ENT9098EE07 - High-Resolution Performance Analysis and Optimization of a Real-Scale 350 V LVDC Residential Microgrid

Principal Investigator

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Programme	ENT9098 Master of Science by Research in Electronics Engineering
Research Area and Specialization:	Low Voltage Direct Current (LVDC) residential microgrids Hybrid AC/DC smart residential energy systems Photovoltaic (PV) integrated microgrids with Battery Energy Storage Systems (BESS) Energy Management Systems (EMS) optimization and performance analysis Data-driven energy modelling and system identification in power systems Energy efficiency and performance benchmarking of residential electrification systems under real operational conditions

Background of the problem

Applications are invited for two Master by Research positions within a large-scale, fully operational Low Voltage Direct Current (LVDC) residential microgrid research programme in Bahrain. The project is embedded in a real-world energy system comprising a 92 kW photovoltaic generation plant, a 130 kWh battery energy storage system (BESS), a 100 kW bidirectional grid converter, and three operational 350 V DC residential villas, alongside AC-based control houses used for comparative analysis.

This infrastructure represents one of the few known fully operational residential LVDC microgrid testbeds globally, operating continuously under real environmental conditions and live residential occupancy. The system integrates renewable generation, storage, and hybrid AC/DC residential loads under a centralized Energy Management System (EMS).

Despite its uniqueness, the platform currently lacks high-resolution instrumentation at appliance and converter level, limiting the ability to fully quantify internal energy flows and conversion

efficiencies. This research programme is therefore designed to extract maximum scientific value from existing operational data while developing advanced analytical methods to address current measurement limitations.

List of publications related to the field

J4. Dimitrios Mathioulakis, Nikolaos Vasilikos, Panagiotis Kapiris and Christina Georgantopoulou, Ground Clearance Effects on the Aerodynamic Loading of Tilted Flat Plates in Tandem, (20205), Fluids MDPI, 10, 155. https://doi.org/10.3390/fluids10060155

J6. Gaaliche, N., Alsatrawi, H., Georgantopoulou, C.G. (2024). A Fluid-Thermal-Electric Model Based on Performance Analysis of Semi-transparent Building Integrated Photovoltaic Solar Panels. In: Hamdan, A., Aldhaen, E.S. (eds) Artificial Intelligence and Transforming Digital Marketing. Studies in Systems, Decision and Control, vol 487. Springer, Cham. https://doi.org/10.1007/978-3-031-35828-9_10

J7. N. Vasilikos, C. Georgantopoulou, H. Alajaimi, S. H. Almajed, M. Ahmed and D. Mathioulakis, (2024), Tilted global solar irradiance in Bahrain: an experimental study, Clean Energy, 2024, Vol. 8, No. 2, 27–34, https://doi.org/10.1093/ce/zkae003

J14. Georgantopoulou C., Vasilikos Nikolaos, "Solar Systems Analysis and Estimation for Buildings in Bahrain and GCC Countries", International Journal of Computing and Digital Systems, Vol. 6, Issue 6. (2017)

C8. Mohamed Zayer*, Mohamed Ahmed, Nikolaos S. Vasilikos, Christina G. Georgantopoulou, Development and integration of experimental systems for solar power projects, GCC Power Conf. 2024, Manama, Bahrain.

Research Objectives and Expected Outcomes:

Aim

The aim of this research is to develop a high-resolution, data-driven understanding of energy generation, storage, conversion, and consumption dynamics within a real operational LVDC residential microgrid, and to benchmark its performance against conventional AC residential systems under identical climatic and behavioral conditions.

Research Objectives

The research will focus on five core objectives:

The first objective is to systematically analyze long-term operational energy data from LVDC and AC residential houses in order to quantify consumption patterns, identify seasonal trends, and evaluate the influence of occupancy behaviour and appliance usage diversity.

The second objective is to develop engineering-based analytical models capable of reconstructing internal system energy flows across photovoltaic generation, battery storage, grid

interaction, and residential loads, despite the absence of direct sub-metering at appliance or converter level.

The third objective is to evaluate the real-world operational performance of DC-specific residential technologies, including 350 V DC split air-conditioning systems and DC refrigeration units, particularly under continuous 24-hour usage scenarios in high-temperature climates.

The fourth objective is to assess the efficiency and operational behaviour of the integrated Energy Management System, including battery cycling patterns, PV utilization, and grid import/export interactions under both islanded and grid-connected conditions.

The fifth objective is to develop validated performance indicators and engineering recommendations for the optimization, scalability, and future deployment of LVDC residential systems in Gulf-region environmental conditions.

Expected Outcomes:

The project is expected to produce high-impact academic and technical outputs, including:

• A validated, high-resolution dataset derived from a real operational LVDC residential microgrid.

• Advanced analytical models describing energy flow behaviour in hybrid PV–BESS–grid systems.

• Peer-reviewed journal publications in high-impact energy and electrical engineering journals.

• A completed Master by Research thesis documenting methodology, findings, and engineering insights.

• Technical recommendations for improving LVDC system design, instrumentation, and scalability.

• A structured framework for future deployment of LVDC residential communities in similar climatic regions.

Research Design/Methodology

The research will be conducted using real operational datasets collected from the LVDC residential microgrid in Bahrain. These datasets include aggregated house-level energy consumption, PV generation profiles, battery charge-discharge cycles, and grid interaction data over extended monitoring periods.

A key component of the methodology involves advanced data processing and modelling techniques to infer sub-system behaviour that cannot be directly measured due to current instrumentation limitations. This includes estimating conversion losses, reconstructing partial energy flow pathways, and identifying load-level behaviour patterns using system-level observations.

Comparative analysis between LVDC and AC houses will be performed under real-world conditions, with careful normalization based on occupancy, appliance configuration, and environmental temperature variations. Particular attention will be given to air-conditioning loads, which represent the dominant energy consumption component across all residential units.

The study will also explore system scalability scenarios and optimization strategies, including increased DC load integration, improved energy management strategies, and future expansion of LVDC residential communities.

Significance and potential impact of research in Bahrain

This research project is significant because it addresses a critical gap between theoretical modelling and real-world performance of Low Voltage Direct Current (LVDC) residential microgrids. While LVDC systems are widely proposed as a next-generation solution for improving energy efficiency, integrating renewable energy, and reducing conversion losses, there is still limited empirical evidence from fully operational residential-scale systems under continuous real-life conditions. This project directly tackles that limitation by analysing one of the few known operational LVDC residential microgrid testbeds worldwide, located in Bahrain.

The significance is both scientific and practical. Scientifically, the project will generate validated, high-resolution insights into energy flow behaviour across photovoltaic generation, battery storage systems, grid interaction, and residential loads. It will also develop advanced data-driven modelling techniques capable of reconstructing internal system behaviour despite incomplete sub-metering, contributing to methodological innovation in power systems analysis.

Alignment with Bahrain's national research strategy

This research aligns strongly with Bahrain's national priorities in energy transition, digital transformation, and sustainable infrastructure development. By investigating a real operational Low Voltage Direct Current (LVDC) residential microgrid integrated with photovoltaic generation and battery storage, the project directly supports Bahrain's strategic goals for improving energy efficiency, increasing renewable energy penetration, and enhancing grid resilience.

For Bahraini society, the research contributes to long-term sustainability by providing evidence-based insights into reducing residential electricity losses and optimizing energy consumption in high-demand climates. Given the significant role of air-conditioning in household energy use, particularly under Bahrain's extreme summer conditions, the findings can support more efficient residential energy practices and inform future housing and urban development strategies.

From an industry perspective, the project offers valuable performance benchmarks and analytical tools that can support utilities, energy service providers, and technology developers in designing and deploying next-generation smart grids and LVDC infrastructure. It also provides a practical framework for evaluating hybrid AC/DC systems under real operating conditions, which is highly relevant for future commercial applications in residential and district energy systems.

In terms of national research priorities and EDB strategy, the project contributes to Bahrain's focus on innovation-driven economic diversification, clean energy technologies, and smart city development. It supports the Economic Development Board's objectives of fostering advanced energy solutions, attracting technology-oriented investment, and positioning Bahrain as a regional testbed for smart grid and renewable energy innovation.