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Multi-Port Converters for Combined Solar–Wind Hybrid Systems: A Review

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ABSTRACT

The growing world energy demand and environmental concerns have accelerated the adoption of renewable energy sources like solar and wind. Solar and wind are intermittent by nature, hence hybrid systems using both energy sources are increasingly used to improve reliability. One of the effective strategies for integrating these multiple sources is through multi-port converters (MPC), which help manage the power flow between sources, energy storage, loads, and grid interface. In recent years, various multi-port DC-DC and DC-AC converter topologies have been developed to efficiently combine solar photovoltaics (PV) and wind generators into a single hybrid system. This paper reviews the state of the art in multi-port converters applied in solar–wind hybrid systems, discusses the classification of converter types, and explores control strategies, performance metrics, pros and cons of different topologies. Special attention is given to converter design challenges, energy management approaches, and future directions. The review also includes comparative tables and schematic illustrations for clarity. The objective is to offer a broad understanding for researchers new to this field and to highlight trends in practical hybrid energy power conversion.

KEYWORDS: - *Multi-port converters; solar–wind hybrid systems; DC-DC converters; energy management; renewable energy integration; MPPT; bidirectional converters*

INTRODUCTION

The transition toward renewable energy systems is vital to reduce carbon emissions and achieve sustainability. Solar and wind energy are among the most widely deployed renewable sources due to their abundant availability and rapidly decreasing cost. However, both sources are inherently intermittent which leads to fluctuations in power output. A hybrid configuration that combines solar PV and wind turbines is often proposed to mitigate individual source variability, offering more stable energy production. But integrating multiple energy sources to serve loads or connect to the grid requires effective power electronic interfaces. Traditional approaches connect each source through separate converters, which increases cost, reduces compactness, and introduces efficiency losses.

Multi-port converters (MPCs) are specialized power electronic devices that integrate multiple inputs (like PV panels and wind generators) and outputs (loads, battery systems, or the grid) in a single power converter topology. MPCs reduce the number of independent converters, minimize passive and active components, and offer centralized control for power management. This review explores various MPC topologies, control strategies, and how they benefit solar–wind hybrid systems.

BACKGROUND AND MOTIVATION

The increasing penetration of renewable energy sources into modern power systems is driven by the need to reduce greenhouse gas emissions, minimize dependency on fossil fuels, and ensure long-term energy sustainability. Among the available renewable resources, solar photovoltaic (PV) and wind energy have gained significant attention due to their technological maturity, declining installation costs, and wide availability. However, the standalone utilization of either solar or wind energy faces serious limitations because of their intermittent and unpredictable nature. Variations in solar irradiance due to clouds and daily cycles, as well as wind speed fluctuations caused by weather conditions, lead to unstable power generation. These characteristics motivate the integration of multiple renewable sources into a single hybrid system to improve overall system reliability and efficiency.

Hybrid renewable energy systems are especially attractive for remote areas, microgrids, and distributed generation applications where grid access is limited or power quality requirements are strict. In such environments, the combination of solar and wind energy sources ensures that power generation is available for a longer duration over the day and across different seasons. Nevertheless, hybridization introduces new technical challenges related to power conversion, control coordination, and energy management, which require advanced power electronic solutions.

1. Renewable Energy Hybridization

Solar photovoltaic systems generate electrical power directly in DC form, whereas wind energy systems typically produce variable-frequency AC power through generators such as permanent magnet synchronous generators (PMSGs) or doubly fed induction generators (DFIGs). For most practical applications, both sources require power conditioning before being supplied to DC loads, battery storage systems, or the utility grid. PV systems generally use DC-DC converters for voltage regulation and maximum power point tracking (MPPT), while wind systems require AC-DC rectifiers followed by DC-DC or DC-AC conversion stages.

In solar–wind hybrid systems, an energy storage element, commonly a battery bank or supercapacitor, is integrated to address short-term power fluctuations and to ensure continuous supply during periods of low renewable generation. The storage system absorbs excess energy during high generation periods and releases it when the generation is insufficient to meet load demand. This buffering capability significantly improves system reliability and power quality. Hybrid solar–wind systems provide several important advantages:

1. **Complementary generation characteristics:** Solar energy is predominantly available during daytime, while wind energy often shows higher availability during night hours or in different seasonal patterns. This complementary behavior reduces the overall variability of the power output.
2. **Reduced dependence on a single energy source:** By combining two renewable sources, the system becomes less vulnerable to the failure or unavailability of one source, enhancing supply security.
3. **Improved overall energy yield:** The utilization of multiple energy sources increases the total harvested energy over time, making better use of installed infrastructure and land resources.

Despite these benefits, the effective realization of solar–wind hybrid systems strongly depends on the efficiency and flexibility of the power conversion architecture. Conventional hybrid systems usually employ separate converters for each source and storage unit, which increases system complexity, component count, cost, and power losses. Moreover, coordinating multiple independent converters can complicate control and energy management.

Multi-port converters address these challenges by consolidating multiple energy sources, storage units, and loads into a single power electronic interface. By sharing switches, passive components, and control hardware, multi-port converters reduce hardware overhead and improve system compactness. They also enable centralized control of power flow, making it easier to implement advanced energy management strategies. As a result, multi-port converters have emerged as a key enabling technology for efficient, reliable, and cost-effective solar–wind hybrid renewable energy systems.

OVERVIEW OF MULTI-PORT CONVERTERS

The integration of multiple energy sources, storage units, and loads in renewable energy systems demands flexible and compact power electronic interfaces. Multi-port converters (MPCs) have emerged as an effective solution to meet these requirements, particularly in hybrid renewable energy systems such as solar–wind configurations. Unlike conventional converter arrangements where each source is connected through an independent power converter, MPCs allow several ports to be interconnected through a single converter structure. This approach improves system efficiency, reduces hardware redundancy, and simplifies coordinated control.

1. Definition and Concept

A **multi-port converter (MPC)** is defined as a power electronic converter that has more than two electrical ports, where each port can act as an input, an output, or both depending on system operation. These ports are typically connected to renewable energy sources such as solar PV arrays and wind generators, energy storage elements like batteries or supercapacitors, and loads or grid interfaces. The primary function of an MPC is to manage and regulate the power flow among these connected ports in a controlled and efficient manner.

In solar–wind hybrid systems, MPCs serve as a common power processing unit that enables simultaneous energy harvesting, storage charging or discharging, and load supply. Depending on the system architecture, an MPC may be implemented as a DC-DC converter when all ports are DC-linked, a DC-AC converter when interfacing with AC loads or the utility grid, or a hybrid DC-DC-AC converter that performs both functions within a single topology.

One of the key characteristics of MPCs is their ability to support **multi-directional power flow**. For example, power can flow from solar PV and wind sources to the load, from sources to storage during surplus generation, or from storage to the load when renewable generation is insufficient. In many applications, bidirectional energy transfer is essential, especially for battery-connected ports that must support both charging and discharging modes. This flexibility makes MPCs well-suited for hybrid renewable energy systems with varying operating conditions.

Another important advantage of MPCs is the **centralized control structure** they offer. Instead of coordinating multiple independent converters, a single control framework can manage all connected ports. This reduces control complexity at the system level and enables advanced energy management strategies such as priority-based power sharing, optimized MPPT operation, and state-of-charge regulation. Furthermore, MPCs reduce the overall component count by sharing switches, inductors, and capacitors among multiple ports, which leads to improved power density and reduced system cost compared to traditional multi-converter solutions.

2. Classification of MPCs

Multi-port converters can be classified in several ways depending on their structural features, isolation requirements, power flow capability, and application domain. The most common classification approaches are discussed below.

1. Based on Electrical Isolation

- **Non-isolated MPCs:**

These converters do not provide galvanic isolation between ports. They are typically based on buck, boost, buck-boost, or interleaved converter structures. Non-isolated MPCs are widely used in low-voltage DC microgrids and small-scale hybrid renewable systems due to their simple design, high efficiency, and low cost. However, the lack of isolation may limit their use in applications requiring safety isolation or wide voltage matching.

- **Isolated MPCs:**
  Isolated MPCs employ high-frequency transformers to provide galvanic isolation between ports. These converters offer enhanced safety, fault tolerance, and flexibility in voltage level conversion. Isolated MPCs are preferred in grid-connected systems and high-power applications, although they involve higher cost, increased component count, and more complex control.

2. Based on Power Flow Direction

- **Unidirectional MPCs:**
  In these converters, power flows in only one direction for each port. They are suitable for systems where energy storage charging or regenerative operation is not required.
- **Bidirectional MPCs:**
  Bidirectional MPCs allow power to flow in both directions at one or more ports, making them ideal for battery-integrated hybrid systems. These converters are commonly used in solar–wind systems with energy storage, where bidirectional charging and discharging is essential.

3. Based on Port Configuration

- **Multiple-Input Single-Output (MISO):**
  Multiple energy sources such as PV and wind are connected to a single DC or AC output.
- **Single-Input Multiple-Output (SIMO):**
  One source supplies multiple loads or storage units at different voltage levels.
- **Multiple-Input Multiple-Output (MIMO):**
  These are the most flexible MPCs, supporting multiple sources, storage devices, and loads simultaneously.

4. Based on Application

- **DC microgrid MPCs** for renewable energy and storage integration
- **Grid-connected MPCs** with DC-AC conversion capability
- **Standalone hybrid system MPCs** for remote or off-grid applications

Overall, the choice of MPC topology and classification depends on application requirements such as power rating, voltage levels, isolation needs, and control complexity. Proper selection and design of MPCs play a crucial role in achieving efficient and reliable operation of combined solar–wind hybrid energy systems.

MPCs can be broadly classified based on architecture and isolation requirement:

Category	Description
Non-isolated MPC	Uses direct DC connections without galvanic isolation; simpler and lower cost.
Isolated MPC	Provides electrical isolation between ports; adds safety and flexibility in voltage levels.
Partially isolated	Combines both isolated and non-isolated sections.

Non-isolated converters are popular for low to medium voltage DC microgrids, while isolated converters are preferred where source and load separation or safety isolation is needed.

SOLAR–WIND HYBRID SYSTEM ARCHITECTURES

Solar–wind hybrid system architectures are designed to combine the advantages of both renewable energy sources while ensuring reliable and high-quality power delivery to loads or the utility grid. The overall architecture defines how different components—generation sources, power electronic converters, energy storage, and loads—are interconnected and coordinated. An effective architecture not only improves energy utilization but also simplifies control and enhances system reliability under varying environmental conditions.

A typical solar–wind hybrid system consists of the following major components:

1. Solar PV Modules

Solar photovoltaic modules convert solar irradiance directly into DC electrical power. The output voltage and current of PV modules depend on environmental factors such as solar irradiance and temperature. In hybrid systems, PV modules are usually connected to the multi-port converter through a DC port that includes maximum power point tracking (MPPT) capability. MPPT ensures that the PV array operates at its optimal point to extract maximum available power at all times. The DC nature of PV output makes it suitable for direct integration into DC-linked hybrid architectures.

2. Wind Turbine Generator Interface

Wind turbines generate mechanical energy that is converted into electrical energy using generators, commonly permanent magnet synchronous generators (PMSGs) or induction generators. The electrical output of a wind generator is typically variable-frequency AC, which cannot be directly used by DC loads or synchronized with the grid. Therefore, a rectifier stage is employed to convert the AC output into DC. This rectified DC power is then fed into the multi-port converter. In advanced systems, controlled rectifiers or AC–DC converters are used to enable variable-speed wind operation and improve energy capture efficiency.

3. Energy Storage System

Energy storage systems play a critical role in solar–wind hybrid architectures by compensating for the intermittent nature of renewable sources. Battery banks are the most commonly used storage devices, although supercapacitors or hybrid storage combinations are also employed in some applications. The storage system is connected to the multi-port converter through a bidirectional port, allowing charging during periods of excess generation and discharging when renewable output is insufficient. Proper management of the storage system helps maintain DC bus stability, improves power quality, and enhances the reliability of supply to loads or the grid.

4. Multi-Port Converter Topology

The multi-port converter acts as the central power processing unit in the hybrid system. It interfaces simultaneously with the solar PV array, wind generator (through rectifier), energy storage system, and the DC bus. By sharing power electronic components among multiple ports, the converter reduces hardware redundancy and system cost. The MPC also enables coordinated control of power flow, ensuring balanced energy distribution based on source availability, storage state of charge, and load demand. Depending on system requirements, the MPC can be non-isolated or isolated and may support bidirectional power flow.

5. DC Bus and DC–AC Inverter

The DC bus serves as a common coupling point for all energy sources and storage units in the hybrid system. It provides a stable DC voltage that supplies DC loads directly or feeds a DC–AC inverter for AC loads or grid connection. The inverter is responsible for converting DC power into synchronized AC power with controlled voltage, frequency, and phase. In grid-connected systems, the inverter also ensures compliance with grid codes, power quality standards, and protection requirements.

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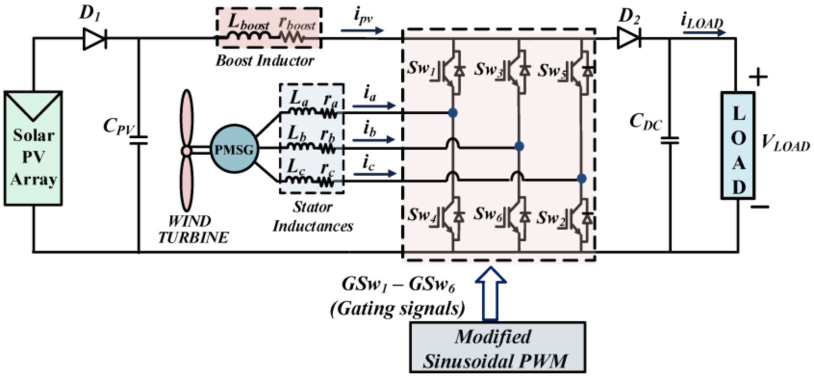

Figure 1: Solar–Wind Hybrid System with Multi-port Converter

MULTI-PORT CONVERTER TOPOLOGIES

Several multi-port converter configurations exist for solar–wind systems. Here we review the main topologies reported in recent literature.

1. Non-Isolated Multi-Port DC-DC Converters

Non-isolated DC-DC multi-port converters are widely used due to simplicity, low cost, and high efficiency. One common implementation is a multiple input single output (MISO) converter that combines boost converters from each source to a common DC link.

An example topology is a three-port DC-DC boost converter where solar PV and wind inputs share an output to a DC bus. The duty cycles are independently controlled to regulate output voltage and power flow. This architecture helps in reducing the number of passive components and shared control strategy.

Table 1: Example Non-Isolated MPC Comparison

Topology	Input Sources	Isolation	Pros	Cons
MISO Boost	PV + Wind	No	High efficiency, simple	Limited voltage variation handling

Topology	**Input Sources**	**Isolation**	**Pros**	**Cons**
Interleaved multi-input	PV + Wind	No	Reduced ripple	Control complexity

2. Isolated Multi-Port Converters

In some systems, isolation is desirable between sources and loads. Isolated multi-port converters incorporate transformers or galvanic isolation elements to separate electrical domains. Isolated converters often use multi-winding transformers or dual active bridges to route power among sources.

An example is a fully isolated multi-port DC-DC converter that integrates PV, wind, battery, and load connections through a transformer network. These converters can offer flexible voltage scaling and safety but at the expense of more components and design complexity.

3. Hybrid Topologies (DC/DC + DC/AC)

Hybrid multi-port converters combine DC-DC and DC-AC stages to directly interface sources with both DC microgrid and AC grid loads. A DC bus connected to an MPC can feed an inverter that supplies AC loads while PV and wind sources are connected through the converter. This type of architecture is increasingly common in grid-tied microgrid systems.

CONTROLLER STRATEGIES AND ENERGY MANAGEMENT

Effective control of multi-port converters is essential for stable operation. Control encompasses:

- **Maximum Power Point Tracking (MPPT)** for PV and wind
- **DC bus voltage regulation**
- **State of charge (SoC) management** of batteries
- **Power sharing algorithms**

MPPT strategies track the optimal operation point of PV and wind generators to maximize energy extraction. Combined MPC systems usually have independent MPPT loops for each source, and a supervisory energy management system allocates power flows based on priority and demand conditions.

In some advanced studies, robust control strategies and Lyapunov-based schemes are proposed to maintain stability under varying conditions and source fluctuations.

PERFORMANCE METRICS AND ANALYSIS

The performance of multi-port converters in hybrid systems is assessed based on:

- **Conversion efficiency** – Higher overall efficiency reduces energy losses.
- **Dynamic response** – Ability to handle rapid changes in power generation.
- **Voltage regulation** – Stable DC bus voltage under source variations.
- **Component count and cost** – Fewer components reduce cost and complexity.

In many recent works, simulation and hardware validation show that MPCs can maintain voltage stability and efficient energy transfer while reducing hardware requirements compared to separate converters.

CASE STUDIES AND REPORTED RESEARCH

A number of practical multi-port converter designs have been implemented or simulated. For example:

- **Four-port DC-DC converter** integrating PV, wind, battery, and load interface, validated with hardware prototype in hybrid wind/solar system models.
- Multi-input boost converters designed for hybrid PV and wind systems demonstrating improved performance and reliability.
- Multi-port converters with soft-switching or interleaved methods to improve efficiency and reduce current ripple.
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These case studies show practical considerations such as power quality improvement, efficient MPPT integration, and bidirectional flow for storage charging/discharging.

CHALLENGES AND FUTURE TRENDS

While MPCs present many advantages, challenges remain:

- **Control complexity:** Coordinating multiple sources and storage demands complex algorithms.
- **Scalability:** Designing converters that scale to higher power levels while maintaining efficiency is non-trivial.

- **Cost vs. benefit:** Added components for isolation or advanced control may not always justify performance gains.

Future research may focus on:

- GaN and SiC-based switches for increased efficiency.
- Modular multi-port converters with plug-and-play capability.
- Intelligent energy management using AI or predictive control.

CONCLUSION

Multi-port converters are effective interfaces for combined solar–wind hybrid energy systems, enabling energy from multiple renewable sources to be integrated efficiently into microgrids or the utility grid. By consolidating multiple converters into a single topology, MPCs reduce hardware, enhance power management, and improve overall system performance. For hybrid systems with PV and wind inputs, MPCs with robust control strategies and MPPT integration provide improved stability and energy utilization.

Although challenges like control complexity and design trade-offs remain, continued research and improvement in converter topologies and control methodologies will drive wider implementation of MPC-based hybrid renewable energy solutions.

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