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RESEARCH ARTICLE

IoT-Driven Monitoring and Optimization of Hybrid Energy Storage Systems with Supercapacitors in Distribution Networks

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ABSTRACT

The prevailing challenges, namely the escalating energy demand and the integration of renewable resources into the grid, have led to a marked increase in the importance of energy storage systems. This study proposes a novel energy storage system that integrates supercapacitors and Lithium Iron Phosphate (LFP) batteries in a hybrid configuration within the electricity distribution grid. The system's design incorporates supercapacitors, which are distinguished by their rapid charge-discharge capabilities, to address sudden fluctuations in demand, while batteries are utilized to fulfill long-term energy requirements. The hybrid configuration offers optimization in terms of energy and power density, thereby extending battery life and enhancing system safety. The three-dimensional battery pack design, developed using the Altium Designer (CITAI) program, is supported by special connection busbars, voltage regulation, and a Battery Management System (BMS). The prototype system was tested in the Water Tank Electricity Kiosk connected to a 400 kVA transformer in Diyarbakır. The field tests conducted revealed the system's capacity to cater to both single-phase and three-phase loads. Furthermore, the output voltages, voltage unbalance, and frequency parameters were found to be in accordance with the EN50160 standard. Furthermore, the harmonic analysis results demonstrated that the total harmonic distortion (THD) values remained well below the stipulated limits, thereby ensuring the system's energy quality remained uncompromised. This study provides a technical model for the integration of hybrid energy storage systems into smart grids and makes significant contributions to the fields of energy supply security and power quality.

Index Terms—Electricity distribution network grid, hybrid energy storage, power quality, supercapacitors, voltage stability energy efficiency

I. INTRODUCTION

The increase in energy demand, diminishing fossil fuel reserves, and increasing environmental impacts accelerate the shift towards renewable resources in energy policies. Sustainable energy sources such as solar, wind, and hydroelectricity have great potential in terms of ensuring energy supply security and environmentally friendly energy production.

According to Ember's 2024 Global Electricity Review, renewable energy sources have reached a 30% share in global electricity generation, and electricity demand is projected to increase by 9000 TWh by 2030 [1]. In parallel with this increase, energy storage solutions will have a key role in balancing energy production and consumption.

Energy storage technologies offer significant benefits in smart grids and in ensuring the continuity of energy systems. Energy storage plays a crucial role in optimizing grid capacity, regulating frequency, and balancing load fluctuations. As shown in Fig. 1, the energy storage topology in smart grids involves the integration of generation, transmission, and distribution systems. According to the BloombergNEF (BNEF) report, global energy storage installations are estimated to reach 358 GW/1028 GWh by the end of 2030 [2].

Battery technologies stand out as one of the main methods of energy storage solutions. While lithium-ion batteries attract attention for their high energy density and long life, supercapacitors offer advantages with their fast charge/discharge characteristics

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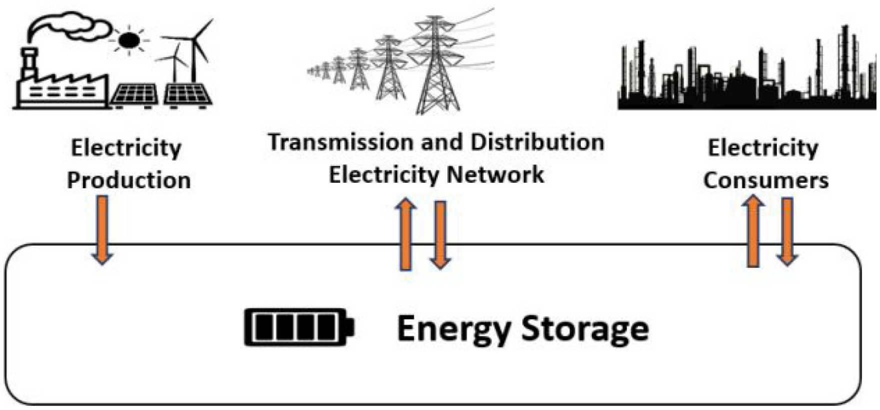

Fig. 1. Storage topology in smart grids.

and high power density [3] Supercapacitors have significant potential in areas such as sudden power changes, frequency regulation, and microgrid integration. Solutions such as hybrid energy storage systems allow the development of more flexible and efficient systems by combining the benefits of batteries and supercapacitors [4, 5].

As demonstrated in Table I, a comparison of lithium-ion batteries and supercapacitors reveals that both technologies are suited to different application areas. While supercapacitors are distinguished by their longevity and rapid charging capabilities, lithium-ion batteries are regarded as optimal for long-term energy storage due to their superior energy density and cost-effectiveness [6, 7]. The increasing integration of renewable energy sources necessitates the more widespread use of these technologies.

The present study analyzes the effects of supercapacitor-supported energy storage systems on smart grids, investigating energy quality, grid stability, and integration methods in the process. The objective is that the findings obtained will contribute to innovative approaches in the field of energy storage and to making energy systems more secure, efficient, and sustainable.

II. RELATED WORKS

Energy storage systems play a key role in facilitating the integration of increasing amounts of renewable energy into the grid. Emrah Solak's study [3] analyzes the contribution of battery-based energy storage systems to grid flexibility and suggests that flexibility can be further enhanced by integrating nuclear power as a baseload source in the Thrace region alongside battery installations. Prasad et al. [8] carried out a comprehensive review of the structure, operating principles, and various applications of supercapacitor technology. As an alternative to conventional batteries, which suffer from limitations such as low power density, high internal resistance, and long charging times, supercapacitors offer advantages such as high power density, rapid charge-discharge capability, and extended life. The study details the basic design, material components, and different energy storage mechanisms of supercapacitors. It also highlights their applications in hybrid energy systems, electric vehicles, microgrids, and renewable energy storage while assessing their future development potential. Haiat et al. [4] demonstrated that the integration of solar energy with supercapacitors in electric vehicles significantly increases their range. Taken together, these studies highlight the critical role of energy storage technologies—particularly batteries and supercapacitors—in supporting the integration of renewable energy sources.

Hybrid solutions have become a central focus of efforts to improve the performance of energy storage systems. Díaz-González et al. [9] developed a hybrid energy storage system combining batteries and supercapacitors to store excess energy from photovoltaic power plants and demonstrated its effectiveness in minimizing

Main Points

- Increasing energy demand and the variable production of renewable resources make energy storage systems mandatory.
- Supercapacitor-based hybrid energy storage systems are an effective solution to improve energy quality and grid stability.
- This paper aims to develop more efficient and reliable energy storage methods by analyzing the integration of supercapacitors and battery systems.

TABLE I.
COMPARISION OF SUPERCAPACITOR AND LITHIUM-ION

Features	Supercapacitor	Lithium-Ion
Energy intensity	Low	High
Power density	High	Low
Lifetime	Very long (millions of cycles)	Limited (thousands of cycles)
Charging time	Too short	Longer
Internal resistance	High	Low
Cost	Higher	Lower

battery degradation and maintaining optimal service levels. In the research by Jayasinghe et al. [10], batteries and supercapacitors were connected directly via DC link capacitors, eliminating the need for additional DC-DC converters, and thus reducing system cost and power losses. These hybrid architectures enable more efficient operation of energy storage systems and lower overall costs. Choi et al. [11] proposed an energy management optimization approach for HESS consisting of batteries and supercapacitors. While batteries have high energy density, their low power density makes them vulnerable to power fluctuations. In contrast, supercapacitors offer high power density to meet instantaneous energy demands but lack sufficient long-term storage capacity. The study presents an active HESS model that dynamically regulates energy flow via DC/DC converters, using an optimization algorithm to minimize current fluctuations and energy losses. MATLAB simulations confirm that the proposed model improves energy efficiency and extends battery life by reducing the internal resistance load.

Control and optimization strategies are equally important to improve the performance and efficiency of energy storage systems. Jiang et al. [12] developed energy management algorithms to minimize energy losses and improve voltage profiles. Deng et al. [13] focused on improving the energy efficiency of supercapacitor-supported hybrid systems, demonstrating that improved charging efficiency leads to reduced operating costs. Zhang et al. [14] developed power distribution strategies aimed at prolonging battery life and minimizing energy dissipation, thus contributing to the sustainability and reliability of storage systems.

The strategic integration of batteries and supercapacitors is becoming increasingly important to improve grid stability. Jing et al. [15] analyzed battery-supercapacitor hybrid systems in stand-alone DC microgrids and concluded that such systems reduce battery stress and improve microgrid reliability. Similarly, Reigstad et al. [16] showed that supercapacitors effectively stabilize power fluctuations in DC networks, contributing to more resilient microgrid architectures. These results highlight the ability of supercapacitors to respond quickly to load variations, making them essential for grid stability.

The integration of energy storage systems into the grid is of pivotal significance in ensuring the balance between supply and demand. Moreover, it is instrumental in enhancing the long-term sustainability of the system. Hybrid solutions are of particular relevance in microgrid applications, and the economic and technical advantages of these structures have been demonstrated in numerous studies. For instance, cost analyses of microgrids operating in islanding mode demonstrate the efficacy of supercapacitors in managing sudden load fluctuations and significantly extending battery life. In this context, hybrid energy storage systems have been found to be approximately 11% more economical than conventional battery systems [17, 18].

The efficacy of control strategies developed to enhance the flexibility and performance of microgrid architectures has been demonstrated, particularly in the domains of voltage regulation and instantaneous load balancing of supercapacitors. Photovoltaics (PV)-battery-supercapacitor-based microgrids with hierarchical control structures and nonlinear management algorithms have been shown in the literature to be stable and reduce energy losses [19, 20, 21, 22]. Furthermore, the utilization of artificial intelligence-based energy management systems has been demonstrated to enhance the energy efficiency of supercapacitor-based structures. In particular, studies employing optimization methods such as artificial rabbit algorithms have demonstrated successful outcomes in load sharing and voltage stability [23, 24]. Another issue that has been identified is the provision of active power management in medium voltage microgrids with fuel cell-supercapacitor hybrid systems. It is emphasized that when these hybrid systems are integrated with a three-loop control structure, both costs are reduced and the system becomes more reliable [25].

Energy storage systems (EES), especially batteries and supercapacitors (SCs), are essential for enhancing the reliability and performance of modern energy systems, particularly in renewable-integrated microgrids. Supercapacitors are gaining attention due to their high power density and long lifespan [26], and they are increasingly used alongside batteries in hybrid systems like PV–battery–diesel setups with bidirectional converters for efficient power flow [27]. To address wind-induced power fluctuations, hybrid battery–SC systems reduce battery microcycling and extend lifespan [28], while similar configurations in Electric Vehicle (EV) drives improve speed-range and smooth battery discharge [29]. In standalone PV systems, batteries integrated via bidirectional converters ensure stability during irradiance variability [30]. Grid-connected systems benefit from hybrid energy storage optimization to lower costs, boost reliability, and cut emissions [31], and frequency instabilities are tackled through BESS-DSTATCOM integration [32]. Supercapacitor-based ESSs also help regulate power and voltage in DC microgrids with mixed renewable inputs [33].

Consequently, the development of energy storage systems and the integration of hybrid solutions have enabled the large-scale utilization of renewable energy sources. Specifically, hybrid systems incorporating batteries and supercapacitors enhance energy efficiency, reduce costs, and ensure grid stability. The future implementation of these systems in a wider range of application areas is anticipated to make substantial contributions to energy security and sustainability.

III. METHODOLOGY

The objective of this study is to determine the most suitable battery selections for incorporation into a hybrid storage system, with the ultimate aim of ensuring its compatibility with the electricity distribution network.

A. Hybrid Storage System Design

Energy storage systems have a critical role to play in both improving energy efficiency and addressing the imbalance between supply and demand caused by the intermittent nature of renewable energy sources. Applications such as waste heat storage in industry and commerce support sustainable energy management by reducing energy losses [34].

Hybrid energy storage systems offer substantial benefits in terms of energy management by optimizing energy and power density through the integration of batteries and supercapacitors. In meeting long-term energy needs, these systems extend battery life and reduce maintenance costs by responding quickly to sudden power demands [35]. Hybrid systems play a critical role in the integration of renewable energy sources, maintaining grid stability and increasing energy supply security by storing the energy produced by intermittent energy sources such as solar and wind [36]. Capacitors find application in a variety of energy storage and electrical stabilization contexts, exhibiting diverse structural and performance characteristics. For instance, the high voltage and rapid response time exhibited by capacitors of the dielectric type are notable characteristics [37].

The combination of LFP batteries and supercapacitors has been shown to be effective in the management of critical parameters such as frequency regulation, voltage stability, and power quality in smart grids, with the advantages of long cycle life and high power density.

In integrating hybrid storage systems into smart grids, it is essential to determine the technical characteristics of energy storage systems, such as capacity, power density, and response time, in accordance with the grid's requirements. Guidance for the integration of energy storage systems with the grid is provided by the IEEE 2030 and 1547 standards, and communication protocols to improve system reliability and performance are also recommended [38].

In the context of designing a battery pack appropriate for integration within the electricity distribution network, a highly efficient, durable, and secure energy storage system has been developed through the integration of LFP batteries and supercapacitors. The three-dimensional configuration and interconnection of the battery packs are illustrated. The CITAI program was utilized for the design and drafting of the battery packs. The connection between the battery packs is designed using copper or aluminium busbars that provide high conductivity and low resistance. The selection of these busbar systems was made with a specific cross-sectional area, coating material (e.g., nickel or tin plating), and geometrical structure in mind, with the objective being to increase current carrying capacity, optimize heat dissipation and minimize voltage drop. Special pressing techniques, laser welding, or screw connection methods were used to reduce heat dissipation, and minimize contact resistance at the joints. The result of these measures is a system that is safer, more efficient, and more durable, due to the high level of current energy transfer.

As illustrated in Fig. 2, a configuration of prismatic LFP cells is demonstrated, wherein the cells are interconnected in series through the utilization of bus bars and screws, thereby establishing a 48V, 40.32 kWh battery assembly with a 15s-3p connection arrangement.

Fig. 3 presents the circuit diagram of the battery pack under consideration. The battery pack has been constructed using prismatic LFP cells with a nominal capacity of 280 Ah and has 15 series (15 s) and 3 parallel (3p) connection structures. In accordance with this configuration, 15 cells, each with a nominal voltage of 3.2 V, were connected in series, thereby yielding a total output voltage of 48 V. When the capacity of each cell is considered to be 280 Ah, the nominal energy capacity of the battery pack is calculated to be 48 V × 280 Ah = 13.44 kWh. When this configuration is repeated three times with a parallel connection, the total energy capacity is obtained as 13.44 kWh × 3 = 40.32 kWh.

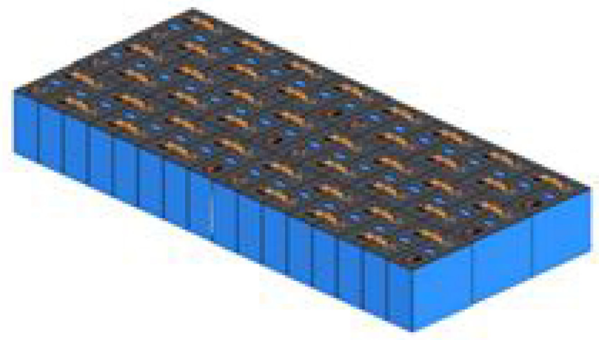

Fig. 2. Battery pack design (3D design).

As illustrated in Fig. 4, the circuit diagram, the proposed supercapacitor package incorporates balancing voltage regulator boards, which have been integrated into the supercapacitors. The designed supercapacitor package consists of supercapacitors, each with a nominal voltage of 2.7 V and a capacity of 100 000 F, and a total of 21 supercapacitors are planned to be connected in series. The series connection configuration ensures that the total voltage level of the system is equivalent to 2.7 V × 21, which is 56.7 V. This configuration is notable for its high power density and its fast charge/discharge characteristics. The result is a supercapacitor system with the capacity to provide in excess of 2 kW of power. The circuit incorporates balancing voltage regulator boards, which are essential for ensuring voltage equality among the series-connected supercapacitors. This is crucial for preventing overvoltage situations and promoting the long-term operational safety and reliability of the system.

As demonstrated in Fig. 5, the circuit diagram provides a comprehensive representation of the Battery Management System (BMS) integrated into the hybrid energy storage system. The diagram meticulously delineates the configuration of the battery pack, comprising LFP (Lithium Iron Phosphate) cells, in both series and parallel

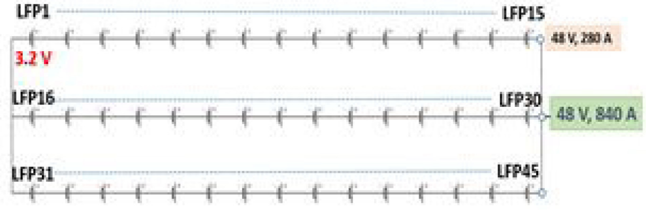

Fig. 3. Lithium iron phosphate battery circuit diagram.

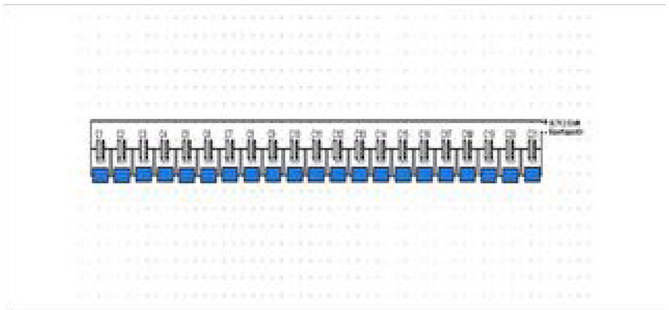

Fig. 4. Supercapacitor circuit diagram.

configurations. It also elucidates the interconnections between the battery pack and the BMS unit, facilitated by balance cables connected to each cell group.

The BMS is a critical component in ensuring the safe, efficient, and long-lasting operation of battery packs. It prevents risks such as overheating and short circuits by controlling the charge-discharge processes [39]. The BMS optimizes the performance of the battery by performing functions such as energy management, voltage balancing, and fault detection. The BMS consists of both hardware and software components. The hardware component, with its incorporation of voltage, current, and temperature sensors, ensures the safety of the battery. The software component, through its execution of tasks such as charge management, cell balancing, and fault prediction, contributes to the safe and efficient operation of the system. The integrated operation of these two components plays a critical role in extending the life of the battery and ensuring its safety. The completed storage system is shown in Fig. 6.

IV. FINDINGS

The design, installation, and connection process of energy storage systems to the distribution network has been completed. The storage system, which was developed for the efficient use of electrical energy and to ensure the security of supply, was designed by taking into account various design criteria. Its installation was completed and finally connected to the distribution network and subjected to

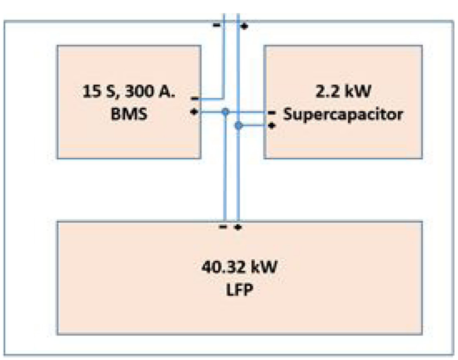

Fig. 5. Battery pack circuit diagram with a battery management system.

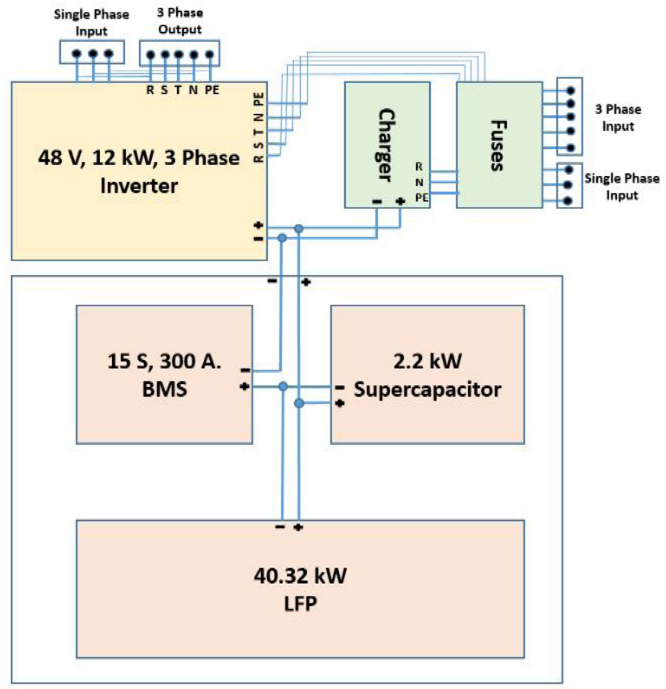

Fig. 6. Hybrid energy storage system circuit diagram.

detailed tests. The developed system has been subjected to detailed tests in a panel integrated with a 400 kVA transformer connected to the Water Tank Electricity Kiosk located in Diyarbakır 4 TM, City Cable 2 feeder, and successful results were obtained. The test location is shown in Fig. 7.

In the Alternating Current (AC) output tests, both three-phase and single-phase AC outputs were tested under load. It was found that the devices could operate stably and that the output voltages were within the specified value ranges. Single-phase and three-phase

Fig. 7. Hybrid energy storage test location.

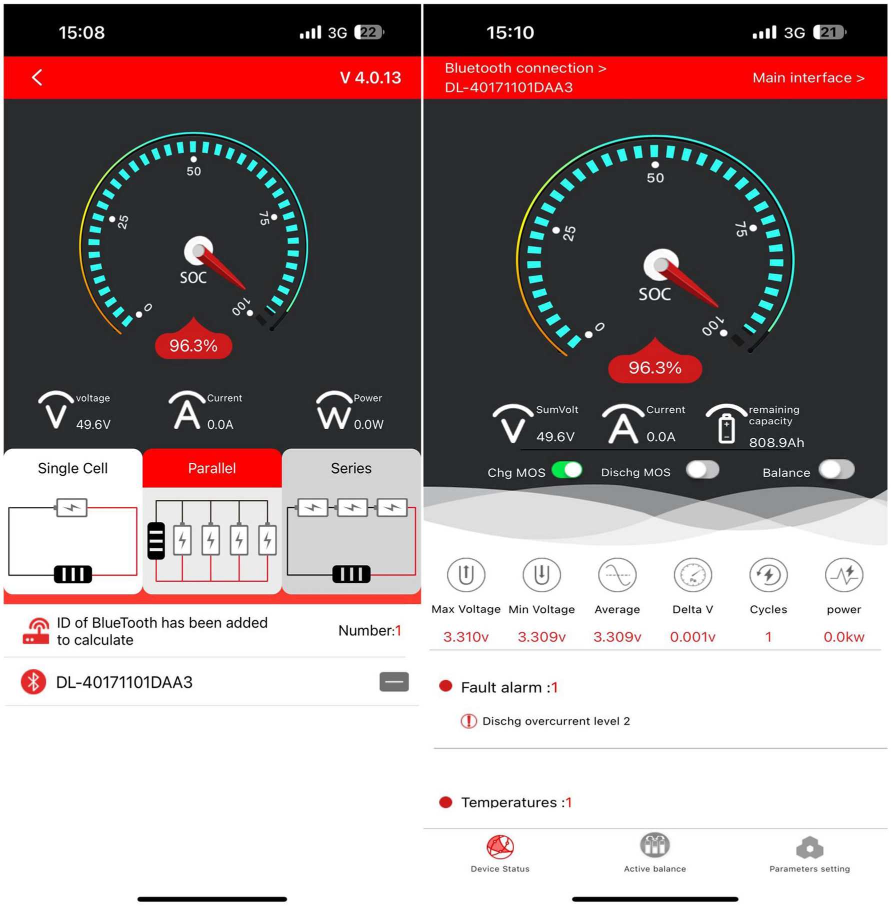

Fig. 8. Battery management system storage instant monitoring screens.

devices were tested separately, and it was verified that both systems could provide energy in a stable and reliable manner. Furthermore, the capacity of the system to concurrently supply both single-phase and three-phase devices was assessed, and it was observed that it functioned seamlessly. The system connected to the BMS was monitored in real-time, as illustrated in Fig. 8.

The relevant test location was fed by connecting the storage system for a duration of 45 minutes. During the course of the tests, the instantaneous power values and connection status were monitored via the display on the inverter to ensure effective monitoring of system performance. As demonstrated in Fig. 9, the stability of the power flow and the operating dynamics of the system were observed and evaluated in detail.

The Eberle Power Quality (PQ) Box 150, utilized in this study, is a sophisticated device that offers exceptional precision and dependability in the domains of electrical power quality analysis and energy monitoring applications. The device under scrutiny has been shown to comply with the IEC 61000-4-30 Class A standard and is thus capable of analyzing voltage, current, frequency, power, energy consumption, and harmonic components. The PQ Box 150 is a highly effective tool for comprehensive monitoring in three-phase systems, particularly in industrial plants, energy distribution networks, and renewable energy systems.

The results of the tests indicate that the network parameters generally show values in accordance with the EN50160 standard. As demonstrated in Fig. 10, no adverse conditions were identified in the network with regard to frequency, voltage imbalance, and event indicators.

The tests carried out on the tester are reported in accordance with the EN50160/IEC61000-2-2 standards and are shown in Table II. The voltage measurement results showed a maximum of 231.28 V and a minimum of 230.68 V in the L1 phase, a maximum of 231.14 V and a minimum of 227.08 V in the L2 phase, and a maximum of 228.50 V and a minimum of 222.18 V in the L3 phase. When compared with the nominal voltage of 230V determined according to the EN50160 standard, these values are within the limits. However, the minimum value of 222.18 V in phase L3 indicates a significant voltage drop. Such fluctuations can be caused by a lack of reactive power compensation.

The fact that the voltage unbalance ratio is 0.57%, well below the limit of 2%, indicates that the system is operating in balance and that

Fig. 9. Inverter instant monitoring screens.

there is no serious unbalance between the three phases. Following the results of the tests, harmonic analysis was carried out and the total harmonic distortion (THD) values remained below the limit values for phases L1, L2, and L3, as shown in Fig. 11. The low THD levels contributed to the protection of the power quality in the network.

As seen in Table III, THD for the L1 phase is 1.31%, 2.22% for the L2 phase, and 2.04% for the L3 phase. These values show that the level of harmonic distortion in the network is at an acceptable level in terms of power quality. It is well below the 8% limit specified in the EN50160 standard, showing that the storage product does not generally cause harmonic pollution. However, significant increases in some harmonic components were observed. It is noteworthy that

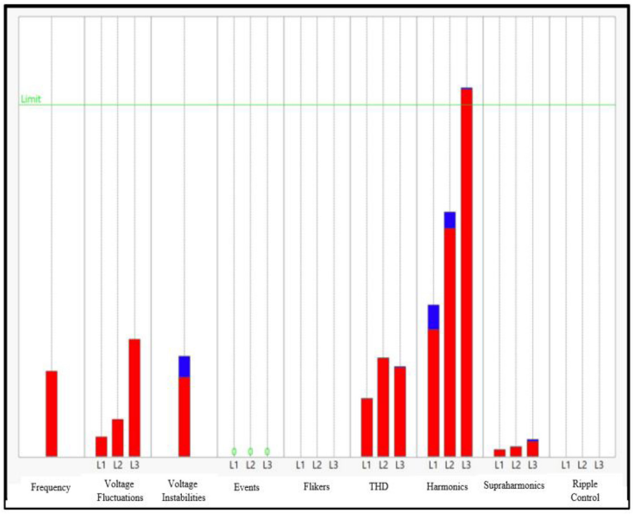

Fig. 10. Total test results in the distribution network.

TABLE II.
VOLTAGE CHANGES

	Max. Value	95.00%	5.00%	Min. Value
Voltage changes L1	231.28 V	231.26 V	0.00 V	230.68 V
Voltage changes L2	231.14 V	231.11 V	0.00 V	227.08 V
Voltage changes L3	228.50 V	228.41 V	0.00 V	222.18 V

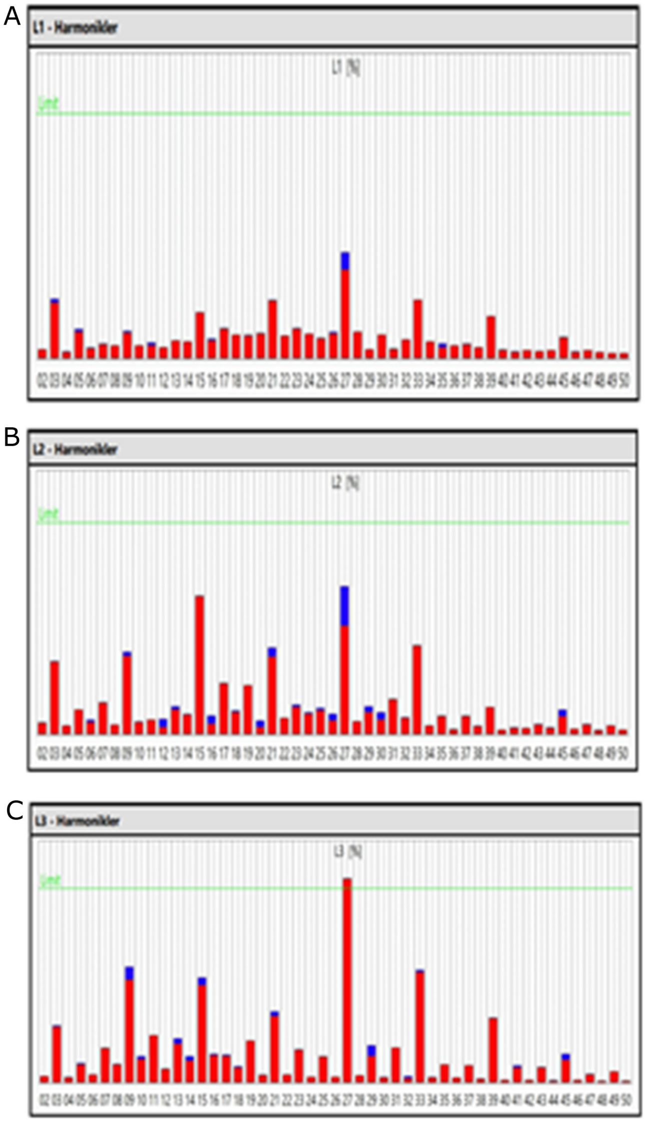

Fig. 11. (A) L1 phase harmonic analysis. (B) L2 phase harmonic analysis. (C) L3 phase harmonic analysis.

TABLE III.
HARMONICS

	Limit Values [%]	L1 - 95.00% [%]	L1 - Max [%]	L2 - 95.00% [%]	L2 - Max [%]	L3 - 95.00% [%]	L3 - Max [%]
THD	8.00	1.31	1.31	2.22	2.24	2.01	2.04
2	2.00	0.07	0.07	0.11	0.11	0.06	0.06
3	5.00	1.13	1.20	1.70	1.72	1.42	1.46
4	1.00	0.03	0.03	0.04	0.04	0.03	0.03
5	6.00	0.64	0.72	0.68	0.69	0.54	0.58
7	5.00	0.28	0.29	0.74	0.75	0.87	0.88
27	0.20	0.07	0.09	0.10	0.14	0.21	0.21

THD, total harmonic distortion.

the values of the 3rd harmonic (L1: 1.13%, L2: 1.70%, L3: 1.42%) and the 5th harmonic (L1: 0.64%, L2: 0.68%, L3: 0.54%) are relatively higher. These harmonics can cause additional losses and heating in industrial loads such as electric motors and transformers. The fact that the 7th harmonic values reach 0.87% in the L3 phase shows that the risk of resonance and voltage distortion should not be ignored. 27th harmonic (L1: 0.07%, L2: 0.10%, L3: 0.21%). According to the analysis, the 0.21% value measured in the L3 phase shows a significant increase compared to the L1 and L2 phases. This indicates that there is more harmonic distortion or phase imbalance in the L3 phase.

Hybrid storage systems are innovative solutions developed to minimize the negative impact of energy storage technologies on the grid and improve energy quality. According to the harmonic analysis results in this study, the THD values after the integration of the hybrid storage system are well below the 8% limit specified in the EN50160 standard. This shows that the hybrid storage system does not impose a significant harmonic load on the grid and helps protect the energy quality. However, the increases observed in the 3rd, 5th, and 27th harmonic components in certain phases indicate that high-frequency components from the inverter circuits are reflected in the system.

Thanks to the dynamic energy support provided by the supercapacitors used in hybrid storage systems, voltage fluctuations during sudden load changes are minimized. The fast charge-discharge capability of the supercapacitors helps to maintain the quality of the power in the grid by increasing voltage stability.

The main advantages of supercapacitors include high power density and fast response due to low internal resistance. This feature plays a crucial role in ensuring energy balance during sudden load changes and reducing voltage fluctuations in the grid. In addition, the long cycle life and maintenance-free nature of supercapacitors offer the potential to increase reliability and reduce operating costs in energy storage systems. As a result of these features, supercapacitors are seen as an effective solution for improving grid stability and energy quality.

V. CONCLUSION

This study has investigated the performance of hybrid energy storage systems that integrate supercapacitors with conventional batteries in low-voltage distribution networks. Through detailed modeling in CITAI, the dynamic and steady-state behavior of hybrid configurations were compared with standalone battery systems. The results demonstrate that the inclusion of supercapacitors significantly improves voltage regulation, reduces power losses, and enhances system response under sudden load fluctuations. Furthermore, the implementation of an IoT-based BMS, as presented in the system interface, offers a real-time monitoring and control framework that enhances the operational efficiency and reliability of the hybrid storage system. These findings highlight the potential of smart, hybrid storage solutions in supporting grid modernization efforts and managing the increasing variability introduced by distributed energy resources. Future work may focus on experimental validation, real-time control algorithms, and cost-benefit analyses for practical deployment.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer-reviewed.

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