Transactive Energy Challenge Energy Management in Microgrid Systems

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***Abstract*—There has been extensive work in the abstract TE model as well as other standards based on Energy Interop, such as the Transactive Energy Market Information Exchange (TeMIX). However, we have yet to see a pilot demonstration that proves the efficacy of this mechanism in the context of a microgrid.**

The output of this team's work in the TE Challenge is the framework for an open-source, open-standards, Java-based implementation of the TeMIX platform, from use cases and requirements to a sample architecture for both Market Participants and a Market Facilitator. This will provide the basis for a live implementation of the Transactive Energy concepts in the next phase of the Transactive Energy Challenge.

***Index Terms*—microgrid, TeMIX, Common Transactive Services (CTS), Internet of Things (IoT), energy storage, Energy Interoperation**

I. Introduction

MICROGRID implementations, both on and off the utility power grid, are growing at an increasing pace year after year. This can be attributed to several factors including the increased availability and affordability of energy storage and renewable energy sources, advancement of interconnection standards the proliferation of rural electrification projects, and increasing cybersecurity requirements. The complexity of off-grid microgrids increases depending on the number and type of energy resources, storage, and loads on the system, as well as the increasingly complex network control systems that maintain balance and inform the network operators. As participants in the NIST Transactive Energy (TE) Challenge, the Microgrids team seeks to develop a reference implementation, including both simulation and pilot demonstration, to show the reduction of the complexity within microgrid solutions through self-organization of resources by using market principles. This reference architecture will provide the basis for future research and demonstration projects for a variety of grid-connected customers including campuses, commercial spaces, households, and other members of the Internet of Things.

II. Problem

Operating a microgrid off the electric grid can be a challenging endeavor. Traditionally, microgrids have relied primarily, if not solely, on gas generators as an energy source. This is a very reliable source of power as long as the fuel source is reliable and loads are managed.

A. Introduction of Renewable Energy Sources

Renewable energy sources are beginning to replace generators as the primary energy resource due to lowered long-term costs as well as environmental regulation. Their intermittent generation characteristics often force the addition of energy storage into the microgrid installation, which can create challenges in the operation of the grid including the optimal scheduling of energy storage devices and the scheduling of non-critical loads to balance the energy of the system.

Fortunately, as the shift is occurring to use more renewable energy, improved control of individual loads in the system is becoming possible through the class of devices belonging to the Internet of Things. These devices include electric vehicle chargers, appliances, light bulbs, and plugs that are newly addressable using modern, easily implementable communication protocols.

B. Need for Forward Looking Operation

Traditional management of the electrical grid requires some forward-looking operation planning to maintain the reliability of the grid as well as for economic dispatch. Despite the reduction in scope of a non-grid-connected microgrid, forecasting is a vital part of optimized and reliable operation, especially when renewable energy is the primary energy source.

For example, a microgrid that is solar-powered should be sized to produce power in excess of loads throughout the day. Knowing that several overcast days are in the forecast may change the strategy of the execution of non-critical loads, and prioritize maximizing energy storage.

This forward operation can be done through complex

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customized controls installations as is frequently done today. However, this team seeks to demonstrate that through the implementation of a standards-based transactive energy approach, the microgrid resources can self-organize to produce optimized results with minimal integration time.

Further, the support of forward market transactions can incentivize and minimize the risk of investments in generation and storage assets by allowing participants to purchase long term forward contracts with those assets.

C. Current software availability

The TeMIX [1] implementation of transactive energy defined by Ed Cazalet was chosen in the early stages of the project due to excellent support of forward tenders, scalability, ease of implementation, and adherence to the OASIS Energy Interoperation (EI) standard [2] which is widely adopted and used in demand response and transactive energy today. Additionally, the TeMIX specification is compatible with the Common Transactive Services [3] defined by the TE Challenge group which developed a simple set of services to allow integration and mix-and-match deployment currently available transactive energy implementations.

III. Design Activities

An agile software engineering process that included use case elicitation, requirements specification, formal design, and testing procedures largely governed the activities of the team. Completed in Phase I of the TE Challenge were steps from the Design Phase. Implementation and testing will follow in Phase II.

A. Use Cases

Use cases are the series of related interactions that help users of the system to achieve a goal. Both UML Diagrams and text-based use cases were developed in the initial phases of the TE Challenge. The use cases developed are described in Table I.

The three actors in the system as defined by the Microgrids Team are the Market Participant, the Market Facilitator, and the Market Maker.

The Market Participant can be a solar inverter, a battery system, an electric vehicle, a IoT-enabled lightbulb, or even another microgrid. Market Participants are usually represented by an *agent* that supports market interaction.

The Market Maker is a special kind of Market Participant in the TeMIX implementation that is not a producer or consumer or energy. Instead, it helps to increase market liquidity by frequently issuing a series of small buy/sell forward tenders.

The Market Facilitator's role in the system is to allow Market Participants to enroll in the market, determine if tenders are valid in the current market context, record tenders and transactions, and determine transaction settlement.

B. Requirements Specification

The defined use cases lay the groundwork for the requirements specification. A requirement consists of the smallest unit of individually testable work. The requirements do not specify the details of the technical implementation.

TABLE I
Use Case Summary

Use Case Name	Description
Enroll	Market Participants registered with the Market Facilitator confirm presence in order to begin receiving and sending tenders.
Tender tender	Submit a new tender in the expected format, or accept/reject an existing tender as the counter party.
Determine price	If submitting a new tender, determine the ask price; otherwise, determine if ask price is acceptable.
Accept transaction	If price is acceptable, accept tender as a transaction and schedule Market Participant accordingly.
Provide power	At the start time recorded in the transaction, the Market Participant will modify operations to provide the requested power to the local microgrid.
Accept power	At the start time recorded in the transaction, the Market Participant will modify operations to accept the requested power from the local microgrid
Deliver report	At the completion of the transaction or on another agreed-upon interval, the Market Participant reports telemetered data recording the power generated or accepted.

Full text-based use cases are available online at: https://github.com/TransactiveEnergy/microgrids/blob/master/UseCases.docx

However, they do lay the groundwork for the system design and testing procedures. The developed requirements [4] were specified in the context of all market participants within an off-grid microgrid but most are applicable in a larger setting.

C. Software design

The design of the demonstration system is based on the development of multiple software packages, which in turn are composed of multiple components. Each package would be created in the Java programming language. This software design will be implemented in the next phase of the TE Challenge.

The Energy Services Interface (ESI) [5] package will be composed of two major components: a lightweight agent interface that represents the Market Participant, and the communications framework necessary to send and receive transactive messages in the chosen implementation, in this case, TeMIX.

The complexity of the creation and acceptance of the transactive messages is to be separated from the agent implementation to allow for the rapid development of compliant devices that can participate in the market. The agent interface is a minimal distillation of the technical requirements that must be completed for a device to function effectively in the market as a participant:

1) Price Strategy

The agent implementation for the device must be able to provide a function or a constant to gauge the acceptability of a price listed in a particular tender in order for the ESI to determine whether the tender should be accepted or rejected. This may be a very simple function for a light bulb or similar, or a more complex curve for an energy storage device. If the participant were initiating the tender, the function or constant would allow the ESI to list the appropriate price for the time period in terms of the tender.

2) *Forecasting*

In order to accept or reject tenders appropriately, the agent implementation must be able to forecast power generation capabilities or demand. A solar inverter may implement forecasting based on historical averages along with the upcoming weather forecast in order to participate days in advance, while a plug load may only be able to forecast the need for the same quantity of power for the next forward interval.

3) *Scheduling and Control*

Once a tender is accepted and a transaction is recorded, the agent implementation must have a mechanism to ensure that the changes in operation occur as documented. For a light bulb, this may be as simple as turning the light on, whereas a battery system may require a stream of constant commands based on the voltage and current.

4) *Reporting*

At the completion of the transaction (or more frequently if needed), the ESI will transmit telemetered data associated with the scheduled activity as confirmation of adherence to the transaction. This requires the agent implementation to have some level of data acquisition and historian functionality in order to adequately produce the data necessary for the report.

A secondary code package would contain the TeMIX implementation for the creation of binding and non-binding tenders, transaction acceptance, and reporting. The ESI will be developed such that interaction with the market can be overridden to implement other transactive energy methodologies as desired.

The Market Maker software package will use a subset of the functionality in the ESI package. It will require only the ability to determine the next price to include on the forward tenders, and to do that, the ability to forecast the system demand based on the acceptance of tenders in the various forward time intervals.

The Market Facilitator software will be composed of multiple software packages that may be installed locally to the microgrid or in a cloud such as Amazon Web Services. Larger implementations may have a distributed network of Market Facilitators for resiliency and scalability. For the purposes of the next phase of the TE Challenge, this will be centralized in the cloud-based Amazon Web Services EC2 service to allow access to multiple participants.

The Market Facilitator will be implemented in a modular fashion such that any of the required components can be replaced and can be developed independently. For example, in an off-grid microgrid setting, particularly with a single owner, the Market Facilitator implementation will not require the complete functionality that future grid-connected implementations will need. These modules within a Market Facilitator include:

1) *Enrollment*

The Enrollment module provides the functionality to authenticate and authorize Market Participants in the system. This module must implement the enrollment mechanism outlined in the Energy Interoperation standard. This would also include the necessary functionality for registration, user management, and the user repository itself.

2) *Validation*

Tenders and transactions submitted are subject to validation against the market context. This may be implemented as a simple set of conditions or as a complex rule processor depending on the complexity of the implementation.

3) *Ledger*

In addition to recording upcoming tenders and transactions, the Ledger would manage the delivery of meter data from the Market Participants and record it within the system. The implementation for this may range from a simple centralized ledger to the newer block chain implementations that allow for a more easily distributed architecture.

4) *Transaction Settlement*

This element would be required for any microgrid where the assets in the system that are the Market Participants are owned by more than one person. This module would be responsible for using the Ledger module to determine the settlement of the transactions.

The Market Facilitator's modular design will allow the implementation to evolve over time. For example, if desired, the Validation module can be implemented as a set of conditions in the beginning stages, and later incorporate a formal semantic model in subsequent stages of the project.

Cybersecurity and data privacy are also technical requirements that are central to the development of the Market Facilitator. The system will require strong encryption in all communications and stored data, as well as careful authorization of users within the system to perform various functions.

The Market Context [1][2] informs the final aspects of the technical design of the system. The context can describe the products transacted, the transaction interval, how often tenders are created, and other rules that govern the system.

An off-grid microgrid may or may not offer transport as a product, but if it is offered, a separate Market Facilitator may be needed for each of the power and transport products offered. A smaller 4-second transaction interval would require more computing resources than a system with 5-minute transaction intervals.

IV. Implementation

The next phase of the TE Challenge will focus on implementation and testing of the Energy Services Interface and reference Market Facilitator in both a simulation and demonstration in a working microgrid.

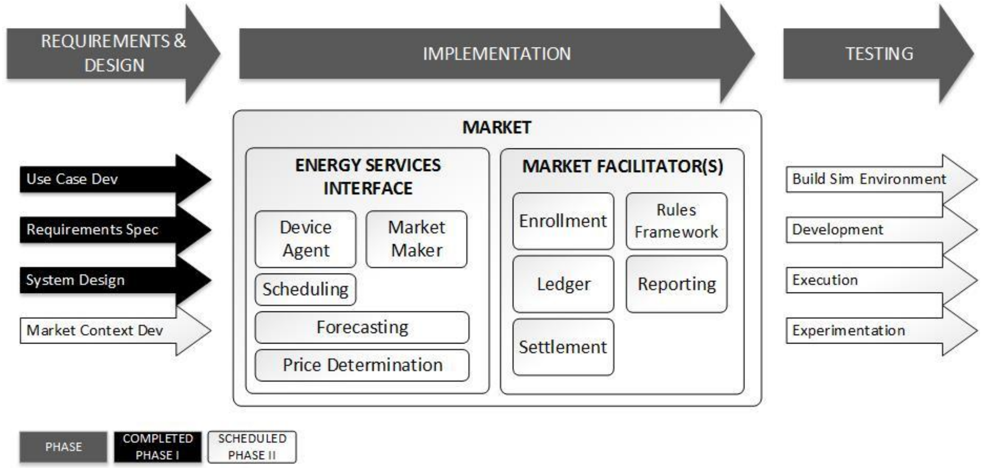

Fig. 1 Outlined tasks for the Microgrids team for the TE Challenge.

As the implementation is completed in the next phase, specific experiments will be conducted which modify aspects of the demonstration (see Figure 1). Examples may include updates to the market context to change the transaction interval, evaluating nested microgrids, or the addition of multiple market makers. The goal of these experiments will be to illustrate the effects on liquidity and stability of the market and the stability of the microgrid as a whole.

V. Related Work

Although this TE Challenge project's reference implementation is in progress, there are related efforts in a microgrid setting that we can examine as case studies.

A. Dynamic Microgrid Configurator

As an active member in the TE Challenge Microgrids group, Tata Consultancy Services (TCS) developed a simulation showcasing their concept of a Dynamic Microgrid Configurator using Transactive Energy principles to dynamically honeycomb (irregular honeycombs) the Utility's territory into numerous Microgrid cells linked together by smart technology [5]. This will serve as an effective tool to implement a Microgrid Based Operation Model (MGBO). This will be effective in: maximizing the number of customers served under all conditions (including major contingencies) as well as effective utilization of distributed green energy resources

The DMC needs to be well integrated into the TE architecture through mature interfaces based on standards such as Energy Interoperation (EI). This treatise will propose an interface model of the DMC to the other systems whereby the Distribution System Operator can interact with the entities involved (Customers, Aggregators, Other Microgrid Operators, and other Market facing entities) to effectively operate and manage the entire distribution service area.

The detailed implementation of DMC in progress. The mathematical basis for the DMC algorithm is being developed by Indian Institute of Technology Bombay (IITB) a co-innovation partner of TCS. Presently a simulation model with limited interfaces (Event & Report) has been completed.

In the next phase, DMC and its interoperability requirements will be tested through simulated TE scenarios and the results will be analyzed to enhance the design. Message structure defined in Energy Interoperation specification **Error! Reference source not found.** will be adapted with necessary extensions to realize the MGBO, mainly to exchange information on reliability, and emergency condition information.

B. Dynamic Market Mechanism

Since 2012 the Active Adaptive Control Lab (AACLab) at MIT has been developing a dynamic market mechanism (DMM) to solve the optimal power flow problem in a fast, distributed, and adaptive way [7]. Taking advantage of the fast timescale, recent DMMs have been developed to regulate frequency in wide-area grids [8]. Currently, DMMs are also being developed to manage power in combined heat and power microgrids and to work with the active primary control systems in microgrids.

The core technology of the DMM is an iterative primal-dual convex optimization method. The DMMs require iterative methods in order to be dynamic, which allows the algorithm to incorporate new information, such as updated grid conditions or renewable energy forecasts as it is available, even within transactive windows.

VI. Conclusion

The second phase of the TE Challenge Microgrids project is key to laying the groundwork for future Transactive Energy demonstrations with a larger group of Market Participants utilizing the existing power grid. The experiments and simulations conducted as part of this work will help to guide these future implementations, and the software product deliverables will also provide the base for continuing work in this area.

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Edward Cazalet is a leader in the design of transaction services for electricity, the commercialization of electricity storage, and the analysis of energy decisions. Ed is the founder and CEO of TeMix Inc., a transactive energy services company and a founder and VP of MegaWatt Storage Farms Inc., a grid storage advisory firm. He was previously a Governor of the California Independent System Operator (CAISO). He was also the founder and CEO of Automated Power Exchange (APX), the first on-line, wholesale power exchange.

Dr. Cazalet has extensive experience in designing, building and operating high-speed, reliable transaction systems for electric power that interface with existing transaction systems and markets. Dr. Cazalet was also co-chair of OASIS Energy Market Information Exchange Technical Committee. Dr. Cazalet holds a Ph.D. from Stanford University focused on economics, decision analysis and power systems. He also holds BS and MS degrees in engineering from the University of Washington.

William Cox is a leader in commercial and open source software definition, specification, design, and development.. He is co-chair of the OASIS Energy Interoperation and Energy Market Information Exchange Technical Committees, past Chair of the OASIS Technical Advisory Board, and a member of the WS-Calendar and oBIX Technical Committees. He participates in related IEC standards work.

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Thomas Nudell graduated from Kalamazoo College magna cum laude in Physics, and received a MS and a PhD, both in Electrical Engineering, from North Carolina State University. He is currently a postdoctoral associate in the Active Adaptive Control Lab at the Massachusetts Institute of Technology. Dr Nudell is a member of the IEEE and Phi Beta Kappa honor societ. His research goals include actualizing the rapid and widespread integration of renewable and energy efficient resources through transactive energy.

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