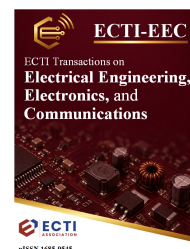


Unbalance Reduction in LV Networks with High PV and EVs via Droop-Controlled BESS

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Unbalance Reduction in Low-Voltage Networks with High PV and EV Penetration via Droop Controlled Battery Energy Storage Systems

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ABSTRACT

Low-voltage distribution networks are experiencing increasing phase current unbalance due to the widespread installation of single-phase photovoltaic systems and electric vehicle chargers. These unbalance results in increased power losses, transformer thermal stress, and accelerated asset degradation. This article proposes a decentralized droop control method using three independent single-phase battery energy storage systems mounted on LV transformers. The proposed control scheme regulates the charging and discharging of each BESS based on the deviation between individual phase currents and the average phase current, while explicitly considering the state of charge limitation. This method relies only on local current measurements and does not require centralized communication. The effectiveness of the proposed method was validated using a real residential low-voltage distribution network with high PV and EV usage. Simulation results demonstrate a significant reduction in the current unbalanced factor, improved phase current symmetry, reduced feeder losses, and relief from transformer thermal stress. Technical and economic assessments further demonstrate that the proposed strategy is a more cost-effective alternative to traditional grid strengthening in low-voltage networks.

Keywords: Unbalance mitigation, Low-voltage network, Battery energy storage systems, Droop control.

Nomenclature

VUF	Voltage unbalance factor (%)
CUF	Current unbalance factor (%)
I	Current (A)
R	resistant (Ω)
$I_{negative-seq}$	Negative-sequence current
$I_{positive-seq}$	Positive-sequence current
$P_{grid,ph}$	Phase active power on grid (kW)
$P_{grid,max}^*$	Maximum power denotes the power available on the DC side (kW)
$i_{ph,max}$	Maximum allowable current (A)
$P_{BESS,ph}$	Active power on BESS (kW)
$P_{BESS,ph,max}$	Maximum power that BESS can handle (kW)
$P_{balance,ph}$	The results of energy balance control (kW)
P_{bat}	The exchanged power of the BESS (kW)
P_{SOC}	Power by the charging state limit (kW)

$i_{ph,min}$	Minimum allowable current (A)
i_{avg}	The current is starting to reduce its power (A)
i_{ph}	Phase current can be measured (A)
$SOC(t)$	State of charge at different times (%)
$SOC(t-1)$	State of charge at the previous time step (%)
SOC_{min}	Minimum state of charge (%)
SOC_{max}	Maximum state of charge (%)
Q_{nom}	Rated battery capacity (Ah)
$I(t)$	Current supplied or received (A)
η	Charge/discharge efficiency (%)
Δt	Time between the sample's measurements
C_{loss}	Loss cost
$C_{loss\ of\ life}$	Transformer loss of life cost
$C_{O\&M}$	Operation and maintenance cost
V	Relative aging rate (%)
L	Loss of life
C_h	Base cost per hour
NPV	Net present value
Cf_0	Cash flow at the beginning
Cf_1	Cash flow in the following year

1. INTRODUCTION

The global shift to renewable energy has had a significant impact on the electricity distribution network, particularly with the rise of distributed generation (DG), such as photovoltaics (PV), and the increasing adoption of electric vehicles (EVs). Distributed network operators (DNOs) face significant challenges in maintaining power quality. Power quality issues, including voltage drops and grid unbalance, caused by DG units and single-phase EV charging loads, can impact the low voltage network (LV), particularly in high-demand areas. Voltage unbalance (VU) occurs due to uneven loading or single-phase connections.

Voltage unbalanced problem It is found that single-phase connected PV panels can cause uneven three-phase power flow, resulting in unbalanced power and voltage in the grid [1]. In addition, the random charging behaviour of EVs equipped with single-phase chargers on board is expected to further increase the voltage unbalance as the number of these devices increases [2]. Despite advances in modern compensation devices and control strategies that can reallocate power, challenges remain.

However, previous work has emphasized the problem of reducing unbalance using a hierarchical control strategy, which can effectively reduce voltage unbalance and neutral current by coordinating EVs. This involves a

central controller and local controllers, which minimize the number of EVs needing coordination, thus reducing computational complexity and data processing overhead [3]. There is research that talks about phase restructuring devices being installed strategically within the grid. This approach involves analysing the location and different objective functions to optimize the placement and operation of these devices [4]. A dynamic power balancing system is implemented, enabling the transfer of unbalanced power from a heavily loaded feeder to a nearby, lightly loaded feeder using a tie-wire voltage source converter (VSC) [5]. A novel approach using genetic algorithms is proposed to optimize the discharge rate of EVs to reduce unbalance in the LV distribution grid. The approach aims to distribute the load evenly across all three phases, addressing the unbalance caused by the PV system and EV charging demand. It can reduce the voltage unbalance to less than 2% across all nodes and minimize the neutral current on the supplying feeders [6], and the smart charging algorithm for EVs is based on predicted future grid load probability with grid congestion prediction, which reduces congestion. Using higher percentiles in PV generation forecasting during EV scheduling significantly reduces transformer congestion, even though EV charging costs increase slightly [7]. To address the unbalanced of the low-voltage power grid caused by PV and EV, it has been proposed to optimize the transmission of PV and EV power using a Differential Evolution (DE) algorithm. This approach minimizes the total power loss and increases the bus voltage by ensuring that the power delivered from each source remains within its operating limits. The approach also considers the state of charge (SOC) of the EV batteries, enabling the efficient integration of distributed power sources in an unbalanced distribution grid [8].

Most research remains limited by the complexity of communication systems and focuses solely on achieving technical results without evaluating the cost-effectiveness of the investment. To demonstrate the strengths of the proposed methodology, addressing phase unbalance in LV networks with high PV and EV integration is a critical challenge. While a recent review [9] outlines various compensation methods, many require complex communication or rely on three-phase BESS, limiting their flexibility in handling single-phase loads. Recent literature [10] has explored coordinated control of three single-phase inverters using local measurements to address voltage unbalance; however, these efforts focus almost exclusively on technical metrics.

The following Table 1 summarizes and compares the differences in the control structure and objectives of this research with the relevant literature.

This paper presents an alternative approach using a decentralized droop control strategy with three independent single-phase BESS units. This method operates without central communication, dynamically managing charge and discharge based on the deviation of each phase current from the average. Most importantly,

this work expands beyond technical validation by incorporating a techno-economic assessment. By explicitly accounting for loss reduction and delayed transformer degradation, it demonstrates the financial feasibility of the proposed BESS strategy over conventional grid strengthening.

Battery energy storage systems (BESS) are also an alternative solution to address grid unbalances and improve grid stability. A battery installation simulation project, called the Neighborhood Battery Projects, is piloting the installation of batteries on low-voltage grid poles in communities to support local distribution networks and postpone costly infrastructure upgrades [11]. To mitigate voltage unbalance, a BESS can be connected to the same phase as a single-phase PV system to effectively reduce the VU [12] and significantly improve the voltage profile by absorbing excess energy during peak solar generation periods and releasing it during peak demand periods [13]. Distributed power generation strategies have been explored to address both overvoltage and undervoltage during the evening when EVs are being charged. Although BESS offers a promising solution to voltage unbalance that can lead to phase unbalance and system overloads, challenges remain, such as balancing the power supply by considering the phase currents to determine the battery charge and discharge times. This may require more sophisticated management strategies to achieve more realistic operation. Using battery energy storage systems for phase balancing. Most of the research has focused on three-phase BESS, which consists of a three-phase inverter that controls the combined active and reactive power of all three phases. Therefore, it is suitable for controlling pressure and total energy in systems with a relatively balanced load. But it has limited flexibility when unbalanced loads or single-phase production occur [14]. A single-phase energy storage system (single-phase BESS) uses one inverter per phase. This makes it possible to directly supply or receive energy for only the phase in question. This results in high efficiency in reducing current and voltage unbalance in low-voltage systems with many single-phase PV and EV connections [10]. Despite the need for multiple inverters and higher costs, single-phase BESSs offer greater flexibility and accuracy in controlling phase-by-phase current. Therefore, it is suitable for low-voltage networks that have severe unbalanced problems.

With the promotion of renewable energy, the application of PV, EVs, and BESS has increased significantly recently. Costs and benefits are key factors driving investment in integrated energy systems [15]. Therefore, optimization for cost-benefit analysis of investment has become a promising solution, offering both technical and economic benefits to the low-voltage grid.

In addition to energy profitability and peak charge reduction, BESS can also provide strategic control to reduce current unbalances and adjust for fluctuations caused by solar and EV charging, significantly reducing grid energy losses and even eliminating the need for costly power reinforcement

Table 1: Comparison of the proposed method with existing approaches

Feature	Centralized Architecture [10]	Proposed Decentralized Architecture
Problems to be solved	Voltage Unbalance (VUF)	Current Unbalance (CUF)
Control Strategy	Optimization-based	Current-based droop control
Measurement Requirement	System-wide data	Local current only
Communication	Required	Not required
BESS Configuration	3 Single-Phase Inverters	3 Single-Phase
Evaluation Method	Technical	Techno-economic

In “Fig.1:”, illustrates an approach to analyse the impact of unbalances caused by connecting PV modules and single-phase EV chargers to the low-voltage network, focusing on designing an optimal BESS control mechanism to balance the load and maintain system stability. This is a key issue facing DNOs, addressing key challenges in long-term investment in low-voltage distribution networks, such as transformer replacement and cable sizing.

Despite the extensive research on unbalanced mitigation using EV coordination, power electronic devices, and centralized optimization algorithms, most existing approaches either rely on centralized communication, complex optimization frameworks, or three-phase BESS configurations. These methods may face scalability, implementation complexity, or limited flexibility when addressing severe phase current unbalanced caused by widespread single-phase PV and EV connections in low-voltage networks.

This article addresses the research gap by proposing a decentralized, electrically driven control approach using three independent, single-phase battery energy storage systems (BESS) installed at a low-voltage transformer. The main findings of this article are summarized as follows:

- A current-based droop control strategy for three independent single-phase BESS units is proposed to mitigate phase current unbalance in low-voltage networks heavily utilized by single-phase PV and EV chargers.

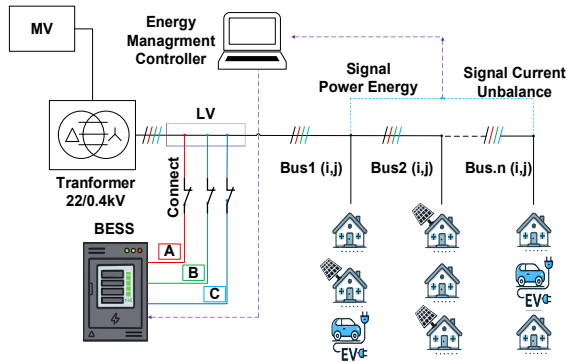


Fig.1: Diagram of LV network with unbalanced conditions management

- A comprehensive techno-economic assessment is conducted, including loss reduction, transformer aging, payback period, and NPV analysis.

2. MANAGING UNBALANCED CONDITIONS IN LOW-VOLTAGE NETWORK

Low-voltage networks are particularly prone to phase unbalance due to the widespread use of single-phase loads and distributed power sources. In residential networks, rooftop PV systems and EV chargers are often single-phase, resulting in uneven power supply and usage across three phases. This uneven phase loading leads to asymmetrical current flow at transformers and along transmission lines.

Phase-current unbalance has significant technical implications in LV systems, where a high reactance-to-resistance ratio (R/X) makes current a major factor contributing to power loss and thermal stress. Excessive current unbalance increases losses in conductors and transformers, accelerates equipment degradation, and can negatively impact three-phase equipment operation.

Current unbalance is typically measured using the current unbalance factor (CUF), a condition where the three-phase currents differ in magnitude and angle. A high CUF directly indicates inefficient network operation and increased thermal load on distribution equipment. Unlike centralized or three-phase compensation methods. In a three-phase system, voltage unbalance is defined as the condition where the three-phase voltages are not equal in magnitude and/or their angles differ by 120 degrees [16]. A voltage unbalance of less than 2% as defined by the IEC standard [17] serves as the primary indicator of voltage unbalance in a three-phase electrical system, and the maximum current unbalance value of the electrical system is 5%, which is regulated in ANSI C84.1-1995 [18]. It is defined by the following equation 1.

$$CUF = \frac{|I_{negative-seq}|}{|I_{positive-seq}|} \times 100\% \quad (1)$$

This research focuses on managing and resolving unbalance by controlling three single-phase battery energy storage units (BESS) mounted on poles at the transformer junction. To detect power unbalance in the system, we control the actual power output by measuring the current at the phase common junction (PCC) at the inverter terminals. The measured currents for each phase are then

compared to the average current (I_{avg}) to determine the phase current difference. Subsequently, a current-based droop control strategy optimized the charging and discharging behaviour of each BESS to minimize deviations from the average phase current while maintaining the battery's State of Charge (SOC). The efficiency of the proposed method was evaluated using CUF as the primary performance indicator, as shown in “Fig. 2.”.

3. PROPOSED CONTROL TECHNIQUES UNBALANCED REDUCTION USING SINGLE PHASE BESS

Various control strategies have been proposed by researchers, which can be broadly classified into (1) centralized control and (2) decentralized control. Although centralized control can effectively manage the overall network, in practice for LV networks, installing a centrally coordinated communication system is costly and carries a risk of communication failure. Therefore, this research proposes a decentralized control system that is more robust, cost-effective, and can respond promptly to current unbalance problems, where each BESS responds only to local current measurements without communication. Different BESS control systems have been developed based on different parameters. In [19], two BESS strategies are proposed, in which the decision to store or release energy is based on the energy available from the primary power source. This means that if the power of the BESS is higher than a certain maximum value, the BESS is charged, and in contrast, if the power is lower than a certain value, the BESS is charged. The disadvantage of this approach is that the BESS sometimes becomes overloaded even when the grid voltage is within its limit. A droop control strategy for BESS is proposed, which uses grid voltage measurement and charges the battery according to a set voltage threshold. Therefore, in this research, the same approach is applied to the BESS controller, replacing voltage measurement with current flow measurement, which considers current as the input signal to the battery in the low-voltage network.

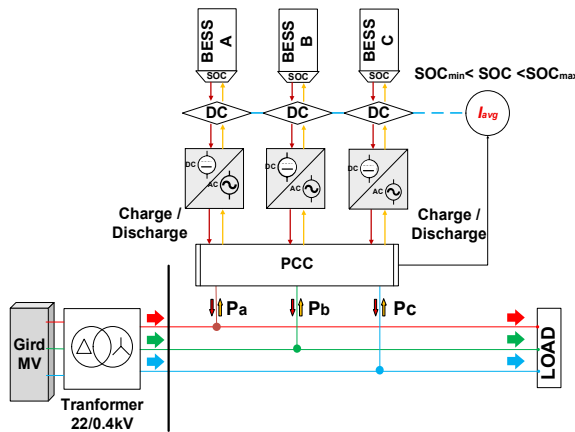


Fig.2: Diagram of a single BESS system for managing unbalanced conditions

3.1 Proposed Droop Control Strategy

This droop controller measures the average value of the three-phase fundamental current, and this value is used as the input to the slack function, as shown in “Fig. 3.”. If i_{ph} is in zone 1, the droop controller allows the distributed power source $P_{grid,ph}$ to supply the entire power received from the mains. The first zone runs from the lowest voltage $i_{ph,min}$ to a constant current i_{avg} . In the second zone, the controller zones from i_{avg} to the maximum allowable grid current $i_{ph,max}$, and drops the supplied power in a linear manner. In the third zone, if the grid current is higher than $i_{ph,max}$, the DRES is disconnected from the grid, and all states are limited. The parameters $i_{ph,min}$ and $i_{ph,max}$ are set to define threshold values that affect the network, which are 0.2 and 0.9 p.u., respectively. The droop controller can be mathematically described as a piecewise linear function as follows:

$$P_{grid,ph} = \begin{cases} P_{grid,max}^* & \text{if } i_{ph} \leq i_{avg} \\ P_{grid,max}^* \cdot \left(\frac{i_{ph,max} - i_{ph}}{i_{ph,max} - i_{avg}} \right) & \text{if } i_{avg} < i_{ph} \leq i_{ph,max} \\ 0 & \text{if } i_{ph} > i_{ph,max} \end{cases} \quad (2)$$

The power available on the direct current (DC) side is equal to the power delivered on the alternating current (AC) side, so $P_{grid,ph}^* = P_{grid,ph}$. The index “*” denotes the power available on the DC side, which can vary from 0 to $P_{grid,ph}^*$ depending on the power delivered from the primary power source.

In equation 3, if i_{ph} is lower than the minimum grid current $i_{ph,min}$, the calculated battery output will be equal to the minimum value between the maximum battery power ($P_{BESS,ph}$) and the difference of i_{ph} with respect to i_{avg} at the BESS. The slack energy will be used to charge the battery. If the grid current is between $i_{ph,min}$ and the minimum threshold of the charging range i_{avg} , the calculated power will be in the linear zone of the charging section. This approach is called symmetric scaling by analogy with the maximum deviation. The output battery power will be equal to 0 only if and only if the grid current is equal to i_{avg} . When i_{ph} is greater than i_{avg} and lower than the maximum grid current $i_{ph,max}$, the droop controller will operate and can supply. In this case study, i_{avg} is chosen to determine the SOC. Therefore, the sign of the output battery power becomes negative. In the final section, i_{ph} is greater than $i_{ph,max}$, so the total power available from the mains will decrease. Therefore, the power output from the battery will be negative and equal to its maximum value during the discharge. Maximum Battery Power ($-P_{BESS,ph}$) with the difference of i_{avg} compared to i_{ph} is in the linear zone of the discharge section.

In “Fig. 4.”, it can be seen that the battery power has both positive and negative values, defined as if the unbalance of each phase has different sizes, which will be considered to distribute the power with the average current to adjust each phase to be balanced by defining the symbol “plus” as charge and “minus” as discharge of the BESS, which can be described as a linear function as follows:

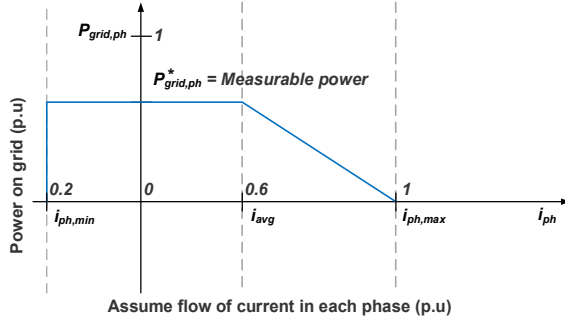


Fig.3: Active power based on the current droop control.

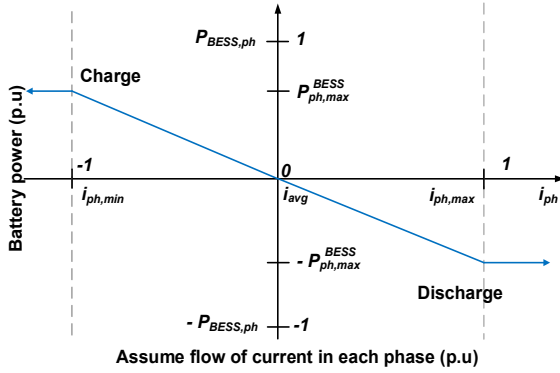


Fig.4: BESS power output on the average current value.

$$P_{ph}^{BESS} = \begin{cases} \min(P_{ph}^{BESS}, (i_{ph} - i_{avg})); & \text{if } i_{ph} \leq i_{ph,min} \\ \begin{cases} P_{ph,max}^{BESS} \left(\frac{i_{avg} - i_{ph}}{i_{avg} - i_{ph,max}} \right) \\ \text{if } i_{ph,min} < i_{ph} \leq i_{avg} \end{cases} \\ 0; & \text{if } i_{ph} = i_{avg} \\ \begin{cases} P_{ph,max}^{BESS} \left(\frac{i_{ph} - i_{avg}}{i_{ph,max} - i_{avg}} \right) \\ \text{if } i_{avg} < i_{ph} \leq i_{ph,max} \end{cases} \\ \max(-P_{ph}^{BESS}, (i_{avg} - i_{ph})); & \text{if } i_{ph} > i_{ph,max} \end{cases} \quad (3)$$

3.2 SOC Constraints in BESS Control

In this step, battery SOC is checked, and the battery controller ensures the minimum and maximum battery charge. In this case, it should be between 10% and 90%, and the battery SOC should be maintained within the limit to extend the battery life.

In equation 5, it is divided into 4 main cases by using the IF condition to set the BESS power value. In the first condition, it checks that SOC does not charge more than 90%, for which we can choose any value between $P_{BESS,ph}$ and $-P_{BESS,max}$ but must not exceed $P_{BESS,max}$. In the second condition, to prevent SOC from exceeding 90%, the charging power calculation will be enough for SOC to charge to 90% accurately. In the third condition, limit the power supply if it exceeds the available power by combining the power from BESS and the electricity demand from the grid, which can supply power that does not exceed the minimum value of 10%. In the last condition, if the power demand of BESS is less than 10,

BESS will not be able to supply power according to $P_{BESS,ph}$ and will stop working immediately.

$$P_{bat} = \begin{cases} \begin{cases} \max(P_{BESS,ph}, -P_{BESS,max}) \\ \text{if } SOC_t - P_{BESS,ph} \cdot \eta \frac{\Delta t}{Q_{nom}} < 1 \end{cases} \\ \begin{cases} (1 - SOC_{t-1}) \cdot \frac{Q_{nom}}{\Delta} \\ \text{if } SOC_t - P_{BESS,ph} \cdot \eta \frac{\Delta t}{Q_{nom}} \geq 1 \end{cases} \\ \begin{cases} \min(P_{BESS,ph}, ((SOC_{min} - SOC_{t-1}) \cdot \frac{Q_{nom}}{\eta \Delta t})) \\ \text{if } SOC_t \leq SOC_{min} \end{cases} \\ 0; & \text{if } SOC_{min} - SOC_{t-1} = 0 \end{cases} \quad (5)$$

In addition, equation 6 is the integral SOC calculation, which is used for systems where the current into/out of the battery is measured over time to calculate the change in SOC.

$$SOC(t) = SOC(t-1) - \eta \frac{\Delta t}{Q_{nom}} \cdot I(t) \quad (6)$$

To prevent the charging and discharging of the battery from exceeding the specified limits, Equation 7 is devised to define that limit.

$$P_{soc} = \begin{cases} \max(P_{bat,ph}, -P_{BESS,ph}); & \text{if } SOC_t \geq SOC_{max} \\ \min(P_{BESS,ph} - P_{bat,ph}); & \text{if } SOC_t \leq SOC_{min} \end{cases} \quad (7)$$

After calculating the result, Equation 8 can be used to verify the energy change of the balanced phase.

$$P_{balance,ph} = P_{grid,ph} - P_{BESS,ph} \quad (8)$$

4. COST ANALYSIS OF BESS INSTALLATION

From an economic perspective, financial modeling techniques are used to determine alternative and performance parameters, such as return on investment [20], payback period [21], and net present value [22]. These techniques will be considered to compare all three scenarios: the base case, the transformers upgrade case, and the BESS installation case. These will be important economic indicators for evaluating BESS investment.

4.1 Cost Analysis

To determine the economic cost of electrical energy losses, input data is summarized as economic parameters to assess the cost-benefit analysis of the proposed BESS integration into the network. Table 2 highlights parameters related to the BESS, and Table 3 presents the economic parameters of the distribution transformer, including battery technology cost (including BESS and inverter installation costs), lifespan, and annual operating and maintenance (O&M) costs. All these factors are interrelated for both asset types, ensuring a fair comparison between the baseline and BESS integration scenarios when these parameters are combined. Transformer O&M costs are calculated at 2% of the transformer's capacity and at

\$35/kW/year for the BESS. 30% was used as the maximum planning limit for BESS sizing, based on the recommended transformer load limit of 70–80% of rated capacity according to IEC 60076-2 [23]. However, in the networks tested, it was shown that the maximum phase current unbalance required compensation of less than 10 kW. Therefore, a rating of 10 kW for each BESS unit was chosen as it was sufficient to alleviate the observed imbalance while avoiding unnecessary oversizing.

Equation 8 shows that the total annual operating cost of the low-voltage distribution system can be expressed as the sum of energy loss cost, transformer loss-of-life cost, and operation and maintenance cost. This aggregated cost function provides a unified metric for evaluating the economic impact of the current unbalances and the effectiveness of the proposed single-phase BESS control strategy.

$$C_{total} = C_{loss} + C_{loss\ of\ life} + C_{O\&M} \quad (8)$$

This energy loss cost calculation is done by converting the total energy loss per period (kWh) into a monetary value (dollar) based on the electricity price or the electricity traded back into the system. The loss cost reflects the cost impact of inefficient system operation and is used as an important criterion for evaluating the benefits of installing a BESS to reduce energy losses in the system. As shown in equation 9.

$$C_{loss} = \sum_{t=1}^{phase} (I^2 R) \times \frac{Price/kWh}{per\ hour} \quad (9)$$

Furthermore, the lifespan of a transformer is not determined by the copper windings or the iron core, but by the paper insulation of the windings, operating temperature, humidity, oxygen, and the acidity level of the oil, and it is estimated to have a lifespan of approximately 50 years, assuming no thermal design weaknesses.

Although the degradation of cellulose insulation is a function of time and depends on temperature, humidity, oxygen, and acid content, the model provided in the IEC Load Guide [24] uses temperature as the only independent parameter. The coefficient of temperature change, which can be considered constant over the actual temperature range from 80°C to 140°C for class “A” insulation, causes the degradation rate to double for every 6°C increase in temperature. The degradation rate here refers to the hot spot temperature of the windings. In transformers constructed according to IEC 60076, the hot spot temperature with a normal degradation rate is 98°C at normal load and an ambient temperature of 20°C [25].

$$V = 2^{\frac{\theta_h - 98}{6}} \quad (10)$$

The loading guide also gives equations for evaluation of the loss of life for isolation. The loss of life L during the time periods t_1 and t_2 is

$$L = \int_{t_1}^{t_2} V \cdot dt \quad (11)$$

Table 2: Battery Cost Parameters

Parameter	Unit
BESS (10 kW/20 kWh)	\$4,773
Electricity cost	\$0.13/kWh
Operational life	10 years
Annual O&M cost	\$35/kW

Table 3: Transformer Cost Parameter

Parameter	Unit
Transformer 315 kVA	\$18,306
Electricity cost	\$0.13/kWh
Operational life	35-50 years
Annual O&M cost	\$35/kW

The base cost per hour is calculated by comparing the cost per hour of a new transformer to its standard lifespan. A typical 180,000 hours (approximately 20.5 years) is used as the IEEE standard [26] for normal insulation.

$$C_h = \frac{Replacement\ cost}{Standard\ life\ expectancy\ (h)} \quad (12)$$

This will produce an overall equation for loss of life.

$$C_{lost\ of\ life} = C_h \times L \quad (13)$$

4.2 Economic Assessment

The economic feasibility of installing the proposed BESS was assessed using an investment evaluation criterion, which defines a set of economic indicators. Among the various financial indicators, the payback period and net present value (NPV) were used as the main investment evaluation criteria in this work.

The payback period is the number of years required to recoup the investment. Therefore, a shorter payback period makes the project more attractive. The payback period can be calculated as follows:

$$Payback\ period = \frac{cost\ of\ investment}{annual\ revenues} \quad (14)$$

By quantifying these parameters over typical operational periods, it becomes possible to estimate the reinvestment timeframe, payback period, and overall cost effectiveness of installing BESS in low-voltage networks with high PV and EV penetration. Consequently, a well-designed BESS strategy can deliver both technical improvements and long-term economic benefits, positioning storage as a key enabler of future smart distribution systems.

Net present value is one of the most used investment criteria for making decisions about specific investments. Net present value is the discounted sum of future benefits minus the calculated costs [15]. The discount rate will be set at 5% of the total benefits.

$$NPV = -CF_0 + \sum_{t=1}^N \frac{CF_t}{(1+r)^t} \quad (15)$$

The economic assessment aims to quantify the financial benefits arising from the technical improvements achievable with the proposed BESS control strategy. Specifically, reducing current unbalance leads to lower power losses and improved transformer loading conditions, directly impacting cost savings and extending asset life for power distribution network operators.

5. CASE STUDY AND RESULT DISCUSSION

To evaluate the performance of the proposed droop control strategy of single-phase BESS for unbalanced reduction, the real residential LV network is used as a test network. This examined network was designed with high levels of single-phase PV usage and EV charging, simulating the penetration levels of PV and EV power at 10%, 20%, and 30%, which will cause fluctuations in current unbalance. System performance was evaluated through key technical indicators, including phase current profiles, CUF, SOC, and transformer load conditions, providing a comprehensive basis for assessing the technical and economic impacts of the proposed approach.

5.1 Tested Network Overview

The network in this study is a real residential low-voltage network. This distribution network is a 22/0.4 kV power system, consisting of a 0.315 kVA total power transformer and 28 buses “*Fig. 5:*” connected to residential loads and distributed generation. The electrical system was analyzed and simulated in DlgSILENT Power Factory.

The simulation involves randomly deploying PV and EV units across each phase of the low-voltage grid based on system penetration levels of 10%, 20%, and 30% from the power provider's perspective. 6, 12, and 18 PV units, respectively, with a capacity of 5 kW, are expected to supply electricity according to a daily power distribution profile with a maximum capacity of 100%. Additionally, 5, 9, and 14 EV charging modules, respectively, with a capacity of 7 kW, are randomly selected and deployed to supply AC power to residential households, using the charging profile derived with a maximum capacity of 100%. For simplicity, the same daily PV and EV load profiles are applied to each bus, allowing the simulation to capture diverse energy consumption patterns across the grid. Table 4 specifies the significant parameters used in technical simulation.

Table 4: Parameters of Case Study

Device	Unit capacity	Unit
Transformer	315	kVA
Voltage level	22/0.4	kV
PV penetration levels	30 / 60 / 90	kW
EV penetration levels	35 / 63 / 98	kW
Load resident	231.516	kW
BESS capacity	20/phase	kWh
Inverter	10	kW

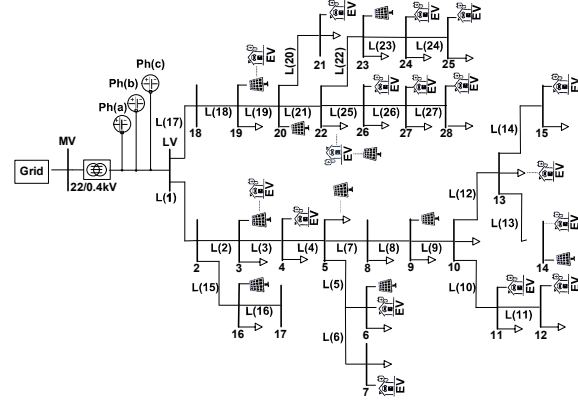


Fig.5: Single line diagram for test case

5.2 Technical Result and Discussion

Strategic management control refers to the coordinated evaluation of technical performance indicators such as current imbalance, power losses, and transformer load by integrating the operational behavior of the proposed single-phase BESS control strategy with cost-benefit indicators.

This approach supports informed decision-making regarding the deployment of BESS as a strategic alternative to traditional grid strengthening in low-voltage networks.

“*Fig. 6:*”, Illustrates the phase current profiles measured at the secondary side of the distribution transformer under the base case scenario, where no BESS is installed. The results clearly show significant discrepancies among the three-phase currents throughout the day. Current unbalances occur during periods of high PV generation in the daytime and during peak EV charging in the evening. These deviations are mainly caused by the uneven distribution of single-phase PV and EV connections across the phases. Consequently, certain phases experience persistent overloading, resulting in increased thermal stress and higher losses.

In contrast, “*Fig. 7:*” shows the phase current profile after implementing the proposed single-phase BESS control strategy. Compared to the baseline case, the three-phase currents are more uniform and noticeably concentrated around the average current level. During critical operating times, especially between 18:00 and 21:00, when EV charging demand is highest, the peak current is significantly reduced. This demonstrates that an independently controlled single-phase BESS unit can efficiently absorb excess current from the heavily loaded phases. And it supplies power to lightly loaded phases through phase-specific charging and discharging.

In “*Fig. 8:*”, The comparison of single-phase PV and EV charger penetration levels at 10%, 20%, and 30% shows that local compensation plays an important role in phase balance. PV generation helps reduce the load on the connected phase by supplying power locally, while EV charging distributes demand depending on how it is allocated across phases. Because of these factors, the spatial distribution of PV and EV units can sometimes improve phase balance. However, the increase in

unbalance is not directly proportional to the penetration level. Although higher penetration would normally be expected to cause greater phase current deviations, the simulation results show only small differences in imbalance indices among the three cases. The CUF profiles also follow similar daily patterns, suggesting that unbalance is mainly driven by load and generation behavior over time. Even so, the magnitude of unbalance still increases as penetration becomes higher. The 30% case shows the highest CUF values, especially during peak periods (07:00–10:00 and 15:00–17:00), due to the uneven distribution of PV generation and EV charging across phases. Therefore, while higher penetration does increase phase imbalance, it is not the only factor that determines how severe the imbalance will be in the network.

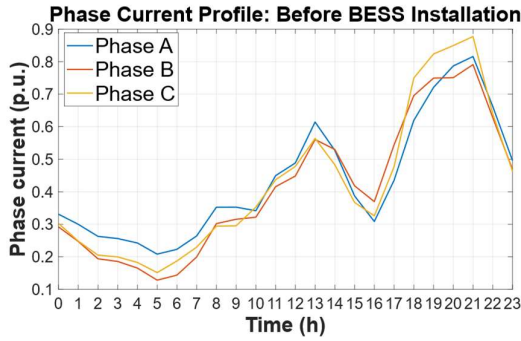


Fig.6: Phase current profile at base case without BESS

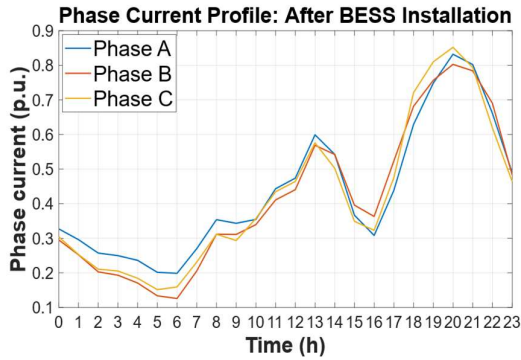


Fig.7: Phase current profile of BESS control strategy

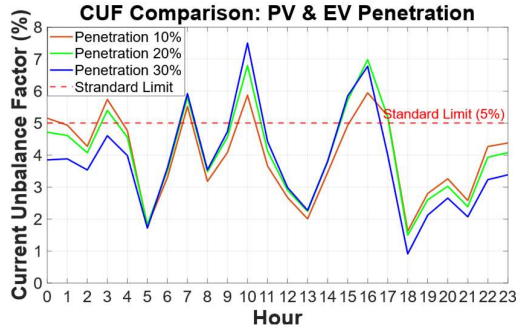


Fig.8: Penetration levels of single-phase PV and EV at 10%, 20%, and 30%

The study suggests that the percentage penetration in the three scenarios shows only slight differences in the unbalance index; therefore, the results presented in this study focus only on the 30% penetration scenario, as it has the highest CUF value across multiple time periods. The results comparing the coefficient of phase unbalance CUF in “Fig. 9:” over a 24-hour period show that without a BESS, the CUF typically exceeds the acceptable operating limit during peak usage conditions. After implementing the proposed control strategy, The CUF value decreases significantly, but it still cannot fall below the limit because the controller operates according to the sag curve defined in Equation 3 and practical limitations, including the battery energy storage system (BESS) capacity, the state of charge (SOC) limit to maintain battery life, and normal network asymmetry. Therefore, the CUF converges to a minimum achievable level, which is still sufficient to ensure safe and reliable system operation.

The CUF is preferred for identifying and mitigating load unbalance, VUF serves as a complementary metric for evaluating system-level impacts. To verify the results, the proposed current droop control that contributes to voltage balancing was used to examine the VUF values in the bus where the unbalance is most pronounced. It was observed that the VUF could be maintained below 2% throughout the network when comparing before and after BESS installation. This confirms that phase current balancing directly contributes to improving voltage capability in the low-voltage network, as shown in Figure “Fig. 10:”.

Based on the control strategy, we can represent the power output of each single-phase BESS unit in “Fig. 11:”. The results indicate that the BESS units operate asymmetrically between phases, charging or discharging depending on the current imbalance at each point. This phase-specific response confirms the capability of the proposed droop control strategy to dynamically distribute power between phases without central coordination.

“Fig. 12:” shows the SOC profiles of three single-phase BESS units. Even when operating under different charging and discharging modes, most SOC changes remain within a predefined range of 10% to 90%, demonstrating that the proposed SOC management strategy allows for realistic battery operation while effectively minimizing unbalance.

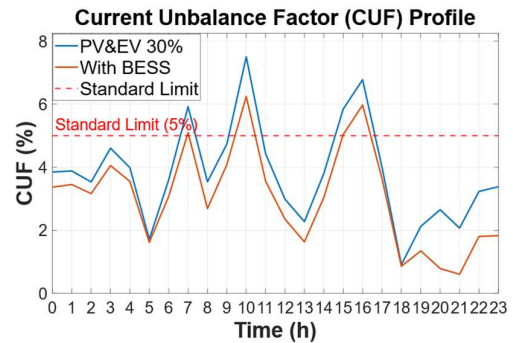


Fig.9: Comparison of current unbalance factor (CUF)

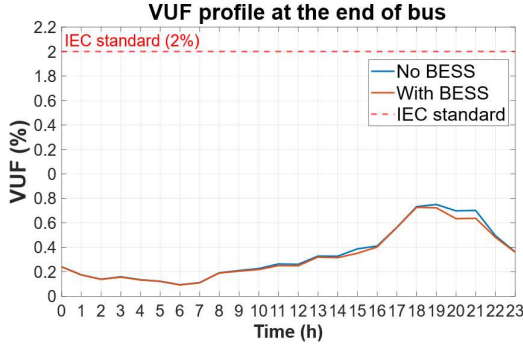


Fig.10: Comparison of Voltage Unbalance Factor (VUF)

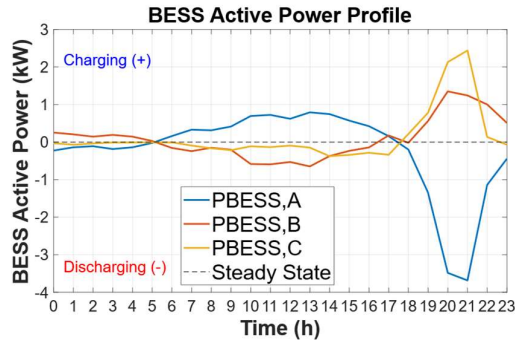


Fig.11: Active power output of the single-phase BESS

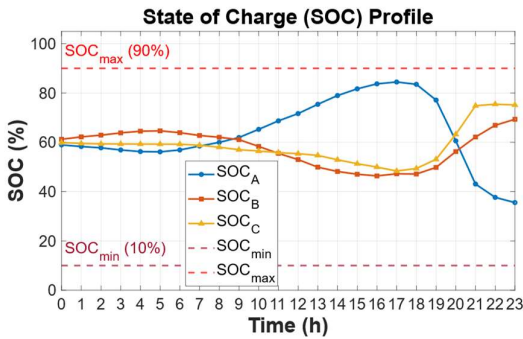


Fig.12: State of charge (SOC) profiles of the three single-phase BESS units

5.3 Economic Result and Discussion

The economic results of the scenarios studied are presented in this section and the financial feasibility of the proposed solution is discussed. This analysis compares the base case, transformer reinforcement and BESS installation in terms of energy loss cost, transformer loss of life and investment performance. The total cost-effectiveness and feasibility of each approach are evaluated by taking into consideration the key economic parameters such as payback period and net present value (NPV).

Table 5 presents the economic comparison between the base case, transformer upgrade and proposed BESS

installation. The impacts of the reduction in unbalanced current in transformer efficiency, system losses and overall operating costs are highlighted. The transformer upgrade did not reduce annual energy losses or annual loss costs compared to the base case but significantly reduced the life span of the transformer by about 78.3%, resulting in net annual savings of \$1,547.3. However, the high replacement cost of \$18,306 limits the economic attractiveness; hence a payback period of 12 years, which is relatively long, and an NPV of \$-4,812.17, which is significantly negative.

However, the proposed BESS installation provides more comprehensive technical and economic benefits. Annual energy losses are reduced by about 0.08%, and annual loss costs are reduced by only a small amount of \$0.58 over the base case. More importantly, the lifetime of the transformer is reduced by about 98%, which is much higher than that of the transformer upgrade. Despite the higher annual O&M costs for the BESS (58.7% higher than the base case). However, this increase is offset by decreases in transformer depreciation costs and power loss costs, and therefore net cost savings of up to \$1,807.10 annually, corresponding to a short payback period of only 2.6 years and a significantly smaller negative NPV of \$-395.18. Even at the cost parameters and discount rate, the NPV remains slightly negative. However, this does not consider all the indirect benefits such as the deferred transformer replacement, improved power quality and increased operational flexibility. So, the estimated payback period of 3 years is more accurate.

From an investment perspective, while both transformer upgrades and BESS installations effectively mitigate the impact of transformer life cycles, BESS offers superior economic efficiency, providing 20.1% higher net cost savings per year, a 78% shorter payback period, and a 91.8% better NPV compared to transformer upgrades. Therefore, the BESS installation represents a more cost-effective and technically efficient solution for mitigating unbalanced conditions and extending transformer lifetime in the low-voltage network.

The significant economic benefits observed in the case of BESS installations stem primarily from the thermal degradation characteristics of multiplier transformers. In the baseline severe phase, current unbalance during peak operating conditions forces specific phases to operate above their rated capacity. This localized overload dramatically increases losses, causing winding hot spots (θ_h) to spike. According to IEC 60076 Load Guidelines (Equation 10). Therefore, even short periods of high unbalance negatively impact the transformers' life. The proposed decentralized single-phase BESS effectively reduces peak currents in high-load phases and efficiently redistributes the current. This prevents the rise of critical temperature points that cause multiplier degradation, significantly reducing the annual loss of life cost. This clearly demonstrates that reducing current unbalance directly contributes to enormous long-term capital expenditure (CAPEX) savings.

Table 5: Economic comparison between base case and proposed BESS installation

Parameter	Unit	Based case	Transformer Upgrade	BESS Installation
Replacement cost	USD	-	18,306	4,780
Annual energy loss	kWh/year	5,620.10	5,620.10	5,615.65
Annual loss cost	USD/year	\$94.97	\$94.97	\$94.90
Transformer loss-of-life	USD/year	\$1975.05	\$427.73	\$39.16
Annual O&M cost	USD/year	\$220	\$220	\$350
Annual net saving	USD/year	-	\$1,547.3	\$1,806.5
Payback period	years	-	12	2.6

6. CONCLUSION

This research presents a decentralized droop control BESS method utilizing three single-phase battery energy storage systems to mitigate current unbalanced in low-voltage networks heavily reliant on solar and EV power. The proposed method efficiently balances the current with only on-site measurements without the need for centralized coordination. Simulations in a real residential network confirm significant reductions in current unbalance, feeder losses and transformer thermal stress, resulting in extended equipment life. Technical and economic analysis shows that the reduced life of the transformers and energy losses compensate for the increased operating costs of the batteries, resulting in a much shorter payback period than the conventional transformer reinforcement. In summary, the proposed single-phase BESS control strategy is a practical and scalable solution for improving the technical and economic efficiency of future low-voltage distribution systems.

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