



Cyprus
University of
Technology

Faculty of Engineering
and Technology

Doctoral Dissertation

**GRID-CONNECTED PHOTOVOLTAIC SYSTEM IN
BUILDINGS WITH HYBRID ENERGY STORAGE**

Maria Argyrou

Limassol, June 2021

CYPRUS UNIVERSITY OF TECHNOLOGY
FACULTY OF ENGINEERING AND TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING, COMPUTER
ENGINEERING AND INFORMATICS

Doctoral Dissertation

**GRID-CONNECTED PHOTOVOLTAIC SYSTEM IN
BUILDINGS WITH HYBRID ENERGY STORAGE**

Maria Argyrou

Limassol, June 2021

Approval Form

Doctoral Dissertation

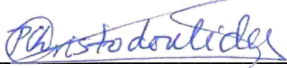
GRID-CONNECTED PHOTOVOLTAIC SYSTEM IN BUILDINGS WITH HYBRID ENERGY STORAGE

Presented by

Maria Argyrou


Supervisor*: Dr. Paul Christodoulides, Assistant Professor

Faculty of Engineering and Technology, Cyprus University of Technology

Signature  _____

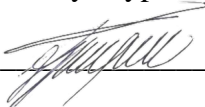
Chair of the committee: Dr. Christakis Damianou, Professor

Faculty of Engineering and Technology, Cyprus University of Technology

Signature  _____

Member of the committee: Dr. Alexis Polycarpou, Assistant Professor

Department of Electrical Engineering, Computer Engineering and Informatics,
Frederick University, Cyprus

Signature  _____

*Co-supervisor: Dr. Soteris Kalogirou, Professor

Faculty of Engineering and Technology, Cyprus University of Technology

Cyprus University of Technology

Limassol, June 2021

Copyrights

Copyright © 2021 Maria Argyrou

All rights reserved.

The approval of the dissertation by the Department of Electrical Engineering, Computer Engineering and Informatics does not imply necessarily the approval by the Department of the views of the writer.

ACKNOWLEDGEMENTS

Firstly, I would like to express my deep gratitude to my supervisor, Dr. Paul Christodoulides, for his valuable support and guidance throughout my journey. I also acknowledge my co-supervisor, Prof. Soteris Kalogirou, for his feedback and support during this study. Moreover, I would like to thank Dr. Christos Marouchos for his encouragement and his helpful suggestions and guidelines.

I am also grateful to my friends and colleagues at the Department of Electrical Engineering for supporting me all these years. Specifically, I want to thank Panayiotis, Harris and Chrysovalantis for the valuable discussions we had, their recommendations and their support. Furthermore, I would like to acknowledge all the academic and administrative staff I collaborated with, especially the academics who believed in me and trusted me as their teaching assistant, Dr. H. Michael, Dr. K. Kalli and my supervisor Dr. P. Christodoulides.

Furthermore, I would like to express my sincere gratitude to my family, who believed in me and raised me to be the person I am today. Finally, I want to thank my life partner, Yiannis, for his unconditional love and patience all these years. Without their endless support and encouragement, none of my goals would have been achieved.

PUBLICATIONS

List of publications (peer-reviewed journals and conferences):

- **M. C. Argyrou**, C. C. Marouchos, S. A. Kalogirou, and P. Christodoulides, “A novel power management algorithm for a residential grid-connected PV system with battery-supercapacitor storage for increased self-consumption and self-sufficiency,” *Energy Conversion and Management* (submitted).
- **M. C. Argyrou**, C. C. Marouchos, S. A. Kalogirou, and P. Christodoulides, “Modeling a residential grid-connected PV system with battery-supercapacitor storage: Control design and stability analysis,” *Energy Reports* (submitted).
- S. Ioannou, **M. C. Argyrou**, P. Christodoulides, and C. C. Marouchos, “Small signal transfer functions and mathematical model of the boost power converter,” in *MEDPOWER 2020*, 2020, pp. 1–6.
- S. Ioannou, **M. C. Argyrou**, M. Darwish, and C. C. Marouchos, “Modulation Processes in Power Electronic Converters,” in *2020 55th International Universities Power Engineering Conference (UPEC)*. IEEE, 2020, pp. 1–6.
- R. Agathokleous, G. Bianchi, G. P. Panayiotou, L. Aresti, **M. C. Argyrou**, G. Georgiou, S. Tassou, H. Jouhara, S. A. Kalogirou, G. Florides, and P. Christodoulides, “Waste heat recovery in the EU industry and proposed new technologies,” *Energy Procedia*, vol. 161, pp. 489–496, 2019.
- S. Ioannou, **M. C. Argyrou**, C. Marouchos, and M. Darwish, “Efficiency Investigation of a Grid Connected PV System with Power Smoothing,” in *2019 54th International Universities Power Engineering Conference (UPEC)*. IEEE, 2019, pp. 1–6.
- **M. C. Argyrou**, C. Spanias, C. C. Marouchos, S. A. Kalogirou, and P. Christodoulides, “Energy management and modeling of a grid-connected BIPV system with battery energy storage,” in *2019 54th International Universities Power Engineering Conference (UPEC)*. IEEE, 2019, pp. 1–6.
- **M. C. Argyrou**, P. Christodoulides, and S. A. Kalogirou, “Modeling of a photovoltaic system with different MPPT techniques using MATLAB / Simulink,” in *2018 IEEE International Energy Conference (ENERGYCON)*, 2018.

- **M. C. Argyrou**, P. Christodoulides, C. C. Marouchos, and S. A. Kalogirou, “Hybrid battery-supercapacitor mathematical modeling modeling for PV application using Matlab/Simulink,” in 2018 53rd International Universities Power Engineering Conference (UPEC). IEEE, 2018, pp. 1–6.
- **M. C. Argyrou**, F. Paterakis, C. Panagi, C. Makarounas, M. Darwish, and C. Marouchos, “Supercapacitor application for PV power smoothing,” in 2018 53rd International Universities Power Engineering Conference (UPEC), 2018, pp. 1–5. (*Best Oral Presentation Award by a Young Engineer*)
- **M. C. Argyrou**, P. Christodoulides, and S. A. Kalogirou, “Energy storage for electricity generation and related processes: Technologies appraisal and grid scale applications,” *Renew. Sustain. Energy Rev.*, vol. 94, pp. 804–821, 2018.
- **M. C. Argyrou**, C. C. Marouchos, M. Darwish, E. Iosif, and F. Paterakis, “Investigation of the switched inductor circuit for harmonics compensation,” in 2017 52nd International Universities Power Engineering Conference (UPEC). IEEE, 2017, pp. 1–5.
- G. P. Panayiotou, G. Bianchi, G. Georgiou, L. Aresti, **M. Argyrou**, R. Agathokleous, K. M. Tsamos, S. A. Tassou, G. Florides, S. Kalogirou, and P. Christodoulides, “Preliminary assessment of waste heat potential in major European industries,” *Energy Procedia*, vol. 123, pp. 335–345, 2017.
- **M. C. Argyrou**, P. Christodoulides, C. C. Marouchos, and S. A. Kalogirou, “A grid-connected photovoltaic system: mathematical modeling using MATLAB/Simulink,” in 2017 52nd International Universities Power Engineering Conference (UPEC). IEEE, 2017, pp.1–6.
- **M. C. Argyrou**, P. Christodoulides, C. C. Marouchos, and G. A. Florides, “Energy storage technologies, nearly Zero Energy Buildings and a short-term storage application,” in 5th International Conference on Renewable Energy Sources & Energy Efficiency - New Challenges, 2016.
- **M. C. Argyrou**, P. Christodoulides, C. C. Marouchos, S. A. Kalogirou, G. A. Florides, and L. Lazari, “Overview of energy storage technologies and a short-term storage application for wind turbines,” in Proceedings of the International Offshore and Polar Engineering Conference, 2016.

ABSTRACT

The increasing penetration of renewable energy technologies causes major problems in the power network, as their generation cannot be totally predicted. Along with fluctuations in Renewable Energy Sources (RES) production due to weather uncertainties, storage is very important for mitigating several problems that may arise, affecting the stability and reliability of the grid. Thus, storage technologies have gained an increased attention in recent years. In particular, there has been an emphasis on residential storage applications (behind-the-meter storage), with the aim of increasing the energy self-consumption and therefore reducing electricity bills.

A model containing a 3 kW_p rooftop solar photovoltaic (PV) system connected to the grid through converters and a battery-supercapacitor hybrid energy storage system is proposed. The storage devices are connected to the common 400 V DC-bus in a fully active parallel configuration through two bidirectional DC-DC converters. This configuration allows the battery and supercapacitor to have different voltages and their power flow to be controlled separately. A small-signal stability analysis is considered for the design of the current controllers for both the bidirectional converters of the battery and supercapacitor. Moreover, the small-signal stability analysis of the voltage source inverter (VSI) is considered in order to design the DC-bus voltage controller, from which a reference output current is extracted using a phase-locked loop (PLL) for grid synchronization. A new filtration-based power management algorithm (PMA) is proposed, which prioritizes the utilization of the PVs and battery-supercapacitor instead of the grid, thus increasing the self-consumption and self-sufficiency of the building. A comparison between a battery-only and a battery-supercapacitor storage application is performed in long-term operation (24 hours), verifying the effectiveness of the integration of the supercapacitor. In addition, the dynamic performance of the proposed model is verified through several simulations for different scenarios over short time periods (10–30 seconds). The results show that the model works properly and responds extremely fast during different mode transitions, exhibiting a fast DC-bus voltage regulation with a very low ripple voltage (a maximum of $\pm 0.625\%$). Also, the supercapacitor handles rapid changes that occur within 0.2 seconds, which can relieve the battery stress and, hence, extend the battery lifetime. Finally, an effective power sharing is achieved between the PV, the battery-supercapacitor storage, the building load and the grid. The proposed model is developed and simulated in the MATLAB/Simulink software environment, based on mathematical analysis and average modeling.

Keywords: grid-connected photovoltaics, battery, supercapacitor, hybrid energy storage, modeling, control, filtration-based power management