A Peer-to-Peer Market Algorithm for a Blockchain Platform

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***Abstract*—In an era of technological revolution in which everything becomes smarter and connected, the blockchain can introduce a new model for energy transactions able to grant more simplicity, security and transparency for end-users. The blockchain technology is characterized by a distributed architecture without a trusted and centralized authority, and, therefore, it appears as the perfect solutions for managing exchanges between peers. In this paper, a market algorithm that can be easily transferred to a smart contract for maximizing the match between produced and consumed energy in a micro-grid is presented. The algorithm supports energy transactions between peers (both producers and consumers) and could be one of the main executables implemented using a blockchain platform. The case study presented in this paper shows how the end-users through the blockchain could select among the possible energy transactions those more suitable to offer specific ancillary services to the grid operator without involving the grid operator itself or a third-party aggregator.**

Keywords—market algorithm, blockchain, smart contract, micro-grids, energy transaction, peer-to-peer, ancillary services, P2P.

I. Introduction

Blockchain technology is in continuous evolution and it has applications in many sectors, like finance, politics (e-voting), tracking of goods (supply chain) and also in the electricity market [1].

Blockchains are designed to be decentralized operating as a digital register maintained by a distributed network [2]. This allows the creation of economic systems in which financial transactions are transparent, secure, reliable and can be performed without intermediaries.

In general terms, the blockchain is a transaction register based on Distributed Ledger Technology [3]. According to this definition, transactions are assembled into blocks linked together to form a chain (hence the name blockchain); a new block can only be inserted after the last one (see Fig. 1).

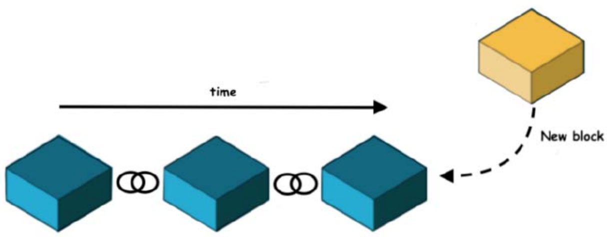

Fig. 1. New block insertion process.

The main features of blockchain technology are:

- *Immutability*, because the information within each block, once it added to the chain, cannot be changed anymore
- *Transparency*, because each block added to the chain is accessible to all participants;
- *Traceability*, because is possible to get the transactions' history;
- *Security* and *control*, because thanks to the use of cryptography, data protection is greater and the risk of fraud is lower.

The blockchain can be confused with a distributed database, but it has characteristics that go beyond the functions of such a structure. In fact, unlike a database, blockchain transactions are validated before becoming part of new blocks, after the approval of most of the nodes participating in the network and, once confirmed, it becomes impossible to modify them. Those providing the validation are called "miners" and the process of reaching "consensus" on a block of transactions is called "mining" [4]. This feature provides the authoritative validation that in a centralized system is guaranteed by the trusted authority or, more generally, by the system operator. Furthermore, decentralization makes it possible to prevent market abuse through monopolies and reduce costs and regulatory control. After the validation, transactions can be inserted in the blockchain and cannot be deleted or modified, otherwise, all the chain would be invalidated.

This innovative technology can be used in the energy field employing a blockchain platform to execute transactions in the power network (or a micro-grid) between end-users (peers), realizing peer-to-peer (P2P) transactions and at the same time providing a balancing service to the network.

The energy blockchain is a distributed protocol devoted to energy transactions between generation and load nodes in power systems [5]-[6]. The use of a blockchain system in the P2P energy transactions context allows a significant change in the energy sector, in particular by encouraging decentralization [7].

Indeed, the growing use of small renewable energy installations, such as solar panels on building roofs, can encourage P2P energy exchanges for increasing consumption from local sources during production hours. Nevertheless, high shares of renewables in the power system can lead to frequency instability or needs for voltage regulation. The use of blockchain technology for energy transactions could help in stabilizing the network and favoring decentralization. An interesting application is the Brooklyn micro-grid, based on a local energy market where members can exchange energy with their neighbors [8]. The Brooklyn micro-grid represents the first project that simplifies an energy transaction thanks to blockchain technology.

An important feature of the blockchain systems is the possibility to implement "Smart Contracts" which represent the "translation" in code of a contract between the parties, able of verifying automatically specified predefined conditions and executing actions when conditions between the parties are fulfilled and verified[4]. Smart contracts were introduced with Ethereum, a global and open-source

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platform for decentralized applications that implements smart contracts for the execution of the transaction [9]-[10]. In a smart contract, information is collected in a deterministic way, with the same results for identical conditions (if the inputs are the same, the results will be the same). The parties are responsible for defining control and action clauses, methods, conditions and rules. A smart contract must ensure that:

- the code cannot be changed;
- the data that determine the conditions are certified and reliable;
- the methods of reading and checking the sources are also certified.

In traditional contracts, trust between parties is guaranteed by a third party, in smart contracts, the role of the third party is reinterpreted by the blockchain.

This paper aims to describe a peer-to-peer market algorithm, formulated in the form of smart contract, for the matching between power offers and demand in a micro-grid, minimizing or modulating the power flow through the Medium Voltage/Low Voltage (MV/LV) transformer. This allows creating a local market at the micro-grid level trying to guarantee the balance of the power system starting from the low voltage level. The algorithm, however, can also be applied in medium voltage micro-grid minimizing the power flow through the High Voltage/Medium Voltage (HV/MV) transformer.

The developed algorithm allows achieving an optimal solution (both for the network and for users) in terms of offers to be activated (generation and load profiles) to guarantee the stability of the power system and ensure the matching between supply and demand. In the last section of the present paper, a case study is reported showing how the proposed methodology can solve the balancing problem.

II. Proposed P2P Market Algorithm

The proposed P2P market algorithm has the aim of allowing energy transactions between producers and consumers in a micro-grid and, at the same time, offering a balancing service to the network. The algorithm was developed with some features that make it simple and deterministic for simplifying its translation into a smart contract.

The condition used to realize the optimal matching between offers and requests in the micro-grid is to minimize or modulate the flow through the MV/LV or HV/MV transformer (Figures 2 and 3).

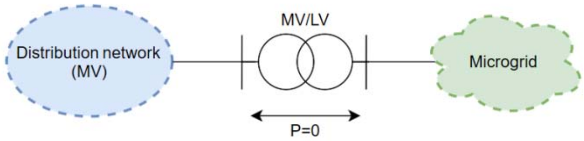

Fig. 1. Layout of the MV system for the application of the algorithm.

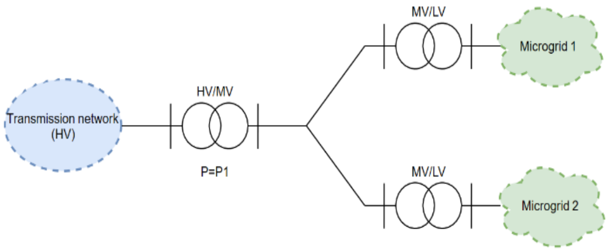

Fig. 2. Layout of the complex HV-MV system for the application of the smart contract.

The micro-grids in Figures 2 and 3 give their contribution to the system's stability by providing a precise power profile to the upstream network through the transformer. In fact, in the considered scenario, the Transmission System Operator (TSO) can ask the Distribution System Operator (DSO) a specific power profile at the transformer level for balancing purposes. This scenario is considered as a different model of the balancing service market named "Programmed HV/MV exchange profile" that is applied to the interface between the DSO and the TSO [11]. According to this model, the TSO imposes a certain power profile at the MV level and the DSO manages local resources in its network to guarantee the profile. By setting a defined target, this market can be implemented.. This scenario of power flow modulation through the transformer can also be applied at LV level: in this case, the DSO imposes a given profile to perform a balancing or adjustment at the MV/LV transformer.

The following Fig. 4 shows the inputs and outputs of the proposed algorithm.

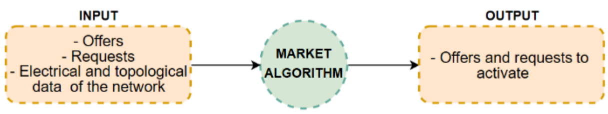

Fig. 3. Inputs and outputs of the market algorithm.

The inputs of the algorithm are:

- the active power offered by the generators with the related time intervals and costs;
- the active power required by loads with time intervals and costs;
- the data for the network's characterization (nodes, typology of the nodes, connections between nodes, limits, voltage, etc…).

The algorithm operates at a daily level by dividing a day into 96 intervals of 15 minutes.

The simplifying hypothesis of reactive power equal to zero is assumed so that only active power exchanges are considered. This assumption has no influence on the validity of the algorithm presented.

The generators can offer different generation profiles with a different price, and each load can have more than one profile, each with its own price. The algorithm elaborates all possible combinations of generation and load profiles (depending on load and request) to calculate all the k-combinations of n elements Com_{nk}:

$$Com_{nk} = \frac{n!}{(n-k)!\,k!} = \binom{n}{k} \quad (1)$$

where:

- n is the total number of generation and load profile;
- k = 1, 2, … n.

The total number of combinations is:

$$Com_{n,tot} = Com_{n1} + Com_{n2} + \cdots + Com_{nn} \quad (2)$$

In this process, it is required to eliminate the combinations obtained with more than one profile from the same generator or load; the following table shows an example:

TABLE I. RIGHT AND WRONG SOLUTIONS.

Acceptable combinations	Generator 1 Profile 1	Generator 2 Profile 1	Generator 3 Profile 2
Not acceptable combinations	Generator 1 Profile 1	Generator 1 Profile 2	Generator 2 Profile 1

After that, the cost index ΔC_a is introduced to evaluate the maximization of the matching between generator offers and load requests in terms of costs. The indicator identifies the most convenient combination for which consumers would buy energy at a price close to the minimum price they are willing to pay and producers would be rewarded as required. For each combination made by a generator profile (b) and a load profile (c), ΔC_a is calculated as:

$$\Delta C_a = \sum_{i=1}^{96} \left| C_{gia} - C_{lia} \right| \quad (3)$$

where:

- C_{gia} is the sum of the prices offered by the generators in the i-th time interval for the a-th combination;
- C_{lic} is the sum of the costs that the loads would pay in the i-th time interval for the a-th combination;
- a = 1,2, …, $C_{omn,tot}$.

Furthermore, interval by interval, it is verified that the difference between the costs is equal or less than a limit:

$$\left| C_{gia} - C_{lia} \right| \leq \Delta Clim \quad (4)$$

This allows determining how close offer and demand are. For a given combination, if this difference exceeds the imposed limit, the combination is excluded. All the remaining combinations are listed from the lowest to the highest value of ΔC_a.

Besides, the maximization of the matching between generators' offers and loads requests in terms of power is evaluated, conditioned to the analysis of the power flow through the transformer, which must not exceed the size of the transformer itself. For this analysis, it is necessary also to know the contribution to the power flow due to generators and loads present in the micro-grid and not participating in the P2P energy market. In this case, for each combination and for a generic i-th time interval the power balance is:

$$P_{g,tot,i} - P_{l,tot,i} + N_i \leq P_{xn} \quad (5)$$

where:

- $P_{g,tot,i}$ is the total power generated by the generators participating in the market during the i-th time interval;
- $P_{l,tot,i}$ is the total power requested by the loads participating in the market during the i-th time interval;
- N_i is the total power generated or required by all the other users in the micro-grid not participating in the market during the i-th time interval;
- P_{xn} is the maximum active power allowed by the transformer (in the case of neglecting the reactive power P_{xn} is equal to the size of the transformer).

If equation (5)not satisfied, that combination of generators and loads is excluded.

All the remaining combinations are ordered according to the power index p_a , defined as:

$$p_a = \sqrt{\frac{\sum_{i=1}^{96} \left(P_{g,tot,i} - P_{l,tot,i} + N_i - T_i\right)^2 \cdot W_i}{96}} \quad (6)$$

where:

- T_i is the target power flow through the transformer in the i-th time interval, that represents the value of the power requested by the system operator at HV/MV or MV/LV level
- W_i is a vector with 96 elements whose values range from 0 to 1, introduced for allowing the DSO to give to each time interval a different weight in the calculation and achieving different objectives.

In addition to enabling P2P energy transaction, depending on the considered scenario, with the developed algorithms it is possible:

- to minimize the power flow through the transformer;
- to modulate the power flow through the transformer to obtain the power profile required by the TSO at the HV/MV station for balancing needs.

The obtained solutions are sorted from the smallest value to the biggest value.

Considering the indicators ΔC_a and p_a, the choice of the optimal solution is done by searching within the points belonging to the Pareto front closest to the origin of the $p_a - \Delta C_a$ and performing a load flow analysis of the micro-grid for each eligible combination.

If the points on the first Pareto front do not verify the load flow calculation, the related combinations are excluded and the points of the following fronts are evaluated with the same criteria.

The load flow calculation ensures the technical feasibility of a given P2P market combination and the stability of the network during the energy transaction. The load flow is performed with the Newton-Raphson method, verifying that:

- the branch currents are equal or less than the current rating of the conductors;
- the voltage at the nodes is between 0.9 and 1.1 p.u. of the rated voltage of the network.

III. Case Study

The grid used to test the algorithm is showed in Fig. 5, where:

- the generators G1 to G5 offer one or two generation profiles and participate in the local market;
- the generators G6 and G7 offer only one generation profile but do not participate in the local market;
- the loads L1 to L5 present one or two load profiles and participate in the local market;
- the loads L6 to L8 present only one load profile and do not participate in the local market.

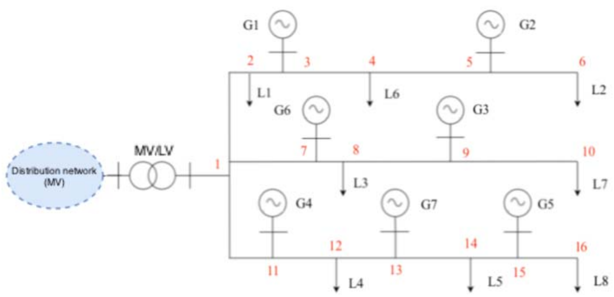

Fig. 4. Test micro-grid.

For this case study, $\Delta Clim = 0.1$ is assumed and the MV/LV transformer is considered as a slack bus for the load flow calculation.

In this case study, a condition is to ensure a power flow through the transformer equal to the imposed target shown in Fig. 6. The weight considered for the analysis are also shown in Fig. 6 The generation and load profile are shown in Appendix A.

By plotting the cost index ΔC_a as a function of the power index p_a, the distribution of the eligible solutions are shown in Fig. 7.

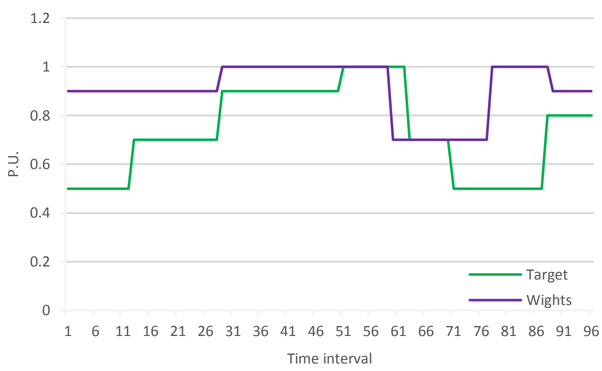

Fig. 5. Target power flow and weights assumed for the calculation.

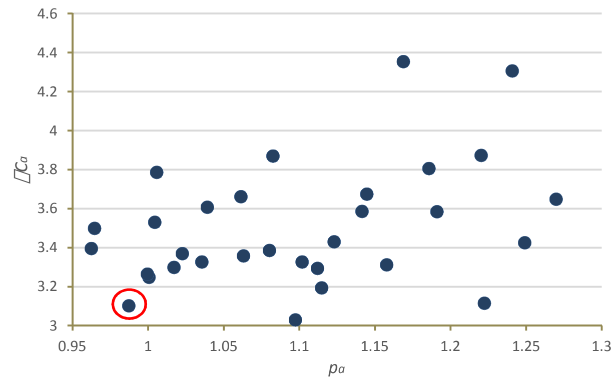

Fig. 6. Pareto front of the eligible solutions.

The best solution is the one circled in red in Fig. 7. The solution satisfies the load flow calculation and is represented by the combinations of generator G2 and load L5.

IV. Conclusions

The paper described a P2P market into a micro-grid, allowing the energy exchange between peers while preserving system stability. The algorithm has been tested on a case study and thanks to its simplicity is well suited for the translation into a smart contract for energy blockchain applications. Future development of this work will present the smart contract implementation of the developed algorithm.

Appendix A

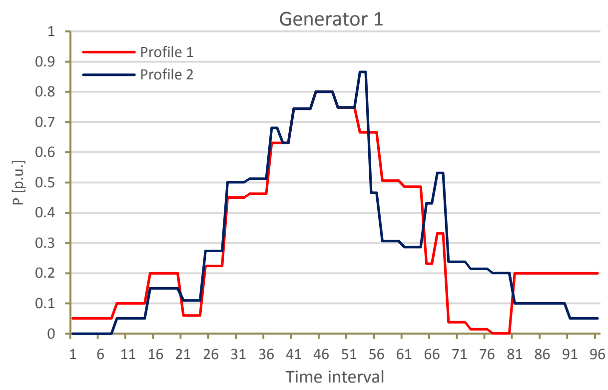

Fig. 7. Profiles generator 1.

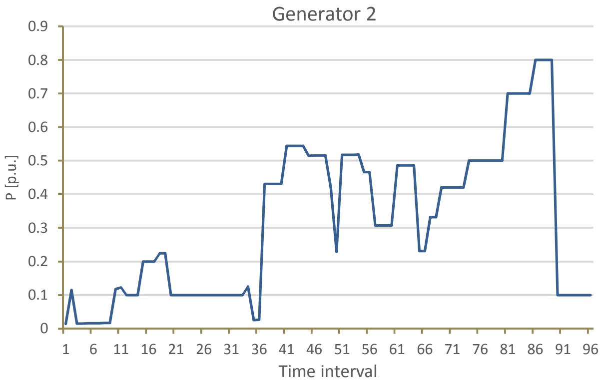

Fig. 8. Profiles generator 2.

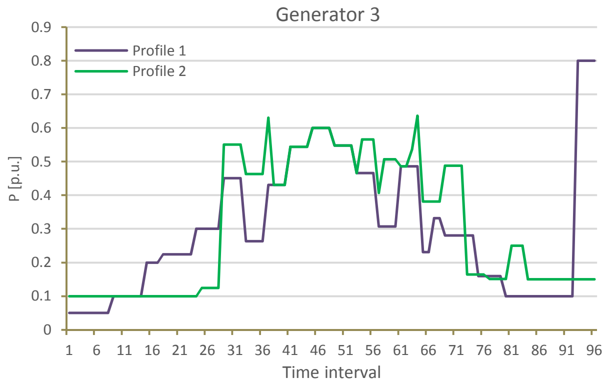

Fig. 9. Profiles generator 3.

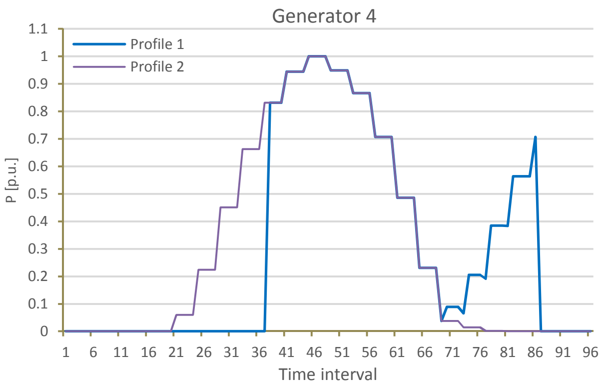

Fig. 10. Profiles generator 4.

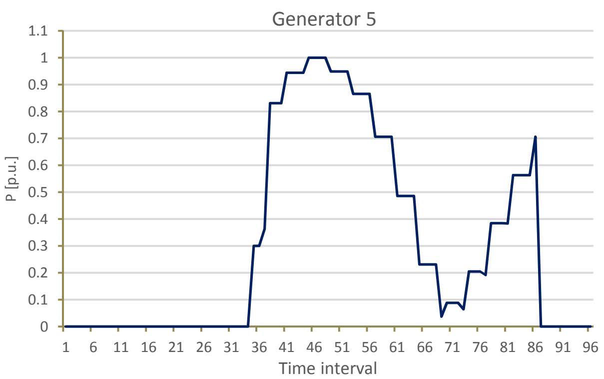

Fig. 11. Profile generator 5.

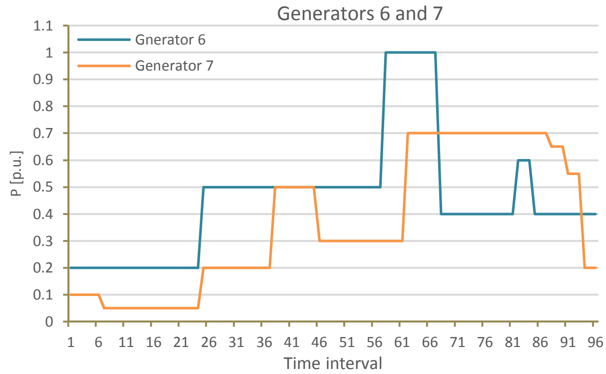

Fig. 12. Profiles generators 6 and 7.

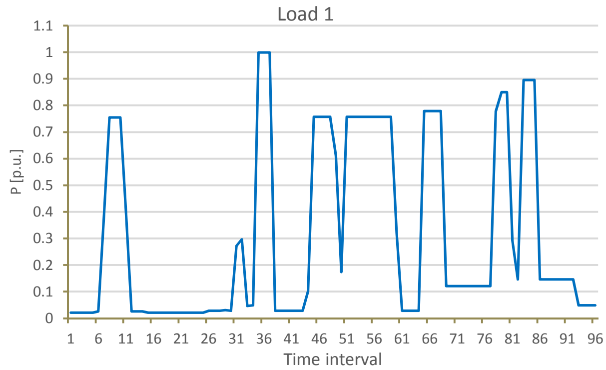

Fig. 13. Profile load 1.

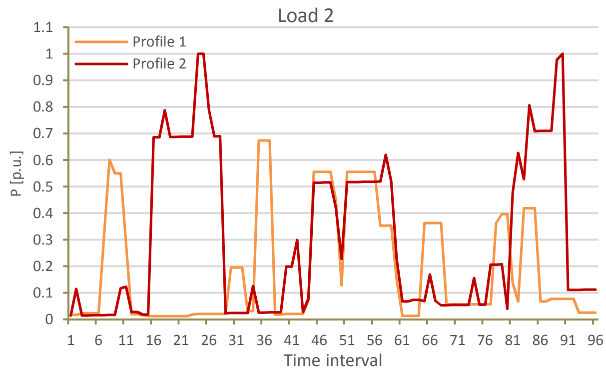

Fig. 14. Profiles load 2.

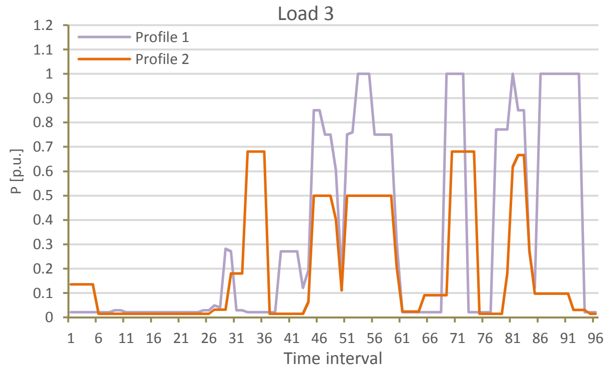

Fig. 15. Profiles load 3.

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