INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
I. J. Hasan et al., Vol.14, No.4, December, 2024

Voltage Sag Mitigation Methods in Low Voltage Networks with Photovoltaic Units: Modelling and Analysis

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Received: 12.08.2023 Accepted:09.09.2023

Abstract- Photovoltaic and battery energy are causing conventional designs of power systems to undergo significant transformations, which is creating new challenges for the systems' dependability as their utilization rates increase. Voltage sags are temporary decreases in voltage levels that can adversely affect the performance of electrical devices and disrupt power quality. With the increasing integration of PV and battery units into low-voltage networks, voltage sags have become a significant concern due to the intermittent nature of solar energy. This paper aims to study voltage sag issues in low-voltage networks with PV units by investigating various mitigation methods and analysing their effectiveness. The research begins with the development of a comprehensive model that captures the dynamic behaviour of PV and battery units. The model also incorporates the interaction between PV units and the grid during voltage sag events. ETAP simulations were used to demonstrate the effectiveness of the proposed approach. The results of this paper provide valuable insights into the mitigation of voltage sags in low-voltage networks with PV and battery units. By analyzing different methods and their associated models.

Keywords Voltage Sag, PV system, Battery units, ETAP, RMS, Study State, DVR.

1. Introduction

Non-linear loads and renewable energy sources are being used more often directly causing an increase in the frequency and severity of worries about the power quality in distribution and transmission networks. The two issues with power systems that individuals encounter most frequently and that present them with the most trouble are harmonics and voltage sag [1-4]. The widespread use of controllers that are powered by power electronics in electrical appliances is one of the primary factors that has led to an increase in harmonic distortion. Voltage drops are typically caused by the following: the starting of large motors, the energization of transformers, the switching of circuit breakers on and off, faults in the customer's facility, failure of equipment, unusual weather (Lightning strikes on electrical networks) and the sporadic nature of renewable energy sources linked to distribution systems [1,5].

The term "voltage sag" comes from the IEEE Standard 1159, which describes it as a drop in AC voltage's RMS (Root Mean Square) voltage from 90% to 10% of the normal voltage [3-9]. Within the scope of this specification are power frequencies ranging from one-half cycle to one minute. The amplitude of voltage dips and the length of time they last are two aspects that are considered while classifying sags. Voltage drop is responsible for 80% of the power quality problems that occur in distribution and transmission networks [10].

The duration of the voltage sag, the size of the voltage drop, and the depth it reaches are the voltage sag characteristics that are the easiest to identify. Dynamic equipment including robots, automated storage devices (ASDs), high-intensity discharge (HID) lighting, and programmable logic controllers (PLCs) may be negatively impacted by harmonics and voltage sags[.

Although passive filters, capacitor banks linked in parallel with the power supply, and uninterruptible power supplies are proven and trusted solutions, they are not guaranteed to be successful in removing harmonics and voltage sags. Other methods may be more effective in this regard. PV-STATCOM is based on research into active power filters, and this research shows that it might be used to maintain renewable energy sources linked to the grid in the face of voltage dips and harmonic distortion. PV-STATCOM is based on this research. Harmonics and voltage sags are produced as a result of the suggested test model, however, this investigation takes into account the sophisticated control strategy of PV-STATCOM, which may actively alleviate these issues.

In order to produce the appropriate quantity of reactive and actual power to enable grid voltage recovery during a sag, it is necessary for all generating units to maintain a continuous connection inside a grid, according to the information supplied in [11-13]. This is the scenario to create the necessary quantity of real and reactive power (Q).

The main focus of grid standards [14-16] is on ensuring that there is no variation in either the frequency or the voltage of the power supply. Anti-islanding protection requires local loads to be de-energized by power plants in the event that there is a fall in voltage or a disruption in frequency on the grid. This is done in the event that the grid experiences a disturbance. Nevertheless, in the event that the operation is not functioning normally, the shunt-connected Voltage Source Converter (VSC) of the PV-STATCOM will add reactive power to the grid in the event of a grid failure. This reactive power will be required in addition to the reactive power that will be necessary to maintain the grid-integrated system's smooth operation and the reactive power that will be necessary for the load and wind generators to remain in compliance with the LVRT standard.

2. Literature Review

In this section, a list of previous studies on this topic will be presented:

In 2023, J. W. Shin et al.[17] According to the kind of SFCL being employed, this research assesses the impacts of increasing the voltage sag's amplitude, duration, and frequency. The power system simulation programmer PSCAD/EMTDC is used to analyses a problem in the power distribution system first according to the kind of SFCL and the fault current-limiting element (CLE). Second, an assessment is made of the anticipated voltage sag frequency brought on by a feeder problem in the power distribution system.

In 2023, H. Sun et al.[18] In order to address transient instability during low voltage ride-through (LVRT) under weak grid circumstances, a full-order large-signal model of the voltage source converter (VSC) is presented in this study. The possibility of current transients causing VSC to lose stability is shown by the study. In order to assure small-signal and transient stability, a stability-enhanced LVRT control is developed after the inherent mechanism of the VSC losing stability under weak grid circumstances is discovered. Through real-time simulation, the theoretical analysis is validated.

In 2023, X. Zambrano et al. [19] Voltage sags are random fault-related power quality problems. Monte Carlo simulations and other probabilistic techniques examine their frequency and severity. This study examines how voltage sag severity is affected by model uncertainty, concentrating on key input factors that affect voltage sag levels. The approach, which is based on ANOVA, determines if uncertainty substantially influences the severity indices for voltage sags. In IEEE test networks and the Ecuadorian power system, the research assesses the impact of uncertainty on the voltage sags indices SARFI90 and SARFI70. To comprehend how the modelling of input factors affects anticipated sags, general patterns are produced.

In 2023, C. A. Ramos-Paja et al.[20] As low-voltage photovoltaic systems are utilized more often in power grids, power converters, static and dynamic modelling, passive components, and controller settings must be adjusted. In order to improve the performance of conventional buck converters, this research proposes a low-voltage system that makes use of a continuous input/output current buck converter. The technique combines a sliding-mode controller for maximum power extraction, perturbation rejection, and a mathematical model of the system's dynamic behaviour. A comparison with traditional buck converters and an application case employing products from the market serves to verify the technology. A perturb and observe technique is used to create the control strategy, This guarantees system stability, monitors peak power, and filters out double-frequency oscillations brought on by micro inverters.

In 2023, S.N. Setty et al.[21] In order to solve power quality difficulties in solar PV-based IEEE 33 bus systems, In this study, a hybrid control technique using a dynamic voltage restorer (DVR) is presented. The DVR uses solar energy to boost dynamic performance and efficiency. The system employs a proportional-integral controller and a fuzzy logic controller to reduce THD for load voltages by 1.06% and 1.05%, respectively. The suggested design performs better than earlier studies and complies with IEEE 519 criteria.

In 2023, Y. Zhang et al. [22] The authors provide a two-stage voltage control technique based on ADMM with an improved power-to-hydrogen model for active distribution networks (ADN). Within RPVCs, the plan optimizes intra-day control, power flow, and residential PV. The method has been updated and lowers voltage violations satisfactorily. Testing was conducted using the IEEE 69-bus and IEEE 33-bus distribution systems.

In 2022, A. S. Al-Qarni et al. [23] The efficacy of a Dynamic Voltage Restorer (DVR) and Distribution Static Compensator (D-STATCOM) in Saudi Arabia in reducing voltage sag at the common coupling point is examined in this article. According to the findings, DVR is more efficient than D-STATCOM in resolving voltage sag problems.

In 2022, Z. Yikun et al. [24] Using sequential trajectory feature learning and the Random Forest algorithm, this study presents a useful and understandable way for categorizing voltage sag origins. In order to find interpretable shapeless sub-sequences, the fused lasso generalized eigenvector (FLAG) technique is employed, then shape let transformation, and finally random forest training. By using shape let interpretability, the technique accomplishes supervised sample classification. The categorization of voltage sag causes using simulation examples shows notable improvements in accuracy and interpretability.

In 2022, Z. Li et al. [25] Power grid voltage depth calculation and real-time sag occurrence depend on voltage sag detection. Under less than perfect grid circumstances like imbalance or harmonic interference, conventional techniques like synchronously rotating frames suffer. The strategy to improve immunity proposed in this work uses a selective harmonic extraction algorithm (SHEA). The controllability, stability, and convergence of SHEA are examined, and the state-space model is constructed. In order to maximize low- and middle-frequency gains, a gain compensator is utilized. Under less-than-ideal grid circumstances, simulation results demonstrate strong dynamic and steady-state performance.

In 2022, Y. Mohammadi al.[26] The primary instantaneous-based and positive-sequence phasor approaches for detecting voltage sag sources in real time are examined in this paper. In order to produce quicker and more precise reactions. It recommends five unique strategies that use modifiers during voltage sags' transient phase, including half-cycle and one-cycle time frames.. By capturing half or one cycle during a short period of voltage sags and demonstrating accuracy comparable to other upgraded techniques, modified methods outperform conventional approaches. To validate their efficacy in transitory brief durations, the chosen modified approaches are tested in a Slovenian power network. The offered methods may be applied as directed functions in relays as well as real-time voltage sag/fault inception time detection algorithms.

In 2019, Yang Han et al.[27] In wind and solar power, there is a danger of voltage sag and fault occurrences that may cause power outages and lower active power generation. These hazards are discussed in the article. It also suggests four voltage sag generators (VSGs), presents a real-time digital simulator for converter controllers, and emphasizes the need of evaluating low-voltage ride-through (LVRT) capabilities in renewable energy systems. The use of VSG in renewable energy systems and potential future study areas are also covered in the report.

In 2017, T. Aziz et al. [28] In low-voltage AC networks, photovoltaic embedded generation presents difficulties, especially when voltage violations surpass limits. According to a survey of the literature, when a sizable distributed generator is put at one location, voltage violations may happen at penetration levels as low as 2.5%. Multiple PVDGs may be hosted by LV networks, with a penetration level of up to 110% if dispersed uniformly across shorter lengths. To create regulations for safe penetration limitations in LV networks, a more logical strategy is required.

3. Mitigation of Voltage Sags

Mitigation of voltage sags refers to the actions taken to minimize or reduce the occurrence and impact of voltage sags in an electrical power system. A voltage sag, which is sometimes referred to as a voltage dip or a transitory interruption, is a brief (usually within a few seconds) drop in the voltage level. Voltage sags may result from a number of things, including power grid problems, abrupt changes in load demand, or the beginning of big motors.

Sensitive electrical equipment and gadgets may suffer negative impacts from voltage sags. For instance, they may result in the breakdown of electronic equipment, the interruption of commercial operations, or the loss of data in computer systems. As a result, preventing voltage sags is essential to ensuring the consistent performance of electrical systems.

There are several methods employed to mitigate voltage sags:

1. Voltage regulators: Automatic voltage regulators stabilize and regulate voltage levels by detecting variations and compensating by adjusting output voltage, minimizing voltage sags in sensitive equipment.
2. Uninterruptible Power Supplies (UPS): UPS systems offer stable backup power during voltage fluctuations, ensuring continuous operation and protection against voltage fluctuations for connected devices.
3. Static VAR compensators (SVC): SVCs regulate voltage levels by rapidly injecting or absorbing reactive power, maintaining stability and mitigating voltage sags, ensuring efficient system operation.
4. Voltage sag ride-through techniques: Advanced electrical equipment, like adjustable-speed drives and industrial machinery, can tolerate voltage sags without disruption using ride-through techniques and energy storage systems.
5. Power quality improvement measures: Improve power quality through grounding, harmonic filtering, and load management techniques to enhance stability and reliability in electrical power systems, reducing voltage sags.

To achieve the goal of minimizing the amount of voltage drop that occurs in a grid-connected setup, Here, The primary objective will be to maximise the alignment of the test model and the dynamic performance of the PV-STATCOM. In order to inject the necessary amount of active and reactive power to recover the grid voltage and correct the harmonics, a PV-STATCOM with a voltage source companion transformer (VSC) was connected to the shunt.

4. Configuration of the Proposed System

The simulation requires us to create an accurate model of the network in order to get precise simulation results. ETAP is used to create a power system model for simulation. The transmission line and the load were modelled using the Distributed Line Parameters and Three-Phase load blocks, respectively. Fig. 1 shows the proposed system for this paper.

Steady-state and voltage sag mitigation studies are performed in ETAP software. The distribution system is analysed in this study. The transmission system voltage level is 220kV. The distribution system voltage level is considered to be 35kV.

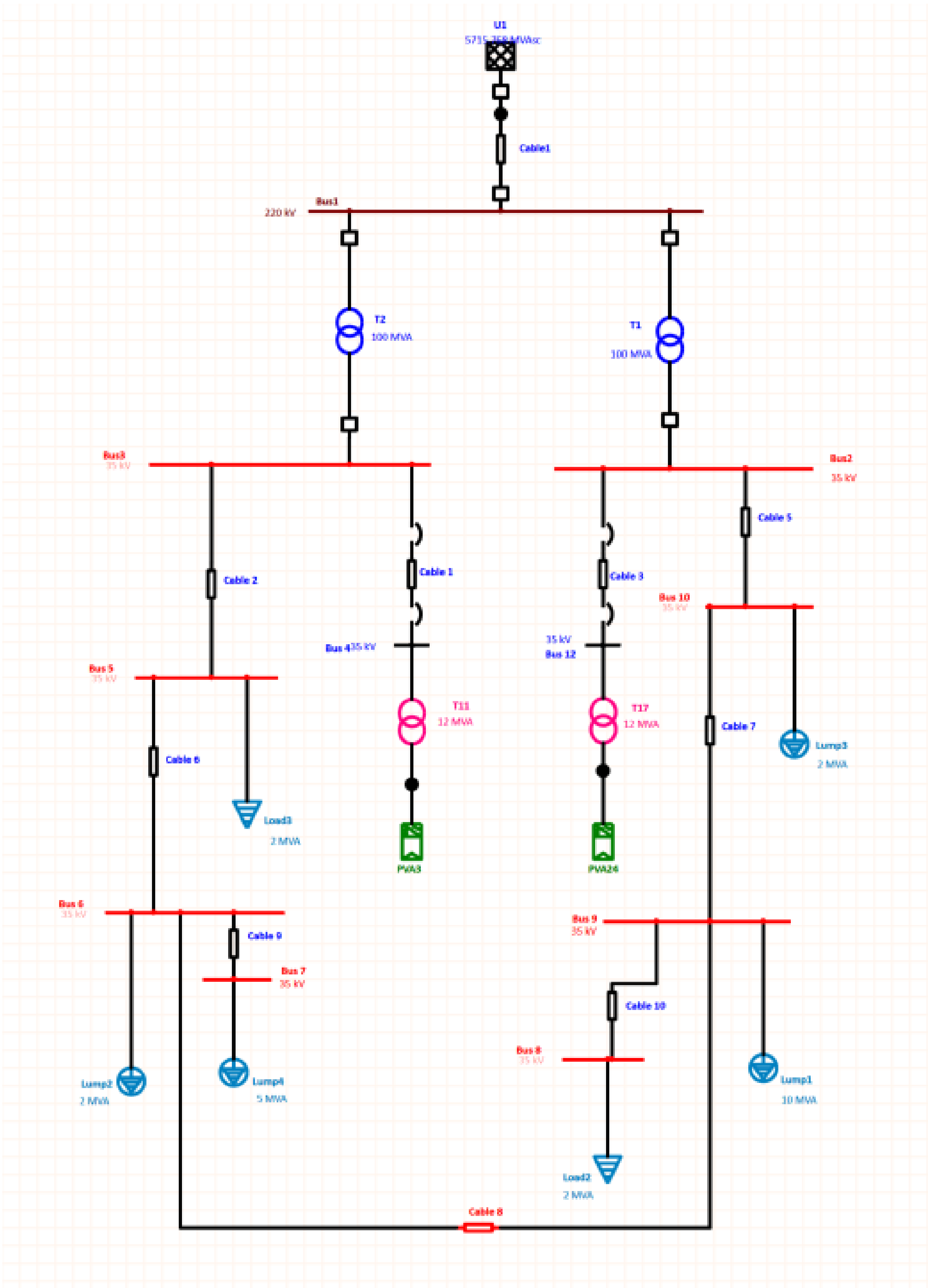


Fig. 1. One-line Schematic diagram of the proposed system using ETAP

5. System Analysis and Results

System analysis and results for voltage sag mitigation methods in low voltage networks with photovoltaic units involved a comprehensive study that focused on the modelling and analysis of various techniques. The research aimed to address the challenge of voltage sags, which can occur due to the intermittent nature of solar energy generation. To assess and decide on the best course of action to reduce the voltage sag, two alternative studies with additional scenarios were simulated. In the first investigation, steady-state studies are carried out to determine the voltage level in typical scenarios.

In the second research, transient study evaluations are carried out to determine how much voltage sag occurs during load shedding. When the amount of voltage on the bus exceeds what is considered acceptable in a typical steady-state analysis, a load-shedding scenario is chosen. With solar PV plants, without solar PV plants, and with battery storage-based DVR, the mitigation of voltage sag is evaluated.

5.1. Study State Analysis

The steady state assessment of a power system network is called a load flow study. The operational condition of the system for a specific loading is determined by a load flow analysis. The voltage, phase angle, real and reactive power (on both sides of each line), line losses, and slack bus power are the results of the load flow analysis.

The results of the load flow calculations performed using the ETAP program are shown in Tables 1, 2, and 3. The load flow analysis is shown in Table 1 and the Power flow through transformers and cables is provided in Table 2. Voltage drop is carried out, and Table 3 displays the outcomes. The voltage loss on all bus bars appears to be outside the acceptable ranges according to the estimates in Table 2. The voltage drop shall not exceed 5% of the operational range.

5.2. RMS Study Analysis

5.2.1. Voltage sag without solar PV plant

In this case, the active and reactive load increased to 50% in the transient study. The simulation time is considered to be as 5.0 seconds. Load shedding time is considered to be at 2.2 seconds. The voltage profile is checked at busses 6,7,8 and 9 as in steady state voltage drop were higher than the accepted limits. Fig. 2 present the load flow analysis without PV plant.

Voltage sag case is performed using transient study package of ETAP. According to the results shown in Fig. 3, the voltage level at bus bar 8 drops to 31.52 kV when the load shading scenario is applied. Voltage angle results are shown in Fig. 4. Load shedding is considered to be 50% for both active and reactive power (as shown in Fig. 5). A load-shedding scenario for both Active and reactive power is provided in Fig. 5. As per the result obtained in this section, the level of voltage is not within the accepted limits, while a transient case happens. The same study is checked in the next section by considering the connection of the solar PV plant at Bus bar 9.

Table 1. Load Flow analysis results

Study ID	Power Flow
Study Case ID	LF
Data Revision	Base
Configuration.	Normal
Loading Cat	Design
Generation Cat	Design
Diversity Factor	Normal Loading
Buses.	14
Branches.	14
Generators.	0
Power Grids	1
Loads.	6
Load -MW	19.197
Load- Mvar	10.854
Generation -MW	19.57
Generation -Mvar	13.577
Loss -MW	0.372
Loss -Mvar	2.723
Mismatch -MW	0
Mismatch -Mvar	0

Table 2. Load Flow analysis results-power flow through cables and transformers

ID	Type	kW Flow	kvar Flow	Amp Flow
Cable1	Cable	897.1	-13576.7	35.71
Cable 1	Cable	10177	-733	169.6
Cable 2	Cable	9160	4978.3	173.3
Cable 3	Cable	10176.7	-736.9	170
Cable 5	Cable	10290.9	7001.3	207.4
Cable 6	Cable	7189.5	4975.8	145.3
Cable 7	Cable	8597.1	5948.6	174.2
Cable 8	Cable	1244.7	923	26.73
Cable 9	Cable	4177.5	2589.5	84.77
Cable 10	Cable	1375	1078	30.44
T1	Transf. 2W	116.5	7817	20.52
T2	Transf. 2W	1015.5	-5756.4	15.34
T11	Transf. 2W	10233.3	0	7418
T17	Transf. 2W	10233.3	0	7438

Table 3. Load Flow Analysis results-voltage deviation

Bus ID	Nominal kV	Voltage	MW Loading
Bus1	220	99.98	1.016
Bus2	35	99	10.291
Bus3	35	99.26	10.176
Bus4	220	100	0.897
Bus 4	35	99.26	10.177
Bus 5	35	99.24	9.159
Bus 6	35	95.64	7.093
Bus 7	35	95.63	4.177
Bus 8	35	92.27	1.362
Bus 9	35	94.67	9.699
Bus 10	35	98.98	10.29
Bus 11	35	99	10.177
Bus12	0.8	99.56	10.233
Bus13	0.8	99.29	10.233

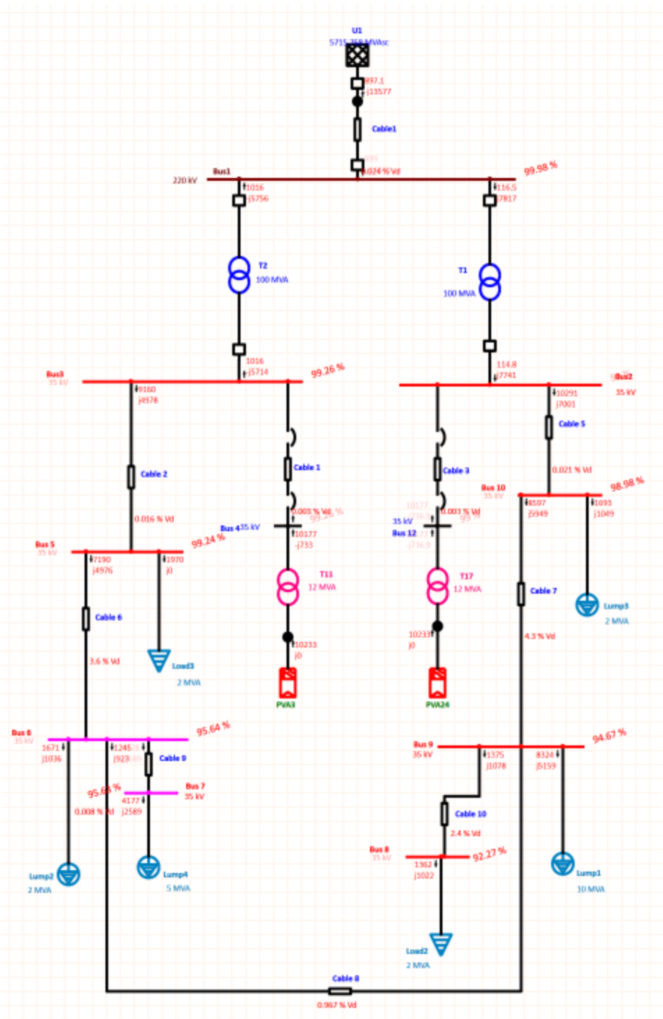


Fig. 2. One-line Schematic diagram of the proposed system without PV plant

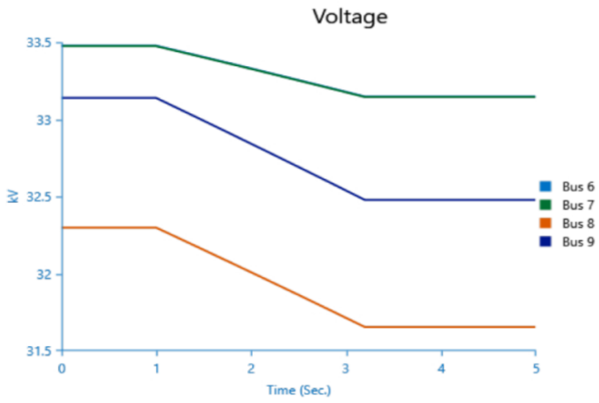


Fig. 3. Voltage sag in transient case

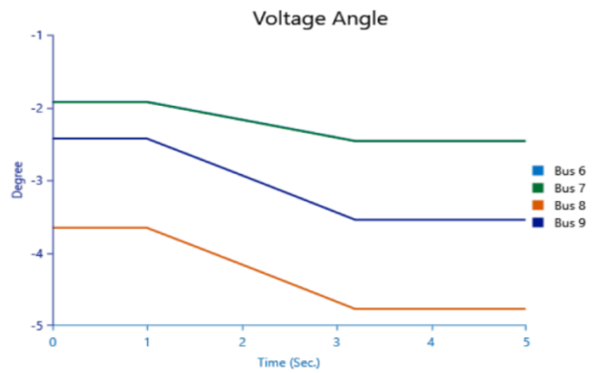
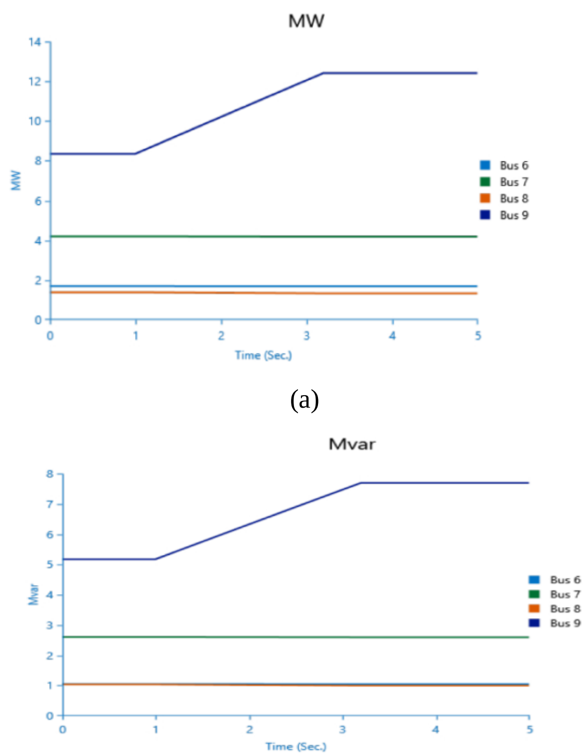


Fig. 4. Voltage angle in transient study-NO SPP



(b)

Fig. 5. Power load increase in transient study: a) Active power and b) Reactive power

5.2.2. Voltage Sag with Solar PV Plant

In this case, the transient study's active and reactive load rose by 50%. Five seconds are taken into account for the simulation time. The average load-shedding time is 2.2 seconds. Buses 6, 7, 8, and 9 had their voltage profiles evaluated since the steady-state voltage loss was greater than the permitted limits. The load flow study with a PV plant in bus bar 9 is shown in Fig. 6.

The transient study package of ETAP is used to execute the voltage sag scenario. Fig. 7 findings indicate that when the load shading scenario is used, the voltage level at bus bar 8 reduces to 35.7 kV. Fig. 8 shows the voltage angle results using SPP on bus 9. For both active and reactive power, load shedding is regarded as 50%, load shedding scenario for both Active and reactive power is provided in Fig. 9.

As per the result obtained in this section, the level of voltage is within the accepted limits in transient case considering the connection of SPP at Bus 9. The same study is checked on the next section with considering connection of battery storage system based DVR at bus bar 9.

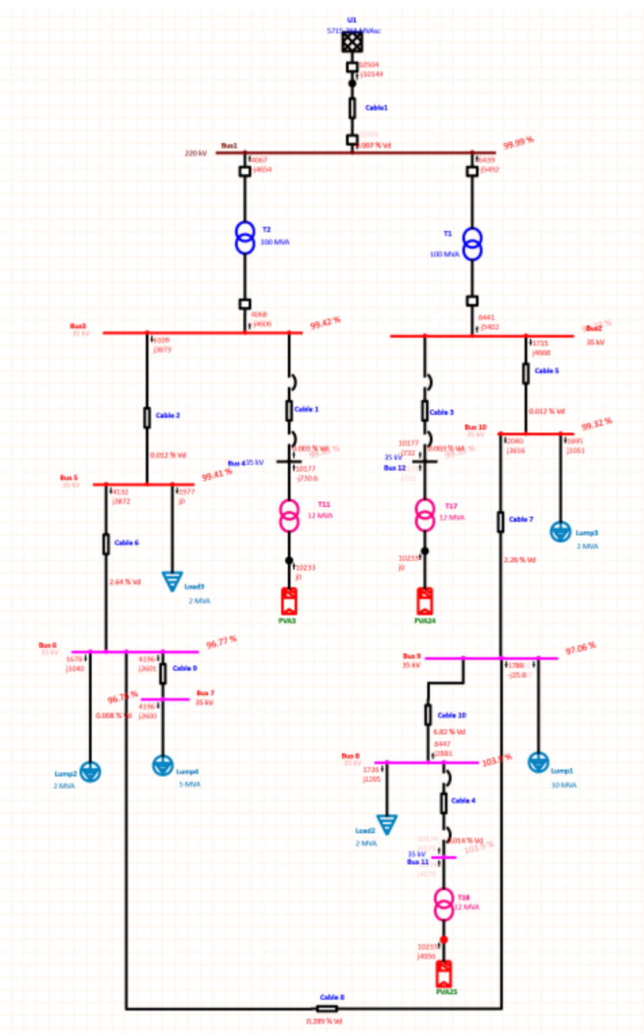


Fig. 6. One-line Schematic diagram of the proposed system with PV plant

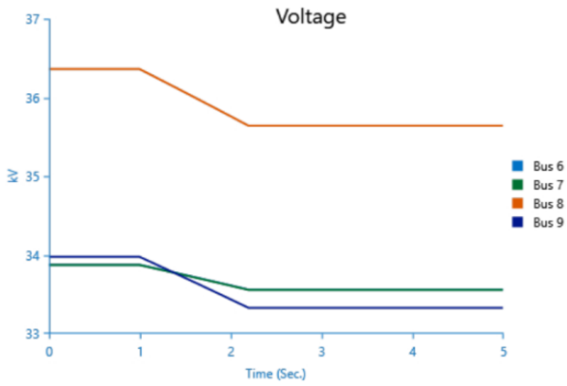


Fig. 7. Voltage sag of the system with PV plant

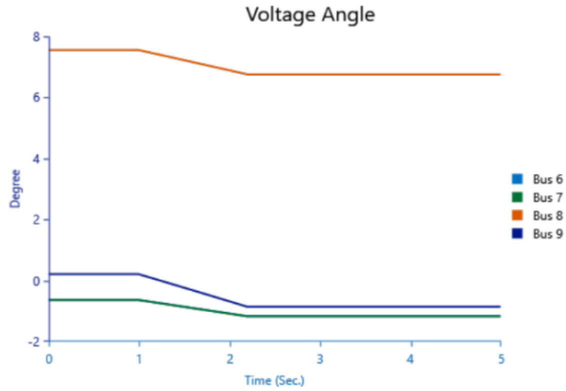
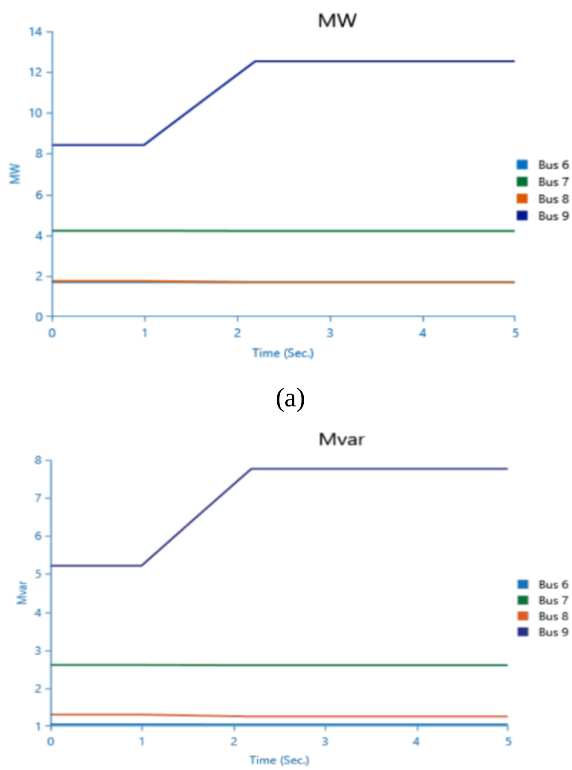


Fig. 8. Voltage angle in transient study-NO SPP



(a)

(b)

Fig. 9. Power load increase in transient study: a) Active power and b) Reactive power

5.2.3. Voltage Sag with Solar PV Plant

In this case the transient study's active and reactive loads both climbed to 50% when the battery-based DVR was connected in bas bar 9 (as shown in Fig. 10). Five seconds are taken into account for the simulation time. The average load shedding time is 2.2 seconds. Buses 6, 7, 8, and 9's voltage profiles are being examined since steady-state voltage decreases exceeded the established thresholds.

Fig. 11's shown to indicate that when the load shading scenario is used, the voltage level at bus bar 8 reduces to 31.57 kV. Fig. 12 shows the voltage angle results using battery based DVR on bus 9.

Refer to Fig. 13 for the definition of load shedding as 50% of combined active and reactive power.

A load-shedding scenario for both Active and reactive power is provided in Fig. 13. As per the result obtained in this section, the level of voltage is within the accepted limits in the transient case considering the connection of the battery storage system at Bus 9.

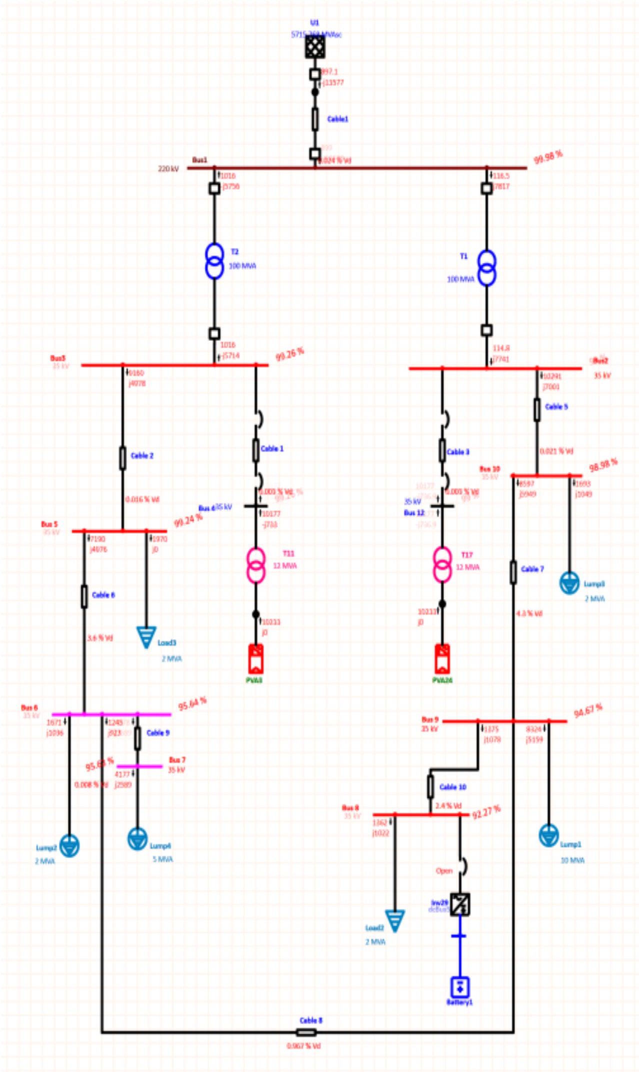


Fig. 10. One-line Schematic diagram of the proposed system with battery based DVR

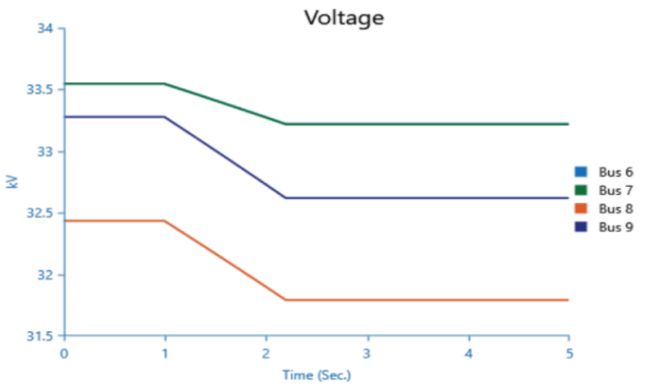


Fig. 11. Voltage sag of the system with battery based DVR

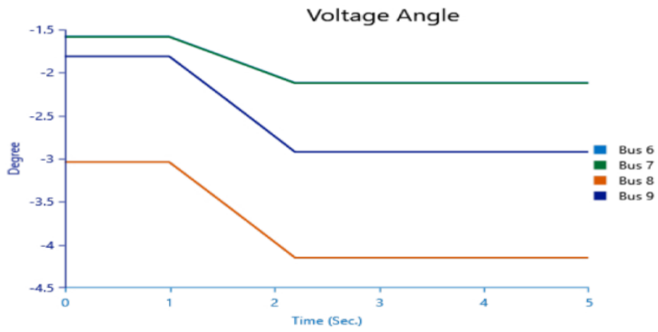
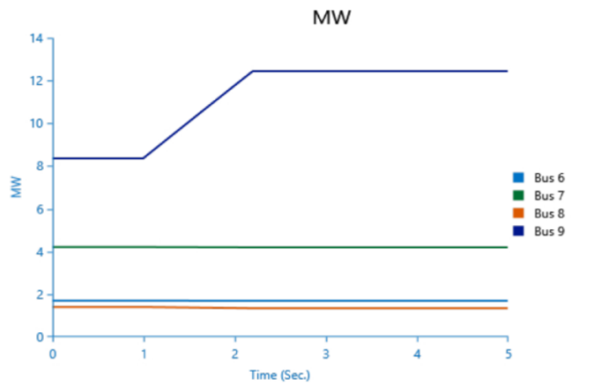
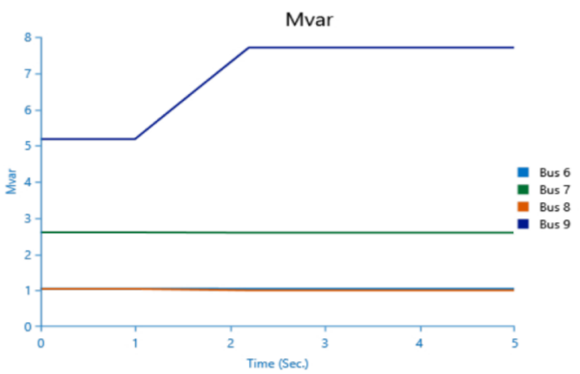


Fig. 12. Voltage angle of the system with battery based DVR



(a)



(b)

Fig. 13. Power load increase of the system with battery based DVR: a) Active power and b) Reactive power

6. Conclusion

Normal steady state and transient state studies are performed in this paper to check the voltage deviation. The normal steady state is performed to determine the weakest points on the basis of voltage deviation. According to the steady-state analysis, the weakest points by voltage deviation are bus bars 6, 7, 8, and 9. These bus bars are further analyzed in transient studies. The transient steady analysis is performed to check the voltage sag in emergency cases (Load shedding). In this study, the following cases are analysed:

- Without SPP and Battery,
- With Solar PV plant,
- With battery storage system.

A comparison of the results is provided, without SPP and Battery kV is equal to 31.52, U, With Solar PV plant kV is equal to 35.7, and with battery storage system kV is equal to 31.5. As per the results, the connection of the PV plant storage system is having a much more positive effect on the bus bars where voltage sag is high in emergency cases.

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