Abstract

Photovoltaic generation represents a key technology for the large-scale integration of renewable energy sources into modern power systems. Accurate modelling and characterisation of photovoltaic devices are essential to assess their performance, predict energy production, and support the design and optimisation of photovoltaic installations. Equivalent-circuit models are widely adopted for this purpose, as they provide a compact and physically meaningful description of the electrical behaviour of photovoltaic cells and modules through a limited set of parameters.

This Ph.D. thesis develops an integrated methodology including theoretical aspects and experimental characterization for the identification and application of equivalent-circuit parameters of photovoltaic modules under varying operating conditions. The proposed methodology proceeds from theoretical formulations that require experimental verification, whose results are subsequently used to perform an a posteriori correction and recalibration of the model parameters, thereby improving the accuracy and physical consistency of the equivalent-circuit representation.

The work addresses the limitations of conventional parameter-estimation approaches, which are often restricted to specific irradiance and temperature levels and therefore unsuitable for long-term energy-yield prediction. The proposed procedure explicitly accounts for the dependence of the model parameters on environmental variables, enabling the use of equivalent-circuit representations as a basis for photovoltaic energy estimation.

Two complementary measurement systems are developed and employed for the experimental characterisation of photovoltaic modules. The first system is based on a capacitor-charging circuit and reconstructs the current–voltage (I–V) characteristic curve from the transient electrical response. The second system employs a programmable electronic load to impose controlled operating points and acquire steady-state current–voltage data. Both platforms are integrated within a unified post-processing pipeline, allowing consistent data handling, parameter estimation, and comparative analysis.

Parameter identification is formulated as a nonlinear estimation problem and addressed using least-squares techniques combined with uncertainty analysis. The Fisher Information Matrix and the associated Cramér–Rao Lower Bound are employed to quantify parameter uncertainty and to guide the optimisation of current–voltage sampling strategies. A D-optimal design criterion is adopted to improve the information content of experimental measurements and enhance estimation robustness, particularly under partial shading and mismatch conditions. This approach is particularly advantageous in practical scenarios where only a limited number of operating points can be acquired for the characterisation of photovoltaic modules, as is typically the case in maximum power point tracking algorithms, where measurement opportunities are constrained by real-time operation and energy-harvesting requirements.

The proposed framework is validated through numerical simulations and experimental campaigns conducted on photovoltaic modules of different technologies and power ratings. The results demonstrate that the identified parameter sets accurately reproduce measured electrical behaviour and enable reliable energy-production estimates when compared against reference models and experimental data. The methodologies developed in this thesis provide a systematic approach to photovoltaic modelling, parameter estimation, and uncertainty-aware energy assessment, with direct applicability to both research and practical photovoltaic system analysis.