The Added Value of Coordinating Inverter Control

Peter Lusis, Lachlan L H Andrew, Ariel Liebman, Guido Tack

Abstract—Coordinated photo-voltaic inverter control with a zero-current injection function and centralised curtailment coordination in low-voltage distribution networks is studied. Comparing to autonomous droop-control inverters, up to 7% more PV output is utilised at high PV penetration with 50 mm² low-voltage conductors. The hosting capacity could be doubled when the high-impedance network is constrained by the transformer capacity limits. The added value of coordinated control in terms of the utilisation of active power is diminishing with larger conductors and at lower penetration levels. However, even in that case, it is demonstrated that coordinated inverter control prevents inverter cycling and gives additional flexibility for achieving different objectives such as the fairer distribution of PV curtailment and rewarding PV customers for utilising the excess power locally.

Index Terms—distribution, PV curtailment, inverter control, voltage regulation

I. INTRODUCTION

Traditionally, the inverters of photo-voltaic (PV) systems were designed to maximise active power injection into the grid. Such PV inverters, which we will call legacy inverters, lead to voltage quality problems in many low-voltage distribution networks. The risk of greater adverse effects during high PV generation period has been addressed by adopting new inverter standards with grid support functions (GSF). However, the operational challenges due to solar PV has led to areas where distribution service network providers (DNSPs) have to reject new solar PV connections.

Voltage regulation methods, such as off-load tap changers, capacitors, and voltage regulators, were designed for one-way power flow [1]–[3] lacking the fast switching ability required to follow the changes in PV generation output [4]. Upgrading transformers and power lines is capital-intensive project, and replacing power transformers will not solve all of the voltage issues on low-voltage residential networks or long radial feeders [5]. An emerging alternative is to use PV inverters as a non-network alternative for mitigating operational challenges. That is the approach taken here.

Overvoltage is when voltage levels exceed statutory limits posing a risk to damage electric appliances. The first generation of inverters with grid support functions (GSF) use autonomous voltage regulation following a droop curve, which relies solely on local voltage measurements. In the preferred form (Volt/VAr), inverters absorb or inject reactive power [6]–[8]. Increasing inverter reactive power support close to the end of the radial network improves the voltage profile compared to fixed reactive power compensation approach that ignore the size and location of PV inverters [9].

Inverters can also be controlled with active power priority (Volt/Watt). A method to optimally design Volt/Watt droop curve reference points for each inverter was presented in [10], [11]. Inverter active power setpoints for equal power curtailment using Volt/Watt droop curve was implemented in [12], while [13] formulated proportional curtailment with a smoothing term to account for the action of uncontrollable voltage regulators. Both algorithms require manual parameter tuning.

Volt/VAr and Volt/Watt were combined in [14] showing a lower overall PV curtailment in all Hawaiian Electric secondary circuits than either by itself. In high PV penetration scenarios in [15] with Volt/VAr-Volt/Watt yields 0.3-0.63% more generation than with Volt/VAr alone. However, [15] only considered the networks with a small number of customers per distribution transformer. Droop control was shown to be less effective in suburban areas with a large number of customers per distribution transformer in [16].

Decentralised voltage regulation typically leads to suboptimal operation of the network [17], [18]. This raises the question of whether the coordination of the power electronic equipment can provide significant benefit in managing distribution networks in the future. On the one hand, adding coordination increases the costs and complexity of the system. On the other hand, the communication equipment can be shared with tasks such as demand response and coordinated electric vehicle charging, and so will not be an additional expense [19].

Coordinated inverter control involves collecting local voltage, load, and PV output measurements at a central location to calculate inverter setpoints such that network constraints and the operator’s objective are met, and communicates the setpoints back to PV inverters. Improved voltage control through optimally controlling the power dispatch from inverters in response to renewable generation outputs is presented in [20]. With the optimal inverter dispatch (OID) formulation, active and reactive power setpoints (P,Q) are updated continuously with an objective to minimize power curtailment and line losses. Solar PV systems with microinverters can provide additional value as output from each panel can be controlled independently [21]. However, such an approach increases complicity significantly.

OID has been formulated to work with clouds [22], uncertainty in load and PV [17], dynamics in the voltage [23] and a combination of infrequent central control and fast local regulation [24]. A combination of local voltage regulation
with a periodic update of droop curve reference points for unbalanced three-phase four-wire networks was demonstrated in [25], while a hierarchical droop-control model for voltage regulation on reduced communication between the supervisory node and local inverters was demonstrated in [26]. However, the use of any kind of droop curve restricts the operational flexibility as shown in [20], [27], [28], where inverter setpoints were limited only by the inverter capacity and the power factor.

Two inverter control strategies for mitigating sudden changes in load or solar PV output relying on a single-loop $P - Q$ regulation method and double loop control method were demonstrated in [29]. Voltage regulation based on network clustering and two-stage inverter output optimisation was presented in [30], but line losses were ignored; we show that reducing line losses is the biggest benefit of OID.

Autonomous inverter control is the standard inverter-based voltage regulation method today, but, with increasing PV penetration, overvoltage disconnection will occur more often lowering the performance of PV systems, leaving negative voltage impacts on the upstream network stability. Increase in the PV hosting capacity are required, as the distribution of curtailment prevents some customers from experiencing a full share of the available network. In this paper, we formulate a coordinated inverter control model that addresses the challenges with autonomous inverter control, and compare the performance of inverter control methods applied on a 114-node low-voltage distribution network. The aim is to examine under what network topology characteristics the deployment of coordinated control outperforms autonomous inverters.

The remaining paper is structured as follows: The inverter control strategies are defined in Section II and the case study is described in Section III. The numerical results are presented and discussed in Section IV. Final conclusions are provided in Section V.

II. INVERTER CONTROL ALGORITHM

A. Coordinated Inverter Control

Coordinated inverter control gathers customers’ inverter voltages, PV output and load data and computes the optimum active and reactive power setpoints ($P^c$, $Q$) for each inverter. These are then communicated back and implemented by the inverters. The following notation will be used: all nodes are collected in the set $N'$, while $N \subseteq N'$ denotes the network without the slack bus (the secondary side of the distribution transformer). $\mathcal{H} \subset N'$ is the set of nodes with coordinated inverters. Lines are represented as $(n,m) \in \mathcal{L} \subseteq N' \times N'$. Voltages $V$ and currents $I$ are complex; subscripts $h \in \mathcal{H}$ or $t \in \mathcal{T}$ denote quantities pertaining to inverter $h$ or time $t$; $\Re$ and $\Im$ denote the real and imaginary parts; constants beyond our control are written in bold. Old notation is as introduced throughout.

Line active power losses are

$$\rho_h(V) = \sum_{(m,n) \in \mathcal{L}} \Re\{y_{mn}^*\} \left( (\Re\{V_{m,t}\} + \Re\{V_{n,t}\})^2 + (\Im\{V_{m,t}\} + \Im\{V_{n,t}\})^2 \right),$$

(1)

$y_{mn}$ denotes the complex conjugate of admittance between nodes $m$ and $n$. The active power curtailment $P_c^d$ for the set $\mathcal{H}$ of coordinated inverters is

$$\phi_h(P^c) = \sum_{h \in \mathcal{H}} P^c_{h,t}.$$  

(2)

A penalty on voltage violations above the nominal maximum value $V_{\text{max}}$ is defined for large $M$ as

$$\kappa_h(V) = \begin{cases} \sum_{h \in \mathcal{H}} M (V_{h,t} - V_{\text{max}}), & \text{if } V_{h,t} > V_{\text{max}} \\ 0, & \text{otherwise}. \end{cases}$$

(3)

PV curtailment $P_c^d$ is limited by the excess power, calculated as the difference between the available active power on the AC side of the inverter $P_{\text{in}}^d$ and customer load $P_d^d$:

$$0 \leq P_{h,t} - P_d^d, \quad \forall h \in \mathcal{H}.$$  

(4)

The active power injection and reactive power support are bounded by the inverter rated apparent power limits $S$ as

$$(Q_{h,t})^2 \leq S^2_h - (P_{h,t}^c)^2, \quad \forall h \in \mathcal{H}.$$  

(5)

Since our focus is entirely on the inverter operation during high voltage periods, we ignore evening periods and operate inverters only in the lagging mode, hence, $Q \leq 0$. Reactive power support is limited to $Q^{\text{min}} = -0.44 \times S$, following [31]. The nodal voltage balance is approximated by

$$\Re\{V_{n,t}\} = V_{\text{nom}} + \sum_{m:(m,n)\in \mathcal{L} \times \mathcal{N}} \left( X_{mn} (Q_{n,t} - Q_{n,t}^d) + X_{mn} (P_{n,t}^a - P_{n,t}^c) \right), \quad \forall n \in \mathcal{N},$$

(6)

$$\Im\{V_{n,t}\} = \sum_{m:(m,n)\in \mathcal{L} \times \mathcal{N}} \left( X_{mn} (P_{n,t}^a - P_{n,t}^c) - X_{mn} (Q_{n,t} - Q_{n,t}^d) \right), \quad \forall n \in \mathcal{N}. $$

(7)

This linearisation method offers fast convergence properties, as demonstrated in [32]. The real and imaginary parts of the inverse of the admittance matrix are $R_{mn}$ and $X_{mn}$. Active and reactive loads are denoted by $P_d^d, Q_d^d$. We assume that line impedances and network topology are known when solving the quadratically constrained quadratic program (QCQP). Although the likelihood of experiencing overvoltage can be reduced by lowering the secondary side taps on the distribution transformer, that can also lead to undervoltages during the peak demand period. Thus, $V_{\text{nom}}$ is kept at 1 pu. The OID control can now be stated as:

$$\min_{V,P_c} \rho_h(V) + \phi_h(P^c) + \kappa_h(V)$$

subject to (4) - (7).

B. Autonomous Inverter Control

Autonomous inverter control is network-agnostic, in that each inverter utilises only local voltage measurements to determine operational setpoints. We use a combination of Volt/VAr (VV) and Volt/Watt (VW) droop curves (Fig. 2). The active zone of each droop curve is a linear function with fixed reference points. In the simulations each inverter is initially
The slope \( m \) output until the cut-off voltage reactive power support. Voltage/Watt linearly reduces active power mode, hence, voltage regulation is first attempted through power support is reached. \( V_{\text{min}} \) denotes the voltage level at which the maximum reactive power injection \( Q_{\text{min}} \) is needed only for simulations. When operating in Volt/Watt response mode, inverters are operated in reactive power priority and shutting off. An artefact of the simulation is that this would happen simultaneously. To avoid this artefact, we allow only one autonomous inverter \( g \in G \subseteq N \) to disconnect in each period, based on random weighted sampling with larger weights \( w_{g,t} \) assigned to nodes with higher voltages \( V_{g,t} \uparrow \). Without this constraint, the simulations amplify voltage oscillations beyond what is found in a real network. Both rules are overridden if \( V_{g,t} \geq V_{\text{max}} \), which leads to instantaneous disconnection of all inverters \( g \). Inverters remain disconnected for at least \( u^\uparrow \) periods, and will reconnect if the voltage is below \( V_{\text{trip}} \). Again, only one simulated inverter can reconnect at a time based on weighted random sampling with weights \( w_{g,t} \downarrow = (V_{g,t} - V_{\text{nom}})^{-2} \).

The concurrent adjustment of inverter setpoints may lead to unwanted voltage oscillations as demonstrated in [33]. We address this issue by applying a low-pass filter \( Q_{\text{pu}} = (1 - \Delta T/\tau_{\text{pu}})Q_{\text{pu},t-1} + (\Delta T/\tau_{\text{pu}})Q_{\text{pu},t} \) with a time constant \( \tau_{\text{pu}} \), which we recommend to be implemented in the actual network, while one-at-a-time rule is needed only for simulations. When operating in Volt/Watt response mode, \( Q_{\text{pu}} = Q_{\text{min,pu}} \). Converting to base units, this gives \( Q_{g,t} = Q_{g,t}^\text{pu}S_g \). Similarly, the active power injection in \( pu \) is given by \( P_{\text{pu}} \) with the filter \( P_{\text{pu}} = (1 - \Delta T/\tau_{\text{pu}})P_{\text{pu},t-1} + (\Delta T/\tau_{\text{pu}})P_{\text{pu},t} \).

Then, the injected active power \( P_{\text{inj}} \) operating in the Volt/Watt mode can be calculated as

\[
P_{g,t} = \min\left\{ \sqrt{S_g^2 - Q_{g,t}^2}, P_{\text{pu},g,t} + P_{\text{pu},t} \right\} u_{g,t} \tag{19}
\]

C. Modelling Legacy Inverters

Legacy inverters located on nodes \( f \in F \subseteq N \) can operate only at unity power factor. In the periods of high voltages, the trip conditions of legacy inverters are governed using the same \( V_{\text{trip}} \), \( V_{\text{max}} \) and \( u^\uparrow \), \( u^\downarrow \) rules as the autonomous inverters. The injected active power \( P_{\text{inj}} \) from legacy inverters is

\[
P_{\text{inj},f,t} = \begin{cases} P_{f,t}^\text{pu} & \text{if } u_{f,t} = 1 \\ 0 & \text{otherwise} \end{cases} \tag{20}
\]

where \( u_{f,t} \) represents the inverter ON/OFF status.

\[ P_{\text{inj}} = \begin{cases} \frac{P_{\text{pu}}}{V_{g,t}} & \text{if } u_{g,t} = 1 \\ 0 & \text{otherwise} \end{cases} \tag{21}\]
III. ANALYSIS FRAMEWORK
A. Evaluation Criteria & Scenario Generation

This paper aims to quantify the added benefits from coordinated inverter control in terms of the number of systems that can be accommodated, energy fed back to the grid, transient overvoltage, wear and tear on inverters, and fairness between payments to customers at different locations. The likelihood of experiencing operational issues due to the presence of solar PV depends on the aggregated capacity of solar PV and the location of each PV system [34], [35]. We characterize the number of systems that can be supported by a pair of values. The lower bound of PV hosting capacity $cap_{\text{min}}$ is defined as the lowest PV customer penetration level such that in at least one scenario some customers experience PV curtailment. The upper bound $cap_{\text{max}}$ is the smallest penetration level such that curtailment is inevitable in all scenarios. That is,

$$cap_{\text{min}} = \min \{ x : (\exists i : |J_{i}|/|N| \leq x), \forall t : P_{i,t}^c > 0 \}$$

$$cap_{\text{max}} = \min \{ x : (\forall i : |J_{i}|/|N| \geq x), \forall t : P_{i,t}^c > 0 \}$$

where the location scenarios constitute the set $S$, and in each case $i \in S$, $J_{i} \subseteq N$ is the set of nodes $j$ with solar PV systems (for all inverter control methods).

To capture the effect of non-uniformity in the PV penetration, two PV deployment scenarios represent the cases where PV systems are clustered around the points of the minimum and maximum effective impedance $Z$ from the distribution transformer. Another 18 PV deployment scenarios were generated at each customer penetration level by applying repeated random sampling to simulate customers independently attaining PV systems.

The utilised active power is

$$\sum_{t \in T} P_{t}^{\text{util}} = \sum_{t \in T} P_{t}^{\text{ev}} - \sum_{t \in T} P_{t}^{c} - \sum_{t \in T} \rho(t)(V),$$

subtracting active power curtailment $\sum_{t \in T} P_{t}^{c}$ and line losses $\sum_{t \in T} \rho(t)(V)$ from the available PV output. An argument for deploying coordinated inverter control would be a significant reduction in PV curtailment, line losses or both, to justify additional costs related to enabling and maintaining communication infrastucture between the inverters and the central node. The network operation for a summer day is simulated using each inverter control mode at 20 discrete customer penetration levels between 5 and 100% in increments of 5%. The inverter control algorithms are available on GitHub.

B. Network Topology

The analysis described in the previous section is applied to the 114-node semi-urban low-voltage network of [56]. It is a three-phase balanced circuit connected to a 20 kV/400 V 400 kVA transformer. The size of solar PV systems is 6kWP, corresponding to an average rooftop PV system in Australia installed to date. The use of uniform nameplate capacity for all PV systems can be justified by implementing a number of random distributions of PV systems across the network. This was derated by 17% to account for reduced PV output below the rated capacity due to factors such as soiling of the panels, shading and ageing, giving a maximum PV output of 5 kW at the AC side of the inverter. The inverter reactive power limit is set to 0.44 lagging of the inverter kVA capacity. This is equivalent to sinking 2.65 kVAR, given a 6 kVA inverter used in this study. Filters (16) and (18) use $\tau^V = 1.75 \text{s}$, $\tau^W = 3 \text{s}$ and $\Delta T = 90 \text{s}$.

Half-hourly household active power consumption from [37] was interpolated to 30-second intervals using cubic splines. Data from the $i$th household, $i = 1, \ldots, 30$ was allocated to our nodes with numbers $i \ mod \ 30$. Simulations run from 8 am to 7.30 pm. Outside these hours, none of the inverter overvoltage response modes was triggered, even at 100% penetration. The average load per household $P^d$ within this period is 0.77 kW with variance of 0.27 kW. Reactive power demand $Q^d$ is fixed at 0.328 $P^d$, giving a constant power factor of 0.95 leading.

Autonomous inverter control settings are standardised within a DNSP network area, often across multiple states or jurisdictions. However, low-voltage networks vary significantly with respect to the type of customers, topology, and other variables. Since coordinated inverter control entails additional implementation and operational costs, one would expect to deploy it when network hosting capacity or utilised power can be increased.

The type and size of conductors installed in the low-voltage network may significantly affect the operation of coordinated and autonomous inverter control. To study this effect, we test autonomous and coordinated inverter control on six commonly installed low-voltage overhead and underground cables. The cable specs are given in Table I.

IV. SIMULATION RESULTS
A. Utilised PV output and hosting capacity

The first study varies customer PV penetration levels with 50 mm$^2$ and 185 mm$^2$ conductors for each inverter control model (Fig. 3). The difference in the utilised PV output between the best and worst case of PV location exceeds 20% at 3 kWp/customer with 50 mm$^2$ conductors. At a higher penetration level, the location-dependent variation in the utilised PV output shrinks and converges to a single point, as there is no variation in PV locations. The lower bound corresponds to a case when PV systems are clustered at the end of the line further from the transformer, resulting in PV curtailment induced by overvoltages at much lower penetration levels.

Coordinated inverter control is superior at all penetration levels utilising up to 7% more energy than autonomous control.

| Name  | Area [m$^2$] | Max I [A] | R [\Omega/km] | X [\Omega/km] |
|-------|-------------|-----------|---------------|--------------|
| OH50  | 3x50        | 150       | 0.65          | 0.1          |
| OH120 | 3x120       | 266       | 0.253         | 0.1          |
| OH150 | 3x150       | 305       | 0.2           | 0.1          |
| OH185 | 3x185       | 350       | 0.164         | 0.09         |
| UG95  | 3x95        | 255       | 0.39          | 0.075        |
| UG240 | 3x240       | 420       | 0.14          | 0.08         |
coordinated inverter control explicitly maximises PV output in the Volt/VAr and Volt/Watt response mode. In contrast, an increased reactive power demand when inverters operate higher than with autonomous inverters (Fig. 4). This is due to conductors. At 90% penetration line losses are multifold proportional to PV penetration levels with 50mm² conductors. The utilisation rate accounts for PV curtailment and line losses that would occur compared to a scenario without solar PV systems. PV penetration is expressed in kWp/customer with 100% corresponding to each customer owning a 6kWp PV system. The solid lines illustrate the highest and lowest PV curtailment recorded at any PV location scenario considering 50 mm² conductors; the dashed lines correspond to a case with 185 mm² conductors. The average PV curtailment of all PV location scenarios is shown with the dotted lines. The bottom figure shows the PV hosting capacity range with 50 mm² cables (the bars on left) and 185 mm² conductors (the bars on right) for each inverter control model. Coordinated inverter control prevent PV curtailment in the scenario with larger cables.

with 50mm² conductors (Fig. 5). This margin diminished for the case with larger cables when a fewer overvoltages are observed. Coordinated inverters also always performs as good as legacy inverters that were designed to maximise PV output injection in the grid.

Below the penetration of 15%, the utilised PV output is above 100%, demonstrating a reduction in line losses compared to a case without solar PV. In addition, when all PV systems are located close to the transformer or at the end of the line, the utilisation rate is up to 5.5% lower. This is an indication that PV clustering leads to higher energy losses as the excess PV output has to be distributed to the parts of the network.

Higher PV hosting capacity was achieved with coordinated inverter control. In fact, the larger cables prevented any curtailment with coordinated inverter control even at maximum penetration. The results suggest that setting a single hosting capacity limit for all networks is a very conservative approach and may unnecessary limit new connections. Therefore, PV hosting capacity should be determined considering the type of dominant conductor characteristics.

Autonomous inverters yields lower PV curtailment than coordinated inverter control when applied to the 50 mm² conductors. At 90% penetration line losses are multifold higher than with autonomous inverters (Fig. 4). This is due to an increased reactive power demand When inverters operate in the Volt/VAr and Volt/Watt response mode. In contrast, coordinated inverter control explicitly maximises PV output injected in the grid subject to the voltage constraints. The optimum setpoints returned to the coordinated inverters show that lower overall energy losses can be achieved by using little to no reactive power support, as the additional energy injected by PV inverters would be offset through increased line losses. The lower line losses at the middle of the day when many inverters follow the governing tripping conditions and shut off reducing the total power flow in the network.

B. Distribution transformer loading

Another factor limiting PV hosting capacity is distribution transformer loading. In a network without solar PV systems, the highest apparent power occurs when power flows from the grid, and so this peak decreases as PV penetration increases (Fig. 5). However, from around 15% penetration, the peak transformer loading occurs when PV output is exported to the grid. Also, the maximum apparent power does not dip to zero at the point when this reversal occurs, since it is the maximum over different times of day.

As shown earlier, the implementation of coordinated inverter control in a low impedance network results in higher utilised power exports than autonomous inverters. Thus, the higher apparent power flow through the transformer with autonomous inverter control in Fig. 5(a) is associated with an increase in reactive power demand. For example, if the low voltage network was connected to a 200 kVA transformer, the maximum hosting capacity with autonomous inverters would be 3.5 kWp/customer at most to prevent overloading, while the 200 kVA limit is not breached even at 100% penetration of 6 kWp PV systems under coordinated inverter control. Although reactive power support would lower voltages on the PV nodes, it is not used since the additional real power injection would be offset by higher line losses.

With the 185 mm² conductors, the difference in power flow occurs at 3.8 kWp/customer (Fig. 5b), when the Volt/VAr response mode is triggered increasing reactive power demand. Above 4 kWp/customer, voltages reach the 10-min voltage tripping levels when legacy inverters shut off due to overvoltage reducing the apparent power flow.

C. The impact of conductor size

The results of reactive power support with autonomous and coordinated inverter control for six different cable sizes are shown in Figs. 6(a) and 6(b). With autonomous inverter
control, reactive power support increases proportionally to changes in the cable size and penetration levels. Larger line impedance leads to overvoltages at much lower PV output levels increasing the number of the time periods over the day when inverters are required to operate in Volt/VAr and Volt/Watt response modes.

Coordinated inverter control demonstrates that reactive power support is the most effective when applied to the 120 mm$^2$ conductors rather than the biggest or smallest cables. As previously shown, smaller cables tend to contribute to higher line losses, and so reactive power support has limited capability to minimise the objective value. In contrast, large conductors do not cause overvoltages preventing the need for reactive power support. These results suggest that coordinated inverter control deployed on a network with small conductors could prevent the excess reactive power demand occurring with autonomous inverters. When reactive power demand can be compensated using, for example, capacitors, or when the goal is to maximise the customer benefit, it is more effective to implement coordinated inverter control in the network with medium-size conductor where it maximises the use of ‘freely’ available reactive power.

Figure 7(a) illustrates the difference in the amount of PV curtailment between autonomous and coordinated inverter control. It further supports the finding that the medium-cable size is more effective as coordinated inverter control results in less PV curtailment for the customers. With the 50 and 95 mm$^2$ conductors, coordinated inverter control curtails slightly less at penetration levels between 15-30% due to a higher PV hosting capacity. At higher penetration levels, the difference in curtailment flips, and coordinated inverter control curtails more PV output than autonomous inverters in order to minimise line losses. This effect can also be seen in Fig. 7(b) which illustrates the net difference in lines losses.

A minimal to no difference in line losses with the 120 and 150 mm$^2$ cables show the effect of higher reactive power demand with autonomous inverter control being offset by coordinated control exporting more active power. Taking a larger cable size leads to fewer voltage problems, thus the difference between control methods become less obvious, although coordinated inverter control dominates at all penetration levels.

D. Fairness

Coordinated inverter control maintains voltage levels below the 10-minute threshold level, preventing inverter tripping. This increases customers’ solar PV output and inverter lifetime compared to autonomous and legacy inverters which disconnect multiple times a day (Fig. 8(a)). Autonomous inverters experience fewer disconnection cases than legacy inverters for most PV systems. Those exceptions occur when legacy inverters remain disconnected for extended time periods as the reconnecting conditions are not fulfilled. Consequently, legacy inverters inject less PV output for those customers than with autonomous inverters.

All inverter control options will reduce more power from the customers further from the transformer. However, coordinated inverter control, as formulated in (8), leads to a much
higher variance of curtailment among customers. Some of the customers see up to 20% higher curtailment than with autonomous inverters, while others don’t experience any curtailment (Fig. 8(b)). Fortunately, coordinated control has the flexibility to optimize different objectives, including objectives that encourage fairness. Such a scheme will now be investigated.

The distribution of curtailment among solar PV owners for a given time instance is illustrated in Fig. 9. Coordinated inverter control \( P_{opt} \) targets the customers further from the distribution transformer in order to minimize line losses. A special case of coordinated inverter control is added to demonstrate that it is possible to alter the distribution of curtailment by adding a fairness objective \( 24 \) to the objective of \( 8 \). Its sole purpose is to redistribute curtailment across the customers with coordinated inverters reducing the lost PV output by any individual customer. The fairness objective attempts to minimize the variance of the curtailment of excess power. It is calculated as a ratio between the curtailed power \( P_c^h \) for each PV customer \( h \) and the net customer excess output \( (P_{av}^h - P_d^h) \). First, this approach ensures that all customers can meet their own demand. Second, it also rewards customers with less curtailment when shifting their load to the periods with excess solar generation.

\[
\alpha \nu_f(P^c) = \alpha \sum_{h \in H} \left( \frac{P_c^h}{P_{av}^h - P_d^h} - \frac{1}{|H|} \sum_{l \in H} \frac{P_c^l}{P_{av}^l - P_d^l} \right)^2 \quad (24)
\]

A weight factor \( \alpha \) is added to control the distribution of energy curtailed occurring along the power line. A small \( \alpha \) value between 1 to 10 can reduce unfair distribution by curtailing less from any individual system and redistribute the curtailment to other households, while yielding lower overall losses than autonomous inverters. The impact of different \( \alpha \) values on line losses and PV curtailment is summarised in Fig. 10. For \( \alpha > 10 \), there is a noticeable increase in line losses as the PV systems at the end of the line push more power back into the grid towards the transformer.

When PV installation capacities vary, it is also possible to curtail so that the absolute curtailment in watts is shared fairly equally, or the generation of those curtailed is equal, or the fractional curtailment is equal. Any notion of fairness can be implemented (and traded off against performance). The goal is simply to achieve fairness towards the customers while delivering lower overall losses than currently deployed autonomous inverter control.

The results here suggest that fair curtailment may incur high energy costs. Since the only reason we need fairness is for fair payment, we may not need to pay people proportional to what they actually produce. Because coordinated control knows the curtailment of each user, it can pay the users in proportion to the amount of electricity they would have generated had they not been curtailed, while still generating electricity in the most efficient manner. Either way, coordination of inverter control is instrumental in ensuring fairness.

V. CONCLUSIONS

This paper has shown that coordinated inverter control provides only a modest improvement (up to 7%) in the amount of energy fed back to the grid, relative to the autonomous Volt/VAr and Volt/Watt control. However, coordinated control can more than double PV hosting capacity when the network without dedicated reactive power support devices is constrained by transformer capacity limits. The highest reduction in overall energy losses was achieved with the smaller 50 and 95 mm\(^2\) conductors, despite a higher curtailment with coordinated inverter control. This demonstrates the need to account for line losses and conductor size when assessing benefits of different inverter control methods.

We showed that coordinated inverter control can be formulated so that it prevents inverter cycling, thus reducing wear and tear and eliminating voltage oscillations. It also provides a guarantee that even the customers at the end of the radial network will be able to use the available output to meet their own demand. The fairness of curtailment distribution can be improved among the customers at the cost of higher overall losses.
energy losses. More importantly, coordinated control allows curtailment to be known by the distributor, meaning optimal energy losses. More importantly, coordinated control allows accordance to the Australian DNSPs Technical Standard [31].

A. Inverter reference setpoints

Inverter Volt/VAr and Volt/Watt drop curves and legacy inverter operational setpoints, given in Table II, are in accordance to the Australian DNSPs Technical Standard [31]. Coordinated inverter control operates below $V_{\text{trip}}^\text{up}$ in the non-export mode at worst.

### References

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