Real-time Edge-based Protocol Converter and Testbed-based Evaluation for DER Networks

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***Abstract*—The increasing penetration of Distributed Energy Resources (DERs) is reshaping distribution grids and turning consumers into active prosumers. To ensure visibility, monitoring, and efficient control of heterogeneous DER assets, IEEE 1547–2018 standard recommends three communication protocols (SunSpec Modbus, DNP3, and IEEE 2030.5). However, these protocols operate at different layers of the DER ecosystem, with SunSpec at the local device/edge layer and DNP3/IEEE 2030.5 at the higher utility layer. This separation results in a significant interoperability gap that hinders the coordinated integration of DERs at scale. This paper introduces a real-time protocol converter that bridges this gap by enabling seamless, bidirectional translation between different DER communication protocols. The proposed edge-deployed protocol converter is implemented using open-source Python and Rust libraries, incorporates an internal JSON-based data model for normalized data exchange, and supports both monitoring and control paths. Experimental validation on a testbed setup demonstrates a reliable conversion of data, with no loss of information and negligible packet drops, and end-to-end latency ranging from 14 to 165 ms for both single-point and multi-point operations. This performance is well within the latency requirements for IEEE 1547-compliant DER networks, highlighting its practical efficacy and suitability for achieving DER interoperability in modern distribution networks**

***Index Terms*—DNP3, DER, IEEE 1547-2018, Interoperability, Protocol Conversion, SunSpec Modbus**

I. Introduction

The global push toward 100% zero-emission electricity [1] is accelerating the adoption of Distributed Energy Resources (DERs) such as rooftop solar and battery storage. Once primarily valued for customer-side benefits, these resources are increasingly becoming grid-interactive, especially with regulations like FERC Order 2222 , which enable consumers to participate in energy markets as active "prosumers." To manage this growing complexity, utilities employ DER Management Systems (DERMS) for coordinated monitoring and control of aggregated DERs. The IEEE 1547–2018 standard [2] underpins this operational framework by defining the Technical Interconnection and Interoperability Requirements (TIIR) and recommends three communication protocols, SunSpec Modbus, DNP3 (IEEE 1815), and IEEE 2030.5, for standardized and interoperable DER-to-utility communication.

However, in real-world DER deployments, DERMS seldom communicate directly with DERs. Instead, data and control signals flow through intermediate DER edge gateways or aggregators, creating a multi-layer communication path. At the utility level, DERMS-to-gateway interactions commonly utilize utility-grade protocols, such as DNP3, over the Wide Area Network (WAN) [3]. At the field level, the edge gateway communicates with each inverter using its vendor-specific interface, most often SunSpec [4]. Although IEEE 2030.5 is also included in IEEE 1547, its adoption remains relatively low in utility operations due to integration complexity and limited vendor support. This protocol mismatch across layers introduces a critical interoperability gap, complicating seamless, end-to-end DER integration. This emphasizes the need for protocol conversion at the DER gateway or aggregator level, enabling efficient communication across heterogeneous DER assets. To bridge this gap, we propose a protocol conversion framework that enables interoperability between the two critical DER protocols: SunSpec Modbus and DNP3. The proposed framework achieves this through: (1) development of a Python-based SunSpec Modbus server, (2) development of a Protocol Conversion Interface between SunSpec Modbus and DNP3, (3) real-time end-to-end DER communication with Protocol Conversion and testbed-based evaluation.

The remainder of the paper is divided as follows: Section II provides background on IEEE 1547 and DER interoperability, highlighting the need for protocol conversion and discussing some related work. Section III describes the proposed protocol converter. Section IV discusses the testbed-based implementation. Section V discusses the experimental evaluation. Section VI concludes the paper with recommendations for future work.

II. IEEE 1547 Standard and DER Interoperability

A. Overview of IEEE 1547

The IEEE 1547–2018 standard [2] defines the technical and communication requirements for DER interoperability and interconnection with the distribution grid. In addition to electrical performance mandates (e.g., voltage/frequency ride-through and power quality), the standard specifies interoperability and communication protocol requirements. IEEE 1547 applies only to the interface between the utility's downstream communications link and the DER's local communications interface; internal utility and device-level communications are out of scope. To support interoperability, the standard defines the required information model, organized into four categories: *nameplate*, *configuration*, *monitoring*, and *management* information. It also outlines the performance and data requirements for DER smart inverter functions (e.g., constant reactive power, Volt-VAR, Volt-Watt, Frequency Droop, etc.).

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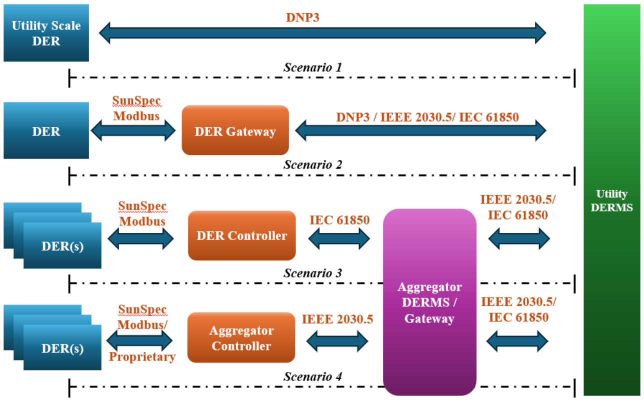

Fig. 1: Various DER deployment scenarios

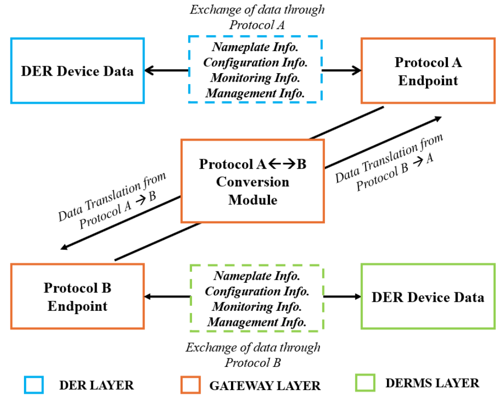

Fig. 2: Overview of protocol converter components

B. DER Deployment Scenarios

From a controls perspective, DERs are typically organized into logical groups based on location, capacity, or vendor implementation. As illustrated in Fig. 1, utilities rarely interface directly with individual devices; instead, communication flows through intermediate layers, gateways, or aggregator platforms. In simpler deployments, utility-scale DERs may communicate directly with the DERMS (Scenario 1). More commonly, individual DERs connect through a DER gateway (Scenario 2). Larger sites use a DER controller to coordinate multiple devices (Scenario 3). At the highest aggregation level, fleets of DERs are managed by vendor-operated aggregator controllers that interface with utility DERMS (Scenario 4). Across these scenarios, utilities typically obtain monitoring and control access through gateways or aggregator platforms rather than through direct device connections.

C. Need for Protocol Conversion

From the deployment scenarios in Fig. 1, it can be observed that wide-area communication between the utility (e.g., DERMS/SCADA) and the edge gateway or aggregator typically relies on DNP3 and IEEE 2030.5, while the local DER interface is most often SunSpec Modbus. This layered architecture creates a natural boundary for interoperability at the DER gateway/aggregator layer because SunSpec Modbus, DNP3, and IEEE 2030.5 are fundamentally different in structure, semantics, and data models. This establishes the need to perform a data conversion from one protocol to another to ensure consistent monitoring and control across layers. Thereby, making protocol conversion a fundamental requirement for IEEE 1547-compliant DER networks.

D. Related Work

Research into protocol conversion for power systems has primarily focused on Modbus or DNP3 to the IEC 61850 standard [5]–[7]. However, these efforts utilize direct communication links (Scenario 1 from Fig. 1) and are not applicable to interoperable DER networks, as specified by IEEE 1547. Several studies have focused on the interoperability [8], detailed analysis of SunSpec Modbus, DNP3, and IEEE 2030.5 to assess their support for various DER functions [9], and assessment of DERMS compliance for the three DER protocols [10]. Several studies have demonstrated SunSpec Modbus implementations [11], [12], while others have focused on DNP3-based testbeds [13]. However, these works focus on single-protocol implementation, rather than heterogeneous DER-DERMS communication as shown in Fig. 1. In summary, while prior work details DER communication requirements, protocol capabilities, and single-protocol testbeds, it does not address the key interoperability gap at the DER Gateway or Controller level. This work addresses this by presenting a practical, standards-compliant, real-time, end-to-end protocol converter that could be deployed at the edge between DER and DERMS.

III. Proposed Edge-based Protocol Converter

An overview of the proposed protocol converter is shown in Fig. 2. At a high level, the converter, deployed at the edge/gateway layer, performs three functions: (1) to manage the data exchange between the DER and the gateway (protocol A), (2) to convert the data from protocol A to B, and vice versa, and (3) to manage the data exchange between the gateway and the DERMS (protocol B).

A. DER Information Model and Protocol Mapping

The downstream system (DER) and the upstream system (DERMS) have the capability to manage DER Device data with respect to the four information exchange categories, as identified in Section II.A, as per IEEE 1547. As the three recommended DER protocols differ from each other in terms of how they store and exchange data, each protocol has its own profiles for DER, such as SunSpec DER Information Model Specification [14], DNP Application Note 2018 [15], Smart Energy Profile 2.0 for IEEE 2030.5 [16]. Developers can leverage these profiles to implement the respective protocol within their utility environments. The protocol converter utilizes these standardized profiles to create an integrated data mapping for the three protocols, where each DER physical parameter (such as active/reactive power, voltage, frequency, current, etc.) and its data type definitions are matched across both the upstream and downstream protocols. For instance, the "Active Power" parameter in monitoring information can be found at holding register 40080 for the SunSpec Modbus profile and at Analog

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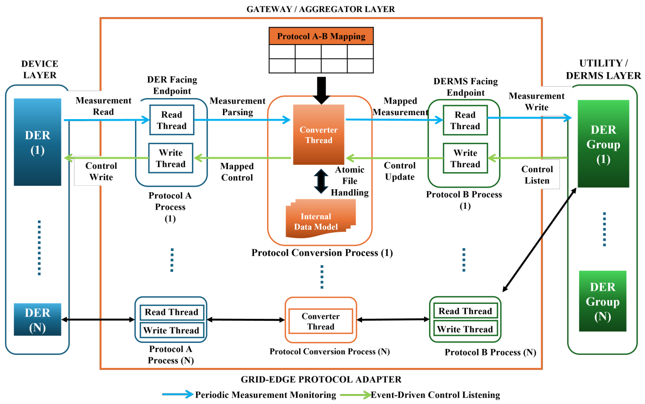

Fig. 3: Functional flowchart of protocol conversion process

Input (AI) 537 in the DNP3 profile. The data mapping resolves this challenge by ensuring the data is preserved and converted across different communication profiles.

B. Protocol Conversion Process

The core of the protocol converter is illustrated in Fig. 3. It enables bidirectional data exchange through three coordinated and computationally lightweight processes, for both periodic monitoring and event-driven control. The overall process is explained below, using deployment scenario 2 as a reference. *(1) Protocol A Process:* This process is responsible for managing the DER devices via Protocol A, and runs two operational threads (for read and write). The read thread periodically retrieves measurements from the DER, parses the Protocol A messages, extracts the relevant DER data, and forwards it to the protocol conversion process. The write thread manages the DER control operations when a command is sent from DERMS. *(2) Protocol Conversion:* This is a single-threaded operation that converts the data between protocols A to B, using the data mapping, and stores it in the internal data model. This internal data model serves as a single source of truth for a DER, utilizing atomic file handling to ensure data integrity. *Process B Process:* This process is responsible for managing the DERMS via Protocol B. It runs two threads: one for reading the DER data from the internal data model and forwarding it to DERMS, and another for receiving control commands from DERMS and sending them to Process 2.

IV. Testbed-based Implementation

To validate the proposed protocol conversion framework, a three-tier DER communication architecture similar to Scenario 2 in Fig. 1 was implemented using the PowerCyber Testbed at Iowa State University [17], shown in Fig. 4. The setup consists of the following: *(i) SunSpec DER device*, *(ii) DER Edge Gateway*, and *(iii) DERMS Emulator*.

A. SunSpec DER Device and Data Model

A key requirement of the framework is a SunSpec-compliant DER device that exposes standardized nameplate, monitoring, and management data. This is implemented as a SunSpec Modbus server running on a Linux VM, using JSON-based SunSpec model definitions and the `pymodbus` library to serve data over Modbus/TCP. Unlike generic Modbus devices with vendor-specific registers, SunSpec Modbus provides a structured, model-based addressing scheme [18] [14], ensuring consistent data representation across DER vendors. A subset of five SunSpec DER models was implemented: Model 1 (Common Model), Model 701 (DER AC Measurements), Model 704 (DER AC Controls), Model 705 (Volt-VAR), and Model 711 (Frequency Droop). The DER also has an interactive session where the DER data can be manipulated local, which allows the user to change the DER data to show dynamic values.

B. DER Edge Gateway and Protocol Data Mapping

The Protocol converter is developed and deployed in the NVIDIA Jetson Orin embedded device. The SunSpec Modbus Endpoint process utilizes the Python-based *pysunspec2* library to manage the DER. The DNP3 Endpoint process handles the DERMS communication using a *Rust-based IEEE* 1815 library. The protocol conversion process uses JSON as its internal data model. For periodic measurement monitoring, the SunSpec read thread polls DER data via SunSpec Modbus, parses the response, and forwards it to the protocol conversion process. The conversion process maps SunSpec data to DNP3 points and stores the results in an internal JSON file. The DNP3 read thread then updates the DNP3 data store and transmits the measurements to the DERMS. For event-based control actions, the DNP3 write thread listens for control setpoints from the DERMS. Upon receiving a DNP3 command, it parses the message and forwards the control values to the protocol conversion process, which maps them to the corresponding SunSpec Modbus registers and stores them in internal JSON. The SunSpec write thread monitors this JSON file, extracts the updated values, and issues the appropriate SunSpec Modbus write commands to the DER.

C. DERMS Emulator

The *Automatak DNP3 GUI*, which is used as a DNP3 master to connect to the DER gateway, is emulated as a DERMS running on a Windows VM. This simulator has the capability to receive and write DNP3 messages, such as monitoring measurements, sending activation or deactivation commands, new control setpoints, or curve settings.

V. Experimental Evaluation

A. Scenario & Assumptions

To evaluate the performance of the proposed protocol converter, representative use cases were selected for both monitoring and control operations. For monitoring, two data-access scenarios were considered. The single-parameter read focused on the DER's Active Power value, located in SunSpec Model 701 at holding register 40080, which is mapped via the protocol conversion rules to DNP3 point AI-537. The multiple-parameter read scenario utilized the 13 data points associated with the Volt-VAR function, comprising two binary indicators and eleven floating-point values. For control, two complementary scenarios were evaluated: writing a single control variable (the Maximum Active Power setpoint from

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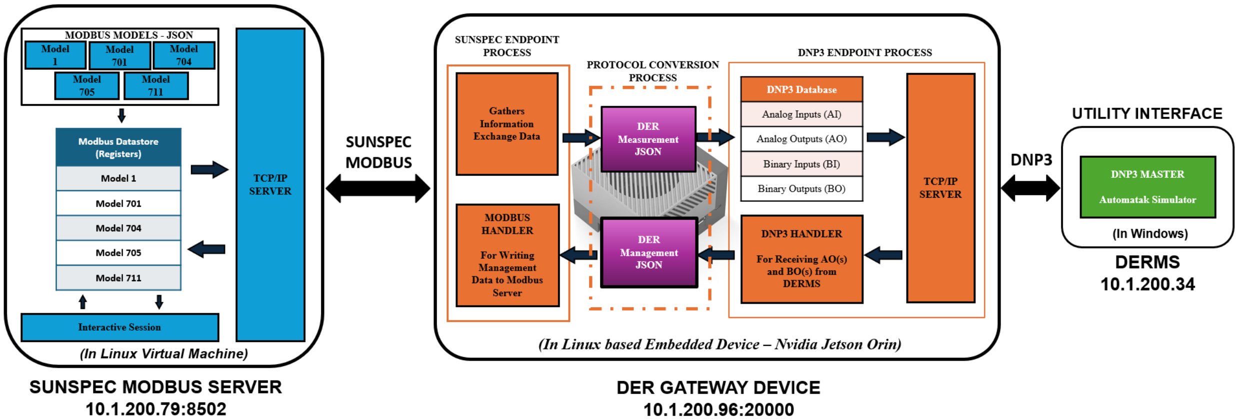

Fig. 4: Experimental testbed architecture for real-time protocol converter implementation

TABLE I: Validation of Implementation against IEEE 1547

Info Exchange Model	IEEE 1547	Our Implementation
Nameplate	✓	✓
Configuration	✓	✓
Monitoring	✓	✓
Management:		
Limit Active Power	✓	✓
Constant PF	✓	✓
Constant Var	✓	✓
Volt-Var	✓	✓
Frequency Droop	✓	✓
Volt-Watt	✓	Future enhancement
Watt-Var	✓	Future enhancement
Voltage & Freq. Trip	✓	Future enhancement
Enter Service	✓	Future enhancement

TABLE II: Latency Thresholds Across DER Levels

DER Assets	Protocols	Latency
DER Clients, Local Controllers	SunSpec Modbus, DNP3, IEC 61850	$\leq$ 10ms
Edge Gateways	SunSpec Modbus, DNP3, IEC 61850	$\leq$ 100ms
DER Aggregators	DNP3, IEC 61850, IEEE 2030.5	500ms$-$1s
DERMS, SCADA	DNP3, IEC 61850, IEEE 2030.5	2 $-$ 5s

the Limit Active Power mode) and writing multiple control variables (the 13 writable parameters corresponding to the Volt-VAR curve settings).

B. Evaluation Metrics

The following metrics have been evaluated to analyze the performance of the proposed protocol converter: *(i) Functional Testing:* verifies DERMS measurement and control exchange through the gateway, ensuring end-to-end interoperability, as per Table I. *(ii) Performance Testing:* measures average latency, maximum latency, and packet drops to assess real-time communication efficiency and reliability, as per Table II.

C. Results & Discussion

Functionality tests verified correct behavior across both monitoring and control paths. As shown in Fig. 5, dynamic changes to the DER's Active Power value were successfully propagated through the gateway and observed at the DERMS in real time, confirming accurate Modbus-to-DNP3 translation

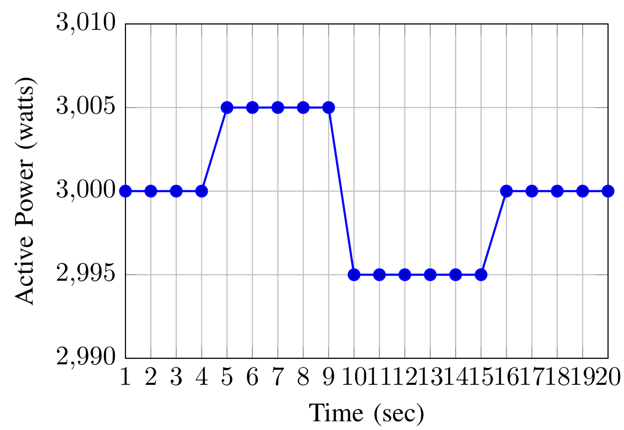

Fig. 5: Periodic DER measurement monitoring at DERMS

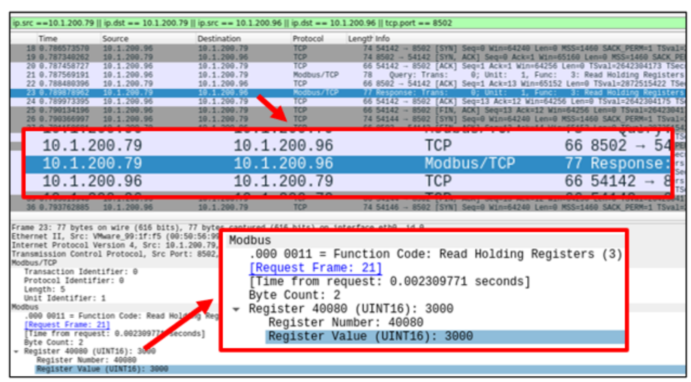

Fig. 6: SunSpec packet capture between DER & gateway

and continuous visibility. For control, the DERMS-issued update to the Maximum Active Power setpoint was correctly received and applied by the DER. SunSpec Modbus messages are captured in Wireshark, shown in Fig. 6. Similarly, the DNP3 messages are also captured and verified, proving that the protocol converter converts the data from SunSpec Modbus to DNP3 for DER Data Monitoring. Similarly, the Control Commands are also verified, proving that the DNP3 control commands are converted to SunSpec Modbus write commands, which are then sent back to the DER.

Performance was assessed across four stages: SunSpec

TABLE III: Consolidated Latency Metrics Across Interfaces

SunSpec Interface	**Avg (ms)**	**Max (ms)**	**Drops (%)**
Single Register Read	2.86	4.86	0.7
Single Register Write	2.84	4.07	0.0
Multiple Register Read	88.09	1044.3	0.9
Multiple Register Write	46.20	900.17	0.5
DNP3 Interface			
Single AI Read	1.66	3.27	0.0
Single AO Write	5.20	9.76	0.0
Multiple BI/AI Read	20.56	121.04	0.0
Multiple BO/AO Write	62.77	78.74	0.0
Protocol Conversion Module			
Single Point Read	12.48	25.07	0.1
Single Point Write	6.02	6.70	0.0
Multiple Point Read	54.83	283.53	0.8
Multiple Point Write	6.06	6.90	0.0
End-to-End Communication			
Single Point Read	17.01	33.19	0.1
Single Point Write	14.06	1448.87	1.7
Multiple Point Read	163.54	20.54	0.0
Multiple Point Write	115.03	985.81	0.5

Modbus, DNP3, the protocol conversion module, and end-to-end communication, as shown in Table III. On the SunSpec interface, single-register operations averaged $\approx$ 3 ms, while multiple-register reads and writes averaged 88.1 ms and 46.2 ms. The DNP3 interface exhibited even lower delays, with single AI reads averaging 1.66 ms and multiple BI/AI reads averaging 20.6 ms, all with zero packet drops. Protocol conversion overhead remained modest: single-point reads averaged 12.5 ms and writes 6.0 ms, while multiple-point reads averaged 54.8 ms. End-to-end communication, including polling, conversion, and DNP3 exchange, averaged 17.0 ms for single-point reads, 14.1 ms for single-point writes, 163.5 ms for multiple-point reads, and 115.0 ms for multiple-point writes, with packet loss under 2%. These results demonstrate that the framework achieves reliable real-time operation well within the IEEE 1547 DER communication requirements, as listed in Table II . Note that the experiments were conducted with only one DER with one instance of the protocol converter.

VI. Conclusion & Future Work

This paper presented a real-time, edge-deployed protocol converter that addresses the interoperability gap between DER and utility/DERMS-level communication. The converter achieves this through a custom SunSpec Modbus server, a protocol conversion module for SunSpec Modbus and DNP3, and real-time end-to-end validation through a testbed setup. Implemented using open-source Python and Rust libraries with a JSON-based internal data model, the converter enables seamless, bidirectional monitoring and control across heterogeneous DER protocols. Experimental results demonstrate reliable data translation with negligible packet loss and end-to-end latencies that meet the IEEE 1547 functional and performance requirements. Future work includes: (1) extending the protocol converter to support other combinations of DER protocols, (2) evaluating the converter's scalability using larger DER deployment scenarios, and (3) incorporating support for additional DER control functions.

Acknowledgment

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