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POWER QUALITY MANAGEMENT IN HYBRID MICRO GRIDS: HARMONIC DISTORTION ANALYSIS AND MITIGATION FOR A 8.75MW PV-DOMINANT CAMPUS SYSTEM USING ETAP

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Abstract

Large institutional campuses are increasingly faced with a dual challenge of guaranteeing high energy reliability while meeting their sustainability mandates. This work presents a design, modelling, and comprehensive performance analysis of the solar-dominant hybrid AC/DC micro grid tailored to the 8.75 MW demand of the University Campus Peshawar. The proposed system architecture integrates a portfolio of distributed energy resources comprising large-scale solar photovoltaic arrays, wind turbine generators, and diesel-powered backup generators interfacing with the local utility grid. A dedicated DC subsystem featuring an 875 Ah battery energy storage system was designed to feed 15 kW of critical loads with 8-hour autonomy, thus enhancing overall system resilience. A suite of simulation studies using the Electrical Transient and Analyser Program (ETAP) was conducted to validate the operational viability of the system. The AC/DC load flow analysis shows stable steady-state operation, and the system is capable of meeting the full campus demand and hence can export surplus power. The short-circuit study verifies the adequacy of the protection scheme, as the fault currents at all buses remain within the interrupting capacity of the selected protective devices. However, a critical power quality problem was revealed, where the THD at the points of common coupling for the PV arrays was exceeding the IEEE 519 standard of 5%. This problem was resolved through strategic placement of passive harmonic filters, which reduces THD to well below the acceptable limits. Results obtained collectively establish that the proposed hybrid micro grid is robust, reliable, and technically feasible to improve energy security and promote sustainable power infrastructures in a large-scale institutional setting.

INTRODUCTION

The Energy Trilemma in Institutional Settings

The world's energy landscape is undergoing a fundamental transformation, impelled by what many commentators describe as the "energy trilemma": the need to simultaneously pursue energy security, environmental sustainability, and economic affordability. For major, power-intensive organizations such as university campuses, this challenge is especially pointed [1]. As small cities, they host a diverse and demanding set of electrical loads, from research laboratories and data centers to residential halls and administrative buildings [2].

They therefore require an exceptionally high degree of power reliability to maintain their core missions of education and innovation [3]. Yet their historical reliance on centralized utility grids has made them vulnerable in multiple ways: to escalating electricity costs, the threat of grid-wide power outages, and high carbon emissions [4].

The University Campus Peshawar is thus a representative case study of these challenges. Similar to many such campuses, it depends on a national grid that can be unstable and characterized by service interruptions, which threaten the continuity of operations for such institutions directly [5]. It thus gives every compelling reason to find decentralized energy solutions to provide a buffer against external grid disturbances while integrating local and clean energy resources [6]. The need for a localized, intelligent, resilient power system is no longer one of convenience but a strategic must-have for the modern academic institution [7].

Hybrid AC/DC Micro grids as a Resilient Solution

In this regard, the paradigm of micro grids has emerged as a state-of-the-art solution to the energy trilemma faced by institutional and commercial consumers. A micro grid is a localized aggregation of electricity sources and loads that always operates connected to and synchronous with the traditional wide-area synchronous grid (macro grid), but it can disconnect and function in an autonomous island mode if needed [8]. This seamless transition between grid-connected operation and islanded operation is the linchpin of its capability to enhance local reliability and energy resilience [9]. Figure 1 illustrates a simple configuration for a micro grid.

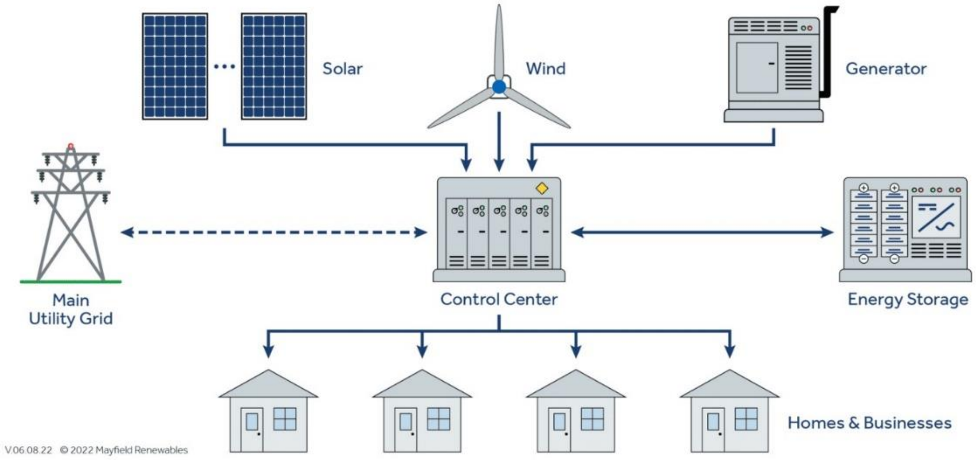

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Fig. 1. A simple micro grid configuration.

Figure 2 illustrates a hybrid AC/DC microgrid that will enable such DC-native components to be interfaced directly onto a common DC bus, thus dispensing with numerous efficiency-sapping DC-AC or AC-DC power conversion stages. At the same time, the AC subsystem can interface seamlessly with the legacy utility grid and serve traditional AC loads such as motors and HVAC. This level of architectural sophistication results in significant enhancements in overall system efficiency, component count, and complexity while increasing flexibility to accommodate a diverse mix of generation and load types [10].

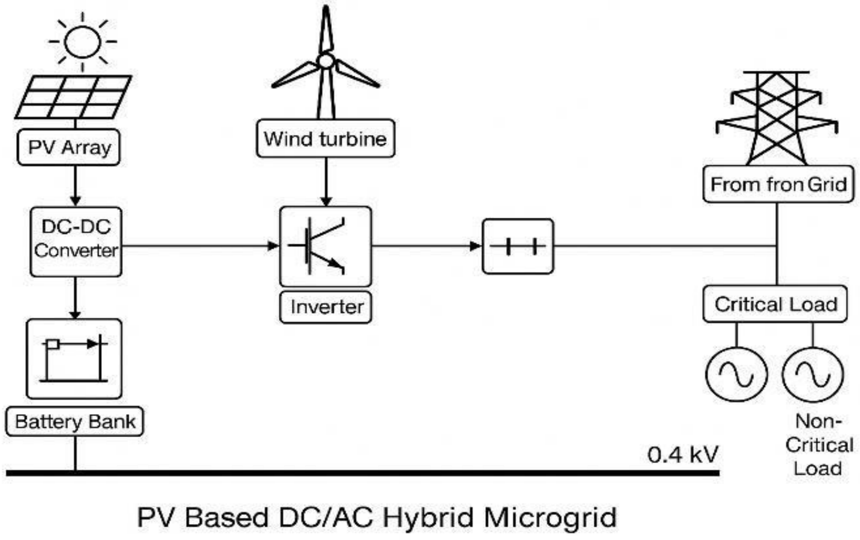


Fig. 2. A hybrid AC/DC micro grid.

Literature Review and Research Gap

The concept of micro grids is one that has been well explored within academic literature, with research normally bifurcating into the study of AC, DC, and hybrid systems [11]. AC micro grids, such as that shown in Figure 3, are the most conventional type, leveraging well-established technology and protection principles from AC power systems. DC micro grids, represented in Figure 4 of the source material, have gained considerable momentum for their high efficiency and ease of integration with renewable and storage technologies [12]. However, protection and standardization pose unique challenges. Hybrid AC/DC micro grids seek to synthesize the positives of both and offer a highly adaptable and efficient platform for the future of energy systems [13].

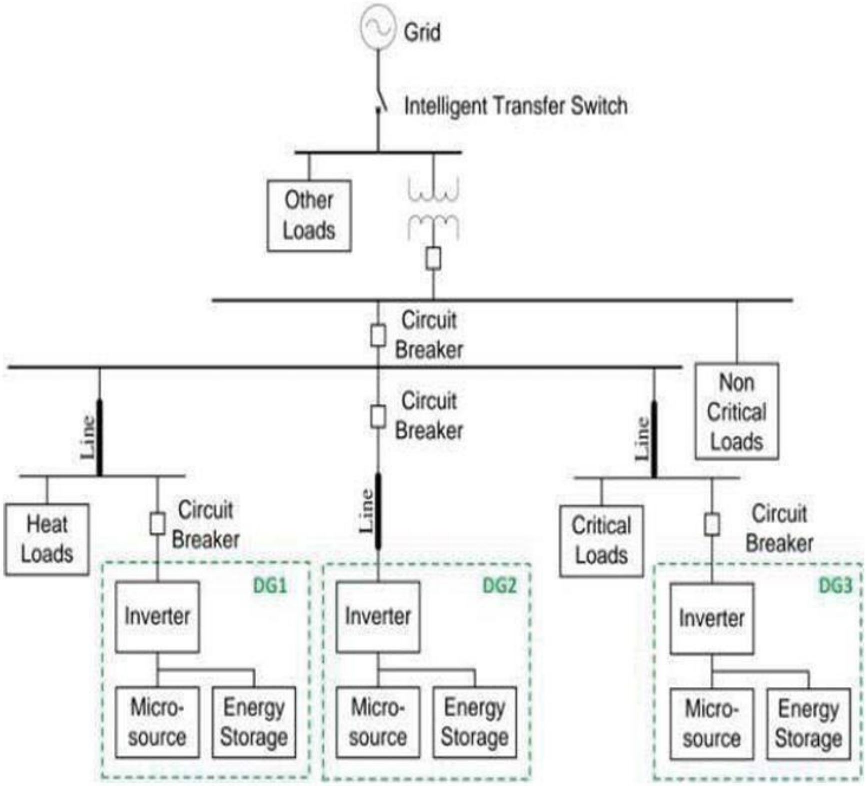


Fig. 3. Example of a conventional AC micro grid.

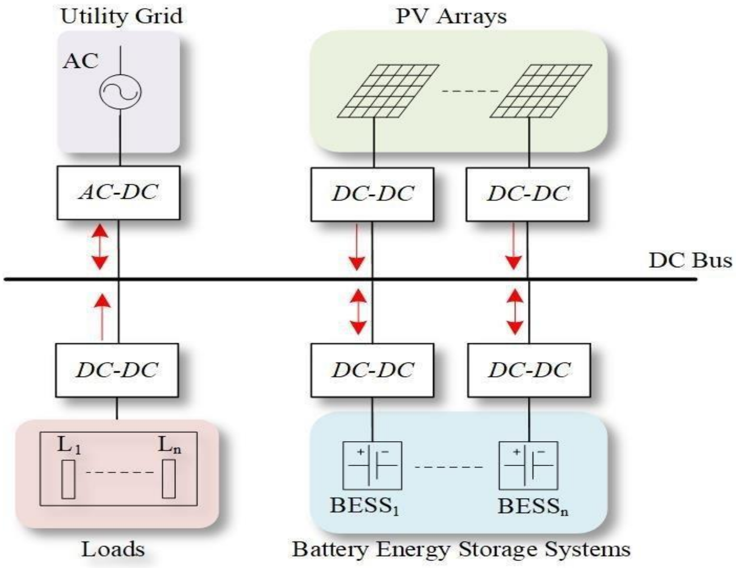


Fig. 4. Example of a DC microgrid.

A critical review of the existing body of work illustrates that although many studies are focused on theoretical aspects related to micro grid control strategies, stability analysis, or performance of individual components, there is a certain lacuna in the literature regarding comprehensive, simulation-validated case studies dealing with large-scale, real-world hybrid micro grids [14]. Almost all the works published are confined to smaller residential-scale systems or focused on some single aspect of performance, such as economic dispatch or primary control [15]. Very few studies provide an integrated, multi-faceted analysis of the system performance that incorporates steady-state power flow, AC and DC fault response, and power quality assessment and mitigation, based on the detailed load profile of a major institutional campus [16]. This points to the need for more practical, engineering-focused research that does not merely propose a system design but rigorously validates the performance, safety, and reliability of the system using industry-standard tools and methodologies.

Contribution and Paper Structure

This paper, therefore, seeks to accomplish the stated research gap through the presentation of a comprehensive design and performance analysis of a multi-megawatt hybrid AC/DC micro grid for the University Campus Peshawar. The key contributions brought forth by this work are summarized as threefold:

Detailed design and modeling of the hybrid AC/DC micro grid, customized for the specific 8.75 MW AC and 15 kW DC load profile of a university campus, provides an actionable, scalable blueprint for use by similar institutional applications.

A thorough performance validation using the industry-standard ETAP software, covering a holistic suite of analyses including AC/DC load flow, AC/DC short-circuit response, and arc flash safety assessment.

This contribution will focus on a practical demonstration of power quality management: the diagnostic process, identification of a serious harmonic distortion problem due to power electronic inverters, and successful design and implementation of the filtering solution to meet international standards.

The rest of the paper is organized as follows: Section II elaborates on the architecture of the proposed micro grid and modeling of its various components in detail. Section III discusses the steady-state performance analysis of the system through AC and DC load flow studies. Section IV explores fault tolerance of the system along with the adequacy of the protection scheme by performing short-circuit analysis. Section V presents the assessment of power quality and operational safety, focusing on harmonic distortion mitigation and arc flash hazard analysis. Finally, Section VI summarizes key findings and outlines some specific directions for further research.

SYSTEM ARCHITECTURE AND MODELLING OF THE UNIVERSITY CAMPUS MICRO GRID

System Topology and Load Profile

The electrical architecture of the proposed hybrid AC/DC micro grid meets the unique energy demand and resilience needs of University Campus Peshawar. The complete system topology is represented in the single-line diagram shown in Figure 5 below, which serves as the central schematic for the analyses conducted in this paper. In this design, the requirements are based on a detailed load assessment, which estimated the TDL at approximately 8.75 MW for the AC system and a dedicated 15 kW for critical DC loads that need uninterruptible power.

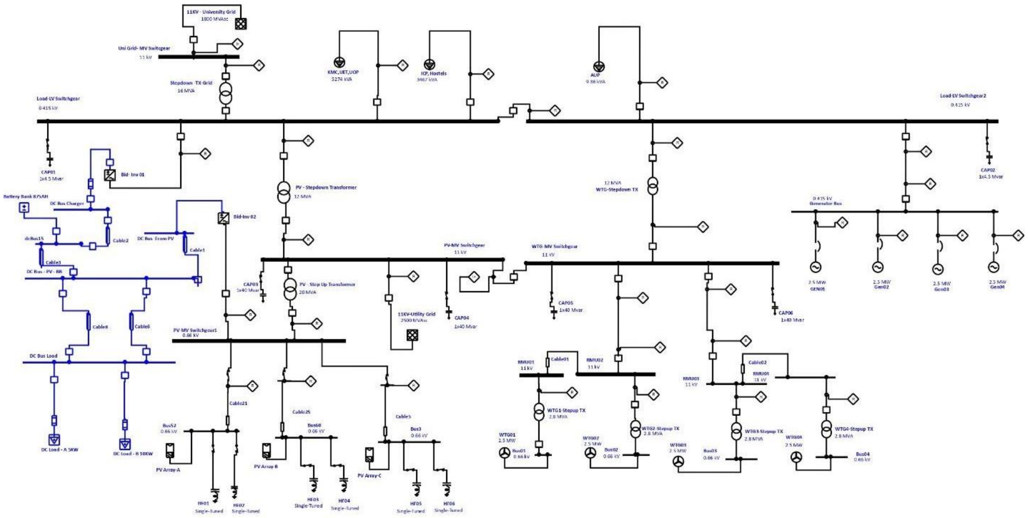


Fig. 5. Single-line diagram of the proposed hybrid AC/DC microgrid topology.

The present infrastructure of the campus is fed through the Defence Grid Station by three main 11 kV feeders, as shown in Figure 6. The load is divided among these feeders in the following manner:

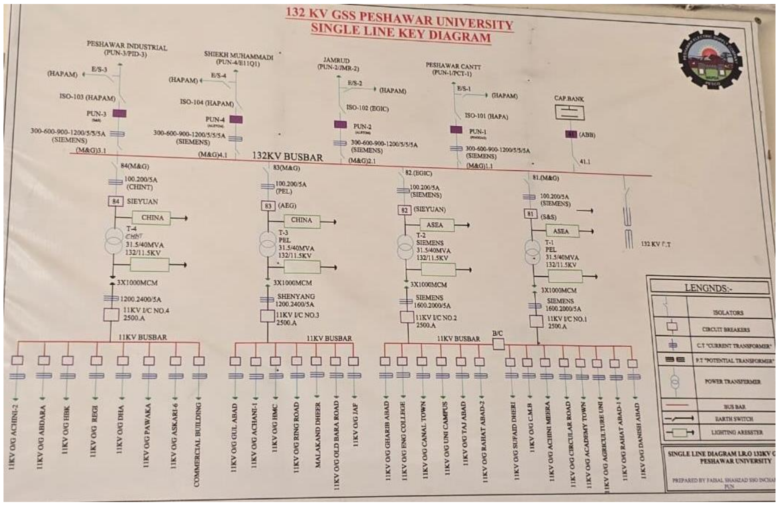


Fig. 6. Diagram of the three main 11 kV feeders from Defence Grid Station.

11 kV Agriculture University Feeder: The feeder shown in Figure 7 serves the Agriculture University along with some surrounding areas and is considered to carry a light load.

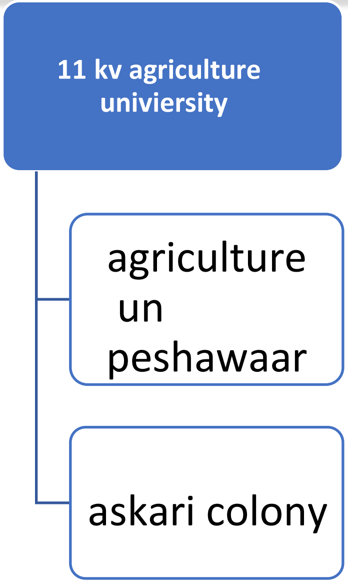


Fig. 7. Diagram of the 11 kV Agriculture University Feeder.

11 kV Engineering College Feeder: This is the most heavily loaded feeder as shown in Figure 8, which supplies the UET campus, Khyber Medical College, and other central academic areas.

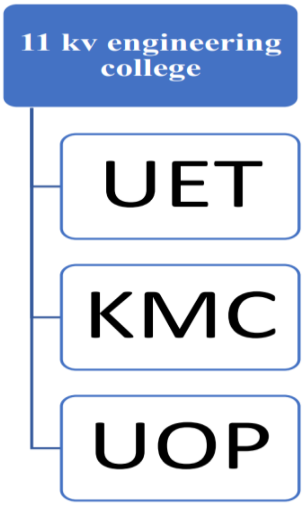


Fig. 8. Diagram of the 11 kV Engineering College Feeder.

11 kV University Campus Feeder: This feeder, as illustrated in Figure 9, supplies electricity to Islamia College Peshawar (ICP) and various major student hostels.

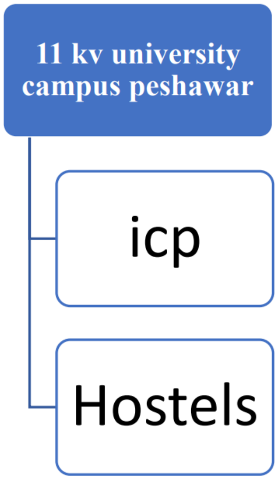


Fig. 9. Diagram of the 11 kV University Campus Feeder.

The detailed breakdown of the AC load distribution, which forms the basis for the micro grid design and sizing, is summarized in Table I.

TABLE I
SUMMARY OF CAMPUS AC LOAD DISTRIBUTION

University/Facility	Upstream Feeder	Downstream Feeder	TDL (kW)	TCL (kW)	Power Factor
KMC	11 kV Engineering College Feeder	400 V	5274.11	6328.93	0.9
UET	11 kV Engineering College Feeder	400 V			
UOP	11 kV Engineering College Feeder	400 V			
ICP	11 kV University Campus Feeder	400 V	3467.32	4160.78	0.9
Hostels	11 kV University Campus Feeder	400 V			
AUP	11 kV Agriculture University Feeder	400 V	9.36	11.23	0.9

Modelling of Distributed Energy Resources (DERs)

The microgrid will integrate various DERs to guarantee a reliable and sustainable power supply. Each of the components was modeled in ETAP based on detailed manufacturer specifications and operational parameters. The technical specifications for the key generation sources are summarized in Table II.

Solar Photovoltaic System: The mainstay of the microgrid's renewable generation capacity is a large-scale solar PV system, divided into three different arrays, namely PV-Array A, B, and C. Each array consists of 7,296 high-efficiency 600 W solar panels, thus providing a significant DC power capacity. The electrical behavior of the selected panels is described by their P-V and I-V curves, as shown in Figure 10 and Figure 11, respectively. These curves constitute the backbone of the simulation model because they define the power output of the panel for any variation in solar irradiance and temperature conditions, and include the critical MPP, where the system has to operate.

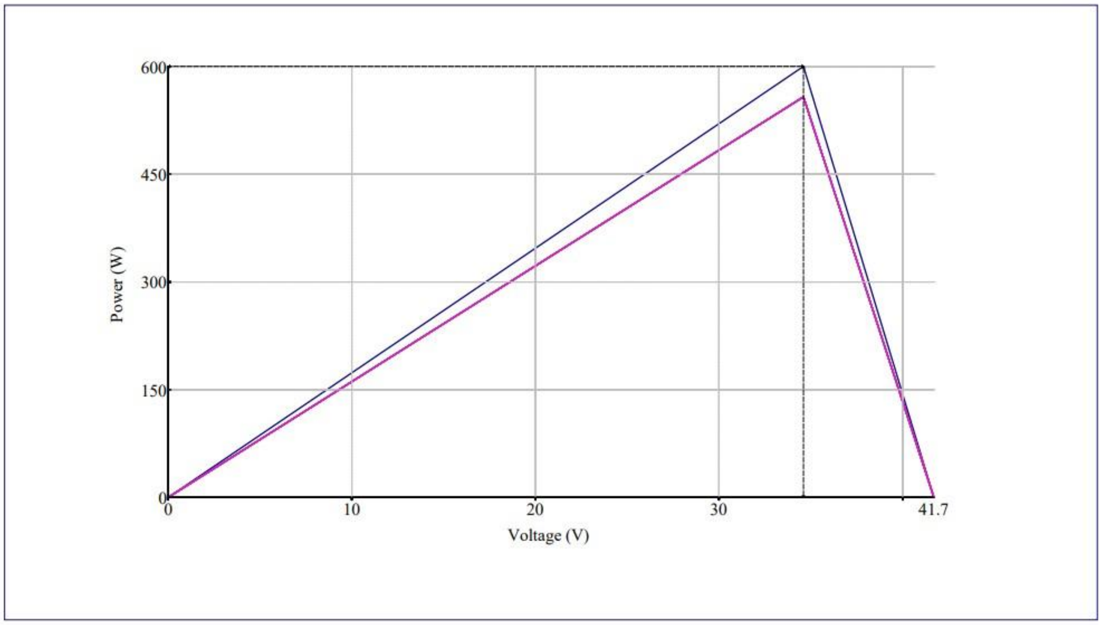


Fig. 10. P-V curves for the selected solar panels.

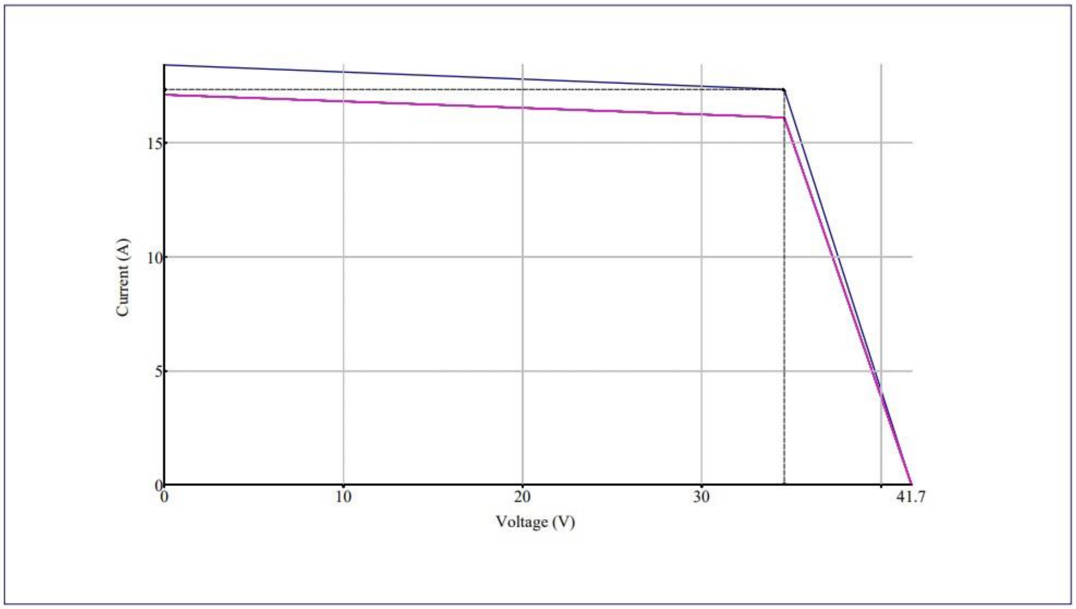


Fig. 11. I-V **curves for the selected solar panels.**

Wind Turbine Generators: Complementing the solar generation, the system includes four 2.5 MW WTGs. These units are a substantial source of clean energy, very much useful when the solar irradiance is low, such as at nighttime or on overcast days. The WTGs have been modeled for a rated voltage of 660 V and a high power factor to contribute more effectively towards the system's real power needs with minimum reactive power demand.

Diesel Generators: The microgrid is fitted with four 2.5 MW diesel generators that ensure uninterrupted power during grid outages lasting more than four hours or when renewable generation is not adequate. Diesel generators can be modeled as an integral backup resource in the microgrid, with their spinning reserve and black start capability critical for stable operation in islanded mode. These generators are able to ramp up very quickly and provide stable voltage and frequency, which helps in holding up the entire system together.

TABLE III
TECHNICAL SPECIFICATIONS OF DISTRIBUTED ENERGY RESOURCES

Resource Type	Parameter	Value
Solar PV Array (per array)	Panel Wattage	600 W
	Solar PV Array (per array)	7296
	Number of Panels	4377.4 kW
	Total DC Power	3939.6 kW
	Rated AC Power	660 V
Wind Turbine Generator (per unit)	Rated AC Voltage	2.5 MW
	Rated Voltage	660 V
	Power Factor	95%
	Poles	4
	Speed	1500 RPM
Diesel Generator (per unit)	Rated Power	2.5 MW
	Rated Voltage	415 V
	Power Factor	80%
	MVA Rating	3.125 MVA
	Speed	1500RPM
	Poles	4

DC Subsystem and Energy Storage

One of the salient features of the hybrid architecture is indeed the dedicated DC subsystem, which has been designed to be efficient and provide the highest level of reliability for various campus-critical loads. This subsystem is based on a 250 V DC bus that directly feeds 15 kW of critical equipment including emergency lighting, server racks, and communication equipment. Table III identifies the breakdown of these DC loads in detail.

This DC network's resiliency is anchored around a robust Battery Energy Storage System (BESS). The BESS contains a large battery bank, rated for a total capacity of 875 Ah at a nominal voltage of 250 V. This system is appropriately sized to allow the critical DC load of up to 15 kW for up to 8 hours of autonomous operation, securing the continuity of all the essential campus functions during a complete loss of all AC power sources coming from either the grid or local generation. The detailed parameters of the BESS and the DC loads that it serves are summarized in Table III.

TABLE IIIII
DC SUBSYSTEM AND BATTERY STORAGE PARAMETERS

Component	Parameter	Value
DC Loads	DC Bus Voltage	250 V
	Total DC Load	15 kW
	DC Load A	5 kW
	DC Load B	10 kW
Battery Energy Storage System	Nominal Voltage	250 V
	Total Capacity	875 Ah
	Backup Duration	8 hours (for 15 kW load)
	Number of Cells	121
	Rated Open-Circuit Voltage	248.7 V

Power Conversion and Grid Interface

A network of power conversion and conditioning equipment enables seamless integration between the various AC and DC components. A number of step-up and step-down transformers are placed at strategic locations within the microgrid in order to manage voltage levels between generation sources, distribution buses, and loads. The ratings and voltage specifications of these transformers are provided.

Bidirectional inverters represent the crucial interface between the AC and DC subsystems. These sophisticated power electronic devices are responsible for appropriately controlling the flow of energy, covering the conversion of DC power supplied by the PV arrays and the battery bank to AC for feeding the main grid, and vice-versa, charging the battery from AC sources when required. In order to ensure power quality and contribute to voltage stability on the AC system, two large capacitor banks, each rated at 4.5 MVAR of reactive power compensation, were installed.

Finally, the point of common coupling between the microgrid and the external utility grid is a key interface. The electrical characteristics of this interface, such as voltage level, short-circuit capacity in MVA, and impedance ratio (X/R), are defined. These parameters are fundamental for modelling the grid behaviour, and are of particular importance for performing valid short-circuit and protection coordination studies.

STEADY-STATE PERFORMANCE AND POWER FLOW ANALYSIS

AC System Load Flow Analysis

A load flow study was performed in order to investigate the steady-state performance of the AC microgrid for a normal operating scenario where all generation sources, such as solar PV, wind turbines, diesel generators, and the utility grid, were active. The basis of this analysis is to confirm that the system can reliably serve the 8.75 MW campus load while the bus voltages and equipment loading are kept within safe operating limits.

The ETAP-simulated results, represented graphically in the one-line diagram shown in Figure 12, show the network to be well balanced and stable. Quantitative results of this study are provided in Table IV, which gives voltage magnitude, active power (MW), reactive power (Mvar), and current loading at selected buses within the system. This analysis confirms that, in this full-generation case study, all bus voltages are held close to their nominal values and no transformers, cables, or any other components are overloaded. Another important outcome from the load flow study is that the capacity of the combined DERs exceeds campus demand, so the microgrid will be able to export excess clean energy back into the utility grid, thus gaining credits for stability of the grid and even benefiting economically.

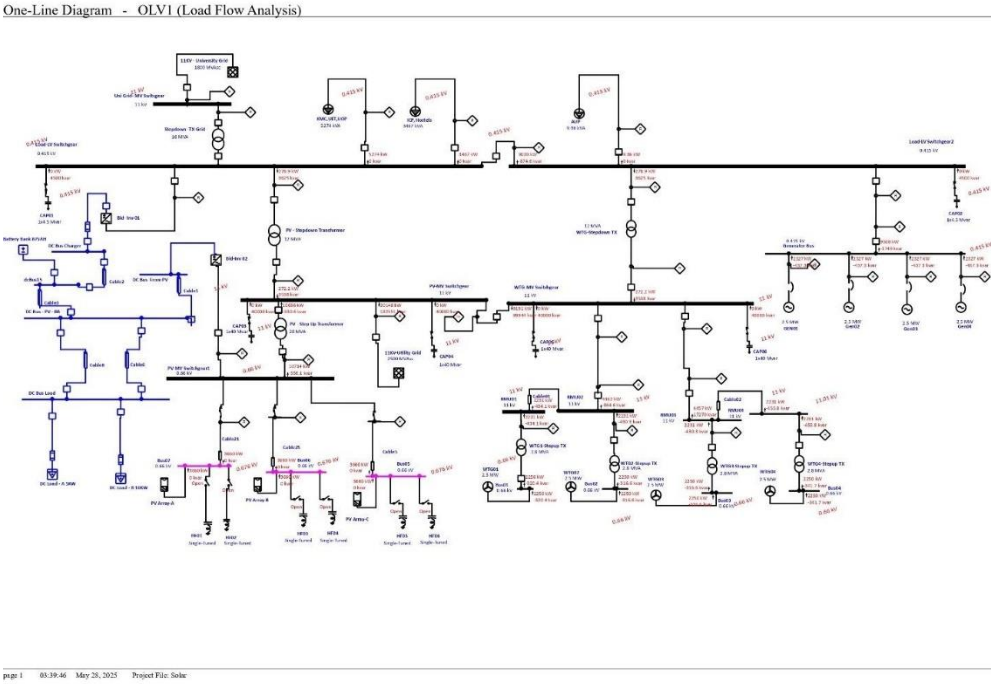


Fig. 12. ETAP one-line diagram of AC system load flow results.

DC System Load Flow Analysis

A separate load flow analysis was conducted for the dedicated DC subsystem in order to verify its capability in reliably serving the 15 kW of critical loads. Shown in Figure 13, the simulation represents the situation when the battery bank acts as the only source for the DC bus, thus simulating an islanded or emergency operating condition.

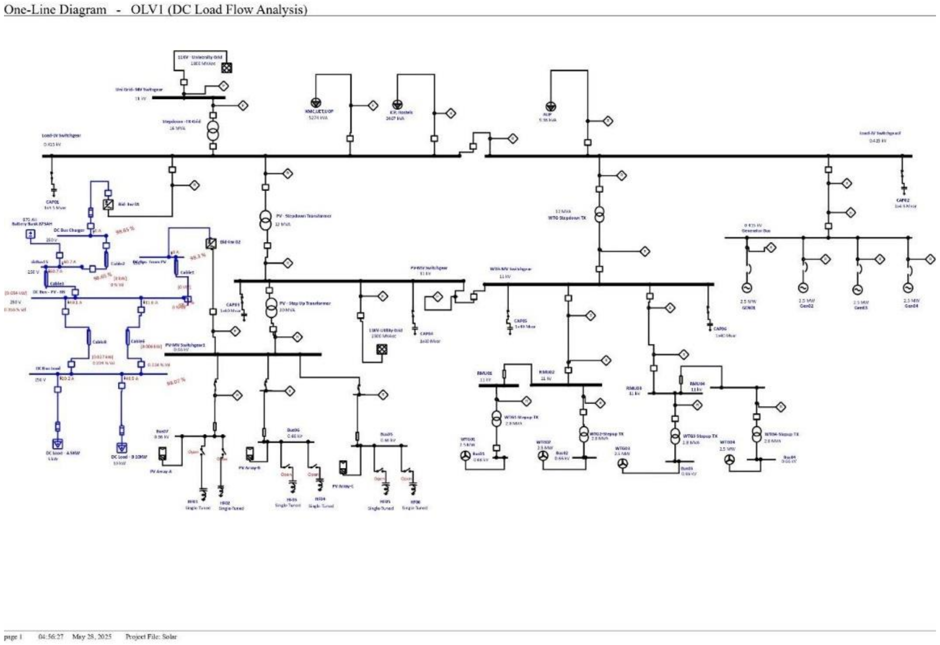


Fig. 13. ETAP simulation of DC subsystem load flow (islanded operation).

These results are verified by the more detailed results and show that the voltage at the DC bus remains precisely at its nominal 250 V rating, while the battery system supplies the full 15 kW load with no operational problems. In this way, this result confirms that the battery, DC bus, and associated cabling are properly sized and that the DC subsystem can fulfill its important role in providing uninterrupted power to critical campus services during failures.

TABLE IVV

AC SYSTEM STEADY-STATE LOAD FLOW RESULTS

Bus ID	Nominal kV	Voltage (% of Nominal)	MW	Mvar	Amp
Bus02	0.66	100.00	2.25	0.317	1988
Bus03	0.66	100.00	2.25	0.317	1988
Bus04	0.66	100.00	2.25	0.342	1991
Bus05	0.66	102.36	3.66	0	3128
Bus06	0.66	102.36	3.66	0	3128
Bus07	0.66	102.36	3.66	0	3128
Generator Bus	0.415	100.00	9.308	1.749	13176
Load-LV Switchgear 1	0.415	100.00	9.02	4.5	14023
Load-LV Switchgear 2	0.415	100.00	9.308	5.375	14953
PV-MV Switchgear 1	11	100.00	20.148	183.482	9688
PV-MV Switchgear 2	0.66	99.95	10.714	0.356	9383
RMU01	11	100.01	2.231	0.434	119.3
WTG-MV Switchgear	11	100.00	9.191	100.808	5313

FAULT TOLERANCE AND SHORT-CIRCUIT ANALYSIS

AC Subsystem Response

It is very important in micro grid design to ensure that the system is capable of withstanding and clearing electrical faults safely. A full short-circuit analysis of the AC subsystem was performed to identify the maximum fault current magnitudes that could be seen at all points within the network. This is necessary so that any protective devices, like circuit breakers and fuses selected for use, have an adequate interrupting capacity to function safely without failure.

This worst-case scenario was represented by applying a three-phase bolted fault to each major bus in the AC network of the simulation. The resultant fault current magnitudes have been illustrated on the one-line diagram shown in Figure 14.

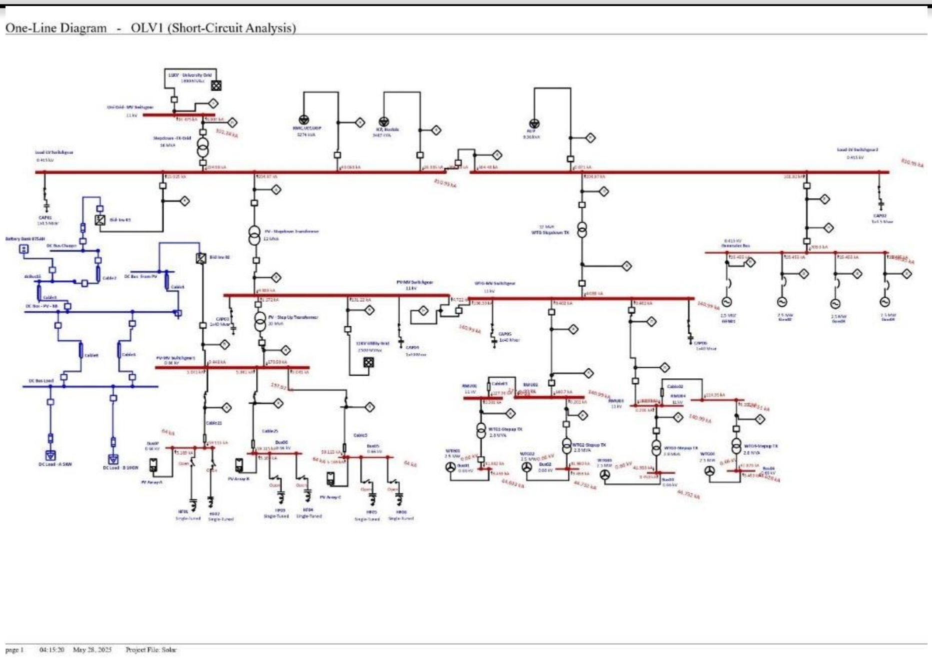
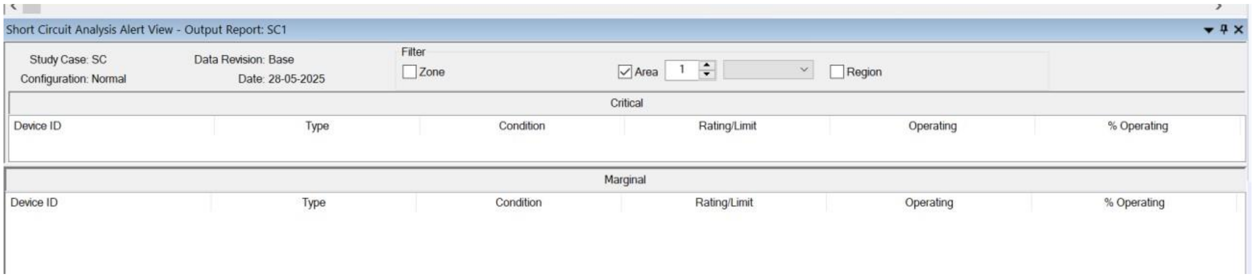


Fig. 14. ETAP one-line diagram of AC short-circuit fault magnitudes.

Quantitative fault levels at each bus have been compiled in Table V. It may be seen from this analysis that maximum fault currents are drawn at those buses that are closest to the utility grid and major rotating machines (generators), which is an expected outcome due to high fault current contribution from these sources. As the fault location progresses further into the campus distribution network, the impedance of cables and transformers limits the fault current progressively.

The alert view of this simulation, as depicted in Figure 15, did not report any critical errors, which means that none of the fault duties calculated exceeded the ratings of any equipment modelled in the study. This extensive analysis ascertains that the protection scheme is adequately designed and the selected switchgear is rated appropriately to safeguard the micro grid against fault conditions.



Study Case: SC
Data Revision: Base
Configuration: Normal
Date: 28-05-2025
Filter
☐ Zone
☑ Area 1
☐ Region

Critical

Device ID	Type	Condition	Rating/Limit	Operating	% Operating

Marginal

Device ID	Type	Condition	Rating/Limit	Operating	% Operating

Fig. 15. ETAP alert view for AC short-circuit analysis.

TABLE V
AC SYSTEM SHORT-CIRCUIT FAULT LEVELS

Faulted Bus ID Peak	Nominal kV	Symmetrical Fault Current I_k (kA)	Asymmetrical Current, i_p (kA)

Bus01	0.66	44.63	99.53
Bus05	0.66	64.00	109.82
Generator Bus	0.415	810.95	2041.10
Load-LV Switchgear 1	0.415	810.95	2041.10
PV-MV Switchgear 1	11	140.99	370.39
RMU02	11	140.99	370.39
Uni Grid-MV Switchgear	11	101.38	261.31
WTG-MV Switchgear	11	140.99	370.39

DC Subsystem Fault Response

Fault analysis in the DC subsystem is equally important; however, it involves a different set of challenges compared to AC systems [17]. A short-circuit study was carried out in the DC network in order to quantify the fault current contributions from both the battery and the interfacing converters. The results of this analysis are shown in Figure 16 and detailed in Table VI.

Analysis of DC fault characteristics reveals a fundamental challenge with major implications for protection design: Unlike AC fault currents, which naturally pass through zero 100 or 120 times per second, a DC fault current rapidly rises to its maximum value and remains there as a constant, high-magnitude current [18]. This absence of a natural zero-crossing makes the process of interrupting the fault current extinguishing the electrical arc within a circuit breaker—significantly more difficult. Consequently, specialized DC-rated circuit breakers are required, which employ mechanisms like magnetic blowouts or arc chutes to forcibly stretch and cool the arc [19].

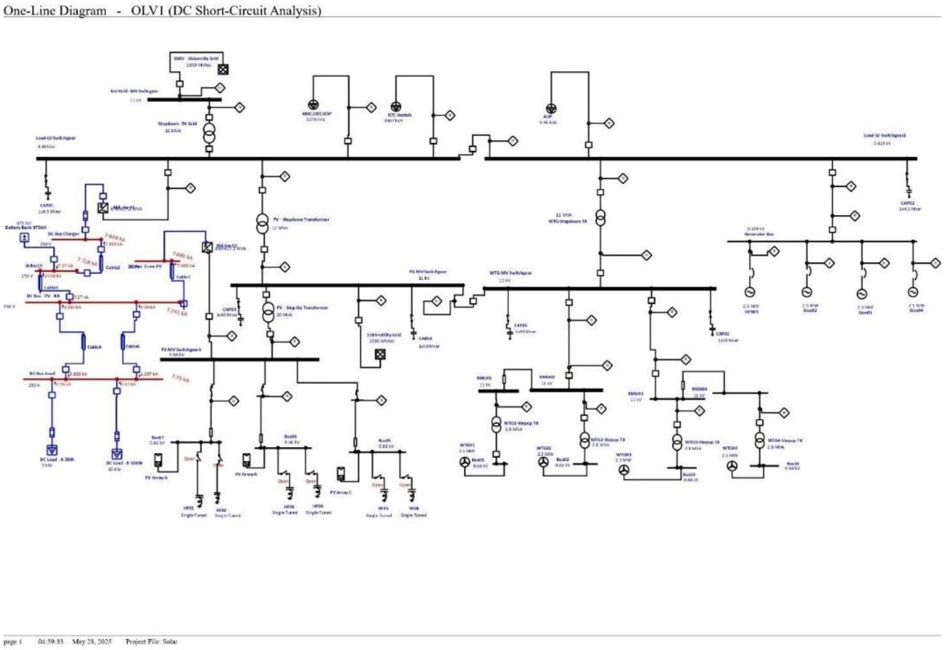


Fig. 16. ETAP results for DC subsystem short-circuit analysis.

TABLE VI
DC SUBSYSTEM SHORT-CIRCUIT FAULT LEVELS

Faulted Bus ID	Nominal V	Fault Current (kA)	Equivalent Resistance (ohm)
DC Bus From PV	250	7.685	0.52115

The fault current source nature is also different in the case of a DC microgrid. Large rotating machines do not provide the predominant fault current, but instead, power electronic converters mainly supply this current, such as those from the battery and AC-DC interface [20]. These converters possess very fast internal protection mechanisms that usually limit their contribution to fault current to a value within 1.2 to 2.0 times their nominal current rating. This leads to a fault current magnitude considerably lower than that in AC systems but much harder to interrupt [21].

This combination of difficult interruption and a potentially low fault current magnitude presents a complex protection challenge. Standard overcurrent relays or fuses, which are designed to operate based on high fault current magnitudes, are unlikely to detect the limited DC fault current reliably or may operate too slowly [22]. Thus, a robust DC protection scheme cannot rely exclusively on simple overcurrent principles. It requires a more sophisticated, multi-layered solution that may involve a combination of ultra-fast-acting fuses designed for DC applications, dedicated DC circuit breakers, and advanced protection strategies such as differential protection schemes or high-speed, communication-based tripping that can send a block signal directly to the converters' control gates to cease current injection almost instantaneously. The calculated fault current value is not just a number for equipment rating; it is a critical parameter that informs the whole philosophy of the DC protection system design [23].

POWER QUALITY AND OPERATIONAL SAFETY ASSESSMENT

Harmonic Distortion Analysis and Mitigation

High power quality is necessary to ensure reliable operation for sensitive electronic equipment, which is common on a university campus. One component of power quality is the management of harmonic distortion--the distortion of the fundamental sinusoidal voltage and current waveforms by higher frequency components. A harmonic analysis was performed to determine the level of THD throughout the microgrid with regard to the IEEE 519 standard, which typically limits voltage THD to 5% in public distribution systems.

The initial analysis, conducted on the system without any dedicated mitigation measures implemented, demonstrated a considerable power quality issue. The results, summarized in the system-wide view in Figure 17, showed that while most of the system had acceptable THD levels, four locations in particular were showing voltage THD above the 5% limit. The distorted voltage waveforms at the problematic buses, Bus 05, Bus 06, Bus 07, and PV-MV Switchgear 1, are given in Figures 18, 19, 20, and 21, respectively.

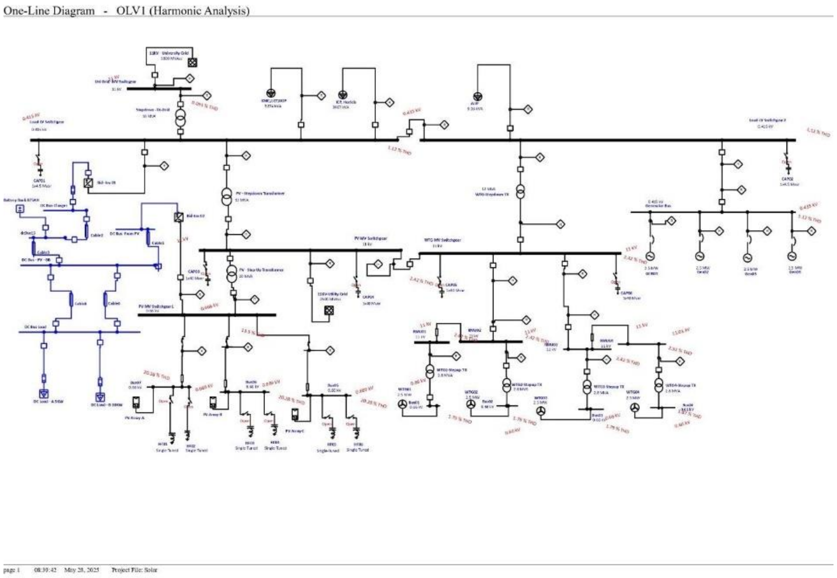


Fig. 17. ETAP system-wide harmonic analysis (pre-mitigation/without filters).

Fig. 18. Distorted voltage waveform at Bus 05 (without filter).

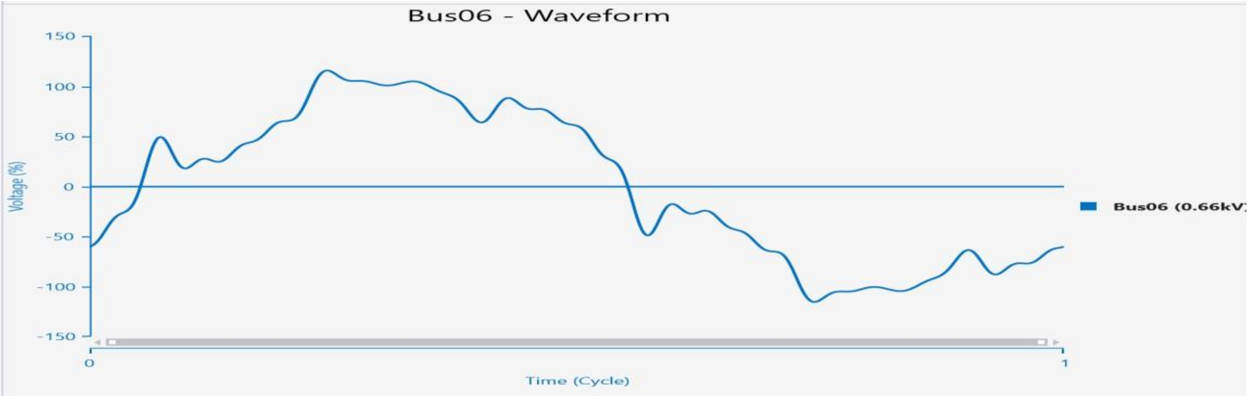


Fig. 19. Distorted voltage waveform at Bus 06 (without filter).

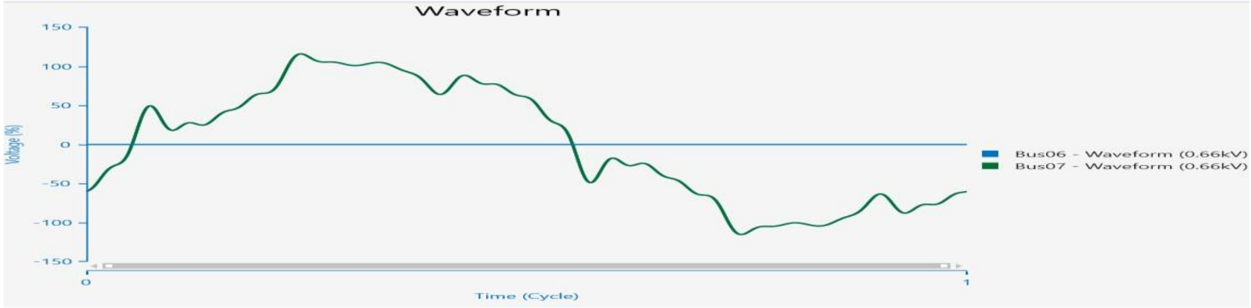


Fig. 20. Distorted voltage waveform at Bus 07 (without filter).

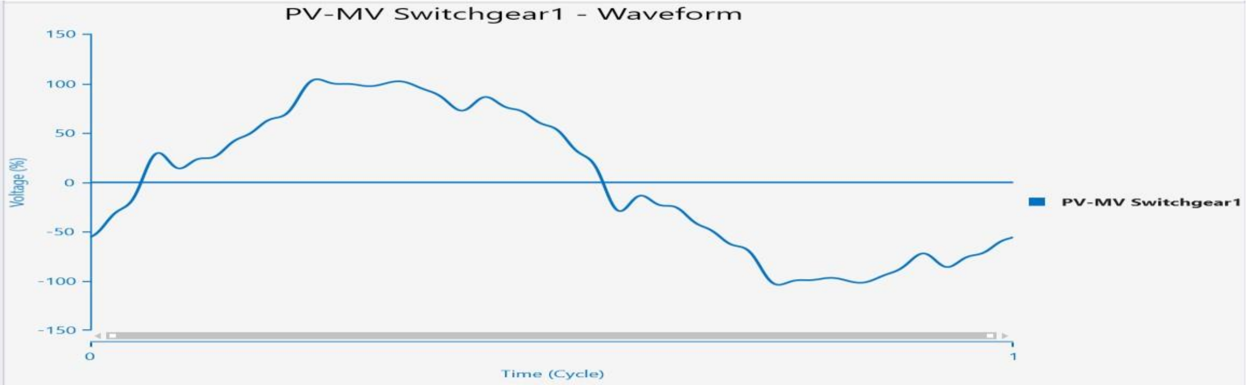


Fig. 21. Distorted voltage waveform at PV-MV Switchgear 1 (without filter).

A diagnostic approach based on the topological information of the system was able to identify the source of this elevated distortion. The main sources of harmonic currents in a modern power system are power electronic devices; in this case, it is the inverters that interface the PV arrays to the AC grid. These employ high-frequency switching techniques, such as Pulse Width Modulation (PWM), that synthesize an AC waveform from a DC source. While highly efficient, this process invariably injects harmonic currents into the electrical system. Spatially correlating the locations of high harmonic distortion with the system single-line diagram shown in Figure 5 yields a clear pattern. Buses 05, 06, and 07 are the direct points of connection for the three PV arrays, while PV-MV Switchgear 1 is the common bus that aggregates the power from all three arrays. This spatial concentration of high THD at exactly these same locations is an immediate and predictable consequence of their electrical proximity to harmonic-injecting PV inverters. The harmonic currents generated by the inverters produce the largest voltage distortion at their immediate points of connection before these harmonics propagate and attenuate throughout the remainder of the system. This diagnostic step confirmed the PV inverters as the primary source of the power quality problem.

To mitigate this issue, passive harmonic filters were designed and inserted into the model at the affected buses. These filters are specifically tuned to provide a low-impedance path for the problematic harmonic currents and effectively shunt them to ground before they can distort the system voltage. This mitigation strategy was then confirmed through the re-run of harmonic analysis. The post-mitigation results, shown in Figure 22, indicate a dramatic improvement in power quality throughout the system. The cleaned-up, near-sinusoidal voltage waveforms at the four critical buses are shown in Figures 23, 24, 25, and 26. Quantitatively, the success of the solution can be described by Table VII, which gives a before-and-after comparison of the voltage THD at the critical buses, showing all are now well within the 5% limit dictated by the IEEE 519 standard.

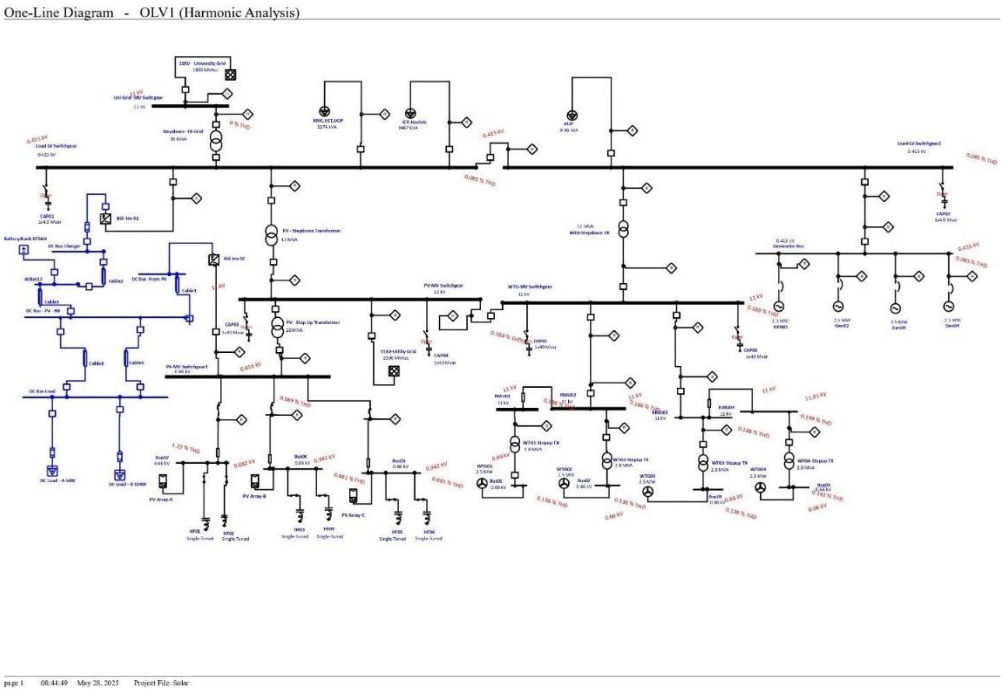


Fig. 22. ETAP system-wide harmonic analysis (post-mitigation/with filters).

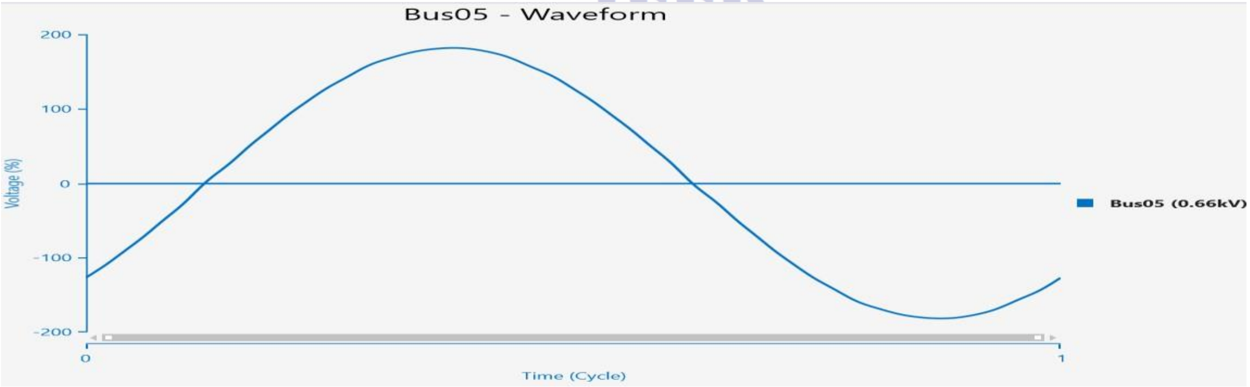


Fig. 23. Cleaned voltage waveform at Bus 05 (with filter).

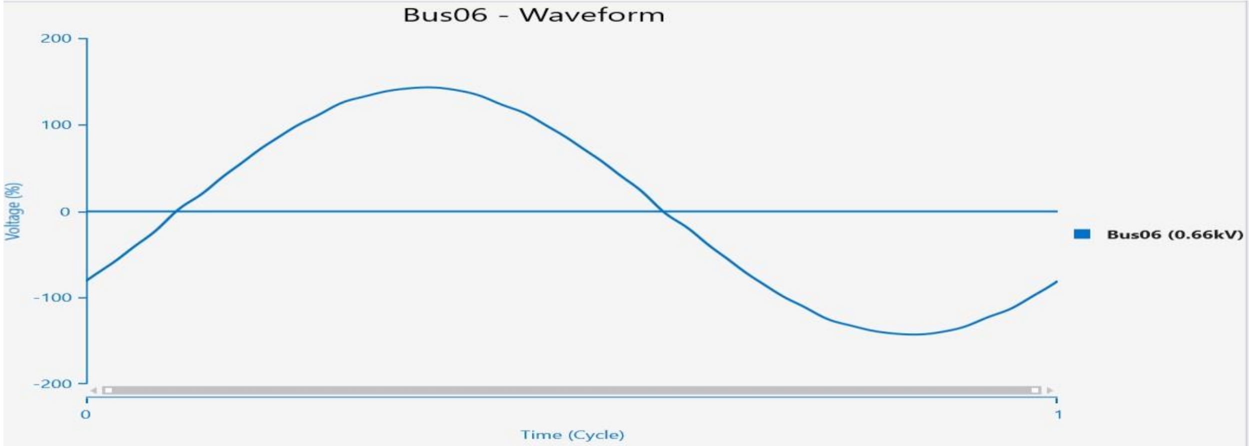


Fig. 24. Cleaned voltage waveform at Bus 06 (with filter).

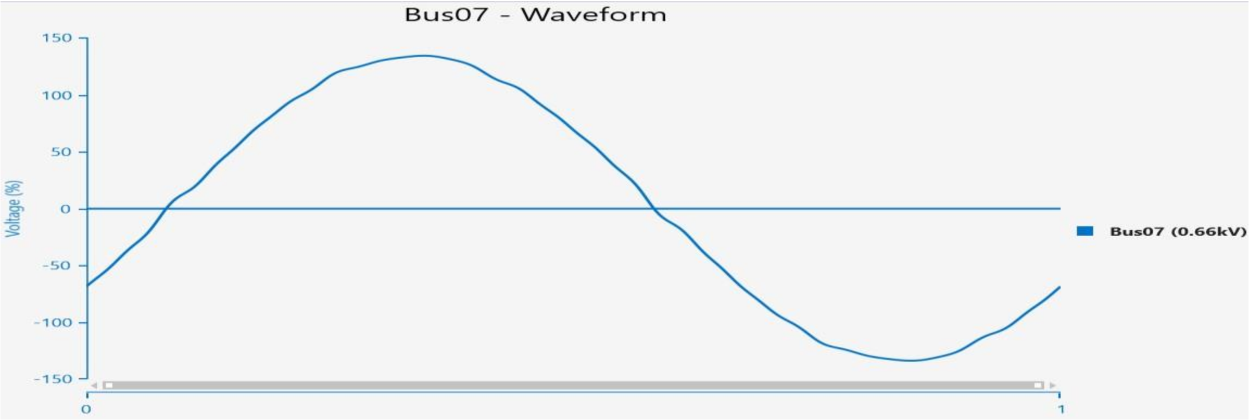


Fig. 25. Cleaned voltage waveform at Bus 07 (with filter).

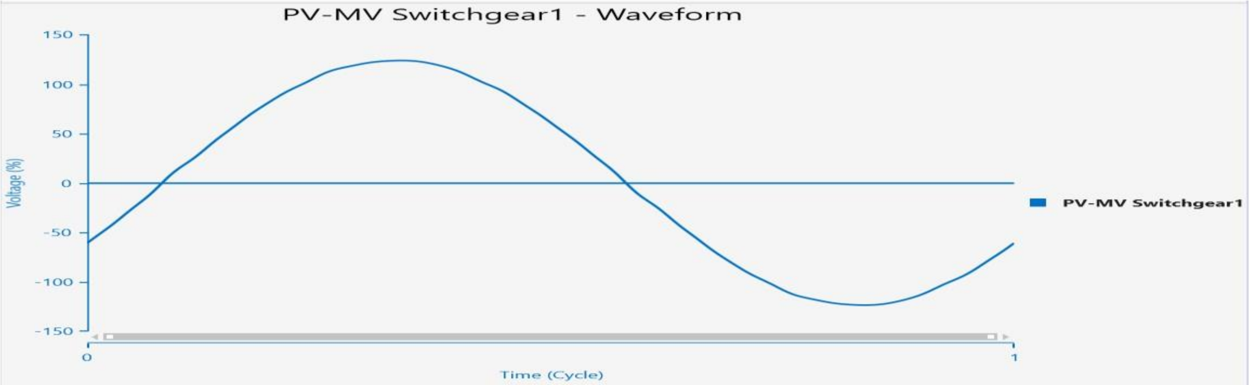


Fig. 26. Cleaned voltage waveform at PV-MV Switchgear 1 (with filter).

TABLE VII
HARMONIC DISTORTION MITIGATION RESULTS

Bus ID	THD (%) Without Filter	THD (%) With Filter	IEEE 519 Limit (%)	Status
Bus05	> 5.0	0.65	5.0	Pass
Bus06	> 5.0	0.65	5.0	Pass
Bus07	> 5.0	0.65	5.0	Pass
PV-MV Switchgear 1	> 5.0	0.19	5.0	Pass

Arc Flash Hazard Assessment

In addition to ensuring system reliability and power quality, a comprehensive microgrid design needs to address the important issue of operational safety for personnel. An arc flash is an electrical explosion due to a fault that may cause serious injury or death. An arc flash hazard assessment was performed to quantify this risk and establish safe working procedures.

The analysis was performed for several locations, and the results for "load-lv switchgear 2" are shown as a representative example in Figure 27. The detailed arc flash report gives some very important information on safety, including:

Incident Energy: The amount of thermal energy that would be experienced at a specific working distance from the fault, measured in calories/cm².

Arc Flash Boundary: The distance from the equipment within which an individual could receive a second-degree burn in case of an arc flash.

PPE: The level of FR clothing and other personal protective equipment that is required in order to work safely on the equipment.

By incorporating this safety engineering analysis into the design process, the operational protocols of the microgrid can be established to minimize risk to maintenance personnel so that not only is the system reliable and efficient, but also safe to operate and maintain.

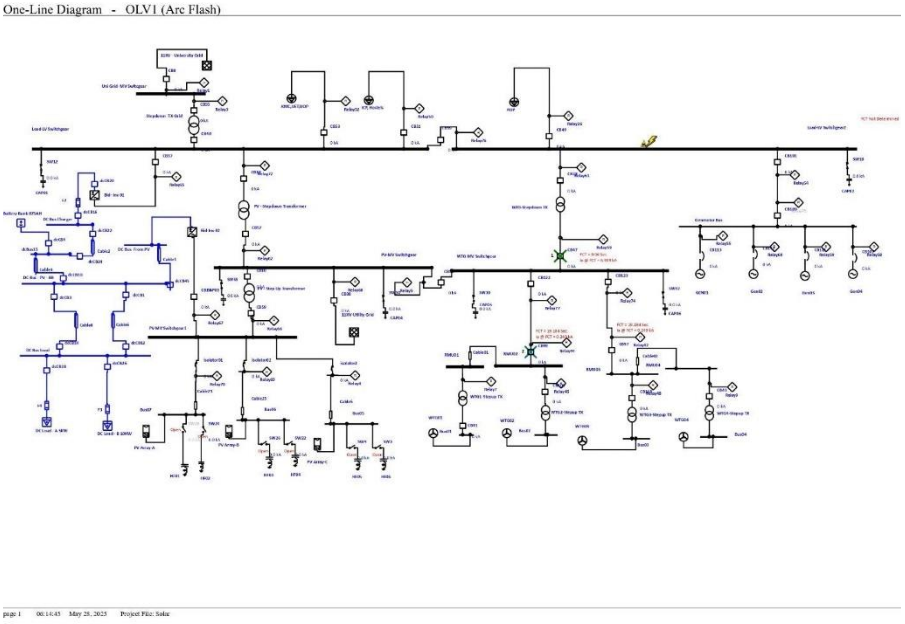


Fig. 27. Arc flash hazard assessment results for "Load-LV Switchgear 2".

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

Summary of Key Findings

This work has presented a detailed design and multi-dimensional performance analysis of a solar-dominated 8.75 MW hybrid AC/DC microgrid for the University Campus Peshawar. The simulation-based validation performed in ETAP provides evidence that the proposed system is technically viable, robust, and resilient, capable of meeting the critical energy needs of the institution. In this regard, some of the key findings of this study are summarized below:

Steady-State Viability: The performed AC and DC load flow analyses confirmed that the microgrid can operate in a stable steady state, reliably serving the full campus load while maintaining all voltages and equipment loading within their nominal design limits. Furthermore, the system can export surplus renewable energy to the utility grid.

Adequacy of Fault Tolerance and Protection: The analyses for the AC and DC subsystems showed that the chosen protective devices are properly rated to sustain and safely interrupt the fault currents in a worst-case scenario without any risk to the system's safety and integrity.

Power Quality Management: The significant power quality problem was identified to be severe harmonic distortion emanating from the PV inverters, which was mitigated by the appropriate application of specially designed harmonic filters. This restored the voltage quality in this system to comply with the stringent requirements of the IEEE 519 standard.

These findings collectively demonstrate the feasibility of a large-scale hybrid micro grid implementation to improve energy resilience, reduce dependency on the national grid, and advance the integration of renewable energy technologies within a major institutional infrastructure.

Future Research Directions

The analysis reported in this paper lays a very strong foundation for the proposed micro grid, but also points to some high-impact future research avenues that can be pursued to advance the performance, intelligence, and efficiency of such systems even further. Based on the obtained insights, the following research directions are recommended:

Voltage Regulation by Advanced Inverter Control: This marginal overvoltage condition presents the opportunity for more sophisticated control of this circuit. Future research will study the implementation and system-wide impact of advanced inverter control strategies, such as Volt-VAR and Volt-Watt functions. This would provide dynamic voltage support and other ancillary services from PV inverters and change their role from simple energy producers to active grid-stabilizing assets.

Adaptive Protection Schemes: The protection of a micro grid with variable fault current levels, especially in the DC subsystem and transition between grid-connected and islanded mode, deserves further research. The development of an adaptive protection system should be considered. Such a system would make use of IEDs and high-speed communication to adjust the settings and logic of the relays automatically and in real time based on the operational state of the microgrid to provide dependable and selective fault clearing under all conditions.

AI-Based Predictive Energy Management: Development of an Artificial Intelligence-driven Energy Management System for the optimization of the micro grid's economic and operational performance is highly recommended. The AI EMS would apply machine learning algorithms for high-accuracy forecasting of campus loads and renewable energy generation. This will then be used to co-optimize in real time all the dispatches of DERs, the charging/discharging schedule of the BESS, and possibly participating in grid ancillary service markets to lower operational costs and increase the use of clean energy.

Transient Stability Analysis: Although this work focused on the performance at steady-state and under short-circuit conditions, a really important sequel should be devoted to a thorough transient stability analysis. In fact, a dynamic simulation should be performed to assess the capability of the micro grid to withstand large disturbances, such as sudden loss of the main grid (unplanned islanding) or a major internal fault. The analysis would be critical in designing the control systems needed to enable a seamless transition between the different operating modes and ensure stability within an inverter-dominated, low-inertia environment.

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