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Published

2020

Conference Title

2020 IEEE Power & Energy Society General Meeting (PESGM)

Version

Accepted Manuscript (AM)

DOI

10.1109/PESGM41954.2020.9282128

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Regulated P2P Energy Trading: A Typical Australian Distribution Network Case Study

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***Abstract*—This paper presents an approach to deploy virtually settled peer-to-peer (P2P) energy trading in existing grid-connected networks without considering post-trading protection schemes that may be required for bus voltage regulation. To achieve this goal, this paper demonstrates to consider the maximum power export limit fixed by the network operators while modelling the P2P trading framework in the virtual layer and then to determine the traded quantity of each prosumer in the P2P market along with the associated price per unit of energy traded. The developed P2P mechanism in this paper is tested on a real low-voltage (LV) distribution network in Australia, where the maximum local power injection limit has already been defined for the prosumers. The simulation results show that both prosumers and other customers of the network can still be benefited significantly, compared to the current feed-in-tariff (FiT) and electricity retail prices respectively, even though P2P traded quantities are regulated by the network operator. It is also observed that the prosumers' engagement in P2P trading at various time slots do not rise bus voltages beyond the prescribed limit. Thus, virtually settled P2P transactions considering the power export constraint are suitable for practical deployment.**

***Index Terms*—P2P energy trading, financial benefits, bus voltage rise, power injection limit.**

I. INTRODUCTION

In the last decade, feed-in-tariff (FiT) emerged as a promising platform to incorporate the small-scale prosumers, consumers who generate clean energy locally [1], into the local electricity market [2]. Under this scheme, prosumers can sell their excess electricity, the difference between local generation and internal power demand [3], back to the energy grid at a price per unit of energy set by the market operator [4]. However, the financial benefits that prosumers reap from FiT scheme has been evidenced to be insignificant [5]. For instance, in Queensland, Australia, the current FiT rate is around 10 ¢/kWh [6], whereas the average electricity retail price is between 24 and 28 ¢/kWh [7]. Thus, due to market operator-centric feature, FiT scheme is becoming ineffective to retain existing customers [8] and attract new prosumers [5]. For this reason, a prosumers-centric market structure is required to stimulate the presence of the prosumers in the local electricity market [4].

Peer-to-peer (P2P) is such kind of prosumer-centric market strategy where prosumers can negotiate electricity prices among each other using the virtual communication platform, such as blockchain, to facilitate clean energy trading within the community [9]. Hence, the benefits provided by the P2P trading is expected to be substantial [5]. In fact, the traditional consumers without local generation, unlike FiT, can also participate in P2P trading as sole buyers and can reduce their electricity bills. However, the actual delivery of traded energy is going to be taken place over physical networks monitored by the distribution network service providers (DNSPs) [9]. Therefore, virtually settled P2P transactions should essentially respect the network constraints, specially the voltage rise issue [4].

It is well-known that internal generation can increase the voltage profile at prosumers' buses [10], [11]. P2P trading may affect the situation by increasing the bus voltages beyond the prescribed upper voltage limit [4]. This is because in physical P2P trading, prosumers are going to push their locally generated energy at their respective buses to execute mutual transcations, resulting in the issue of voltage rise in some phenomena. To address this issue, a P2P trading scheme is formulated under voltage constraints in [12], where user blocking approach has been adopted whenever the over-voltage arises at a particular bus and the blocked users' transaction is not permitted by the network operator. Since P2P is a prosumer-centric approach, user blocking mechanism, even for some time instants, may discourage the prosumers psychologically to participate further in the P2P trading market. In [13], to support the bus voltages, the authors propose an optimisation technique for reactive power compensation and active power curtailment of each inverter participating in the P2P voltage control. The idea of power curtailment in the physical layer, however, may compel the DNSPs to readjust the P2P transactions finalised in the virtual layer in some trading periods as available P2P trading algorithms [5], [14]–[16] do not consider any power injection restrictions while deciding P2P exchanged amounts. Therefore, further investigation is necessary to consider the local power export limit while settling the trading agreements so that the network operators do not need to adopt any extra steps to regulate the bus voltages during actual P2P power transfer and the prosumers' agreed P2P exchange quantities in the virtual layer remain unchanged.

To this end, this paper focuses on formulating P2P trading mechanism considering power injection limit to avoid protection schemes required to control voltage rise in the prosumers' buses. To do so, prosumers' P2P transactions are modelled under the maximum power injection constraint. Further, simulation studies are carried out on an existing Australian LV distribution network, where prosumers are bound to comply with the pre-set power injection limit, to capture the monetary benefits offered by the P2P trading for the participants at various trading periods and to confirm that the regulated P2P methodology keeps bus voltages within the safe margin.

Please note that although this paper uses a typical distribution network in Australia as a case study, the regulated P2P energy trading framework can be deployed on any grid-connected networks.

The rest of the paper is structured as follows: Section II explains the necessity of taking the local power export constraint into account while finalising the P2P transactions. The regulated P2P trading mechanism is modelled in Section III. The following section contains the simulation results of P2P trading performed on a typical distribution network in Australia. To end with, the concluding remarks are provided in Section V.

II. PROBLEM STATEMENT

Let consider a P2P network with N households, where $N = |\mathcal{N}|$. Each household represents one prosumer at all time periods. The sets of sellers (prosumers that sell energy) and buyers (prosumers that purchase energy) are denoted by $\mathcal{I}$ and $\mathcal{J}$ respectively, where $\mathcal{I}, \mathcal{J} \subset \mathcal{N}$. The seller $i \in \mathcal{I}$ has power surplus of $P_i, \forall i$ and the buyer $j \in \mathcal{J}$, on the contrary, has power deficiency of $P_j, \forall j$. To carry out physical P2P trading, the seller i may inject the entire P_i or part of P_i into the network based on the contract with buyer j in the virtual layer. However, it is required to ensure that the injection of P_i should not create over-voltage issue in the network. Otherwise, the DNSP has to implement some protection schemes for voltage regulation.

The protection schemes anticipated to be undertaken in the physical layer of P2P trading, however, may affect the approved P2P power quantities decided in the virtual layer between the traders. This is because if any transaction is labelled as impractical and the prosumers' intended trading amount is curtailed using advanced techniques for network protection, the P2P payment has to be readjusted as well. Further, the prosumers may need to pay for the additional services adopted to maintain the bus voltages according to the grid codes.

Given this context, this paper urges to take the local power injection limit into account while deciding P2P market solutions, trading amount and price, virtually between the participants of the P2P network. This is because the DNSPs have already defined the maximum local power export limit, Pi_{max}, for the residential prosumers in many parts of the world, e.g., Queensland, Australia [8], for maintaining the network voltages. In other words, the injected power of seller i, P_i, should not be greater than the maximum power injection, Pi_{max}, i.e., $P_i \leqslant Pi_{max}, \forall i$, in all P2P intervals. Otherwise, it should not be approved in the virtual layer for the safe network operation.

III. REGULATED P2P TRADING FRAMEWORK

This section describes prosumers' selection strategy, P2P price and quantity determination, and the evaluation of the financial benefits.

A. Selection of Participants

Once registered in a P2P network, prosumers can communicate with each other using a decentralised communication technology. The detail explanation of virtual communication platform can be found in [4], [9], [17]. Prosumers are categorised in the group of either sellers or buyers depending on their generation surplus and load deficiency for each trading periods. This paper defines a futuristic P2P market policy, as advised in [18], in which both sellers and buyers are given permission to declare their preferred trading quantities and prices for every P2P intervals. The priority order of sellers and buyers are settled according to the least and most announced prices respectively. In case of same declared price value, valid for both sellers and buyers, priority is offered in the sequence, in which they registered in the P2P network.

B. Trading Quantity and Price

Let $\lambda_i, \forall i$, and $\lambda_j, \forall j$, be the prices declared by seller i and buyer j to sell P_i and buy P_j power at time t respectively. Seller i looks for higher price to sell power compared to the FiT rate, λ_f, to earn significant profits. On the contrary, buyer j is not going to be motivated to take part in P2P trading if it cannot purchase power at cheaper price in comparison with the time-of-use (ToU) tariffs of the grid (or equivalent retail), λ_g. In order to encourage both seller and buyer to involve in the P2P market, this paper emphasises to organise the declared pricing range of the participants between λ_f and λ_g, i.e., $\lambda_f < \lambda_i, \lambda_j < \lambda_g$.

The participants' hourly maximum welfare function for k^{th} P2P transaction, where $k \in \mathcal{K}$, can be written using linear representation as:

$$f\left(k|i,j\right) = \lambda_j^{(k)}\ P_j^{(k)} - \lambda_i^{(k)}\ P_i^{(k)} \tag{1a}$$

subject to

$$P_j^{(k)} - P_i^{(k)} = 0 \tag{1b}$$

$$0 \leqslant P_i^{(k)} \leqslant Pi_{max} \tag{1c}$$

$$0 \leqslant P_j^{(k)} \leqslant Pj_{max} \tag{1d}$$

where Pj_{max} is the maximum demand of buyer j.

The above constraint optimisation problem can be solved using Lagrange Multipliers [19] and the traded amount for k^{th} P2P transaction is:

$$P_{tr}\left(k|i,j\right) = \min\left\{P_i^{(k)}, P_j^{(k)}\right\} \tag{2}$$

In contrast with the market clearing price of the pool-based electricity market [19], each P2P exchanged price is defined as the middle value of $\lambda_i^{(k)}$ and $\lambda_j^{(k)}$ to incentivise both participants fairly. Hence, P2P trading price, $\lambda_{tr}(k|i,j)$, for k^{th} P2P transaction is considered as:

$$\lambda_{tr}(k|i,j) = \frac{\lambda_i^{(k)} + \lambda_j^{(k)}}{2} \tag{3}$$

The regulated P2P trading framework allows seller i to conduct transactions with multiple buyers as long as its total exchanged power is not greater than Pi_{max} for a given time slot, i.e., $\sum_{k=1}^{|\mathcal{K}|} P_i^{(k)} \leqslant Pi_{max}$. Similarly, buyer j is also permitted to purchase P2P power from sellers until it is fully satisfied and the total sellers' power is zero. In that case, average P2P trading prices for each seller and buyer, Λ_i and Λ_j, are computed as:

$$\Lambda_i = \sum_j {}^{\lambda_{tr}(\cdot|i,j)}/_{k_i} \tag{4a}$$

$$\Lambda_j = \sum_i {}^{\lambda_{tr}(\cdot|i,j)}/_{k_j} \tag{4b}$$

where k_i and k_j are the number of P2P transactions for seller i and buyer j respectively.

C. Financial Benefits

The total profit of seller i, $\mathcal{A}_i$, and and the total saving of buyer j, $\mathcal{B}_j$, for each P2P trading interval can be calculated as:

$$\mathcal{A}_i = \sum_j (\lambda_{tr}(\cdot|i,j) - \lambda_f) \times P_{tr}(k|i,j) \times \sigma_t \tag{5a}$$

$$\mathcal{B}_j = \sum_i (\lambda_g - \lambda_{tr}(\cdot|i,j)) \times P_{tr}(k|i,j) \times \sigma_t \tag{5b}$$

where σ_t is the P2P trading period.

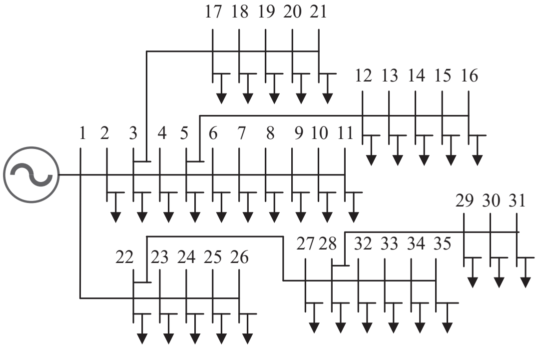
IV. A TYPICAL AUSTRALIAN LV DISTRIBUTION NETWORK CASE STUDY

As widespread involvement of prosumers were anticipated in FiT scheme, the DNSPs in Australia have already defined the maximum local power export limit for voltage regulation, which is capped at 5 kW. This limit is monitored by the DNSPs at all households equipped with solar photovoltaic (PV) systems [8]. This section illustrates how the modelled P2P trading can be performed on an existing Australian network under the power export limit constraint. Also, simulation results are provided to judge the performance of prospective P2P tradings at various time intervals.

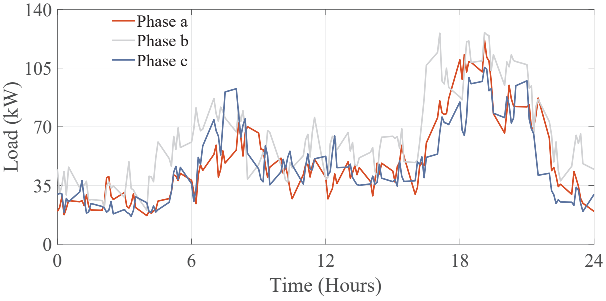
Fig. 1a represents a 3 phase, 35 bus 415V LV distribution network in Australia with 102 household customers [20]. The kW load demands of each phases on a typical day are given in Fig. 1b. Households located at buses 5-14 of this network have rooftop solar PV systems ranging from 3 to 6.6 kW$_\text{p}$. These households are regarded as sellers when they have power surplus after satisfying their internal demand. Other households are labelled as buyers.

To simulate P2P transactions at numerous trading intervals, the following approaches are adopted:

- Based on the recorded PV system and load demand data, taken from a research centre linked with The University of Queensland, Australia, the excess generation are calculated for all sellers and the excess generation data are used as sellers' intended trading data. On the other hand, load demand data of non-solar PV households are used as buyers' intended trading data.



(a) Single-line diagram of a typical Australian LV network.



(b) Three-phase unbalanced loads for the entire day.

Fig. 1: Demonstration of the three-phase loads of a real LV distribution network in Australia.

- All the participants are assigned with identity based on their respective bus numbers. The P2P pricing range is considered between 15 and 20 ¢/kWh during trading hours and participants are allowed to declare their intended prices within this range.
- The regulated P2P trading framework, proposed in Section- III, is executed every 30 minutes apart and a power flow analysis is conducted on the test network, shown in Fig. 1a, with the P2P exchanged power to inspect the network voltages.

A. Prosumers' Benefits

As reported by many other studies, such as [5], [14]–[16], the financial benefits offered by the P2P trading for both sellers and buyers are also figured out in this sub-section. The purpose is to signify that considering power injection limit is not going to have adverse impact on the economic gains expected for the P2P participants.

The number of P2P transactions executed in each trading intervals on a typical sunny day are exhibited in Fig. 2. The P2P tradings at 12 pm present the highest number of transactions, i.e., 101, due to having greater quantity of prosumers' power surplus at mid-day.

In general, the total buyers' demand of the considered network, shown in Fig. 1a, are found to be greater than the total sellers' excess generation due to limited solar PV production at the household levels. That is why, all the sellers have got the opportunity to take part in the trading market and sell their entire power surplus to different buyers at dynamic P2P prices. For instance, the average P2P trading prices of 'Seller 14a' are depicted in the first part of Fig. 3. As is seen that the average P2P prices are quite higher than the flat FiT rate at trading periods. As a result, 'Seller 14a' is going to be benefited economically. On the other hand, the second portion of Fig. 3 captures the average P2P prices of 'Buyer 18c' compared to the ToU grid prices, which indicates that the buyer can also save some money. Other buyers also follow the identical trend. Please note that the unmet P2P buyers have to trade with the grid at ToU prices and cannot reap benefits from the P2P market.

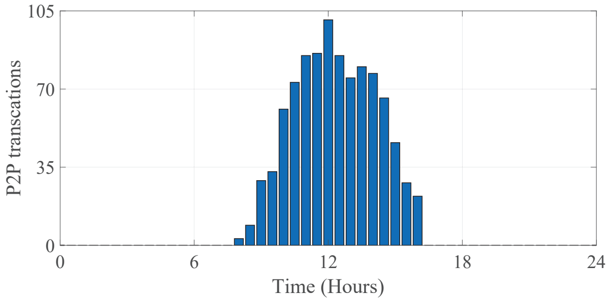


Fig. 2: Number of P2P transactions executed on a typical sunny day.

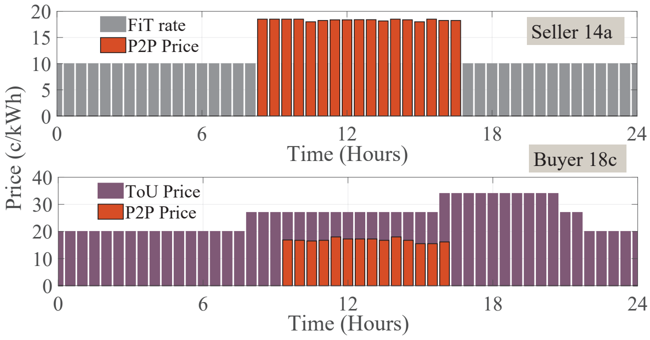


Fig. 3: Average P2P prices of a seller and a buyer compared to flat FiT rate and grid's ToU prices on a typical sunny day.

Table I illustrates the earnings of sellers in Australian dollars (AUD) if they trade in the P2P market for the entire day. According to the information described in this table, the P2P trading framework always outperforms the FiT practice in terms of gaining profits. For example, \$1.8, \$1.7 and \$1.6 are earned more by 'Seller 14a', 'Seller 10a' and 'Seller 6c' respectively because of their engagement in P2P transactions. In addition, other sellers also receive more than a dollar over the course of a day. The daily cost analyses of the P2P buyers, on the other hand, are provided in Table II. The obtained information suggests that P2P buyers can get some monetary benefits during P2P trading slots if they purchase power from the sellers at P2P prices. In particular, 'Buyer 4b', 'Buyer 22a', 'Buyer 24b' and 'Buyer 28c' have been able to cut down their daily electricity bills by \$1.3, \$1.0, \$1.1 and \$1.2 respectively. Therefore, this paper emphasises that regulated P2P trading mechanism is not affecting the lucrative monetary gains envisaged for the P2P traders.

TABLE I: Cost analysis of P2P sellers on a typical day

Identity	FiT earnings (AUD)	P2P earnings (AUD)	Profits (AUD)
Seller 6c	2.1	3.7	1.6
Seller 7b	1.8	3.0	1.2
Seller 8c	1.4	2.5	1.1
Seller 9b	1.8	3.0	1.2
Seller 10a	2.1	3.8	1.7
Seller 10b	1.8	3.1	1.3
Seller 11b	1.7	3.3	1.6
Seller 13b	1.9	3.2	1.3
Seller 14a	2.1	3.9	1.8
Seller 14c	2.0	3.4	1.4

TABLE II: Cost analysis of P2P buyers on a typical day

Identity	Grid expenses (AUD)	P2P expenses (AUD)	Savings (AUD)
Buyer 4b	3.3	2.0	1.3
Buyer 17b	2.5	1.5	1.0
Buyer 18c	2.4	1.5	0.9
Buyer 22a	3.0	2.0	1.0
Buyer 24b	3.1	2.0	1.1
Buyer 25a	2.7	1.7	1.0
Buyer 27c	2.7	1.8	0.9
Buyer 28c	3.0	1.8	1.2
Buyer 29a	2.7	1.8	0.9
Buyer 31b	2.5	1.5	1.0

B. *Bus Voltage Assessment*

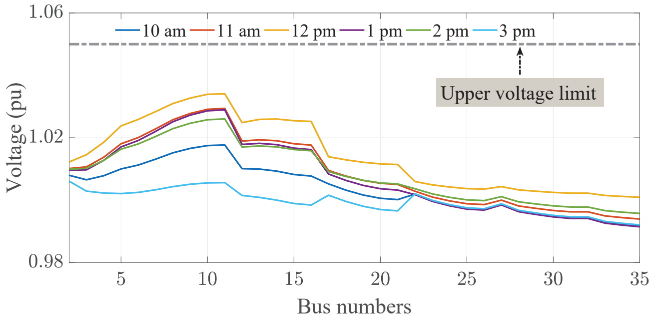
The upper bus voltage limit defined for the network, shown in Fig. 1a, is 1.05 pu [21]. This sub-section investigates the effect of the modelled P2P trading mechanism on the three-phase bus voltages of this network.

As is observed from Fig. 4a that prosumers' bus voltages of Phase a are increased due to local power injection for P2P trading purposes. The maximum recorded bus voltage value is 1.034 pu, which is found at 12 pm while there has been ample sunlight. Fig. 4b displays approximately equivalent bus voltage values of Phase b at 12 pm but further rise in the bus voltages of Phase b are noticed at 10 am and 11 am, whose highest magnitudes are 1.036 pu and 1.04 pu respectively. Fig. 4c reveals slight upsurge in prosumers' bus voltages of Phase c at all P2P trading intervals except at 12 pm, where substantial amounts of locally generated power are exported.

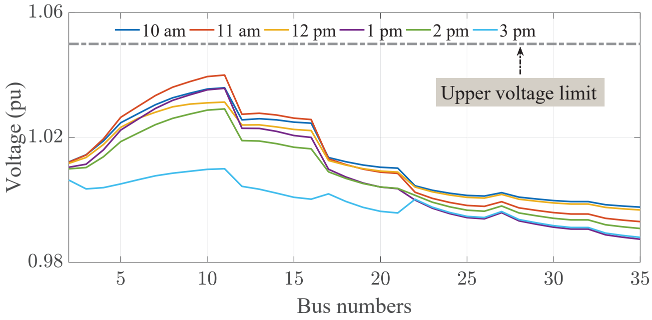
Importantly, the bus voltages of Figs. 4a-4c are within the prescribed voltage margin at all P2P trading periods. Thus, regulated P2P trading can rise voltages at prosumers' buses upto a certain extent but there are no high voltage issues in the network. Thus, P2P trading framework considering power injection limit can be approved by the network service providers by labelling as safe for the networks.

V. CONCLUSION

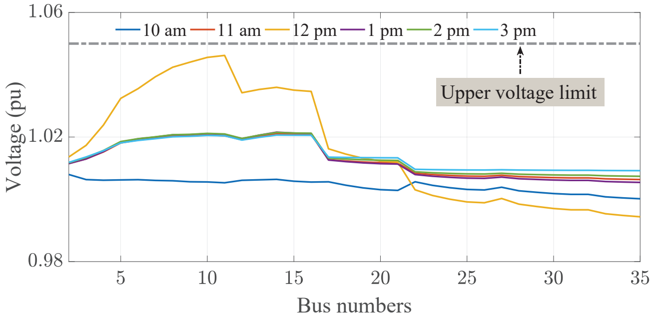
This paper highlights the necessity of taking local power export limit into consideration while deciding the P2P trading



(a) Variation in bus voltages of Phase a.



(b) Variation in bus voltages of Phase b.



(c) Variation in bus voltages of Phase c.

Fig. 4: Demonstration of three-phase bus voltages of the LV distribution network during P2P trading periods.

contracts in the virtual layer to avoid the possible voltage rise phenomena at some prosumers' buses. To do so, a P2P mechanism is developed, in which prosumers' P2P transactions are modelled considering the power injection constraint imposed by the network operators. Then P2P market solutions, i.e., quantities and prices, for all the participants are evaluated. Finally, the proposed P2P model is tested on a real LV distribution network in Australia with the fixed local power export limit for the residential customers. The simulation results ascertain the financial benefits that P2P traders can reap even the trading is formulated respecting the power injection limit set by the network operators. Further, this regulated trading mechanism keeps the bus voltages within the safe margin defined for the network. Consequently, extra voltage protection services are not required to adopt.

In summary, Australian networks or any other networks can approve the participation of the existing prosumers, with or without storage, in the P2P market if the trading framework is modelled following the prescribed network constraints required for voltage regulation.

Future work will deal with the optimal P2P penetration in power networks with storage facilities.

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