Harness the Power of DERs for Secure Communications in Electric Energy Systems

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***Abstract*—Electric energy systems are undergoing significant changes to improve system reliability and accommodate increasing power demands. The penetration of distributed energy resources (DERs) including roof-top solar panels, energy storage, electric vehicles, etc., enables the on-site generation of economically dispatchable power curtailing operational costs. The effective control of DERs requires communication between utilities and DER system operators. The communication protocols employed for DER management and control lack sophisticated cybersecurity features and can compromise power systems secure operation if malicious control commands are issued to DERs. To overcome authentication-related protocol issues, we present a bolt-on security extension that can be implemented on Distributed Network Protocol v3 (DNP3). We port an authentication framework, *DERauth*, into DNP3, and utilize real-time measurements from a simulated DER battery energy storage system to enhance communication security. We evaluate our framework in a testbed setup using DNP3 master and outstation devices performing secure authentication by leveraging the entropy of DERs.**

***Index Terms*—Authentication, distributed energy resources, DNP3, hardware security, power grid.**

I. Introduction

As the electric power grid advances towards a decentralized architecture, distributed energy resources (DERs) are becoming more prevalent all over the globe. DER generation capacity is expected to proliferate from 132.4 GW in 2017 to 528.4 GWs by 2026 due to their contribution in more efficient grid operation, economical power, low carbon emissions, and more reliable power systems [1], [2]. DERs are small-scale power generation or storage assets, often in the range of 1 kW to 10 MW, placed on the distribution level close to consumers and loads. Examples of DERs include PV systems, electric vehicles, wind turbines, etc. often bolstered by energy storage solutions such as battery energy storage systems (BESS), fuel cells, and flywheels. BESS-based DERs incorporate mostly lithium-ion (li-ion) battery cells as their energy storage elements due to their long life-cycles, high energy density, and low maintenance costs [3].

To harness the power of DERs for grid services, interconnection and interoperability standards, such as IEEE 1547-2020, enforces DERs to include communication interfaces enabling local and bulk power system management and control [4]. DER-to-utility or DER-to-aggregator communication is supported by embedded devices and network protocols [5]. Prominent communication protocols include IEEE 1815-Distributed Network Protocol v3 (DNP3), Modbus, and IEEE 2030.5 [6]. Their non-proprietary nature aids manufacturers in developing custom implementations which lack robust security features or require computationally intensive processes to meet security requirements [7], [8].

Although IEEE 1547-2020 Std. mandates secure communications for DER monitoring and control, there is a plethora of already deployed legacy devices utilizing insecure or outdated communication protocol versions. For example, more than 75% of North American utilities employ DNP3 for supervisory control and data acquisition [7]. DNP3 vulnerabilities undermine not only the security of the communication channel but also the security of devices relying on this protocol. In [9] a comprehensive presentation of DNP3 vulnerabilities is presented. Recently, DNP3 received updates to conform with IEEE 1547-2020 and feature cryptographically secure properties similar to newer protocols (e.g., IEEE 2030.5) [10], however, the protocol has still significant drawbacks and legacy devices still remain a valid concern [11], [12].

As with most cybersecurity problems, there is no single silver bullet which can single-handedly fend off all attacks [13]. We provide a security extension that can enhance utility-to-DER communications while requiring minimum redesign efforts. In this work, we leverage the inherent cell entropy from BESS-enabled DER devices, demonstrated in DERauth [14], to develop a hardware-based security primitive which can be incorporated in DNP3 communications and support secure authentication. We port DERauth functionality to the OpenDNP3 library, an open source reference implementation for the DNP3 protocol [15]. DERauth's security mechanism leverages a challenge-reply scheme, which incorporates real-time BESS measurements, to generate unique cell signatures (secure authentication). Experimental results implemented on the OpenDNP3 stack validate our scheme using battery data generated by simulated li-ion cells. Specifically, our contributions can be summarized as follows: *(i)* we expand our previous work and port DERauth's BESS-based authentication scheme into the OpenDNP3 protocol stack, *(ii)* we utilize simulated li-ion battery measurements factoring their real-world discrepancies for the secure authentication process, and *(iii)* we provide the implementation details of the design which can be ported in any DNP3-assisted industrial control environment reinforcing communications security.

The rest of the paper is organized as follows. Section II describes our methodology. Section III presents the experimental

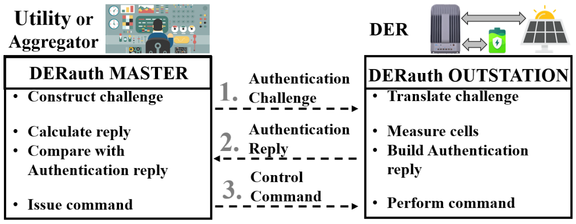


Fig. 1. DERauth secure authentication framework.

setup and results of our implementation. Section IV concludes the paper and discusses future work.

II. DERAUTH FRAMEWORK

The DERauth framework secures the measurement and control command data issued to DERs. It provides a security extension that can be retrofitted to any BESS-enabled grid asset which uses DNP3 with minimum redesign requirements, serving as an authentication layer on top of the DNP3 protocol stack. A high-level overview of the DERauth framework is presented in Fig. 1. It operates using a 64-bit *challenge-reply scheme* between DNP3 master and DNP3 outstation devices (located on the DER side). It requires DER outstation devices to be authenticated before control commands can be issued from the DNP3 master. The authentication process leverages the intrinsic characteristics of the BESS li-ion battery cells to generate entropy. The concept leverages the BESS cell voltage and state-of-charge (SoC) measurements, and incorporates the inherent randomness – caused by the unique li-ion physical properties due to their manufacturing process – for the protocol replies. Below, we outline the core components of DERauth; more details about the implementation are provided in [14].

A. System Components

The communication between a DNP3 master and DER outstation devices is initiated after the enrollment and authentication phases.

Enrollment phase: In this phase, the DNP3 master and DER outstation device start their communication and exchange their cell-reply tables, C_{rt}. The C_{rt} table includes 8-bit sequences (r_i) for each BESS cell which are returned if the specific cell gets authenticated. C_{rt} is defined as $C_{rt} = N \times < c_i, r_i >$, where N is the number of BESS cells, and c_i and r_i represent the i-th BESS cell and its predefined reply, respectively. Notably, the contents of the C_{rt} table get updated at every authentication round and at both communication ends asynchronously. Thus, in the event of a compromise, the attained information does not provide useful details to man-in-the-middle adversaries.

Authentication phase: This phase comprises the main portion of DERauth and can be segmented into three parts.

① First, the DNP3 master constructs the 64-bit challenge. The first 16 bits of the 64-bit challenge define which BESS cells will be polled for their real-time voltages and SoCs. The next 32 bits, indicate which BESS cells need to be authenticated (their corresponding r_is from the C_{rt} table will

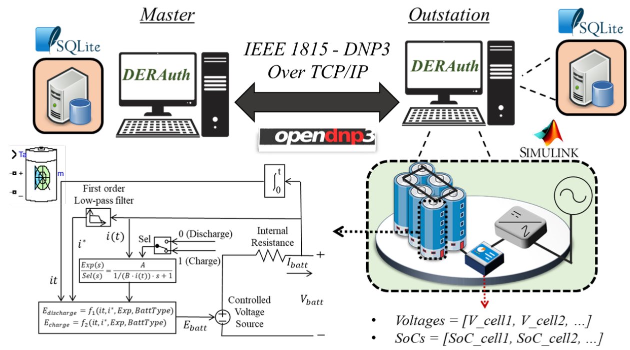


Fig. 2. Top-level diagram of test setup for evaluating the DERauth process using the DNP3 communication protocol.

be returned if the authentication succeeds). The remaining 16 bits instruct the DNP3 outstation device, monitoring and controlling the operation of the DER asset, regarding the type of transformation that will take place before the reply is forwarded to the DNP3 master device.

② The next part of the authentication process occurs on the DNP3 outstation device. Upon receiving the 64-bit challenge, the outstation first translates the challenge and builds a corresponding 64-bit reply following the format specified by the DNP3 master. The DNP3 reply includes the real-time voltage and SoC BESS cell measurements, and the r_is from the requested cells. After this temporary reply is built, it gets transformed using a predefined transformation function, and the last 16 bits of the issued challenge. This transformation increases the reply entropy and once the temporary reply is transformed, it is forwarded to the DNP3 master for validation. The real-time voltage and SoC measurements, in addition to the constantly updating r_is and the transformation function, effectively increase the challenge-reply entropy and the security of our protocol, rendering reconstructing or decoding the exchanged data infeasible.

③ Upon receiving the 64-bit reply, the DNP3 master calculates locally the *expected* reply according to the challenge format and then compares it with the received one. If the local version of the reply – calculated by the DNP3 master – coincides with the received one from the DNP3 outstation, then the authentication round is performed successfully. In any other case, the round has failed, and hence, any exchanged information is dropped and the authentication phase is repeated. Only if the authentication succeeds, then both the DNP3 master and outstation can update their C_{rt} table copies using the exchanged real-time voltage and SoC information. Following this procedure, static information is not retained anywhere in our system (both C_{rt} tables are updated asynchronously), impeding attackers from gaining sufficient system information and reverse-engineering our security protocol extension.

III. EXPERIMENTAL SETUP & RESULTS

A. Setup & Design Parameters

For the evaluation of the DERauth authentication process, we implement a testbed setup where two computing stations

TABLE I

LI-ION CELLS PARAMETERS AND CHARACTERISTICS.

Parameters	**Cell #1**	**Cell #2**
Nominal Voltage (V)	3.5	3.5
Rated Capacity (Ah)	2	2
Initial SoC (%)	64	65
Response Time (s)	5	5
Max. Capacity (Ah)	2.05	2.02
Cut-off Voltage	2.625	2.622
Fully Charged Voltage (V)	4.1	4.1
Nominal Discharge Current (A)	0.4	0.4
Internal Resistance (Ohms)	0.017	0.012
Capacity at Nominal Voltage (Ah)	1.8087	1.7897
Exponential Zone [V, Ah]	[3.88, 0.2]	[3.81, 0.2]

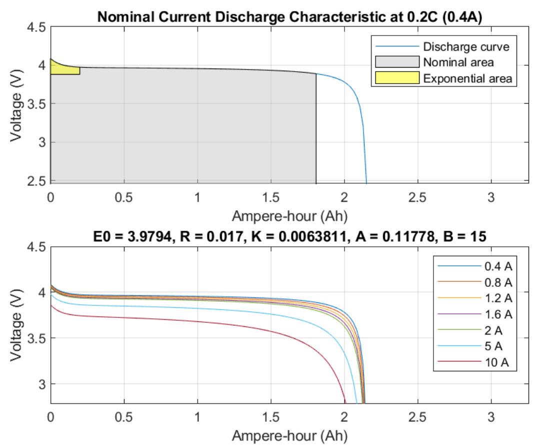


Fig. 3. Li-ion cell #1 discharge characteristics. C is a measure of the rate at which the battery cell is discharged relative to its max. capacity. R is the internal resistance of the battery cell. The parameters E_0, K, A, and B are parameters that model the behavior of the battery cell. E_0 is the constant voltage in V, K is the polarization constant in V/Ah, A is the exponential voltage in V, and B is the exponential capacity in Ah^{-1}.

communicate via DNP3, as master and outstation. Fig. 2 depicts the overall top-level diagram of the test setup. The master and outstation devices are running modified versions of DNP3, using the open-source OpenDNP3 library [15], which integrates the DERauth challenge-reply mechanism and supports an SQLite database to store the temporary challenge-reply values exchanged during authentication. In this implementation, the DNP3 outstation is modeled as an agent that interacts with the BESS, i.e., the DER, and the master DNP3 device is modeled as an agent that sends the corresponding charge/discharge setpoints to the outstation DER.

B. DER Li-ion Battery Modeling

The li-ion cells of the BESS interacting with the DNP3 outstation agent are modeled using the MATLAB/Simscape battery model [16]. This model provides predetermined behaviors for different types of battery chemistries such as nickel-cadmium, lead-acid, and li-ion batteries. It also supports the simulation of temperature and aging effects in the battery cells. In order to obtain realistic values from the battery cell simulations, the cell temperature is also considered, since it can affect the voltage during charge and discharge operations.

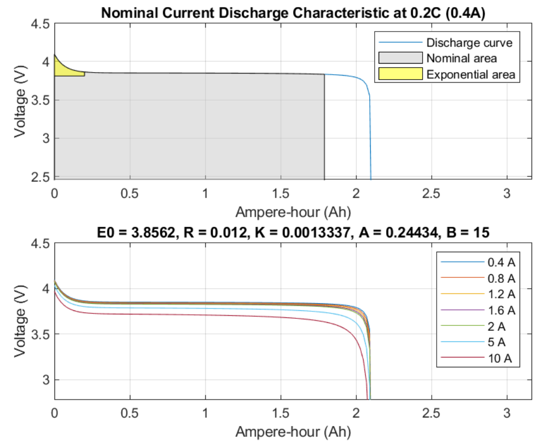


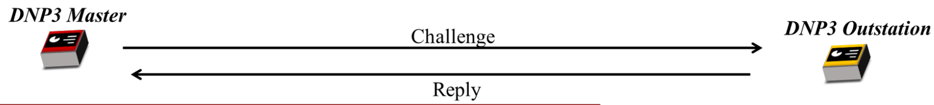
Fig. 4. Li-ion cell #2 discharge characteristics. C is a measure of the rate at which the battery cell is discharged relative to its max. capacity. R is the internal resistance of the battery cell. The parameters E_0, K, A, and B are parameters that model the behavior of the battery cell. E_0 is the constant voltage in V, K is the polarization constant in V/Ah, A is the exponential voltage in V, and B is the exponential capacity in Ah^{-1}.

Six li-ion cells are modeled and two of those cells are used for the DERauth authentication. Figs. 3 and 4 depict the cell and discharge characteristics of the two battery cells selected to provide their respective voltages and SoC values. A battery management system is devised to provide the voltage and SoC measurements from individual cells in the battery system. Table I shows the parameters and characteristics that define the behavior of the battery cell models.

C. Case Study & Results

To assess the operation of DERauth within the test setup presented in Section III-A, a modified version of OpenDNP3 integrating DERauth is deployed in two different computers connected via an Ethernet switch. The DNP3 communication protocol runs over TCP/IP and the master and outstation are configured to interchange 64-*bit float Analog* values, i.e., *Group* 32, *Variation* 8 [10].

In this case study, the master device initiates the DERauth authentication process every time it sends a new setpoint command to the outstation controlling the DER. Specifically, in our scenario, the DERauth authentication challenge is predefined to occur 5 *seconds* before the master sends the corresponding operation command to the respective outstation. Although a 5-second interval is selected for this case study, any other value could also be used depending on the operational requirements. Figs. 6 and 7 present the voltage and SoC measurements from the two cells used in DERauth. The total simulation time is 5000 *seconds*, and four battery operations are requested by the master controller. These operations are: *(i)* a 10 W discharge request at 500 *seconds*, *(ii)* a no-operation (`no-op`) request at 2000 *seconds*, *(iii)* a 10 W charge request at 3000 *seconds*, and *(iv)* a no-operation (`no-op`) request at 4500 *seconds*. At each of these points, DERauth is executed before (5 seconds) the setpoint command is issued. The specific values exchanged by the master and outstation devices during these four authentications are presented in Fig. 5. Notably, the



	Challenge	Reply Authentication		Voltage 1	SoC 1	Voltage 2	SoC 2	Auth. Succeded?
op: #1	0111100000101101000101110101100111000101001111001000101001011100	1011100010111000101110010011100100010111010110011100010100111100	Values	3.69	56	3.70	57	✓
			Binary	101110001	0111000	101110010	0111001	
op: #2	0101010101110001011001011100100110111000110011001001101101101100	1010010000010100101001010001011001100101110010011011100011001100	Values	3.28	20	3.30	22	✓
			Binary	101001000	0010100	101001010	0010110	
op: #3	0011011010101001000101110010011110101100110001010011010010010000	1010110000010100101011001001010100010111001001111010110011000101	Values	3.44	20	3.45	21	✓
			Binary	101011000	0010100	101011001	0010101	
op: #4	1010011010001101010101101100101000110101001110100001110101011101	1011101110110110101111000011011101010110110010100011010100111010	Values	3.75	54	3.76	55	✓
			Binary	101110111	0110110	101111000	0110111	

Fig. 5. 64-bit challenge and replies exchanged between the DNP3 master and outstation during the DERauth authentication process.

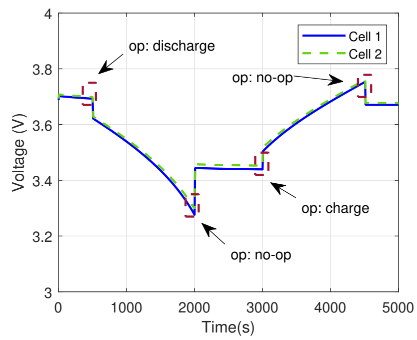


Fig. 6. Voltage measurements for li-ion cells during test scenario operations. The red boxes mark the time when DERauth is performed 5 *seconds* before an operation is carried out.

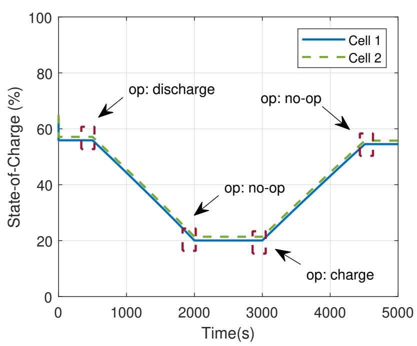


Fig. 7. State-of-charge (SoC) measurements for li-ion cells during test scenario operations. The red boxes mark the time when DERauth is performed 5 *seconds* before an operation is carried out.

voltage and SoC values polled, are used to construct the reply for each corresponding challenge.

IV. Conclusion and Future Work

This paper demonstrates the implementation of a hardware-based authentication framework for DERs. We port DERauth, which leverages existing hardware and li-ion manufacturing variations, into OpenDNP3 enabling BESS-based DER system secure authentication. The implementation is evaluated in a testbed setup comprised of a DNP3 master and outstation device with a simulated li-ion BESS. Future work will focus on assessing the DERauth secure authentication extension in a full-fledged distribution system with multiple DERs.

Master devices upon verifying the authenticity of DER assets will be able to issue control commands to the respective outstation devices. Real-time simulation environments will be used to evaluate the practicality of the DERauth authentication process against other protocols implementations in realistic scenarios and under stringent operational constraints (e.g., traffic, latency) [17]. Finally, the necessary application program interface to integrate our hardware-based security scheme in other existing protocols, such as Modbus and IEEE 2030.5, will be designed.

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