Peer-to-Peer Electricity Trading in Distribution Grid: Effects of Prosumer's Elasticities on Voltage Levels

Lin Herenčić
Department of Energy and Power Systems
University of Zagreb, Faculty of Electrical Engineering and Computing
Zagreb, Croatia
lin.herencic@fer.hr

Perica Ilak
Department of Energy and Power Systems
University of Zagreb, Faculty of Electrical Engineering and Computing
Zagreb, Croatia
perica.ilak@fer.hr

Ivan Rajšl
Department of Energy and Power Systems
University of Zagreb, Faculty of Electrical Engineering and Computing
Zagreb, Croatia
ivan.rajsl@fer.hr

***Abstract*—Peer-to-peer electricity trading between consumers, producers and/or prosumers located in a low voltage distribution grid is a concept that goes well with the trends of democratization, decarbonization and decentralization in the power sector. However, the impacts of peer-to-peer electricity trading on voltage levels in distribution grids are still in the early stage of research. The aim of this work is to investigate effects of a near real-time peer-to-peer electricity trading in a distribution grid on voltage levels. It is analyzed if a contribution to the sustention of the voltages under limits can be achieved without security-constrained dispatch calculations for the observed time horizon and each trading period. The peer-to-peer electricity trading is simulated as an auction-based local market and implemented in the modified IEEE European Low Voltage Test Feeder where the impacts on voltage levels are analyzed for different elasticities of demand bidding curves.**

Keywords—electricity, peer-to-peer, trading, voltage stability, distribution grid, renewable energy sources

I. Introduction

Ongoing transition of the power sector from centralized system based on conventional power plants towards decentralized system based on renewable energy sources (RESs) [1], energy storage systems (ESSs) [2], information and communication technology (ICT) [3], and active participation of citizens [3] enables development of innovative business models in the power sector. Peer-to-peer (P2P) electricity trading at local energy markets (LEMs) is a concept that should provide an opportunity for electricity trading between peers (consumers, producers, prosumers) [4] in local low-voltage distribution grid [5]. That way, added value to the participants (increased global welfare), integration of RESs, improved grid stability, and auxiliary services to the rest of the power system [6, 7], could be provided. LEMs can be organized as P2P electricity trading, electricity trading through a mediator, or combination the both [4]. Further, the organization of LEMs can have only a business layer but can include also grid constraints in trading algorithms [4]. There, the application of advanced ICT and control systems are decisive [6, 8]. However, many barriers and challenges still have to be overcome to accelerate the implementation of P2P electricity trading in practice and in wider scope. Recognized challenges include management and control of P2P electricity trading to remain under network constraints and to further contribute to the stability in distribution grid, P2P electricity trading market design, market-clearing approaches and integration trading within the electricity markets [4, 9, 10, 11, 12].

Important stability concerns in grid-connected microgrids refer to voltage stability [13], and the line power flow constraints have to be respected [14]. When microgrid control functions are observed from the market design perspective, the attention has to be paid to timeframes of certain activities, as stability issues vary from milliseconds to minutes/hours. In contrast, the time intervals for electricity trading on markets are commonly not lower than 15 minutes, only in some cases the near-continuous trading is conducted, where energy is dispatched every 5 minutes [15, 16]. Therefore, only some of the control functions have the same timeframe as the electricity trading (unit commitment, economic dispatch, optimal power flow and Volt/VAr control), while the other control functions can be further regulated by grid codes [17], market for the auxiliary services [18], added control loops [19], and/or by the deployment of energy management systems [20]. The existing papers that investigate impacts of P2P electricity trading on distribution grid proposed various means of supervision and/or control. The existing proposals include role of DSOs for reviewing of the orders in the periods between the gate closure and the energy exchange [10], pricing based on game theory that would support demand peak shaving [21], P2P electricity based on the multiclass energy management concept to allow trading between prosumers with beyond only financial preferences [12]. Further, a methodology was proposed based on the network sensitivity analysis that should facilitate P2P energy trading under low-voltage (LV) distribution grid constraints [22]. That methodology is compatible with the continuous double auction (CDA) market mechanism.

In this paper, it is analyzed what are the effects on the bus voltage levels if a near-real-time P2P electricity trading is implemented. It is researched if a contribution to the sustention of the voltages under limits can be provided without time-demanding security-constrained unit commitment (SCUC) calculations for the analyzed time horizon (for example one day) and without security-constrained economic dispatch (SCED) calculations for every trading period (for example every five minutes). The simulated P2P electricity trading is organized as a local power-exchange where supply and demand offers are aggregated and market clearing prices and quantities are calculated [23]. Further, it is analyzed what are the effects of demand elasticities on voltage levels in the environment of P2P electricity trading in LV distribution grid.

To get the results, the scenario analysis of the impacts of different demand offering curves of the peers is conducted in

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the case of the IEEE European LV Test Feeder [24]. Near-continuous (5 min trading period) P2P electricity trading is simulated using the double-auction trading mechanism for estimation of equilibrium prices and volumes. The results are compared with the reference results simulated on the IEEE European LV Test Feeder without P2P trading. The implemented method is briefly described in Section 2. The case study analysis is presented in Section 3. Finally, the conclusions are discussed in Section 4.

II. Method for Simulation of Peer-to-Peer Electricity Trading and Estimation of Effects on the Voltages in the Grid

For the investigation of the effects of different trading strategies and offering curves on voltage stability, the centrally aggregated double auction P2P electricity trading mechanism was implemented based on the EUPHEMIA [25] mechanism approach. The market is simulated over 24 hours, and the resolution of trading intervals is five minutes. Unit commitment of the peers is obtained from the trading mechanism based on the estimated equilibrium prices and volumes. The dispatched energy of the peers is applied as an input in the IEEE European LV Test Feeder [24, 26]. That approach allows analysis of the power flows and voltage levels. A more detailed explanation with the flowchart of the method is available in [23]. The method can be divided into four steps. Firstly, peers in the distribution grid make projections of their supply possibilities and demand needs. Secondly, they define elasticity and volumes of energy demand as well as production volumes and offering prices. Thirdly, those supply and demand offers are submitted to the double-auction market, where bids are aggregated, and market equilibrium volumes and prices are determined. In the last step, the least-cost dispatch of the peers is sent to the IEEE European LV Test Feeder grid, and there the impacts of P2P electricity trading on voltage levels can be analyzed. The simulation in the IEEE European LV Test Feeder is carried out based on a five-minute energy dispatch from the previous step, and in a resolution of one second.

Besides the reference scenario, analysis is carried out for two cases, where peers' demand offering curves simulate high to low demand elasticity in the local energy market. The detailed explanation of the used method can be found in [23] where the implementation code is also available.

III. Case Study

In this section, the effects of different demand offering curves are assessed. The study is conducted for the case where supply offer strategies reflect moments of high electricity prices and scarcity of supply, i.e. the case where producers bid with the costs over their short-run marginal costs. Contrary, the demand biding curves are varied between scenarios to allow the analysis of the effects of changing demand elasticity of the peers.

A. Input Data and Scenarios

The analysis is conducted for the cases where producers practice high markup intending to achieve added revenue on top of production cost and are even ready to curb the production. The impact of strategies of demand peers is analyzed for two cases: (1) higher elasticity, where flexibility and demand response of the peers is assumed higher, and (2) lower elasticity, where flexibility and demand response of the peers is assumed lower. It can be noticed that in the area where supply and demand curves cross, the demand of the peers is inelastic (absolute value of elasticity < 1), which is in line with the usual elasticity of electricity demand [27, 28].

Based on the assumed different behavior of the peers, the two scenarios are created and analyzed (scenarios S1-S2). Also, those scenarios are compared with the reference scenario (SREF), where the production is presumed maximal. It is a conceptual case that simulates the effects of feed-in tariffs for electricity production from RES. Moreover, in the SREF scenario, the demand is assumed inelastic, to represent the common behavior of the peers in traditional electricity LV distribution grids, which can be summarized by the slogan 'use it when you need it'. The main differences in the simulated and analyzed scenarios are shown in Table 1.

TABLE I. Key differences of the analyzed scenarios and input data for individual peers, where "High" supply price is set at 0.075 EUR/kWh and "Low" supply price at 0.025 EUR/kWh.

Item \ Scenario	SREF	S1	S2
Maximal supply offering price	NA (feed-in-tariff)	High	High
Price elasticity of demand	Perfectly inelastic (passive demand)	Increased*	Decreased*

* Compared to one another (Fig. 2).

In all scenarios, the initial demand needs are same as in the the default IEEE European LV Test Feeder [24], but it is assumed that every fourth peer has a PV system installed with the nominal power capacity of 4 kW. The applied approach resulted in total of 14 solar single-phase PV systems among 55 peers, where 5 solar PV systems are located at phase A, 6 solar PV systems at phase B, and 3 solar PV systems at phase C, as depicted in the Fig. 1.

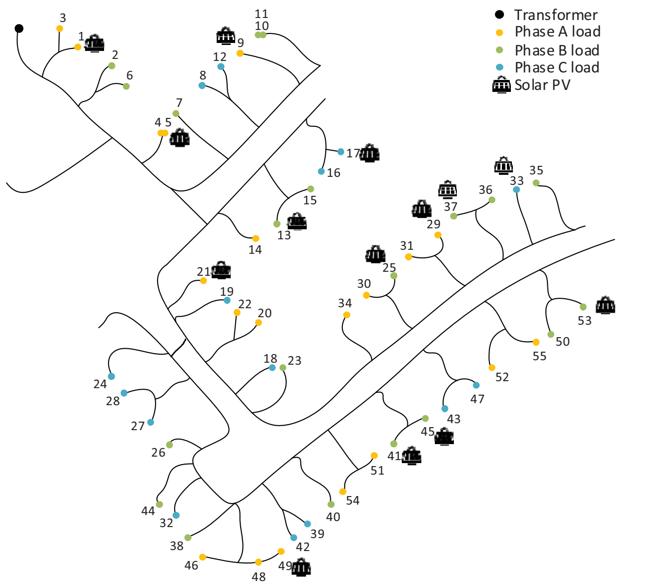


Fig. 1. Topology of the IEEE European LV Test Feeder where simulation of the P2P electricity trading was conducted.

The potential maximal production from the PV systems for each five-minute interval for the assessed day was obtained from [29] for June 1st. Same as in [23], the minimal volumes of the offering blocks are rounded to 0.5 kW. The creation of offering blocks for the peers is based on the approach in [23] and is performed accordingly with Equation (1) and Equation (2) for supply and demand offers, respectively. The principle for creation of offering blocks is also depicted in Fig. 2.

$$p_{s,t,b,i} = \frac{p_{N\,s,t,i}}{q_{MAX\,s,t,i}} q_{s,t,b,i}\,, \quad \text{where: } 0 \le q_{s,t,b,i} \le q_{MAX\,s,t,i} \tag{1}$$

$$p_{d,t,b,i} = -\frac{2 \cdot p_{N\,d,t,i}}{1+k} q_{d,t,b,i} + \frac{p_{N\,d,t,i} \cdot 2 \cdot q_{MAX\,d,t,i}}{1+k}, \quad \text{where: } 0 \le q_{d,t,b,i} \le q_{MAX\,d,t,i} \tag{2}$$

where $p_{N\,s,t,i}$ is the nominal supply price (final price in the supply curve) of the peer i in period t, $p_{N\,d,t,i}$ is the nominal demand price of the peer i in period t. There, $p_{N\,d,t,i}$ is assumed equal as the price from the upstream grid, i.e., 0.100 EUR/kWh. Values for reference consumption $q_{N\,d,t,i}$ of the peers (i) in time periods (t) are obtained from the IEEE European LV Test Feeder and can be increased by the k blocks where each block equals 0.5 kW, i.e., $q_{MAX\,d,t,i} = q_{d,N\,t,i} + \frac{1+k}{2}$ (kW). The described approach for creation of supply and demand bids is sam as in [23] and allows transparent analysis based on the modification of supply prices $p_{N\,s,t,i}$ and slopes of the demand curves around price $p_{N\,d,t,i}$ (Fig. 2). Ilustration of varying slope around the price $p_{N\,d,t,i}$ of the demand curves are shown in Fig. 2.

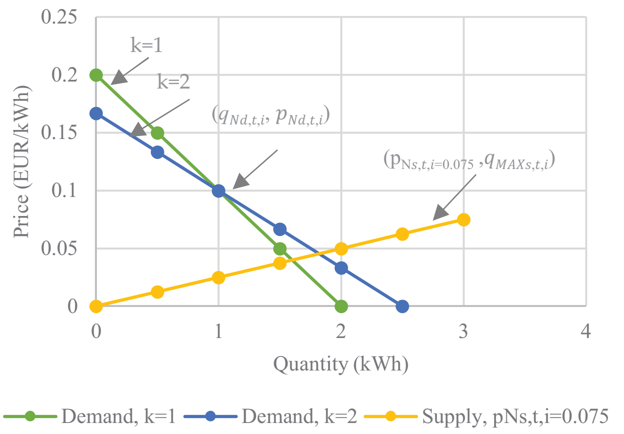


Fig. 2. Depiction of the demand bidding curves of the peers for the cases where $p_{N\,d,t,i}$= 0.100 EUR/kWh, $qD_{N\,t,i}$= 1 kWh and the differences relate to the slope of the curves which is defined by the factor k, where (1) k=1 and (2) k=2. At the same time, the supply curve is defined with the $q_{MAX\,s,t,i}$= 3 kWh and the nominal supply price is defined by the $p_{N\,s,t,i}$=0.075 EUR/kWh.

Besides through the P2P electricity trading, peers have the option to purchase the electricity from the upstream grid, but with the assumed supply price of 0.100 EUR/kWh, while the price of selling to the utility grid is assumed at 0.050 EUR/kWh. For the case study, the time horizon of 120 min is analyzed when demand and PV production are available at the same time. The simulation was implemented via the MATLAB software package [26].

B. Results of the First Stage of the Simulation: Equilibrium Quantities and Prices

The results of the first stage of the P2P electricity trading are the equilibrium (market clearing) prices and volumes, based on the least-cost market mechanism. The calculated quantities are input for the second stage, where analysis of the impacts on voltage levels in the IEEE European LV Test Feeder is performed. The aggregated values of volumes traded between 55 peers are displayed in Fig. 5.

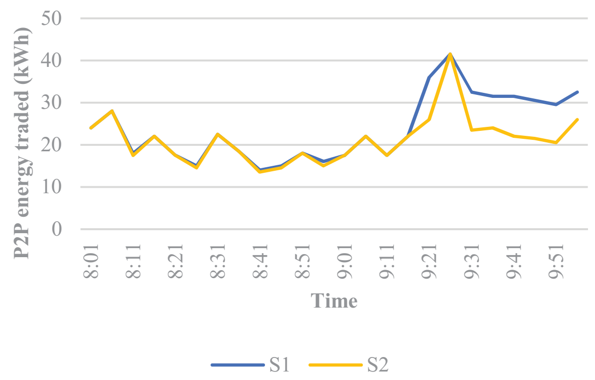
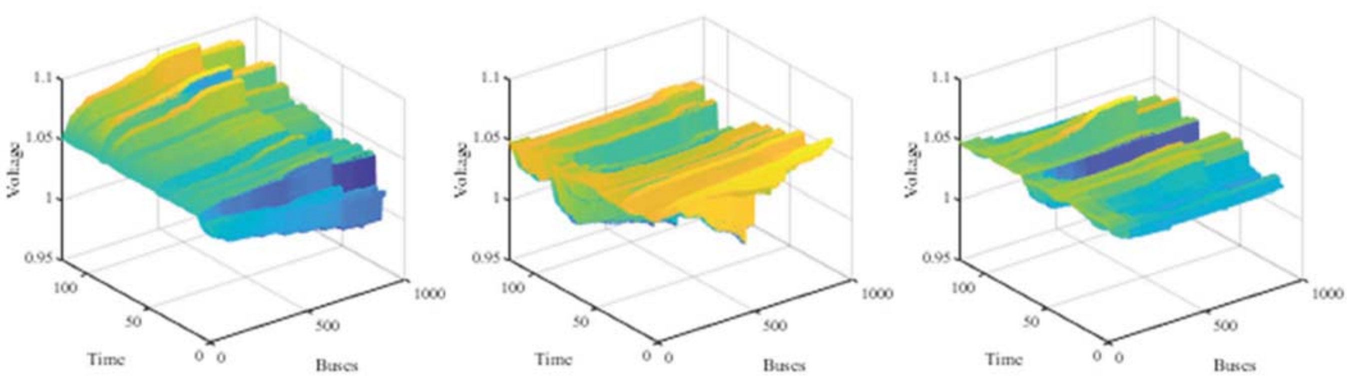


Fig. 3. The quantities of P2P energy traded in the analyzed time-span.

The scenario S2 compared to the scenario S1 (Fig. 3), has less quantities traded at higher prices. This is due to decreased demand elasticities which enable producers to withhold some production to achieve higher markup consequently increasing equilibrium prices and decreasing equilibrium quantities.

C. Results of the Second Stage of the Simulation: Voltage Levels

The impact of the market-clearing on the voltage levels in the IEEE European LV test feeder is quantified and presented in Fig. 4-6 and Table 2-3. In Fig. 4, three-phase voltage profile is shown over 120 min. In Fig. 4(a) - 4(c), voltage profiles for the reference scenario (SREF) are shown. In Fig. 4(d) – 4(f) voltage profiles for the scenario S1 are shown and in Fig. 4(g) – 4(i) the voltages profiles for the scenario S2 are shown. Due to a large amount of data (voltages for 906 buses × 7.200 s × 3 phases × 3 scenarios), 3D graphs are for a brief insight.



(a) (b) (c)

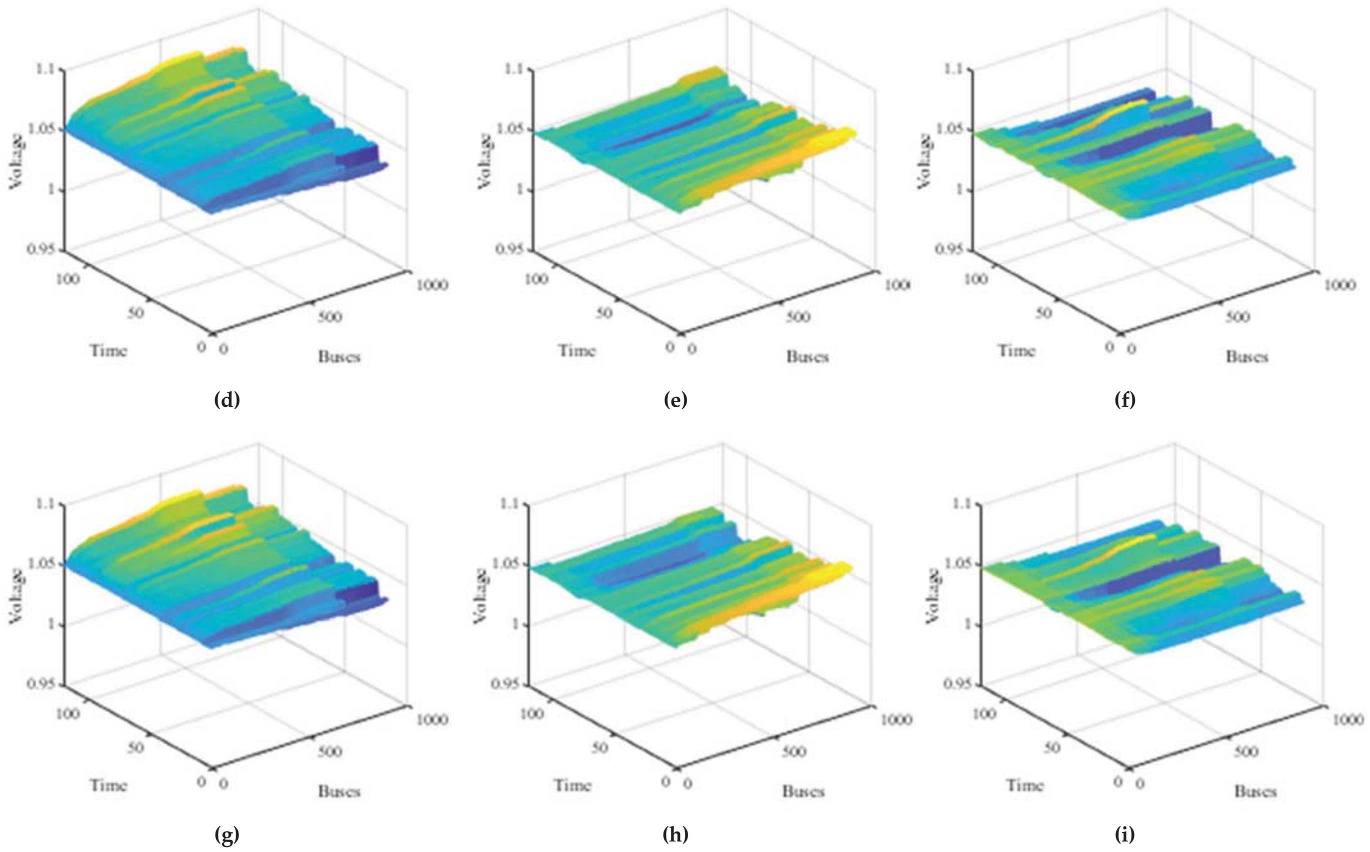


Fig. 4. Voltages profiles (p.u.) over 120 minutes**: (a-c)** Voltage in reference scenario SREF for phases A-C; **(d-f)** Voltage in scenario S1 for phases A-C; **(g-i)** Voltage in scenario S2 for phases A-C.

The average voltage levels and differences from the nominal voltage in the analyzed scenarios are shown in Table 2 and Fig. 5. It can be noticed that on average, in SREF scenario, voltages in phase A are 0.781% above nominal voltage, while in phase B and phase C are 1,166% and 1,071% below nominal voltage, respectively. The differences of voltages in S1 and S2 scenarios compared to the nominal voltage are smaller. In phase A, the voltages decrease, while in phases B and C voltages increase. Those results can be explained as the effects of the decreased energy consumption and decreased imports from the upstream grid, which steems from the high equilibrium prices and activation of the flexibility of the peers that participate in the P2P electricity trading. In the S2 scenario (Table 2 and Fig. 5), voltage levels are nearer to the nominal voltage than in S1 scenario. Reasons for this are in lower consumption, production and P2P energy traded, which initiated lower power flows on lines compared to S1 scenario, resulting in lower deviations from the nominal voltage (as set on LV side of the transformer substation).

TABLE II. AVERAGE VOLTAGE LEVELS AND DIFFERENCES IN COMPARISON WITH THE NOMINAL VOLTAGE IN ALL SCENARIOS.

Item	Phase	SREF	S1	S2
Average voltage level	A	1.05820	1.05755	1.05695
	B	1.03776	1.04913	1.04868
	C	1.03875	1.04264	1.04387
Average voltage level difference from the nominal	A	0.781%	0.719%	0.662%
	B	-1.166%	-0.083%	-0.125%
	C	-1.071%	-0.701%	-0.584%

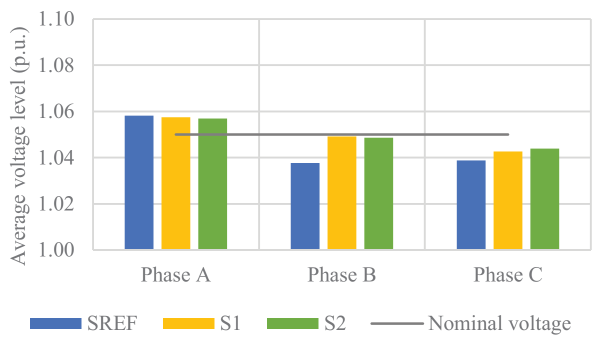


Fig. 5. Average voltage levels in the analyzed scenarios.

Further, differences between voltage deviations in comparison with the nominal voltage are calculated using the mean absolute error (MAE) across the scenarios. That quantification allows comparisons and provides insights into the impacts of demand elasticity on voltage levels and voltage deviations. The calculation of the voltage deviations using MAE is conducted for all voltage deviations (dU), positive voltage deviations (dU+), and negative voltage deviations (dU−). The data is shown in Table 3 and Fig. 6,.

From Table 3 and Fig. 6, it is evident that in the SREF scenario, MAE for all voltage deviations is between 1.18% and 1.46% of the nominal voltage, across the phases. Thereby, negative voltage deviations are dominant (in scope of 1.10% to 1.74% across the phases for negative compared to scope of 0.35% to 1.30% across the phases for the positive deviations). In scenarios that simulate P2P electricity trading (scenarios S1–S2), MAE is approximately halved for all voltage deviations and for all phases, except for phase B in S1 and S2 scenario. In the S1 scenario (high supply prices, higher demand elasticity), MAE of all voltage deviations ranges in the scope of 0,53%-0,83%, with the greater contribution of positive voltage deviations (0.18%-0.86%) and lower contribution of the MAE of negative voltage deviations (0.45%-0.77%). The impacts of lower demand elasticity in the S2 scenario resulted in a decrease of voltage deviations (all, positive, and negative) (Table 3, Fig. 6) on average across the phases when compared with the S1 scenario. At last, it can be noticed that the MAE of voltage deviations across the scenarios that simulate P2P electricity trading are, on average, 48% lower than in the SREF scenario for all voltage deviations, 23% lower for positive voltage deviations, and 57% lower for negative voltage deviations across the phases, meaning P2P trading could stabilize voltage levels nearer to the nominal voltage and decrease voltage fluctuations.

TABLE III. MAE BETWEEN MICROGRID VOLTAGE AND NOMINAL VOLTAGE FOR EVERY PHASE (FOR ALL DEVIATIONS, POSITIVE DEVIATIONS, AND NEGATIVE DEVIATIONS) IN THE ANALYZED PERIOD AND BUSSES. FOR THE SAKE OF CLARITY OF THE RESULTS, MAE IS DIVIDED BY THE NOMINAL VOLTAGE AND EXPRESSED AS A PERCENTAGE.

Item	Phase	SREF	S1	S2
MAE (all voltage deviations) (%)	A	1.26%	0.83%	0.77%
	B	1.46%	0.53%	0.55%
	C	1.18%	0.75%	0.63%
MAE (positive voltage deviations) (%)	A	1.30%	0.86%	0.81%
	B	0.51%	0.86%	0.46%
	C	0.35%	0.18%	0.18%
MAE (negative voltage deviations) (%)	A	1.10%	0.45%	0.38%
	B	1.74%	0.60%	0.64%
	C	1.25%	0.77%	0.64%

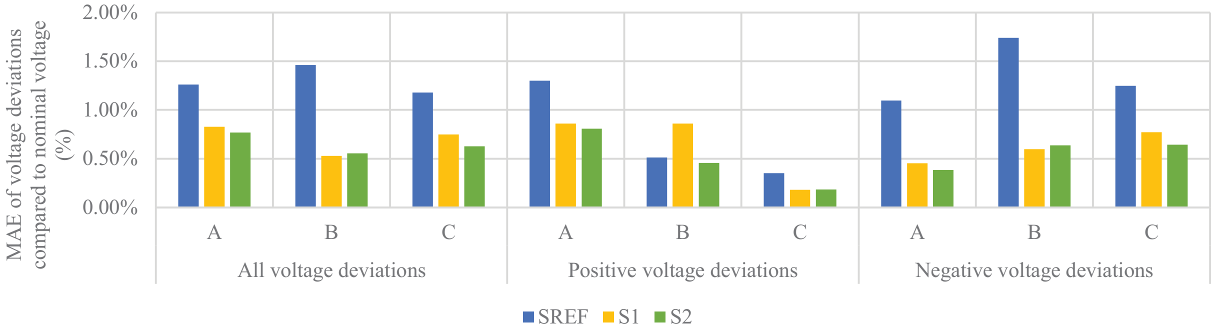


Fig. 6. MAE of the voltage deviations from the nominal voltage across the phases (for all deviations, positive deviations, and negative deviations) in the analyzed period and busses. For the sake of clarity of the results, MAE is divided by the nominal voltage and expressed as a percentage.

IV. Discussion

The method for simulation of P2P electricity trading was utilized in the paper and effects on voltage levels in the IEEE European LV test feeder were analyzed for different elasticities of demand bidding curves of the peers. The results point out that local P2P electricity trading can provide a contribution to the stabilization of voltage levels nearer to the nominal voltage and decrease the voltage fluctuations. In a simulated P2P electricity trading, the demand bidding strategies of the peers have an important effect on equilibrium prices and volumes on the market. Consequently, local electricity production and consumption are affected, and finally, that defines power flows and voltage levels in the grid. The simulated scenarios showed that a decrease in demand elasticity caused a decrease in market-clearing prices and quantities. Further, the analysis pointed out that the P2P electricity trading can provide listed positive effects without SCUC and SCED calculations for the used input data. Those insights can have important implications for designing of the P2P electricity trading and associated market and control mechanisms.

Future work includes research and implementation of strategies for optimal coordinated operation of variable RES and controllable ESS based on the game theory [30, 31, 32] for the peers that participate in the P2P electricity trading. Also, in the IMPACT project [33], testing of P2P electricity trading is foreseen in the laboratory environment as well as in the real-life distribution grid.

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