

To whom it may concern

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## OFFICIAL OPPONENT'S REVIEW

**on the thesis "Energy Router for Hybrid Microgrids  
for Efficient and Robust Energy and Power Management"  
of Mohammadreza Azizi**

*submitted for the degree of Doctor of Philosophy  
in specialty 141 "Electrical Power Engineering, Electrical Engineering and Electromechanics"*

### 1. Relevance of the chosen topic of the dissertation research

Decarbonization of the built environment and rapid electrification of end-uses are pushing distribution systems toward higher penetration of behind-the-meter photovoltaics (PV), battery storage systems (BSS), and power-electronic interfacing. In this context, hybrid AC/DC nanogrids and low-voltage DC (LVDC) subsystems are increasingly viewed as an enabling layer for improving end-to-end efficiency, resilience, and controllability of modern buildings. Comparative studies in the literature (including NREL/Bosch assessments of commercial-building architectures) indicate that DC microgrid topologies can utilize locally generated PV energy several percent more efficiently than equivalent AC systems due to reduced conversion stages, strengthening the case for practical LVDC integration.

However, the transition from concept to deployment remains hindered by three persistent challenges: (i) safe and compliant integration of a DC subsystem with legacy AC installations, (ii) protection and fault isolation in DC circuits with fast current rise and no natural current zero, and (iii) robust control of multiport converters under strongly time-varying source/load conditions. The thesis under review directly targets these gaps by proposing an energy-router (ER) architecture intended for residential-scale hybrid microgrids/zero-emission buildings, with a particular focus on grounding/leakage current mitigation, fast DC protection, and enhanced low-level control dynamics.

### 2. Assessment of the validity and reliability of scientific propositions, conclusions and recommendations

The dissertation is grounded in a coherent methodology that combines: (a) a broad and well-structured literature review; (b) analytical modeling and design of converter subsystems; (c) time-domain simulation studies; and (d) laboratory experimentation on a hardware prototype. The author describes the employed toolchain (MATLAB/ PSIM/ PLECS for modeling and control verification; Altium and embedded development environments for implementation) and uses a simulation-to-experiment progression to substantiate the main claims.

Most conclusions are logically derived from the presented results. In particular, the work demonstrates that the proposed control approach improves transient response of the ER's DC-link regulation and grid-side current control under abrupt load/source changes, which is practically important because slow response can otherwise trigger protective shutdowns. The grounding/leakage-current analysis is supported by clear scenarios and comparative reasoning, leading to defensible recommendations for equipotential connection between AC neutral and a corresponding DC reference in selected cases.

Overall, the evidence base is adequate for a doctoral thesis. Reliability would be further strengthened by expanding the statistical breadth of experimental tests (sensitivity analysis with parameter sweeps), and by providing more systematic uncertainty reporting for key measured quantities (e.g., efficiency, leakage current and protection timing). These points, however, do not invalidate the presented findings.

### 3. Structure and content of the thesis

The thesis is presented in a logically consistent structure and contains an introduction, five technical chapters, a conclusion, references, and an appendix with the applicant's publications. The manuscript comprises 149 pages and includes 57 figures, 13 tables, and a bibliography of 169 references.

Chapter 1 reviews power-electronics solutions relevant to PV-integrated residential buildings and motivates ER technology as a flexible interface among PV, storage, DC loads, and the AC grid.

Chapter 2 provides a comprehensive discussion of DC integration challenges, with emphasis on protection, leakage current mechanisms, and grounding configurations at the AC/DC interconnection point.

Chapter 3 introduces the proposed single-cell three-phase ER (SC-TP) based on a common-ground inverter, including design of passive elements and an embedded solid-state circuit breaker (SSCB).

Chapter 4 develops the control architecture across levels and formulates a flatness-based control (FBC) approach for low-level control loops, with discussion of PR control as an alternative for grid-current harmonic mitigation, and with an overview of possible high-level EMS concepts.

Chapter 5 presents simulation and experimental results covering DC mode, grid-forming and grid-following operation, and tests under dynamic conditions.

The thesis presentation is generally clear, with good use of figures and design flow descriptions. Minor editorial issues (occasional typos, notations, duplication of automatic references like that in page 31, and some tables that would benefit from unit/format harmonization) are present but do not impede understanding.

### 4. Scientific novelty of the obtained results

The dissertation contains a number of original contributions. The most important elements of scientific novelty can be summarized as follows:

For the first time, an ER topology based on a Single-Cell Three-Phase (SC-TP) concept is developed as an interlink solution between a residential DC distribution grid and a three-phase AC grid, with the objective of mitigating phase imbalance without a full three-cell conversion stage.

For the first time, it is demonstrated (through scenario analysis) that galvanic isolation alone may be insufficient to eliminate DC leakage current in specific configurations; the thesis recommends potential equalization measures between a DC reference (e.g., midpoint) and the AC neutral where appropriate.

For the first time, it is shown that a non-isolated ER based on a common-ground inverter can be connected to a residential AC system using a dedicated grounding approach and conventional protection philosophy, while suppressing leakage currents associated with parasitic capacitances.

Flatness-based control is applied to a multiport ER for low-level control to improve dynamic response and thereby enhance operational robustness under disturbances, compared to conventional PI-based methods.

### 5. Theoretical and practical significance of the presented results

From a theoretical standpoint, the thesis contributes a control-oriented modeling and design workflow for applying differential flatness concepts to the ER's DC-link and grid-current dynamics, together with a transparent discussion of implementation aspects. The grounding analysis consolidates and extends prior studies by explicitly linking leakage-current mechanisms to grounding topology and connection scenarios.

Practically, the work is significant because it addresses deployment-critical elements (protection and grounding) rather than limiting the contribution to converter topology alone. The integration of solid-state protection devices and the experimental verification of multiple operating modes (DC mode, grid-forming, grid-following, and dynamic transients) demonstrate engineering maturity. The SC-TP concept, if complemented with a dedicated phase-selection/energy-management algorithm, could offer a cost-effective pathway for behind-the-meter phase balancing in three-phase buildings.

The thesis outcomes are therefore relevant for researchers and engineers working on residential hybrid microgrids, building-integrated LVDC, and converter-based grid interfacing.

### 6. Completeness of dissemination

The results of the dissertation have been sufficiently disseminated through peer-reviewed publications and international conference papers. The provided list includes journal articles (e.g., *Energies* and *IEEE Power Electronics Magazine*) and multiple IEEE conference contributions, with indexing in Scopus indicated. The publication record is consistent with the scope of the dissertation and demonstrates the applicant's active engagement with the international research community.



## 7. Academic integrity

The dissertation contains an explicit author statement regarding the originality of the research and the necessity of proper attribution. Based on the presented manuscript, the referencing is extensive and generally adequate. No indications of plagiarism, unethical borrowing, or other violations of academic integrity were detected.

## 8. Remarks, limitations, and critical comments

**High-level EMS/phase-balancing layer:** The SC-TP architecture relies on a smart energy-management/phase-selection mechanism to realize its full benefit. The thesis itself states that the development of such an algorithm lies beyond the scope of the work. As a result, phase-balancing claims remain primarily conceptual; future work should demonstrate the full closed-loop system with realistic unbalanced three-phase load profiles and switching/relay constraints.

**Protection and fault validation:** While the SSCB concept is integrated and well-motivated, the experimental section would be strengthened by a more extensive fault scenarios testing (e.g., various fault impedances, coordination with upstream/downstream protective devices, and quantified interruption times/energies).

**Efficiency and loss accounting:** The thesis emphasizes reduced weight/volume and improved performance. A more systematic efficiency map (across operating modes and power levels) and a clear loss breakdown would further substantiate the "efficiency" dimension of the contribution and enable comparison against state-of-the-art ER implementations.

**Control-quality trade-offs:** The results indicate that FBC achieves faster transients, while PR control provides superior harmonic rejection. A clearer, quantitative discussion of the trade-off (e.g., THD versus settling time, sensitivity to grid distortion and frequency drift) would help readers choose between the alternatives for specific grid-code contexts.

**Standards and terminology:** Given the strong safety/grounding focus, the discussion could benefit from a more explicit mapping to modern LVDC installation standards and safety standards (noting that some legacy equipment-safety standards have been superseded). Minor terminology and notation consistency improvements are also recommended.

## 9. Final evaluation and assessment of the thesis

Despite the minor remarks given above, the dissertation presents complete and coherent scientific work that addresses an important and timely topic in power electronics and hybrid AC/DC microgrids. The author demonstrates solid theoretical knowledge, appropriate research methodology, and the ability to implement and experimentally validate nontrivial converter and control solutions. The results are scientifically novel, practically relevant, and sufficiently disseminated.

Therefore, I conclude that the thesis meets the established requirements for a Doctor of Philosophy dissertation in specialty 141 "Electrical Power Engineering, Electrical Engineering and Electromechanics", and I recommend that Mohammadreza Azizi be awarded the degree of Doctor of Philosophy.



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