A Cooperative Market-based Decision Guidance Approach for Resilient Power Systems

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Abstract: National and local economies are strongly dependent on stable power systems. While the problem of power system resilience in the face of natural disasters and terrorist attacks has been extensively studied from the systems engineering perspective, a major unsolved problem remains in the need for preventive solutions against the collapse of power systems. These solutions must ensure the most economically efficient operation of power systems, within the bounds of any remaining power capacity. Transferring power usage rights from the lowest-loss to the highest-loss entities would result in significant reduction of the combined loss. The existing power systems do not take this fact into account. To address this need, we envision a paradigm shift toward three-step system for (1) a cooperation power market where power usage rights can be transferred among participating entities, (2) decision guidance to recommend market asks and bids to each entity, and (3) optimization that, given the market clearance, will recommend precise operational controls for each entity's microgrid. The key challenge to address is the design of this three-step market system that will guarantee important properties including Pareto-optimality, individual rationality, and fairness, as well as privacy, security, pseudo-anonymity and non-repudiation.

1 INTRODUCTION

National and local economies are strongly dependent on power systems, which involve power generation, transmission, distribution and, increasingly, distributed renewable power sources such as photovoltaic arrays and wind turbines, local micro-turbine generation, and power storage. The power systems are getting increasingly complex, due to the shift toward distributed and multidirectional flow of power and largely unpredictable supply of power from renewable sources, which are not dispatchable (Moslehi & Kumar 2010). Figure 1 depicts a prototypical electric power system with renewable sources and power storage (US Energy Information Administration.)

Power systems are highly vulnerable to natural disasters and terrorism, resulting in huge economic losses, such as the 2003 northeast blackout estimated at \$6 billion (Rose et al. 2007) (Lassila et al. 2005). Sectors that are highly affected include non-durable and durable manufacturing, construction, food processing, wholesale trade and business services to name a few (Rose et al. 2007).

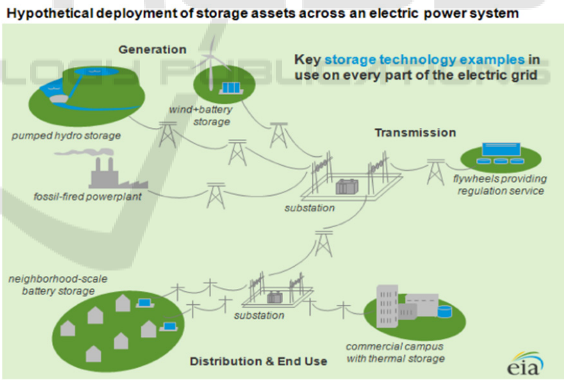

Figure 1: Distributed power system with storage technologies (Source: U.S. Energy Information Administration).

While outages may occur due to natural causes, such as hurricanes, blizzards, wildfires or technical failures, preparedness for major disasters due to terrorism is paramount. Unlike natural disasters or technical failures, which occur randomly, terrorist attacks, especially conducted by more sophisticated state-supported players, can be optimized to cause maximum damage with the payoff of high economic impact and instilling fear (Rose et al. 2007). It is

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therefore critical to solve the problem of resiliency and response to low-probability but extremely high-impact scenarios (Wang et al. 2016).

While the existing power systems are far from resilient, the problem of resiliency has been extensively studied and is well-understood from the system engineering perspective (e.g., see Wang et al. 2016, Guikema et al. 2006, Liu & Singh 2011, Wang et al. 2015, Mohagheghi & Yang 2011) including (1) hardening and resilience investment, such as vegetation management, undergrounding and elevating substations; (2) corrective actions and emergency response, such as emergency load shedding, special protection systems and islanding schemes, and (3) damage assessment and system and load restoration, such as distributed generation, microgrids, distribution automation, mobile transformers and decentralized restoration strategies.

A major unsolved problem remains, however, in the need for mitigation solutions that incrementally protect against the collapse of power systems as their capacities become degraded. These mitigation solutions must ensure most efficient operation of power systems, in terms of their economic impact, within the bounds of any remaining power capacity, whether it is 80%, 50%, or 20% in large distribution areas. The key difficulty in this problem is lack of expressiveness into account for the economic impact on diverse affected businesses and communities, some of which may sustain huge economic losses, while others would only be marginally affected.

Estimates of losses per kilowatt-hour (KWH) from electricity disruptions range from $1.5 to $7.5/KWH and, according to a more recent estimate, at $50/KWH for some sectors (Rose et al. 2007). This means, for example, that a business in these high-loss sectors consuming 40 MW of power and losing half of its power supply will be losing $1M per hour, while a business at the lower end of the spectrum will be losing "only" $0.03M per hour, with the combined loss of $1.03M per hour.

It is easy to reduce this combined loss to "only" $0.06M from $1.03M, by transferring 20 MW power capacity from low-loss to high-loss business, and compensating the low-loss business. This is over 94% savings over the combined loss, but the power control systems do not currently have the ability to take this fact into account. Similarly, in the case of $1.5/kWh vs. $7.5/kWh losses, we can save ⅔ of the combined loss; in the case of $1.5/kWh vs. $4.5/kWh, we can save ½ of the combined loss; and in the case of $1.5/kWh vs. $3.0/kWh, we can save ⅓ of the combined loss.

Optimally reducing the combined economic loss through secure cooperation markets for power is exactly the focus of this position paper. This is a challenging problem, given the complexity of power systems and diverse economic impacts to participating (business, public or community) entities. We believe, however, that this problem is solvable, as discussed in the next sections.

2 PROPOSED SOLUTION

Power systems control, for every entity having a microgrid (MG), is actuated for every time interval, typically of 15, 30 or 60 minutes. Figure 2 depicts prototypical microgrid components. The control deals with how each power system resource/component is operated, including: whether or not each power load (e.g., for HVAC, lighting, data center) is activated and at what level; whether each local generator is activated and at what level of output; whether a power storage device (e.g., high-capacity lithium battery) is activated in charge or discharge mode and at what level of power; and, the amount of power the entity pulls from the grid (subject to contractual agreement with a utility company), or possibly contributes to the grid, when the power flow is reversed.

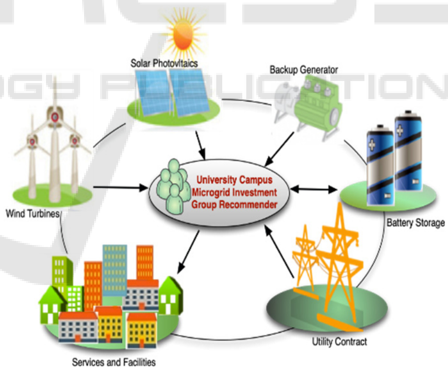

Figure 2: An Example of Microgrid Components.

We propose a three-step system for (1) a cooperation power market where power usage rights can be transferred among participating entities, (2) decision guidance to recommend market asks and bids to each entity, and (3) optimization that, given the market clearance, will recommend precise operational controls for each entity's microgrid. The main research challenge is the design of this three-step market system that guarantees important properties including Pareto-optimality, individual rationality, fairness, as well as privacy, security, pseudo-anonymity and non-repudiation.

2.1 Three Step Cooperation Market System

We envision the cooperation market be realized by the three main steps:

- *Cooperation market of power futures (or options)*: This market runs before the beginning of every time interval. Traded in this market are rights to increase, or commitment to curtail, power consumption upper bounds in time intervals *1,...,n* for each participating entity. The market clearance results in (1) precise amounts of power in these rights/commitments for each participating entity over time intervals *1,...,n* and (2) the amount of money each entity receives from or gives to the market in lieu of these rights/commitments. Of course, market clearance must result in equilibrium of supply and demand, for both power and money.

Before market runs, each participating entity submits a combined (parametric) *bid-ask,* which we formulate in the terminology of *bids*: agreeing to pay at most the value $v(kw_1, ..., kw_n)$ for the right to increase power upper bounds by $(kw_1, ..., kw_n)$ in time intervals *1,...,n.* Note that, in this terminology, agreeing to pay a negative amount, say -\$1000, means receiving \$1000; and the right of power increase by a negative amount, say -50 KW, means the commitment to curtail power consumption upper bound by 50KW. A *bid-ask* by a participating entity is a value function

$$v : [minKW_1, maxKW_1] \times ... \times [minKW_n, maxKW_n] \rightarrow R \quad (1)$$

where $minKW_1,..., minKW_n$ are negative lower bounds, $maxKW_1, ..., maxKW_n$ are positive upper bounds, and the value $v(kw_1, ..., kw_n)$ represents the (maximum) amount of money the entity is ready to pay for increasing the power consumption bounds by $(kw_1, ..., kw_n)$ in time intervals *1,...,n,* relatively to the current power upper bounds $(UB_1 ,..., UB_n)$ allocated to the entity. Note again that $kw_i < 0$ means that the entity will decrease the power upper bound by $-kw_i$ in time interval *i.* And that $v(kw_1 ...., kw_n) < 0$ means that $-v(kw_1 , ..., kw_n)$ is the (minimum) amount of money the entity is ready to receive for $(kw_1,...., kw_n)$.

Given all *bid-asks* submitted in a market round, market clearance results in precise rights/commitments for power increase/curtailment as well as payments made or received by participating entities, as explained earlier.

- A *decision guidance solution* that, given a description of all existing resources for an entity (power loads and their equivalent values, local generation, power storage, renewable sources, as well as current power bounds), recommends the entity a precise *bid-ask* to the market.
- A *decision guidance solution* that, given market clearance, as well as the description of all existing resources for an entity, performs value optimization and recommends to the entity the precise optimal operational parameters for each interval *1,...,n.* The operational parameters include which power loads are activated at what level (in KW) and which are shed; which local generation resources are activated at what level; which storage devices are being used in charge or discharge mode and at what level; etc.

2.2 Critical Properties of the Market System

A major design challenge of the market system is to assure some critical properties dealing with optimality and fairness, which is easier to understand in the framework of cooperative games. Consider a cooperative game in which players who form a coalition are entities that participate in the market. Each entity (player) decides on bids/asks; then, the market clears; finally, the entity decides on optimal operation for *n* time intervals.

This optimal operation results in some *value* for each participating entity, which is the total *benefit* of running power loads (i.e., avoiding negative economic impact) minus the total *costs* of operation, plus (resp. minus) the *money* received from (resp. given to) the market. If the entity does not participate in the market, it can extract the value by optimizing its resources within the available bounds of power consumption. Let $(v_1,..., v_k)$ be the resulting *values* for entities for the case when they do not cooperate (i.e., do not participate in the market); and $(v'_1,..., v'_k)$ be the resulting values for the entities if they do cooperate, i.e., these are the values assigned to players (entities) of the cooperative game (the market system). A key research challenge is to design the market system that will satisfy a number of important properties of cooperative games, including the following:

- *Pareto-optimality (also called efficiency):* it is impossible to improve the resulting value v'_i of one entity without sacrificing the value v'_j of at least one other entity ($i \neq j$). It is not difficult to show that this property is equivalent to having operational parameters of all entities that maximize the combined benefit $\sum_{i=1}^{k} v'_i$. This is as though there were a centralized authority that would jointly optimize all entities and enforce the resulting operational decisions across the board. This may be impractical, particularly because business and communal entities have very diverse power system and economic impact characteristics, and, furthermore, may not want to share this detailed (and sometimes confidential) information with others or the centralized authority. A major challenge that we need to overcome in the envisioned market-based solution is the design of the market system in which participating entities only share their *bid-asks* yet the resulting operation of power systems is equivalent to the result of joint operational optimization (without actually doing it).

- *Individual Rationality:* $v_i' \geq v_i$ for every entity $i = 1,...,k$. In other words, every entity can only improve its value by participating in the game (market), because otherwise it would not.
- *Fairness:* This property deals with how the cooperation benefit

$$\Delta = \sum_{i=1}^{k} v_i' - \sum_{i=1}^{k} v_i = \sum_{i=1}^{k}(v_i' - v_i) = \sum_{i=1}^{k} \Delta_i \quad (2)$$

is distributed among the players (entities). Note that, for each entity *i,* its cooperation benefit $\Delta_i = (v_i' - v_i)$ must be non-negative to satisfy the individual rationality property. An important question that needs to be answered is how to define the most appropriate definition of *fairness* in the context of power system resilience and disaster response aimed at minimizing losses. We believe that some proposed notions of *fairness,* such as *symmetry* in cooperative games, may not be appropriate, as we explain further in the Technical Approach section. Intuitively, we would like to have the notion of *fairness* by which low-loss entities are compensated, possibly with some premium, for their loss and agreement to further curtail power consumption, to maximize loss reduction of high-loss entities. This is as opposed to the situation when low-loss entities would use a disaster as an opportunity to make very high profits (as opposed to cutting losses) due to them having a valuable resource of power rights during a huge shortage of power supply.

Privacy, security, confidentiality, pseudo-anonymity, and non-repudiation: Transparency into how the fair-market-price is computed and set will build confidence in the fairness of the ecosystem, but the underlying bid-asks expose some aspects of market participants' financial interests and disposition. The privacy and security of this data must be enforced by the implementing architecture. The necessary properties of such an architecture will be a model which will publish (to a subset of semi-trusted audit/regulatory entities) and verify the existence of any and all bid-asks that have been made, pseudo-anonymity that will protect the privacy of the identity of market participants associated with ask and bid information, and provide non-repudiation (so that once pseudo-anonymous bids and asks are published and used to calculate the fair-market-value of power, the submitting market participant cannot disavow their existence).

3 TECHNICAL APPROACH

3.1 Design of Three-step Market System

As described in the prior section, we need to perform three tasks: (1) guiding entities on how to generate their *bid-asks*; (2) market clearance given *bid-asks* from all participating entities; and, (3) after the market clears, optimization of operational controls of power system for each entity. We discuss directions for the solution, starting with market clearance.

3.1.1 Market Clearance

Assume that the *bid-asks* submitted to the market are value functions $v_1,..., v_k$, where $v_i\,(kw_1^{(i)},..., kw_n^{(i)})$ represents the (maximum) amount of money the entity i is ready to pay for increasing the power consumption bounds by $(kw_1^{(i)},...,kw_n^{(i)})$ in time intervals *1,...,n,* relatively to the power upper bounds $(UB_1^{(i)},...,UB_n^{(i)})$ currently allocated to entity *i.* The first step is to determine optimal flows of power $(kw_1^{(i)},..., kw_n^{(i)})$ for each entity $i = 1,...,k$ by maximizing the combined value of all entities

$$\sum_{i=1}^{k} v_i(kw_1^{(i)},\ldots,kw_n^{(i)}) \quad (3)$$

subject to:

- the (negative) lower bounds and (positive) upper bounds on power transfer for every entity $i = 1,...,k$ and every time interval $j = 1,...,n,$ and
- power equilibrium (balancing) constraints, for each time interval $j = 1,...,n.$

This optimization results in power flow values $(kw_1^{(i)*},...,kw_n^{(i)*})$ for each entity *i,* as well as the associated entity value $v_i^* = v_i\,(kw_1^{(i)*}d,..., kw_n^{(i)*}).$ This gives the market clearance for power flows. We also need to determine the payment made or received by each entity $i = 1,...,k.$ To do that, consider the optimal combined value *V'* of all entities achieved by cooperation: $V' = \sum_{i=1}^{k} v_i^*$ Also consider the combined value *V* of all entities without cooperation: $V = \sum_{i=1}^{k} v_i$, where v_i is the result of stand-alone value maximization for entity *i,* subject to its power usage upper bounds. The difference $\Delta = V' - V$ is the cooperation benefit, i.e., increase in the combined value due to cooperation. Depending on the *fairness criteria* to be used, the cooperation benefit Δ will be distributed among the entities: $\Delta = \Delta_1 + ... + \Delta_k$. Thus the new value v_i' of each entity *i* must be the old value (without cooperation) v_i plus the cooperation benefit Δ_i: $v_i' = v_i + \Delta_i$. But the value for entity *i* from the combined value optimization is v_i^*. Therefore, the payments paid or received by each entity *i* must be done to cover the difference between v_i' and v_i^*, so that the cooperation benefit for entity i will be exactly Δ_i, in accordance with the fairness criteria. This completes the payment part of the market clearance. While these are general ideas, we envision a careful design and formalization of the three-step cooperation market, developing its clearance algorithm and mathematically proving that it satisfies the desirable properties of Pareto-optimality, individual rationality, and fairness.

3.1.2 Guiding Entity's Decision on Bid-ask to Market

We envision the development of a composite model for power microgrid and its components, which will express the value function V for the entity's microgrid. The value $V(kw_1, ..., kw_n, UB_1,..., UB_n, x)$, where x is a vector of all microgrid operational controls over time intervals *1,...,n,* is the total value achieved by microgrid operation, which is the benefit of running all activated load (e.g., preventing loss) minus all costs. The model will also include the Boolean function $C(kw_1, ..., kw_n, UB_1,..., UB_n, x)$ which expresses microgrid operational feasibility constraint in terms of $kw_1, ..., kw_n, x$.

Recall that operational control involve which loads are activated at what level, which local generators are activated at what level, which batteries are activated in charge and discharge mode and at what level etc. Given this information, we need to compute *bid-ask* to the market, which is a function

$v: [minKW_1, maxKW_1] \times ... \times [minKW_n, maxKW_n] \rightarrow R$

where the value $v(kw_1, ..., kw_n)$ represents the (maximum) amount of money the entity is ready to pay for increasing the power consumption bounds by $(kw_1, ..., kw_n)$ in time intervals *1,...,n,* relatively to the current power upper bounds $(UB_1 ,..., UB_n)$ allocated to the entity.

We need to generate (a representation of) function v under the assumption that, given $(kw_1, ..., kw_n)$ added to the existing power upper bounds, the microgrid will be optimally operated. In other words,

$$v(kw_1, ..., kw_n) = max_x \, V(kw_1, ..., kw_n, UB_1,..., UB_n, x) \quad (4)$$

subject to

(1) upper bound constraints for total power consumption for every time interval,

(2) power balance constraints for every time interval and

(3) microgrid operational constraints $C(kw_1, ..., kw_n, UB_1,..., UB_n, x)$.

The challenge in computing a representation of this function is that it may not have a closed analytical form, which is needed if we want to use efficient mathematical programming algorithms (e.g., branch and bound for mixed integer linear programming) in market clearance optimization. Thus, we may need to resort to its approximation. Computing this approximation efficiently yet accurately is a research challenge that needs to be addressed.

3.1.3 Optimization of Microgrid Operational Controls

Market clears with instantiated power usage right increases $(kw_1^*, ..., kw_n^*)$ for an entity's microgrid for time intervals *1,...,n.* Microgrid optimization is maximization of the operational value $V(kw_1^*, ..., kw_n^*, UB_1,..., UB_n, x)$ for x subject to operational constraints $C(kw_1^*, ..., kw_n^*, UB_1,..., UB_n, x)$, when all power usage right increases are fixed as per market clearance. The challenge here is being able to mathematically model microgrid operational value and constraints for diverse set of resources used in the microgrid. Also, since this optimization needs to be done before the start of every time interval, efficiency of an optimization algorithm is critical. We discuss these challenges in more detail in the next section.

3.2 Power System Modeling, Decision Guidance, and Optimization

All three steps in the three-step market system require decision optimization. Finding *bid-ask* to be submitted to the market and finding operational control of the microgrid require modeling and optimization of the underlying power system, as described earlier. The model of the power system is quite involved, because it must capture, in addition to general computation of benefits, costs and balancing constraints, the precise models of power network components. They may include various types of utility contracts; diesel generators; power storage including batteries, spinning wheels, and hydro-storage; schedulable loads such as ice generation for cooling, boiling water and charging electric cars in a parking garage; solar panels and wind turbines. These models are quite involved and diverse.

To be able to scale the development of diverse microgrid model instances, we would like to create a reusable extensible repository of component models, so that specific microgrid models can be easily composed based on model components, similar to how it is done in simulation-based systems (Lambert et al. 2006). At the same time, we would like to get efficiency of the best mathematical programming algorithms, such as for Mixed Integer Linear Programming (MILP), which significantly outperform simulation-based optimization algorithms. To bridge the gap, we envision to leverage some research ideas from our prior work, the work on microgrid component models (Altaleb & Brodsky 2013, Levy et al. 2016b, Levy et al. 2016a, Ngan et al. 2014), as well Unity Decision Guidance Management System (Unity DGMS) (Nachawati et al. 2017, Brodsky & Luo 2015). It allows modular simulation-like modeling, automatically generates mathematical programming models, and solves them using the best available mathematical programming algorithms. We plan to use mixed integer linear programming solvers as well as gradient-based non-linear programming solvers on power system optimization.

To support the three-step market system we envision the development of a Decision Guidance solution based on Unity DGMS. The decision guidance solution will be based on formal modular, extensible analytic performance model which expresses metrics of interest and feasibility constraints as a function of investment and operation decision variables. Metrics of interest include benefit, cost and overall value of power system operation over a number of time intervals. Feasibility constraints include capacity limitation of physical resources, power flow equation, contractual terms, and power demand. Decision variables include all power system operational controls over the planning time intervals such as (1) power flows in the network as a whole, (2) specific controls for each physical network component such as power generators, transmission lines, distribution, power storage, and renewable sources of energy, and (3) financial instruments such as contracts with power providers.

3.3 Market Privacy, Security, Confidentiality, Pseudo-anonymity, and Non-repudiation

Entities involved in the energy marketplace will need to expect that the market value of energy will be computed fairly. The fair-market-value must be computed by evaluating what each participating consumer is willing to spend, how much energy is needed, and (under appropriate circumstances) how much power a customer may be willing to *provide* to the power grid (and at what price). The ability to audit how this price is computed and set will build confidence in the fairness of the ecosystem. Nevertheless, these data elements expose some aspects of entities' financial interests and disposition, and the privacy and security of these data must be enforced by the implementing architecture. To ideally accomplish this, the information used will need to be publishable to a set of entities (who may not necessarily be market participants, but may be regulatory), so that the market's fairness can be inspected and regulated. However, because exposure of this level of consumer-interest in pricing would be considered private information, it may result in gaming of the system, and many market participants may not want it to be publicly discoverable *and* attributable, a pseudo-anonymous approach that provides non-repudiation is critical. Such a viable architecture will need to provide the necessary transparency that allows inspection into how the fair-market-value of energy was arrived at by a community of auditing/regulatory entities, while also protecting the security and privacy of consumers so that their private data and interests maintain a sufficient level of privacy protection, and must offer non-repudiation facilities so that entities can be held accountable after committing to asks/ bids.

The necessary properties of such an architecture will be to create a model which allows market participants to "bid" on energy (as previously described), to be able to create an "ask" to *provide* energy to the grid (as previously described). These properties must also allow audit and regulatory entities to verify the existence of any and all bids that have been made by the set of market participants, the existence of any and all asks that have been made by the set of market participants, to protect the privacy of sensitive information (such as the identity of clients that can be associated with ask and bid information), and non-repudiation (so that once bids and asks are published and used to calculate the fair-market-value of power, the submitting client cannot disavow their existence). In this architecture, it is envisioned that there will be a set of semi-trusted entities (such as the utility provider, possibly a set of entities to compute the fair-market-value, or a regulatory entity, etc.). This structure should ensure that the marketplace and fair-market-value computations are transparent enough that these semi-trusted entities have only enough information to verify bids and asks at admission time against the pseudo-anonymous authors before publishing them.

The pseudo-anonymity architecture will be the focus of additional research. With the data from bids and asks being critical to computing and providing transparency into the determination of a fair-market value, the ability to disseminate these data to a semi-trusted set of entities, for the data to be immutable, and for it to be transparent will be explored in the context of distributed ledgers. Initial considerations will be given to blockchain technologies such as private Ethereum, private bitcoin, and more recent approaches such as those described by private DLedger (Nakamoto n.d.; Zheng et al. 2017). Each bid and ask will be separately represented in the distributed ledger and will uniquely, and pseudo-anonymously, indicate the specific market participant who placed it. These investigations will underscore the need for semi-public and immutable data to bolster marketplace confidence, while still providing privacy and non-repudiation.

To provide authentication and integrity protections to the system's semi-trusted providers, we envision using their public DNS domain names (such as example.com) and the DNS-based Authentication of Named Entities (DANE) to build a reduced attack surface security model (Osterweil et al. 2014). This will allow protections to be managed by the power utility, and will allow certificate's to be issued to each market participant. Each of these certificates will act as a trust anchor for that entity and will correspond a private key that will only be known to the market participant whom the signing certificate was issued to. These private keys will be used to create attestations to revolving End Entity (EE) certificates, which are created for every time interval of bids and asks. These EE certificates will be used to create digital signatures over each bid and ask, and that signature will accompany its corresponding bid or ask in the distributed ledger (with no other identifying information). This will allow inspection of the data in the ledger (by the subset of entities who are semi-trusted), pseudo-anonymity of the market participants (without the time interval-specific revolving EE certificate, signatures do not identify the author's identity), and non-repudiation of each element (given the EE certificate, each bid or ask can be verified and attributed).

As an example, consider that a utility provider issues subordinate signing certificates to k market participants ($c^1 \ldots c^n$). At the beginning of each time interval i, each client c^n will create a new EE cert (c_e^n). A bid b_e^n and ask a_e^n may be entered into a distributed ledger with accompanying signatures from that clients EE certificate from that epoch:

$$(b_e^n, signature(b_e^n))$$

Because c_e^n is not publicly published, it is not independently attributable. However, if a compulsory audit is called for, each bid and ask can be verified by having its corresponding EE certificate disclosed, along with its pkcs7 signature chain to the utility provider's root certificate.

One key success criterion for the proposed technology is scalability of optimization algorithms for market clearance and microgrid operational controls. This will be verified through a carefully conducted experimental evaluation on a realistic cooperation scenario to make an initial assessment on the magnitude of economic losses that can be saved during disaster response, as well as scalability of optimization algorithms to deal with realistic size of power systems in near real time.

Also, success criteria include the ability to mathematically prove the desirable properties of Pareto-optimality, individual rationality, and fairness for the proposed three-step market system.

4 CONCLUSIONS

In a major shortage scenario, transferring power usage rights from lowest-loss to highest-loss entities has the potential of significantly reducing combined loss and improving overall system resilience. Unfortunately, the existing power systems do not take this fact into account. With this drastic unutilized reduction in combined losses, it is clear that power systems need a paradigm shift, which we described in this position paper. The market-based solution could lead to a significant improvement of the resilience of power cyber-physical systems.

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