BLOCKCHAIN LOCAL MARKETS FOR THE DISTRIBUTED CONTROL OF MICROGRIDS

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ABSTRACT

Tailored energy markets are of interest for local communities with the aim to maximise the exploitation of local resources. Demand side integration policies allow controllable loads participating in the microgrid control. In this scenario, a double-sided market for ancillary service which exploits a continuous double auction as trading mechanism and a Blockchain platform as a settlement tool is proposed in this paper. The aim is to make microgrid participants responsible for their imbalances, quickly solve the decentralised resource allocation problem by identifying the parties for the P2P service provision. Furthermore, settlement requirements are reduced due to transactions automatically executed by smart contracts. By combining the three topics, a unique framework for a market-based microgrid control is formalised.

INTRODUCTION

The concepts of microgrid (MG) and Local Energy Community (LEC) led the power system to a decentralized or distributed model. MGs are MV and/or LV networks where distributed generators, loads, and storage form a unique controllable system. LEC generalizes the concept of MG since the community may not own the physical network, therefore the MG is virtual. MG management can be obtained according to a centralized or a decentralized control [1, 2]. Moreover, the availability of distributed resources (DR) enables the creation of local markets since even small customers can sell energy surplus and offer grid service. A customized local electricity market may maximize the use of local resources and increase the social welfare of participants. Local pools for exchanging goods and services are an emerging trend in the society [3]. Decentralized management allows to define market schemes which comply with local customer preferences. Indeed, the Information and Communications Technology (ICT) advancements influence the availability of platforms for exploiting the collaborative economy. This bottom-up approach is known as *consumer-centric* [3]; the most extreme consumer-centric configuration is the Peer-to-Peer (P2P) market. To sum up, the decentralization of power system is twofold, it involves both control and market schemes. For both, a centralized scheme within the MG shows some drawbacks: high operating costs, lack of transparency, and high security risk since a Single Point of Failure (SPoF) exists [4]. In the context of markets, to outclass those weak points, platforms based on Blockchain technology are emerging. Blockchain technology relies on a cryptographed distributed ledger for transactions automatically executed by means of smart contracts. Therefore, cooperation among distributed users, automation, and security are provided by protocols and cryptographic features [5]. Moreover, Blockchain enables Peer-to-Peer (P2P) energy transactions; therefore, market automation, transparency, security, and burden sharing among actors are provided. The Blockchain technology stimulated corporate and academia initiatives on P2P electricity markets [1, 3]. With the aim to define a novel market-based framework for MG control support, a P2P local market for the provision of Ancillary Service (AS) is proposed. A double sided Continuous Double Auction (CDA) allows the MG players to negotiate P2P agreements on reserve capacity for secondary control. A Blockchain platform is used as settlement tool with the aim to provide a transparent, direct, and safe transaction mean. Moreover, the requests for services are coupled considering the position of parties in the grid; the aim is to support the distributed voltage control by reducing the probability of voltage constraints violation.

The structure of the paper is as follows. In the first section the evolution of AS is discussed; the second section describes the CDA, while the third section presents the structure and the mechanism behind the proposed local AS market. Then, a case study is presented in the fourth section. The closing remarks are provided in the last section.

EVOLUTION OF ANCILLARY SERVICE

ASs are operation practices useful for solving congestions and for frequency and voltage regulation [1]. Traditionally, AS are defined according to the load following paradigm, i.e. power imbalances are solved by adjusting the generation level to match with load fluctuations. This practice requires to procure sufficient reserve capacity in order to be provided when needed. Consequently, power plants have to be flexible thus their operating level is usually below their full capacity [1]. In general, power plants provide their flexibility to network operators (typically, TSOs) through single sided AS markets or by compulsory policies [1, 6, 7]. Since the increased penetration of RESs, the traditional mechanism for obtaining reserve and providing AS becomes less sustainable. On one hand, the intermittent RES production requires additional share of reserve, on the other hand, decarbonation policies are reducing the number of traditional power plants which provide reserve. In this scenario, the social cost related to AS is expected to rise [7]. Government bodies and system operators are concerned about future reserve capacity shortage [8]. Furthermore, the burden of determining the amount of required reserve is on the system operator which has to foresee the uncertainties of the power profiles. In this scenario, novel practices for AS provision are of interest [1, 7, 8]. Demand-side provision of AS increases the share of providers, avoids keeping active unprofitable power plants, and guarantees a more reliable response [6]. Distributed control strategies allow to devise novel AS provision mechanism which involve the several layers of the power system [1, 2, 9, 10, 11, 12]. Double sided AS markets move the responsibility for balancing from grid operators to the actors which are responsible of imbalances [7, 13]. This strategy encourages the parties in improving the accuracy of the power exchange estimation and in respecting the committed energy exchange volume.

CONTINUOUS DOUBLE AUCTION (CDA)

Apart from the supervisor, market participants are considered as rational selfish agents whose goal is to maximise an utility function. In an AS market, each user tries to minimise its expenses for obtaining the services, while each provider is interested to profit maximization. Regardless of the bidding strategy, in free markets the transaction prices in CDA are expected to converge to the competitive equilibrium price [14]. CDA is an efficient tool for quickly solving the allocation problems. It is considered a suitable approach to decentralised allocation control, widely exploited on electronic trading [14, 15]. Its features combined with the exploitation of an electronic platform makes CDA suitable for smart MG trading. Basically, CDA requires to share few information among traders, therefore computation and communication burden are low [14, 15]. The idea of exploiting the CDA as a mechanism for defining P2P transactions has been inspired by [15] in which CDA is used for P2P matching in PX market. Considering that a P2P energy market may led to availability shortage [1], and the legal frameworks in force nowadays [3], a P2P energy market deployment is not foreseen in near future. Conversely, in AS market a grid service is traded; thus, a higher social acceptance is conceivable; therefore, P2P AS market may pioneer on this field. Moreover, AS provision from users involved in DSI policy is a business opportunity, within a P2P framework no middlemen are required. Despite its great advantages, the CDA framework needs to be carefully designed since it may lead to an unsustainable rush to increase the speed of transactions [16], and unfair cooperative bidding strategies. In addition, the trading platform has to guarantee high efficiency and reliability, and the traders have to develop their own bidding strategies. However, in the contest of smart MGs the number of traders is limited; moreover, the users' bidding process may be carried out by artificial intelligence embedded within the users' smart controller, hereby enabling a Machine-to-Machine (M2M) AS market. Finally, in AS market only uncleared requests may cause imbalances in the grid. The user which experience an uncleared request for service can: i) avoid the imbalance using its internal resources, ii) pay a higher cost for the backup service provided by the aggregator.

LOCAL ANCILLARY SERVICE MARKET

According to the smart grid paradigm, a safe, reliable, sustainable, and economic energy supply is ensured if the actions of all grid players are coordinated. To provide flexibility, DRs are involved in Demand Side Integration (DSI) policies, hence a new market for AS is enabled. Several system schemes yield to novel AS frameworks [1]. In this paper the P2P approach is of interest. In light of social acceptance, instead of defining a mechanism that forces the DRs to act according to imposed plans, a market-based interaction among users is preferred. Inspired by the activities of the ePRICE project [7, 13], a double-sided market for the provision of secondary regulation capacity is defined. The MG participants are involved in the definition of the reserve required for the MG operation. In fact, each Balance Responsible Party (BRP) has to assess the required reserve for operation and to buy it in the CDA AS market of the MG. Since both upwards and downwards service have to be provided, two CDA pools are required. Within each CDA pool, demands and offers are matched continuously on the basis of price, volume, and proximity. Therefore, the price of the service changes according to market status. Once demand and offer are matched, a smart contract between parties is written. Then, the behaviour of BRPs is tracked by means of smart-meters. If the demanding BRP experiences imbalance of the expected power exchange, the offering BRP acts for compensating it. According to the measured data, the previously negotiated smart contract is executed in the Blockchain platform. If the imbalance exceeds the negotiated volume, the responsible BRP has to pay a surplus to the MG aggregator who provides the backup imbalance service. To guarantee the market feasibility, this cost has to be higher than the cost of the service traded in the CDA [13]. In a smart MG, generation is expected to be provided by RESs; furthermore, loads are expected to be controllable, automated, then responsive to price signals. Therefore, the BRPs which more likely expect imbalances are the generators, while the BRPs which offer balancing service are controllable loads, energy storages, and electric vehicles (EV). Along with the AS market, the MG users participate in the electricity energy market (PX).

AS market options

The AS market is formed by two parallel CDAs: AS^+ market (for upward service) and the AS^- market (for downward service). The power exchange is considered positive if it flows to the MG, conversely it is negative. The sign of the service nomenclature is defined according to the grid point of view. A BRP offers to decrease the power injected by a S^- offer, while offers to increase its power injected by a S^+ offer. Similarly, a BRP requests to increase the injected power by the request R+, while it asks for decreasing its injected power by R^-.

Roles of MG participants

The MG is supervised and operated by an aggregator. The aggregator supervises the local market for guaranteeing fairness and sustainability. In light of MG safety and security, the aggregator can send extra-market price signals to MG participant to influence their behaviour. The aggregator does not participate in the AS CDA market; however, it provides extra imbalance reserve if needed. The cost of this backup service is higher than the cost in the AS CDA market [13].

Producers inject power in the MG. A producer participates in the DSI programs if its power exchange is adjustable (e.g. adjustable power sources, RES equipped with storage and/or self-consumption). In the PX market producers only sell energy. In the AS market, a producer asks for upward R^+ (increase its production level) and downward R^- (decrease its production level) services. If some control is available, a producer provides downward service S^- (decrease its production level) and upward service S^+ (increase its production level).

Consumers adsorb power from the MG. If the consumer's load is controllable, it is involved in DSI policies. In PX market consumers only buy energy. In AS market controllable consumers sell and buy options. A Consumer can ask for R^+ service (decrease its consumption level) and for R^- service (increase its consumption level). Moreover, a consumer can offer for S^+ service (decrease its consumption level) and S^- service (increase its consumption level).

Prosumers have production and consumption means. A prosumer may behave as a consumer; however, when its production exceeds its self-consumption the prosumer is seen as a producer by the MG. Prosumers act in the PX and in the AS market both as a consumer and a producer. Independent energy storage devices and vehicle-to-grid (V2G) EV act in the MG likewise prosumers; however, their operational strategy may differ.

CDA mechanism for AS P2P market

The CDA protocol defines the features of the demanding and offering shouts, the length of the trading period, the clearing rule, the pricing rule, and the information released to traders [14]. Key elements for clearing the market are: the outstanding bid (current highest uncleared request for service in the market), the outstanding ask (current lowest uncleared offer of service in the market), the clearing price. In this paper, the service is considered provided on hourly basis, hence each shout is referred to 1 hour of service. The parameters which define a shout are: the BRP identifier, the shout timestamp, the shout type (ask or offer), the amount and the price of service (asked or offered), the timeframe to which the service will take place. The trading period is assumed to last 23 hours, it starts 24 hours before the timeframe for which the service is required and closes 1 hour before. As in [15], the market clears continuously during the trading period as bid and ask shouts are submitted by traders. The clearing rule depends on the ordering criteria adopted. In this paper, the "price first and time first" criterion is modified to include the proximity among traders: "price first, proximity first, and time first". It is assumed that the node of the grid to which each BRP is connected is known by the market platform. Since the described mechanism refers to distribution MGs, a radial topology is assumed. The shouts are received by the market platform and ordered in a book. The asking shouts are continuously sorted in descending order (from highest to lowest) while the offering shouts according to the ascending order (from lowest to highest). Firstly, the shouts are grouped in terms of the belonging feeder. For each asking shout, the distance between the related BRP and the offering BRPs is evaluated. To illustrate, if different shouts offer the service for a suitable price, the BRP closest to the asking BRP is preferred. Then, if different shout offers have the same distance, the oldest one is preferred. If no match is found on the same feeder, a complying offer is sought out in the other feeders once the trading period is closed. More than one offer can be involved in satisfying the service of a unique request. Once the shouts are ordered, the matching process looks for the best offer to match with the outstanding ask. The clearing price of the transaction is evaluated as the mean of the shout prices involved in each bilateral exchange (round of transaction) [15]. Once a round of transaction ends, the information about the transaction is written in term of smart contract and sent to the Blockchain platform. A request is completely cleared once that the whole service required is allocated among the offering BRPs. The information published for allowing adjusting strategies is, for each feeder, the outstanding ask and bid, the transaction price [15].

Blockchain platform

The Blockchain platform for the AS market among the MG participants allows for real-time automated transactions driven by measured electric parameters. The Blockchain platform exploits the Hyperledger framework formed by the Composer and the Fabric. The former allows to model the Blockchain and to define the features of transaction and participants. Once the Blockchain is modelled, the Composer allows to test it and to release it to the users. The market platform realises a private Blockchain in which the access is restricted by the access control. Hyperledger Composer allows defining the Blockchain participants' characteristics. Specific classes identify the aggregator and the MG members respectively. One of the key features of the Hyperledger technology is token customisation. The exchanged good is called asset. Each Blockchain realization on Hyperledger has its own asset and the related custom token. The asset/token ratio is defined according to the rules agreed by the parties in the CDA round. In this paper, the asset is the energy related to service provision. Once a smart contract (or chain-code) is defined, the related transaction is executed when the monitored parameters complies the defined condition. In this paper, the monitored parameter is the hourly energy exchange of each BRP. According to the outcome of the round of transaction, a smart contract links the asking and offering BRPs. The class smart contract is formed by: the ID of the parties and of the aggregator, the amount of upward or downward energy for the service, the identifier of the CDA outcome and the hour of the day to which is referred, the unitary service cost, the unitary cost of the backup service, the reference value of energy for both parties involved. For each hour, the energy exchanged by the MG participants is measured and saved in the Blockchain energy register. The amount of downward or upward energy exchanged by the asking and the offering BRPs is evaluated in terms of the difference between the reference value embedded in the smart contract and the actual energy exchange measured and saved in the energy register. By comparing the differences of both parties, the smart contract determines the share of service provided, the related token transaction is executed by considering the cost of the service obtained from CDA. Once the smart contract is executed, the related transaction is confirmed in the Blockchain if the consensus process is passed. The consensus mechanism exploited in Hyperledger is known as Kafka [17]. Kafka is based on permissioned voting several nodes are involved in the validation process; hence the crash fault tolerance is provided. However, it does not provide security against malicious or faulty nodes as the Practical Byzantine Fault Tolerance method does. When the Blockchain process is accomplished, the result in terms of updated agents' wallet is available on the market platform.

CASE STUDY

The case study presents an example of the CDA mechanism combined with Blockchain smart contracts, the AS$^+$ market is described. On a same feeder, 10 BRPs are involved, 5 of them offer S$^-$ service while 5 ask for R$^+$. Once the shouts are received by the CDA platform, the R$^+$ asks and the S$^-$ offers are ordered according to the unitary price, as shown in Table 1 and Table 2. Then, the outstanding bid is found and the suitable offering shouts which have a price lower than the outstanding bid are identified. The outstanding bid and ask are the first rows of Table 1 and Table 2, respectively. The service is paid in terms of tokens Tk.

Table 1. Ordered book of bid shouts for AS$^+$ market at 5 pm

Shout ID	BRP ID	Quantity [kWh]	Price [Tk/kWh]
AS+R17_...7778	F1B11_011	4	0.13
AS+R17_...7002	F1B05_005	5	0.12
AS+R17_...7593	F1B09_009	3	0.10
AS+R17_...7419	F1B07_007	5	0.08
AS+R17_...6458	F1B03_003	5	0.06

Table 2. Ordered book of offering shouts for AS$^+$ market at 5 pm

Shout ID	BRP ID	Quantity [kWh]	Price [Tk/kWh]
AS+S17_...5556	F1B02_002	3	0.05
AS+S17_...7153	F1B06_006	4	0.05
AS+S17_...7593	F1B10_010	3	0.07
AS+S17_...6840	F1B04_004	3	0.13
AS+S17_...7593	F1B08_008	1	0.13

As shown in Table 2, the suitable offers are all the offering shouts. Then the topology is considered, the subset of suitable offering shouts is ordered according to the distance from the BRP to which the outstanding bid belongs. In this case study, the merit order according to distance from F1B11_011 is: F1B10_010, F1B08_008, F1B06_006, F1B04_004, F1B02_002. Therefore, the first trading round involves F1B11_011 and F1B10_010. Since the service request is greater than the offer, the shout of F1B11_011 is involved in a further round of transaction with F1B08_008. Then, the request of F1B11_011 is satisfied, the shout AS+_R17_...7778 is removed from the order book, AS+_R17_...7002 becomes the outstanding bid, the clearing process continues. As shown in Table 3, three requesting bids are cleared by 4 offering bids in 5 transaction rounds. Each transaction round defines a P2P transaction, the price for the service is the mean price of the shouts involved. Since the low price offered and the high price asked, no match is found for the remaining shouts: the requests by F1B07_007 and F1B03_003, the offer by F1B04_004. Once a transaction round is closed, the outcome parameters define the smart contract. In this example, Matlab is used for writing the smart contracts and posting the transactions on the Blockchain platform by means of the Hyperledger Composer API REST server interface. Figure 1 shows the record of the transaction executed between BRP010 and BRP011. The parameters are related to the outcome of the CDA. It is assumed that the reference value of energy exchange for timeframe 17 is 6 kWh for BRP010 and 10 kWh for BRP011. The backup imbalance service cost is considered as 0.50 Tk/kWh. Measuring the actual energy exchange of both actors during the timeframe, the information for executing the smart contract is gathered. In the scenario in which BRP010 injects 10 kWh, whereas BRP011 injects 7 kWh, the BRP010 fully exploits the amount of reserve capacity requested. The surplus of BRP010 is partially compensated by the reduction of the injection of BRP011; for instance, this behavior is achieved by increasing its self-consumption. For this service, the smart contract transfers 0.3 Tk from the BRP011's wallet to the BRP010's.

Table 3. Outcome from transaction rounds

Transaction CDA ID	Quantity [kWh]	Price [Tk/kWh]
AS+17_...80141401B11S10	3	0.100
AS+17_...56504536B11S08	1	0.130
AS+17_...17779636B05S06	4	0.085
AS+17_...53950119B05S02	1	0.085
AS+17_...48657274B09S02	2	0.075

```
{"$class":"org.cired2019.ServiceTransaction",
   "EnergyRifBuyer":6,
   "EnergyRifSeller":10,
   "ServiceQuantity":3,
   "ServiceCost":0.1,
   "ServiceCostAGG":0.50,
   "Seller":"resource:org.cired2019.Member#ID010",
   "Buyer":"resource:org.cired2019.Member#ID011",
   "Owner":"resource:org.cired2019.Aggregator#0000",
   "CDAid":"AS+_17_737699.5686995832948014l401_B_011_S_010",
"transactionId":
"18e9bda8533b0c147ffd3f9d6b1fb35dba5431261abcc8cf3695805be77f8915",
   "timestamp":"2019-01-10T15:03:49.343Z"}
```

Figure 1. Transaction between from BRP 011 to 010

CONCLUSIONS

Communities of customers forming a MG or a LEC may devise a tailored market scheme to maximise the exploitation of local resources; moreover, the provision of AS can be demanded to local BRPs. By means of DSI policies controllable loads can contribute to the AS market. In this scenario, the paper proposes a double-sided AS market which exploits a CDA as trading mechanism and a Blockchain platform as a settlement tool. The double-sided market for reserve capacity makes each MG participant responsible for its imbalances, it leads to a potential reduction of the overall reserve capacity requirement. The CDA mechanism allows to quickly solve the decentralised resource allocation problem by identifying the parties for the P2P service provision. By exploiting the Blockchain as a settlement platform, transactions are automatically secured on a distributed ledger and the time required for AS settlement is way shorter than the time experienced nowadays in the wholesale market. By combining double sided AS market, CDA, and Blockchain, the main contribution of this paper is the formalization of a unique framework for a market-based MG control support. Further work will be devoted to improving each component and to devise and embed a local energy market mechanism.

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