Transactive energy systems for distributed blackstart and service recovery

Bishnu Bhattarai¹ | Vishvas Chalishazar¹ | Donald Hammerstrom¹ | Manisha Maharjan²

¹Pacific Northwest National Laboratory, Richland, Washington, USA
²North Dakota State University, Fargo, North Dakota, USA

Abstract

Current transactive controls use marginal benefits and marginal costs to achieve an economic market efficiency during normal grid operations. However, the transactive mechanisms designed for normal economic operations cannot be applied directly for the contingencies because the grid operations during contingencies are often dictated by technical needs rather than purely economic criteria. For instance, one of the key technical requirements for the blackstart is to have at least one blackstart capable resource cleared which cannot be ensured by the transactive mechanism designed for normal economic operations because they work primarily based on the marginal benefit and marginal cost of the participants. This article presents one of the first attempts to develop a transactive mechanism to be used during grid contingencies. A distributed blackstart and service recovery is used as an example contingency to evaluate the performance of the proposed transactive mechanism. The performance of the proposed transactive mechanism is demonstrated for various use cases using a modified IEEE-123 node test system. The simulation results demonstrated the proof of concept of applying a transactive mechanism to enable distributed blackstart and service recovery by engaging the mix of blackstart capable and non-capable distributed energy resources.

1 | INTRODUCTION

Power system operations involve risks and uncertainties ranging from small forecast errors up to very large natural or manmade disasters (e.g. hurricanes, tornados, cyberattacks) that can potentially affect large portions of the system. In extreme cases, these uncertainties may lead to a complete system blackout. Even though distributed energy resources (DERs) can provide services during grid contingencies, there is no proper market mechanism to engage DERs during grid contingencies. Proper transactive controls that could engage DERs during grid contingencies add benefits to both DERs and system operators. However, to properly apply transactive controls during contingencies, one needs to answer three questions. First, what must happen for a transactive mechanism to change course from normal economic operations to contingency operations? Second, how does DER flexibility during contingent operations differ from normal economic operations? Third, how can utilities meet the technical requirements needed for the contingency?

Recently, transactive energy systems (TESs) have been gaining increased attention from the research community [1–7]. These efforts range from theoretical development of the TES up to field demonstration of TES control and coordination concepts. There have been several continued efforts since the first proof-of-concept validation of TES control and coordination during 2006 and 2007 [2,3]. The Olympic Peninsula Demonstration project used a double-auction market for congestion management using the flexibility from the DERs. Building upon that demonstration, the gridSMART® Demonstration introduces residential load control and coordination using real-time pricing [5]. Similarly, the Pacific Northwest Smart Grid Demonstration used peer-to-peer negotiations based on consensus principles to coordinate the operation of DERs [4,6]. Moreover, there were similar efforts (e.g. the PowerMatching City Demonstration) in Europe that used the TES mechanism to

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balance supply and demand in the system [7]. Those demonstration projects have proven the feasibility of using transactive energy principles for normal economic operations.

Although the use of TESs for normal economic operations has been studied extensively, the application of TESs during contingencies has not been explored widely. Because grid requirements during contingencies are mostly driven by technical needs rather than pure economic control, the TES during a contingency needs to address additional grid requirements. For instance, if TESs were to be used for the distributed blackstart process, one of the extreme contingencies in the grid, bid curves would have to reflect the opportunity cost of DERs rather than marginal cost/benefits during normal economic operations. Moreover, to ensure technical requirements such as the need for enough blackstart capable resources in the system to make the distributed blackstart feasible, additional attributes such as resource types will be included within DER bids. It is worth mentioning that, in the context of this article, the distributed blackstart is used to mean the blackstart that utilizes small-scale DERs to start the process from a small segment in a distribution network as opposed to the conventional blackstart process which uses predefined generating units and switching sequence for the blackstart. Even though prior studies showed that TESs can potentially be used during contingency situations to improve the grid resiliency [8], very little effort has been made so far [9].

Conventional approaches for making the grid more resilient are usually designed from the system operators’ standpoint whereby the system operator procures enough reserves to ride-through the contingencies. The majority of all these conventional approaches use the resilience curve presented in [10] to model power system performance and quantify the resiliency [11–14]. However, there are two issues with the existing approaches. First, the existing market mechanism does not allow DERs to participate in reserve markets. Second, there are no existing retail market mechanisms for properly using DERs, especially non-utility owned resources, during the contingencies. A properly designed TES can use non-utility owned DERs too during contingencies that would otherwise not be available to contribute towards system resiliency.

This study investigates potential TES mechanisms that could be used for distributed blackstart and service recovery. Presuming that contingency events cannot be avoided, we explore what must happen for a TES to address contingencies. The TES design is focused on blackstart and service recovery (i.e. recovery from a complete power outage) as an example contingency. Unlike normal distribution system operations, the blackstart process requires at least one blackstart generating unit (e.g. a synchronous generator) to be activated to energize other components in the system. Because of limited resources, we can serve only a subset of customers. It is worth mentioning that the conventional blackstart process procures enough blackstart capable resources usually in a yearly time frame using optimal allocation of blackstart resources methods [15,16]. While the existing blackstart allocation and the procurement process work well with the conventional generating resources, it excludes the DERs because they usually cannot commit a year in advance. Moreover, there are only very few works that have done in using the TES to engage DERs during resiliency events [9,17,18]. For instance, the authors in [17] provided a conceptual definition of resiliency metrics for TES, whereas the authors in [9] prepared the conceptual framework for reliability and resiliency considerations within the TES. While these efforts are focused on defining requirements for TES during normal economic operations, this paper presents a new TES application in resiliency and provides insights on how the TES can potentially be used for resiliency applications as opposed to developing a TES mechanism. This article presents a proof of concept of a new transactive mechanism that can be used for distributed blackstart and service recovery. The key contributions of this paper are summarized as follows:

1. Developed a new transactive conceptual framework for applying TES during contingency conditions taking blackstart and service recovery as an example contingency case.
2. Developed a two-step market approach (resource commitment–service recovery) that is capable of ensuring technical requirements that are needed for blackstart process.
3. Developed and demonstrated the blackstart process using the proposed transactive framework and two-step market approach for different scenarios and resource mix.

The rest of the article is organized as follows. Section 2 presents an overview of the proposed transactive mechanism to be used for distributed blackstart and service recovery. Section 3 provides details of the mathematical formulations for various stages of the blackstart and recovery process. Section 4 provides simulation setups and definitions of use cases. In Section 5, the simulation results are presented and discussed in detail. Finally, Section 6 presents conclusions and planned future work.

2 | BLACKSTART AND SERVICE RECOVERY PROCESS

The proposed TES mechanism for the distributed blackstart process is based on the assumption that a distribution system operator or utility procures/commits resources upfront to be deployed for blackstart using the retail market, either on a regular basis or in anticipation of outages. Whenever a blackout occurs, the system operator or utility first uses the committed resources. However, the proposed TES mechanism is designed such that it provides a mechanism to engage additional non-blackstart capable resources during the blackstart and service recovery phase. Note that non-blackstart capable resource refers to the resource that cannot blackstart but can be used when the system is energized by other blackstart capable resources. The proposed method considers parallel negotiations—one to be used for normal economic operations and another fail-safe alternative market to be used upon recognition of an event. The proposed approach is based on commitment-recovery-compensation between a retail TES market and a blackstart service provider, and it runs a TES market ahead of
time to acquire enough resources to position them for addressing potential contingencies.

First, all resources that would like to provide blackstart services should submit their bids to the retail TES market. The bids from those blackstart service providers should reflect resources capability such as blackstart generating resources, non-blackstart generating resources, and flexible loads. For example, blackstart generating resources (e.g. synchronous machines, grid-forming inverters, and so on) are the only resources that can initiate grid formation, while non-blackstart generating resources and flexible loads can only be used in subsequent steps of the recovery process. A blackstart service provider bid curve is constructed by extending bids for normal economic operations so additional flexibilities can be used during the blackstart process. Once TES markets receive bid curves from blackstart service providers and the total demand required for blackstart from a distribution system operator, the retail TES market will run to select enough resources with the correct composition (e.g blackstart generators, non-blackstart generators, flexible loads) such that the combination of resources is capable of blackstarting. When a blackout recovery process begins, the TES market issues dispatch instructions to committed blackstart service providers, and the blackstart service providers should follow the dispatching signals from the resources. Overall, the blackstart process proceeds through the following market stages:

- **Stage 1**: The distribution system operator or utility procures resources to be deployed for blackstart using the retail market either on a regular basis or in anticipation of outages.
- **Stage 2**: Each supplier/buyer submits supply/demand bids to be considered for blackstart depending on their capacity and degree of flexibility. In particular, each supplier/buyer prepares bids based on anticipated outage/contingency, the criticality of its service, and its available flexibility during that period. Such bids are then sent to the market operator.
- **Stage 3**: The market operator receives bids/offers and runs an optimization to determine the optimal procurement of the resources such that the procured resources are enough to blackstart the system.
- **Stage 4**: As the part of the service recovery, the market operators run a retail market to engage additional resources that cannot blackstart but can use the blackstart resources to provide support once the system is energized. Additionally, this also will allow trading of the uncommitted portions of the blackstart resources. This step is intended to exploit additional flexibility that could not be used by the pre-blackout market clearing.

While the aforementioned steps provide a market mechanism for the distributed blackstart and service recovery, the following steps define the technical steps that are followed as a part of the blackstart and service recovery. These technical steps are consistent with the wholesale blackstart process [15] but are tailored to engage small scale DERs through a new service recovery mechanism that is described in Section 3.

- **Blackout and disconnection**: At the begging of a blackstart event, all loads will be disconnected, and the distribution system will be segmented immediately as a part of the blackout and disconnection.
- **Jump-start**: As a jump-start step, the blackstart generators selected as jump-start units from the commitment phase will start and energize the system.
- **Re-energize**: Once the blackstart generating units start, the system operator re-energizes different distribution system segments in steps as shown in Figure 1. The key intent of the re-energize step is to progressively expand service recovery by engaging any uncommitted blackstart resources and non-blackstart capable resources. The segment energized in the previous recovery period will continue to be energized in the next recovery period until the whole distribution network is restored. Given the focus of the paper is on developing a new transactional mechanism to be applied for distributed blackstart and service recovery, we assumed the network as strong with no operational constraints.
- **Reconnect and stabilize**: The system operator directs the re-connection of loads as additional generators come online—initially to help stabilize generation and then to restore normal operations. Please note that the ‘re-energize’ and ‘reconnect and stabilize’ steps work back and forth while expanding the service recovery.

### 3 | MATHEMATICAL FORMULATION

The TES for distributed blackstart and service recovery consists of two major stages: (1) resource commitment and (2) service recovery. The resource commitment stage deals with the procurement of blackstart capable resources in advance of blackout events to position the resources to respond to blackout events. The service recovery stage includes the steps taken after the occurrence of the blackout event to engage additional resources and/or uncommitted blackstart resources from the resource commitment phase. Figure 2 illustrates a high-level overview of the major steps involved in the resource commitment and service recovery.

**Figure 1**: Process of subsequent service recovery after blackstart
phase. Within the scope of the article, the following terminologies have been used.

- **Blackstart provider**: A resource that is capable of energizing circuits under complete outage conditions is considered a blackstart capable resource and hence a blackstart provider. Examples of blackstart capable DERs include diesel generators and grid-forming inverters. Note that any blackstart provider is assumed to be capable of operating in non-blackstart mode as well. If the resource owner wants to operate his/her resources as a non-blackstart capable resource, they simply need to reflect this while submitting the bid.

- **Non-blackstart provider**: Resources that are capable of providing generation into the system but cannot energize the circuit from the complete outage conditions are considered non-blackstart providers. Examples of non-blackstart DERs include grid-following inverter-interfaced DERs, non-synchronous generators etc.

- **Critical load**: High priority loads (e.g. hospitals, communication loads, security office loads, and so on) that need to be served even during the resource scarcity phase are considered critical loads. Therefore, the critical loads are taken as the must-serve loads.

- **Flexible load**: Loads that can offer operational flexibility with respect to incentive signals (e.g. electricity price) are flexible loads.

- **Non-flexible load**: Loads that cannot offer operational flexibility with respect to incentive signals are taken as non-flexible loads. From a TES perspective, non-flexible loads are similar to critical loads, but the utility of critical loads will be significantly higher than that of non-flexible loads so critical loads would be served before non-flexible loads.

\[
\text{find : } \quad U^F_{d,i}, U^C_{d,i}, U^{NF}_{d,j,k}, U^{NF}_{s,j,l}, U^{BS}_{s,j,m}, F^F_{d,j}, F^{NF}_{d,j,k} \quad i,j,k,l,m \\
\text{Max. } \quad \sum_{i \in S} U^F_{d,i} P_{d,i} dU_{d,i} + \sum_{j \in S} \int_{0}^{L^F_{d,j}} P_{d,j} dU^F_{d,j} \\
+ \sum_{k \in S} \int_{0}^{L^F_{d,k}} P_{d,k} dU^{NF}_{d,k} \quad (1) \\
- \sum_{m \in S} \int_{0}^{L^F_{s,m}} P_{s,m} dU^{BS}_{s,m} \\
\text{s.t. : } \quad \sum_{i \in S} U^F_{d,i} + \sum_{j \in S} U^C_{d,j} + \sum_{k \in S} U^{NF}_{d,j,k} \\
- \sum_{j \in S} U^{BS}_{s,j} - \sum_{m \in S} U^{NF}_{s,j,m} = 0 \quad (2)
\]

**Figure 2** A high-level flowchart for the blackstart and service recovery

**Figure 3** A representative market-clearing process

### 3.1 Resource commitment

Resource commitment is intended to procure and position enough resources to blackstart the system. The resource commitment phase will help quantify the critical loads needed from customers and commit the supply capacities that each blackstart supplier could provide. More specifically, the objective of the resource commitment phase is to find the cleared price and quantity what will maximize the social benefit, which means the transactive market operator will select cost-effective blackstart providers to serve the loads. We formulate an optimization problem for a resource commitment during blackstart where each consumer (e.g. critical, flexible, non-flexible loads) submits a price–quantity demand curve as shown in Figure 3, and each provider (e.g. blackstart provider and non-blackstart provider) submits a price–quantity supply curve as shown in Figure 3.

When clearing the market as shown in Figure 3, the goal is to maximize the social welfare that meets both the demand–supply balance and resource limitations such as physical capacity and operational strategy/limits. It is worth mentioning that the market clearing shown in Figure 3 is illustrative only. Actual market clearing would be accomplished using the following optimization:
\[ U_{d,j}^e \leq U_{d,j}^{\text{max}} \quad (3) \]
\[ U_{d,j}^i \leq U_{d,j}^{\text{max}} \quad (4) \]
\[ U_{d,j}^{NF} \leq U_{d,j}^{\text{max}} \quad (5) \]
\[ U_{d,j}^{BS} \leq U_{d,j}^{\text{max}} \quad (6) \]
\[ U_{i,m}^{NBS} \leq U_{i,m}^{\text{max}} \quad (7) \]
\[ \sum_{l \in S} I_{l}^{BS} U_{s,l}^{BS} \geq \sum_{j \in S} F_{d,j} U_{d,j}^i \quad \forall \ l, j \in S \quad (8) \]

where,
- \( i \): index for flexible loads
- \( j \): index for critical loads
- \( k \): index for non-flexible loads
- \( l \): index for blackstart capable resource
- \( m \): index for non-blackstart capable resource
- \( s \): index for supplier
- \( S \): index for segment
- \( d \): index for demand
- \( I_{l}^{BS} \): binary variable indicating state of the \( p^b \) blackstart resource

\[ I_{d,j}^c : \text{binary variable indicating state of the } j^{th} \text{ critical load} \]
\[ U_{d,j}^{NF} : \text{quantity of } j^{th} \text{ flexible load at price } P_{d,j} \]
\[ U_{d,j}^{BS} : \text{quantity of } j^{th} \text{ critical load at price } P_{d,j} \]
\[ U_{d,k}^{NF} : \text{quantity of } k^{th} \text{ non-flexible load at price } P_{d,k} \]
\[ U_{d,l}^{BS} : \text{quantity of } l^{th} \text{ blackstart supplier at price } P_{d,l} \]
\[ U_{s,m}^{NBS} : \text{quantity of } m^{th} \text{ non-blackstart supplier at price } P_{s,m} \]

By solving this non-linear optimization problem, the market operator can determine the resource commitment in terms of cleared quantities that maximize the societal benefit (1), while satisfying the supply–demand balance (2) and resource physical and operational constraints (3)–(9). Constraints (3)–(5) express the demand capacity constraints for flexible, critical, and non-flexible loads. Similarly, Equations (6) and (7) denote the supply quantity constraints for blackstart and non-blackstart resources. Equation (8) ensures that at least one blackstart resource in each segment is selected. Finally, constraint (9) guarantees that all the critical load units are supplied by the blackstart resources in each segment. It is worth mentioning that the (1)–(9) are generic and can be applied to any combination of blackstart capable, non-blackstart capable, flexible, non-flexible, and critical loads provided the bidding is done for the given combination of resources.

Note that grid operational constraints and resource constraints (e.g. ramping and start-up constraints) are not specifically included in this research as the focus was more on demonstrating the transactive mechanism and the process of using it during blackstart and service recovery. We will address those aspects in the future.

### 3.2 Service recovery

The service recovery phase runs the market multiple times throughout the recovery process. In each market interval, the function of the transactive market is to determine (1) which blackstart provider is called and how much power this provider can supply and (2) which customer is served and how much power this customer can be served if it is flexible. Also, similar to the resource commitment, the transactive market operator will aim to maximize the social welfare by selecting the most cost-effective blackstart providers to serve the most valuable customers. Note that the service recovery market provides an additional opportunity for previously uncommitted or non-participated resources to provide flexibility which can eventually improve the service recovery.

For simplicity, we assume a targeted recovery time period for energizing each segment in the distribution system. This time period will be divided into multiple market intervals where the TES market will run. In this section, we formulate the optimization problem for the transactive market operator to determine the recovery dispatching instructions to the blackstart providers, non-blackstart providers, and customers in each time step during the energizing period of a segment, which is denoted as \( S \). This optimization problem only involves the providers and customers in that segment. To determine the status of customers and providers (both blackstart and non-blackstart) in each time step, we introduce the additional binary variables \( I_{d,j}^c \in \{0, 1\} \) and \( I_{l}^{BS} \in \{0, 1\} \), where \( I_{l} = 1 \) means that the customer/provider \( p^b \) is committed, and \( I_{l} = 0 \) means that the customer/provider \( p^b \) is not committed. In the recovery dispatch, a blackstart provider/customer may or may not be called in each time step. This is different from the resource commitment where all blackstart providers and customers are considered. The dispatch can be determined by solving the following problem:

\[
\text{find : } U_{d,j}^{F}, U_{d,j}^{I}, U_{d,k}^{NF}, U_{d,l}^{BS}, U_{s,m}^{NBS}, \nonumber
\]
\[ I_{d,j}^c, I_{d,k}^{NF}, I_{d,l}^{BS}, I_{s,m}^{NBS} \quad \forall \ i, j, k, l, m \]

\[
\text{max : } K_i \sum_{j \in S} F_{d,j} U_{d,j}^{F} + K_i \sum_{k \in S} F_{d,k} U_{d,k}^{NF} + \sum_{k \in S} F_{d,k} \int_{0}^{U_{d,k}^{NF}} P_{d,k} dU_{d,k}^{NF} \nonumber
\]
\[ + \sum_{j \in S} F_{d,j} \int_{0}^{U_{d,j}^{F}} P_{d,j} dU_{d,j}^{F} + \sum_{k \in S} F_{d,k} \int_{0}^{U_{d,k}^{NF}} P_{d,k} dU_{d,k}^{NF} \quad (10) \]
\[ - \sum_{i \in S} P_{B,i} \int_{0}^{U_{B,i}^{NF}} P_{B,i} dU_{B,i} \nonumber \]
\[ - \gamma \sum_{i \in S} P_{NBS,i} \int_{0}^{U_{NBS,i}^{NF}} P_{NBS,i} dU_{NBS,i} \nonumber \]

\[
\text{s.t. : } \sum_{i \in S} U_{d,j}^{F} + \sum_{j \in S} U_{d,j}^{I} + \sum_{k \in S} Q_{d,k}^{NF} \nonumber
\]
\[ - \sum_{i \in S} U_{d,j}^{BS} - \sum_{m \in S} U_{s,m}^{NBS} = 0 \quad (11) \]
\[ U_{d,i}^F \leq U_{d,i}^{max} \]  
(12)

\[ U_{d,j}^F \leq Q_{d,j}^{max} \]  
(13)

\[ U_{d,k}^{NF} \leq U_{d,k}^{max} \]  
(14)

\[ U_{s,l}^{RS} \leq U_{s,l}^{max} \]  
(15)

\[ U_{s,m}^{NBS} \leq U_{s,m}^{max} \]  
(16)

\[ I_{s,l}^{RS} \geq 1 \quad \forall \ l \in S \]  
(17)

\[ \sum_{l \in S} I_{s,l}^{RS} U_{s,l}^{RS} \geq \sum_{j \in S} I_{j}^{RS} U_{j}^{RS} \quad \forall \ l, j \in S \]  
(18)

where

- \( I_{d,k}^{NF} \): binary variable indicating state of the \( k^{th} \) non-flexible load
- \( I_{d,i}^{F} \): binary variable indicating state of the \( i^{th} \) flexible load
- \( I_{NBS,m} \): binary variable indicating \( m^{th} \) non-blackstart resource state

By solving this non-linear mixed-integer optimization problem in each time step, the transactive market operator can determine which blackstart provider in the given segment is called, which customer in that segment is served, and the cleared price/quantity for the blackstart providers and flexible customers. The demand–supply balance in the formulation is ensured by constraint (11). Constraints (12) through (16) ensure that the resource capacity is not exceeded for flexible, critical, non-flexible loads, and blackstart and non-blackstart units, respectively. Finally, constraint (18) confirms that sufficient blackstart capable generating units are available to energize the considered segment. During the blackstart process, to energize a segment of the distribution system, at least one blackstart generating unit will need to be activated, while the non-blackstart generating units can be used or not used at all. In fact, the following constraint is used to ensure at least one blackstart generating unit is used:

\[ \sum_{l \in S} I_{RS,l} > 0 \]  
(19)

Moreover, to differentiate between blackstart generating units and non-blackstart generating units, we introduced different gains for blackstart and non-blackstart resources. Here, \( \gamma > 1 \) is a gain to be chosen to place less priority on non-blackstart generating units. The gain for a blackstart resource is chosen to be 1. The first two terms in the optimization function are introduced to differentiate between critical (high priority) and non-critical loads. Therefore, \( K1 \) is generally higher than \( K2 \).

The binary variables \( I_{d,j}, I_{s,l}^{RS}, I_{s,m}^{NBS} \) can be configured such that resources are either allowed or not to change their position (energized to de-energized and vice versa) in subsequent market intervals. If a utility intends not to allow the already activated generators/loads to be deactivated in the following market intervals, the following constraints will ensure that requirement:

\[ I_{d,j}(t-1) \leq I_{d,j}(t), \]  
(20)

\[ I_{d,j}(t-1) \leq I_{d,j}(t), \]  
(20)

\[ I_{d,k}(t-1) \leq I_{d,k}(t), \]  
(20)

\[ I_{s,l}(t-1) \leq I_{s,l}(t), \]  
(20)

\[ I_{NBS,m}(t-1) \leq I_{NBS,m}(t) \]  
(20)

This condition can be applied to a single segment or throughout the entire service recovery process. After a segment is energized, we will enlarge this segment and use the recovery dispatch step described above to energize the enlarged segment. In the latter step, we will require that all blackstart providers and customers that already had been activated in the first segment have to be active in the enlarged segment. In case the utility intends to allow already activated resources to be deactivated in the following time steps, it can simply be achieved by not considering constraint (20).

4 | SIMULATION DESCRIPTIONS AND USE CASES

The proposed concept is demonstrated using a modified IEEE-123 node test system. The system is modified by dividing it into three different segments/microgrids and by adding various DERs as shown in Figure 4. In total, there are five DERs added with the overall capacity of 3600 KW split between two blackstart capable generators providing 1850 KW and three non-blackstart capable providing 1750 KW. As shown in Figure 4, four nodes are designated as critical loads that amount to 735 KW of total demand. The rest of the demand is split between 15 flexible and 66 non-flexible loads amounting to 695 KW and 2060 KW, respectively.

The IEEE-123 node test system is divided into three microgrids, with each microgrid representing a segment that needs to be recovered in a single block. Microgrid 1 contains the two blackstart capable generators and four critical designated loads. Microgrid 2 contributes two non-blackstart capable generators, and microgrid 3 contributes one non-blackstart capable generator. This division of the grid into smaller segments/microgrids is taken into consideration when the actual service recovery process is carried out. Note that these segments and their sequence of energizing can be different from time to time depending on the criticality of service at various segments at the given point in time. However, it is worth mentioning that the selection of the segments and their sequence of restoration will have no impacts on its capability to maximize the load restoration from the given available resources. In the next subsection, various use cases are described both for resource commitment and service recovery. The proof of concept of the transactive mechanism for the distributed blackstart is demonstrated through simulations.

The following three use cases are simulated to demonstrate the performance of the proposed transactive mechanism during resource commitment phases.
• Use-case_RC1: Only blackstart capable generators and critical loads participate in the market proceedings and bid for themselves.
• Use-case_RC2: Blackstart and non-blackstart capable generators as well as critical and flexible loads participate and bid in the market.
• Use-case_RC3: Blackstart and non-blackstart generators and critical, flexible, and non-flexible loads participate and bid in the market.

Similarly, the following two use cases are simulated to demonstrate the performance of the service recovery:
• Use-case_SR1: Commitment from market participants in the previous market interval is kept intact in the subsequent intervals.
• Use-case_SR2: Commitment from the market participants in the previous market interval is allowed to change their position in the subsequent recovery market intervals.
5 | SIMULATION RESULTS AND DISCUSSIONS

5.1 | Resource commitment

5.1.1 | Use-case_RC1

As described in Section 4, use-case_RC1 considers only blackstart capable resources and critical loads. Figure 5 illustrates the bid curves for blackstart capable generators and critical loads. The bid curves for the blackstart capable generators are represented by a quadratic cost curve to be consistent with the generation cost curve of most of the generation resources. The bid curves for critical loads have a step function primarily because the critical loads always will be served as a priority as long as the electricity price is below the maximum price the asset owner is willing to pay. The bar chart in Figure 6 shows the final cleared quantity for each of the blackstart capable generators and critical loads, which is used by blackstart capable resources to meet critical loads. In this use case, blackstart capable resources are committed to supplying critical loads. Depending upon the availability of blackstart capable resources, the system may not serve all critical loads.

Figure 7 shows the total dollars earned by the blackstart service providers, their actual cost of producing the power, and the net profit for the participating blackstart capable generators. It also shows the maximum amount critical load customers were willing to pay along with how much they actually paid and the net monetary benefit achieved. If we add profits to the participating generators and profits made by customers, the overall societal benefit is represented.

5.1.2 | Use-case_RC2

This use case considers both the blackstart and non-blackstart capable providers as well as flexible and critical loads. The bid curves for blackstart and non-blackstart generators along with the bid curves for the critical loads and flexible loads are shown in Figure 5. Similar to the bid curves for blackstart generators in use-case_RC1, the bid curves for all three non-blackstart generators also have a quadratic form. As can be seen from Figure 5, the bid curves of the non-blackstart generators are configured to be cheaper than that of the blackstart generator. The bid curves of flexible loads, unlike the bid curves of critical loads from use-case_RC1, have a quadratically decaying form because the flexible loads pay less per kWh as the demanded kWh increases.
The bar chart shown in Figure 8 describes final cleared quantities of blackstart and non-blackstart generators along with both critical and flexible loads.

Figure 9, similar to use-case_RC1, provides the net benefit for all five generators and loads (4 critical and 15 flexible). This is more of a societal benefit than the value observed for use-case_RC1 when only critical loads participated.

5.1.3 Use-case_RC3

The bid curves for both blackstart and non-blackstart generators are the same as for use-case_RC2. Along with those curves, bid curves for the critical, flexible, and non-flexible loads are also shown in Figure 5, out of which the bid curves for critical and flexible loads are the same as in use-case_RC2. The bid curves for non-flexible loads have the step function form like critical loads, but they pay less than the critical loads. The bar chart shown in Figure 10 shows the final cleared quantities of all five generators and all loads of all different types.

Figure 11, similar to that for use-case_RC1 and use-case_RC2, provides the net benefit for all five generators and for all 85 loads (4 critical, 15 flexible, and 66 non-flexible). The total societal benefit, including the generators and loads for this example use case, is $723.28. This is more than the benefit observed for use-case_RC2 when both critical and flexible loads participated.

5.2 Service recovery

5.2.1 Use-case_SR1

In this use case, we simulate 10 time steps and previously committed resources were not allowed to change their ON/OFF position from one time step to the next. However, the resources can trade remaining flexibility in the following market intervals and change their operating position. The results of this use case are shown in Figure 12, which shows that the total number of customers being served increases to 77 (out of 85) until the 5th time interval of market clearing is reached, after which it settles at that value. The figure also shows the amount of committed resources and amount of demand being served by type (critical/flexible/non-flexible) in
each interval of market clearing. All of these quantities remain the same or increase from the prior time step to the next one. This is expected because of the constraint that already committed resources must remain committed.

5.2.2 Use-case_SR2

In this use case, committed resources can change their ON/OFF positions from one time step to the next one. The results for the total number of customers online, amount of committed resources, and amount of demand being served by type in each time step are shown in Figure 13. It can be observed that the total number of customers online, from a previous market-clearing interval to the next, increases and then decreases and does not settle to one value. This observation is consistent with the initial condition in which a committed resource in the previous interval can choose to decommit in the next interval, thus adding to the uncertainty towards resource availability. However, throughout the use case, the amount of critical load being restored and served stays the maximum because they are prioritized, which is consistent with their bid curves that show the amount paid by the critical loads is higher than all other types of loads.

6 CONCLUSION

This article presents a conceptual transactive mechanism to be used for distributed blackstart and service recovery. The performance of the proposed TES for a blackstart mechanism was demonstrated in a modified IEEE-123 node test system using various use cases. The simulation results provide the proof of concept to enable distributed blackstart and service recovery by engaging DERs through TESs, which otherwise could not participate during such fail-safe operations. Because blackstart is one of the extreme cases of contingency, this work can engage DERs during grid contingencies and hence contribute to improving the overall system resiliency.

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DECLARATION OF DATA USAGE
The authors hereby declare that all the data used in this paper is open source and publicly available.

AUTHOR CONTRIBUTIONS
Bishnu Bhattarai: project administration, conceptualization, supervision, methodology, and formal analysis. Vishvas Chalishazar: investigation, software, and formal analysis. Donald Hammerstrom: conceptualization, methodology, and supervision. Manisha Maharjan: methodology, software, and formal analysis.

ORCID
Bishnu Bhattarai https://orcid.org/0000-0001-9748-458X

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