

High Power-Density, High-Gain Power Systems for Next-Generation Tsunameters

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ABSTRACT

Subsea tsunameter networks require reliable long-distance power delivery, yet current systems rely on grid-supplied AC feeders that are costly, difficult to deploy in remote regions, and vulnerable during extreme events. Furthermore, AC transmission introduces reactive losses and reduced efficiency over long subsea cables, motivating the need for a compact, renewable-powered HVDC alternative. This work presents a renewable-driven system architecture combining solar and wind generation, lithium-based battery storage, and a dual-cascade high-gain boost converter for long-distance delivery, alongside a controlled buck stage for regulated sensor-node supply. By utilizing high-frequency wide-bandgap converters with PI regulation, the system achieves low ripple, stable current control and high efficiency. Hardware results confirm minimal steady-state error and performance comparable to commercial subsea power units. In addition, cable modelling shows that while long HVDC links naturally filter ripple, they also slow dynamic response. The prototype demonstrates that a high-power-density, fully DC renewable system can replace grid-dependent AC infrastructure. This can reduce costs and enabling scalable, autonomous tsunami-monitoring networks in remote regions.

Keywords: Dual-Cascade DC–DC Converter, High Gain Converter, Wide Bandgap Switches, Tsunameter Supply

1. INTRODUCTION

Tsunami early-warning systems protect coastal communities by detecting seafloor disturbances and transmitting timely alerts before hazardous waves reach vulnerable regions. Several types of tsunameters are used globally, each employing different sensing principles and deployment configurations. Table 1 summarizes the principal sensor categories, their installation locations, monitoring methods, and the practical advantages and limitations within operational warning networks.

Fig. 1 illustrates three widely adopted offshore

tsunami-monitoring approaches. In the DART-type configuration (Fig. 1a), a Bottom Pressure Recorder (BPR) measures water-column pressure variations on the seafloor and transfers data acoustically to a surface buoy for satellite communication. A second method (Fig. 1b) uses a cabled seafloor BPR directly linked to the shore, providing continuous high-bandwidth data and power. The third approach (Fig. 1c) employs a GNSS buoy that detects vertical sea-surface displacement using high-precision satellite positioning.

Among these systems, cabled BPR observatories provide the most stable and accurate deep-ocean measurements because they benefit from continuous power, secure communication links, and immunity to surface-weather damage or vandalism. However, their primary drawbacks include the high cost and complexity of subsea cable installation, as well as the requirement for a specialized Ocean Bottom Unit (OBU) to house the pressure sensor, subsea communications electronics, and control hardware.

Furthermore, the deployment of subsea instrumentation faces significant engineering challenges regarding hardware connectivity and extreme environmental conditions. A critical vulnerability lies in the connector interface between the power and telecommunication cables and the instrument, which presents a high risk of failure in deep-ocean environments [1]. In addition, as tsunameter sensors are typically deployed at depths reaching approximately 4,100 meters [2], the resulting hydrostatic pressure requires specialized enclosure designs to ensure the unit remains securely sealed. Beyond pressure, the chemical composition of saltwater poses a constant threat of rapid degradation to metal housings. Consequently, design strategies must prioritize highly corrosion-resistant materials or incorporate sacrificial anodes to protect the structural integrity and long-term reliability of the OBU.

While commercial applications often utilize AC fed systems, Table 2 provides a direct side-by-side comparison with the HVDC architecture to highlight significant advantages in cost, reliability, and system complexity.

To deliver power over long distances with minimal loss, modern observatories typically employ high-voltage DC (HVDC) transmission [3]. Table 3 summarizes major cable-based tsunami and deep-ocean observatory systems deployed globally, including those in the USA, Canada, Japan, Taiwan and Indonesia. While Japan and Canada operate the largest deep-water networks, the USA maintains several coastal and mid-ocean platforms, Indonesia has expanded coverage in the Indian Ocean,

Manuscript received on January 17, 2026; revised on April 10, 2026; accepted on May 3, 2026. This paper was recommended by Associate Editor Vuttipon Tarateeraseth.

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Digital Object Identifier: 10.37936/ecti-ec.2026242.263281

Table 1: Summary of major tsunameter types with their key features [3-5].

Type	Location	Monitoring Method	Key Advantage	Limitation
Seafloor Bottom Pressure Recorder (BPR)	On seabed	Detects water column pressure changes	Most accurate	Needs subsea power + data link
Deep-Ocean Assessment and Reporting of Tsunamis, DART	Seafloor + surface buoy	BPR on seabed + acoustic link to surface buoy	Real-time satellite reporting	Buoy vulnerable to storms/vandalism
Cabled BPR + Fibre/HVDC Power	Onshore via cable	Continuous power and direct communication	High reliability, long-life	Costly cable deployment
Free-Floating Buoy Tsunami Sensor	Surface, anchored	Sea-surface displacement and wave height	Easy to deploy, low cost	Easily damaged, lower accuracy
GNSS-Buoy Tsunami Sensor	With GPS positioning	Measuring vertical movement of sea surface	Good for wide-area detection	Satellite-dependent + surface risks
Tide Gauge (Coastal Monitoring)	Ports and coast	Sea level and wave arrival detection	Simple, useful for near-shore	No deep-ocean warning capability

Table 2: Comparative analysis of traditional AC versus the HVDC architecture [6-9].

Comparison Metric	Conventional HVAC	Proposed HVDC
Transmission losses	High (due to skin effect and reactive power)	Minimal (pure resistive losses only)
Cable charging current	Limits transmission distance	Negligible, allows longer cable runs
Power stability	Vulnerable to frequency fluctuations	High stability; decoupled from grid
Infrastruct. cost	High (heavy transformers)	Lower (compact WBG converters)
Renewable integration	Complex (requires synchronization)	Seamless (direct DC coupling)
System footprint	Large (bulky AC components)	Compact (high power density)

and Taiwan focuses on dense monitoring near tectonic boundaries. Collectively, these installations reflect a global shift toward renewable-compatible, remotely deployable DC power systems. Such architectures support long-distance subsea monitoring while eliminating the dependence on conventional, grid-tied AC infrastructure.

In these systems, HVDC transmission levels generally fall into three ranges: low-voltage ($\approx 100 - 400$ V), medium-voltage ($\approx 400 - 1,500$ V), and high-voltage ($\approx 1.5 - 10$ kV). These levels address the requirements of diverse deployments, from short coastal links to ultra-deep observatories spanning nearly 1,000 km. Most cabled networks utilize constant-current (CC) transmission to manage cable resistance and voltage drops over long distances, while constant-voltage (CV) stages regulate local node supplies after conversion. Such hybrid CC/CV architectures dominate modern observatories because HVDC eliminates reactive power requirements, minimizes losses, and reduces conductor and insulation size. These benefits align with the emerging adoption of compact, high-efficiency power converters based on wide-bandgap (WBG) semiconductor technologies [10,11].

Despite these technical advantages, cabled BPR systems remain expensive and logistically complex. Their reliance on purpose-built cables limits installation sites,

particularly in regions far from existing AC-grid infrastructure. Furthermore, because seafloor instrumentation operates on DC, AC-grid supplies require additional conversion, and renewable sources, though abundant in coastal areas, are often not effectively integrated. These high costs and siting constraints have restricted broader adoption compared to buoy-based systems.

To address these limitations, recent studies have explored high step-up non-isolated DC–DC converter topologies [10–15] capable of converting renewable inputs into the HVDC levels required for subsea use. While many advanced topologies achieve high voltage gains, they often introduce excessive component counts and increased parasitic sensitivity, reducing their practicality in harsh, remote environments. In contrast, simpler structures that minimize current paths and semiconductor stress demonstrate higher efficiency and reliability. Specifically, the two-switch cascaded boost converter offers an optimal balance between gain capability and device stress distribution. Its suitability for WBG high-frequency switching and its compact magnetic design improve both EMI performance and long-term operational robustness without the need for complex multiplier cells.

Ultimately, a renewable-driven HVDC architecture provides a practical alternative to conventional grid-fed systems. Solar and wind resources, paired with appropriately sized battery storage, can support continuous autonomous operation. By utilizing high-power-density converters designed for tsunameter loads, these systems enable efficient long-distance delivery with reduced cable losses. This approach extends monitoring coverage to remote or deep-ocean regions that were previously too costly to access, significantly enhancing the warning capabilities and resilience of coastal populations.

Representative high-gain, non-isolated step-up converter topologies are summarized in Table 4. This comparison highlights the trade-offs between circuit complexity, efficiency and WBG compatibility. However, note that while many designs achieve the required gain, few offer the specific combination of simplicity and robustness needed for subsea renewable applications.

Deep-ocean tsunameters are critical components of

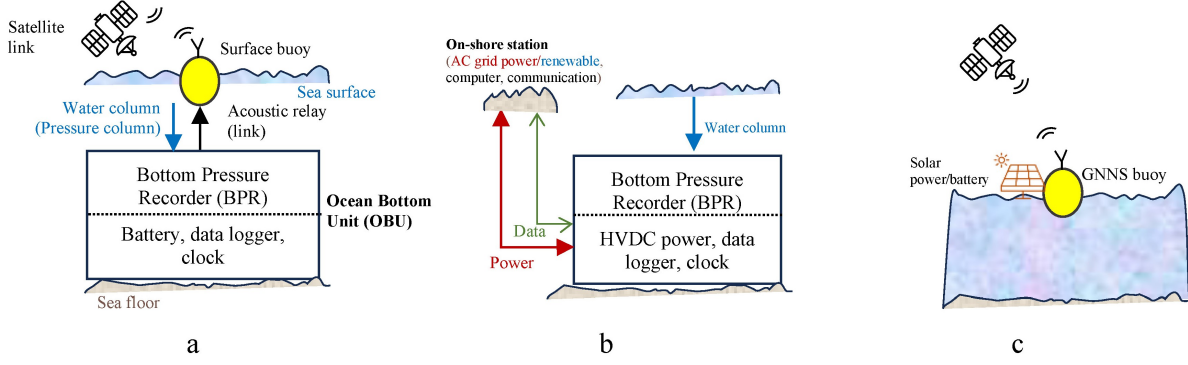


Fig. 1: Schematic illustration of three major tsunami-monitoring methods: a) DART-type system using a seafloor, BPR, b) Cable-based seafloor BPR, c) GNSS-buoy system.

Table 3: Major cable-based tsunami and ocean observatory systems [3-5].

Region	Representative Projects	Typical HV Level	Common Mode	Depth Range	Cable Length
USA	LEO-15, H2O, MVCO, ALOHA, MARS, OOI	Medium–High	HVDC (CC/CV)	Coastal to deep ocean	Short–very long
Canada	VENUS, NEPTUNE	Medium–High	HVDC CV	Shelf to deep	Mid–very long
Japan	DONET, DONET2, S-NET	High	HVDC CC/CV	Ultra-deep deployments	Long–ultra long
Taiwan	MACHO	Low	HVDC CV	Shallow coastal	Short
Indonesia	INA-CBT	Medium	HVDC CC	Deep	Medium

global warning networks, yet current systems remain expensive, maintenance-intensive, and sparsely distributed. By developing low-cost, reliable, and energy-autonomous sensing and power-conversion hardware, large-scale distributed arrays become feasible. Such dense networks provide multi-point measurements that enhance triangulation, directional analysis, and early-warning accuracy. Achieving this requires converter systems capable of multi-year operation, stable current-source behaviour, and resilience to intermittent renewable supplies.

Motivated by these needs, this paper develops and evaluates a compact, high-efficiency current-source step-up converter designed for next-generation tsunameter platforms. The primary objectives are to design a dual-cascade synchronous boost architecture optimized for WBG devices. The study models its performance under various DC network, renewable-generation, and subsea cable constraints. In addition, it demonstrates stable autonomous operation within a distributed sensing framework. Finally, the work experimentally validates the system’s efficiency, transient characteristics, and suitability for long-duration offshore deployment.

The remainder of the paper is organized as follows. Section 2 details the system-level specifications, including the renewable-input model, the dual-cascade HVDC boost stage, constant-current regulation, and the buck-converter interface. This section also covers component selection, WBG gate-drive configuration, subsea cable modelling, and the simulation framework. Section 3 provides experimental validation of a laboratory prototype

(limited to 50 V for safety), focusing on efficiency, gain, ripple, and transient behaviours. Additional analyses address power density and renewable supply viability. Finally, the paper concludes with consolidated performance benchmarking and recommendations for future field deployment and long-term reliability studies.

2. SYSTEM SPECIFICATIONS AND DESIGN

Subsea sensing platforms for tsunami early-warning systems require power converters that operate efficiently at light loads, minimize magnetic volume, and provide long-term environmental robustness. Conventional marine power feeds rely heavily on shore-based AC infrastructure and bulky low-frequency components, which limits scalability and hinders autonomous deployment in remote regions. These constraints motivate the development of a GaN-based dual-cascade converter capable of high-frequency operation and high-power density.

The primary goal of this work is to develop a modular, renewable-powered HVDC supply for cable-based seafloor BPR tsunameters. The design focuses on four key elements:

- Modelling and selecting onshore renewable energy sources paired with battery storage.
- Developing a high-gain front-end HVDC boost converter featuring high efficiency and controlled ripple.
- Implementing a regulated HVDC back-end stage with offshore battery buffering for improved reliability and fault tolerance.
- Constructing and testing a small-scale experimental

Table 4: Representative high-gain non-isolated DC–DC Step-up converter topologies.

Topology	Principle / Technique	Voltage gain (ideal)	Typical Efficiency Range
Double boost converter [12, 16, 17]	Symmetric cascade of two boost stages; shared inductor current	$\frac{1}{(1-D)^2}$	85–97%
Quadratic boost converter [12, 17]	Uses additional energy storage cells to form a quadratic boost structure	$\frac{1}{(1-D)^2}$	85–93%
Interleaved quadratic boost converter (QBC) [16]	Two-phase interleaving reduces ripple and shares current	$\frac{2}{(1-D)^2}$	92–95%
Boost converter with voltage-multiplier cell (VMC) [16]	Adds switched capacitor / multiplier stages to enhance gain	$\frac{M+1}{1-D}$	93–96%

Note: D shows the duty cycle and M denotes the number of multiplier stages.

prototype that incorporates representative subsea cabling and loads.

Fig. 2 illustrates a general overview and the adopted system architecture. Onshore renewable sources generate power, which is stabilized by a battery subsystem. A dual-cascade boost converter then raises the DC voltage for long-distance transmission through the subsea cable. At the seafloor termination, a regulated buck stage and local battery provide a reliable, low-noise supply to the BPR sensors, embedded electronics, and communication interface. This boost–cable–buck configuration enables low-loss power transfer while maintaining stable operating conditions for the tsunameter.

2.1 Dual-Cascade Boost Converter Architecture

The high-voltage, high-gain, current-source converter is shown in Fig. 3. It is implemented using TI’s LMG1210EVM GaN half-bridge modules [18], which provide the high-speed switching and timing precision required for cascaded operation. In this configuration, switches S1–S3 form the first synchronous boost stage, while S2–S4 form the second. Energy transfer is managed through inductors L1 and L2, intermediate capacitor C1, and output capacitor C2.

Each half-bridge utilizes independently driven high-side and low-side GaN FETs to enable accurate synchronous boost operation. The gate driver supports both single PWM control with adjustable dead time and fully independent gating, providing flexibility across the two cascaded stages. Furthermore, fast propagation delays and tight channel matching facilitate reliable MHz-range switching, which reduces cross-coupling and switching losses. The devices are rated for 100 V and 10 A and include thermal protection and under voltage lockout to prevent switching during low-supply conditions.

As previously noted, the symmetric cascaded-boost structure is highly compatible with GaN half-bridge operation. It achieves high gain without requiring extreme duty cycles, thereby distributing voltage stress across devices and maintaining a compact magnetic design. Moderate duty ratios reduce switching stress, while synchronous conduction minimizes losses. In addition, complementary switch operation allows both

stages to be driven by a single PWM signal, simplifying the control scheme. This topology also exhibits intrinsic current-source behaviour, ensuring predictable input current regulation under varying environmental and load conditions.

These characteristics make the dual-cascade synchronous boost converter a compact, efficient, and robust HVDC front-end, ideally suited for powering cable-based BPR tsunameters.

2.2 Dual-Cascade Boost Converter Simulation

High-frequency converter design requires rigorous device-level modelling, as switching transitions, parasitic elements, and gate-drive behaviour significantly influence overall performance. Because these effects cannot be captured by the simplified models typically used in environments like MATLAB/Simulink, a detailed SPICE-based simulation was conducted. This approach accurately represents the behaviour of the GaN half-bridge stages and their interaction with passive components.

The converter was evaluated through a detailed circuit simulation (Fig. 4) using TINA-TI. This platform provides a behavioural model of the LMG1210 gate driver used to drive the EPC2001C GaN transistors in both half-bridge stages. In the simulation, a single PWM input signal was applied synchronously to both bridges, while inductors and capacitors implemented the cascaded step-up conversion. The load resistance, R represents the combined effect of the subsea cable and the downstream electronics.

Passive component values were determined analytically before conducting the full simulation. The inductor and capacitor values for each boost stage were calculated using standard continuous-conduction-mode design equations for a synchronous boost converter. Specifically, the required inductance is determined by the allowable inductor current ripple ΔI_L and the switching frequency f_{sw} as follows:

$$L = \frac{V_{in} D}{\Delta I_L f_{sw}} \quad (1)$$

Similarly, the minimum capacitance required to limit

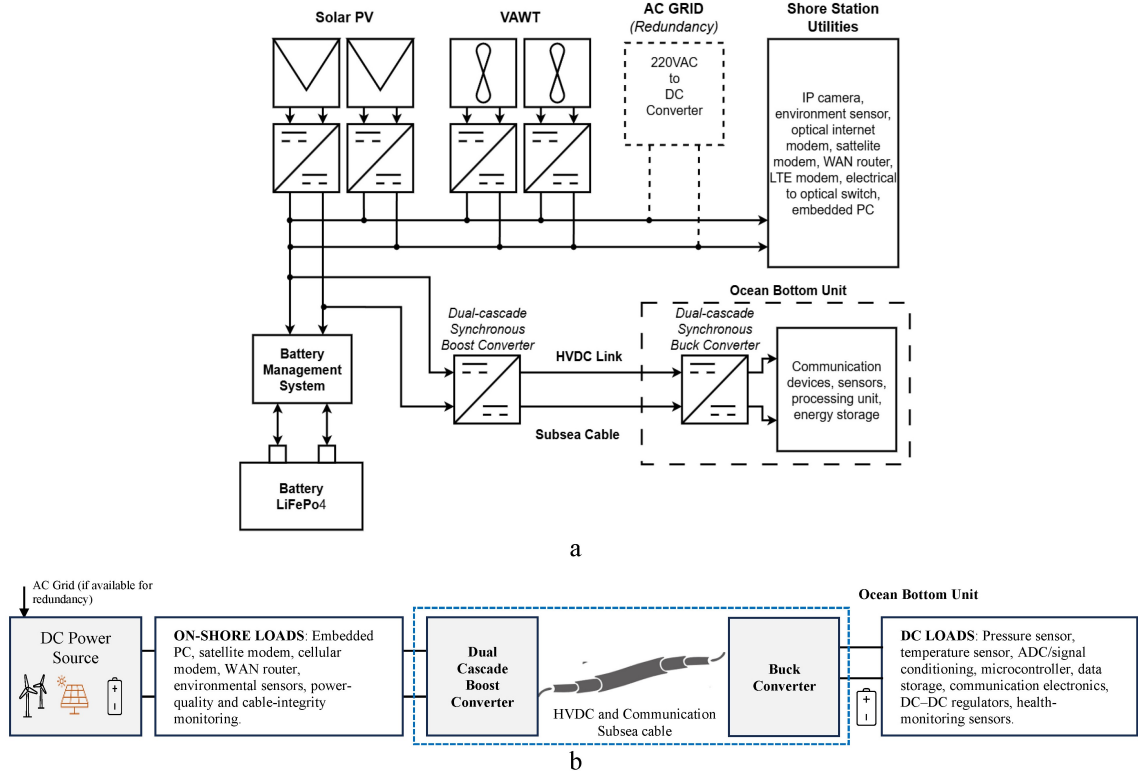


Fig. 2: a) A general overview to link the theoretical design, simulation modelling and experimental validation.

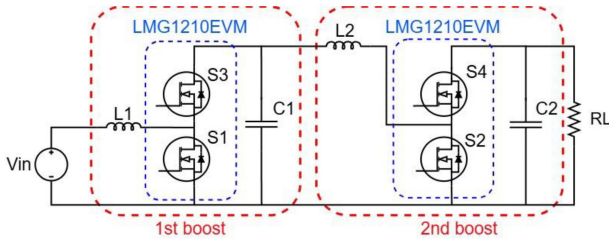


Fig. 3: Dual-cascade synchronous boost converter using two GaN half-bridge modules.

the output voltage ripple ΔV_{out} is

$$C = \frac{I_{out} D}{\Delta V_{out} f_{sw}} \quad (2)$$

These equations apply to each stage of the cascaded topology, where the output of the first stage serves as the input to the second. In these expressions, V_{in} and V_{out} represent the stage input and output voltages, I_{out} is the output current, and D is the duty cycle.

These expressions formed the basis for selecting commercially available components for the simulation study. The design objective was to maintain current ripple below 30% and voltage ripple below 10%. To ensure the simulation captured realistic power-loss behaviour, the chosen inductor models included their internal series resistance $R_{inductor}$. The resulting inductor and capacitor values for switching frequencies ranging from 100 kHz to 3 MHz are illustrated in Fig. 5.

As illustrated in Fig. 5, increasing the switching frequency substantially reduces the size of the required energy storage components. Between 100 kHz and 3 MHz, the necessary inductance and capacitance decrease by up to 96%, significantly improving power density by reducing the physical footprint of the inductors.

The converter's performance was simulated using the calculated capacitance and practical inductor models. Fig. 6 shows the simulated efficiency across various switching frequencies and output currents. Efficiency varies with frequency due to changes in inductor resistance, which directly impacts conduction losses. At an output current of 1.25 A, several operating points achieved efficiencies exceeding 85%, demonstrating that high-frequency operation is viable without excessive loss when passive components are carefully selected.

While several frequencies met the performance thresholds, only the highest were chosen to maximize power density. Based on the simulation results, 800 kHz, 1.5 MHz and 2 MHz were selected for further analysis and prototype development. These frequencies offer an optimal balance between high efficiency, reduced passive-component size, and controlled output ripple, aligning with the design objectives of the dual-cascade converter.

2.3 HVDC Transmission Cable Analysis

For long-distance subsea power delivery, HVDC transmission is advantageous because seafloor instrumentation operates at a low current. Resistive losses

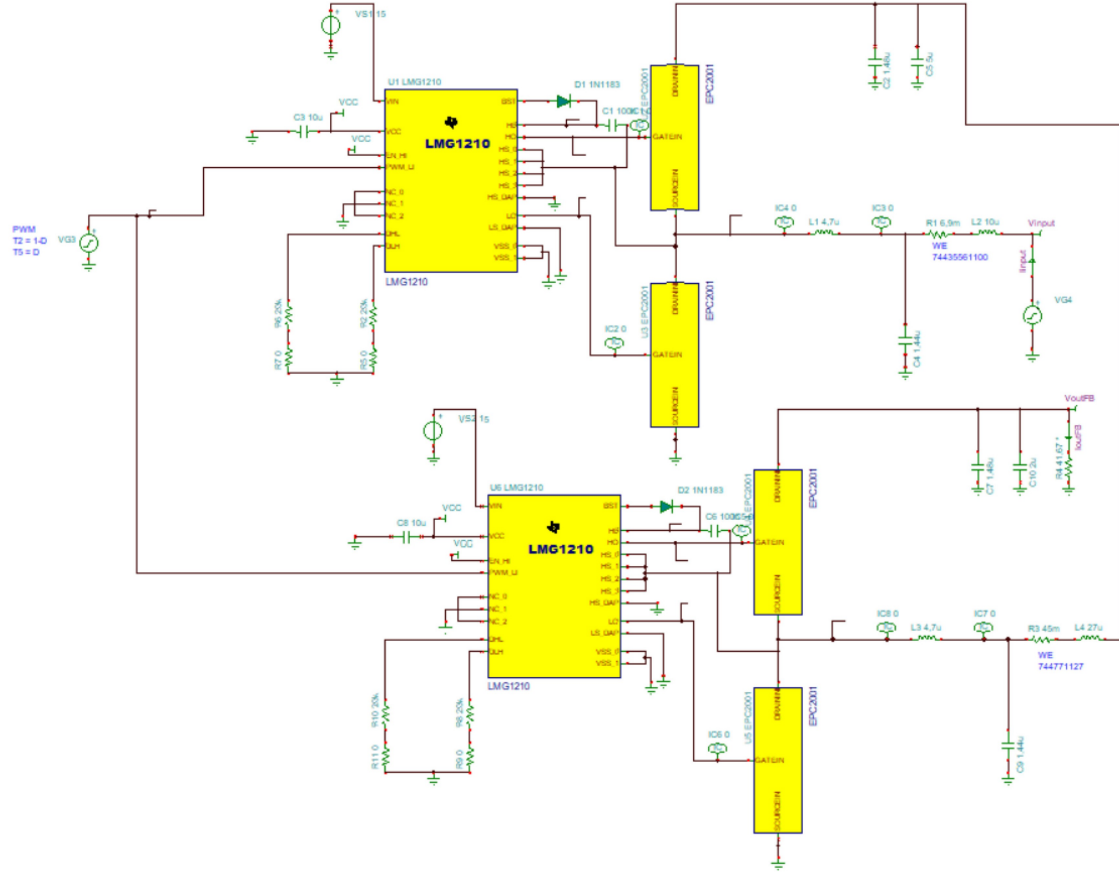


Fig. 4: Computer simulation schematic of the converter using LMG1210 drivers and EPC2001C GaN FETs.

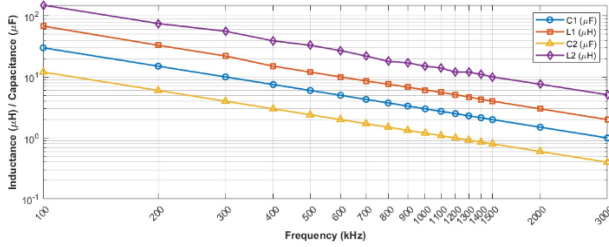


Fig. 5: Calculated inductor and capacitor values as a function of switching frequency.

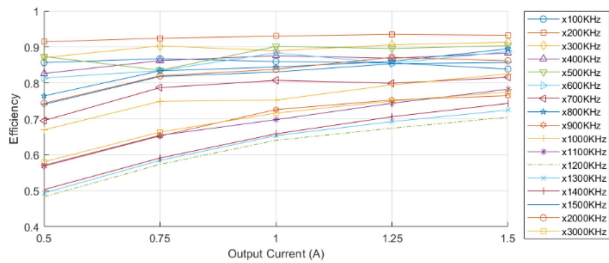


Fig. 6: Simulated efficiency for different switching frequencies and output currents.

along the cable are determined by $P_{loss} = I^2 R$, where I is the DC line current and R is the total cable resistance.

A range of commercial subsea HVDC cables was examined to identify suitable parameters for low-power transmission. The ZTT DC-HYJQ41-F cable was selected as the representative model due to its low resistance of $0.268 \Omega/\text{km}$. At an 18 mA operating current, this results in a resistive loss of only 8.68 mW over a 100 km (2 x 50 km) link. Consequently, the electrical characteristics of this cable were adopted as the baseline for system-level performance evaluation.

In addition to resistance, the distributed inductance and capacitance of subsea cables influence system dynamics. Based on the investigated cables, the total inductance and capacitance for a 100 km link were assumed to be approximately 47.3 mH and 16.6 μF , respectively. Under steady-state conditions, the cable capacitance acts as a voltage-smoothing element, while the inductance reduces current ripple. Fig. 7 illustrates the simulated output voltage and current responses, comparing the system with and without these cable parameters to evaluate transient behaviour during switching.

The simulations show that incorporating the cable's distributed parameters significantly influences converter behaviour. The added capacitance reduces voltage ripple from 6.27% to 2.25%, while the inductance lowers current ripple from 4.98% to 0.99%, thereby improving steady-state performance. However, the additional stored energy in the cable results in a slower transient

response, which is characteristic of long-distance HVDC links. These effects must therefore be considered in the converter and control design, particularly for systems that require fast startup, rapid load transitions, or tight dynamic regulation.

2.4 Dual-Cascade Buck Converter Architecture

Fig. 8 illustrates the converter topology designed and implemented to derive a regulated low-voltage DC supply from the HVDC link. The circuit is a dual-cascade synchronous buck converter that mirrors the boost stage's structure but operates in step-down mode. Dividing the conversion into two stages allows for higher overall step-down ratios while maintaining moderate duty cycles, improved efficiency, and more linear control characteristics. For reference, a single-stage buck converter follows the standard relation $V_{out} = DV_{in}$.

A single PWM signal drives both GaN half-bridge modules, with logic inverters generating the complementary gate signals required for synchronous operation. The first stage, comprising the upper half-bridge with inductor L_1 and capacitor C_1 , performs the initial step-down; the second stage, featuring L_2 and C_2 , provides further regulation. The load R_{load} represents the combined DC load of the OBU, including the BPR sensor electronics, embedded processor, and communication modules, as depicted in the system architecture in Fig. 2.

The selection of energy storage elements follows the same ripple-based design approach used for the dual-cascade boost converter. Substituting the design specifications ($V_{in} = 30.25$ V, $V_{out} = 5$ V, $f_{sw} = 1.3$ MHz, and $I_{out} = 100$ mA) into the design equations yields the required inductance and capacitance values. Both stages are assumed to operate at the same switching frequency and duty ratio to ensure synchronized behaviour. These component values are then validated through a detailed TINA-TI simulation of the complete dual-cascade buck topology prior to hardware implementation.

2.5 Renewable Source Sizing

Many cable-based tsunami and ocean observatory systems are deployed in remote locations with limited access to conventional grid power but substantial renewable potential. To assess the feasibility of a renewable-powered HVDC supply, a representative load profile was developed based on a continuous demand of approximately 408 W. This includes 40 W for the OBU (supporting two BPR sensor nodes) and the necessary onshore equipment, such as IP cameras, environmental sensors, communication modems, routing devices, network switches and an embedded industrial PC. This configuration results in a total daily energy requirement of approximately 9.81 kWh.

Given the remote nature of typical onshore stations, a conservative autonomy period of seven days was established to represent a worst-case scenario where both

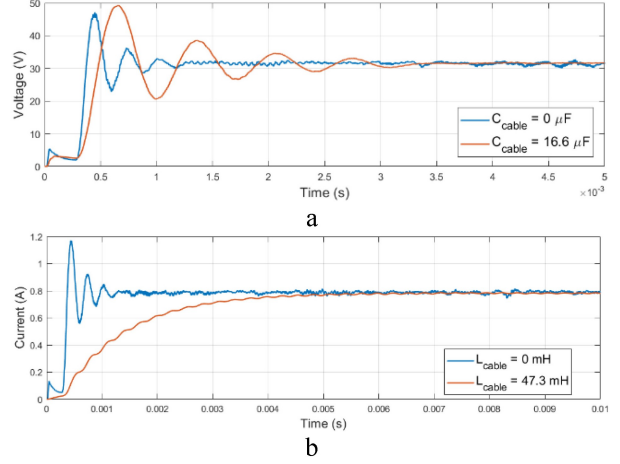


Fig. 7: Simulated output voltage response (a) and current response (b) with and without cable C and L .

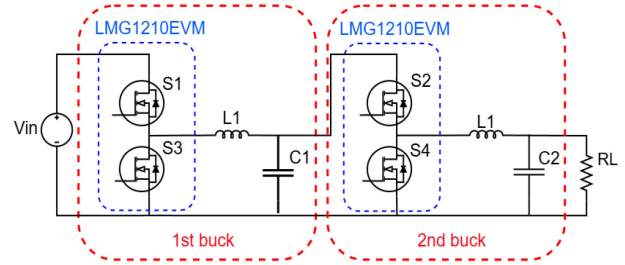


Fig. 8: Circuit schematic of dual-cascade synchronous buck converter.

solar and wind sources fail. For a continuous 408 W load, this requires a minimum battery capacity of 68.67 kWh. Lithium-based storage technologies, such as Lithium Iron Phosphate (LFP/LiFePO₄), are preferred for their high cycle life, intrinsic stability, and low maintenance, characteristics ideally suited for unmanned installations.

The sizing of the renewable subsystem is informed by regional environmental data [5]. In the target region, effective solar radiation reaches up to 10.6 h/day during peak seasons, with a monthly average irradiance of 5.86 kWh/m²/day. The site also indicates usable wind resources, with peak speeds around 4 m/s and a monthly average of 2.11 m/s. Consequently, a hybrid configuration comprising solar PV and vertical-axis wind turbines was selected to supply the continuous load and manage battery recharging.

Based on the daily energy baseline, the solar subsystem was sized to generate approximately 10 kWh/day, while the wind subsystem provides an additional ~4 kWh/day. This combined output of roughly 14 kWh/day exceeds the daily load, ensuring sustained operation and gradual battery recovery. Under these conditions, a fully depleted battery can be recharged in approximately 17 days using the excess generation. This solar-wind-battery arrangement provides sufficient capacity for continuous tsunami meter operation and ensures resilience during extended periods without renewable generation.

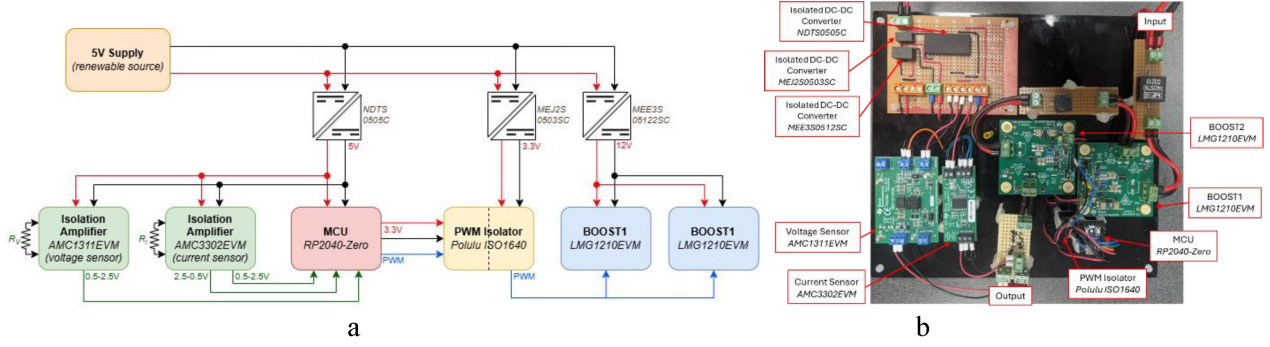


Fig. 9: Wiring diagram of the experimental dual-cascade synchronous boost converter with isolated power supplies, sensing circuits, PWM isolation, and GaN half-bridge stages (a), and the photograph of the constructed prototype (b).

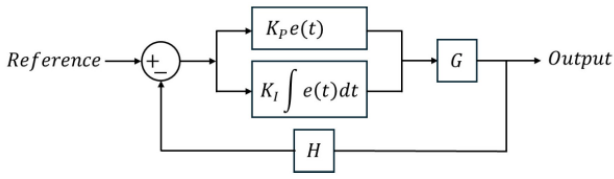


Fig. 10: PI control block diagrams for regulating the converter current and for voltage control.

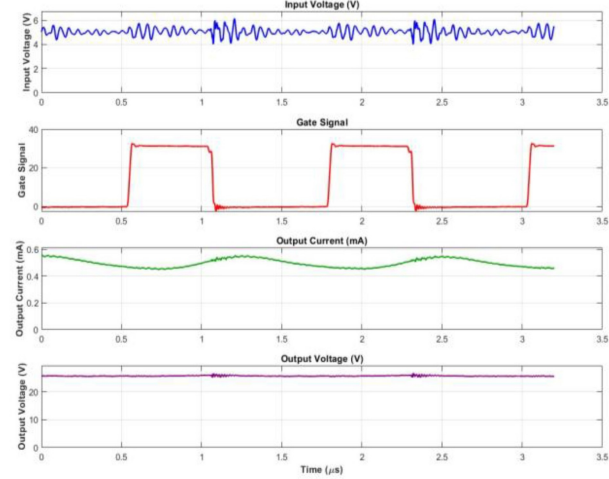


Fig. 11: A sample measured input voltage, GaN gate signal, output voltage, and output current waveforms.

3. EXPERIMENTAL VALIDATION AND PERFORMANCE RESULTS

Fig. 9 illustrates the hardware architecture used to validate the proposed dual-cascade synchronous boost converter; a similar structure was subsequently applied to the dual-cascade buck converter. The prototype integrates several key modules. Isolated DC-DC converters provide 5 V, 3.3 V, and 12 V rails for the MCU, PWM isolator, and GaN driver boards, ensuring galvanic isolation between the control and power domains.

Voltage and current measurements are captured via an

AMC1311EVM isolation amplifier and an AMC3302EVM current-sensing module. High-frequency PWM signals are generated by an RP2040-Zero microcontroller and transmitted through a Pololu I^2C ISO1640 PWM isolator. Note that, the isolator's 1.7 MHz maximum switching capability serves as the upper limit for the PWM operating frequency in this experimental study.

A PI controller (Fig. 10) is implemented on the MCU to maintain constant-current operation for the boost stage and constant-voltage regulation for the step-down converter. The controller parameters were tuned experimentally, yielding $K_P = 0.5$ and $K_I = 0.4$.

Hardware testing was conducted using a programmable load, digital oscilloscope, regulated DC supply and specialized high-bandwidth probes. These tools enabled the detailed observation of steady-state and transient responses, high-frequency switching waveforms, and overall efficiency. A critical component of this setup was the high-bandwidth current probe (Tektronix TCP0030A), which provided noise-immune measurements of MHz-range switching currents, a capability beyond the reach of conventional clamp-type sensors.

3.1 Typical Experimental Results

Fig. 11 presents a typical oscilloscope capture of the converter operating at 800 kHz with $I_{out}=0.7A$. This setup used component values of $L_1 = 7.6\mu H$, $L_2 = 18\mu H$, $C_1 = 3.9\mu F$, $C_2 = 1.5\mu F$. The waveforms illustrate key electrical quantities for efficiency and ripple calculations, including the PWM command, gate-drive signals, output voltage, and inductor current. As previously noted, measuring instantaneous current in WBG converters is challenging due to fast switching edges that introduce strong dv/dt and di/dt interference; the high-bandwidth probe proved effective in managing these conditions.

Fig. 12a details the signal propagation delays through the control chain, which determine the practical limits for switching frequency and dead time. The delay between the MCU PWM output and the isolated signal is 17.78 ns, while the delay from the isolator to the gate output is 60.48 ns, resulting in a total minimum propagation delay of approximately 78.26 ns.

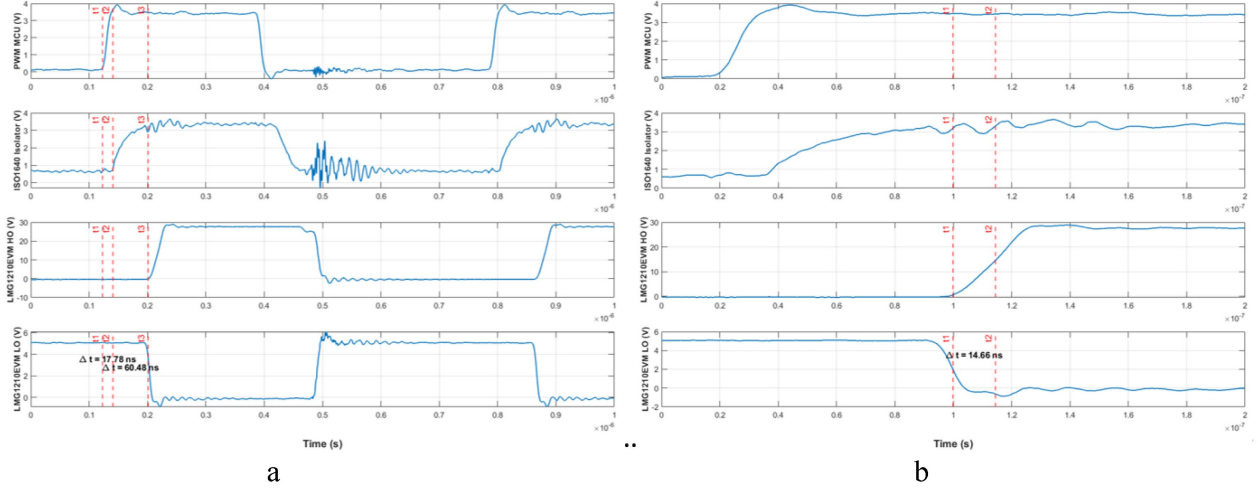


Fig. 12: The signal propagation delays through the control chain: a) Propagation delays between MCU, isolator and gate driver; b) Dead time between high-side and low-side GaN gate signals.

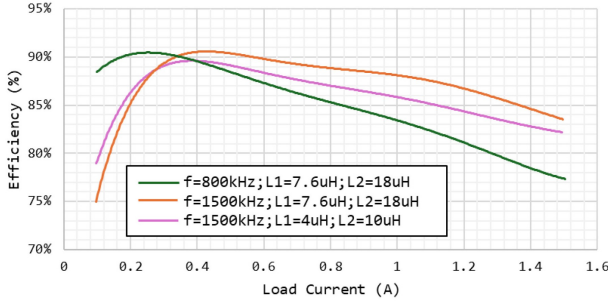


Fig. 13: Measured converter efficiency versus output current for different f_{sw} and L values.

Fig. 12b shows the measured dead time of 14.66 ns between the high-side and low-side gate signals. While this dead time prevents shoot-through and ensures safe GaN operation, it slightly reduces the effective duty cycle and voltage gain. Additionally, the PWM signal from the isolator exhibits minor distortion due to internal RC filtering. While not critical for this prototype—as the PI controller regulates the output directly—this effect may require compensation in applications necessitating precise duty-ratio tracking.

Efficiency measurements were conducted using component sets optimized for 800 kHz and 1500 kHz operation. Fig. 13 illustrates the efficiency curves versus output current at a fixed duty ratio of 0.6. Using identical component values, the higher switching frequency improved efficiency by reducing ripple and lowering switching-related losses in the passive components. Similarly, at a fixed frequency, larger inductance and capacitance values resulted in higher efficiency. The maximum measured efficiency reached 91.35% at 1500 kHz using $L_1 = 7.6\mu\text{H}$ and $L_2 = 18\mu\text{H}$ with an output current of 0.4 A.

Fig. 14a demonstrates that voltage ripple remains relatively constant across the test range, staying below

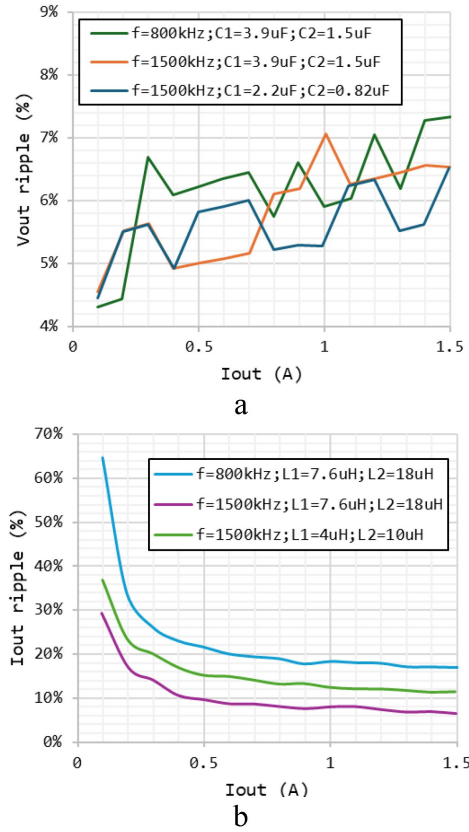


Fig. 14: Percentage output voltage ripple (a) and output current ripple (b) versus output current.

2% regardless of the component set or switching frequency. In contrast, current ripple is strongly influenced by both inductance and switching frequency. As shown in Fig. 14b, increasing L_1 , L_2 , or the switching frequency significantly reduces ripple. The minimum measured current ripple was 0.048 A (9.6% of the output current) at 1500 kHz with the previously specified inductance

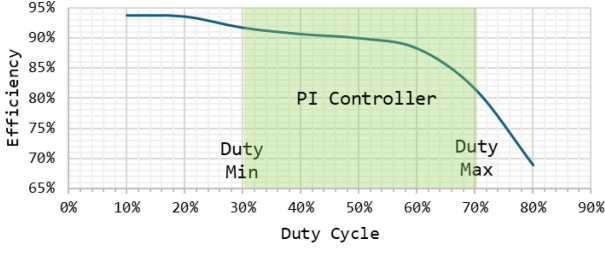


Fig. 15: Converter efficiency versus duty cycle at constant $I_{out} = 0.4A$, highlighting PI controller region.

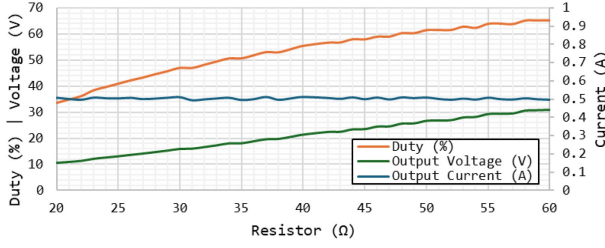


Fig. 16: PI control to control duty cycle and variation of output voltage and duty cycle with load resistance.

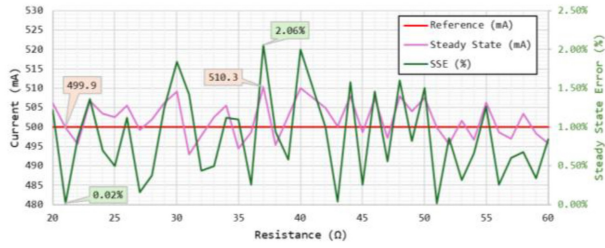


Fig. 17: PI-controlled output current and steady-state error versus load resistance, <3% regulation accuracy.

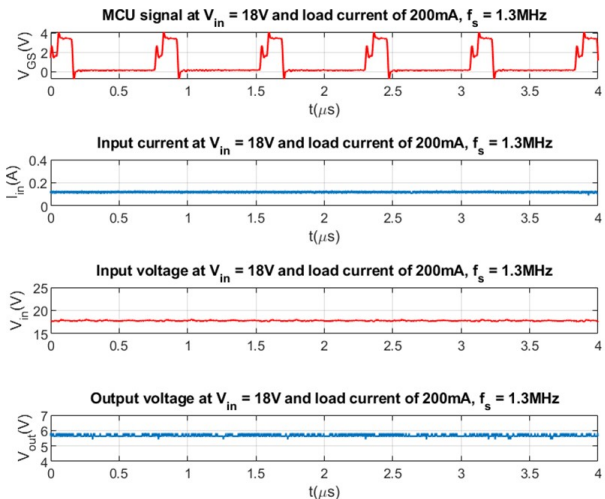


Fig. 18: Measured PWM gate signal, input and output quantities of the buck converter.

values, which also coincides with the point of maximum efficiency.

Fig. 15 illustrates converter efficiency versus duty

cycle at a constant output current of 0.4 A. Efficiency peaks at 93.77% at a duty ratio of approximately 10% and declines to 68.91% at an 80% duty cycle, primarily due to higher input current and conduction losses. The shaded region (30–70% duty) represents the operational window utilized by the PI controller to ensure stable current regulation while maintaining high efficiency and sufficient voltage gain.

The performance of the PI-based current control is illustrated in Figs. 16 and 17. As load resistance increases, the output voltage rises accordingly, while the PI controller maintains the output current at the 0.5 A reference level. The steady-state current error remains between 0.02% and 2.06%, demonstrating effective regulation under varying load conditions and keeping the total error consistently below 3%.

Fig. 18 shows representative waveforms from the dual-cascade buck converter operating at $V_{in} = 18$ V with a 200 mA load current and a 1.3 MHz switching frequency. The MCU-generated PWM signal exhibits clean transitions, confirming stable gate-drive delivery to the synchronous stages. Despite MHz-range switching, the input voltage trace shows minimal disturbance, indicating effective decoupling and low input-side ripple. Similarly, the input current remains steady with negligible high-frequency components, validating the inductor sizing and current filtering. The output voltage maintains a regulated level with low ripple, confirming that the cascaded topology and control loop provide stable performance at high frequencies.

The sensing, ripple quantification, and efficiency evaluation methods used for the boost converter were also applied to this buck configuration, as both share the same high-bandwidth measurement and analysis requirements.

Finally, a qualitative cost analysis indicates significant economic viability. By connecting ten identical 100 V prototypes in series, a complete 1 kV DC–DC converter setup can be implemented for approximately AU\$1,328. Compared to the roughly AU\$4,030 market price for a standard commercial 1 kV HVDC supply, the proposed design offers a substantial cost advantage, particularly when considering the potential for mass production.

4. CONCLUSIONS

This paper presented a renewable-powered HVDC architecture and dual-cascade WBG-based DC–DC converters designed for long-distance subsea tsunameter systems. The proposed system addresses the limitations of conventional AC-fed subsea observatories by enabling efficient, autonomous, and scalable power delivery to remote ocean-bottom units.

Firstly, a high-gain dual-cascade synchronous boost converter was developed to interface renewable onshore sources with long subsea HVDC links. Detailed modelling and SPICE-based simulations demonstrated that MHz-range switching using WBG devices significantly reduces passive-component size while maintaining high

efficiency and low ripple. Cable modelling confirmed that while realistic subsea cable inductance and capacitance naturally suppress ripple, they also slow the dynamic response—a critical consideration for long-range HVDC design.

A complementary dual-cascade synchronous buck converter was implemented to provide a regulated low-voltage supply at the seafloor. Experimental results for both architectures verified stable operation, with efficiencies exceeding 90%, voltage ripple below 2%, and PI-controlled current regulation with less than 3% steady-state error. Furthermore, the measurement and estimation methods used for the boost converter proved directly transferable to the buck stage.

Finally, the renewable-energy sizing study demonstrated that a hybrid solar–wind–battery subsystem can sustain continuous tsunameter operation with sufficient autonomy for remote deployments. Collectively, the modelling and hardware results confirm that a compact, WBG-based DC architecture can replace grid-dependent AC infrastructure, reducing system cost and complexity while enhancing the reliability and coverage of next-generation tsunami-monitoring networks.

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