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Rethinking solar energy conversion: efficiency, reliability, and control challenges in PV-connected DC–DC converters

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ABSTRACT

Photovoltaic (PV) systems depend on DC–DC converters to regulate variable module output, extract available energy, and provide a suitable interface to downstream loads or grid-connected stages. Although converter efficiency is often treated as the principal design objective, field performance is also shaped by reliability, control quality, thermal stress, and operating conditions such as partial shading and rapid irradiance variation. This review examines these coupled challenges through a focused synthesis of literature published up to 2016, covering converter topologies, maximum power point tracking (MPPT), digital control, and reliability-oriented design. Conventional buck, boost, buck–boost, Ćuk, and single-ended primary-inductor converter (SEPIC) structures are considered alongside high-gain and interleaved solutions, with attention to their trade-offs in component stress, conversion loss, complexity, and suitability for PV applications. The review highlights how MPPT dynamics interact with converter bandwidth and switching behaviour, while environmental mission profiles influence component ageing and system availability in real operating environments. It argues that efficiency, reliability, and control should be evaluated as a unified design problem rather than as independent specifications. The final section identifies practical research priorities for robust, cost-effective PV power conversion.

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1. INTRODUCTION

Photovoltaic (PV) technology has become an important option for distributed electricity generation, yet the electrical output of a PV module is inherently dependent on irradiance, temperature, and operating conditions. A DC–DC converter is therefore more than a voltage adaptation stage because it also provides the controllable interface through which the PV source is operated near its maximum power point. The converter topology, switching devices, passive components, and control algorithm jointly determine how much energy can be transferred to the load or subsequent conversion stage. Earlier reviews have examined PV converter structures and maximum power point tracking (MPPT) methods, but efficiency, reliability, and control are often discussed as separate design concerns [1]–[4].

This separation can lead to misleading design choices because a converter with a high peak efficiency may experience excessive thermal stress or poor dynamic performance under realistic conditions. Similarly, a sophisticated MPPT algorithm cannot compensate fully for an unsuitable power-stage topology, inadequate component ratings, or unstable control-loop design. The central problem addressed in this review is how to assess PV-connected DC–DC converters as integrated energy-conversion systems rather than as isolated circuits. The discussion synthesizes research published up to 2016 and connects converter selection, MPPT behaviour, digital implementation, and reliability considerations.

2. REVIEW SCOPE AND TECHNICAL FRAMEWORK

The review focuses on non-isolated DC–DC converters commonly considered for PV applications, including buck, boost, buck–boost, Ćuk, single-ended primary-inductor converter (SEPIC), high-step-up, and

interleaved configurations. It also considers MPPT methods and digital control because the converter's operating point is determined by the interaction between its power stage and controller. The literature selection emphasizes peer-reviewed journal and conference publications with identifiable publication records and persistent DOIs. The analysis is qualitative and comparative, concentrating on recurring design trade-offs rather than claiming a new experimental performance ranking.

Three dimensions guide the assessment: energy efficiency, operational reliability, and control performance. Efficiency concerns conduction and switching losses, passive-component losses, and the operating range over which the converter maintains acceptable performance. Reliability concerns component stress, thermal cycling, environmental exposure, and the likelihood that a failure will interrupt energy conversion. Control performance concerns tracking accuracy, transient response, stability, sensing requirements, and implementation complexity.

3. CONVERTER TOPOLOGIES AND EFFICIENCY TRADE-OFFS

The choice of converter topology establishes the basic limits of voltage conversion, current ripple, component stress, and achievable efficiency. Buck converters are appropriate when the required output voltage is lower than the PV-side voltage, whereas boost converters are used when voltage elevation is necessary. Buck–boost, Ćuk, and SEPIC structures provide wider voltage flexibility, although their additional components and energy-transfer paths can increase conduction losses and design complexity. Taghvaee *et al.* [1] reviewed these non-isolated converter families and emphasized that topology selection should reflect the PV system configuration and application requirements.

High-step-up converters are particularly relevant when a relatively low PV voltage must be raised to a higher DC-link voltage. Conventional boost converters can become less attractive at high conversion ratios because extreme duty-cycle operation increases electrical stress and may reduce practical efficiency. Alternative high-gain structures use coupled inductors, switched-capacitor cells, voltage multipliers, or combinations of these techniques to obtain higher voltage gain without relying entirely on an extreme duty ratio. Li and He reviewed non-isolated high-step-up converter approaches for grid-connected PV applications, while Revathi and Prabhakar later compared high-gain topologies and their application characteristics [2], [3].

Interleaved converters offer another approach to improving power-stage performance, particularly where current ripple and thermal distribution are important. By operating multiple phases with phase-shifted switching signals, an interleaved structure can reduce input-current ripple and distribute current among parallel branches. These benefits may reduce filtering requirements and help manage component heating, but they come with additional switches, gate-drive circuits, sensing needs, and control coordination. Consequently, the benefits depend on careful design and cannot be assumed from the topology alone.

A meaningful efficiency assessment should extend beyond a single peak-efficiency figure. Conduction losses depend on device resistance, diode drops, winding resistance, and current levels, while switching losses are influenced by switching frequency, voltage stress, and device characteristics. Magnetic and capacitive components also contribute losses and may impose thermal constraints that become important during continuous operation. A converter should therefore be evaluated across its expected input-voltage, output-power, and environmental operating ranges rather than under one nominal test condition.

4. MPPT AND CONVERTER CONTROL CHALLENGES

MPPT is essential because the maximum power point of a PV array changes with irradiance and temperature. Conventional perturb-and-observe and incremental-conductance methods remain attractive because they are comparatively simple to implement and require limited computational resources. However, fixed perturbation steps can produce a compromise between tracking speed and steady-state oscillation, while rapidly changing irradiance can complicate the interpretation of measured power variations. Esram and Chapman compared major PV tracking techniques, and later reviews discussed their performance under uniform irradiance and partial-shading conditions [4], [5].

Partial shading creates a more difficult control problem because the PV array power-voltage characteristic may contain multiple local maxima. Conventional local-search algorithms can converge to a local peak rather than the global maximum, resulting in avoidable energy loss. Liu *et al.* [6] reviewed MPPT techniques for uniform and partial-shading conditions, while El-Khozondar *et al.* [7] surveyed a broad range of algorithms and their implementation characteristics. Jordehi further classified MPPT approaches and identified continuing challenges in selecting methods that balance tracking performance, computational demand, and practical implementation [8].

The MPPT algorithm cannot be designed independently of the converter's dynamic response. The controller changes the converter duty ratio or reference signal, and the resulting power-stage response

determines how quickly the PV operating point can move. If the MPPT update rate is poorly matched to the converter's bandwidth, the system may exhibit sluggish tracking, excessive oscillation, or unstable interactions between control loops. Rezk and Eltamaly's comparative assessment of MPPT techniques reinforces the importance of considering both transient and steady-state behaviour when evaluating tracking performance [9].

Digital control provides flexibility for implementing adaptive algorithms, protection functions, and supervisory logic. Microcontrollers and digital signal processors can support sampling, filtering, PWM generation, and closed-loop control, while field-programmable gate arrays can provide parallel processing and deterministic timing for more demanding applications. Nevertheless, digital implementation introduces practical concerns such as sampling delay, quantization, sensor accuracy, computational limits, and software verification. Buccella *et al*. [10] reviewed digital power-converter control and highlighted the importance of hardware and software choices in high-performance converter design.

5. RELIABILITY AND OPERATIONAL STRESS

Reliability is a fundamental design requirement because PV converters are expected to operate for long periods under changing environmental and electrical conditions. Semiconductor switches, diodes, capacitors, inductors, and interconnections experience electrical and thermal stresses that can accumulate over time. High switching frequency, large current ripple, elevated junction temperature, and repeated thermal cycling may accelerate component degradation. Reliability-oriented design must therefore consider the converter's operating profile rather than relying exclusively on nominal component ratings.

The connection between converter architecture and reliability is illustrated by studies comparing the reliability and cost of multistage boost converters connected to PV panels. Aghdam and Abapour examined this relationship and showed why the number and arrangement of conversion stages should be considered alongside the electrical performance of the system [11]. De Leon *et al*. [12] investigated PV-system reliability using seasonal mission profiles and applied their approach to a DC–DC converter, demonstrating that environmental conditions can influence estimated failure behaviour. These studies indicate that reliability assessment should reflect the location and operating conditions in which the converter will be deployed.

Reliability also depends on how effectively thermal and electrical stress are managed during normal operation and disturbances. A design that reduces semiconductor stress or distributes losses more evenly may improve long-term robustness, although added components can introduce additional potential failure points. Wang *et al*. [13] discussed broader reliability challenges in power electronics, emphasizing design methods that account for physical failure mechanisms rather than relying only on statistical prediction. For PV-connected converters, this perspective supports the integration of thermal design, component selection, protection, and condition monitoring from the earliest design stage.

6. INTEGRATED DESIGN CHALLENGES AND RESEARCH PRIORITIES

The principal design challenge is that efficiency, reliability, and control can conflict when optimized independently. Increasing switching frequency may reduce passive-component size and improve dynamic response, but it can also increase switching losses and electromagnetic interference. Increasing voltage gain may reduce the need for additional conversion stages, yet some high-gain structures introduce more components and complex control requirements. Likewise, aggressive MPPT tuning may improve transient tracking but increase converter stress or produce undesirable oscillations.

A more useful design process begins by defining the PV source characteristics, required voltage range, power level, and environmental mission profile. Candidate converter topologies can then be screened according to voltage gain, component count, current ripple, device stress, and expected loss distribution. The MPPT and inner converter-control loops should be designed together, with attention to bandwidth separation, sampling frequency, sensing accuracy, and protection limits. Finally, efficiency and reliability should be validated over representative operating conditions, including partial shading, temperature variation, load changes, and start-up or fault events.

Future research should place greater emphasis on comparable evaluation procedures that report efficiency over a broad operating range rather than at a single operating point. Reliability studies would benefit from realistic mission profiles, thermal measurements, accelerated testing, and transparent reporting of component failure assumptions. Control research should also connect algorithmic performance with embedded implementation constraints, including processor capacity, sampling delay, sensor cost, and maintainability. These priorities can help close the gap between promising simulation results and converter systems that are practical for long-term PV operation.

7. CONCLUSION

PV-connected DC–DC converters should be understood as integrated systems in which topology, efficiency, reliability, and control are closely interdependent. Conventional and high-gain converter structures offer different compromises in voltage conversion, component stress, current ripple, and implementation complexity. MPPT performance depends not only on the selected algorithm but also on converter dynamics, sensing quality, and digital-control implementation. Reliability, in turn, requires attention to thermal stress, component ageing, and realistic environmental mission profiles. The literature available up to 2016 supports a design philosophy that evaluates energy yield, operational robustness, and control quality together. Such an integrated approach offers a more credible basis for developing efficient, dependable, and cost-effective PV power-conversion systems.

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