Ancillary Services in the Energy Blockchain for Microgrids

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Abstract*—TTT The energy blockchain is a distributed Internet protocol for energy transactions between nodes of a power system. Recent applications of the energy blockchain in microgrids only consider the energy transactions between peers without considering the technical issues that can arise, especially when the system is islanded. One contribution of the paper is, thus, to depict a comprehensive framework of the technical and economic management of microgrids in the blockchain era, considering, for the first time, the provision of ancillary services and, in particular, of the voltage regulation service. When more PV nodes are operating in the grid, large reactive power flows may appear in the branches. In order to limit such flows, a reactive optimal power flow (R-OPF) is solved, setting the voltage at the PV buses as variables within prescribed limits. Each PV generator will thus contribute to voltage regulation, receiving a remuneration included in the transaction and certified by the blockchain technology. For showing how this system can work, a test microgrid, where some energy transactions take place, has been considered. For each transaction, the R-OPF assigns the reactive power to the PV buses. The R-OPF is solved by a Glow-worm Swarm Optimizer. Finally, the paper proposes a method for remuneration of reactive power provision; this method, integrated into the blockchain, allows evaluating the contribution to voltage regulation and increases the transparency and cost traceability in the transactions. The application section shows the implementation of a Tendermint-based Energy transaction platform integrating R-OPF and the above cited technical assessments.

***Index Terms*—Transactive energy; energy blockchain; distributed generation; P2P; Optimal reactive power flow; Glow-worm Swarm Optimization.**

I. Introduction

The advent of transactive energy as one of the most relevant technologies in the Gartner Hypecycle [1] and the birth of several startups around the bitcoin technology [2] for crypto-currency show that the interest around the possibility of managing certified transactions on the Internet, without the need of a trusted third-party entity, is raising more and more.

Some recent microgrid projects in New York city in the Brooklyn district, based on the blockchain technology for managing energy transactions, are setting the prerequisites of a new energy system [3]. This new energy system is based on distributed generation (DG), energy trading between neighbours, and a different role of distribution utilities as we have known them up to now. What appears to be disruptive in the energy sector is the strong reduction of time for managing the economic transactions and the possibility to set free from central authorities. Although this movement is currently largely being triggered by startups, utilities are catching up in these energy blockchain applications and are starting joint ventures and cooperations [4], [5]. The basic value that new companies show to potential customers and investors is quite similar to that of initiatives in the bank sector. Any need for an intermediary between two parties disappears: switching to a decentralized energy system, detaching the related financial transactions from a centralized control unit, is undoubtedly another important step towards a full decentralization of the electricity sector. For now, however and still in this paper, the authors are envisaging an evolutionary role for the Distribution System Operator (DSO), the end users and the energy vendors.

Many companies have recently set up energy exchange platforms between buyers and sellers. As an example, the Dutch company Vandebron [6] gives the possibility to buy directly from producers. In this example, there is still a central party that manages the network, does the billing and makes sure production and consumption stay balanced. In principle, in microgrids, decentralized regulation could offer the opportunity to manage effectively the blockchain technology for energy transactions. However, the strong physical limitations and constraints (voltage limits, cables ampacity, etc.) reduce the realistic possibility of energy exchanges between prosumers.

The main contribution of this paper is, thus, to depict a clear and comprehensive framework of the technical and financial management of energy distribution networks in the blockchain era, considering, for the first time, the provision of ancillary services and, in particular, of the voltage regulation service. Two features of the blockchain that distinguish it from other technologies, such as databases, are transparency to users and immutability. As every transaction is added to the ledger, every end-user taking part to the platform can monitor and trace back all transactions. No other market provides such transparency about its transactions without further information-sharing costs for participants in almost real time. In the paper, the blockchain is considered as enabling technology for providing shared voltage regulation services to a microgrid. In the problem formulation, reactive power support, essential for reducing energy losses and eventually flattening voltage profiles, is carried out acting on P-V buses. Active power injections, instead, being the object of the energy transactions, are assumed as fixed at the generation buses according to the transactions running in the considered timeframe. In this context, a new architecture for the energy blockchain is defined.

The latter is based on a permissioned blockchain, where only some 'allowed' nodes can write the blocks of energy transactions. In the proposed architecture, the DSOs still hold a central role since they may interact with Metering Operator and surely interact with TSOs, consumers and prosumers. In the application section, the paper presents an example of a set of energy transactions between the nodes of a residential medium voltage (MV) 9-bus microgrid together with the calculation of losses and reactive support and verification of the technical feasibility of the same transactions. As the aim of this paper is to show how the provision of ancillary services can be integrated into a permissioned blockchain, the choice of the method for the attribution of losses to transactions is, for the sake of clarity, the global method as described in [7], while the method for reactive power dispatch is the Glow-worm Swarm Optimization [8].

II. The energy blockchain

In the last years, decentralization and digitalization have imposed the appearance of new digital business models, based on the use of platforms in which the parties meet. Physical distributed resources are not owned by a single entity and roles may not be strictly separated (production and consumption of a resource and regulation tasks). Moreover, transparency is one of the main features of these businesses. Thanks to digitalization, each party in this transaction can have feedback about the service from the community and about the perception on the quality of service provided/received. Technically this possibility is supported by platforms but also by new ways of exchanging values and services. In this frame, blockchain appears as an enabling distributed digital transaction technology. It allows for secure data storage and smart contracts execution in decentralized and untrusted environments. In this section, the blockchain technology is briefly outlined, describing its basic principles and how it is tailored to address energy transactions for microgrids.

A. Blockchain principles

Blockchain is a technology designed for simplifying transactions between peers without the central control of any trusted third-party. Bitcoin management, and in general crypto-currencies management, are classic Blockchain applications. In recent years, Blockchain technology has been applied successfully also in non-monetary fields (e-health, identity management, industrial production [9]–[13], etc.) and many other applications are currently under study in the energy field (e.g. load aggregation [14]). Blockchain operates as a distributed ledger containing a continuously growing list of data records called blocks [15]. Each block is a time-stamped, shared, unalterable unit connected to preceding blocks. Two things enable the blockchain technology functioning: an effective validation mechanism and a communication network connectivity to share the ledger. Validation is a very crucial issue. It must account for the semantic and syntactic correctness of each block. All transactions are verified by the nodes, namely machines run by the network's users; they are distributed, public, and encrypted. Blockchain allows users to keep track of every transaction: all users have a copy of the blockchain and none of them is able to modify (by proposal or by mistake) neither the blocks content nor their order, since modification should be done at every node. In this way, anyone can control that all blocks have not been subjected to tampering, quickly and efficiently, by checking only the last block. The Secure Hash Algorithm SHA256 is used for checking the validity of each block [16]. The security of a hash algorithm is given by two main characteristics: 1) the function is not reversible (i.e. it cannot be traced back to the original message knowing only this data); 2) it should never be possible to intentionally create two different messages with the same digest. The hash function is applied to several elements belonging to the block header, including the blockID (for protecting from changes in the order of blocks), a nonce, the root of a Merkle tree built with transactions, and a copy of the hash of the previous block. The nonce is specifically mined so that the resulting hash verifies specific conditions (e.g. it starts with a given number of zeros). In case one or more blocks get tampered, even in a single bit, with high probability the hash changes and the block is not considered valid anymore. A malicious user could mine a new nonce in order to obtain a valid block, however, the tampering is made evident by comparing the hash with those owned by the other nodes. Besides, blocks are "chained", so that the hash of block i-1 is included as input to the SHA256 function to obtain the hash of the subsequent i-th block. In this way, any tamper on a block creates an invalid condition over all the following blocks in the chain. These characteristics, together with the consensus algorithm make the Blockchain technology highly resilient to tampering and protect, with a certain degree of security, against colluding nodes. In this largely simplified description, anyone knows about anyone else's transactions, exposing private data about energy generation and consumption. However, blockchains with confidential transactions have recently appeared and provide a solution to such privacy concerns [17].

B. Energy Blockchain for ancillary services provision in microgrids

The application of the blockchain technology is largely justified in the energy case as recalled in [18], since in this field, the market is certainly a multi-party environment, does not need a trusted authority, operation is not centralized, transparency and immutability are required while there is no need for high speed of storage operations over the blockchain. In this paper, a blockchain architecture for this specific application must be considered. In (Fig. 1) a possible architecture is proposed. Nodes of permissioned Blockchain, in green in Fig. 1, are allowed to write the blocks of energy transactions and thus they have access to the related information. Distribution System Operators (DSOs) gather measures from the grid and selling/buying proposals and approve/match them based on the feasibility of each transaction through the energy blockchain

Fig. 1: Ancillary services and the blockchain technology.

platform. Some generation buses can also regulate voltage and reactive power injections using power converters (red nodes in Fig. 1), and are indicated as 'regulator nodes'. Other generation buses (blue nodes) can only control active power injection while reactive injection is fixed as a percentage of active power or is set to zero. The main actions required for monetizing reactive power and voltage regulation are:

- the computation of energy losses for each transaction
- the estimation of the amount of reactive power required at the 'regulator nodes' and its remuneration;
- the use of smart contracts for automatic interaction between production and consumption nodes;
- the writing of transactions of active and reactive power in the blockchain.

The optimization of reactive power injections produces an optimal operation point, while keeping the same active power injections. The optimal operation point reduces the circulation of reactive flows, which can be large in case of voltage-regulated nodes. However, the provision of reactive power in a given timeframe impedes the selling of a given amount of active power to a generic customer in subsequent hours. For this reason, in this paper, it is hypothesized that reactive power provision must be remunerated and a specific field in the transaction block is allocated for accounting for the provision of this ancillary service. In a recent paper [7] an algorithm was proposed for tracing power flows providing evidence about how things are physically evolving. In this paper, the role of all the actors is rethought: the DSO, the energy vendors and the users, as reported in the architecture shown in Fig. 1. For each proposal of energy transaction, the DSO can run the tracing algorithm of [7] as well as the algorithm for optimal reactive power dispatch proposed in this paper, then results can be somehow monetized and included in the blockchain. Energy vendors interact with users, register and add them to the white list for accessing the permissioned blockchain. This architecture makes transparent the communication among competing vendors and between vendors and the DSO. All is visible also to end users, filling their gap due to knowledge asymmetry.

End users acquire a renewed role since they are not only producers and consumers but they can also participate to voltage regulation. This means that users can be remunerated not only when they produce active power, but also when they inject reactive power for regulation, with a lot of new opportunities given by the remuneration of the effort spent for supporting efficient operation of the the network. In this vision, the blockchain enables direct transactions between users, facilitates traditional interactions with the other actors of the energy market and provides the full range of possibilities in the grade of involvement of the DSO and energy vendors.

In this paper, the blockchain technology in the energy field is considered. The "Energy Blockchain", including ancillary services provision, can be, in our vision, simplified as in the conceptual scheme of Fig. 2. It is applied to energy transactions between prosumers, which are the perturbing events, then the DSO calculates the optimal contribution given by nodes to regulation, finally the global losses are computed.

In Fig. 2, each block contains one or more transactions. We foresee transactions organized in different Merkle trees respectively for active power, losses and reactive power. Transactions of active energy contain *source (generator), destination (load), transferred energy* [kWh] *, timestamp, duration, power profile* [kW]. Transactions related to ancillary services provision indicate the timestamp, the node that injects reactive energy and its value in [kVAR].

The organization in Merkle trees allows the simultaneous verification of several transactions in a block by the verification of a single hash of the root of the Merkle tree. Nevertheless, although energy blockchain is becoming more and more a realistic perspective, especially in energy district characterized by a large number of generators and loads, from a technical point of view, a correct formulation of the energy blockchain poses some challenges that are here analysed. It is well-known that an energy transaction between a generator and a load may not correspond to the actual physical situation revealed by applying power flow tracing methods [7], in particular, distributed generation with voltage supported systems (P-V nodes) may give rise to a large circulation of reactive power. Therefore, before the transaction is started, a physical feasibility check is executed, to verify whether the considered transaction is viable in the current system.

So, referring to Fig. 3, the transactions of active power P_i, P_{i+1} and P_{i+2} in the different time intervals $[t_0, t_5]$ are all the perturbing events in the microgrid.

In the first time interval $[t_0, t_1]$, a set of nodes, indicated by the DSO for providing ancillary services, injects reactive power Q_j into the microgrid. In parallel, the DSO evaluates the overall losses during the same time interval, ΔP_{totj}. At time t_1 a new transaction starts and the network hosts a new flow between a generator and a load. As a new transaction starts in t_1, it causes, as indicated by tracing algorithms, a superposition of flows between generators and loads involved in transactions, for the time interval $t_1 - t_2$ as indicated in Fig. 3. Unfortunately, when calculating losses, a non-linear

Fig. 2: Simplified conceptual scheme of an energy blockchain.

Fig. 3: The blockchain technology takes care about the superposition of operating conditions in three domains: status of energy losses, status of regulation, status of energy transactions.

coupling of power flows referring to the different transactions happens. The new distribution of power flows can either increase or reduce the efficiency of the distribution system in terms of losses.

The just cited issue is not considered in most papers on the energy blockchain and the relevant literature is divided into two parts. Some papers consider the infrastructural issue as not relevant since the blockchain is only considered as a means for economic transactions, some others underline the importance of energy transactions at local scale as tools for reducing balancing costs [19]. In a wider perspective, it can be here claimed that the application of blockchain technology to microgrids and electrical districts considering physical proximity becomes relevant, when a match between consumption and generation can be made and when the effects of each transaction are followed closely in almost real time. In this way, blockchain can provide for aggregation services and reduce balancing costs. Before a new transaction between a generator and a load takes place, it must be evaluated and approved by the DSO. The following steps are thus taken by the DSO:

1) reads the blockchain and/or forecasts expected loads/generators at the producers and consumers from the grid and the selling/buying proposal;
2) Sets generators that are not taking part to the new energy transaction as P-V or P-Q nodes (depending on their role in the grid) with the value they had in the preceding block;
3) Increases the load and generator which are involved in the considered proposal of the specified amount in kW;
4) Runs the R-OPF and find the new reactive set points for the regulator nodes keeping fixed the generator and load involved in the desired energy transaction and giving the other nodes the forecasted values;
5) Identifies the contribution of each existing transaction to active losses in the network;
6) Quantifies the increase/reduction of active losses in the grid for the new energy transaction.
7) Quantifies the amount of reactive power required by the regulatory nodes, even if they are not directly involved in the transaction, to guarantee an optimal operation point
8) Quantifies the active losses that can be attributed to all transactions including the new one.

One of the main steps of the verification procedure is the power flow tracing and losses attribution to each energy transaction, that can be done using various methods in literature as, for example, those proposed in [7]. In this paper, for the sake of clarity, the so called Global method taken from [7] is used.

III. Reactive optimal power flow

Reactive Optimal Power Flow (R-OPF) is a multi-objective optimization problem aiming at ensuring an optimal technical and economical planning of reactive power production in a grid. The main objective of the R-OPF problem can be the allocation of reactive power compensation devices or the set-point of the existing devices, satisfying all the technical constraints [20].

Many algorithms are used in literature for solving the R-OPF problem: classical and hybrid Evolutionary Programming [22], [23], Genetic Algorithms [24], Fuzzy Logic [25], Evolutionary Strategies [26], Particle Swarm Optimization [26]. In this paper, the Glow-worm Swarm Optimization (GSO) method is used to solve problem [8]. The ability of this method is to fully explore the objective function space and find the local optimal setting. The movement of agents will be decided based on the signal strength that picked up from its neighbours. The brighter agents will be more attractive and the best one will be chosen as the solution of problem.

(a) (b)

Fig. 4: Capability curve for the PV generators connected to the grid [21] (a); Test network for the two considered case studies (b).

In this problem, the optimal reactive power flow was used to find the minimum power losses for the microgrid system operation. The objective function of problem can be expressed as follows:

$$OF = P_{LOSS} = \sum_{i=1}^{n_{bus}} P_{i(Q_{Gi})} \quad (1)$$

where $P_{i(Q_{Gi})}$ is the generic power injection at bus i and can be written as:

$$P_{i(Q_{Gi})} = \sum_{j=1}^{n_{br}} |V_i| \cdot |V_j| \cdot |Y_{iJ}| cos(\theta_{ij} - \delta_i + \delta_j) \quad (2)$$

Y_{ij} is the admittance of branch ij; V_i is the voltage at buses i and V_j is the voltage at bus j; δ_i and δ_j are the phase angles of the voltages at bus i and bus j; θ_{ijis} the phase angle of Y_{ij}; nbr is the number of branches connected to bus i; $nbus$ is the number of buses in the system.

The above objective function needs to satisfy the following constraints:

The balance between generated power and total demands plus losses in the power grid:

$$\begin{aligned} \sum_{i=1}^{n_G} P_{Gi} &= \sum_{i=1}^{n_d} P_{L_i} + P_{loss} \\ \sum_{i=1}^{n_G} Q_{Gi} &= \sum_{i=1}^{n_d} Q_{L_i} + Q_{loss} \end{aligned} \quad (3)$$

The inequality constraints representing the limits on all variables:

$$\begin{aligned} P_{Gi_{min}} \leq P_{Gi} \leq P_{Gi_{max}} \\ Q_{Gi_{min}} \leq Q_{Gi} \leq Q_{Gi_{max}} \\ V_{min} \leq V_i \leq V_{max} \end{aligned} \quad (4)$$

where P_{Gi} and Q_{Gi} are real and reactive power generated at node i, while $P_{Gi_{min}}$ and $P_{Gi_{max}}$ respectively are minimum and maximum values of real generation at bus i and $Q_{Gi_{min}}$ and $Q_{Gi_{max}}$ respectively are minimum and maximum values of reactive generation at bus i. The optimization variables are the reactive power injections at the generation nodes involved in the transactions. The optimization is implemented in Matlab.

IV. Cost allocation: power losses

As a result of the R-OPF run, the reactive power set-points are deduced at the DSO server and sent to the regulator nodes. A part of the transaction block is thus devoted to host the estimation of the power losses after the R-OPF execution.

Starting from the consideration that distribution systems power losses are generally expressed as percentage of purchases [27], a simplified method can be used for the allocation of power losses to a transaction characterized by a certain increase of load [7]. Being G_i and L_i the generator and load involved in the transaction, respectively, and indicated with P_{Li}^{Δ} the power purchased in the considered time interval, the losses that can be attributed to the transaction according to the simplified Global method in [7] are expressed by:

$$\Delta P_{G_i, L_i} = \Delta P_{tot} \cdot \frac{P_{Li}^{\Delta}}{L_{tot}} \quad (5)$$

being ΔP_{tot} and L_{tot} the total power losses and the total load in the microgrid considering the increment due to the transaction, respectively.

Costs for reactive voltage will also be estimated at this point and allocated to the transaction as well. In the following section, a methodology for monetizing the reactive voltage support service is proposed.

V. Remuneration: reactive voltage support and power losses reduction

According to local technical regulations, as for example the Italian Standard CEI 0-16 [21], all generators must provide ancillary services and exchange reactive power with the microgrid which they are connected to. The injection of reactive power for guaranteeing the security of the system is primary with respect to the injection of active power and is implemented by limiting the active power exchange if needed according to a capability curve like that represented in Fig. 4.

The problem gets even more relevant for islanded microgrids where the voltage support contribution of the main grid is not present and only distributed generators can provide reactive power.

Both in the case of grid connected and islanded microgrids, the evaluation of voltage support service can be assessed as an *'opportunity cost'*. With this term, we usually refer to a benefit that could have been received by a party (but is not received) for taking a decision.

Namely, an opportunity cost (OC) represents an alternative that was not taken, when a decision is made. This cost is, thus, most important and straightforward for two mutually exclusive events, such as it happens when a generator with circular capability curve produces reactive power and cannot produce active power. In this case, the opportunity cost (OC) can be defined as:

$$OC = RMLO - RCO \tag{6}$$

where RMLO is the Return of Most Lucrative Option (the production of only active power) and RCO is the Return of the Chosen Option (the production of active power with a given power factor).

In this way, the evaluation of reactive support in P2P transactions could be assessed for every time interval t and for each generator DG_i as it follows:

$$\begin{aligned}\Delta P_Q = \max\Big\{0; \Big(&\sqrt{Sni^2 - Q_G(t)^2} \\ &- \sqrt{Sni^2 - (Q_G(t) + \Delta Q)^2}\Big)\Big\}\end{aligned} \tag{7}$$

$$RPC = \Delta P_Q \cdot k \cdot \Delta P_{tot}(t) \cdot C_{kWh}(t) \tag{8}$$

where RPC is the reactive power cost, $k \cdot \Delta P_{tot}(t)$ is a real valued degradation factor lower than 1 that depends on the effect of reactive power management on losses reduction, $C_{kWh}(t)$ is partly a production cost and partly a losses cost evaluated as indicated above or in any more detailed other way. $P_G(t+1)$ is the forecasted power generated at time $t+1$; Sni is the rated power of the i-th generator; $P_G(t)$ is the active power produced at time t. It is intended that the remuneration of the reactive service as opportunity cost is as more valuable (higher value of $k \cdot \Delta P_{tot}(t)$) as larger the effect of R-OPF on the reduction of power losses is. The above formulas are valid for symmetrical capability curves.

VI. Application

This section shows an application of the proposed methodology for ancillary services valorization in a 9-bus residential MV microgrid, in which a set of energy transactions supported by the blockchain technology between the nodes takes place. The test system is shown in Fig. 5. The electrical line data are shown in Table I. Three distributed generators are connected at buses 2, 3, and 4.

TABLE I: Electrical line-data of the network

Sending bus	Ending bus	R [Ω]	X[Ω]
1	5	0.6076	0.098
1	7	0.868	0.14
1	2	0.4487	0.091
2	8	0.641	0.13
3	6	1.302	0.21
5	3	0.868	0.14
7	4	1.302	0.21
8	9	0.9615	0.195

TABLE II: Load-bus data

	CASE1		CASE2	
Bus	Pload [kW]	Qload [kVAr]	Pload [kW]	Qload [kVAr]
1	-	-	1062.500	534.500
2	764.300	422.358	-	-
3	254.400	172.587	-	-
4	563.400	279.126	-	-
5	646.400	370.550	646.400	370.550
6	817.700	437.850	817.700	437.850
7	696.700	458.406	696.700	458.406
8	319.300	167.939	319.300	167.939
9	764.100	414.908	764.100	414.908

The microgrid is able to work both connected to the main grid and islanded. In this last case, the three distributed generators will supply all power demand. Both operating modes are analysed in the two case studies considered in this section and named in the following as CASE 1 and CASE 2.

In CASE 1, the microgrid is connected to the main grid at node 1. The DGs present in the network are three inverted interfaced PV plants with energy storage which satisfy the active power demand of the loads fed by the node in which they are inserted.

In CASE 2, the microgrid works isolated from the main grid. The three DGs on the network supply loads at the nodes and losses of the network.

In both cases, DGs are available for energy transactions with the users, compatibly with the characteristics of their capability curve, and take part in the voltage regulation service, also producing reactive power. The rated features of DG2, DG3 and DG4 are 1.5 in case 1. In case 2, DG2 and DG3 are 2.5, DG4 is 2. The load-bus data are reported in Table II differentiated based on the case which the are referring to.

Three partially overlapping transactions have been taken into account, which are established between generators and load nodes in successive time intervals. During transaction tr_1 DG2 sells 300 kW to L5, during tr_2 DG3 sells 200 kW to L7, and during tr_3 DG1 sells 250 kW to L9.

For each case study, a comparative analysis is carried out between the cases in which the generators are free to supply power without any imposition from DSO, and the case in which the DSO requires the generators to respect a given generation profile, to serve the technical needs of the network. The amount of reactive power required by the regulatory nodes is obtained as an output of the R-OPF optimizer, with the aim to obtain the minimum losses in the system.

Table III shows the results obtained for CASE 1 and CASE 2 respectively. For each considered time interval, the table reports the contribution of each existing transaction to active losses in the network $\Delta P_{G_i,L_i}$, and the value of the total losses in the network ΔP_{tot} both with the use of the optimizer and without it.

Moreover, in the table is reported the incremental reactive power (ΔQ) supplied from each DGs during each considered time interval, with respect to the previous time interval in the fully optimized operation. To quantify ΔQ in the first interval $t_1 - t_2$, we needed to make assumptions for the previous interval. In particular, in CASE 1 we imagine that the reactive power injected from DGs is zero; in CASE 2 the hypothesis is that the three generators share the total request of reactive power of the network proportionally to their rated powers.

From the analysis of the results, it is clear that the total losses of energy in the network and the losses associated with each transaction are reduced as a result of the regulating effect of the generating nodes. As it appears in Table III, sometimes the ΔQ obtained from the calculation of R-OPF can result equal to zero or assume negative value for a given node. It means that for the subsequent time interval the generator connected to the node must reduce the previous injection of reactive power, and therefore it will not be remunerated as a consequence of the application of the opportunity cost criterion. Generally, the optimization of the reactive powers injected by the DGs also produces a slight improvement of the voltage profile at buses reducing the maximum value, as shown in Fig. 5a and 5b. Fig. 5a refers to CASE 1 and to $t_3 - t_4$ time interval, and shows voltages at buses obtained adopting a generation profile calculated both using R-OPF and not. Fig. 5b shows the same type of comparison, but referring to CASE 2 and to the $t_1 - t_2$ time interval.

Finally, Fig. 6 shows the trajectory of the solutions in the search space. The figures show the first iteration in which all solutions are spread in the search space (a), iteration 70 in which solutions gather around local optima (b), and the last iteration in which solutions are totally collapsed into the different multiple optima (c).

Besides, Fig. 7 shows the trajectory of the same glowworms in which one of the variables has been omitted, for the sake of clarity of representation, but in which the objective function is also plotted. As it can be noted the objective function of the final solutions is strongly reduced as expected. The best solution has to satisfy all constraints of the system as well.

VII. Workflow validation

We functionally validated our distributed energy system using a blockchain network with few nodes running Tendermint 0.24. Prosumers run our custom application where Model and Controller are written in Java, the View uses JavaFX, the blockchain support relies on the dedicated API [28]. Based on promises of generations, regulation and consumption from end users, a market-matching algorithm, that is out of the scope of this paper, on the Blockchain creates purchase-offer couples. The latter show a strong commitment as these promises are digitally signed. The couples created by the market matching algorithm are the input data for the R-OPF. Our view for generators is reported in Fig. 8a; selecting starting and ending dates and times, available active power, and regulation capacity they provide, as well as the details of their energy offer.

In Fig. 8b only the DSO knows the status of the whole distribution network and computes the evolution given by the superposing conditions indicate in Fig. 3. The results provided by the algorithm are then written on the blockchain and used by the smart contracts to actually enforce the energy flows. In Fig. 8b phases 1 and 2 are devoted to the offer and demand writing on the blockchain, phases 3,4,5 and 6 relate to the R-OPF calculations and request for operation from the DSO to regulator PV buses for the coming transaction. In the same phase, the DSO computes the new losses in the new coming operating condition. Finally, after phase 6, the transaction takes place. Energy is injected in the grid and payment through digital token or fiat currency is executed. We ran the R-OPF for the network described in Fig. 4b on an Intel(R) Core(TM) i5-7300U CPU @ 2.60GHz, equipped with 8GB of RAM200 running Windows 10. The algorithm chooses randomly the first generation of solutions, then it processes 200 fireflies and converges to the solution in few iterations. For our simple test network the average R-OPF computation time is 48 sec. As we use an heuristic algorithm, with the same computational complexity of a load flow algorithm ($\mathcal{O}(n^2)$). This timing fits well the requirements given by our test network and are feasible also for larger microgrids assuming that offers are evaluated every 5 minutes. In our tests we experienced an average of thousands transactions per seconds on the blockchain, sufficient to process the asynchronous generation offers and load offers as well as the periodical R-OPF outcomes and the transactions of energy flows.

VIII. Conclusion

In this paper, a realistic logical architecture of a blockchain-based energy transaction platform is considered. In the proposed framework, the DSO is the technical manager of the physical grid, participating, together with energy vendors and even end users, to the technical and economical maintenance of the distribution network. In this way, a new digital business can be enacted, because end users actively participate both to the distributed generation and to the provisioning of ancillary services. Differently from other digital businesses, the electrical energy transactions strongly depend on the infrastructure capability and efficiency and have an impact on the status and the reliability of the distribution network. In this paper, the issue of ancillary services provision is considered and handled within the blockchain framework. A method for assessing the economic value of the services is also proposed. All technical verifications such as it happens today in the electricity world are managed by the DSO using a client-server architecture towards prosumers, although the valorisation of losses and ancillary services provision should be registered transparently as parts of a smart contract. Finally, this paper suggests a way to value reactive injections as an opportunity cost. These are

TABLE III: Valorization of the transactions

			CASE 1					CASE 2				
	R-OPF	trans	$\Delta P_{Gi,Li}$ [kW]	ΔP_{tot} [kW]	ΔQ [kVAR]/ΔP_Q[kW] DG2	DG3	DG4	$\Delta P_{Gi,Li}$ [kW]	ΔP_{tot} [kW]	ΔQ [kVAR]/ΔP_Q[kW] DG2	DG3	DG4
$t_1 - t_2$	N	tr_1	5.481	17.019	–	–	–	5.164	18.118	–	–	–
	Y	tr_1	5.367	16.592	540/81.3	0	0	3.869	13.449	-40/ –	1070/457.9	-1010/ –
$t_2 - t_3$	N	tr_1 tr_2	4.930 3.469	15.270	–	–	–	5.842 4.111	18.102	–	–	–
	Y	tr_1 tr_2	4.382 3.083	13.549	0	750/147.3	0	4.648 3.270	14.409	-0.11/ –	440/267.3	-770/ –
$t_3 - t_4$	N	tr_1 tr_2 tr_3	5.466 3.485 4.251	16.975	–	–	–	8.124 5.715 6.317	25.202	–	–	–
	Y	tr_1 tr_2 tr_3	4.273 3.288 3.634	14.466	0	1200/321.9	-356/ –	8.124 4.549 5.028	17.487	-540/ –	0	-800/ –

(a)

(b)

Fig. 5: Voltages at buses obtained with and without R-OPF in $t_2 - t_3$ time interval of CASE 1 (a); Voltages at buses obtained with and without R-OPF in $t_1 - t_2$ time interval l of CASE 2 (b).

useful for voltage support and power losses limitation and as such must be remunerated. Further studies will be addressed towards the issue of balancing generation and loads using the same logical architecture and providing efficient means for achieving this task.

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(a) (b) (c)

Fig. 6: Initial placement of glow worm swarms in the space based on the injected reactive powers from three generators (a); The location of glow worm groups after 70 iterations (b); The location of glow worm groups after 100 iterations (c).

(a) (b) (c)

Fig. 7: Initial placement of glow worm swarms in the space find minimum Plosses (a); The location of glow worm groups after 70 iterations find minimum Plosses (b); The location of glow worm groups after 100 iterations find minimum Plosses (c).

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(a) (b)

Fig. 8: Client GUI at the prosumer for providing energy offers (a); Energy blockchain workflow (b).