A Unified Testing Platform to Mature Blockchain Applications for Grid Emulation Environments

Preprint

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A Unified Testing Platform to mature Blockchain applications for Grid Emulation environments

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Abstract—**Blockchain technology is a relatively novel technology that can be used to develop more decentralized, autonomous and tamper-evident solutions. A feature that can aid Transactive Energy Systems to reach their goals by enabling individual actors to communicate and reach consensus with other participants in a decentralized fashion. However, technical barriers to evaluate and adopt this type of technology within the electrical domain still exist. To facilitate this task, Blockchain for Optimized Security and Energy Management (BLOSEM) Unified Testing Platform (UTP), a DOE-sponsored, multi-lab effort intends to accelerate the development of solutions by offering a common set of reusable services that can be used to interconnect existent grid tools with blockchain services. The UTP is intended to serve as a development platform that can provide application engineers with the technical means to evaluate potential blockchain solutions, by enabling them to concentrate on the actual application functionality while at the same time abstracting the connectivity and performance measurement tasks. The versatility of UTP is further demonstrated by integrating two use cases to validate the feasibility of implementing these applications as blockchain-based solutions while also demonstrating the UTP features.**

Index Terms—**Blockchain co-simulation, FERC order 2222, Blockchain for TES applications**

I. Introduction

The traditional structure of centralized control is evolving into a decentralized energy system with the accelerating adoption of distributed energy resources (DER) and customer participation. This future includes new stakeholders and regulatory frameworks while maintaining traditional grid goals of reliability, safety, and affordability. Emerging deployments introduce supply variability with little control capabilities, yet present demand side opportunities driving Transactive Energy Services (TES). New stakeholders add the need for equitability and balancing incentives amongst collaborating yet competing entities for shared realization of benefits. Increased trust between stakeholders to integrate operations is required to balance grid constraints with prosumers incentivized to support it. Blockchain and distributed ledger technologies (DLT) provide properties such as transparency, immutability, and distributed consensus. TES applications may leverage these properties for (a) auditability, (b) tamper detection, (c) digitally enforcing contracts, and (d) incentivizing cooperation through secure and efficient transactions.

The Department of Energy (DOE) national laboratories and academic research demonstrations actively explore the use of blockchain for coordinating and controlling DER. For example, the National Renewable Energy Laboratory (NREL) and BlockCypher partnered to demonstrate peer-to-peer energy trading from home solar generation [1], and Virginia Tech demonstrated a home trading market with laboratory scale solar on HyperLedger® [2]. In [3], a co-simulation framework is proposed within *Hierarchical Engine for Large-scale Infrastructure Co-Simulation* (HELICS) [4] to create and evaluate market designs, supplemented by blockchain settlement layers. DOE sponsored small business innovation grants have targeted smart contract orchestration of flexible loads [5] as well as a private network that mediates transactions between prosumers and grid system operators [6]. Additionally, industry has pursued partnerships and pilot projects. One example is the partnership of Ameren Corporation with Opus One Solutions [7] to explore blockchain coordinating DERs as active participants for grid services and transactive energy marketplaces leveraging a microgrid in Illinois. Blockchain performs the role of a distributed ledger for tracking prosumer data and adherence to terms of service. The project begins with software simulation of devices and markets, and progresses to integrating the microgrid's diverse devices and controls.

These projects demonstrate the early stage momentum for solving decentralization and equitability challenges in emerging TES space with blockchain-based solutions. This paper presents a *Unified Testing Platform* (UTP) framework and implementation template, developed as a part of the BLOSEM project [8], for abstracting communication between blockchain and grid tools, and enabling application-centered testing for agnostic performance evaluation. By enabling rapid reconfigurability, reusability, and interoperability through the UTP, technology developers can focus on maturing target applications and accelerating solutions to market. For this paper, the UTP is demonstrated with a DER-based use-case intended to help address FERC's order no. 2222 requirements [9], in which a local grid operator has oversight capabilities over DER aggregator bids participating in wholesale markets. Section II of this paper details the architecture and functional responsibilities. Section III details the application of the framework, while section IV and V present the results and conclusions.

II. Platform Architecture

A. BLOSEM Overview

BLOSEM is sponsored by the U.S. DOE's Grid Modernization Initiative (GMI) and is a multi-laboratory effort led by National Energy Technology Laboratory (NETL) with Pacific Northwest National Laboratory (PNNL), National Renewable Energy Laboratory (NREL), Ames Laboratory, and SLAC

This work was developed based on co-funding from the U.S. Department of Energy's Office of Fossil Energy & Carbon Management, Office of Electricity, and Office of Nuclear Energy as a part of the Grid Modernization Initiative.

National Accelerator Laboratory. The goal of BLOSEM is to create a modular and interoperable testing platform, the UTP, to represent a variety of use case scenarios in a modern grid for evaluating the performance of blockchain solutions. The UTP is currently deployed with two demonstration use cases implemented within the UTP services. The vision of the UTP is to help validate prototypes, enabling an increase in the Technology Readiness Level (TRL), and to accelerate the transition pipeline from the lab to the energy sector.

B. Architectural Domains

When designing the approach to investigate concepts for blockchain applications in the energy sector, it is helpful to assign the planned functional components and integration points to three relevant domains for an evaluation (see Fig. 1). These domains are defined as Blockchain, UTP Core, and Grid Emulation. In this manner, components such as blockchain peer nodes and physical devices may be assigned to a domain. Additional required components are then identified to enable the routing of commands and information between domains. Throughout this paper, requirements and example implementations will be presented in these three domains.

1) Blockchain: This domain contains all technology and network specific components needed to evaluate a blockchain application. As shown in Fig. 2 most components are intended to be coupled to the specific blockchain under test. However, it would also contain client components that abstract execution of smart contracts and integration points for UTP components to execute those transactions. Example components include peer nodes, ledgers, smart contracts, consensus protocols, access management, off-chain storage, and support applications.

2) UTP Core: This domain contains all middleware and support services to connect the blockchain to grid emulation and test components for evaluating performance. Additionally, this domain would contain the integration points for blockchain applications to publish and query the environment as well as the communication connections to the grid emulation. Example components include data storage, APIs, log storage, search engines, and emulation platforms.

3) Grid Emulation: The grid emulation domain contains all cyber-physical components, simulation applications, and communication protocols that emulate grid components and dynamic behaviors. Example components include grid simulators, supervisory control networks, physical devices, and custom simulation modules (such as HELICS).

C. Functional Responsibilities

As a part of the BLOSEM objective of accelerating the maturation and de-risking the adoption of blockchain solutions for energy applications, the UTP services were developed to enable interoperability and reusability for rapid connection to existing grid co-simulation and cyber-physical laboratories. The UTP is designed to decouple the dependencies for grid emulation components from a blockchain under test, and enable the evaluation of diverse blockchain technological approaches to solving a common use case. Additionally, the UTP enables more rapid reconfiguration of the grid emulation components for new end-to-end grid emulation scenarios. To implement UTP core services, the following five functional responsibilities have been defined for the UTP environment:

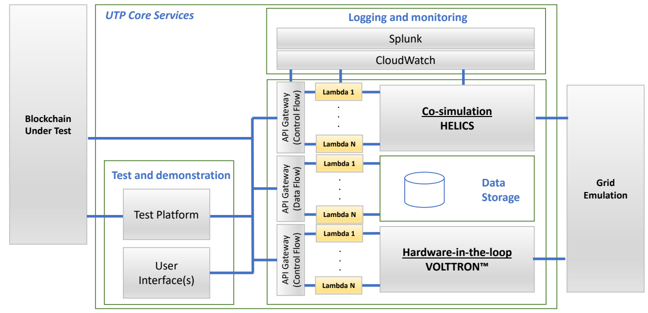

Fig. 1. Unified Testing Platform (UTP) Architecture

- *Edge connectivity*– Provides communication interfaces for the grid emulation environment. These are the connection endpoints, request formats, and authentication/authorization mechanisms for submitting requests to publish control actions and query data into the grid scenario.
- *Control and data flow*– Software modules and infrastructure enabling the flow of information between the blockchain and grid emulation environments. This is an extension of the connectivity responsibility, it appends processing and routing of information (source-destination) within the UTP which includes the ability to route information to data storage, co-simulation modules, and cyber-physical components.
- *Time synchronization and management*– Coordination of time within asynchronous, concurrent environments. End-to-end solutions include three independent time domains (blockchain, UTP, and grid emulation). These environments represent needs for independent time and shared time to coordinate tasks which includes both real-world time and faster/slower co-simulation time.
- *Testing infrastructure*– Infrastructure to host and execute the testing and analysis applications necessary for a blockchain evaluation framework. This responsibility includes the resources to execute tests, collect logs, collect metrics, calculate performance, and analyze the results.
- *System automation and data orchestration*– Rapid configurability and deployment to define components, resources, and data connections within the grid scenario.

III. Application

A. Demonstration Blockchain

To demonstrate an implementation of use cases, BLOSEM implemented a HyperLedger Fabric network in the IBM Cloud. Fabric is a permissioned, private blockchain enabling BLOSEM to experiment with different configurations of channels and data sharing paradigms. The Fabric solution provides metrics and logging interfaces (e.g., Prometheus) to enable direct collection of information for evaluation requiring direct information from the network. Fig. 2 illustrates the template architecture and components utilized for a demonstration blockchain. This is responsible for providing the following functionality to enable the maturation of UTP core services:

- *API service gateways*– Decouples the UTP from direct integration to the blockchain network, API applications imple-

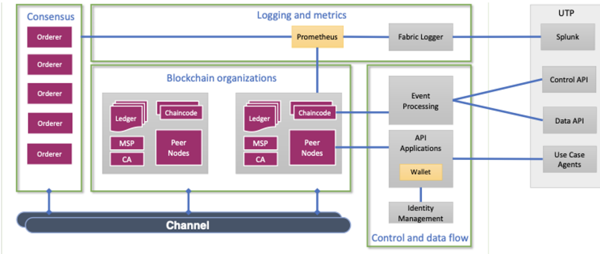

Fig. 2. Demonstration Blockchain Architecture

ment reusable endpoints to route publish and query requests to the Fabric network smart contracts. To participate in a blockchain network, client applications use digital wallets to establish their identity within the system.

- *Fabric network*– Fabric components are implemented for executing smart contracts, immutable ledgers, and distributed consensus (using cloud infrastructure). Each use case configures multiple channels, deploys smart contracts, and specifies endorsement requirements from peers and organizations. Transactions are submitted to peer nodes, organizations then authenticate and authorize identities.
- *Support applications*– When necessary, use cases may leverage the Fabric feature to emit events (e.g. smart contract, block, and transaction) to trigger specific tasks within the UTP. Virtual infrastructure services enable the execution and connectivity of support applications to listen and process events from the Fabric network.
- *Logging and metrics*– Service provider logging from virtual infrastructure and Fabric metrics capture execution logs and internal metrics from peers and orderers.

This demonstration network and template architecture, provides an example for interfacing new blockchains and decoupling dependencies from the grid emulation environment.

B. UTP Services

Fig. 1 illustrates the functional components necessary to provide the five functional responsibilities. To demonstrate the blockchain evaluation framework, the BLOSEM team implemented the UTP core services in an Amazon Web Services (AWS) environment. However, the UTP provides a template architecture for both on-premises and multi-cloud adoption. The primary elements of the UTP core services are:

- *API Gateway*– The API gateway service is used to expose control and data endpoints via HTTPS requests within the UTP environment. These endpoints are defined to perform data format validation, authentication/authorization, and to forward the request to processing layer Lambdas.
- *Control and data flow*– The processing of inbound requests is handled by Lambda functions. Lambdas extract context information from the request body, perform immediate error handling, and route the request to the target processing service (e.g. data storage). For cyber-physical systems (e.g., hardware-in-the-loop components), an instance of VOLTTRON™ serves as an I/O bridge to real world devices. For co-simulation environments, instances of HELICS handle simulation requests (e.g. PV DERs).
- *Data storage*– Off-chain databases enable use cases to store operational information such as measurements, configurations, and processing logs. The VOLTTRON™ and HELICS platforms incorporate storage agents to publish use case information to the database. Blockchain and external applications may utilize the REST API endpoints for data flow to publish and query into data storage services.
- *Logging and monitoring*– Each UTP component publishes application logs to a monitoring service such as CloudWatch or log tables in data storage. Inbound/outbound data exchanges within the UTP are recorded for metric calculation and performance analysis. The logs are ingested into a data management platform such as Splunk. Common logging modules and example log formats optimize Splunk indexing and correlate common tags across events.
- *Test and demonstration*- Use cases may leverage virtual machines to deploy, initiate and demonstrate use case requirements. This includes User Interface applications and custom scripted scenarios. Automated testing platforms, such as PyTest, can be leveraged to execute automated test scenarios (e.g., to validate use case workflows).

C. Platform's demonstration use cases

Through the aforementioned architecture, the UTP can host reusable functionalities as well as mechanisms to automate metric collection. This accelerates the ability to evaluate the fit of a blockchain solution for an energy delivery application, while enabling interoperability between real world hardware and emulated energy delivery environments. However, in order to demonstrate its functionality, a set of sample use cases serve both as validation tools and to demonstrate the capabilities of UTP. These use cases can be summarized as follows:

1) DER coordination and control: The use-case provides an implementation of the FERC order 2222 [9] which mandates independent system operators (ISO) to integrate DER-Aggregators (DERA) as a new category of market participants on behalf of the DERs. This work focuses on enabling bid-level verifications by the local grid operator.

2) Supply chain security: The energy sector is supported by a multistakeholder, global supply chain. The integrity of an asset through logistics and during operations as well as a traceable provenance of changes throughout a lifecycle become critical for trusting operations. This demonstration use case utilizes blockchain strengths to more securely confirm asset integrity, track lifecycle changes, digitize contextual information such as bills of materials, and correlate shared vulnerabilities across organizational actors.

IV. Demonstration of DER use case

A. DER coordination and control

In this section, an extended presentation on the DER coordination and control is demonstrated. The use case has the following high-level objectives: (1) Demonstrate BLOSEM platform components, under a blockchain-based environment, leveraging existing grid simulation tools, (2) Serve as a template for a distributed architecture that enables disparate DERs and other energy entities to participate in wholesale market

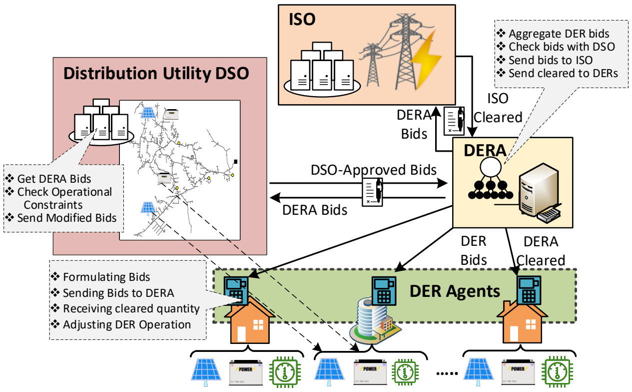

Fig. 3. Conceptual overview of the DER coordination use-case.

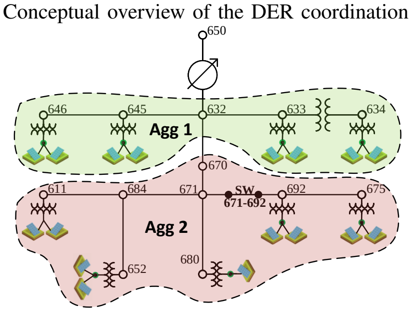

Fig. 4. Modified IEEE 13 bus test system.

operations through the use of DERA and (3) Enabling the establishment of trust anchors through the use of blockchain technology in an otherwise trustless environment.

A secure and reliable integration of DERs to wholesale markets would require coordination among the different entities such as DERs, DERAs, DSO and ISO (as shown in Fig. 3). These actors are implemented as agents through a blockchain enabled co-simulation framework to evaluate the market implementation. The co-simulation tool, HELICS is integrated to the framework which facilitates the information exchange process among the distribution network simulator, DERs agents, DERAs and ISO while offering time-synchronized operations. In addition to the market specific components, the framework also incorporates agents to perform the UTP services; (1) web agent to perform the blockchain actions enabling DERA-DSO interactions and (2) storage agent to interface with data storage services.

1) Feeder Agent: The feeder agent emulates the operation of active distribution networks and uses the power system simulation tool OpenDSS [10], to model distribution feeders along with DERs and run the power flow simulations based on the setpoints received by the DER at each timestep. A python wrapper was used to interface with OpenDSS for dispatching the DERs and obtaining grid measurements such as voltage from the power system at the end of each time step and store it in the database via the storage agent.

2) DER Agent: The DER agents (e.g software-based actors) are responsible for coordinating bids with the DERA at every market cycle. The agent estimates the DER's consumption/generation, $Q^{bid}_{DER}(t)$, for the market interval t based on current, self-determined operating conditions and formulates its price-responsiveness (bids) based on forecasted prices ($P^{bid}_{DER}(t)$). The agent communicates their bids to the registered DERA along with the device IDs, at every market cycle and adjusts its operation based on the cleared allocation and sends the dispatch set points to the feeder agent.

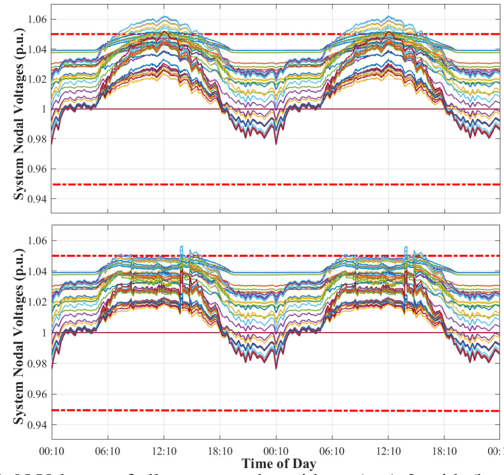

Fig. 5. L-N Voltages of all system nodes without (top) & with (bottom) DSO.

$$DER_{bid} = \left\langle Q^{bid}_{DER}(t), P^{forecast}_{DER}(t) \right\rangle \quad (1)$$

3) Aggregator (DERA) Agent: The DERA agent receives and validates bids (e.g. DER registration, quantities). The agent then communicates assembled bids (per-DER IDs), using blockchain, to the distribution system operator (DSO) which asserts the operational feasibility for the DERA bids. Blockchain provides a neutral trust anchor while enhancing the system's overall transparency. The feasible bids, returned by DSO, are aggregated and sent to the ISO for clearing. During dispatch, the DERA agent determines the DER allocations and returns them to corresponding DER agents.

4) DSO Agent: The DSO agent design ensures operational feasibility as DERs participate in wholesale markets. This agent computes the node voltages based on the DERA bids for a given market cycle. This is achieved through a network simulator model (via GridLAB-D [11]) which acts as a digital twin of the feeder for the DSO. In the event of a voltage violation, the agent proportionally modifies all DER bids until the system voltages are within permissible limits ($\{0.95, 1.05\}$). Once the operational feasibility is verified, the updated DER bids are sent to the DERA through the blockchain. Although, the current design only evaluates the bids for voltage violations, it can be easily extended to incorporate other concerns.

5) ISO: The ISO model is relatively simple where all DERA offers are cleared and allocations are sent for dispatch.

B. Experiment Design

The proposed use-case is demonstrated using a modified IEEE 13-bus test feeder that assumes select-nodes to have customer owned solar PVs acting as DERs (shown in Fig. 4). The solar PVs are registered to DERAs (*Agg 1* & *Agg 2*) which enables their market participation. The experimental setup is simulated over a period of 2 days. The experiment is supported by an AWS-hosted Fabric environment with a dedicated bid evaluation application via a smart-contract. The smart contract and associated access credentials are exposed to

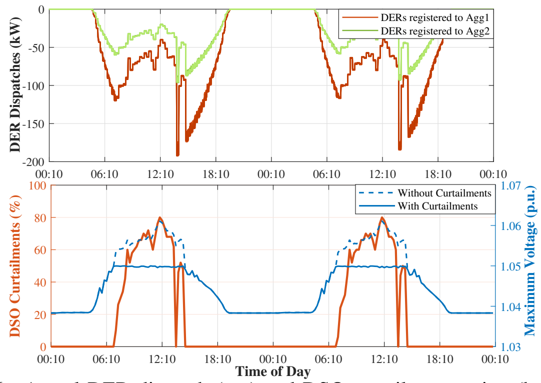

Fig. 6. Actual DER dispatch (top) and DSO curtailment action (bottom).

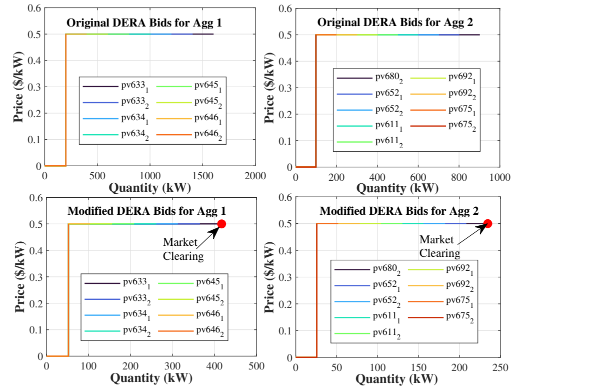

Fig. 7. *Agg 1* & *Agg 2* Bids for the market cycle at 12:29 of Day 1.

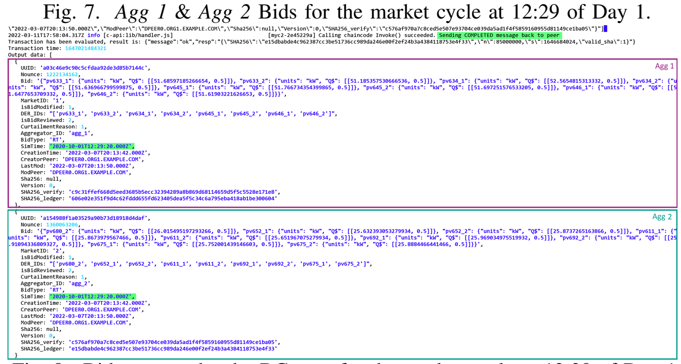

Fig. 8. Bids as seen by the BC peer for the market cycle at 12:29 of Day 1.

participants via an API interface. A screenshot demonstrating a request as is being processed is presented in Fig 8.

C. Performance Evaluation

The L-N node voltages of the test system, in absence of DSO interactions, are shown in Fig. 5(top). This indicates susceptibility to voltage violations when DERAs directly participate without any DSO supervision. The DERA-DSO interaction through blockchain exchanges ensures operational voltages to be within limits (see Fig. 5(bottom)), as the DSO checks all the DERA bids for possible violations and proportionally curtails them for feasible operation. Fig. 6(bottom) shows the maximum system voltages with the original and modified bids as identified by the DSO along with the imposed curtailments. Fig. 6(top) illustrates the actual DER dispatches. The DERA bids for one such interval are shown in Fig. 7 where the original DERA bids were curtailed to ensure feasible operation. The use case illustrates the end-to-end interactions among the grid entities and demonstrates the platform's capability of evaluating FERC order no. 2222 implementations.

V. Conclusions

Emerging architectures for TES are introducing the need for equitable, decentralized, and democratized operations with customer participation. Blockchain and DLT solutions present an opportunity to meet these needs through their inherent technological properties. This work presented a UTP design template and implementation of services for technology developers to more rapidly mature and reduce risk to accelerate solutions into the energy sector. This work described the UTP responsibilities and implementation details to achieve this in a use case agnostic manner with blockchain interoperability. Additionally, the services presented enable application-centered testing for evaluating diverse blockchains for an implemented use case. For demonstration, this paper implemented a blockchain-based FERC order 2222 application for integrating DERA participation in wholesale market operations with oversight from a DSO acting as the local grid operator. This demonstration integrated a HyperLedger Fabric solution as the trust anchor for transactions using HELICS, GridLAB-D, and OpenDSS to simulate participants and the grid scenario. Additional metric capturing and analysis tasks are on-going and will be published in upcoming works, it is expected that the UTP will continue to grow its evaluation capabilities and physical laboratory integrations which will enable BLOSEM to reduce overall developer effort and accelerate blockchain application readiness.

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