Prosumer-centric P2P energy market under network constraints with TDF's penalization

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***Abstract*—The global trend guided by the energy systems decarbonization, decentralization and digitalization combined with the increase of distributed Renewable Energy Sources (RES) are allowing prosumers to take a more active role in the electricity markets. In this context, a market structure based on Peer-to-Peer (P2P) transactions is very promising but presents challenges for the network's operation. A critical challenge is to ensure that network constraints are not violated during energy trade between peers. Thus, the main contribution of this paper is the development of a methodology for the optimization of P2P energy transactions, accounting for network operation. The paper proposes a three-step approach (P2PTDF), using Topological Distribution Factors (TDF) to penalize peers responsible for violations that may occur, ensuring a feasible solution. Simulations were performed with the modified IEEE 14-bus system with 19 peers, including the possibility of exchanging energy with an external grid.**

***Index Terms*—Network constraints, Peer-to-peer energy trading, Prosumer, Prosumer-centric electricity market, Renewable energy integration, Topological distribution factor.**

I. INTRODUCTION

In the last decade, the global energy sector has undergone a paradigm change. The demand for global energy is mostly supplied by large generation plants, centralized and based on non-renewable energy sources, but the renewable and decentralized sources of energy, also called distributed RES, has been gaining more space in the market [1]. This paradigm shift is guided by the so-called "*3 D's*" of the energy sector, which is based on the growing need for decarbonization, decentralization and digitalization of the global power system [2].

In this context, RES penetration in the system is continuously growing, turning traditional energy consumers into prosumers, who can consume and generate energy. Therefore, these players are performing more active roles in the power system and energy market [3]. From the perspective of prosumers, when generation exceeds demand, there is a decision to be made. Among the decision options, the following can be highlighted:

- The prosumer can reduce his generation in order to match his demand, thus making an energy self-consumption [4];
- The prosumer can store the surplus with energy storage devices [5];
- The prosumer can export the energy back to the grid or sell it to other energy consumers [6].

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One of the most promising solutions to take advantage of surplus energy is to negotiate in innovative Local Energy Markets (LEM), such as P2P electricity markets, where prosumers can negotiate with each other. A complete review of these P2P markets, challenges and suggestions for their proper implementation in the power systems are discussed in [7, 8]. The incorporation of P2P markets in electricity commercialization raises two main problems that must be taken into account, namely an energy market problem and a network operating problem.

In the energy market problem, all peers sell or buy energy from all other peers and at the end of these bilateral transactions, the amount of energy sold must necessarily be equal to the amount of energy purchased, as solved in [7, 8]. This process is supervised by the market operator.

The network operating problem consists of solving the network constraints, such as the power transport capacity of the lines, electrical losses of the system and voltage limits in the nodes, accounting for the solution of the energy market problem. This task is responsibility of the Distribution System Operator (DSO). To try to solve this issue, Guerrero et al. [9] propose a methodology based on sensitivity analysis to assess the impact of P2P transactions on the network and ensure an energy exchange that does not violate its restrictions. In contrast, Orlandini et al. [10] propose a coordinating methodology between the DSO and the P2P market operator, iteratively penalizing exchanges between peers that may cause congestion problems, by assigning them a network tariff.

A major challenge of integrating market problem and network operation solutions into a P2P energy market is to know exactly which exchanges are linked to the network constraints violation. Consequently, only the peers associated to such trades must be penalised. Tracking the flow of electricity in the system can be a solution. Using power flow tracing methods, like the TDF [11, 12] to find out who and how makes use of system lines or contributes to the violation of some constraint can be a smart strategy.

In this context, this work contributes with a smart iterative methodology to solve and coordinate both the P2P market and the electrical network problems. The proposed P2PTDF methodology determines all P2P energy transactions between prosumers and consumers in a LEM without any constraints being violated. The proposed model uses the TDF method to find exchanges and peers that may cause congestion and voltage problems, being these peers penalized. The P2PTDF is fair, as it only encourages peers who can cause congestion and voltage problems to renegotiate in the LEM.

In addition to this introductory section, the article is organized into three other sections. Section II presents the methodology used. Section III describes the results obtained for the electrical system under study and section IV presents the main conclusions.

II. P2P MARKET VIA DISTRIBUTION FACTORS

A. Energy market problem

To solve the energy problem of P2P transactions, the general mathematical formulation for the so-called "*Full P2P market*" presented in [7] was used. This market design is based on peers trading electricity directly with each other.

Therefore, the basic mathematical formulation of the energy problem can be defined as (1a) - (1e) for a given period $t \in T$:

$$\min_{D} \quad \sum_{n\in\Omega} C_{n,t}\left(\sum_{m\in\omega_n} P_{nm,t}\right) \tag{1a}$$

$$\text{s.t.} \quad \underline{P_{n,t}} \leq \sum_{m\in\omega_n} P_{nm,t} \leq \overline{P_{n,t}} \quad \forall n \in \Omega, \forall t \in T \tag{1b}$$

$$P_{nm,t} + P_{mn,t} = 0 \quad \forall (n,m) \in (\Omega, \omega_n), \forall t \in T \tag{1c}$$

$$P_{nm,t} \geq 0 \quad \forall (n,m) \in (\Omega_p, \omega_n), \forall t \in T \tag{1d}$$

$$P_{nm,t} \leq 0 \quad \forall (n,m) \in (\Omega_c, \omega_n), \forall t \in T \tag{1e}$$

where $D = (P_{nm,t} \in R)_{n\in\Omega, m\in\omega_n}$, with $P_{nm,t}$ corresponding to the energy exchange between peers n and m at time t, for which a positive value means sales/production (1d) and a negative value is equal to a purchase/consumption (1e). Ω, Ω_p and Ω_c as sets for all peers, producers and consumers, respectively (hence Ω_p, $\Omega_c \in \Omega$, $\Omega_p \cap \Omega_c = \emptyset$). The set ω_n contains the trading partners of a certain peer n. Bilateral negotiations $P_{nm,t}$ have the property of reciprocity, as defined by (1c). It is noteworthy that the dual variable $\lambda_{nm,t}$ associated with the exposed problem represents the price for each bilateral trade at time t. The function $C_{n,t}$ corresponds to the production cost and in this work a quadratic function is used as [13], thus $C_{n,t} = \frac{1}{2}a_n {P_{n,t}}^2 + b_n P_{n,t} + d_n$. According to (1a) the objective is to minimize the total cost of all bilateral trades carried out between the peers, i.e., to maximize the so-called *Social Welfare*.

B. Network operating problem

The validation of P2P transactions under the network constraints is an important problem for ensuring the feasibility of P2P market solutions. $P_{nm,t}$ values between peers from the P2P market solution are used to establish the setpoints $P_{n,t}$ for all peers, hence used by the Alternating Current Power Flow (AC-PF) to analyze grid conditions. Assuming that P2P transactions will occur in low and medium voltage distribution networks, an AC-PF model using pandapower [14], which is a python-based tool, was used. Pandapower allows the modeling of radial or meshed electrical networks and includes a Newton-Raphson [15] method to solve the AC-PF.

Note that reactive power is considered to be fixed for consumers while generators have voltage control capability. The voltage level and maximum active power generation for each generator and the load demand of each consumer is defined and fixed for each hour analyzed. However, the reactive power generation will depend on the generation's type, varying within pre-established limits. Lastly, a slack bus has to be defined in pandapower with the voltage level and angle fixed at 1 $p.u.$ and 0°, respectively. In this work, the node representing the connection between the local community and the external network (upstream connection) is defined as the slack bus.

As physical network constraints, the voltage in the buses (2) and the lines thermal limits (3) are considered, respectively.

$$0.95\,p.u. \leq V_i \leq 1.05\,p.u., \quad i = 1, ..., n_i \tag{2}$$

$$L_l \leq 100\%, \quad l = 1, ..., n_l \tag{3}$$

where V_i is the voltage on the bus i, n_i is the number of buses in the system, L_l is the load level of the line l, and finally, n_l is the number of lines in the system.

C. Tracing power flow

As previously mentioned, it is extremely important to know which peer is responsible for the violation of the pre-established network constraints. To this end, a power flow tracing method is implemented, which allows determining the contribution that each generator and consumer have individually on all lines of the network.

In this paper, the TDF method proposed by Bialek [11, 12] was applied. This method has been chosen due to its good performance under distribution grids with high penetration of distributed energy resources and bidirectional power flow [16]. For a detailed description of the TDF method, the reader are referred to [11, 12].

D. Iterative Methodology

This work proposes a three-step iterative approach to solve the complete problem of bilateral energy transactions between peers through the P2P market, accounting for distribution grid operation. The P2PTDF has been designed to allow penalizing both the generator and the consumer. Based on this premise, it is possible to identify the peers that are responsible for the network's constraints violation. It then becomes possible to penalize them, encouraging such peers to renegotiate their bilateral energy transactions in the LEM.

It is worth mentioning that when choosing to penalize a generator, in this case, it means limiting its maximum energy dispatch capacity, while penalizing a consumer is limiting its maximum load demand. So, penalizing consumers has the same effect as reducing their energy consumption profile. This effect is already known in the literature as load shedding. However, only consumers with a certain level of flexibility are able to meet this profile. In light of this previous scenario, the authors followed the line of penalizing generators instead of consumers.

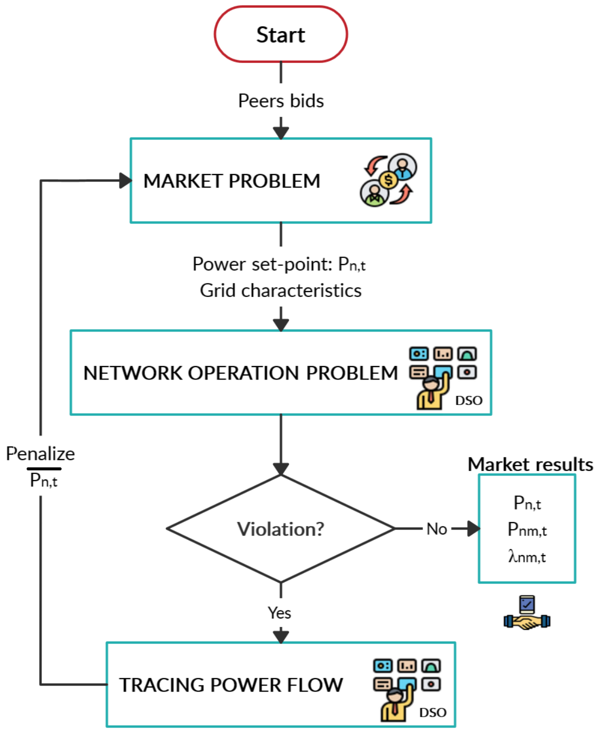

Fig. 1. Iterative methodology flowchart.

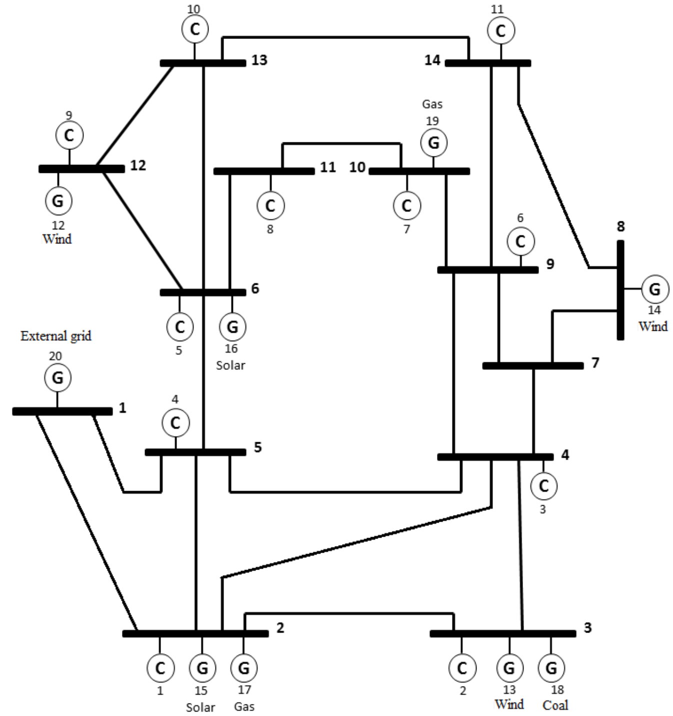

Fig. 2. Modified IEEE-14 bus system.

Defining how much to penalize a peer can be tricky. To avoid an excessive penalty, the generator's power bid must be decreased by a certain value $K\%$ at each iteration, where K should not be a high value.

Figure 1 represents the flowchart of the proposed iterative approach, consisting of three main steps:

- **Step 1:** Optimizes the P2P market (1a) - (1e) without considering network constraints. Analyzing the bids and purchase offers of all peers, the values of $P_{n,t}$ and $P_{nm,t}$ are calculated. These values are used as input data for step 2;
- **Step 2:** Reads input data and network characteristics. Based on $P_{n,t}$ and $P_{nm,t}$ values, the proposed transactions feasibility is verified through an AC-PF. The AC-PF determines the flows $P_{ij,t}$ between all lines $l \in L$ of the system and the voltage levels $V_{i,t}$ of all buses $i \in n_i$, for all $t \in T$. The stopping criterion used is the verification of network congestion (3), that is, if the lines power flow is above its maximum capacity, as well as if the buses voltage level is out the limits (2). If any of the constraints are violated, the method goes to step 3. Otherwise, the iterative process is stopped and the results $P_{n,t}$, $P_{nm,t}$ are displayed;
- **Step 3:** This step is composed by the TDF algorithm. Based on the data calculated by the AC-PF (Step 2), this algorithm determines the share of a specific generator in every line flow $P_{ij,t}$, for all $t \in T$. In other words, it means determining which peers make use of a specific system line or contribute to the violation of some constraints. Then, it is possible to penalize the power bid of the generator that caused the violation. Returns to step 1.

It is well known that one of the problems caused by power injection of distributed generation in the distribution grid is the increase in the buses' voltage, in which the generation is allocated [17]. Thus, the proposed method helps to minimize this problem, since it tends to decrease the generators' power injection that overload the system.

III. Case Study

This section presents a case study illustrating the application of the developed iterative method and its performance.

A. *Case Characterization*

The case study is based on a modified IEEE-14 bus with 19 peers and a single external network connection, as illustrated in Figure 2. The system voltage level is 13 kV for all buses $i \in n_i$ and the maximum line loading current is 0.6 kA for all lines $l \in L$.

Daily profiles for all peers, both prosumers and consumers, were considered and detailed in Table I. More precisely, peers 1 to 11 are prosumers with excess demand (consumers), while peers 12 to 19 are prosumers with generation surplus (producers).

The producers are categorized by their generation technology, i.e. 3 wind turbines, 2 photovoltaic systems, 2 gas turbines and 1 coal based system. Note that producers 17 (gas turbine), 18 (coal unit) and 19 (gas turbine) have constant maximum generation equal to 20MW, 50MW and 10MW, respectively. Peer 20 represents the external network connection, which can

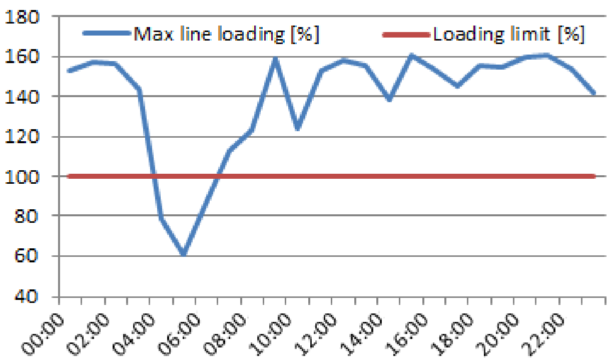

Fig. 3. Most loaded line for each time-step [%].

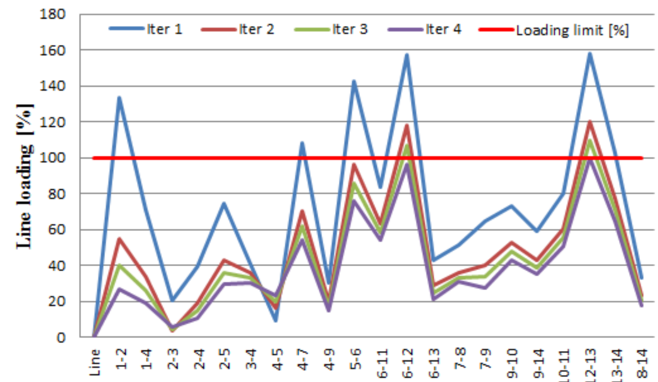

Fig. 4. Power flow over iteration k at time-step 12:00 [%].

be the local utility network, another energy community, etc. Consumers have a flexibility, in their demand, of 10%. The penalization factor K is set in 5%.

The AC-PF model used requires the specification of reactive power limits, where $Q_{n,t}$ is the reactive power of peer n at time $t \ \forall \ T$. With the same proposal as Orlandini et al. [10], we assume that consumers have a fixed reactive power equal to 20% of the active power traded in P2P market, that is, $Q_{n,t} = 0.2P_{n,t}$. Producers can generate reactive power with an upper limit equal to 40% of the active power traded on P2P market, that is, $0 \leq Q_{n,t} \leq 0.4P_{n,t}$. Consumers are supposed to consume reactive power and producers generate reactive power.

The Table II shows the parameters a_n and b_n for each peer, to be used in the cost function $C_{n,t}$. Finally, as the purpose of this work is to promote and analyze a LEM among the peers of the same community, electricity commercialization with the external grid is only allowed as a last resource. Thus, the price to import energy from the external grid was considered equal to 150 $/MWh and to export energy to the external grid equal to 10 $/MWh.

B. Results

The test case is simulated over a day with 1 hour time-step. The P2P market is optimized for each hour, and the steps established in the flowchart of Figure 1 are followed until there is no further constraints violation. To properly analyze the proposed method, it is compared with a benchmark. The benchmark corresponds to the first step of the first iteration of the proposed model, i.e., the initial P2P market optimization.

Figure 3 shows the most congested line in each time-step for the benchmark. For almost all scenarios there is a line with loading above 100%. Besides, more than one line may also be congested at certain time-steps.

This proves the need for a methodology that can optimize the P2P market taking into account network constraints, as there is a high risk of network congestion.

The P2PTDF is applied to each time-step and, as a final result, no line is overloaded. The resulting power flow for the first iteration (benchmark solution) at 12:00h, when there are the most congested lines (average), is shown in Figure 4. One can see that congestion occurs often in the day, and therefore the benchmark solution is not grid operating feasible. The iterative process reaches a feasible solution after four iterations. This result is achieved by limiting the energy supply of generators that cause congestion. The evolution of line-loading over the four iterations is shown in Figure 4. The last iteration achieves grid operating feasibility, as can be seen in Figure 5. In all the final solutions reached, there is no violation of the pre-established voltage limits.

The social welfare results of the benchmark and the proposed model, as an economic metric, are presented and compared in Table III. The social welfare tends to decrease with interactions, since the proposed method penalizes the bid of the generator that causes congestion and that generator tends to be among the "cheapest". So another generator (a little more expensive) has to be dispatched to make up the difference, causing social welfare to decrease.

It is noteworthy that despite the decrease in the social welfare, the P2PTDF solution represents a feasible network operating solution, while the benchmark solution does not. In a real operating situation, the proposed initial transactions could not take place. More precisely, it would require load shedding and, consequently, decrease the total system generation, reaching a viable operating point that would probably lead to a lower social welfare than that achieved by the proposed methodology.

IV. Conclusions

The P2P markets actively contribute to a greater RES penetration through small and medium-sized prosumers, providing consumers with a higher degree of freedom in the energy trade. However, the impact of this market design on the network's operation still needs detailed studies in order to avoid network congestion and voltage problems. This work presents a simple methodology (P2PTDF) for the optimization of bilateral P2P energy transactions taking into account network constraints. To this end, the problem is divided into two sub-problems, energy market and network operation, being solved iteratively. That is, the results of each sub-problem are used iteratively to solve the other sub-problems, converging to a global feasible solution.

TABLE I

CONSUMERS' HOURLY LOAD DEMAND.

Time [h]	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
C1 [MW]	3,57	9,77	7,68	8,26	8,72	4,19	5,89	3,86	4,87	4,40	4,72	6,26	3,93	3,92	3,92	3,91	6,51	3,84	3,73	4,80	6,21	7,72	5,47	8,60
C2 [MW]	53,09	47,80	9,91	9,73	10,13	10,04	10,25	9,47	10,43	9,12	10,22	9,03	10,08	29,75	12,05	9,52	10,13	10,17	9,03	10,30	10,43	9,21	10,30	54,45
C3 [MW]	5,05	4,95	4,95	5,06	5,06	5,14	5,12	5,08	5,06	4,82	6,57	6,43	6,89	6,67	7,76	9,42	8,87	8,12	8,18	42,10	9,27	6,06	4,98	5,09
C4 [MW]	0,65	0,65	0,60	0,59	0,63	0,60	0,60	0,60	0,80	0,81	0,58	0,78	0,64	0,64	0,73	0,62	0,60	0,65	0,61	0,57	0,59	0,61	0,81	0,62
C5 [MW]	3,98	2,84	2,75	2,81	2,68	2,51	2,57	2,75	5,27	4,93	3,80	2,87	3,28	5,67	3,04	3,32	4,23	4,39	6,13	5,67	5,94	5,22	4,96	4,58
C6 [MW]	2,62	2,53	2,43	2,59	2,44	2,39	2,50	2,64	4,04	2,83	6,12	6,04	4,57	7,55	4,75	2,31	2,15	4,59	15,96	15,65	2,23	2,24	2,14	2,27
C7 [MW]	1,06	1,05	1,06	1,05	1,05	1,04	1,03	1,02	0,99	1,75	3,24	2,43	1,12	6,53	2,35	1,89	1,38	1,30	4,23	4,00	2,57	2,66	2,78	2,06
C8 [MW]	0,41	0,42	0,42	0,41	0,44	0,41	0,41	0,41	0,41	1,11	0,46	0,41	0,44	0,41	0,41	0,44	0,41	0,43	1,03	1,61	1,64	1,88	1,76	0,41
C9 [MW]	1,91	0,50	0,52	0,49	0,46	0,50	0,52	0,44	0,44	0,48	0,49	0,44	0,44	0,51	0,45	0,44	0,96	4,37	3,22	1,64	2,75	2,06	2,15	2,00
C10 [MW]	1,49	1,33	1,28	1,34	1,42	1,42	1,71	1,44	1,56	1,44	3,30	1,65	2,17	1,62	1,46	1,56	1,31	1,23	1,15	1,31	10,42	9,74	1,59	1,53
C11 [MW]	1,94	1,95	1,87	1,92	1,94	1,76	1,95	1,82	2,02	2,26	2,42	2,28	2,25	2,29	2,15	2,21	2,79	2,24	2,60	2,34	2,51	2,21	2,27	1,89
G12 (Wind) [MW]	45.14	45.30	45.60	41.57	22.25	17.08	25.09	32.40	34.89	46.01	35.20	45.08	47.00	44.88	40.79	47.13	45.11	45.41	46.91	44.88	46.74	47.08	45.70	41.62
G13 (Wind) [MW]	15.90	12.94	16.75	16.19	14.15	10.70	15.22	15.00	11.95	12.59	15.70	12.04	7.20	11.17	9.03	9.49	8.20	10.59	10.03	6.32	10.13	12.47	7.85	13.33
G14 (Wind) [MW]	1.65	1.57	1.55	1.14	1.19	0.80	0.51	0.78	1.11	0.68	1.74	1.69	3.18	3.87	4.82	3.57	4.33	5.23	4.43	5.27	4.99	5.25	5.09	5.03
G15 (Solar) [MW]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	1.39	3.33	4.91	3.87	0.99	9.17	5.56	1.59	0.05	0.00	0.00	0.00	0.00	0.00	0.00
G16 (Solar) [MW]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.93	3.00	3.18	6.57	2.43	5.82	2.64	1.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TABLE II

PARAMETER a_n AND b_n FOR EACH PEER.

Peers	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	G12	G13	G14	G15	G16	G17	G18	G19
a_n	-1.18	-0.24	-0.57	-1.24	-1.62	-0.31	-4.36	-1.63	-5.15	-1.96	-1.54	0,00	0,00	0,00	0,00	0,00	2.51	0.15	3.64
b_n	50.9	37.8	43.6	50.3	30.4	27.5	46.7	33.2	55.0	62.1	42.9	0,00	0,00	0,00	0,00	0,00	27.7	35.5	30.4

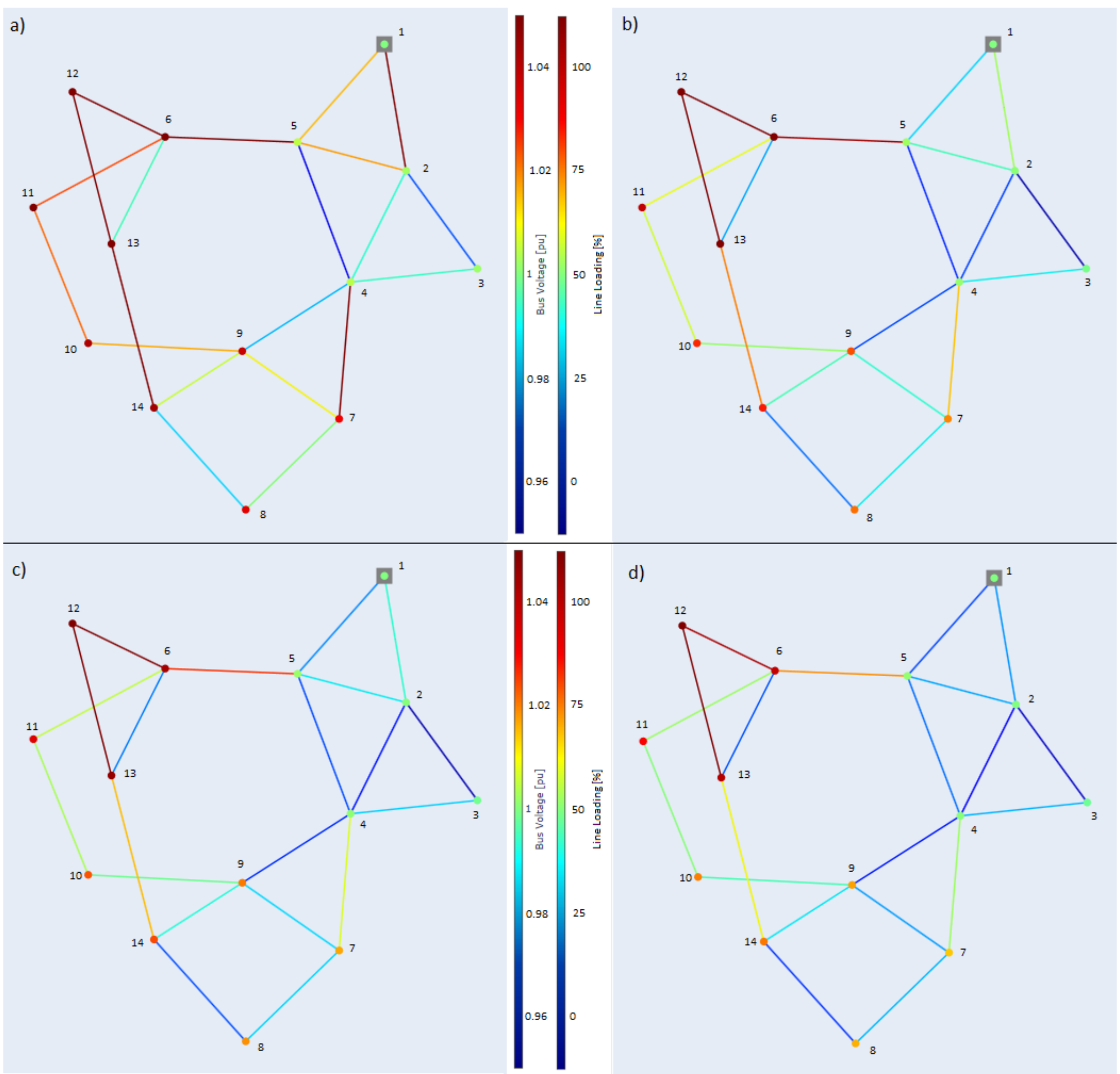

Fig. 5. Power flow for the grid at time-step 12:00. a) Iteration 1, b) Iteration 2, c) Iteration 3 and d) Iteration 4.

TABLE III
BENCHMARK AND P2PTDF SOCIAL WELFARE FOR EACH TIME-STEP.

Time [h]	Benchmark social welfare [$]	P2PTDF social welfare [$]	Time [h]	Benchmark social welfare [$]	P2PTDF social welfare [$]
00:00	1.876,22	1206,87	12:00	1663,65	1419,90
01:00	1.871,77	1142,59	13:00	2020,04	1438,51
02:00	1.580,93	1364,01	14:00	1743,41	1552,63
03:00	1.548,21	1376,14	15:00	1671,94	1420,63
04:00	1.355,31	1355,31	16:00	1687,47	1495,31
05:00	1.114,03	1114,03	17:00	1678,62	1541,64
06:00	1.338,34	1338,34	18:00	1829,9	1363,76
07:00	1.318,11	1258,01	19:00	1264,89	506,89
08:00	1.429,63	1350,7	20:00	2065,13	1629,22
09:00	1.527,94	1314,4	21:00	1998,03	1748,56
10:00	1.707,89	1628,67	22:00	1639,72	1470,74
11:00	1.712,12	1481,87	23:00	1724,99	1108,72

The results obtained for the modified 14-bus system demonstrate that the Benchmark method does not guarantee that the solutions found for the market are feasible in the network's operation. In several hours throughout the studied day, violations of the line loading limits are observed. Thus, it is extremely important to use methodologies in the same guideline as the P2PTDF, capable of verifying whether such violations occur and prevent them. The P2PDF proved to be effective in solving the problem presented, finding viable solutions with few iterations, for all time-steps, as shown in the results section.

Some suggestions for future developments, continuing the line of research described in this paper are: (i) inclusion of electric vehicles and storage systems, (ii) use decentralized optimization methods, (iii) explore adequacy of distribution network fees according to the network usage by prosumers, and (iv) consider a joint energy and ancillary services market.

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