Feasibility study of a local peer-to-peer energy market: Implications on a real-life LV distribution grid

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***Abstract*—The H2020 INTERRFACE project designs, develops, and exploits an Interoperable pan-European Grid Services Architecture to act as the interface between the power system (TSO and DSO) and the customers and allow the seamless and coordinated operation of all stakeholders to use and procure common services. The project exploits state-of-the-art digital tools based on peer-to-peer (P2P) local market to provide new opportunities for electricity market participation and thus engage consumers into the INTERRFACE proposed market structures that are designed to exploit Distributed Energy Resources and empowers customers to become active market participants. In this paper, a network modeling method is introduced and validated through the metering data of a test area. The model considers voltage limits, asymmetry, and overloading violations. Simulation results show that the modeling considerations are adequate to analyze the effects on the local grid assets and provide reflective tariff signals for proper grid utilization. Therefore, the proposed design can serve as the network calculation principle of low voltage P2P markets in the future.**

Keywords*—*dynamic tariff, local market, electricity market simulation, network model

I. Introduction

The electricity sector undergoes major changes due to sustainability goals, such as the reduction of greenhouse gas emission, improvement in energy efficiency, and the growing share of renewable energy generation. The latter aspect is expressly substantial in power grids, where there is a vast difference between the characteristics of conventional energy generation and intermittent renewable energy sources, such as solar and wind power. Besides the weather-dependent output and technical attributes (e.g. low inertia, low short-circuit contribution, different controllability), one of the most important aspects is the distributed connection. This means that the distribution system – which was designed to deliver electricity to the end customers from the supply point of the transmission system, had a dedicated flow direction consequently, and was planned to meet voltage drop and load-driven overload constraints – transforms into an active infrastructure (bi-directional flows, volatile voltage profiles, prosumers that optimize their activities). The traditional distribution network development methods focused on serving any need that occurs. However, the effective integration of new technologies, especially distributed energy resources (DER) requires different approaches to ensure the cost-effectiveness of the infrastructure.

One of the most promising solutions is to enhance the local operation of the system through market activities: participants could be incentivized to operate their power-related assets – either DER [1] or other consumption – in a way that the distribution system operator (DSO) could still meet the supply quality measures without building further grid infrastructure with a lower exploitation factor [2].

Nowadays there is a wide literature of market design concepts [3][4]. [5] introduces and compares the two major bidding models: order book and peer-to-peer (P2P) markets using market financial outflow as a performance indicator. Besides local market mechanism models [6], the issue of safe transaction concepts in P2P scenarios is also a highlighted research field. [7] gives possible applications of blockchain technology related to P2P electricity markets and presents a framework for transaction management.

Use cases from local markets involve voltage management [8], power loss estimation [9] (or loss reduction [10]), congestion management [9], and avoided distributed generation curtailment [11]. These studies offer viable theoretical solutions, and the results on general network architectures are shown to be feasible. However, current research indicates that the modeling of the network infrastructure is a key issue in applicability analysis [12][13]. Therefore, studies conducted on real distribution grid data offer valuable conclusions for further enhancements of the local market concept [14].

The major limitation of market concepts in general is that they only exist in the theoretical stage. The H2020 INTERRFACE project strives to tackle this problem and aims to create a local asset-enabled market pilot to provide practical inputs for further market and regulation model development on the road to sustainable energy systems. It includes a comprehensive way of low voltage (LV) network modeling, which considers the major operation constraints (voltage limits, asymmetry, overloading, losses etc.) and tries to focus on the utilization optimization of the infrastructure through dynamic tariff structure and limiting factors (based on the asset condition).

In this paper, a comprehensive model of a real distribution grid is developed to analyze the potential implications of local peer-to-peer (P2P) trading in the area. Load flow and voltage/current sensitivity factor based calculations offer

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quantitative electrotechnical effects of the transactions. The proposed peer-to-peer trading mechanism is grid-aware in the sense that grid calculations are carried out during the pricing of possible transactions, in order to facilitate flows which are beneficial for the distribution grid. The paper, however, does not introduce the dynamic tariff mechanism or the asset condition in detail, as these aspects of this complex framework will be published in separate publications. It focuses on the modeling consideration to adequately describe the constraints for the further modules. This is critical for the quantification of the utilization improvement of the grid infrastructure. The proposed modelling method is tested and validated with significant amount of metering data from the demonstration site. The paper concludes that the new method is appropriate for asset-enabled LV P2P market and dynamic tariff evaluation.

The paper is organized as follows. Section II introduces the framework of the local market, including the grid module and the tariff considerations. Section III presents the model validation, while Section IV discusses the main results of the simulations. Finally, Section V summarizes the conclusions and sets the directions for future work.

II. LOCAL MARKET FRAMEWORK

The H2020 INTERRFACE project aims to create a P2P local market within a modular framework. The main goal is to have a fully operating structure where the infrastructure is modeled properly, participants can make bids, and the effects of the transactions can be included in the dynamic tariff calculation.

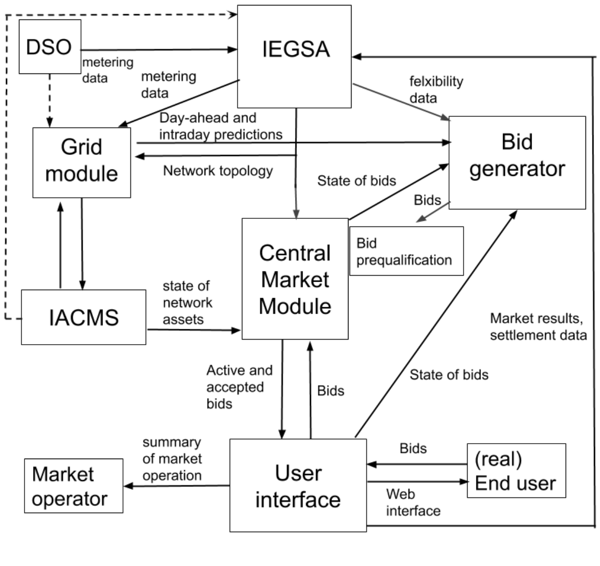

Fig. 1. The modular structure of the local market implementation

The modular structure of the proposed local market scheme is summarized in Fig. 1, where the modules of the system and the information flow is depicted. The grid module, the market module, and the bid generator are discussed in detail in the following subsection. 'IEGSA' stands for the 'Interoperable pan-European Grid Services Architecture', which is a common platform developed in the framework of the H2020 grant No. 824330. The IEGSA stores the grid data, and the metering data necessary for base-case power flow calculations and receives the market results from the Central Market Module. It serves the purpose of interoperability as well, therefore it also shares data to the market module and receives data of the user activity as well. Active users may submit their bids through the User Interface of the system, while for passive participants, the bid generator simulates the bidding behavior. The IACMS is the abbreviation for the Integrated Asset Condition Management System, which continuously monitors the system components (e.g. lines and transformers) in order to provide up-to-date loadability data for the market transactions (the operation details of IEGSA, IACMS and the process of bidding are not the subject of this study). The dashed lines (between the DSO – grid module and IACMS – IEGSA) means a one-time data share (initialization of attributes) between the functional elements.

A. *Grid module*

The grid module is designed to generate a unified grid representation, which helps to convert raw grid topology information into a pre-defined data structure. The model output is standardized, the numbering of the elements is used uniformly by the other modules of the framework. This transformation guarantees that the local market framework is independent of the network size and topology and minimizes the malfunctions of parametrization. The grid module requires standardized input datasets as follows:

- network topology data (graph representation);
- parameter table of line types (impedance calculation);
- attribute table of prosumers (load/generation constraints).

Due to the different types of input data received from demonstration partners, the mentioned data structures are filled with data manually, since not every demonstrator store their data in a Common Information Model format yet. When the preliminary tasks are accomplished, the execution of the grid module starts with the buildup of the network graph representation. This representation is a definite connection structure of the line elements with a corresponding length parameter and line type. The grid module reads the parameter table of the line types and links the corresponding physical parameters to the graph representation of the line. Consequently, the data used for the topology representation include line attributes (impedance per length, length, type definition), transformer electrical data, switching & protection devices, voltage, and current measurements. The developed model is a 4-wire representation which considers asymmetry, as it is an important factor for low voltage networks.

Then in the next step, the program places the prosumers on the graph according to the original topology information. Data sources include consumer smart metering data, synthetic load profiles (where 15 minute resolution measurements are not available), distributed generation measurements. This is provided by two pieces of information stored in the attribute table of the prosumers: (i) linked graph number, and (ii) the distance of the designated entity from the start node of the graph (each line element has a start and end node). At the end of this step, the physical parametrization of the network is terminated, and the full grid representation can be created. For this reason, the grid module is able to compute the admittance matrix of the network, which is essential for further simulations. The results are stored in separate variables. The phase assignment of the loads is based on measurements and can be refined with further data available in the system.

B. Market module

1) General market structure

The local market platform from [15] is introduced, on which peer-to-peer transactions can be executed. The platform is basically a marketplace, where both supply and demand orders can be placed and hit by prosumers of the network. The bidding/hitting mechanism can be manual or automatic, depending on the preferences of a prosumer. The traditional retail market can operate in parallel with this platform, thus allowing the participation to be voluntary. However, trading on the local market obliges the participants to consume or produce the transacted energy.

The operation of the local market is similar to the intraday wholesale electricity market: energy (min. 1 Wh) can be traded in a continuous manner for 15-minute periods of a day, starting from the previous day until gate closure, which precedes physical delivery by 1 hour. The settlement is carried out after energy delivery, taking market data and measurements into consideration.

2) Dynamic network usage tariff

Every transaction induces flows on the local network, which can be categorized either as burdening flows, meaning that the flows cause even greater load on lines, or relieving flows, in which case the flows reduce pressure on the grid.

The dynamic network usage tariff (DNUT – €/MWh), is a tool of incentivization in the local market, which is either added to or subtracted from the energy price of a given order. On the one hand, the tariff can be consistently lower than standard network charges, because the transmission network is not used, thus increasing the number of local market participants. On the other hand, it serves congestion management purposes and ensures adequate voltage values through incentivizing such transactions (or submission of orders) that are advantageous from the perspective of the grid operator.

This tariff consists of three main elements that allocate charges to the deviation in nodal voltages, branch flows, and overall network loss. For every pair of participants, and both flow directions, a DNUT value is calculated with the usage of a representative measure of energy transaction (i.e. fixed transaction volume), thus creating a DNUT matrix by the size of the number of prosumers. Trading between identical nodes (two prosumers on the same network node) has minimal effects on the grid, which are neglected. Therefore, the diagonal of the aforementioned DNUT matrix is set to zero. The calculations of the other elements in the matrix use the charges mentioned above and the estimated state of the system as a result of the fixed transaction. The charges consist of limiting and linear components. Nodal voltages are constrained to be in the nominal ±10% interval in order to ensure sufficient quality of service, while branch currents are constrained in order not to surpass the rated currents of the given lines of the grid (rated current can be determined by the IACMS module).

The linear components account for the physical effects of energy transactions. A cost is calculated for every node based on how much the voltage amplitude is changed, and for every line based on how much the amplitude of the phase current is changed. Costs are also assigned to the deviation in network losses (estimated by line losses using calculations from line resistances and currents).

The resulting DNUT can either be positive or negative, based on how the network is affected by the transacted energy. In the case of accepted transactions, both participants (seller and buyer) pay 50% of the calculated DNUT.

[16] offers a more detailed description of the market structure and tariffs.

3) Generation of bids for the simulation

In this study, the operation of the market was simulated using artificial bids. Each bid was described by the following parameters:

- type of the bid (supply or demand);
- index of the trading period, for which the bid is relevant;
- volume of the bid;
- submission price of the bid.

For every considered participant, bids were generated based on the historical consumption/production data. We assumed that every participant submits bids to the market in two steps: First, day-ahead bids are submitted on the day before the trading period (D-1); and second, intra-day bids are submitted on the day of trading. In the case of intra-day bids, it was assumed that the prediction of consumption/production regarding the trading period is more precise than in the case of day-ahead bids.

In addition, parameters of intraday bids also depend on the outcome of day-ahead bids (e.g., it is possible that upon the time of intra-day bid submission, 50% of the predicted demand is already covered from the local market by accepted day-ahead bids. In this case, intraday bids are submitted only for the remaining 50%). Before the submission of intraday bids, all open positions corresponding to day-ahead bids are closed (these bids are cancelled). Submission prices of the bids were determined relative to the reference price (the regulated price, on which consumers are able to buy electricity from outside the local market). It is assumed that every participant determines the submission price of their bids with a constant margin when trading on the local market. On the other hand, bid prices are also adjusted during the submission process, as we assume that the participants use a lower margin in the case of intraday bids compared to day-ahead bids.

III. Model validation

The proposed P2P market model and the clearing process take into consideration the actual and predicted state of the grid. Since the trading is dominantly affected by the performance of the developed network mapping algorithm (grid module), it determines the applicability of the whole framework. This issue was tackled by the authors and a performance evaluation and validation process was carried out before the extension of simulation scenarios. In this section, the case study network topology including physical attributes is introduced, and the validation results are discussed.

A. Local network description

Local trading of the prosumers is only feasible if the grid infrastructure can handle the market requirements. Therefore, to calculate the base of the grid factors that are constraining the market actions, reliable models are needed. The discussed Slovenian demonstration site is located in Gradišče. The spatial expanse of the grid is noticeable with 8 separate circuits and 154 consumers covering the whole LV side of a transformer with 160 kVA rated power. Due to the highland environment, each circuit is relatively long with a moderate number of junctions. In all consumer connection points, metering devices provide active power and voltage measurements in the 3 phases, respectively. The graph representation of the case study grid is shown in Fig. 2.

The result of the grid calculation process is twofold: it defines the physical representation of the demo sites, and provides an estimation for the day-ahead flows. The latter method is based on historical data (statistical approach), and there is a possibility to use stochastic parameters and a higher number of simulations to increase the visibility of possible customer behavior. It is important to note that estimating the day-ahead profile of consumers or prosumers is a difficult task per se, but with around 50 connection points per LV circuit, the power flow calculations could be seen as representative.

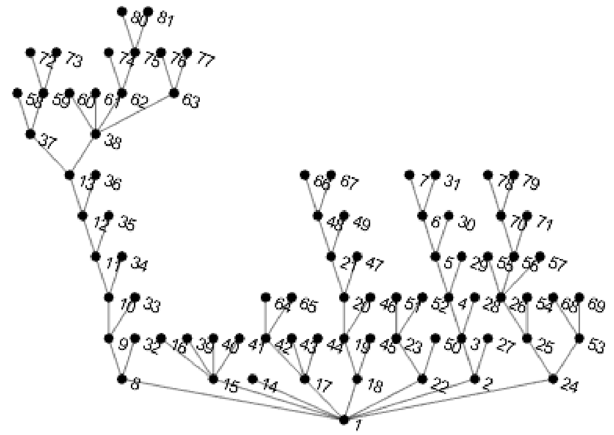

Fig. 2. The topology of the case study location in Gradišče

The modeling phase was investigated under some simplifying assumptions. Reactive power is only available for some industrial/commercial customers; therefore, in other cases it must be estimated. At this stage, the model neglects reactive power flows. Protection devices are neglected (static numbers are available; therefore, separated validation and marking of possible supply interruptions is feasible from the data); transformer LV-side voltages are 1.04 per unit, similarly to the practical settings (based on measurements). Unbalanced calculations are considered with a 4-wire line representation and 3-phase transformer model based on the vector group and impedance data.

B. *Validation of the results*

The proposed P2P local market concept requires an accurate mapping technique of the real-time grid states. The grid module uses power measurements recorded in consumer connection points and a graph-based representation of the real grid to estimate the actual state (and electrical parameters) of the grid. For validation purposes, the load-flow voltage results and the real voltage measurements are compared. Despite the extensive availability of power measurements, a limited set of voltage values were accessible. Naturally, one-phase consumers provided only one time series, and 34 pieces of 3-phase measurements are missing. This means that more than 75% of consumers are taken into the validation, which is significant in the context that an LV site is investigated. While voltage time series have a 10 min resolution, the power meters record data every 15 minutes.

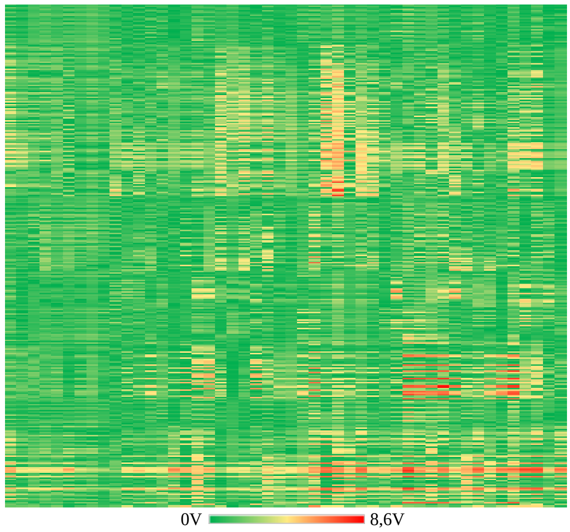

Fig. 3. Heatmap of deviation between simulation and real voltage dataset; each row shows one metering point (node) and each column represents one momentum from 00:00 to 23:30 with 30 min resolution

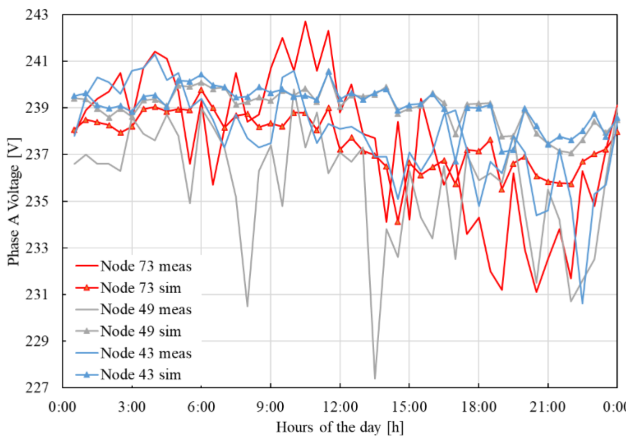

Fig. 4. Metered (solid lines) and simulated (triangle markers) end node voltages in case of three circuits; the node numeration is denoted by Fig. 2

Since the proposed local market uses 15-minute timesteps, the validation process included 48 comparable moments in 24 hours, at the top and the bottom of every hour. The grid model accuracy compared with real-time measurement set was validated on data corresponding to the 13th of August. The deviation between real-time and simulation records are demonstrated via a heatmap in Fig. 3. The rows of the heatmap represent every measurement time series. The 48 columns show the simulation accuracy at a moment with a color gradient from 0% deviation (green) to 8,6% (red), respectively. An optimistic 1% assumed sampling error [17] means approx. 2,3 V deviation between real and metered data. Fig. 3 shows that in most cases the deviation between simulation and on-site measurements is under this threshold. The performance of the grid module simulation is significant and verifies that the model maps the real grid features well. The root cause for larger deviations in the metering data is unknown, it should be considered a significant load element switch, which is hard to predict in the case of low number of LV customers.

While, Fig. 3 introduces a general picture about the performance of the grid module, Fig. 4 shows a comparison of 3 circuit endpoint node voltages. This reveals the voltage patterns of both simulated (triangle marked) and real measurements (solid lines). It is seen that the simulation and measured time series have a similar fluctuation, respectively.

IV. Market Results

Market simulations are carried out for two scenarios for the same day of operation:

- Scenario 1: the original LV network in Gradišče is used, which only contains two prosumers that inject power to the grid throughout the day.
- Scenario 2: two additional, randomly selected nodes are replaced by prosumers, while the energy production profiles of existing ones were used.

In both scenarios, a base case (generation and load) is defined based on measurements, which represents the estimated state of the network without the influence of the local market. In this article, we focus on two of the grid-related aspects of the market results, namely phase voltage deviations and changes in network loss. Therefore, prosumer prices, calculated DNUT, social welfare, and other economic measures are not discussed. The sum of network losses in a given quarter-hour is divided by the total traded volume to ensure comparability between the base case, and local market results. The total traded volume is defined as the sum of generation and consumption in the system.

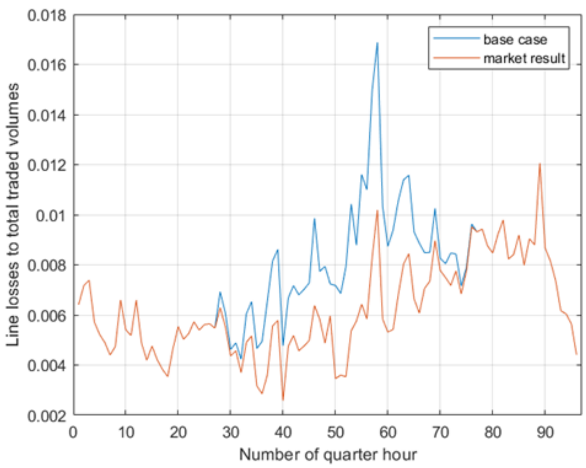

Fig. 5. Comparison of relative losses for the base case and local market results in scenario 1

Fig. 5 summarizes the relative losses (MWh/MWh) in Scenario 1. In this case, the local generation is rather low, most of the consumption is covered by the external grid. Therefore, the loss relative to consumed energy is less favorable, as the flows follow the conventional route from the medium voltage grid through the transformer to the customers. Compared to that, the introduction of the local market provides information on the grid state for participants, thus showing a possibility to bid for the local generation. These added transactions lower the relative losses as the generation is physically closer to the consumption.

Fig. 6 depicts the highest and lowest voltage phase RMS values for both the base case and the local market results, calculated in 15 min time steps for the whole day. Despite the additional trading, the voltage values remain in a tight zone. Although the applied dynamic tariff practically forbids voltage limit violations, this result is rather due to the lack of supply bids (which come from only 2 generators). The number of supply orders is raised by connecting two more producers to the network in Scenario 2.

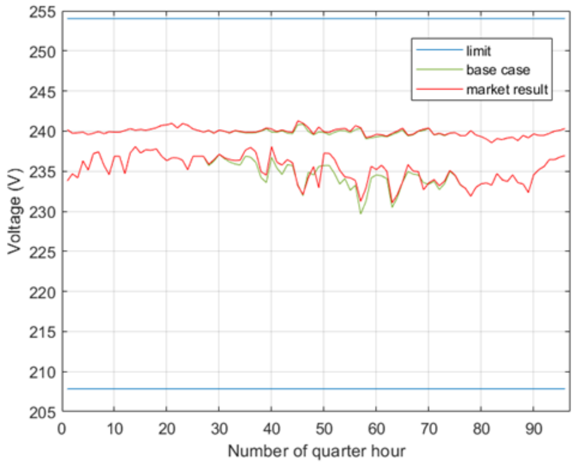

Fig. 6. Comparison of minimum and maximum phase voltages for the base case and local market results in Scenario 1

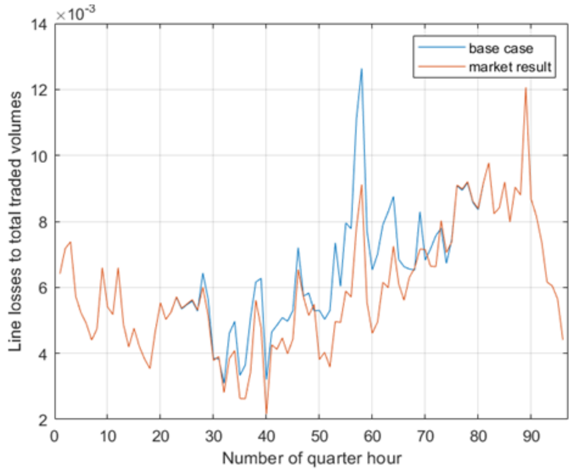

Fig. 7. Comparison of relative losses for the base case and local market results in Scenario 2

In this scenario the relative losses (Fig. 7.) in the base case are already lower compared to Scenario 1 due to the increased number of local generators, which imply less loaded network branches. This loss ratio is further improved by the local market.

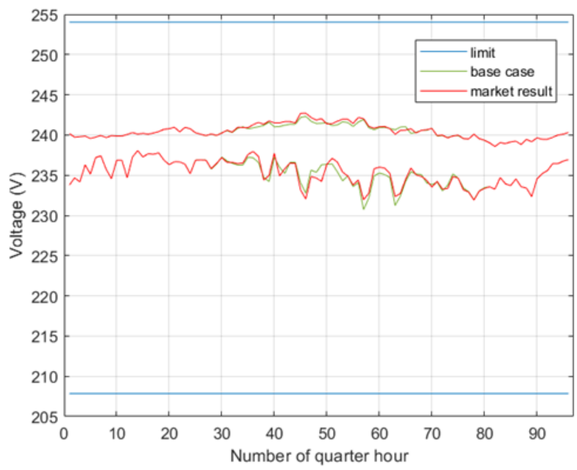

Fig. 8. Comparison of minimum and maximum phase voltages for base case and local market results in Scenario 2

Fig. 8 shows that there is still only a slight rise in voltage RMS values, meaning that the constraints defined by the operation standards are not violated.

V. Conclusion

Due to the proliferation of distributed energy production, the role of distribution system operation is in a transition towards active grid management. The authors aimed to tackle this problem by introducing a P2P local market concept, which was tested on an existing LV site. The network validation process verified that the developed grid model maps the real voltage fluctuations in the threshold of metering devices. Consequently, market simulations were carried out to investigate the physical effects (considering voltages and losses) of P2P trading.

The results of this study show that local market trades are executed in a way that is beneficial from the perspective of grid operation; however, further quantitative and qualitative analysis is feasible. The H2020 INTERRFACE project aims to create a long-term demonstration at this site for a comprehensive analysis to reveal the potential of P2P trading in helping infrastructure utilization.

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