Power Quality Enhancement in Critical Infrastructure Using an AC/DC Three-Level Vienna Rectifier Under Non-Sinusoidal Input Conditions

Ravichandran C, Senior Staff System Architect, Power Products, Renesas Electronics Corporation

Marco Ruggeri, Senior Manager, Power System Marketing & Architecture, Renesas Electronics Corporation

Abstract

Data centers have become essential to almost every part of the global economy with the continuing rise in computing demands. Modern data centers, consisting of rows of equipment racks for storing, processing, and sharing data, require front-end AC/DC converters that are reliable, operate at unity power factor, offer low input current THD, and achieve high efficiency. The Vienna rectifier is a grid-connected, nongenerative three-level PWM boost converter topology that enables reduced semiconductor stress and improved power quality compared to conventional two-level rectifiers. Owing to these advantages, it is widely used in telecommunication power systems, data centers, wind energy systems, and other high-power applications.

This solution presents the design and control implementation of a 3.6kW rectifier aimed at improving input current quality and DC bus voltage regulation. The design employs a uni-directional three-level AC/DC converter based on high-efficiency wide-bandgap Renesas GaN devices. A SPWM control strategy, formulated in the d–q reference frame, ensures simple and effective neutral-point voltage balancing. In

addition, the rectifier integrates power-quality enhancement features to maintain stable energy conversion under dynamic operating conditions. This reference design demonstrates an efficiency > 98%, a power factor > 0.99, and total harmonic distortion < 3%.

Features

- 3.6 kW to 30kW three-phase Vienna rectifier intended to replace conventional AC/DC front end PFC converters utilizing Renesas bi-directional GaN power stages to improve efficiency and switching performance
- AC input supporting 340V to 460V (L–L, rms) at 47 Hz to 63 Hz, allowing operation across typical three-phase mains
- 800V split-DC output (+400V, 0, –400V) with tight regulation
- Converter operates at 50 kHz to 100 kHz switching frequency to reduce magnetic size and increase power density
- RX26T microcontroller manages the voltage and current loops, performing stable operation under grid disturbances
- Maintains <5% THD on the AC input current, supporting compliance with IEC 61000-3-2/3 standards
- The input stage incorporates common-mode and differential-mode EMI filters to satisfy EMC limits
- The PCB layout follows proper creepage, clearance, current handling, mechanical stability, and noise immunity to ensure reliable operation at high power

Design Challenges

- **Performance Optimization of GaN devices:** To achieve high switching frequency and power density, while mitigating dv/dt-induced EMI, gate-drive complexity and parasitic
- **Robust grid synchronization**: Using a high-precision PLL to maintain stable unity power factor and low input current THD under distorted or weak grid conditions
- **Implementation of active neutral-point voltage balancing control:** Through optimized PWM modulation to ensure stable three-level operation
- **DC-link capacitor design:** Emphasizing low ESR, high ripple current capability, and long lifetime suitable for data center operation
- **Advanced thermal management**: To handle concentrated heat flux and maintain high efficiency and reliability in high-density power shelves

Advantages for Target Applications

Three-phase uni-directional, three-level Vienna rectifier has many advantages in comparison with the traditional two-level and three-level AC/DC PFC converters:

- High power density
- Lower switching losses
- Low voltage stress
- Improved power quality: Low total harmonic distortion (THD) of current and near unity power factor
- Fewer switching devices provides improved reliability at lower cost

Hence, the circuit is widely used in:

- Telecommunications power systems
- EV charging systems, aircraft and medium voltage drive systems
- Data center front end converters where high power density and low device voltage stress are required
- High-power battery energy storage systems (BESS)
- Power electronics for aircraft AC/DC systems
- Railway and traction power supplies
- Front-end rectifier for three-phase grid interface in hybrid energy storage systems

Vienna Rectifier for Data Center Applications

In the era of big data, the server power supply industry is experiencing rapid growth. Advances in AI, 5G and cloud technologies are driving large-scale construction of server rooms and data centers, resulting in a significant increase in demand for high-efficiency power conversion solutions. In data center front end power systems, the Vienna rectifier is typically implemented as a three-phase, three-level PWM boost AC/DC converter (shown in *figure 1*). It consists of an input EMI filter, three-phase boost inductors, a diode-clamped Vienna rectifier stage with one active switch per phase and a split DC-link capacitor forming the midpoint.

This architecture enables unity power factor operation, low input current THD, reduced semiconductor voltage stress and high efficiency, making it well-suited for high-reliability and high-density data center power shelves and rectifier modules.

GaN-based data center front end Vienna rectifiers feature:

- High efficiency
- High switching frequency capability
- High power density and compact magnetics
- Reduced switching losses
- Improved light load performance
- Enhanced overall system reliability

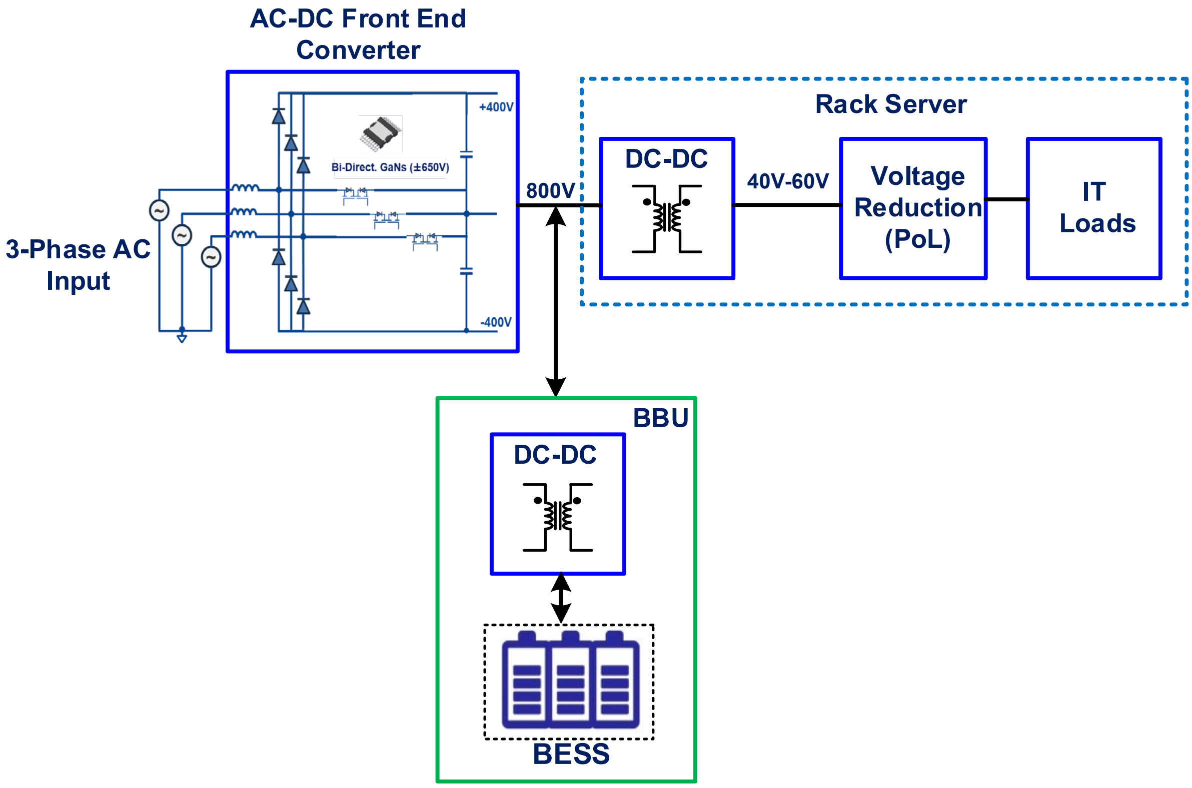


Figure 1 Vienna rectifier for data center applications

Proposed Vienna Rectifier Architecture

A server power supply typically performs AC/DC conversion, followed by isolated DC/DC stages to deliver regulated DC outputs. This architecture focuses on the AC/DC front-end stage, selecting the Vienna rectifier topology due to its high efficiency, low harmonic distortion and suitability for modern high-power server applications.

Figure 2 shows the block diagram of the three-phase Vienna rectifier proposed in this design along with the voltage and current sensing being used. It is a uni-directional, three-phase, three-level PFC rectifier operating as a three-phase boost converter. Its primary objective is to draw sinusoidal input currents that are in phase with the AC grid voltages, thereby achieving a high-power factor and reduced harmonic distortion. This is accomplished using a coordinated control system implemented by digital microcontroller along with passive and active power-stages.

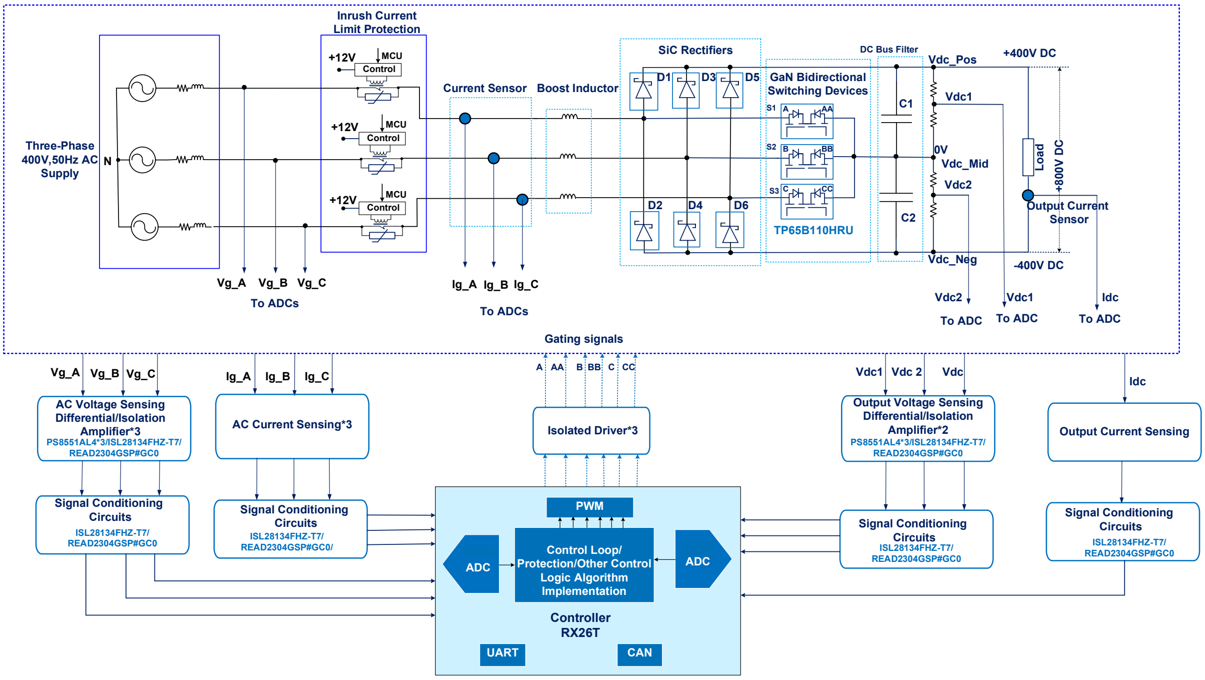


Figure 2 Block diagram of three-phase Vienna rectifier

The design is rated for a 3.6 kW output power and operates over an input voltage range of 340V to 460V (L-L, rms) at 50/60 Hz. The converter employs Renesas bi-directional GaN switching devices, TP65B110HRU, configured in a common-drain configuration to achieve high power density and high efficiency. The use of GaN devices enables reduced switching losses and improved thermal performance, resulting in a compact and lightweight design. The control scheme is implemented using the RX26T Renesas digital microcontroller, which performs PFC operation, harmonic compensation and overall system regulation. *Table 1* summarizes the Renesas key components used in the design.

Table 1 Vienna Rectifier Key Components (Renesas Parts)

Renesas Part Number	Description
TP65B110HRU	650V, 25A,140 mΩ B-directional GaN
PS8551AL4-AX	Isolation amplifier for voltage/current sensing
RAA2230214GSP#HA1	High-voltage buck regulator (700V max input)
ISL28134FHZ-T7	Zero-drift amplifier 1 circuit rail-to-rail
READ2304GSN#GC0 / ISL28214FUZ	Dual op-amp for signal conditioning
RAA2142504GSP#HA0	Adjustable regulator for low-voltage rails (3.3V,5 V, 7V & 12 V)
R5F526TFCDFP	32-bit, 120 MHz, 512KB RX26T MCU

Description of Topology and Operating Modes (Common Drain Configuration)

The main circuit topology of the Vienna rectifier is shown in *Figure 3*, consisting of a main diode bridge and three phase-to-neutral bi-directional switches. In terms of size and cost, it is observed that Vienna rectifier has fewer topology components, such as rectifiers, inductors, capacitors and bi-directional GaN switches. The three bi-directional GaN switching units are controlled to ensure sinusoidal input current and steady DC-link voltage. The Vdc1 and Vdc2 are the voltage value of capacitors *C*1 and *C*2, respectively.

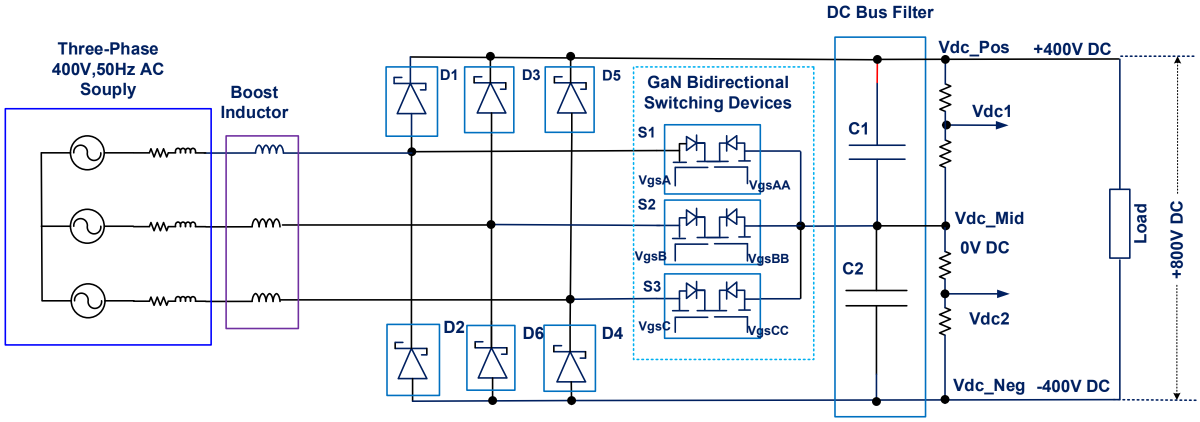
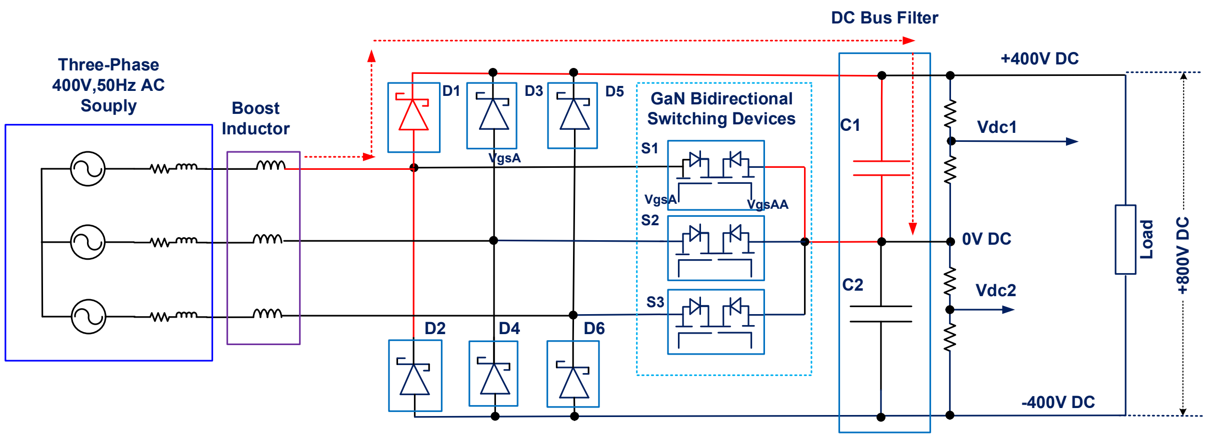


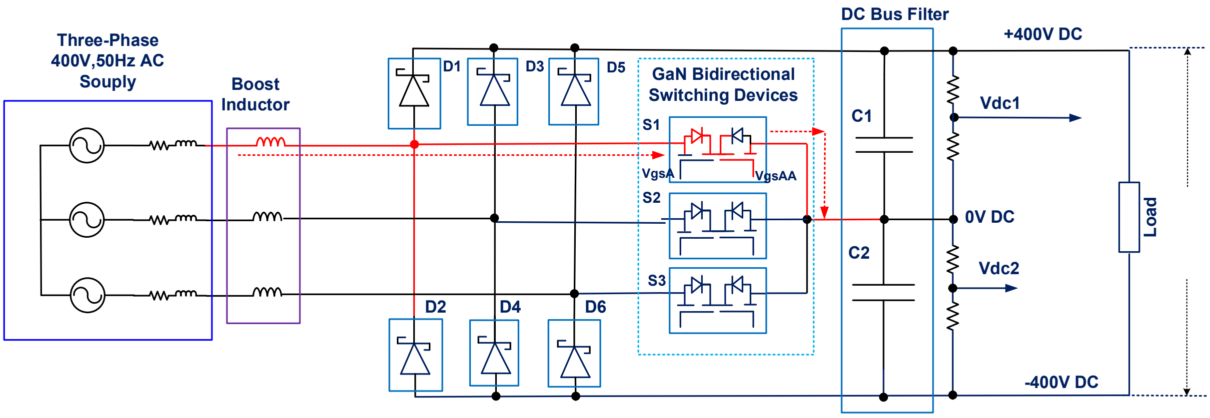
Figure 3 Circuit topology of Vienna Rectifier Common drain configuration

Vienna Rectifier Operating modes (Positive Half cycle)

Figure 4 shows the current path and operating modes of Vienna rectifier (phase A) when the upper switch S1 (AA) is in operation. Mode 1 and Mode 2 illustrates when the grid voltage is positive.



Mode 1 (Diode Conduction)

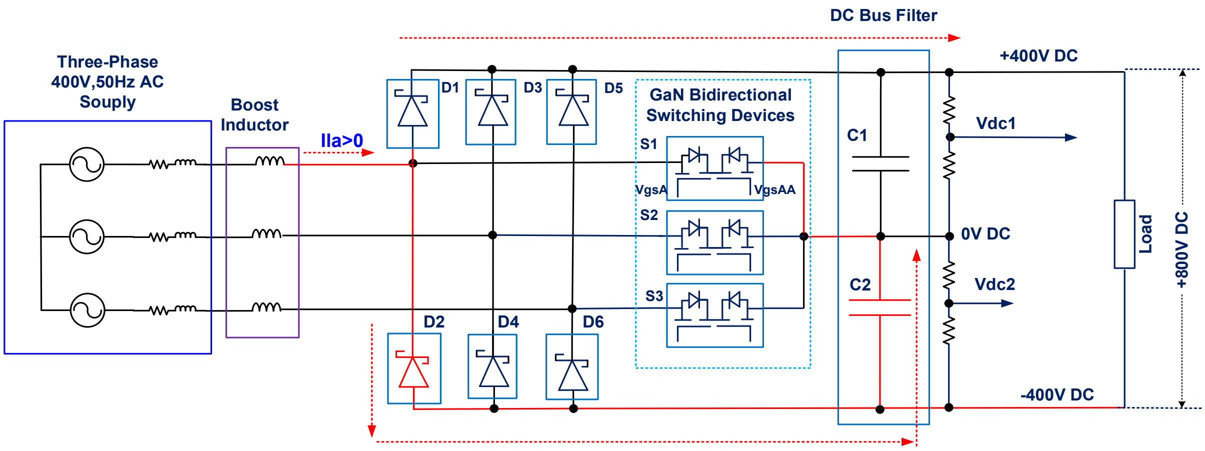


Mode 2 (Switch S1 (AA) Conduction)

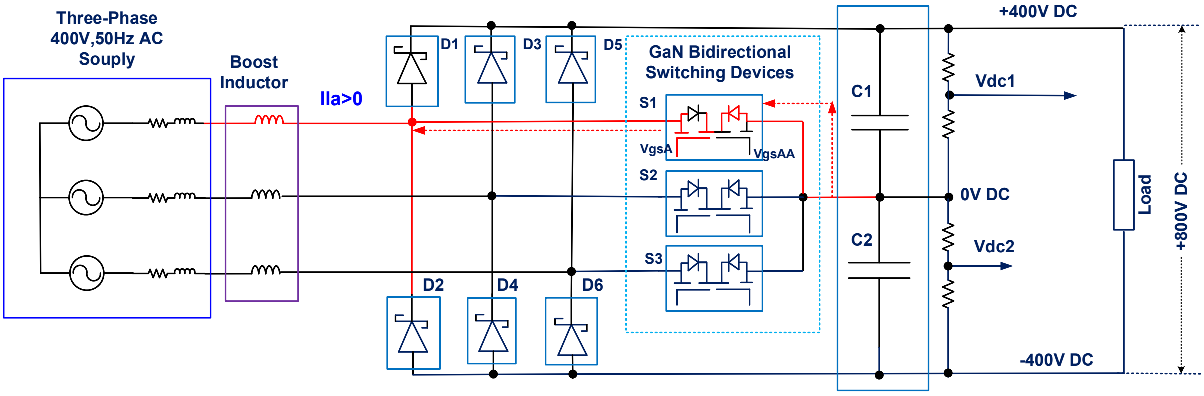
Figure 4 Operating Modes During Positive Half Cycle of AC Input Voltage when the Upper switch is in operation

Vienna Rectifier Operating modes when the lower switch is in operation (Negative Half cycle)

Figure 5 shows the current path and operating modes of the Vienna rectifier (phase A) when the lower switch S1 (A) is in operation. Mode 2 and Mode 3 illustrate when the grid voltage is negative. *Figure 6* shows the switching waveform representing the operating modes in common drain configuration.



Mode 3 (Diode Conduction)



Mode 4 (Switch S1 (A) Conduction)

Figure 5 Operating modes during negative cycle of AC input voltage when the upper switch is in operation

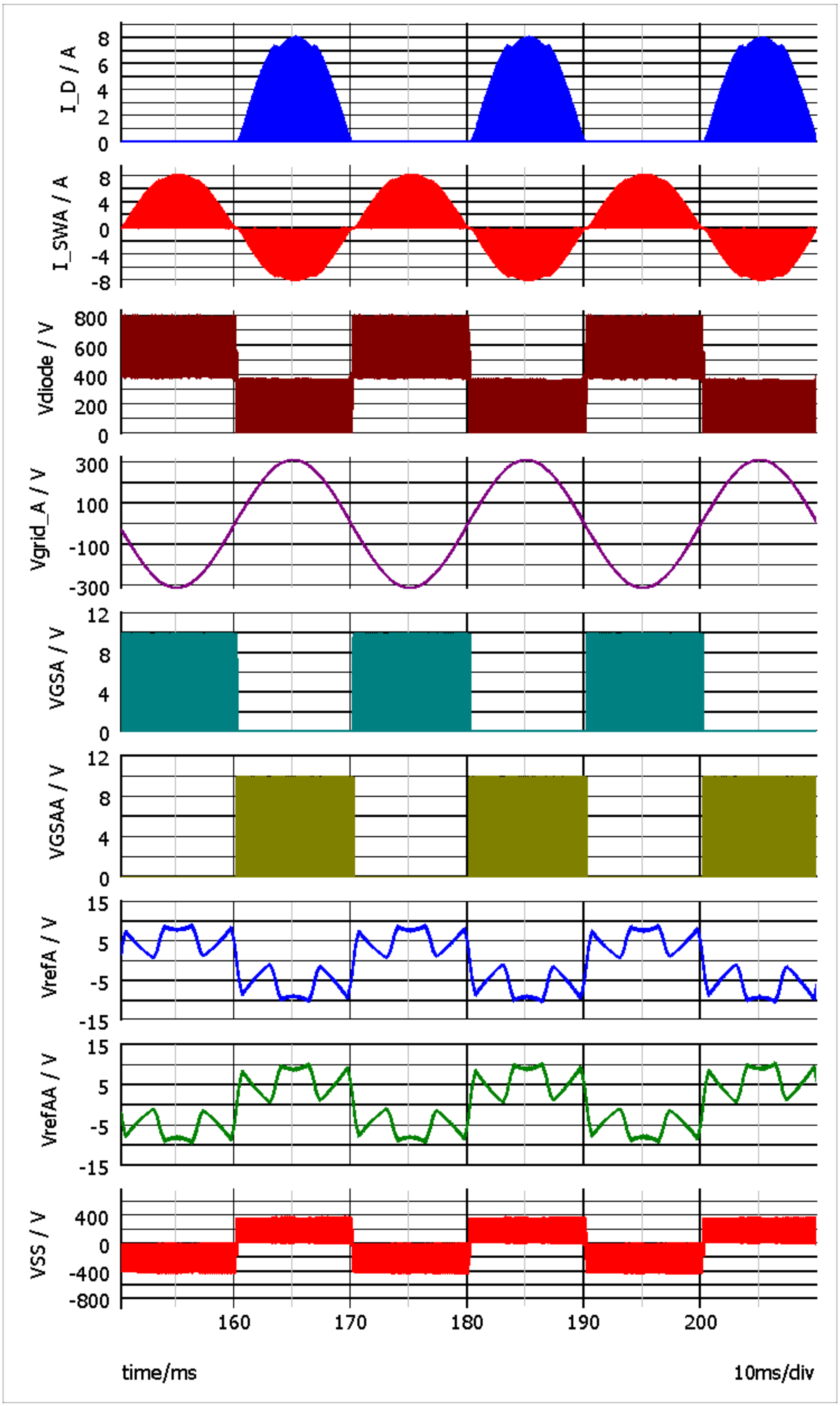


Figure 6 Switching Waveform Representing the Operating Modes in Common Drain Configuration

Functional Description of Components

(i) Sensing and Signal Conditioning Circuits

- Voltage sensor PS8551AL4-AX for isolation or ISL28134FHZ-T7/READ2304GSN#GC0 for differential sensing to measure three-phase input voltages and DC bus voltages for power factor correction and DC bus voltage regulation
- Current sensors used to measure three-phase input currents for power factor correction and current shaping and DC output current sensing
- ISL28134FHZ-T7/READ2304GSN#GC0 for signal conditioning circuit

(ii) Auxiliary Power Supply:

- High-voltage buck regulator RAA2230214GSP#HA1 configured as Flybuck topology and adjustable regulator RAA2142504GSP#HA0 provides low-voltage rails (3.3V, 5V, 7V and 12V) for sensing, control and gate drive circuits

(iii) Gate Driver Circuits

- Provide proper switching and gating signals to Bi-directional GaN device TP65B110HRU
- Ensure safe turn-on/turn-off transitions with protection features (UVLO, desat)

(iv) EMI Filter

- Suppresses conducted emissions to comply with international regulatory standards
- Prevents high-frequency switching noise generated by the rectifier from propagating back into the AC supply network

(v) Surge / Inrush Protection

- Limits inrush current during startup, typically using a resistor in series with a relay
- Protects the rectifier components, input fuse and upstream supply from current surges and potential damage

(vi) PFC Boost Inductor

- Key energy storage element in the Vienna rectifier's boost-type PFC stage
- Ensures sinusoidal input current in phase with the AC voltage and maintain nearly unity power factor
- Reduces current ripple through the rectifier and DC link capacitors

(vii) DC Bus Filter

- Filters out the high-frequency ripple caused by switching actions
- Provides a stable DC link voltage after rectification and PFC operation
- Ensures a constant DC supply for downstream converters

(viii) SiC Diode

- A fast recovery (practically zero reverse recovery charge) 1200V SiC diode is used in the boost leg and freewheeling paths, where high efficiency and low switching losses are required

(ix) GaN BDS

Renesas GaN BDS TP65B110HRU (650V,110 mΩ) connected in common drain configuration, replaces conventional Si/SiC switches to achieve:

- Higher power density
- Higher efficiency (>98%)
- Higher switching frequency (50 to150 kHz)
- Reduced magnetic size

Common Drain Configuration

- Blocks voltage in both directions
- Allows current flow in both directions
- Eliminates reverse recovery issues
- Enables higher frequency operation

(x) MCU Interface

- RX26T Renesas MCU executes control algorithm
- Ensures sinusoidal input current in phase with grid voltage
- Maintains stable output DC voltage
- Balances the split DC bus capacitor voltages

Control Scheme Design and Modulation Strategy

Similar to boost PFC rectifiers, a conventional average current mode control strategy, as shown in *Figure 7*, is employed in the Vienna rectifier. The control scheme consists of an outer voltage loop for DC output voltage regulation and an inner current loop for tracking the phase current reference derived from the input phase voltage. This control approach offers advantages such as simplicity and reduced controller hardware resource requirements. However, the reference current extraction and tracking performance are not optimal and residual distortion persists in the input supply current

The block diagram for synchronous reference frame theory using Clarks and Parks transformation is represented in *Figure 8*. In synchronous reference frame theory, the three phase currents or voltages are converted to its equivalent two dimensions. i.e. *dq* axis transformation. By considering advantages of Vienna rectifier, the generation of control pulses for Vienna rectifier with GaN switches has been carried out using SRF control theory:

- Simple PI control algorithm
- Good transient response
- Perform zero steady error
- Efficient midpoint voltage balancing control
- Reduced harmonic current distortion

.

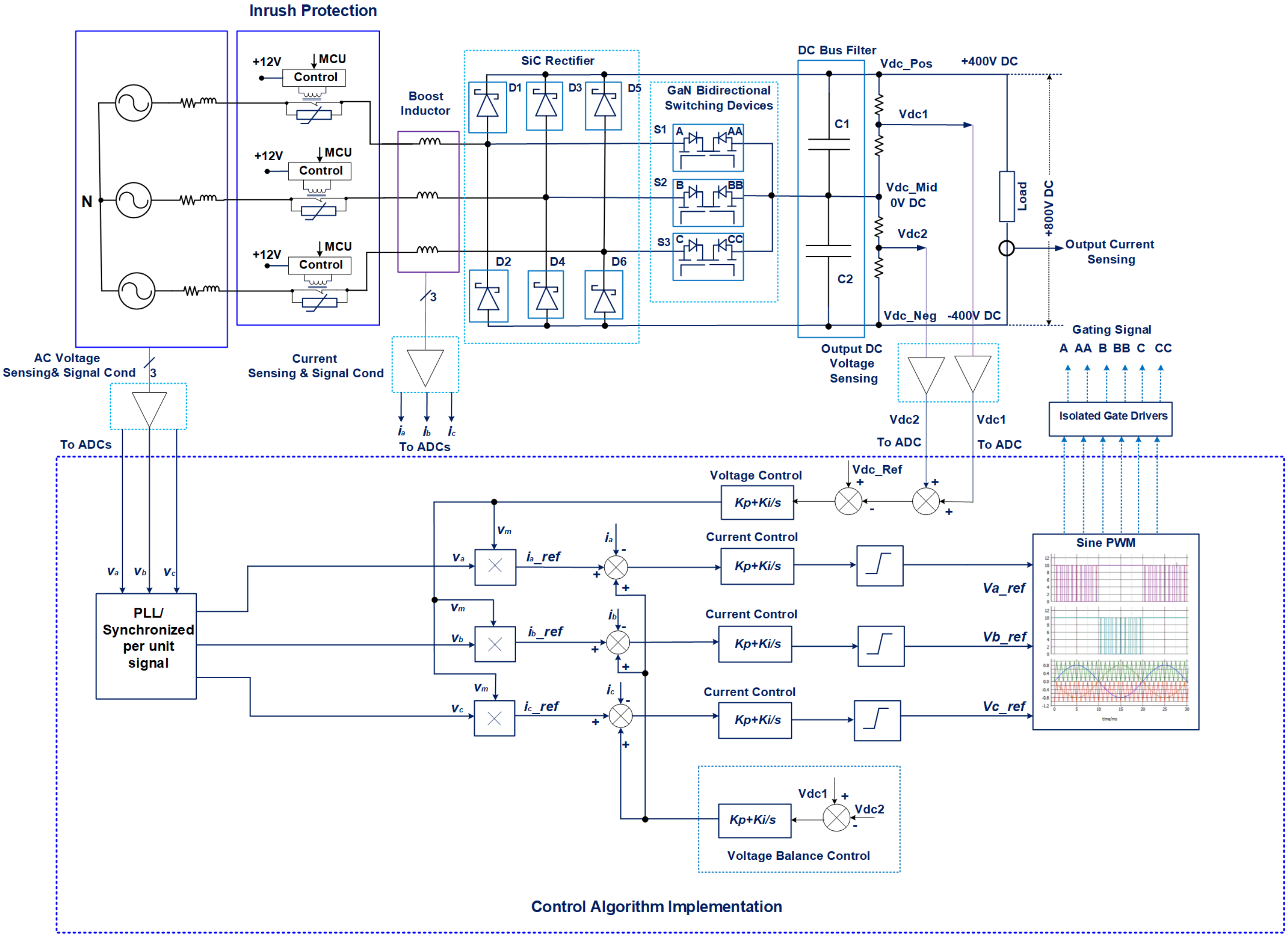


Figure 7 Average Current Mode Control Strategy

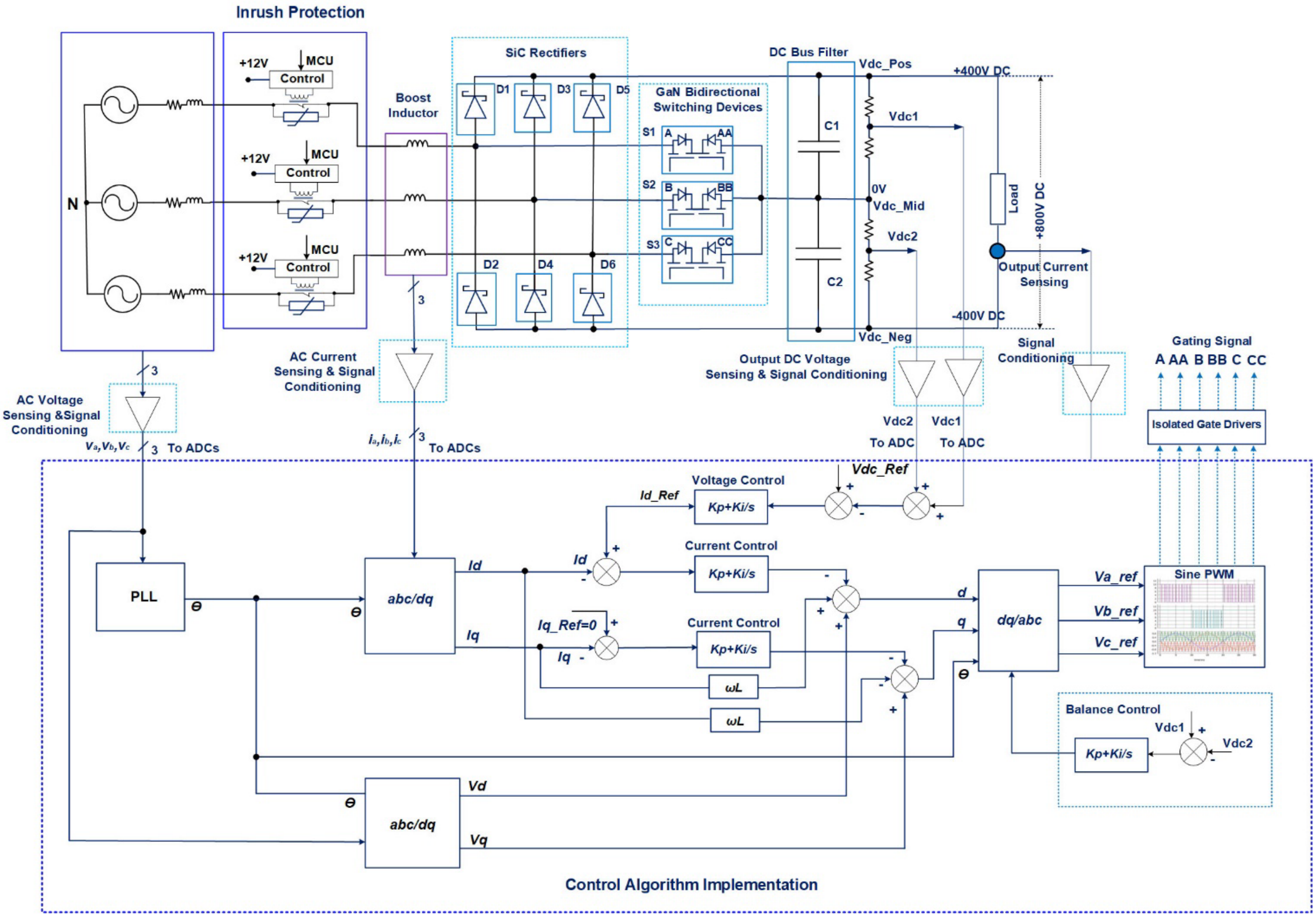


Figure 8 DQ Reference Frame Control Strategy

PWM Strategy

In the Vienna rectifier, both space vector pulse-width modulation (SVPWM) and properly implemented carrier-based modulation can achieve optimal switching performance. However, SVPWM involves higher computational complexity and longer processing time, making it less suitable for very high switching frequency applications.

In contrast, carrier-based modulation offers simpler implementation and faster computational speed. Therefore, the carrier-based modulation method shown in *Figures 9* and *10* is adopted in this control strategy.

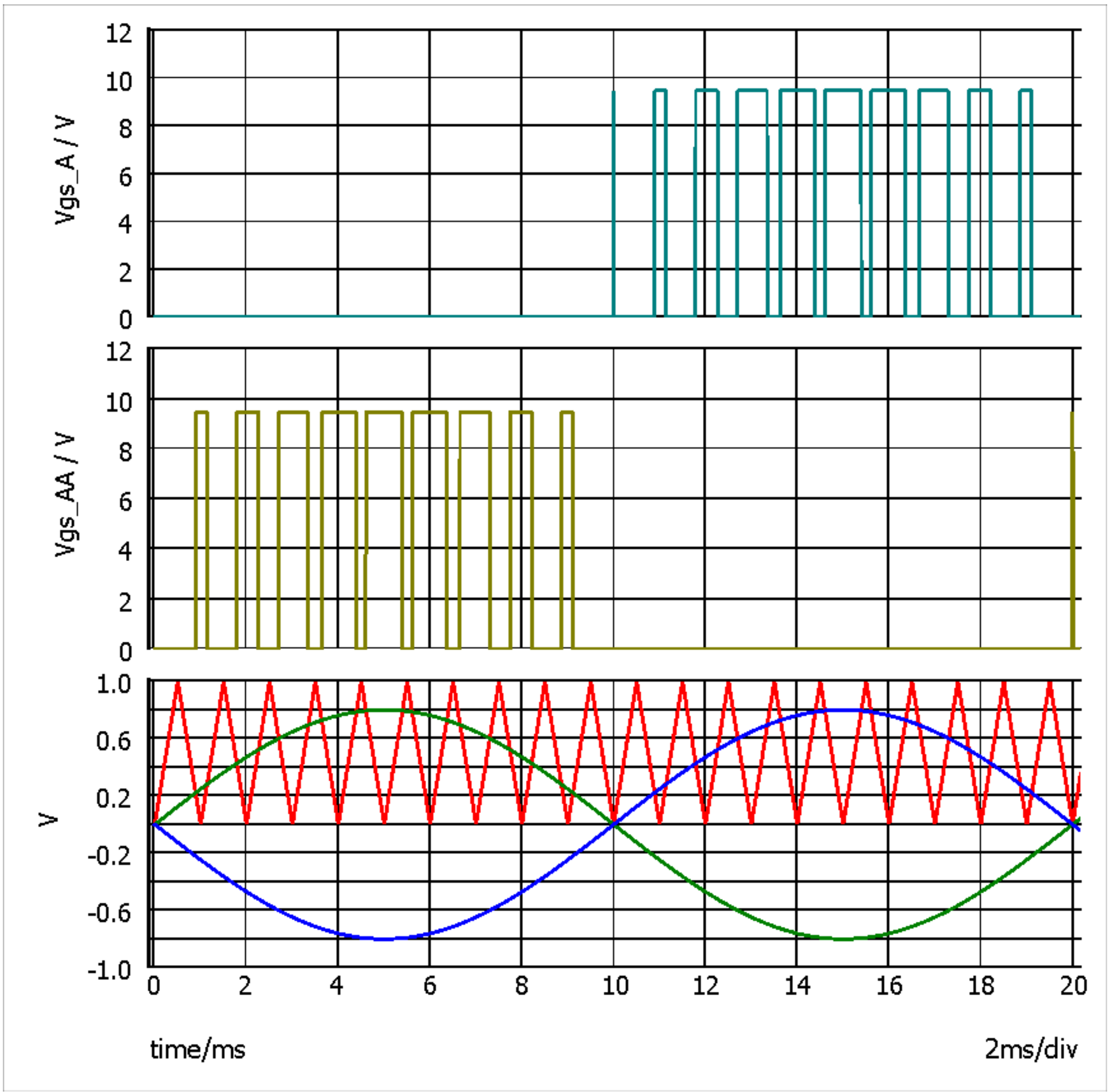


Figure 9 Carrier-based modulation for phase A switch representation (diode rectification of GaN switches in non-PWM period during alternate line cycle)

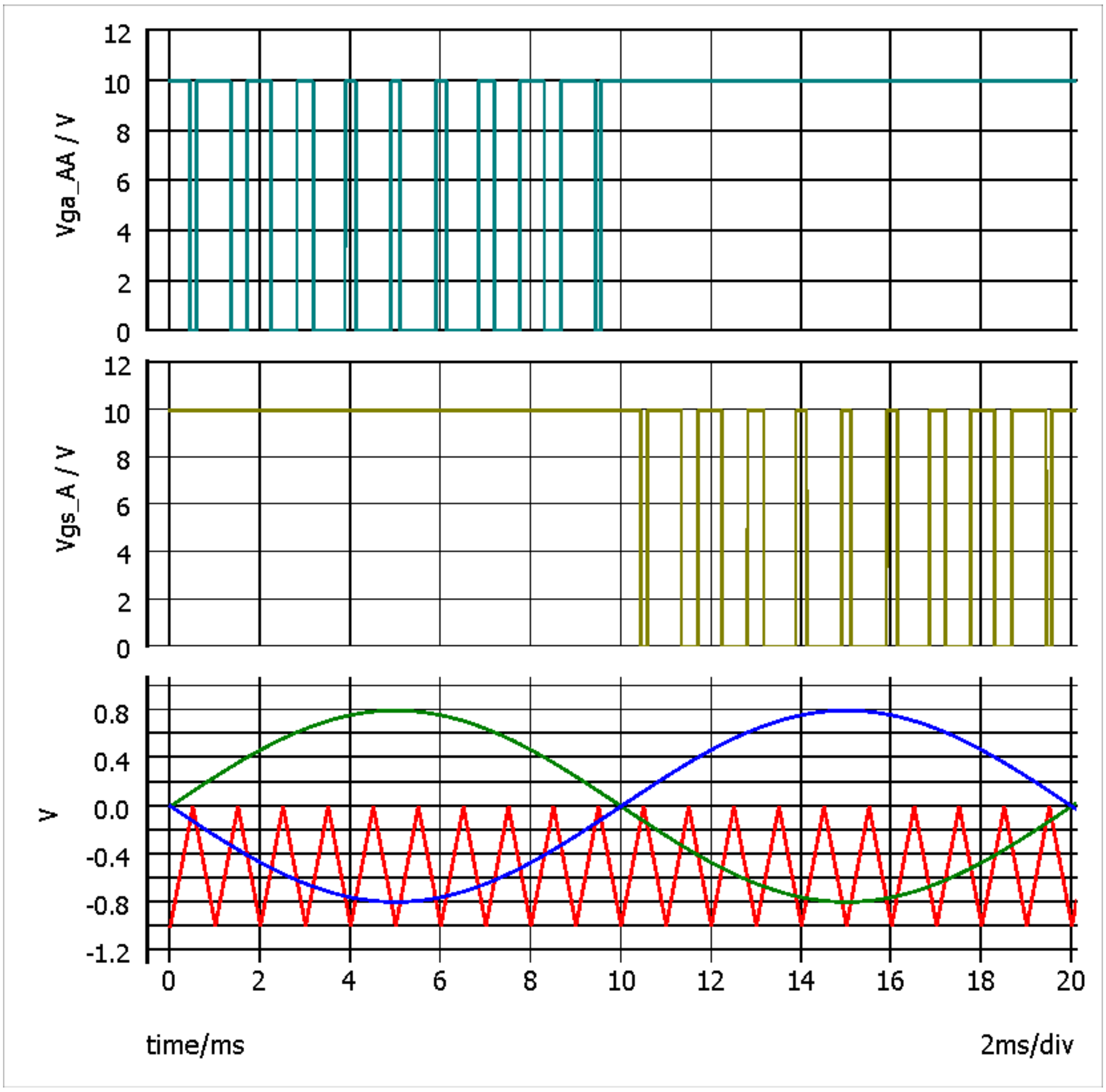


Figure 10 Carrier-based modulation for Phase A switch representation (synchronous rectification of GaN switches in non-PWM period during alternate line cycle)

Modelling & Experimental Analysis

The performance of proposed architectures was verified with both simulation and experimental proto model. The technical key specifications/parameters used for simulation and experimental analysis are listed in *Table 2*. The system is modelled considering topology, firmware architecture and control system aspects, using the real-time Simplis implementation tools. SPICE models including Renesas bi-directional GaN, drivers and controllers are utilized for simulation analysis. The proposed system is designed to operate with grid voltages of three-phase, four-wire 340V to 460V line-to-line (rms), 47 Hz to 63 Hz frequency.

Renesas has introduced a complete system solution for an innovative 3.6 kW to 30 kW power level based on GaN BDS devices with various R_{ds}(on) levels and intelligent digital control algorithm using RX26T MCUs. The initial 3.6 kW prototype of the proposed solution achieves a peak efficiency of 98.25% at 50 kHz, under 360V line-to-line (rms) input and 2.5 kW load conditions, as shown in *Figure 11*. *Figure 12* shows the captured results of three phase input currents and output DC voltage at AC input of 360V and 3.6kW load conditions. Similarly, *Figure 13* shows the captured results of the GaN BDS source-to-source voltage with supply currents, supply voltage and output DC voltage. *Figure 14* shows the measured power factor at various power levels.

These results represent preliminary measurements for the present 3.6kW design. Further optimization and high-power level testing are currently in progress, focussing on evaluating BDS devices with different R_{ds}(on) levels and fine tuning the control loop gains to improve overall efficiency, thermal performance and dynamic response.

Table 2 Technical Key Specifications

S. No	Parameters	Minimum	Typical	Maximum	Units
1	Input Voltage (line-line rms)	340	400	460	V
2	Input Current	4.52	5.2	6.11	A
3	Output Power	0	3.6	4	kW
4	Output Voltage	700	800	900	V
5	Output Current			5.4	A
6	Supply Frequency	47	50	63	Hz
7	Switching Frequency	50	70	100	kHz
8	Power Factor	0.96		0.99	—
9	Total Harmonic Distortion		3	5	%
10	Peak to Peak Ripple (% of output voltage)	2		3	%
11	Efficiency	97		98.5	%

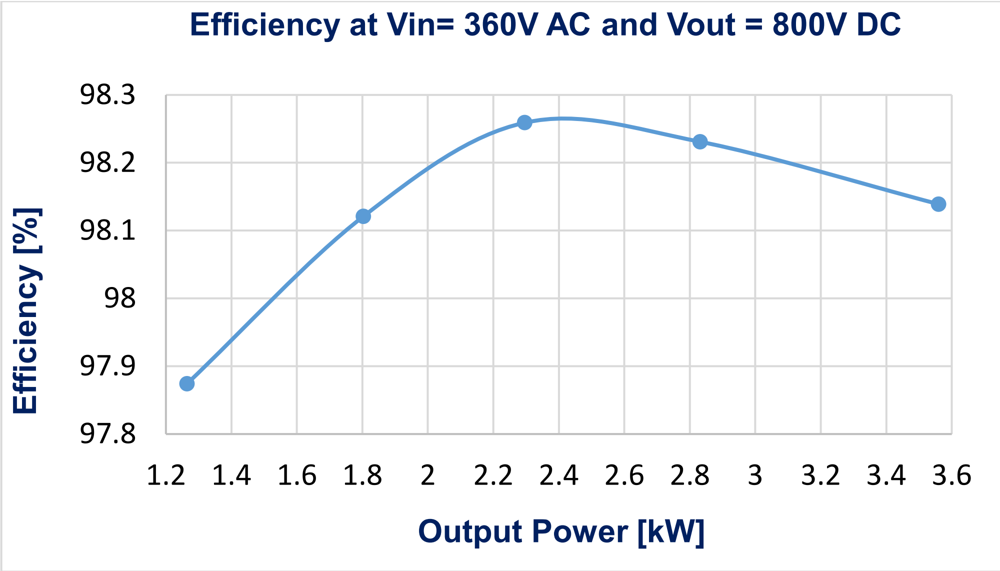


Figure 11 Measured efficiency results at various power levels (under Vin=360V, Vout=800V and Fsw=50kHz)

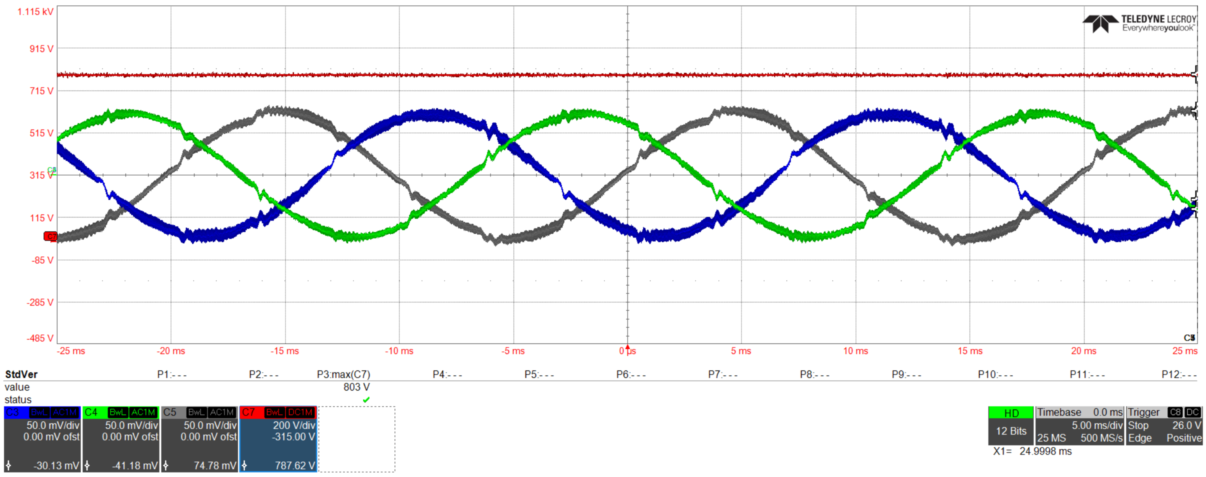


Figure 12 Captured results of three-phase input currents (blue, green and gray trace) and output DC voltage (red trace) at AC input of 360V and 3.6kW load conditions

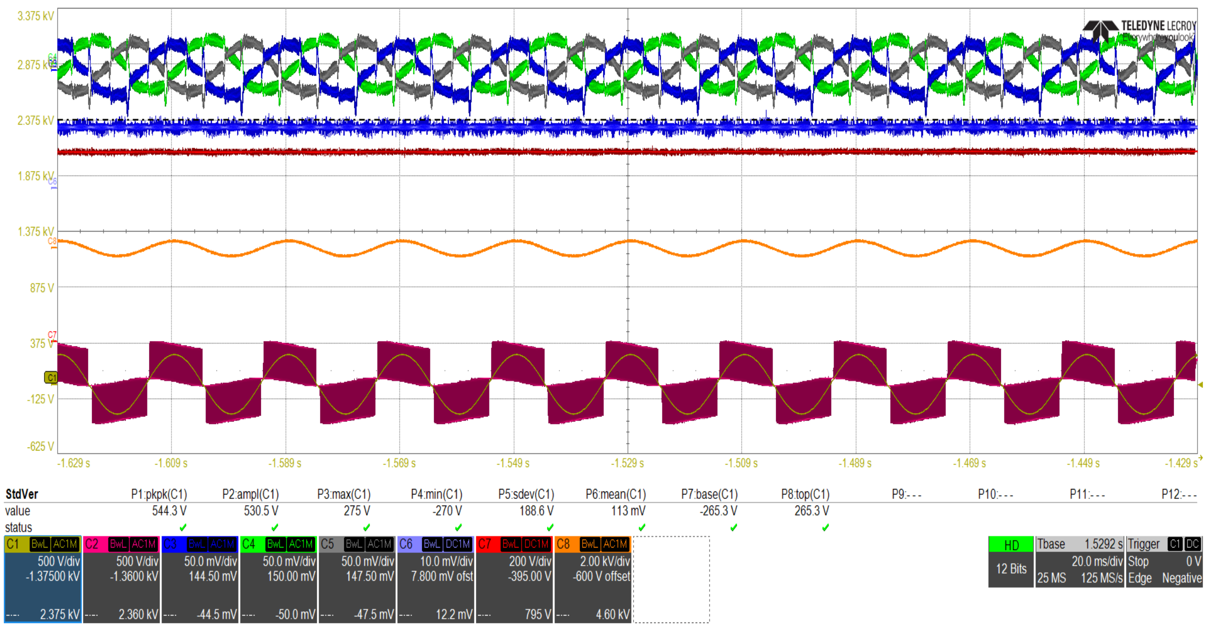


Figure 13 Captured results of three-phase input currents (blue, green & gray trace), output DC voltage (red trace), AC input voltage (yellow), GaN BDS source-to-source voltage (pink trace)

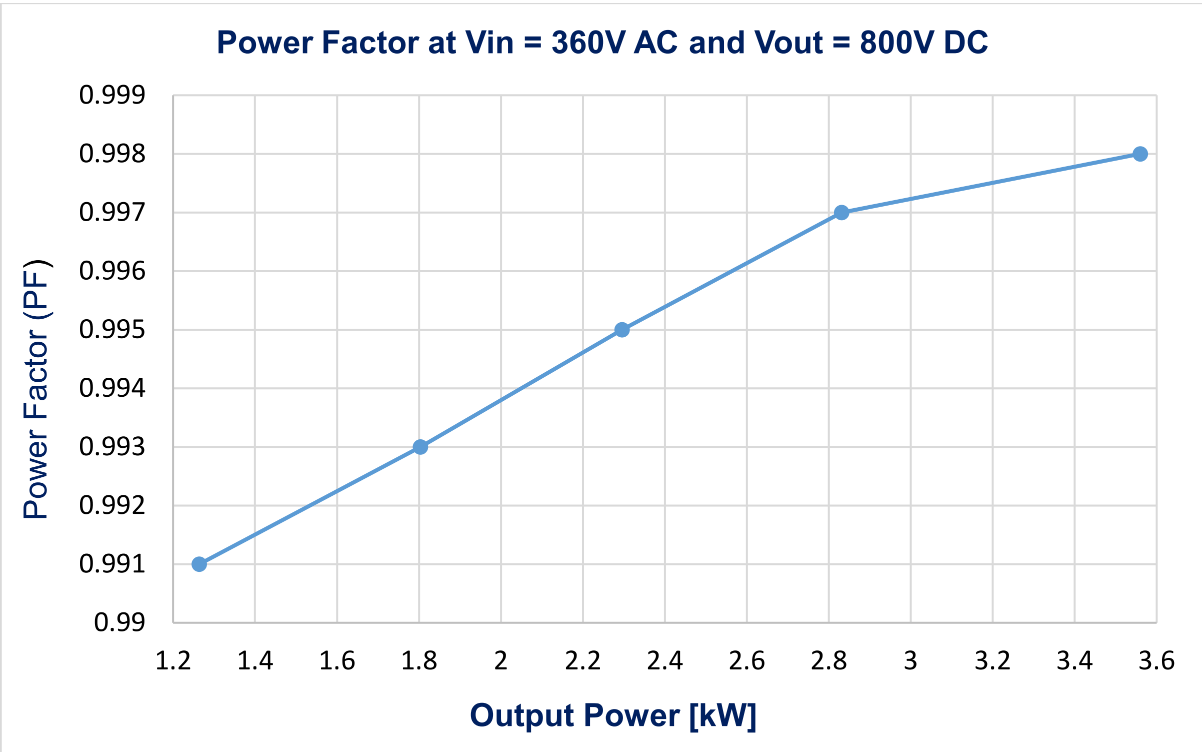


Figure 14 Measured power factor at various power levels (under Vin=360V, Vout=800V and Fsw=50 kHz)

Summary

Renesas offers comprehensive AC/DC front end Vienna rectifier with power quality enhancement solutions for data center, EV charging, telecommunications, aircraft systems and other applications, supporting power ratings from a few kilowatts up to 30 kW and 800V DC output. These solutions integrate advanced power conversion topologies, Renesas GaN BDS devices, gate drivers, power management solutions, integrated auxiliary bias circuit controllers for real-time monitoring and power flow control. Along with delivering a strong price-to-performance ratio, Renesas offers extensive design support resources including reference designs, firmware libraries, design tools and technical assistance to streamline development and ensure industry compliance and protection.

References

[1] GaN BDS product page

[2] RAA214250 product page

[3] RAA223021 product page

[4] READ2304G product page

[5] ISL28134 product page

[6] RX26T product page

[7] GaN FETs product category page

[8] Renesas Power Products brochure

Corporate Headquarters
TOYOSU FORESIA, 3-2-24 Toyosu, Koto-ku, Tokyo 135-0061, Japan
https://www.renesas.com

Contact Information
For further information on a product, technology, the most up-to-date version of a document, or your nearest sales office, please visit:
https://www.renesas.com/contact-us

Doc Number: R16WP0015EU0100