Dual-Stage Converter Control in Grid-Integrated Solar Systems: A Review

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Abstract:

Increasing global electricity demand, coupled with carbon mitigation measures, has accelerated the installation of grid-integrated solar systems as a sustainable solution. One of the major components of GI-SS is the dual-stage DC–DC converter, which attains maximum power from PV arrays and provides voltage stability to the grid and loads. However, the change in solar irradiance and nonlinear nature of loads poses great technical issues, including harmonic distortion and voltage instability, further affecting the power quality of this scheme. Conventional control methods such as PI, PID, and hysteresis controllers—with their mathematical simplicity—are rather weak in responding to fast grid dynamics. Recent developments give prominence to intelligent control techniques using fuzzy logic, neural networks, optimization algorithms, and artificial intelligence for better adaptability, robustness, and efficiency. Moreover, new topologies such as bidirectional and hybrid converters further enhance the scalability and flexibility of GI-SS applications. Emerging AI-based predictive maintenance, digital twin integration, and hybrid optimization framework approaches have shown good potential to improve fault tolerance and allow for real-time adaptive control. However, gaps still exist regarding validation for large-scale structures, scalability, and further standardization of methodologies across different operating environments. This review collates the present development in converter topologies and control strategies, outlining disadvantages of traditional and modern methods, and explores how intelligent and coordinated control will act as a game changer in the future solar-grid system. The reviewed studies demonstrate that dual-stage converter control holds promise for offering an adequate platform to accomplish efficient, stable, and sustainable renewable energy integration.

Keywords: *Grid-Integrated Solar Systems, Dual-Stage DC–DC Converters, Control Strategies, Artificial Intelligence, Power Quality, Renewable Energy Integration.*

I. INTRODUCTION

The increasing global electricity demand and rising environmental concerns related to fossil fuel use have steered energy for renewables. Thus, of all types of renewable energy, solar PV systems have garnered much patronage on account of their abundance, modular nature, and lowering of cost [1],[2]. In particular, GI-SS have become indispensable in virtually all modern energy infrastructures, delivering the benefits of increased power availability and improved reliability, plus the reduction of carbon emissions on the clean energy integration with existing grids of utilities [3],[4].

The development of GI-SS has greatly progressed in recent decades, from isolated solar plants in remote applications to highly sophisticated grid-integrated systems capable of providing ancillary services [5]. The continuous refinement of power electronic converters and inverter technologies has increased efficiency, enhanced stability, and equipped grid support functions with flexibility [6]. Despite these developments, implementation of solar PV into traditional grids remains very technically challenging due to the intermittent and variable nature of solar irradiance [7]. These variations disturb the stability of the DC link, lower inverter performance, and raise synchronization issues with the grid; hence, advanced converters and control strategies need to be considered [8]. Figure 1.describes control strategy evaluation

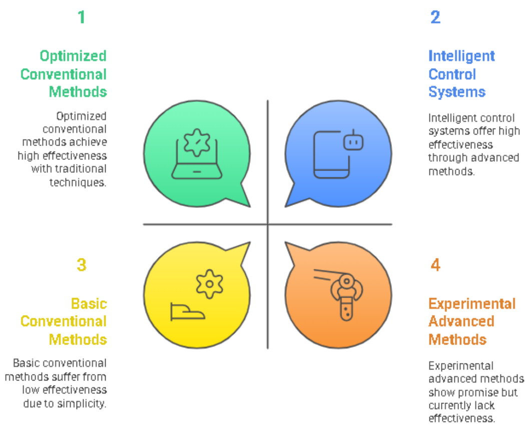

Figure 1: Control Strategy Evaluation

The architecture of a GI-SS is often made up of a PV array, a dual stage DC-DC converter, an inverter, and point load. In a GI-SS, the dual-stage DC-DC converter is the heart of the reliable operation [9]. The first stage of the converter, usually a boost converter, performs maximum power point tracking (MPPT) to extract the maximum power from the PV array [10]. The second stage-buck or buck-boost converter-regulates the DC link voltage to ensure stable inverter input and, hence, maximum power transfer to the load [11]. A two-stage converter configuration has a very good record due mainly to its fast dynamic response, reduced stress on its switching semiconductor devices, and greater stability under sudden solar or load changes [12].

Nonlinear and dynamic load characteristics pose a huge challenge to GI-SS. Created with variable-frequency drives, rectifiers, and electronic appliances, the load currents are not only distorted but also introduce harmonics while reducing the power factor [13]. Given that nonlinearity goes through the inverter and is injected back to the grid, it increases more power quality problems like voltage distortion, harmonic amplification, and efficiency losses [14]. With no proper converter management, these disturbances further worsen grid instability and are in violation of international standards such as IEEE 519 limits on total harmonic distortion [15]. Figure 2 describes stabilizing dc lines with advanced control.

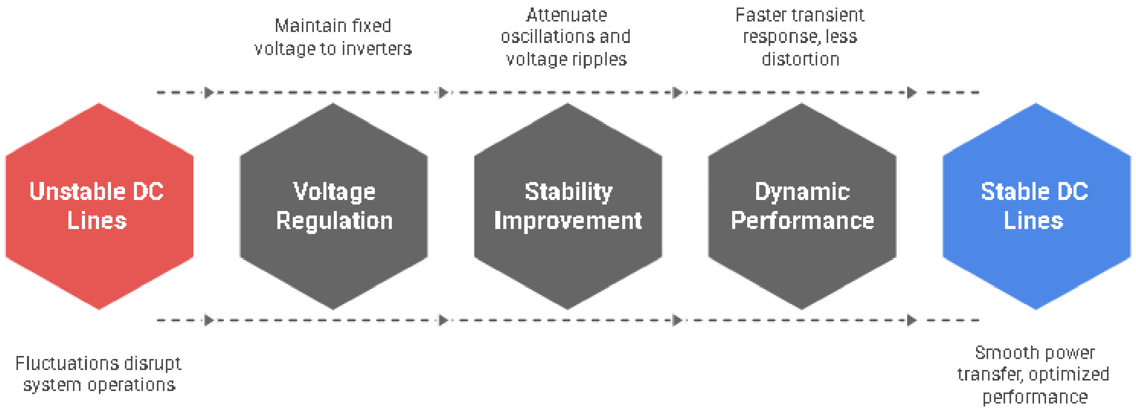

Figure 2: Stabilizing DC Lines with Advanced Control

Typical control schemes include proportional-integral (PI), proportional-integral-derivative (PID), and hysteresis control, and each of them is widely used for converter control in grid-interfaced stand-alone systems [16]. Computations are easy, but these methods have a rather limited ability to adapt to changing irradiance and load conditions. PI controllers do not work well under nonlinearities, PID requires to be tuned perfectly, and hysteresis controllers cause varying switching frequencies, which, in turn, cause stress on the power devices [17]. All these preclude them from being used in the more advanced GI-SSs that work in more complex and increasingly dynamic scenarios [18].

The various research efforts revolve have been aimed at overcoming these limitations to produce advanced and intelligent control strategies for the design and management of the dual-stage DC–DC converter. For example, sliding-mode control has been employed in maximizing MPPT performance and minimizing DC-link ripple in solar systems [1]. Other works deal with PV-fed multi-output converters and hybrid topologies to establish better efficiency and scalability [2],[5]. More-recent studies tend to stress frameworks of intelligent control, like fuzzy logics or neural networks, or adaptive controllers that enable real-time adaptation under variable operating conditions [13],[16]. In parallel, optimization-based approaches comprising evolutionary algorithms and coordinated-control schemes have been seen as guaranteeing fast transient response, harmonic mitigation, and stable operation under nonlinear load scenarios [8],[19].

Emphasis on control techniques design truly stands at the gist of efficient solar-grid integration [7]. Effective power converter control at load points ensures voltage stability and harmonic suppression, conversion of GI-SS into a resilient and reliable system [9],[14]. More so, advanced converter control techniques help with reactive power management, frequency regulation, and fault ride-through capabilities to ensure compliance with grid codes [7],[20]. These features enable GI-SS to be considered not merely as passive power suppliers but active networking entities.

Beyond technical benefits, these advanced control methods for dual-stage DC–DC converters also provide economic and environmental advantages. Enhanced efficiency reduces operational costs, thus improving the economic viability of solar projects [4]. By ensuring stable interconnection, GI-SS advanced controls mitigate reliance on fossil fuel therefore reduce its carbon emission and support sustainable development goals [6]. Moreover, larger-scale converter designs allow for large-scale integration of PV, further extending its benefits from residential systems to utility-grade plants [11].

II. ARCHITECTURE OF GRID-INTEGRATED SOLAR SYSTEMS (GI-SS)

The grid interconnected solar system (GI-SS) architecture includes arrays of power from sunlight, DC-DC converters, inverters, and loads interfaced with the utility grid. Power regulation is better with the dual stage-converter approach, while the inverters synchronize the power with the grid parameters [23]. Load conditions, especially nonlinear ones, largely affect the system behaviour and power quality in general.

a. System components overview (PV array, converters, inverter, load)

In a grid-integrated solar system, there are basically four major components: the PV array, DC-DC converters, inverters, and the loads attached. The solar energy is harnessed through the PV array and converted into DC electricity [24]. However, there are instances when this output is ever variable, being dependent on irradiance and temperature. DC-DC converters come into the picture to smooth and regulate this energy, providing maximum power point tracking (MPPT) and voltage regulation. GI-SS converters ensure that the PV source is compatible with the ensuing stages of the inverter [25]. An inverter takes the regulated DC power and converts it into an AC form synchronized with the grid, observing the frequency and voltage standards of the grid. On the other hand, the load represents residential and industrial consumers that often have nonlinear loads generating harmonics into the system. The solar-grid integration thus forms a seamless platform worthy of reliability, efficiency, and quality power delivery through these components [26].

Dual-stage DC-DC converter configuration: - The dual-stage architecture is usually preferred in grid-interfaced solar systems because of its greater control and efficiency. The first-stage boost converter increases the variable PV voltage to some DC link voltage level [27]. Also, the boost converter performs the MPPT to extract maximum energy. The second stage, basically a buck or buck-boost type converter, controls the DC link voltage for optimum operation of the inverter and load facility [28]. Such a configuration offers better dynamic response, enhanced stability under changing irradiance level, and reduced voltage stress on devices. Thus, dual-stage converters are decisive to guarantee efficient, flexible, and reliable power flow in GI-SS [29].

Nonlinear load characteristics on the AC side: - Nonlinear loads are commonly present in grid-integrated solar systems, especially in residential, commercial, and industrial sectors where electronic devices, variable frequency drives, and rectifiers dominate [30]. These loads draw non-sinusoidal current even when supplied with sinusoidal voltage, introducing harmonics, voltage distortion, and reduced power factor [31]. The interaction between inverters and nonlinear loads can exacerbate power quality issues, leading to inefficiencies, overheating of equipment, and instability in grid operation [32]. Effective control strategies, such as harmonic mitigation and active filtering, are essential to minimize these effects. Thus, understanding nonlinear load characteristics is critical for designing robust and stable GI-SS control strategies [33].

III. ARTIFICIAL INTELLIGENCE-BASED CONTROL TECHNIQUES IN POWER ELECTRONICS

Certain recent works confirm the growing interest in applying artificial intelligence in power electronics. One method developed an ANN-based model predictive control scheme for a three-phase flying capacitor multilevel inverter that allowed reduction of parameter mismatches and harmonic distortion, while the possibility of extending this technique to other converter topologies was not yet assessed [34]. A review indicated enormous opportunities for AI and machine learning techniques in power converter design and optimization pertaining to renewable energy systems, but it stressed the immediate need for standardized methods for evaluation of solutions [35]. Another research delved into the possibilities machine learning may offer to optimization and control in power electronics, though the conclusions had limited empirical validation [36]. Another work analyzed the coupling of AI and digital twin, providing a full theoretical framework, but with practical concerns for real-time implementation and synchronization [37]. These broader perspectives in reviews cover AI-facilitated converter control, fault diagnosis, and power quality improvement while still pointing out the lack of working, large-scale case studies [38]. Less generic methodologies have been proven to work in predictive maintenance and fault detection, yet whether they will scale for large systems remains an open question [39]. More recent debates are in favor of real-time AI control and forecasting for renewable applications, but their credit in fast-transforming smart grid environments still has to be tested [40].

Table 1: Control Strategies for Dual-Stage DC-DC Converters in Renewable Systems

Ref	Technique Used	Key Findings	Results	Limitations
[21]	Fully-controlled bidirectional dual-stage interleaved converter	Efficient interface for hybrid AC/DC grids, enabling power exchange between AC and DC networks	Improved power flow management in simulation	Mostly simulation-based; limited experimental validation
[22]	Hybrid topology: two-phase interleaved buck + three-phase LLC resonant converter	High efficiency and power density in two-stage DC/DC conversion	Achieved high-performance operation for renewable systems	Hybrid design increases control and implementation complexity
[23]	Dual-stage high-gain converter with dual inputs and interleaved structure	Reduced input current ripple and improved efficiency	Demonstrated in prototype systems	Interleaved structure adds components, increasing system complexity
[24]	Robust two-stage tracking controller for bidirectional full-bridge Buck inverter–DC motor	Improved dynamic performance and stability	Better transient response in DC motor applications	Control strategy focused on DC motor systems; limited general applicability
[25]	Two-stage thermal control with switching frequency and MPPT regulation	Temperature regulation and extended converter lifetime	Optimized thermal management for renewable systems	May not be suitable for all converter topologies
[26]	Observability-based voltage control for two-stage DC–DC converters	Efficient voltage regulation in microgrids, EVs, and renewable systems	Stable voltage output achieved	Requires accurate system modeling, difficult in practical setups
[27]	Two-stage bidirectional DC–DC converter with multiple operation modes	Adaptable converter operation for more-electric aircraft	Enhanced versatility in aircraft energy systems	Limited direct applicability to other renewable energy systems
[28]	Ultra-high voltage gain DC/DC converter: coupled inductor + quadratic boost + voltage multiplier	High voltage gain for renewable energy applications	Achieved high voltage conversion	High voltage gain increases component stress, impacting reliability
[29]	Review of control schemes for dynamic response, MPPT, stability	Summarized approaches for renewable energy system control	Provided high-level overview	Did not detail specific control algorithms
[30]	Classification of DC–DC converter topologies	Organized topologies and applications in DC microgrids and renewable systems	Useful reference for converter selection	Classification may not include all new hybrid/topologies

IV. IMPACT OF CONTROL STRATEGIES ON DC AND AC LINE PARAMETERS

Developments in power electronics and control have greatly affected the ways in which AC and DC systems are studied and operated. The research discussed an enhanced AC–DC power flow computation procedure that systematically assesses the impact of control parameters on system performance using the Newton-Raphson technique. Results obtained from this method, when compared with the traditional AC-only models and hybrid models, proved that this method not only improved the accuracy of power flow solutions but also the calculation time [41]. Furthermore, based on such research, a novel parameter design method was introduced for the DC/AC stages of dual-mode converter systems that offer a very unconventional yet efficient parameter configuration method for both the DC and AC parameters for achieving best performance [42].

In converter coordination, a virtual powerline concept (VPL) has been proposed for the interlinking of AC and DC lines. Assuming the line to be purely inductive, the method controlled converter output impedance successfully, improving power sharing and system stability [43]. Analogously, an experimental laboratory study of a low-voltage DC back-to-back converter had encouraging results in power and voltage control of hybrid AC/DC systems. The setup, using two inverters connected by a common DC bus, was flexible in supplying AC loads while ensuring good interaction with the grid [44].

Secondary control schemes had been developed for isolated microgrids to ensure the good sharing of loads out and the voltage restoration of constant power loads. These strategies are therefore considered important to counteract the negative incremental impedance effect that usually destabilizes the islanded DC microgrid [45]. On the other hand, on a large scale, devices including Static Var Compensators (SVCs) and Flexible AC Transmission Systems (FACTS) have been considered as strong means to increase the control flexibility through the dynamic adjustments of transmission line parameters and related controlling of reactive power [46].

Predicting voltage control strategies in a hybrid microgrid environment. These ensure AC and DC subgrids are interacting in the right way, enhancing performance and stability in the load-generation fluctuation environment [47]. In addition, low-level control optimization techniques for DC–AC converters underscore the increasing applications of artificial intelligence and hybrid algorithms as key enablers in future microgrids [48]. Complementarily, models related to power electronic transformers aim at higher efficiency in smart grids and smoother integration of renewables in AC/DC systems [49].

Eventually, coordinated control strategies were also developed for the hybrid AC–multi-terminal DC system, with the intent to counterbalance technical and economic objects. By continuously adjusting converter operating points, droop control methods keep DC voltage and AC frequency within limits for stability and economic purposes such as the minimization of generation cost and voltage deviation [50]. Taken together, these innovations depict the far-reaching approaches that continue to teach strengthening the future power systems for their stability, efficiency, and adaptability on an array.

Table 2: Artificial Intelligence-Based Control Techniques in Power Electronics

Ref	Technique Used	Key Findings	Results	Limitations
[31]	Hybrid AI: H-filtering + ADALINE	Estimated flicker components with improved accuracy	Better robustness and accuracy compared to traditional methods	Unclear performance under varying operational conditions
[32]	LLM-based multi-agent control framework	Objective-oriented autonomous controller design	Efficient, AI-driven control design for power electronics	Implementation and scalability in real-world systems remain untested
[33]	Physics-Informed Neural Network (PINN) control	Merged model-driven and data-driven approaches	Enhanced system stability under uncertainties	Adaptation to a wide variety of power electronic systems not fully explored
[34]	ANN-based Model Predictive Control (MPC) for three-phase flying capacitor multilevel inverter	Circumvented parameter mismatches and reduced THD	Increased inverter performance	Applicability to other converter topologies and conditions not verified
[35]	Review of AI/ML techniques for grid-tied wind energy converters	AI improves converter performance and optimization	Potential performance enhancement	Need for standardized assessment methods of AI solutions
[36]	ML-based optimization and control strategies	Explored AI opportunities in power electronics	Theoretical improvements in control	Lacks empirical evidence supporting suggested methods
[37]	AI + digital twin for power converter control	Improved monitoring and predictive control	Exhaustive analysis of AI integration	Real-time implementation and data synchronization challenges not addressed
[38]	Review of AI in converter design, control, fault diagnosis, PQ improvement	Highlighted major AI techniques	Broad overview of AI applications	Limited case studies demonstrating actual implementation
[39]	AI for predictive maintenance and fault detection	Improved system performance and reliability	Demonstrated convincing implementations	Scalability to large-scale systems remains uncertain
[40]	AI for real-time control and forecasting in renewable systems	Optimized performance of renewable energy systems	Potential benefits for smart grids	Applicability in fast-changing grid environments requires further analysis

V. CONCLUSION AND FUTURE WORK

In this review, the focus was placed on the design and technical analysis of grid-integrated solar systems with an emphasis on dual-stage DC–DC converter management. Conversion topologies were examined from an engineering perspective together with control techniques, discussing how those perspectives concerned system stability, efficiency, and power quality. Conventional methods like PI, PID, and hysteresis controllers were reviewed alongside advanced controllers such as sliding-mode, fuzzy logic, artificial neural networks, and optimization-based controls, analyzing their strengths and limitations. Research into hybrid topologies, bidirectional structures, and multi-output schemes was evaluated to enhance scalability, flexibility, and load management. The study heavily dwelt on the emerging role of AI, ML, and Digital Twin-based concepts for converter control and predictive maintenance. These methods could provide adaptive real-time decision-making to reduce harmonic distortion, improve MPPT operation, and improve resilience against non-linear loads and changing solar profiles. The review then looked into line parameters on AC and DC lines with reference to control strategies, underscoring how coordinated and droop-based strategies contribute to voltage regulation, frequency stability, and satisfying newer grid codes. In spite of all these improvements, it has been noted that a very large chunk of these research remains locked in simulation or laboratory-scale validation procedures. To embrace large-scale adoption, we require real-world testing, scalability assessment, and standard performance evaluation. Henceforth, future investigations work towards pursuing full integration of intelligent, hybrid, and optimization-based solutions within practical environments, thereby strengthening operating efficiency, stability, and sustainability of GI-SS because this would fast-track carbon-neutral energy transitioning.

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