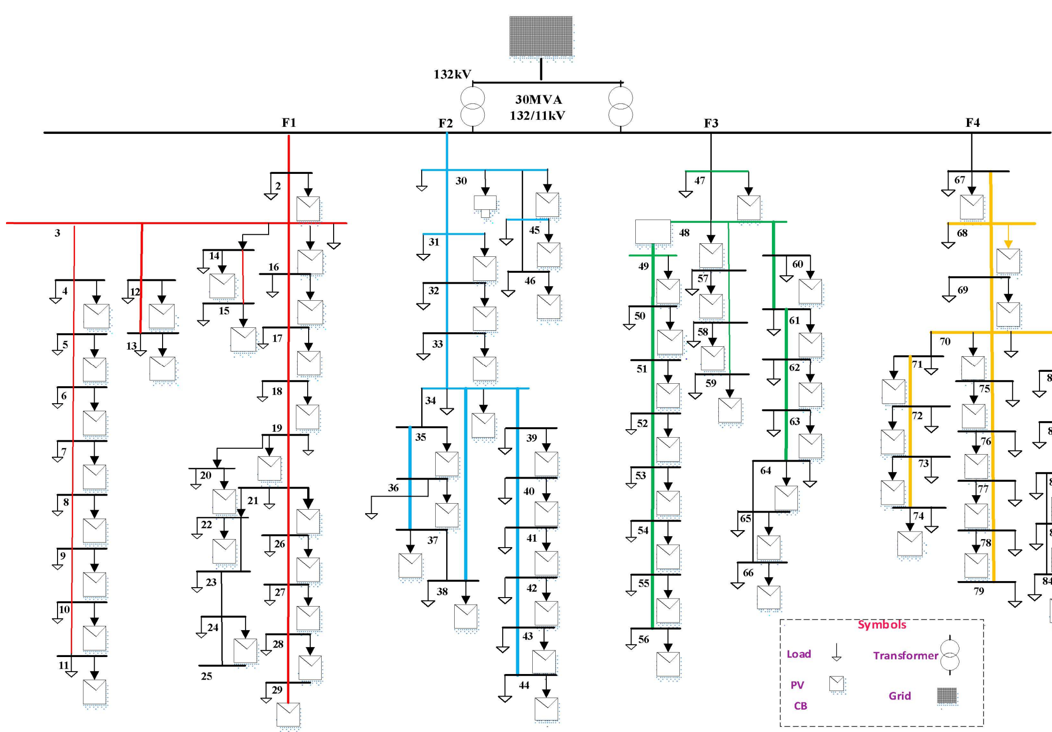


**Figure 1.** Network configuration,81 node through 4 feeders are interconnected to an 11kV busbar through two parallel-connected 132/11kV transformers.

### *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 power generated by the solar system, and SLD represents the power 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).

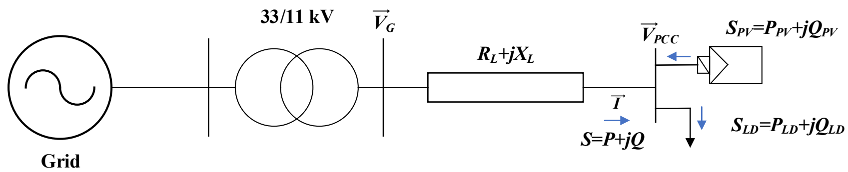


**Figure 2**, 2 busbars network system model.

$$S = VI^* \quad (1)$$

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

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

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

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

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

### *PV Penetration Level*

The PV penetration rate is the ratio between the total coupled and permitted maximum PV capacity. To evaluate the efficiency of a PV system, its energy levels are measured by determining the percentage of the rated 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 : 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 used for the current study, such as solar module power, Vsc, Short Circuit Current, etc. The PV generation can be calculated by Eq:

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

*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 DLC 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***

CBES charging and discharging depend on the network's topology, size, and location. This network has 81 nodes, and the location of CBES should be determined to minimize 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:

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

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, $\eta_c$ and $\eta_d$ are referred to the charging and discharge efficiencies of the battery, respectively. The constraints for the available battery capacity are given by:

$$\begin{aligned} B_{min} \leq SOC \leq B_{max} \\ B_{min} = (1 - DOD)B_{max} \end{aligned} \quad (8)$$

$B_{min}$ 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:

$$0 \leq P_{DB}(K) \leq P_{max} \quad (9)$$

In this case, Pmax represents the maximum hourly discharging power that can be achieved. The 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 placements to mitigate the network's lower limit voltage violation by minimizing nodes' voltage deviation and power losses:

*A: Minimizing Power Losses*

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

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

*B: Minimizing of node voltage deviation*

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

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

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

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

Subject to constraint

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

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

$$I_{ij}^{h} \leq I_{ij}^{Max};\ \forall i,j \in \Omega, h \in T \quad (15)$$

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

$$0 \leq P_{CBES} \leq P_{CBES}^{Max}; \forall i \in \Omega$$

$$P_{CBES}^{min} \leq P_{ch/dis}^{h} \leq P_{CBES}^{max};\ \forall i,j \in \Omega, h \in T \quad (17)$$

$$SOC_{min} \leq SOC_i^h \leq SOC_{max};\ \forall i,j \in \Omega, h \in T \quad (18)$$

$$SOC_i^h = SOC_i^{h-1} + \left\{ \frac{\eta_c P_{ch}^h}{P_{CBES}^R} - \frac{P_{dic}^h}{\eta_d P_{CBES}^R} \right\};\ \forall i,j \in \Omega, h \in T \quad (19)$$

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, 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 its 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 varied to simulate changes in voltage imbalance. The BESS frame control in PF can be used to control the BESS's real and reactive power output. 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 the scope of this study.

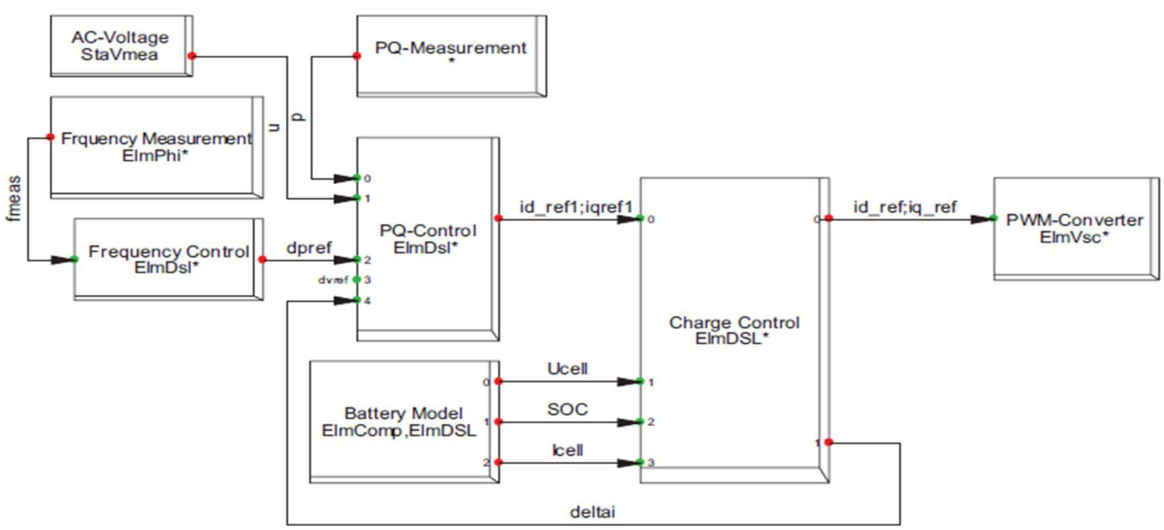


**Figure 3**, The frame control of CBES

### *Directs Load Control Strategy*

DLC 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, DLC can help improve the grid's overall performance and ensure that it can safely and reliably integrate increasing amounts of solar generation. DLC can be used in conjunction with other mitigation techniques, such as BES, to improve the grid's overall performance and mitigate the impact of solar grid connection. In this study, DLC was applied to the network with different levels from 5% to 30% load reduction. Figure 4 shows the DLC program, applied only during the second peak load for 3 hours from 6pm to 9pm. The DLC increased during the peak load to evaluate the minimum DLC requirement to overcome the voltage mitigation.

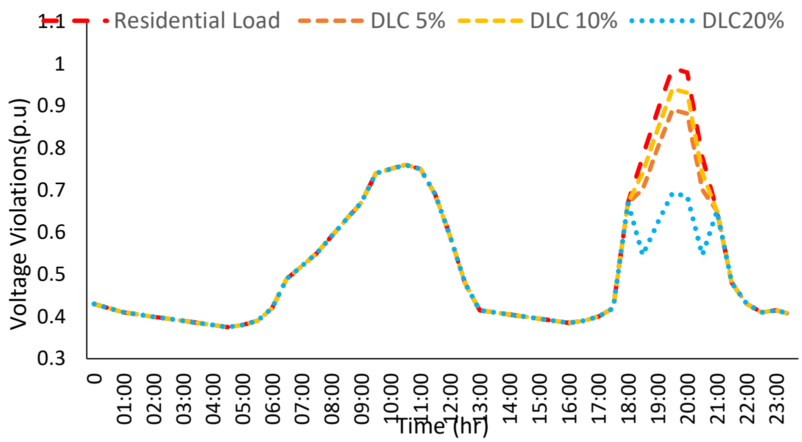


**Figure 4.** Different level of DLC applied on the network during the second peak load. including 5%, 10%, 20% and 30%.

### *Hybrid mitigation techniques*

The third step was to develop hybrid mitigation techniques to address the challenges of high PV penetration. These techniques included DLC 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 the hybrid mitigation technique using DLC 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. Many studies have been 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 connections.

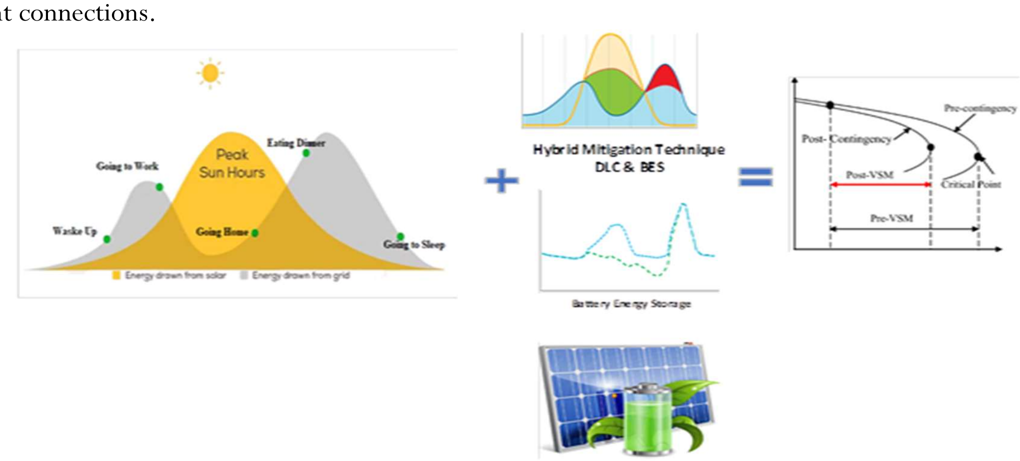


**Figure 5.** Hybrid mitigation technique using DLC and CBES to solve the lower voltage limit.

## 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. The last section integrates DLC (demand response) with the CBES to optimize system mitigations. As shown in Figure 6(a), the voltage profile of the network before PV penetration into the grid. It is observed that the network was 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, 150 kW 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 6(b) shows the voltage profile of all the nodes with 150 kW 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 network heatmap before and after the mitigation technique.

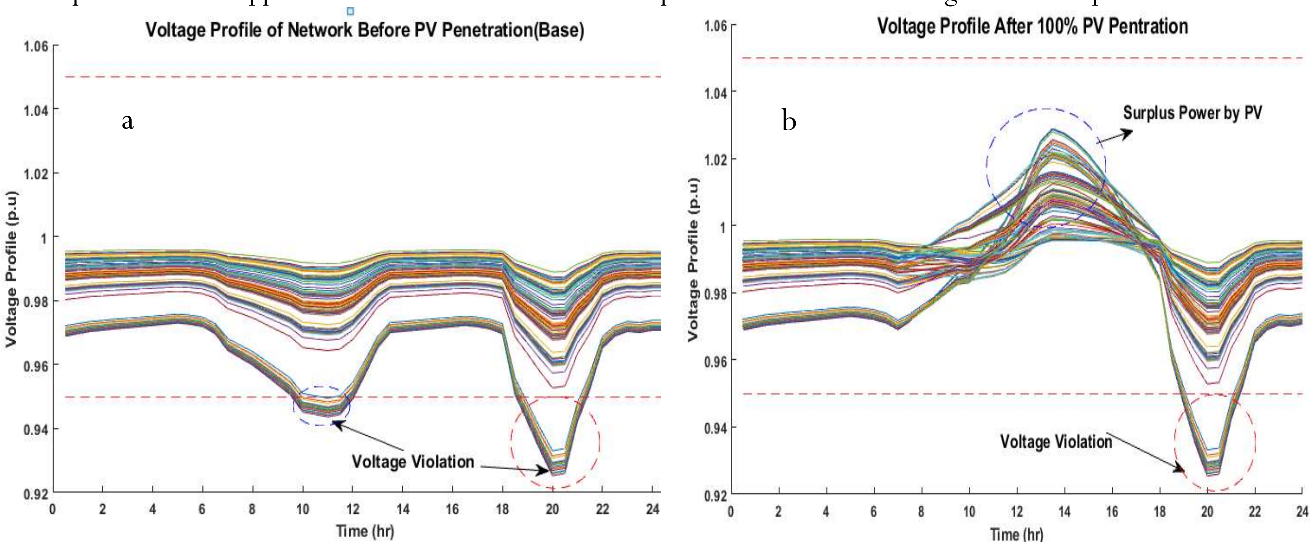


**Figure 6.** Voltage profile for all the nods before PV penetration (a) and after that (b).

The transformer loading is dependent on the load demand. Figure 7 displays the transformer loading before and after PV penetration into the grid. 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, the generation rises and reduces the transformer loading when the sun is up. 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.

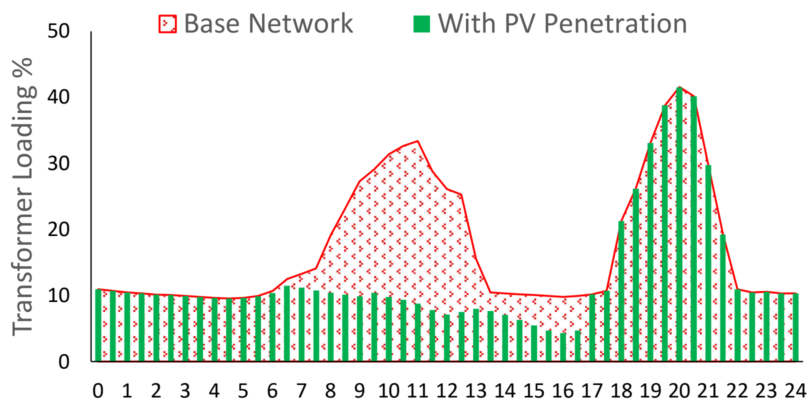


**Figure 7.** Transformer Loading before and after PV penetration into grid

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. This section aimed to minimize both the loss and the number of nodes with violations. Table 4 shows the optimal placements and capacities of CBES based on the two objectives. It is clear that CBES with a capacity of 5 MWh has the best performance compared to the other suggestions. Oversizing CBES, such as to 6 MWh, as shown in the table, increases the number of nodes with violations and the network losses. Undersizing CBES also increases the losses of the system and the number of nodes with violations in the network.

**Table 4**. Optimum placement and capacity of CBES

| Capacity | Objective Function | Best Optimum Place | | |
|---|---|---|---|---|
| | | Bus 10 | Bus 2 | Bus 81 |
| CBES 6MWh | Number of nodes violate | 3 | 4 | 4 |
| | Power Losses (kW) | 95kW | 102 kW | 118 kW |
| CBES 5MWh | Number of nodes violate | 4 | 8 | 6 |
| | Power Losses (kW) | 75 kW | 89 kW | 92 kW |
| CBES 4MWh | Number of nodes violate | 5 | 7 | 8 |
| | Power Losses (kW) | 130 kW | 135 kW | 125 kW |

The following figure shows mitigation techniques using DLC and CBES separately. Figure 8(a) shows the voltage profile of the network after 30% DLC. It is observed that DLC alone, in combination with PV penetration, can almost mitigate voltage violations. However, the graph also shows that even after 30% DLC, the network touches the lower limit value between 7:30 PM and 8:30 PM. One way to overcome this issue is to increase the DLC program to 40% or integrate energy storage to mitigate any violation. Figure 9(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, reducing the need for DLC programs and improving voltage stability. However, the network faces violations again during the night. One way to overcome this issue with CBES integration is to increase the CBES capacity, which would increase the cost of the system. Another way is to combine it with the DLC program.

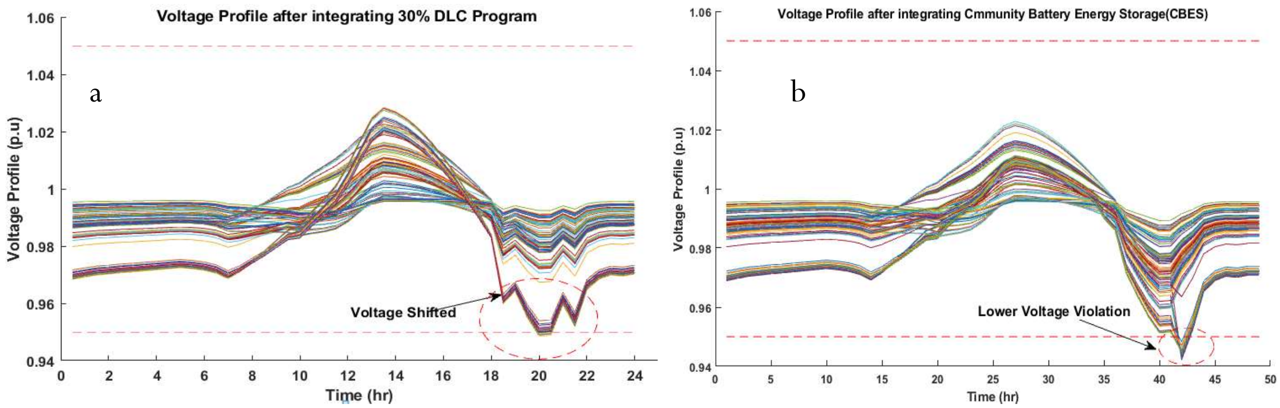


**Figure 8.** Mitigation technique using DLC program (a) and CBES (b)

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 5, 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 the voltage violation can be overcome with a 40% DR program, even without PV penetration.

**Table 5.** Comparing he DLC integration with different PV penetration level.

| PV Penetrations | DLC 5% No, Violations | DLC10% No, Violations | DLC 20% No, Violations | DLC30% No, Violations | DLC40% No, Violations |
|---|---|---|---|---|---|
| 150 kW | 15 | 12 | 9 | 3 | 0 |
| 100 kW | 15 | 15 | 14 | 7 | 0 |
| 50 kW | 15 | 15 | 15 | 10 | 0 |
| 0 kW | 18 | 18 | 18 | 15 | 0 |

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 1and 4 which is critical feeders. 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 9).

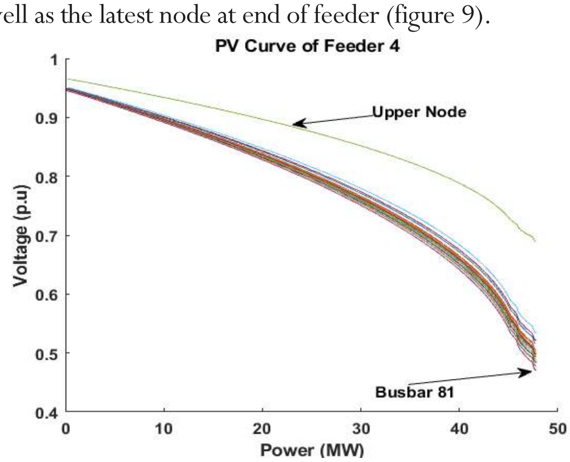


**Figure 9**. PV Curve of network for feeder 4 with high lower limit violations

Sensitive analysis was conducted on different CBES and DLC 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 DLC minimizes voltage violations as well as the required CBES capacity. For example, a system with a 40% DLC load reduction can mitigate voltage violations without needing any CBES. Additionally, the table shows that a 5% DLC with 5MWh of CBES can overcome lower limit violations. 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 DLC and CBES

| PV Penetrations | DLC 5% | DLC10% | DLC 20% | DLC30% | DLC40% |
|---|---|---|---|---|---|
| CBES 5 Mwh | No Violation | No Violation | No Violation | No Violation | No Violation |
| CBES 4 Mwh | Violation | No Violation | No Violation | No Violation | No Violation |
| CBES 3 Mwh | Violation | Violation | No Violation | No Violation | No Violation |
| CBES 2 Mwh | Violation | Violation | Violation | No 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 10 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 DLC 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.

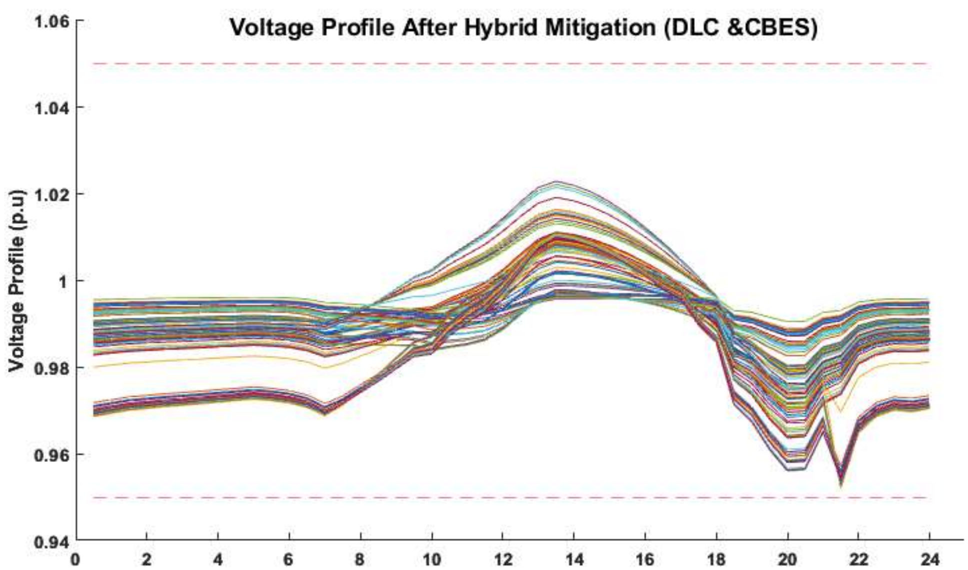


**Figure 10.** Voltage profile of all nodes after hybrid mitigation technique applied.

The charging and discharging of the battery in this case study depends on the variations in load and solar generation. As shown in Figure 11, 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. The battery fully discharges during the second peak (from 6PM till 8:30).

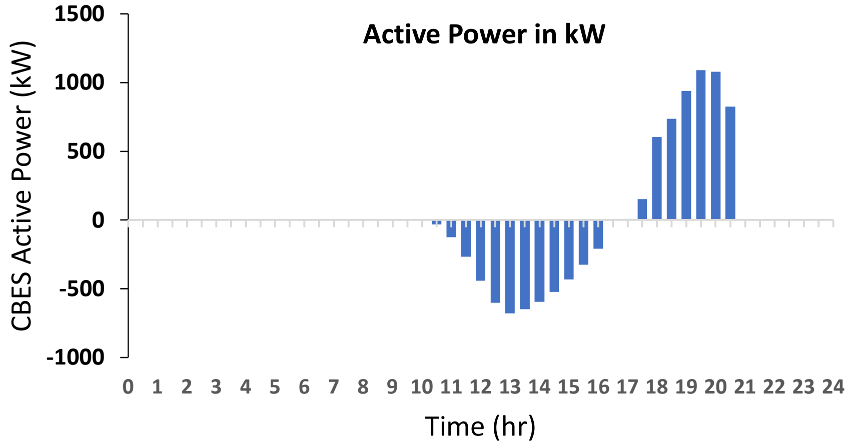


**Figure 11.** Charging and discharging of CBES during the day

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 interact with the grid safely. As reported in the last section, this study aims to use a hybrid mitigation technique, such as battery and DLC, to control voltage stability. Figure 12 shows the grid's power in different scenarios, such as the base system (without PV penetration), with CBES and with DLC program, and with hybrid CBES and DLC program. It is observed that integrating CBES and DLC programs minimizes the grid's power, as shown by the green bar. This is because CBES can store excess energy generated by solar PV systems during the day and release it back into the grid during peak demand times, while DLC can reduce load demand during peak times. The results of this study suggest that hybrid CBES and DLC programs can effectively control the grid's voltage stability 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.

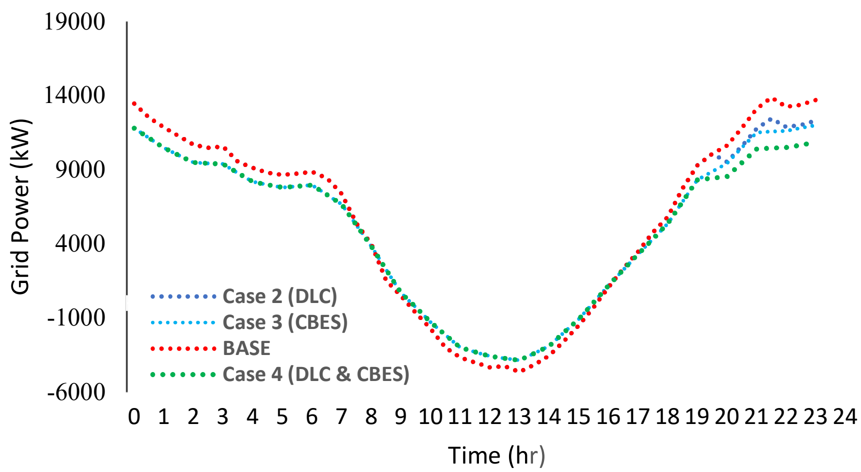


**Figure 12.** Grid power among different case studies.

Increasing solar PV penetration can decrease power loss in the system. Figure 13a the power losses before and after mitigation. It is shows that feeder 4 experiences the highest power losses in the network before mitigation. 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 between 11 and 12 AM peak, 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 lost power. 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. In figure b, it is clear after mitigation by CBES and demand response the losses decreased significantly.

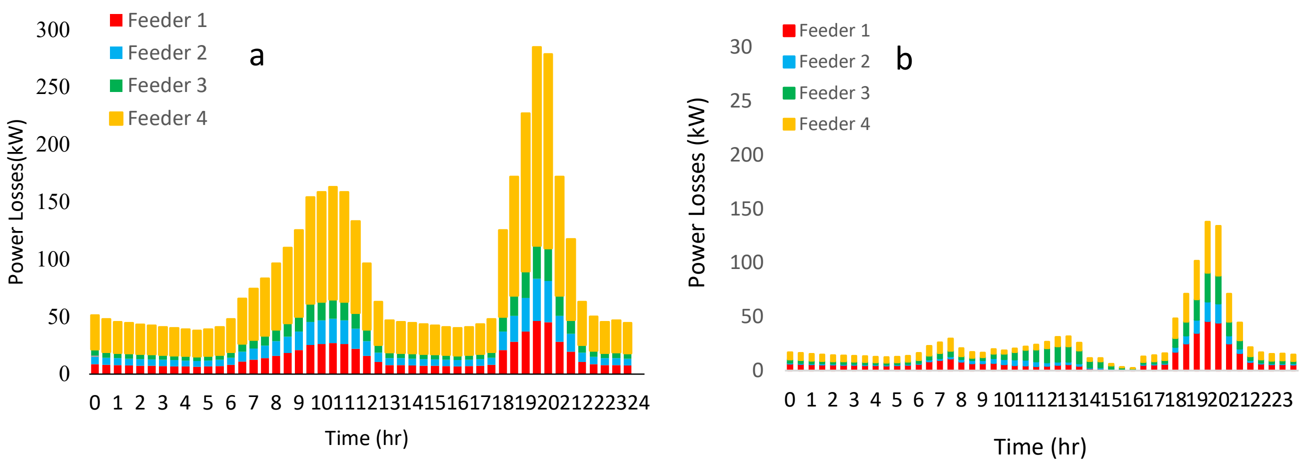


**Figure 13.** Accumulated power losses among different feeders before (a) and after (b) mitigations

## 4. Conclusion

With the growth of distributed generation (DG) worldwide, the challenges faced by power grids will increase. To mitigate these challenges, many research studies have been conducted on voltage control, harmonic and frequency control, islanding, and etc. Many mitigation techniques have been used by researchers, such as tap changer control, Active power control (APC), Reactive-control (RPC), battery energy storage (BES), and others. 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. This study integrated 150 kW of solar PV 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 load control (DLC) and CBES as mitigation techniques to control voltage. Different levels of DLC were applied to the network, and the results showed that with a 30% DLC program, most of the lower limit violations were overcome, but a few nodes still remained. Increasing the DLC 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 many researchers around the world have used. In this study, the optimal placement and capacity of CBES were determined using the power flow Cbc algorithm. The results showed that with a 5 MWh 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 DLC and CBES mitigation technique was applied to overcome voltage violations as well as reduce grid power. The results of this study show that using DLC has a significant impact on voltage stability. This is because DLC can be used to reduce load demand during peak times, which helps to balance the load and generation in the grid.

## Nomenclature and Abbreviations

| Nomenclature | | Abbreviation | |
|---|---|---|---|
| $D_{pv}$ | PV derating factor | **DLC** | **Direct Load Control** |
| $G_T$ | incident solar radiation (kW/m$^2$) | **CBES** | Community Battery Energy Storage |
| $\alpha_p$ | power temperature coefficient (%/˚C) | **AVRs** | automatic voltage regulators |
| $\eta_c$ | charging efficiencies | **BES** | Battery energy storage |
| $\eta_d$ | 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 |

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