A Real-time Control Approach to Maximise the Utilisation of Rooftop PV Using Dynamic Export Limits

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***Abstract*—The soaring intake of rooftop solar photovoltaic (PV) in low voltage (LV) distribution networks has resulted in significant over-voltage issues due to reverse power flows. Although the current practice followed by distribution network operators (DNOs) to tackle this issue is to impose fixed export limits, this results in under-utilisation of export capabilities of consumer-owned distributed energy resources (DERs). This paper presents a LV feeder-level real-time control approach to maximise the utilisation of rooftop PV by assigning 5-min active power export limits for households. The proposed approach consists of two stages. In the first stage, the feeder-level controller performs a snapshot load flow based on 5-min predicted household demand and generation to check for voltage constraint violations. If voltage violations exist, in the next stage, a single-period AC optimal power flow (AC-OPF) problem embedded with voltage constraints is solved to assign 5-min export limits for households.**

The simulation results validated on a real LV network using realistic household demand and PV generation profiles suggest that the proposed approach has the potential to effectively utilise household PV generation while ensuring the operation of the network within preferred limits. Furthermore, the results represent a further step towards developing computationally inexpensive and scalable control schemes to assign time-varying household export limits.

***Index Terms*—dynamic export limits, real-time control, rooftop PV, AC optimal power flow, network constraints, low voltage distribution networks**

I. Introduction

The global trend towards renewable technologies has created a surge in the penetration of rooftop solar photovoltaic (PV) in the generation mix over the past years [1]. For example, it is estimated that 38.9% of the dwellings in Queensland, Australia are equipped with rooftop PV [2]. However, the strong uptake of rooftop PV in low voltage (LV) distribution networks poses significant challenges to distribution network operators (DNOs) to maintain the network integrity.

As per the *AS 60038:2012* standard in Australia [3], allowable voltage limits are redefined at 230 V $(+10\%/-6\%)$ compared to the former 240 V $(\pm 6\%)$ limits, with the intention of absorbing more rooftop PV in LV distribution networks. At the same time, the current practice of DNOs is to enforce a fixed export limit, for example, 5kW, and to shut down the operation of the inverter if the export capacity exceeds this limit [4]. On the one hand, the arbitrary 5 kW export limit has raised issues as end-users with single phase inverter capacity higher than 5 kW are less likely to export power to the grid compared to the houseowners with inverter capacity less than 5 kW. On the other hand, the 5 kW export limit determined based on worst-case conditions (minimum consumption and maximum generation) is too conservative and does not replicate the majority of the real-world scenarios. This leads to an under-utilisation of the available export capacity even if inverters are capable of export power to the grid while maintaining the operation within desired network constraints. Hence, it is undoubted that a systematic approach is essential for effective utilisation of end-user rooftop PV generation while the DNO maintains the operation within preferred network constraints.

To date, several studies have proposed control schemes to maximise the utilisation of rooftop PV in LV distribution grids. For example, the authors in [5] have studied the feasibility of active power curtailment of PV in terms of over-voltage prevention and the sharing of output power losses. Following this, Alyami *et.al* [6] have presented an adaptive real power capping approach for PV inverters to maintain the voltage profile of the network within preferred limits. A multi-period distributed AC optimal power flow (AC-OPF) approach inspired by alternating direction method of multipliers (ADMM) is introduced in [7] for the fair coordination of household PV and battery storage in LV distribution networks. In [8], a multi-period AC-OPF approach is proposed to define customer export limits whereby minimising the curtailment of rooftop PV in LV distribution grids. Furthermore, the approach addresses uncertainties in demand and PV generation via a scenario-based approach. Nonetheless, most of the aforementioned control schemes fall into the category of off-line approaches in which day-ahead export limits are defined for distributed energy resources (DERs). In this regard, the uncertainties associated with longer prediction horizons undermine the process of determining export limits. Not only that, the computational complexity of the resulting multi-period AC-OPF problem increases dramatically with longer prediction horizons even for a small-sized LV network.

Although an uncertainty-aware real-time control scheme is introduced in [9] for the coordination of DERs in an LV network, still the approach relies on solving a convexified version of a multi-period AC-OPF problem which is computationally demanding. Different from a multi-stage OPF scheme, the authors in [10] introduce an approach which comprises a snapshot load flow and a single-period AC-OPF to assign dynamic export limits for households. Nevertheless, the approach is only applicable for the determination of day-ahead export limits. The same idea is utilised in [11] to develop a DNO-based real-time control scheme to define dynamic export limits for households in a combined medium voltage (MV) and LV network. Despite the hierarchical control scheme under which the prosumer problem and the DNO problem are separately addressed, determining time-varying export limits at the DNO level is computationally challenging and often leads to scalability issues as the aggregation size increases. Hence, it is understood that a computationally inexpensive control framework is much favoured to assign dynamic export limits for households in real-time.

Motivated by the drawbacks of the current practice of DNOs and the gaps in the existing literature, the main contributions of this study are:

- developing an LV feeder-level real-time control scheme to assign dynamic active power export limits for households while maintaining the operation within preferred network limits
- a two-stage decision-making process for the LV feeder-level controller which involves a three-phase load flow study and solving an AC-OPF problem
- ensuring the overall control scheme to be consistent with the market clearing interval of the electricity market operator.

The rest of the paper is organised as follows. Section II describes the proposed framework. Section III outlines simulation results based on a case study and section IV concludes the paper.

Notation: Considering the power flow representation, $\mathcal{N}$ is the set of nodes in the network, $\mathcal{E}$ is the set of branches, the network admittance matrix is denoted by $\mathbf{Y} = \mathbf{G} + \mathrm{i}\,\mathbf{B}$, where $\mathrm{i} := \sqrt{-1}$. The polar coordinate representation of the voltage phasor at jth node s.t. $j \in \mathcal{N}$ is given by v_j and $|v_j|\, e^{\mathrm{i}\,\theta_j} = |v_j| \angle \theta_j$, where $|v_j| > 0$ and $\theta_j \in (-\pi, \pi]$. The operator $|\cdot|$ on a set represents the cardinality of that set. The set of households is represented by $\mathcal{H}$.

II. Proposed Control Framework

In this work, a low voltage (LV) feeder-level real-time control scheme is introduced to assign dynamic export limits to households in the grid integration of residential rooftop PV. It is assumed that all the residential customers connected to the feeder own rooftop PV and equipped with smart meters which enable bi-direction communication between end-users and the grid. Further, it is assumed that all the houseowners are interested in exporting PV to the grid. A summarised block diagram of the overall control approach is given in Fig. 1.

According to Fig. 1, the LV feeder-level (FL) controller acts as a hardware device at the LV distribution transformer which is capable of communicating with end-users and also has a built-in cloud platform for computational purposes. As can be seen in step ① in Fig. 1, end-users share 5-min predicted household load consumption data and 5-min predicted household PV generation data with the FL controller at a certain time step. The underlying reasons for the choice of 5-min predicted consumption and generation data are: 1) short-term forecasts, i.e. persistence forecasts, effectively mitigates the effect of uncertainties 2) to align with market dispatch intervals of the Australian Energy Market Operator (AEMO) [12]. In step ②, the FL controller performs a three-phase snapshot load flow in the cloud platform (*Load flow analyser*) based on stored network data and end-user shared consumption and generation data. The outcome of the snapshot load flow determines whether voltage violations exist if end-user demand and generation are scheduled as forecasted for the next 5-mins as shown in step ③. In case of no voltage constraint violations, the FL controller avoids imposing export limits on households and instead allows end-users to export rooftop PV generation at their forecasted values for the next step. However, if the solution to the load flow problem results in voltage constraint violations at any node $k \in \mathcal{N} \backslash \{0\}$ in the network, the FL controller solves a snapshot AC optimal power flow problem (AC-OPF) in the cloud platform (*AC-OPF solver*) to assign dynamic export limits for household PV generation as illustrated in step ④. Thereafter, in step ⑤, the FL controller communicates 5-min household export limits for households via the bi-directional communication infrastructure. Likewise, the aforementioned real-time control approach is repeated every 5-mins for a period of 24-hours.

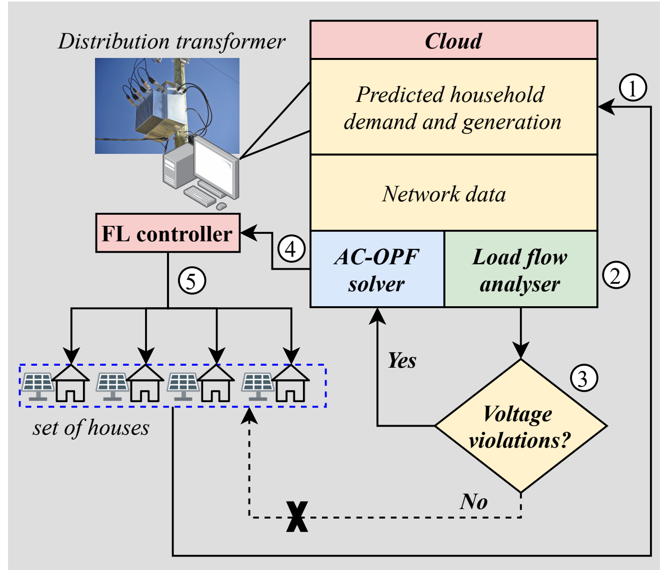

Fig. 1. A summarised block diagram of the proposed LV feeder-level real-time control approach; circled numbers represent the sequence of steps in the overall control process; black cross represents no control action on households.

A. Load flow study

The load flow analysis can be considered as the initial check to determine whether the forecasted PV generation is allowed to export to the grid at the next step without violating network constraints. Since short-term predictions, i.e., 5-min predictions are considered, it is assumed that perfect predictions of household demand and PV generation are available at the FL controller.

Based on 5-min predictions, a three-phase snapshot load flow is carried out by the *Load flow analyser* in the cloud with the help of stored network data to determine the presence of voltage violations if uncontrolled PV generation is allowed at the next sampling instant. If uncontrolled generation of PV leads to voltage violations at the next step, an optimal power flow problem is solved to determine active power export limits for households.

B. AC Optimal power flow (AC-OPF) problem

In this work, an equivalent single-phase model of a three-phase balanced network is considered to formulate the AC-OPF problem at the FL controller. However, the proposed approach can be further extended to account for network unbalance as discussed in [13].

The cost function of the AC-OPF problem at the FL controller is considered to be the sum of squared deviation of active power generation of PV from its forecasted value. This can be mathematically expressed as:

$$\mathrm{F} = \sum_{h\in\mathcal{H}} \left(p_h^{\mathrm{PV}} - \widehat{p_h^{\mathrm{PV}}}\right)^2 \tag{1}$$

where the decision variable p_h^{PV} is the controlled active power generation of PV and $\widehat{p_h^{\mathrm{PV}}}$ is the 5-min predicted active power generation of PV for the house h. Considering unity p.f. operation for rooftop PV, the constraints on controlled active power p_h^{PV} and controlled reactive power q_h^{PV} can be expressed as:

$$0 \leq p_h^{\mathrm{PV}} \leq \widehat{p_h^{\mathrm{PV}}} \leq p_h^{\mathrm{PV_{inv}}}, \quad q_h^{\mathrm{PV}} = 0 \qquad \forall\, h \tag{2}$$

where $p_h^{\mathrm{PV_{inv}}}$ is the inverter capacity of rooftop PV in the house h.

Considering household demand to be a fixed P, Q load operating at a specific p.f.,

$$\widehat{q_h^{\mathrm{d}}} = \left(\sqrt{\eta_h^2 - 1}/\eta_h\right) \cdot \widehat{p_h^{\mathrm{d}}} \qquad \forall\, h \tag{3}$$

where $\widehat{p_h^{\mathrm{d}}}$ the 5-min predicted active power consumption for the house h, $\widehat{q_h^{\mathrm{d}}}$ is the 5-min predicted reactive power consumption for the house h and η_h is the overall power factor for the consumption of load in the house h.

Considering the single phase-equivalent of the balanced three-phase power flow model, it is assumed that only a single household is connected to each node except the slack node, i.e. $|\mathcal{H}| = |\mathcal{N}| - 1$. By slightly abusing the notation to represent $p_{h,k}^{(\cdot)}$ by $p_h^{(\cdot)}$ and $q_{h,k}^{(\cdot)}$ by $q_h^{(\cdot)}$, the non-convex power flow equations can be expressed as:

$$\begin{aligned} p_h^{\mathrm{PV}} - \widehat{p_h^{\mathrm{d}}} = |v_k| \sum_{j\in\mathcal{E}} \big(|v_j|\, \mathbf{G}_{kj}\, \cos(\theta_k - \theta_j) \\ + \mathbf{B}_{kj}\, \sin(\theta_k - \theta_j)\big), \quad \forall\, k \in \mathcal{N}\backslash\{0\} \end{aligned} \tag{4}$$

$$\begin{aligned} q_h^{\mathrm{PV}} - \widehat{q_h^{\mathrm{d}}} = |v_k| \sum_{j\in\mathcal{E}} \big(|v_j|\, \mathbf{G}_{kj}\, \sin(\theta_k - \theta_j) \\ - \mathbf{B}_{kj}\, \cos(\theta_k - \theta_j)\big), \quad \forall\, k \in \mathcal{N}\backslash\{0\} \end{aligned} \tag{5}$$

The constraints on the limits of voltage magnitudes and angles on nodes (except the slack node) are given by:

$$\underline{v} \leq |v_k| \leq \overline{v}, \quad \underline{\theta} \leq \theta_k \leq \overline{\theta}, \qquad \forall\, k \in \mathcal{N}\backslash\{0\} \tag{6}$$

where $\underline{v}$ and $\overline{v}$ are the lower and upper voltage magnitudes specified by the DNO; $\underline{\theta}$ and $\overline{\theta}$ are the lower and upper limits on voltage angles. According to the *AS 60038* standard in Australia [3], $\underline{v} = 0.94$ pu and $\overline{v} = 1.1$ pu. In addition to that, $-\pi \leq \theta_k \leq \pi$ is considered.

For the slack node, the voltage magnitude and the angle are assumed to be,

$$|v_0| = 1, \quad \theta_0 = 0 \tag{7}$$

In addition to that, the power injection at the slack node is limited such that,

$$-\,\overline{p}_0 \leq p_0 \leq \overline{p}_0, \quad -\overline{q}_0 \leq q_0 \leq \overline{q}_0 \tag{8}$$

where p_0 and q_0 are the controlled active power and reactive power injection at the slack node respectively. Furthermore, $\overline{p}_0$ and $\overline{q}_0$ represent the maximum allowable active power injection and reactive power injection at the slack node.

Taken together, the non-linear programming (NLP) problem at the FL controller can be expressed as,

$$\underset{p_0,\, q_0,\, p_h^{\mathrm{PV}}}{\text{minimize}} \quad \mathrm{F}$$

$$\text{subject to: (2) - (8)}$$

The solution to the NLP problem described by (1)-(8), p_h^{PV} for all h, determine the active power curtailment limits for rooftop PV at a certain time step.

Thereafter, the FL controller calculates active power export limits for households for the next 5-min interval as,

$$p_h^{\mathrm{exp}} = p_h^{\mathrm{PV}} - \widehat{p_h^{\mathrm{d}}}, \qquad \forall\, h \tag{9}$$

and sends to all the households via the two-way communication infrastructure. Likewise, the FL controller assigns dynamic export limits for households only when 5-min forecasted rooftop PV generation creates voltage limit violations under uncontrolled operation. Hence, dynamic export limits correspond to active power generation limits for rooftop PV. However, in the presence of battery storage and other controllable loads, net export limits of a particular household at each time instant can be determined by solving a typical home energy management problem. This can be achieved by utilising an approach similar to this work, where the FL controller determines net active power export limits in a receding horizon fashion with a prediction horizon >5-mins to accommodate a foreseeable decision making strategy for battery storage and other controllable appliances.

III. Case Study

The proposed feeder-level control scheme is validated on a real LV residential network in Australia, given in Fig. 2. The overhead conductors in pole-to-pole and transformer-to-pole connections are of the type *Moon* [14]. Since network data is only available up to the pole-level for 34 poles (excluding the transformer which is represented by node ①), 3 residential customers distributed equally among the three-phases are assigned at each pole to form a balanced three-phase network. This leads to a total of $34 \times 3 = 102$ customers. It is assumed that each residential customer is connected to a pole via a 16 mm^2 *XLPE* service cable [15] of length 10 m.

The 5-min sampled household consumption profiles and PV generation profiles obtained from [16] are normalised as shown in Fig. 3 and randomly assigned among 102 households

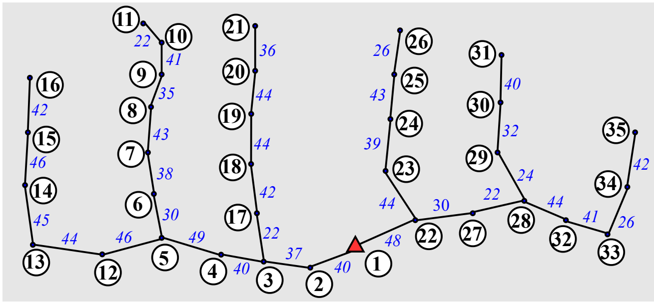

Fig. 2. A real LV residential network in Australia: node 1 (red triangle) represents the LV distribution transformer; blue dots (node 2 to node 35) represent poles; black lines represent overhead conductors; blue italic numbers represent pole-to-pole and transformer-to-pole distances in metres

considering a range of [1-6] kW for household loads and [4.5, 5.5, 6.5, 7.5, 8.5, 9.5] kW for single-phase PV inverters [17]. The power factor of household consumption, $\eta_h \, \forall \, h$ is considered to be 0.95 lagging, after analysing household aggregate consumption data from [16].

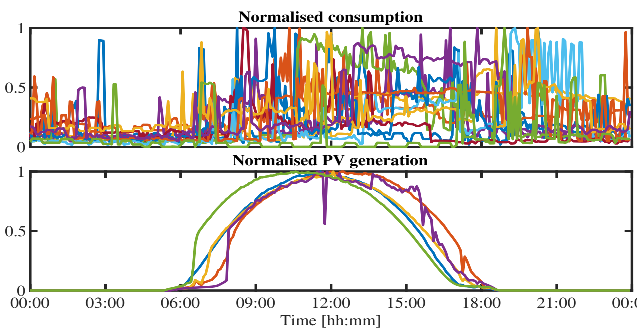

Fig. 3. Normalised power consumption profiles and PV generation profiles for households obtained from [16]

The 5-min snapshot load flow analysis at each sampling instant is performed on the network modelled in *OpenDSS 9.0.2.1* [18] considering node ① to be an infinite bus generator. The line impedances of *Moon* overhead conductors is obtained from [14]; *XLPE* service cables from [15]. Furthermore, the MATLAB-OpenDSS COM interface is utilised to simulate the 5-min snapshot load flow study and to check for voltage constraint violations.

For the AC-OPF problem, a single-phase equivalent of the balanced three-phase model with node ① as an infinite-bus generator is considered. Hence, $|\mathcal{N}| = 35$ and $|\mathcal{H}| = 34$. The AC-OPF problem is modelled in MATLAB with *YALMIP* toolbox [19]. To solve the NLP problem described by (1)-(8), IPOPT v3.12.9 [20] running with linear solver *ma57* is used with parameters tightened such that: *acceptable_tol:* 1e-8 and *acceptable_constr_viol_tol:* 1e-12 to obtain a suboptimal solution of higher accuracy. Furthermore, the simulations are performed on a desktop computer equipped with an Intel(R) Core i7 3.20 GHz CPU and 16 GB RAM memory.

Simulations are performed for three different scenarios:

- *without export limits:* residential customers have no restriction to export the available PV generation at a certain time step
- *with fixed export limits:* the export power is capped at 5 kW limit as in [4] throughout the 24-hour period
- *with dynamic export limits:* time-varying export limits proposed in this work.

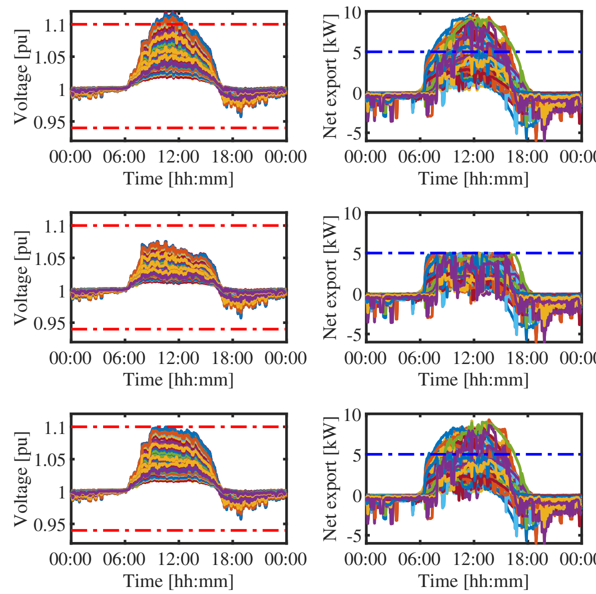

Fig. 4. The household voltage profile and the net active power profile (export power +ve) for the scenarios: 1) *without export limits* (uppermost row); 2) *with fixed 5 kW export limits* (middle row); 3) *with dynamic export limits* (lowermost row). dash-dotted red lines in voltage profiles represent allowable voltage limits; dash-dotted blue lines in net export profiles represent the 5 kW export limit

As can be seen from Fig. 4, the voltage profile exceeds the allowable 1.1 pu limit in certain nodes between 06:00 and 18:00 during the unrestricted operation, i.e., without PV export limits for households. Moving on to the operation under fixed export limits, it is evident from Fig. 4 that imposing a 5 kW export limit eliminates voltage constraint violations observed in the unrestricted scenario and manages the voltage profile within 0.94 pu - 1.1 pu limits throughout the 24-hour period. However, this approach is too conservative as households are not permitted to export PV beyond the 5 kW limit even during periods where exporting beyond 5 kW would not cause voltage limit violations of the LV network. What stands out in Fig. 4 is that, unlike the other two approaches, household voltage profiles are maintained within preferred limits under the maximum utilisation of PV generation in the approach based on dynamic export limits. To explain this, export limits are imposed on households only during the period where the voltage profile exceeds 1.1 pu limit as observed in the unrestricted operation. During this period, export limits are decided at each step by solving a 5-min snapshot AC-OPF problem as in section II-B. For the rest of the period, no export limits are imposed (similar to the unrestricted scenario) as 5-min predictions of demand and PV generation will not result in voltage limit violations. This is clearly observed in the voltage profile of the proposed approach, where voltage constraints are more or less binding at the upper-limit (1.1 pu) around 12:00 whereby snapshot AC-OPF problems are solved to mitigate voltage limit violations.

The average utilisation of the total available PV generation at a certain time step can be expressed as, $\text{util} = \left(\sum_h p_h^{\text{PV}} / \sum_h p_h^{\widehat{\text{PV}}}\right) \times 100\%$. Fig. 5 compares the average utilisation (util) of the available PV generation of the three approaches from 06:25 to 16:30. It is obvious that the approach without export limits achieve 100% utilisation of the available generation. Further inspection of the other two approaches reveals that the proposed approach outperforms the existing approach based on 5 kW export limits in terms of utilising the available PV generation. This is clearly seen before 09:00 and after around 13:00 where the proposed approach achieves 100% utilisation whereas the existing approach fails to aggregate the total available PV generation.

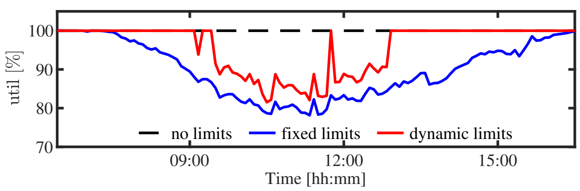

Fig. 5. The average utilisation of the available PV generation under the three scenarios: 1) without export limits; 2) fixed 5 kW export limits; 3) dynamic export limits

A comparison of the total execution time for the three approaches are given in Table I. Considering 5-min intervals for a period of 24-hours, the unrestricted approach and the existing approach with fixed limits only take around 8 sec to solve the load flow problem in $24 \times 60/5 = 288$ steps. On the other hand, the proposed approach takes around 110 sec as it requires solving an AC-OPF problem in multiple steps ($\approx$ 41 steps). Nonetheless, the proposed approach is capable of solving a snapshot AC-OPF problem in less than 5-min before updated forecasts of demand and generation are received at the next step.

TABLE I

A COMPARISON OF THE TOTAL EXECUTION TIME

scenario	**total execution time (sec)**
without export limits	8.82
with 5 kW export limits	8.89
with proposed dynamic export limits	110.56

Note: simulations are performed on a desktop computer equipped with an Intel(R) Core i7 3.20 GHz CPU and 16 GB RAM memory.

IV. Conclusion

In this work, a real-time control approach based on dynamic export limits is introduced to enhance the uptake of rooftop PV in LV distribution grids. In the proposed approach, the LV feeder-level controller utilises a two-stage decision-making process: solving a snapshot load flow problem; solving an AC-OPF problem, to assign 5-min export limits for households while ensuring that network constraints are not violated.

The simulations results validated on a real LV residential network based on real demand and PV generation data reveals that the proposed control scheme has the potential to outperform the current practice where fixed export limits are assigned for households. Furthermore, determining export limits at the LV distribution transformer is computationally inexpensive and scalable as opposed to a DNO-level approach.

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