Integrated Solution for Low-Power Energy Storage Systems

Introduction

Energy storage systems play a critical role in seamless integration of renewable energy sources to the grid for stability and a sustainable energy future. They also support backup power generation during grid outages.

This document presents a comprehensive design overview of Low-Power Energy Storage systems, mainly for residential applications. It consists of a high-efficiency AC-DC PFC converter using GaN power switches, a bi-directional DAB based DC-DC converter, MPPT solar charger and battery management system.

Key Performance Indicators (KPIs), Electrical Specifications and Bill-of-Materials (BoM) are shown for each of the above-mentioned Renesas sub-systems, enabling a fast product design cycle and shorter time-to-market.

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1. Abbreviations and Terminology

PFC	Power Factor Correction
GaN	Gallium Nitride
ZVS	Zero Voltage Switching
SR	Synchronous Rectifier
BMS	Battery Management System
BMIC	Battery Management Integrated Circuit
FGIC	Fuel-Gauge Integrated Circuit
MCU	Micro-Controller Unit
ESS	Energy-Storage System
BESS	Battery Energy Storage System
AC	Alternating Current
DC	Direct Current
DAB	Dual Active Bridge
MPPT	Maximum Power Point Tracking
PV	Photo Voltaic
UPS	Uninterruptable Power Supply
THD	Total Harmonic Distortion
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
HV	High Voltage
LV	Low Voltage
LDO	Low Drop-Out
OBC	On-Board Charger

2. Overview

The demand for efficient and compact Battery Energy Storage Systems (BESS) is driving innovation across the entire Power Electronics industry. Low-power Battery Energy Storage Systems play a critical role in enabling sustainable energy use, portable applications, and uninterrupted power delivery.

The most common applications for Low-Power BESS are:

- **Portable Power Stations** – Ideal for outdoor activities like camping or hiking where access to traditional power grids may be limited.
- **Energy Storage Systems (ESS) and Uninterruptible Power Supplies (UPS)** – Provides reliable backup during power outages or emergencies.
- **Electric Vehicle Charging** – Used as part of mobile EV charging solutions.
- **Industrial Equipment** – Supply machinery in remote locations where conventional electricity is not available.
- **Renewable Energy Systems** – Integrates seamlessly with solar panels and ideal for off-grid living situations like cabins, recreational vehicles and any outdoor/camping activities.
- **Battery Charger Unit for Power Tools** – Targeting gasoline-powered electric generators replacement
- **Energy Storage Systems for Solar Balcony Applications** – Where a few panels (typically 3 to 6) are used to generate electric energy at home.

To meet these market needs, Renesas offers a comprehensive suite of solutions designed to maximize efficiency and reliability while minimizing power loss. These include an advanced Battery Management System (BMS) with integrated fuel-gauge technology for precise charge monitoring, and a GaN-powered ultra-high-efficiency Totem-Pole PFC. Complementing these is a robust Dual-Active Bridge (DAB) isolated DC-DC converter, ensuring optimal power delivery across the system. Together, these cutting-edge technologies provide a seamless pathway to building next-generation low-power BESS with unmatched performance and scalability. A single-line diagram of the Renesas low-power BESS is shown in Figure 1.

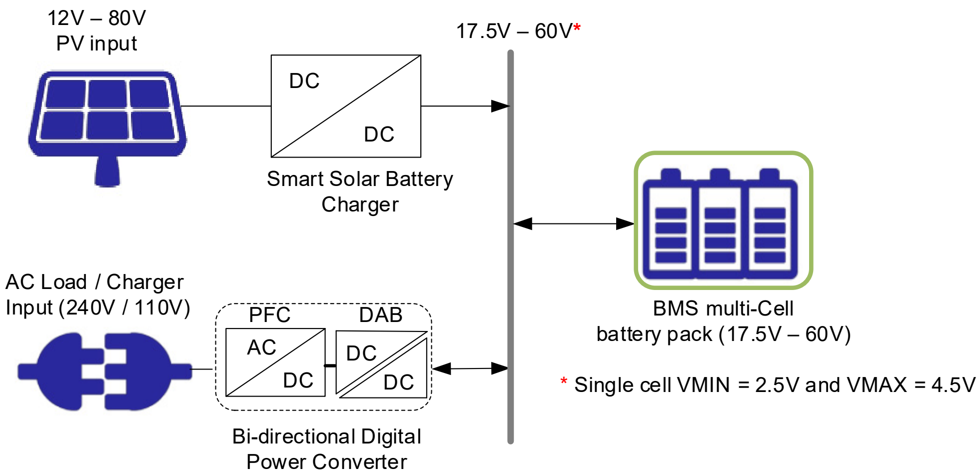

Figure 1. Renesas Low Power Battery Energy Storage System (BESS) Solution

3. Low-Power Battery Energy Storage System Design Challenges

Globally, industries are moving towards sustainable energy solutions to achieve net-zero carbon emissions. Renewable energy sources play a major role in achieving this ambitious target. Typically, these sources are intermittent in nature. Thus, there is an increase in demand for reliable power solutions with Battery Energy Storage Systems (BESS). The BESS-based solution provides numerous advantages along with renewable sources such as solar, wind and fuel cell by improving energy efficiency and dynamic stability of on-grid/off-grid supply. However, the implementation of ESS with advancements in PV power technology presents more design challenges. The Renesas solution provides energy storage systems using a multi-cell battery pack with state-of-the-art technologies for integration with solar PV and grid supply as shown in Figure 1. To achieve the smooth power flow from different loaded sources, several design challenges need to be addressed:

- **High-efficiency Power Conversion** – The conversion stages in these systems typically utilize a Totem-Pole PFC followed by a dual active bridge (DAB) while integrating Battery Energy Storage Systems (BESS) with AC loads. This configuration results in a two-stage power conversion process. Its purpose is to deliver maximum power from the source to the load while maintaining high efficiency. Therefore, it is crucial for each stage to have exceptional efficiency to minimize efficiency losses during cascaded operations. Devices made from wide-band gap materials like GaN and SiC, which allow for high-frequency operation, are preferred for achieving greater power conversion efficiency.
- **Fast Charging Time** – Modern BESS are targeting about 1-hour charging time for a 1kWh to 5kWh battery pack, aiming at minimizing the idle time for battery usage. Fast Chargers are used to achieve such reduced charging time. Wide-Bandgap Semiconductors are heavily used to improve efficiency, hence improving thermal management while increasing charging current level. Moreover, both State of Charge (SoC) and State of Health (SoH) of the battery pack needs to be monitored accurately with suitable BMS to guarantee reliable and safe operation.
- **Charge/Discharge Path** – The energy storage system has several sources and loads connected to a common bus. Sources need to be prioritized based on their availability to serve the loads with suitable charge and discharge paths. A flexible digital controller is essential to monitor and allow the desired power flow path.
- **Multiple Battery Pack Size with FGIC** – Measurement of the cell parameters (such as SoC, cell voltage and battery capacity) and communicating the same with the digital controller is necessary to proper functioning of BMS. The fuel gauge ICs should monitor the multicell battery pack parameters with short-circuit and other protection features.
- **Modular and Scalable Solution** – The solution should be modular and scalable to various power levels to reduce customers R&D time, reduce testing and validation time, and improve reusability of power solutions across multiple projects.

Apart from the challenges noted above, other design considerations need to be addressed for a reliable BESS, such as:

- Ensure Grid compatibility, in other words, support universal input voltage and frequency: 90V to 264V, 50Hz/60Hz.
- Follow various Regulatory guidelines such as IEEE 1679.1, IEC 62933-5-2, UL 9540 etc.
- Guarantee smooth integration with the existing energy infrastructure
- Support complete conversion chain – Grid-Battery-Grid
- Mitigate potential hardware or software integration issues by exploiting top-down, model-based design methodology, suitable for multi-system integration

Considering the above challenges, the Renesas solution is built with cutting-edge technology enabling a modular, scalable and customer friendly lower-power BES system. A high-level block diagram for the low-power BESS is shown in Figure 2.

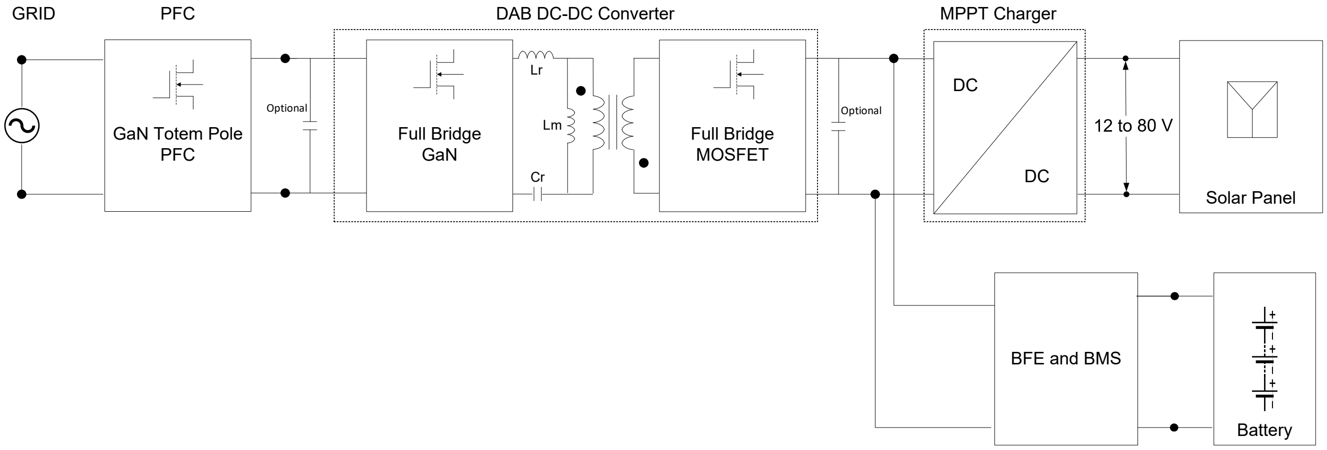

Figure 2. High-Level Block Diagram for Low-Power BESS

4. Renesas Solution for Low-Power Battery Energy Storage System

Renesas BESS solution addresses design challenges by offering cutting-edge technologies for charging the battery pack, regardless of the number of cells, and supplying multiple devices at the same time. A comprehensive block diagram of the Renesas BESS solution is shown in Figure 3.

The following sections describe each sub-system of the solution, enabling system designers to develop a modular and scalable energy storage system.

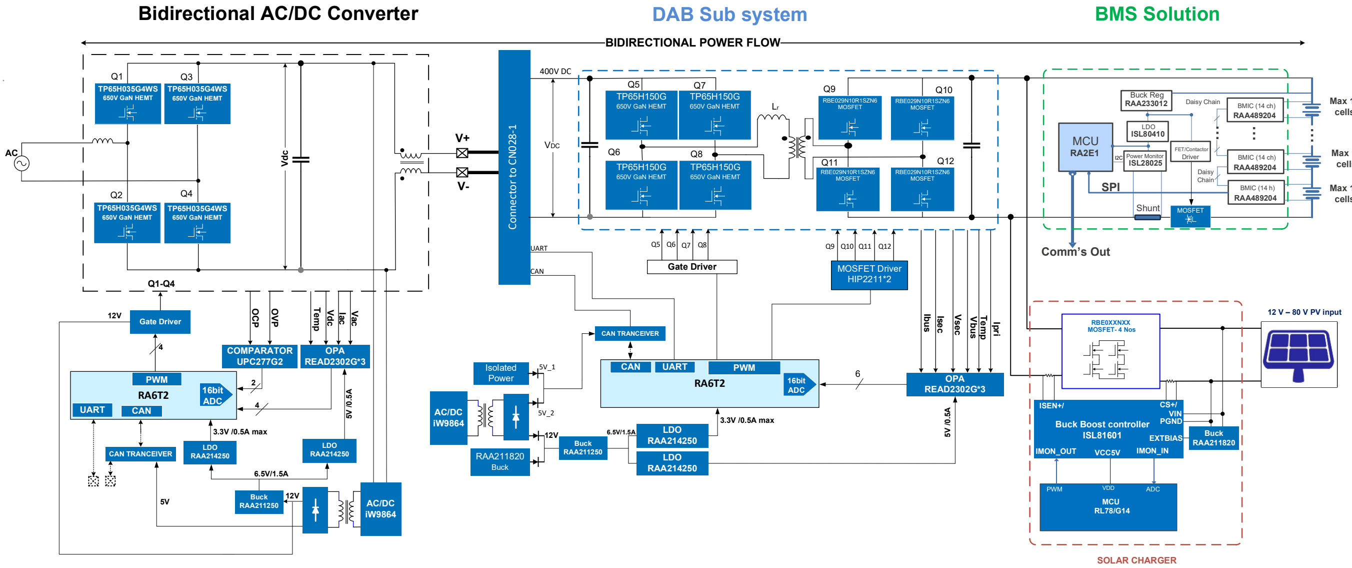

Figure 3. Comprehensive Block Diagram of a Low-Power ESS

4.1 Bi-Directional 3.6kW AC-DC Digital Power (PFC+DAB)

The system is based on Renesas' higher performance RA6T2 ARM core MCU and 650V SuperGaN FET for bi-direction power conversion. It consists of a Totem Pole Bridgeless (TPB) PFC topology followed by a Dual-Active Bridge (DAB) isolated DC-DC converter to realize bi-directional digital AC-DC power conversion.

4.1.1 AC-DC Totem Pole Power Factor Correction (PFC) Converter

The Renesas bi-directional Totem Pole PFC is designed using a 650V SuperGaN FET with drain source resistance of 35mΩ. The RA6T2 ARM core MCU provides high-performance flexible digital control. In comparison with the conventional boost PFC, the Totem Pole PFC topology with wide band gap FETs and no diode bridge rectifiers enables high efficiency operation with reduced conduction losses, both in inverter and PFC mode.

System Benefits:

- High efficiency of operation with peak efficiency of 98.7%
- Low THD of 1.15% at full load in on-grid/off-grid operation
- Bi-directional capability, in other words, ability to work as both PFC and DC-AC converter
- Outstanding power factor of 0.9994 at full load operation

In addition to the above benefits, the Renesas total solution along with Renesas' basic digital power software algorithm package helps customers to reduce design complexity, thus reduce product design and release time to market.

Target Applications:

- **ESS/UPS**: The bi-directional PFC capable of delivering power at unity power factor is ideal for ESS/UPS applications
- **EV/HEV OBC**: Renesas solution that suits Vehicle-to-Grid (V to G) or Grid-to-Vehicle (G to V) applications, delivering power with high-efficiency and high PF
- **Power Conversion**: Various industrial power conversions for industrial applications, in other words, AC/DC or DC/AC
- **Solar Power**: The Renesas solution capable of working with PV to grid applications. The bi-directional capability helps to have energy storage with PV input.

The Totem Pole PFC block diagram, along with key specifications, are provided in Figure 4 and Table 1, respectively. The solution is capable of operating at high-efficiency with high PF and low current THD at various load conditions.

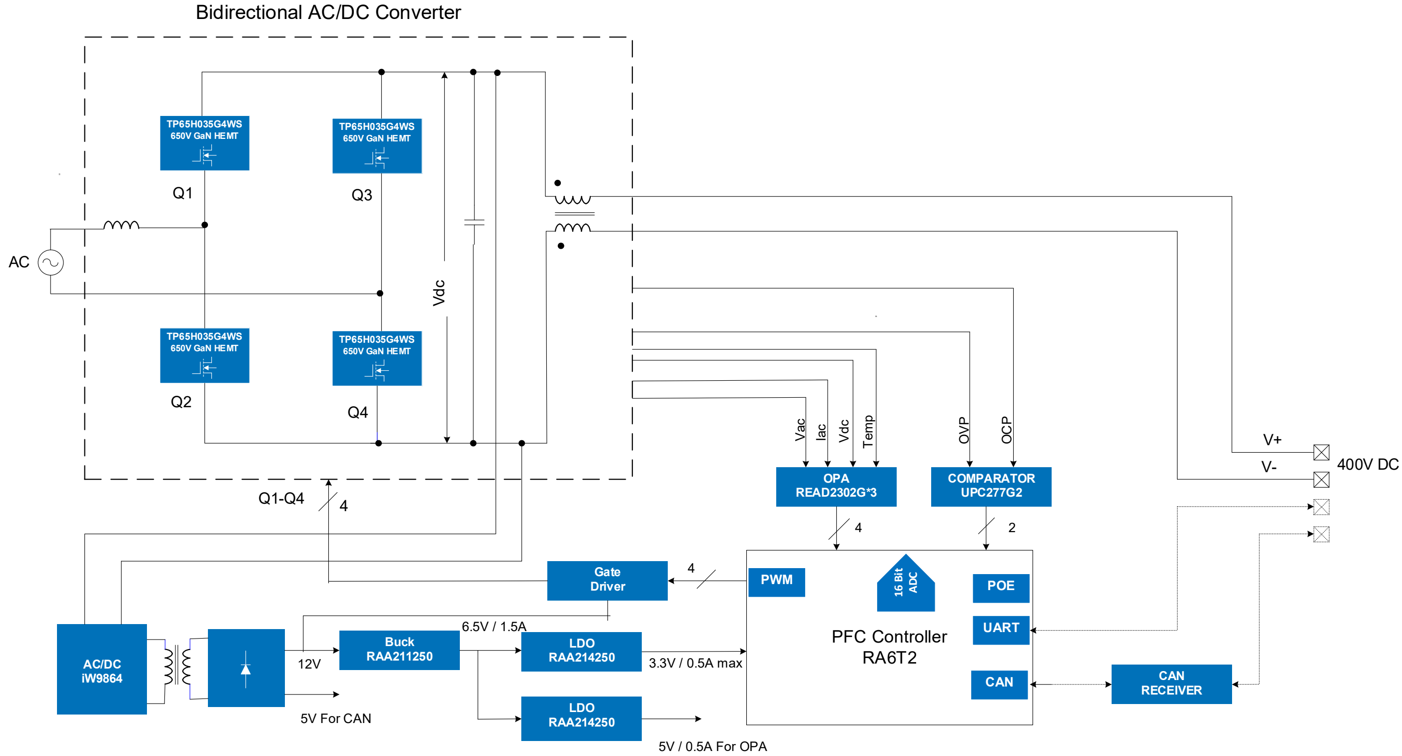

Figure 4. Totem Pole PFC Subsystem

Table 1. Totem Pole PFC Key Specifications

Parameter	Test Condition	Minimum	Typical	Maximum	Unit
RMS Value of AC Input Voltage	-	80	-	264	V
AC Line Frequency	-	45	-	65	HZ
RMS Value of AC Line Current	-	-	-	16.2	A
Output Power	220VAC line	-	-	3600	W
	110VAC line	-	-	1800	W
DC Output Voltage	-	-	-	400	Voc
Current THD (THD_I)	230VIN, 3600W load	-	1.15	-	%
Power Factor (%)	230VIN, 3600W load	-	0.9994	-	-
Peak Efficiency	230VIN, 1610W load, with aux power consumption	-	98.7	-	%
Switching Frequency	-	-	66	-	kHz

The Renesas PFC design solution involves a dedicated MCU, high-efficiency auxiliary power supplies, analog comparators and operational amplifiers for sensing and control applications. See Table 2 for the part numbers and their corresponding features.

Table 2. Totem Pole PFC Key Components and Features

Device	Part Number	Key Features
MCU	R7FA6T2BD3CFP	240MHz Arm® Cortex®-M33 for motor and inverter control solutions
Power	RAA211250	4.5V to 30V input voltage range and adjustable output voltage, 5A Buck
	RAA214250	20V, 500mA linear regulator
	iW9864	Digital Quasi-Resonant AC/DC controller for Zero Standby Power RapidCharge™ power supplies up to 140W
	TP65H035G4WS	650V, 35 mΩ gallium nitride (GaN) FET
Analog	UPC277G2	Comparators utilizing CMOS process suitable for Low Voltage, Low Power consumption, and fast response
	READ2302G	High Drivability & High Slew Rate Operational Amplifier

4.1.2 PFC Efficiency, Power Factor and THD Evaluation

The PFC solution is evaluated in a hardware prototype as shown in Figure 5 and the power conversion efficiency is observed to be greater than 98 % for the output power > 1.7kW as shown in Figure 6.

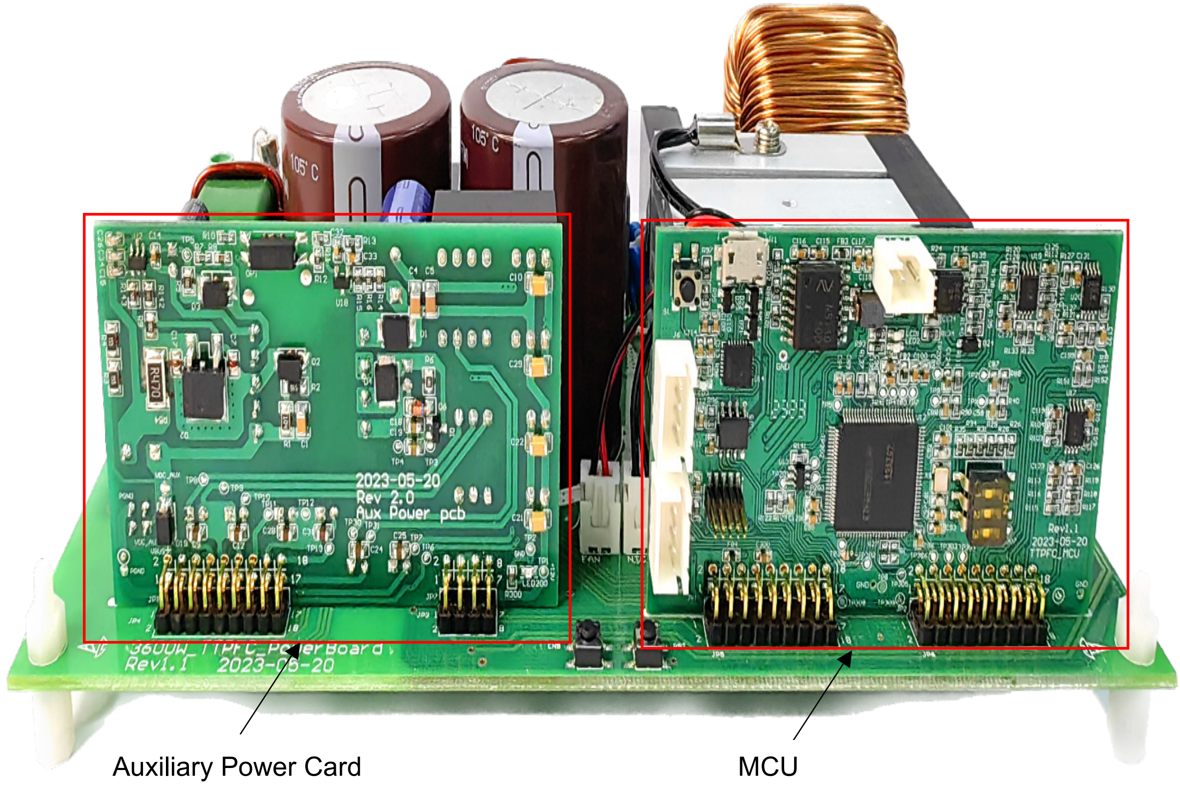

Figure 5. PFC Solution Hardware Prototype

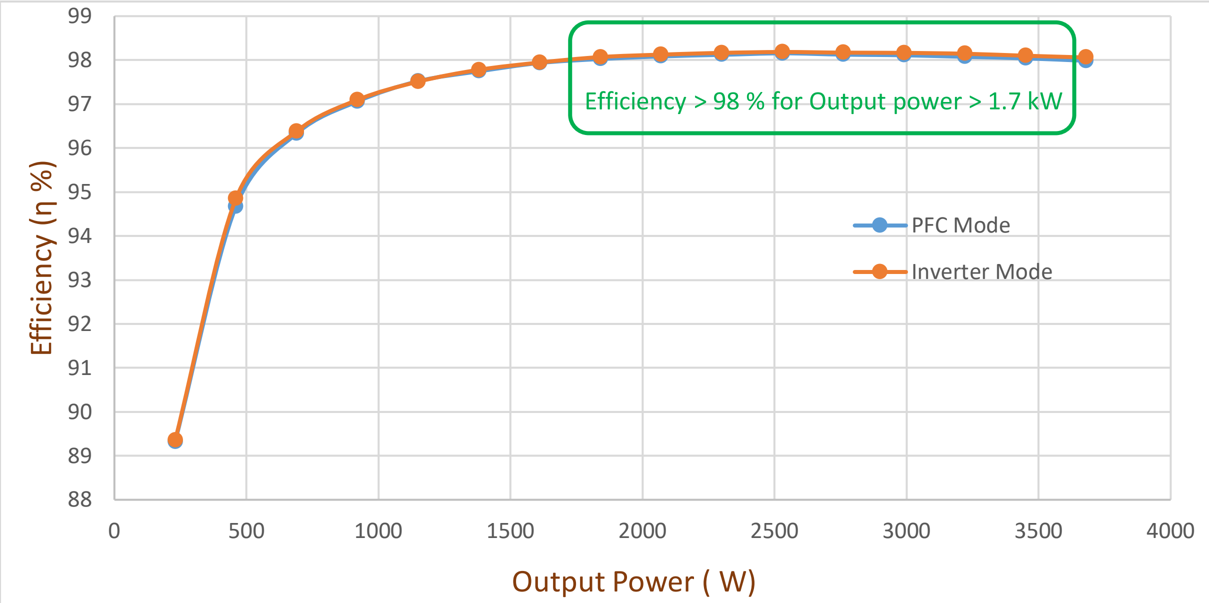

Figure 6. PFC Prototype Power Conversion Efficiency (PFC/Inverter Mode)

The current THD is less than 2% for load power greater than 1.8kW and less than 1.15% at full load condition (see Figure 7). Additionally, power factor is measured for varying load power and observed to be greater than 0.99 for majority of load conditions (see Figure 8).

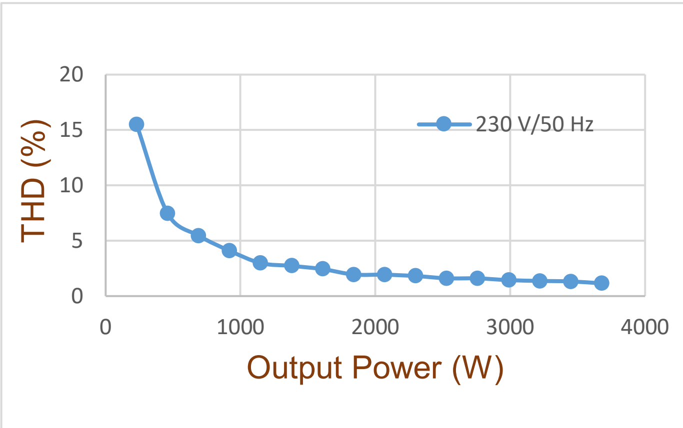

Figure 7. Current THD Against Load Power Variation

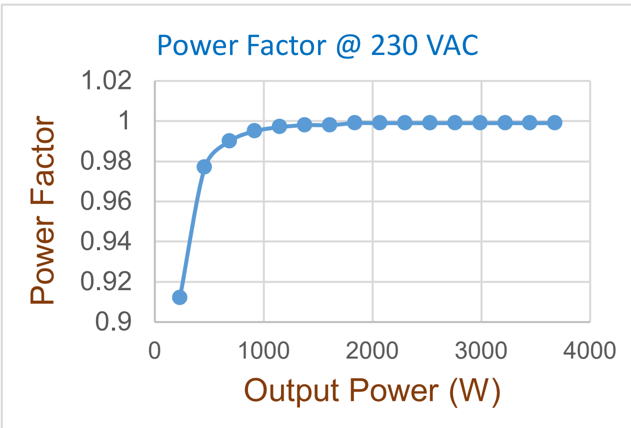

Figure 8. Power Factor for Varying Load Power

4.1.3 DC-DC Dual-Active Bridge (DAB) Converter

The system is based on Renesas' high-performance RA6T2 ARM core MCU and 650V GaN FETs to achieve bi-direction power conversion and state of the art DAB topology to realize bidirectional digital DC/DC power. conversion. The DAB topology with active full bridges on the primary and secondary side of transformer with the corresponding leakage inductance capable of seamless power transfer from primary to secondary side or other way around. The topology due to zero voltage switching (ZVS) operation ensures soft switching for majority of load conditions; thus, ensures high efficiency of operation. The Renesas DAB sub system equipped with RA6T2 MCU and 650V GaN FETs ensures high-efficient DC-DC power conversion with flexible digital control implementation.

System Benefits:

- High efficiency of operation with peak efficiency of 98.9%
- Bi-directional power flow capability
- High power density

Target Applications:

- **ESS/UPS**: Ensures seamless power transfer in bidirectional mode ideally suited for energy storage and UPS based Solution.
- **EV/HEV OBC**: The solution capable of providing power flow from HV source to LV source and vice versa with high frequency transformer isolation.
- **Power Conversion**: The DAB could be used in several industrial and residential application for high efficiency isolated DC/DC power conversion.

The Renesas DAB subsystem operates with the AC-DC PFC/Inverter subsystem and rated for the maximum output power of 3.6kW as shown in Table 3.

Table 3. DAB Subsystem Key Specifications

Parameter	Test Condition	Minimum	Typical	Maximum	Unit
Primary HVDC Voltage	-	370	400	420	V
Secondary LVDC Voltage	-	40	48	60	V
Output Power	-			3600	W
Primary Maximum Current	-			±9	A
Secondary Maximum Current	-			±75	A
Peak Efficiency	400VIN, 46VOUT, 920W load, without fan consumption		98.9		%

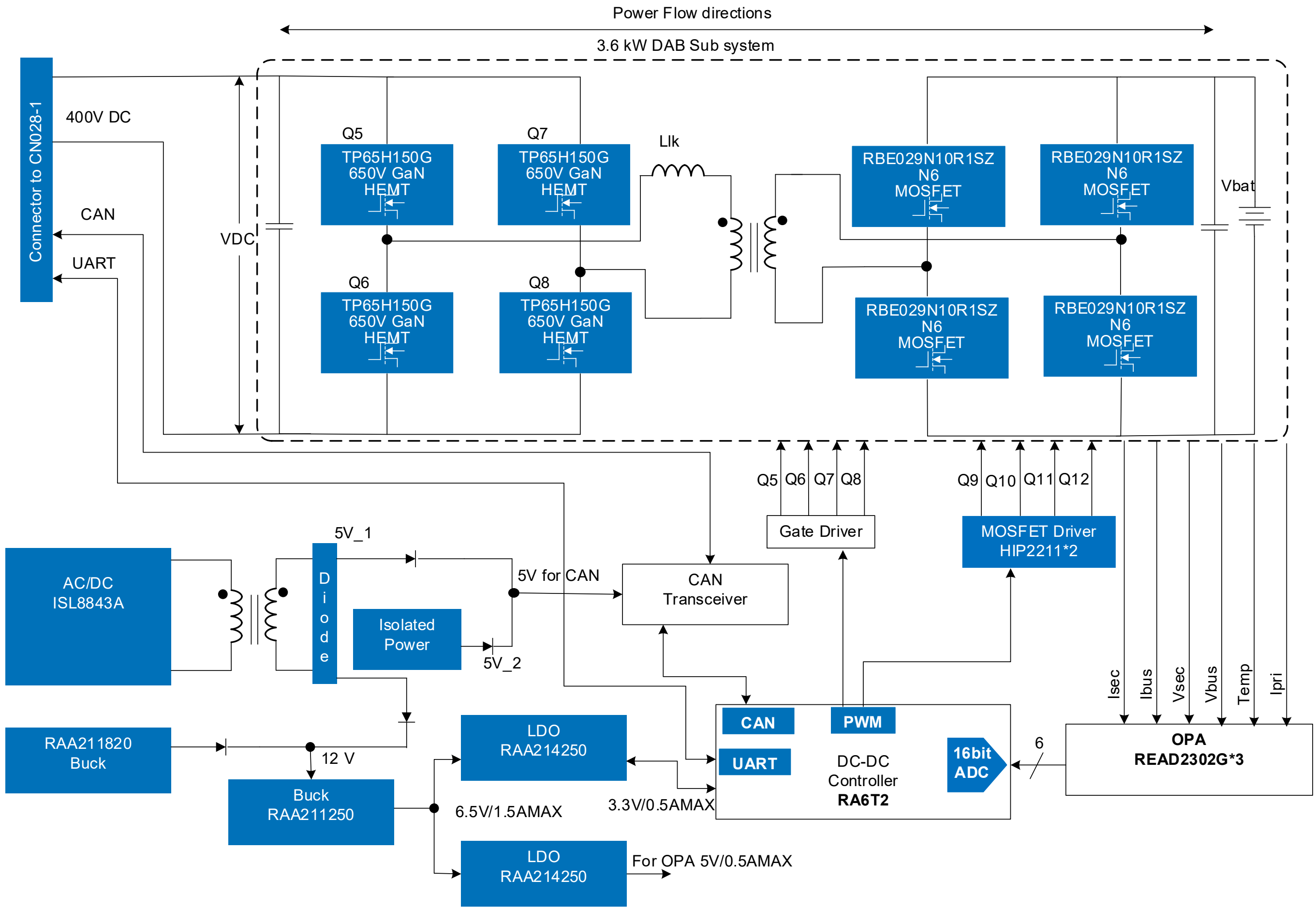

Figure 9. Block Diagram for 3.6kW DAB Subsystem

The Renesas DAB design solution involves a dedicated MCU, high efficiency auxiliary power supplies, analog comparators and operational amplifiers for sensing and control applications. The part numbers and their corresponding features are provided in Table 4.

Table 4. DAB Subsystem Key Components and Features

Device	Part Number	Key Features
MCU	R7FA6T2BD3CFP	240MHz Arm® Cortex®-M33 for motor and inverter control solutions.
Power	RAA211250	4.5V to 30V input voltage range and adjustable output voltage, 5A Buck.
	RAA211820	4.5V to 75V input voltage range and adjustable output voltage, 2A Buck.
	RAA214250	20V, 500mA linear regulator.
	ISL884XA	High-performance PWM controller.
	TP65H035G4WS	650V, 35mΩ gallium nitride (GaN) FET.
	RBE0xxN10R1	100V N-channel MOSFET REXFET-1 families
Analog	UPC277G2	Comparators utilizing CMOS process suitable for low voltage, low power consumption, and fast response.
	READ2302G	High-drivability and high slew rate operational amplifier.

The DAB power converter solution is evaluated in a hardware prototype as shown in Figure 10 and the peak power conversion efficiency is observed to be greater than 98.9% for the 400VIN, 46VOUT, 920W load, without forced air cooling (see Figure 11).

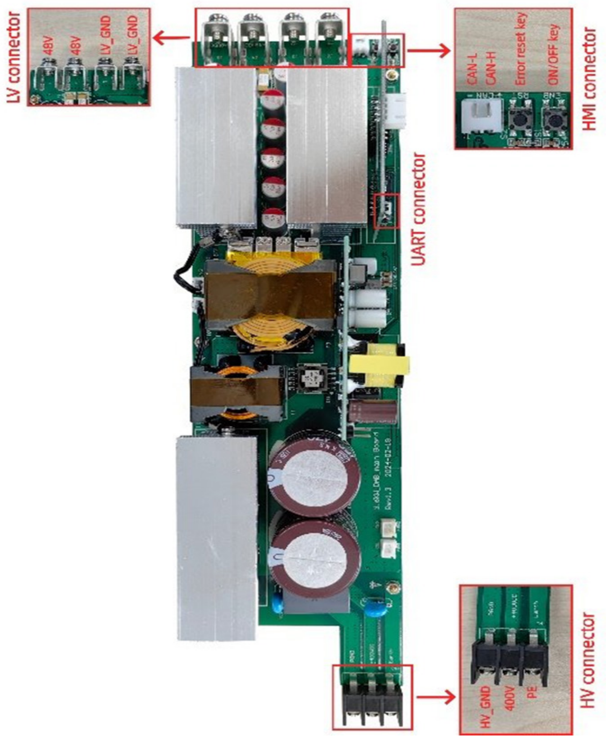

Figure 10. Hardware Prototype for 3.6kW DAB Subsystem

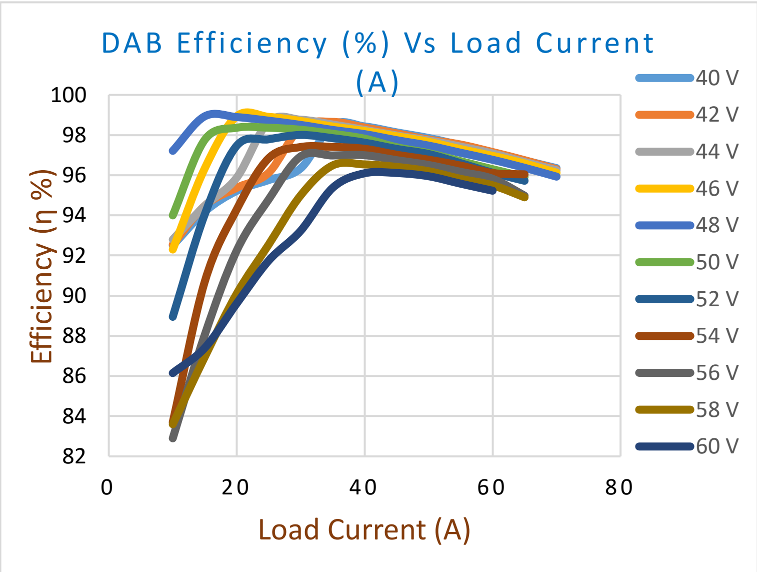

Figure 11. Power Conversion Efficiency vs Load Current for 3.6kW DAB Subsystem

4.2 MPPT Solar Battery Charger

4.2.1 System Overview

The Renesas charge controller solution consists of a PV module, Buck-Boost converter and 48V battery with MPPT functionality. Using the “Green Energy Source” of a solar to charge a battery is a very popular application. Usually, the characteristics of PV modules are nonlinear due to irradiance and temperature variations and have one maximum operating power point (MPP). Hence, it is important to operate the PV module at their maximum power conditions because PV power is relatively expensive due to the nonlinear characteristics. To collect the maximum available power from PV, the operating point needs to be tracked continuously using a MPPT algorithm by sensing the PV voltage and PV current. The buck boost DC-DC converter is used to match the load impedance to the panel equivalent impedance to collect the maximum power drawn from the PV panel. The MPPT algorithm is implemented by the Renesas RL78 core digital MCU. The MCU is powered by the ISL80410 linear low dropout regulator (LDO), and the ISL28413 quad op-amp is used as buffers and amplifies the various sensing and control signals between the buck-boost controller and the MCU. The main power components and controller used for the design are given in Table 5. The technical key specifications are shown in Table 6.

System Benefits:

- MPPT Algorithm maximizes power usage from Solar Panel
- Buck-Boost architecture charges the battery even when the solar panel’s voltage is below the battery voltage
- Programmable charge rates to support various modes such as fast-charge and trickle-charge
- Up to 60V input and adjustable output voltage of 0.8V to 60V
- Monitors battery status and protects battery from damage caused by over-charging.

Target Applications:

- Battery maintenance / trickle charge
- Charging at any remote location without AC power
- Dock Side charger for boating

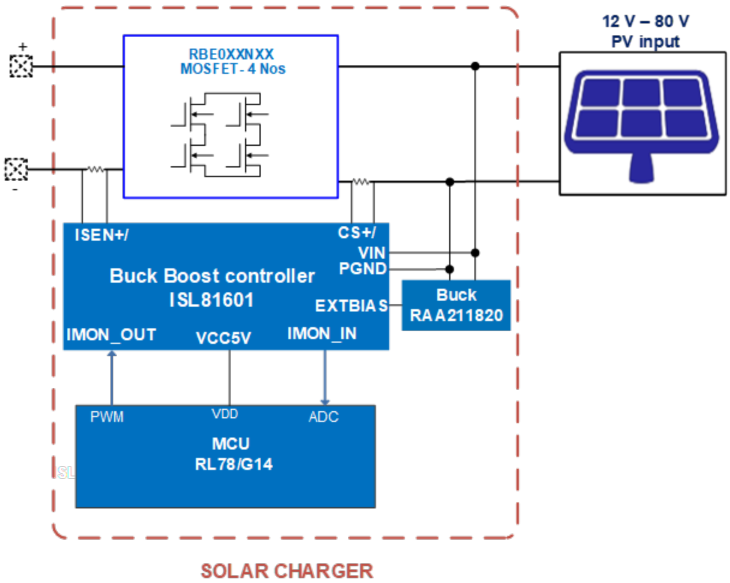

Figure 12. MPPT Solar Battery Charger Schematic

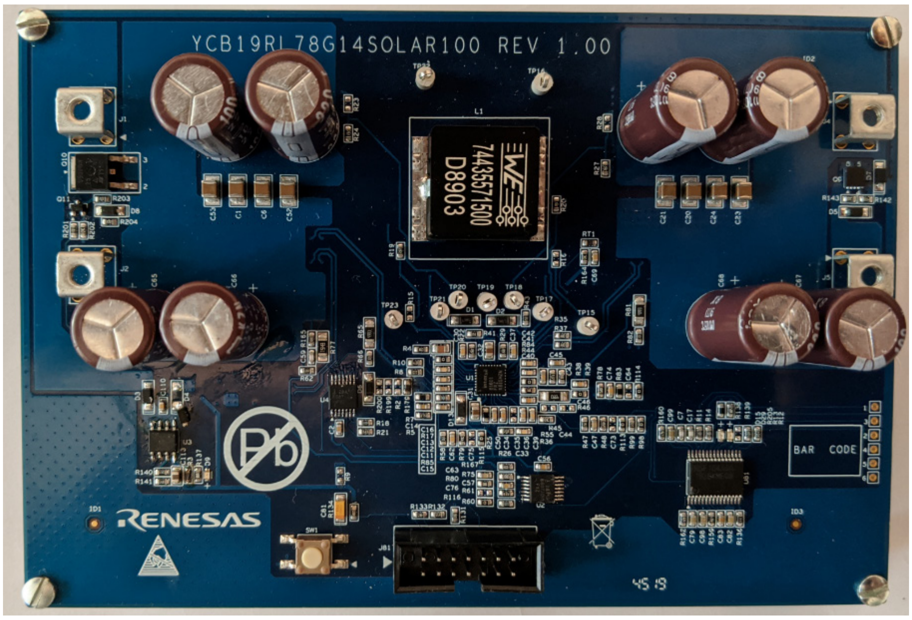

Figure 13. MPPT Solar Battery Charger Hardware Prototype

Table 5. MPPT Solar Battery Charger Key Components

Renesas Part Number	Description
RBE0xxN06R1 / RBE0xxN08R1 / RBE0xxN10R1	60V / 80V / 100V N-channel MOSFET REXFET-1 families
ISL28413	Quad general purpose micropower, RRIO operational amplifier
RAA211820	DC/DC Buck, 4.5 to 75VIN, integrated FETs
ISL81601 / ISL81801/ ISL81100	60V/80V/100V synchronous bi-directional buck-boost controller
R7F100GBG2DFP#AA0	RL78 Core MCU

Table 6. MPPT Solar Battery Charger Key Specifications

Parameters	Minimum	Typical	Maximum	Unit
Input PV Voltage Range	4.5	-	60	V
Output Voltage (adjustable)	0.8	-	60	-
Output Power	240	240	-	W
Battery Voltage	-	48	-	V
MPPT Efficiency	-	-	>99	%

4.3 Battery Management System (BMS)

The Battery Management System (BMS) is a crucial component in all battery powered devices, ensuring the safe and efficient operation of the battery pack. The three primary functions of a BMS include monitoring, protection, and cell balancing. The BMS continuously monitors the status of individual cells within the battery pack for voltage, temperature, and state of charge. It also prevents conditions such as overcharging/discharging, short circuits, and thermal runaway. It also ensures uniform charge distribution among cells to maximize battery life and performance. These functions can be done with discrete devices or a Battery Management Integrated Circuit (BMIC). Switches, such as MOSFET transistors, control the charging and discharging processes. They enable precise control over the current flow which is essential for protecting battery cells and maintaining efficiency. Next, a method for obtaining and processing accurate data for voltage, current, and temperature measurements is done with Analog-to-Digital converters. Finally, a stable power supply to the BMS and its components is critical to maintaining reliability and accuracy in monitoring and control.

The Renesas 14-cell Battery Front-end IC, RAA489204, is an essential component of any Battery Management System (BMS) that periodically scans battery status and the operating environment to optimize battery life and prevent catastrophic failures. It supports up to 14-cells battery pack, widely used in power tools, high-performance drones, professional laptops, and more. This IC can be connected in daisy chain fashion for the systems more than 14 cells and supports SPI and I^2C communication with external MCUs.

System Benefits:

- Renesas BMIC Firmware reduces the design time, validation process and produces shorter times to market
- Internal and external cell balancing provision gives scalable solution

Target Applications:

- E-bike, E-scooter, pedal-assist bicycle
- Power tool, vacuum cleaner
- Drone
- Battery backup system, Energy Storage System (ESS)

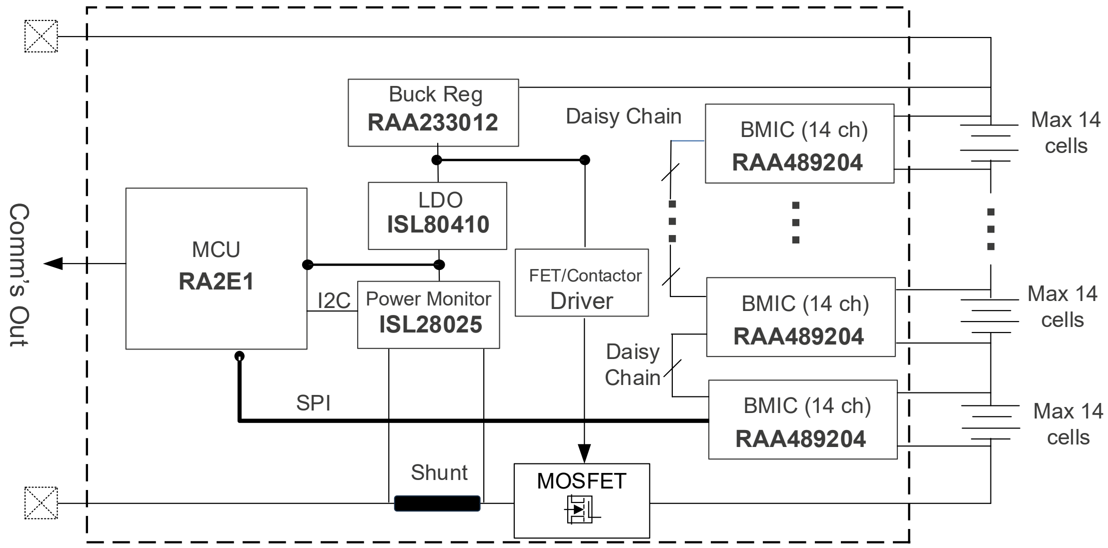

Figure 14. BMS Block Diagram

Table 7. Battery Management Key Components

Renesas Part number	Description
RA2E1	MCU
RAA233012	16V Input, 3A, step-down DC/DC converter
ISL80410	40V, low quiescent current, 150mA linear regulator
ISL28025	Precision digital power monitor with real-time alerts
RAA489204	14-cell battery front end IC
RBE0xxN0xR1	60V / 80V MOSFET REXFET-1 families

Table 8. 16-Cell Battery Front-End IC Key Specifications

Parameters	Typical	Unit
Number of Cells	14	
Voltage	62	V
Vcell Accuracy	±10	mV
ADC Resolution	16	bits
Communications	SPI, I^2C	
GPIO	4	

5. Conclusions

Renesas is the ideal design partner for systems and applications that require comprehensive expertise in power management, embedded processing, connectivity solutions, analog circuitry, and sensor integration.

Our diverse power portfolio includes DC-DC converters, AC-DC converters, and discrete power options such as silicon MOSFETs and GaN HEMT, ensuring high efficiency and reliability tailored to diverse power requirements. This makes Renesas an ideal partner for AC-DC PFC, DAB DC-DC converter, MPPT charger and Battery Management System designs across any application.

Renesas also offers extensive technical support and development tools, facilitating seamless integration of systems across a broad range of industries

6. References

References listed below are the latest published version, unless noted otherwise.

iW9108 – Renesas product webpage

iW676 – Renesas product webpage

iW780 – Renesas product webpage

R2A20132SP – Renesas product webpage

TP65H150G4LSG – Renesas product webpage

TP65H070G4PS – Renesas product webpage

RAA489400 – Renesas product webpage

R9A02G015 – Renesas product webpage

MOSFET REXFET-1 Middle Voltage Product Technology – Renesas application note

RAJ240100 – Renesas product webpage

7. Revision History

Revision	Date	Description
1.01	May 7, 2025	▪ Minor updates for DAB sub-system in section 4.1.3 ▪ Updated BMS IC part number update to support daisy-chain configuration in section 4.3.
1.00	Apr 17, 2025	Initial release.

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Koto-ku, Tokyo 135-0061, Japan
www.renesas.com

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