A PV and Battery Energy Storage Based-Hybrid Inverter Architecture Addressing Future Energy Demands

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Abstract

This white paper presents a hybrid energy storage system designed to enhance power reliability and address future energy demands. It proposes a hybrid inverter suitable for both on-grid and off-grid systems, allowing consumers to choose between Intermediate bus and Multiport architectures while minimizing grid impact. The system integrates a photovoltaic (PV) module with Maximum Power Point Tracking (MPPT), a single-phase grid inverter, and a battery energy storage system (BESS), all using wide band gap GaN devices for high power density and efficiency. It also features power quality enhancement for stable energy supply under dynamic conditions. The 2.5-kW hybrid inverter model, utilizing Renesas components, achieves over 96% efficiency, a power factor above 0.99, and low THD (<3%). Future technological advancements and supportive policies are expected to make these systems more accessible and cost-effective.

Introduction

The widespread deployment of intermittent distributed energy resources (DER), like solar power, in the utility grid, along with new tariff models for end users, requires effective integration. While there is significant research on hybrid inverters and control systems, practical challenges in their implementation

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are often overlooked. This article highlights that overall performances can be significantly improved by overcoming such challenges, particularly in control systems and hardware architecture.

The hybrid inverter shown in Fig.1 combines the functions of a microinverter with energy storage management. It optimizes solar energy use, reduces grid dependency, and intelligently controls the power flow between the battery, grid and PV source.

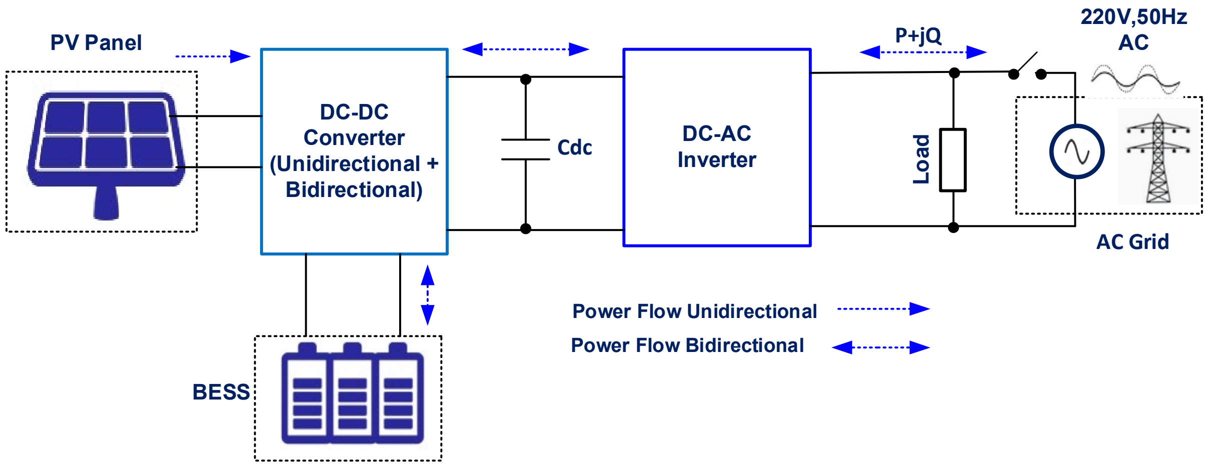

Fig.1 Typical Hybrid Inverter Structure

Features:

- Converts DC electricity from solar panels into AC and maximizes solar energy harvesting.
- Stores excess solar energy in batteries for later use and draw energy from the grid when needed.
- Supports smart energy management and backup during power outages.
- Automatic switching between on-grid, off-grid and hybrid, based on availability and demand.
- Implemented using microcontrollers with real-time monitoring, power flow control, and MPPT algorithms.

System Configuration

The hybrid inverter is configured in two distinct architectures: Intermediate DC Bus Architecture and Multiport Architecture, as shown in Fig. 2 and Fig. 3, respectively. A comparison of the features of each configuration is provided, followed by a detailed description. Each stage of proposed architecture is based on GaN technology to achieve high power density and efficiency, making it suitable for advanced energy conversion systems in hybrid inverters.

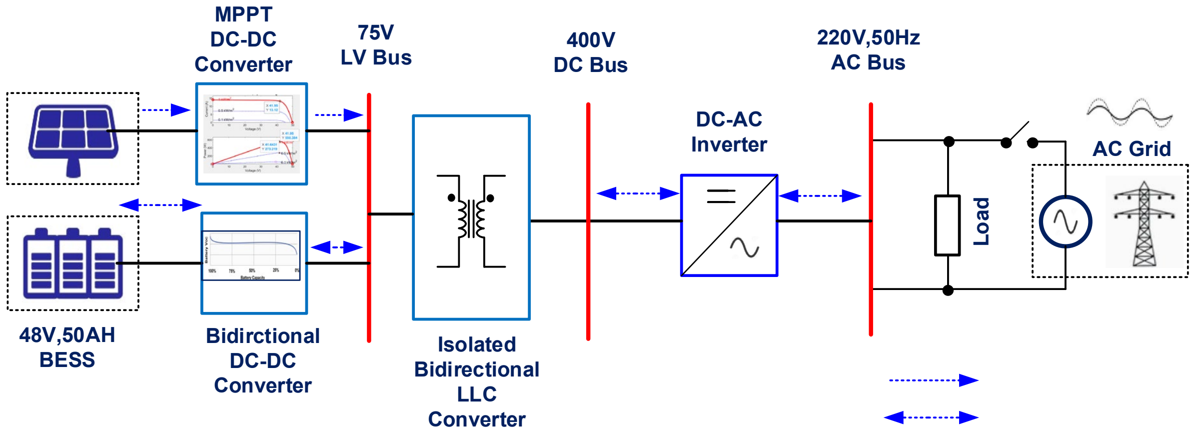

Fig.2. Intermediate Bus Architecture

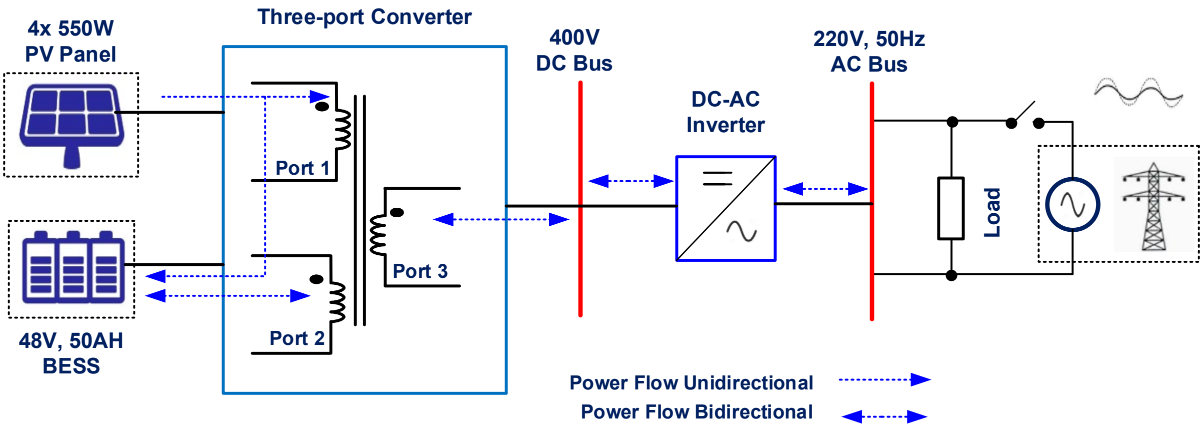

Fig.3 Multiport Architecture

Intermediate Bus Architecture

The Intermediate Bus Architecture shown in Fig. 2 comprises an MPPT boost converter, a non-isolated bidirectional buck-boost converter for battery charging and discharging, a bidirectional LLC DC-DC converter, and a full-bridge grid inverter. This design demonstrates a potential implementation of a 4-channel autonomous MPPT converter, enabling bidirectional power flow between the grid, PV system, and a 48-V BESS. The architecture supports efficient and flexible energy management across all connected sources and loads.

The design includes four main stages:

MPPT DC-DC converter with Autonomous MPPT Functionality

- To extract the maximum available power from PV panel, the operating point must be continuously tracked using an MPPT algorithm, which operates by sensing both the PV voltage and PV current.

- A synchronous boost DC-DC converter is employed to match the load impedance with the equivalent impedance of the PV panel, ensuring optimal power transfer.
- The MPPT algorithm is executed by an RA6T2 ARM core digital microcontroller unit (MCU), which provides precise control and real-time processing capabilities essential for efficient energy harvesting.

Bidirectional Buck-Boost DC-DC Converter

- The bidirectional buck-boost DC-DC converter functions as a back-end converter, designed for efficient power transfer and battery charging.
- In charging mode, the converter operates in buck mode to step down the voltage for battery charging. In discharging mode, it switches to boost mode to step up the battery voltage for system use.
- The battery charge/discharge algorithm is managed by an RA6T2 ARM core digital MCU, ensuring accurate control, safety, and optimized energy management during both charging and discharging cycles.

Isolated Bidirectional LLC Converter

- The bidirectional LLC DC-DC converter serves as an isolation stage between the MPPT converter/battery charge-discharge converter and the grid inverter, enabling efficient power transfer.
- Both input and output voltages of the LLC converter are fixed and regulated externally by the PV or battery on the input side, and the grid inverter on the output side.
- This stage does not perform voltage regulation itself but allows bidirectional power flow with synchronous rectifier operation, and supports Zero Voltage Switching (ZVS) for improved efficiency and reduced switching losses

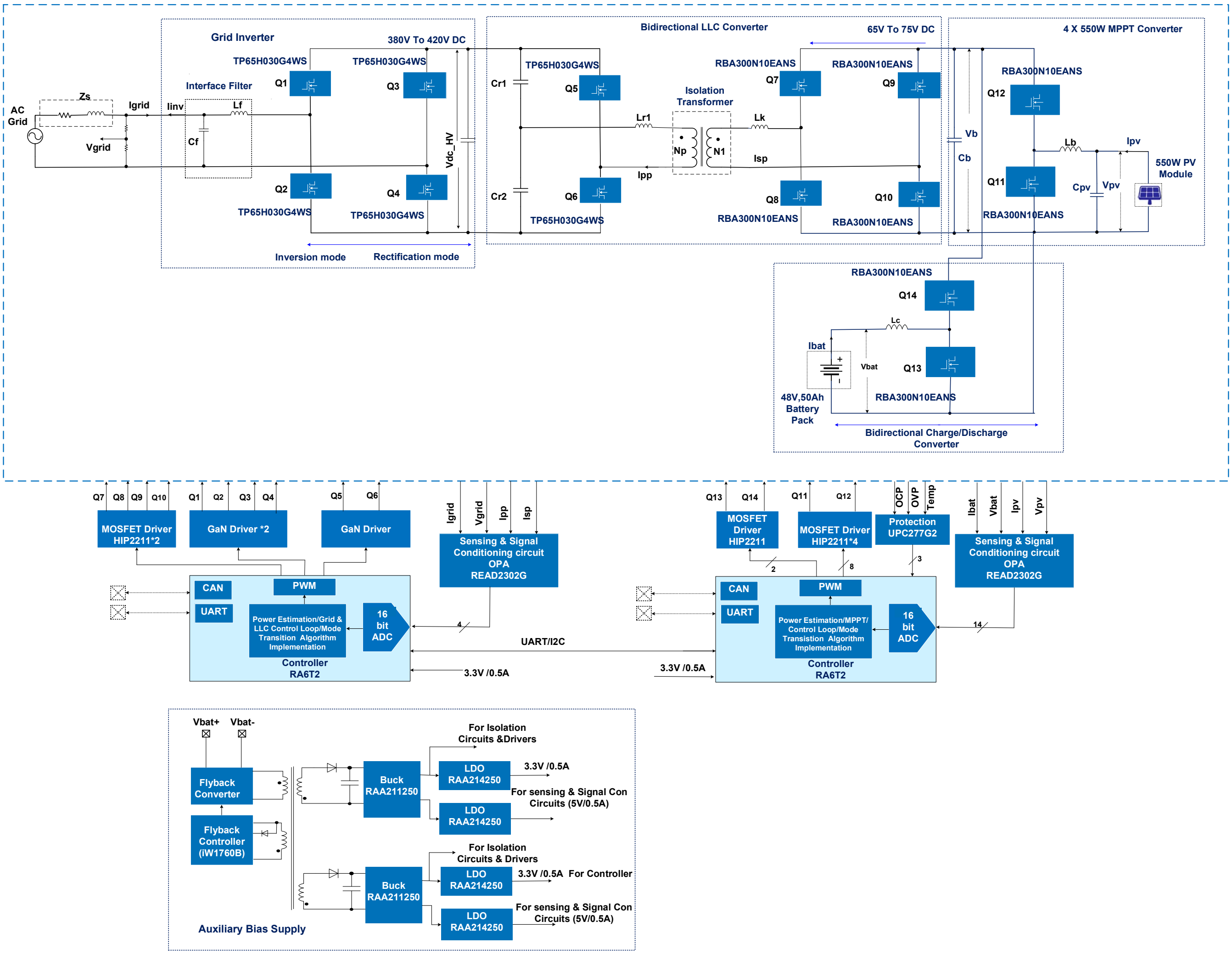

Fig.4 Intermediate Bus Architecture System Block diagram

Totem-pole Grid Inverter

- The grid inverter functions in two modes: as a front-end rectifier when transferring power from the grid to the battery, and as a voltage source inverter when feeding power from the PV/battery back to the grid.
- It incorporates a full-bridge PWM inverter with an LC output filter to inject synchronized sinusoidal current into the grid. The system aims for low total harmonic distortion (THD) and a close-to-unity power factor, ensuring efficient operation under various load conditions and non-ideal grid voltages.

Multiport Architecture

The multiport structure shown in Fig.4 features a three-port converter and a bidirectional grid inverter. The primary function of the three-port converter is to enable single-stage power conversion, which integrates MPPT for PV systems and manages the charging/discharging of batteries with minimum BOM and improved power conversion efficiency. This design targets low-power modular systems and demonstrates a potential implementation of an MPPT converter, bidirectional LLC converter, and a buck-boost converter integrated into a single unit. It facilitates better management and control of power flow between multiple sources (PV/Battery/Grid).

For the multiport structure shown in Fig. 4, the overall power flow expression is following:

$$P_{PV} + P_{BES} = P_{LOAD} + P_{GRID}$$

where P_{BES} represents battery energy storage power, P_{PV} is solar power generated by the PV panel, P_{LOAD} is the power consumed by local users, and P_{GRID} is the power that is injected or extracted from the grid depending on the demands. Thus, P_{GRID} can be both positive (indicating power injection into the grid) or negative (indicating power extraction from the grid) based on the direction of the power flow.

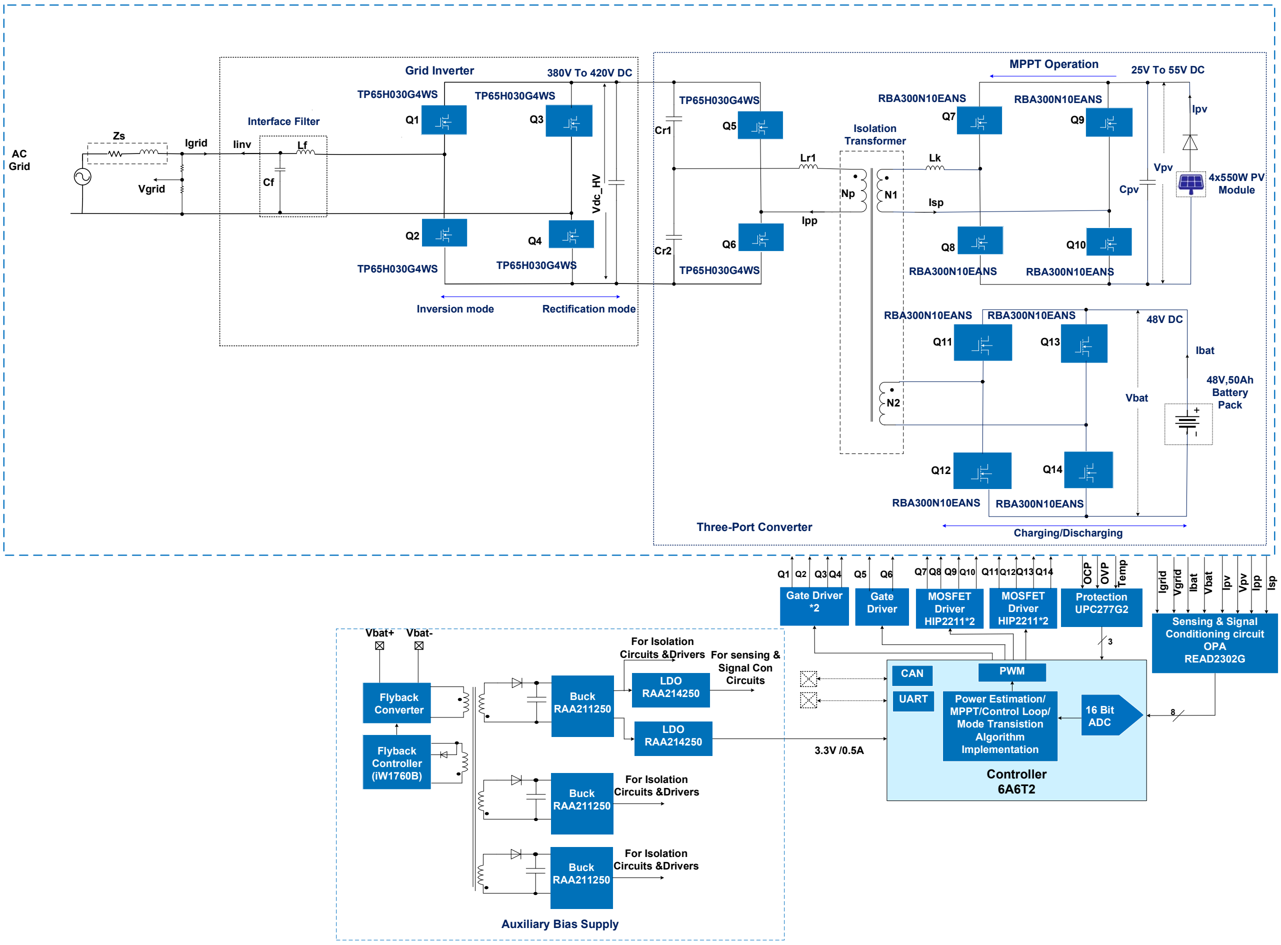

Fig.4 Multiport Architecture System Block diagram

Operating Modes

The three-port converter can operate in six possible power transfer modes and logic are shown in Figure.4 and figure.5 respectively.

Mode1: PV providing power to both the battery and the load/grid.

Mode2*:* Only PV providing power to the load/grid

Mode3: Only battery providing power to the load/grid.

Mode4: Both PV and battery providing power to the load/grid.

Mode5: PV delivering power to the battery.

Mode6: Grid providing power to the battery while PV supplies power to the load.

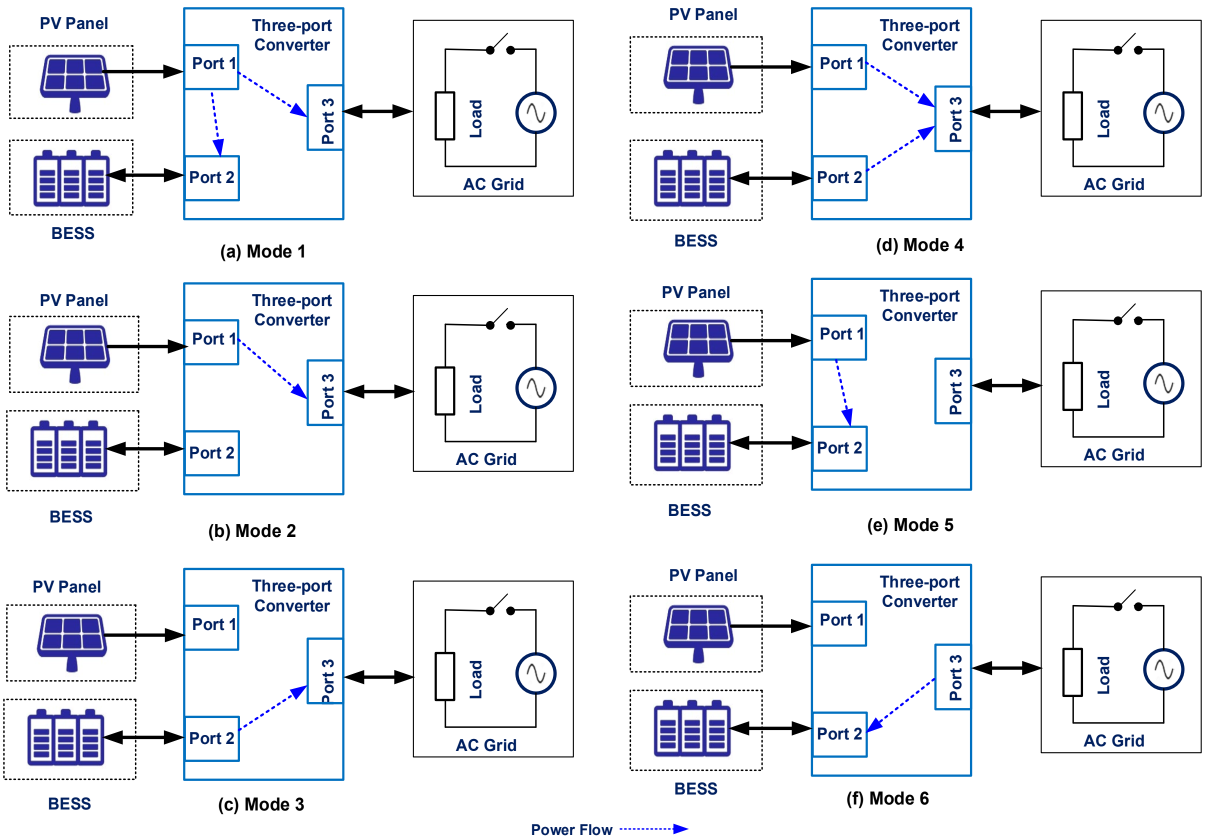

Fig.4 Possible Power Transfer Modes

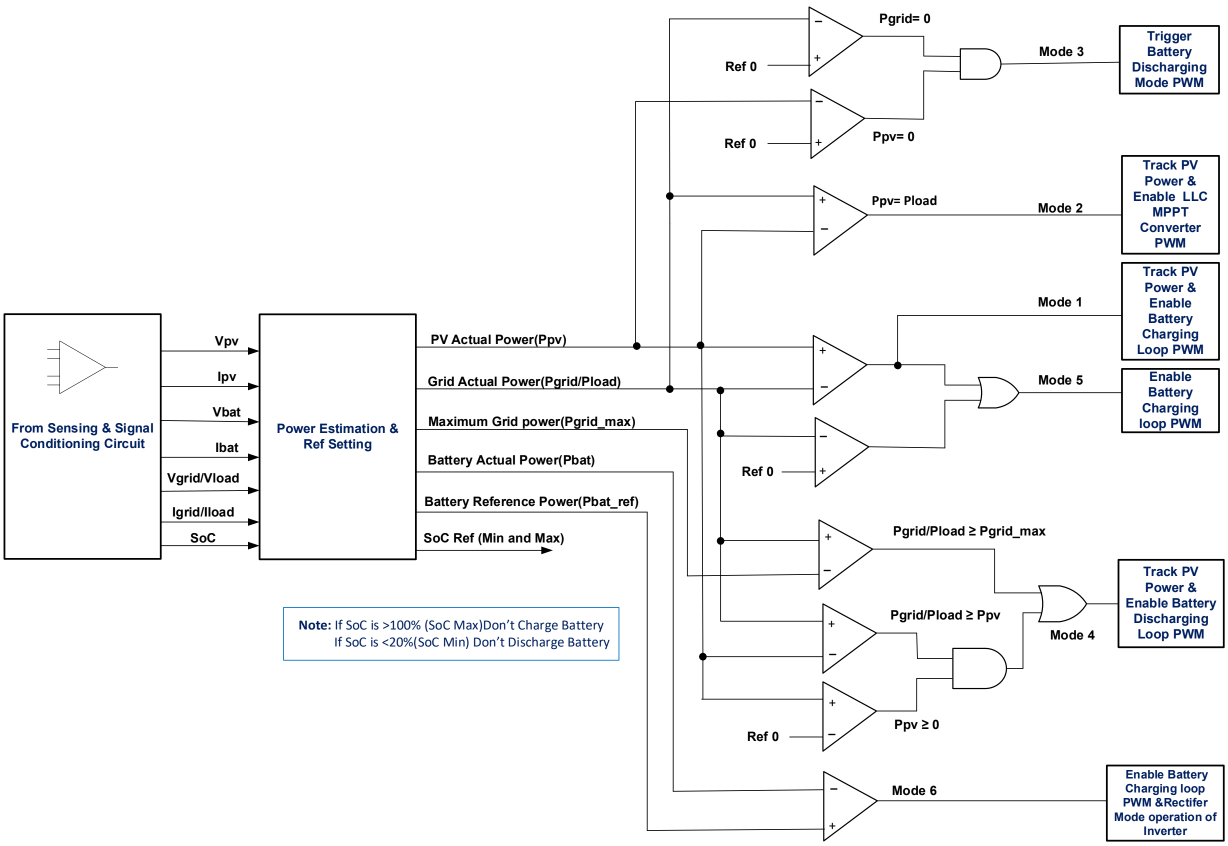

Fig.5 Mode Transition Logic

Advantages

As summarized below, multiport converters offer advantages over standard or intermediate bus converters.

- **Enhanced Energy Management**: Efficiently manages energy flow between solar panels, batteries, and the grid.
- **Improved Efficiency**: Integrating multiple ports reduces losses, improving energy conversion and utilization efficiency.
- **Cost-Effective Design**: Consolidating functions into a single converter reduces the number of components, wiring, and control systems, lowering initial costs and simplifying installation.
- **Space Saving**: A single converter saves space, making it ideal for compact systems like residential solar balcony setups.
- **Flexibility in System Integration**: It can manage various energy sources and storage systems simultaneously.
- **Advanced Control Capabilities**: Sophisticated algorithms improve system reliability and performance.
- **Better Fault Tolerance and Reliability**: Isolating faults enhances reliability, allowing other sources to continue functioning.

- **Reduced System Complexity**: Due to combining functions simplifies system design and operation.
- **Optimized Power Flow**: The converter dynamically adjusts power flow between sources to optimize energy use.
- **Cost Reduction in Operation and Maintenance**: Fewer components reduce operational and maintenance costs over time.

Design challenges

Hybrid inverter design faces following challenges:

- **Integration**: Managing multiple energy sources efficiently.
- **Control System Design**: Ensuring smooth coordination with advanced algorithms.
- **Power Conversion Efficiency**: High efficiency across all modes.
- **Hardware Compatibility**: Ensuring seamless integration of different components.
- **Fault Management:** Designing for stability during faults or abnormal conditions.
- **Certification**: Meeting industry standards and safety regulations include UL 1741, IEC 62109, IEEE 1547, IEC 62619, IEC61000 etc.

Analysis and Modelling

The performance of both architectures is compared based on power conversion efficiency. The system is modelled considering topology, firmware architecture, and control system aspects, using the real-time implementation tools of the Simplis. SPICE models of Renesas devices including GaN transistors, MOSFETs, drivers, and controllers are utilized for simulation analysis. The devices used in the simulation analysis are listed in Table 1. The proposed system is designed to operate with grid voltages of either 110V or 220V and supports a maximum MPPT input voltage of 42V from the PV panel.

In the PV power injection to load/grid mode (2kW power condition), the conversion efficiency achieved is 95.97% for the intermediate bus architecture and 97.563% for the multiport architecture. From Table 2, these results indicate that the multiport architecture demonstrates superior performance in terms of both higher conversion efficiency and a reduced number of power conversion stages.

Table 1 Components Considered for simulation

S. No	Main Power Components	Description	Specifications
1	TP65H030G4PQS	GaN	650V, 55.7A, 30mΩ
2	RBA300N10EANS	MOSFET	100V,300A,1.5mΩ
3	RRW40120	HV side Driver	600V Driver for HV GaN
4	HIP2211FBZ	LV side Driver	100V Driver for LV MOSFET and GaN
5	R7FA6T2BD3CFP	MCU	High-performance 240 MHz Arm Cortex-M33 core

Table 2 Efficiency Performance

S. No	Output Power(W)	Conversion Efficiency (%)		
		Intermediate Architecture	Multiport Architecture	Efficiency Improvement
1	2034.472	95.968	97.563	1.595
2	1028.282	94.046	97.669	3.623
3	520.009	90.042	96.273	6.232

Summary

Renesas offers comprehensive solutions for single-phase hybrid inverters rated from a few kilowatts up to 6.5 kW, enabling efficient and reliable designs through advanced power conversion topologies. Utilizing Renesas MOSFETs, GaNs, drivers, and microcontrollers with real-time monitoring and MPPT control, these solutions deliver an optimal price-to-performance ratio. Renesas also provides technical support, reference designs, firmware libraries, and design tools to accelerate development and ensure compliance with industry standards and protection features.

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