

# Distributed Convex Optimization-Based Control for Distribution Power Loss Minimization of Islanded Three-Phase AC Microgrids

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**Abstract**—In this paper, the distribution power loss of islanded three-phase AC microgrids comprising both line loss and power converter loss is modelled as a quadratic function of current allocation coefficients, which is a convex function with constraints. Using the on-line convex optimization theory, a distributed gradient descent algorithm is adopted for searching the optimal current allocation coefficients of distributed energy resources (DERs) for distribution loss minimization. By adopting the average reactive power sharing scheme, the proposed control strategy is can obtain the optimal power allocation coefficients for minimizing the distribution power loss of AC microgrids in real time. Then, an improved adaptive droop control strategy is proposed to allocate output active power and reactive power of DERs for achieving the given current-sharing rate. In this way, the real-time efficiency optimization control of AC microgrid can be realized, regardless of line resistance and load variations. The effectiveness of the proposed control strategy is validated by simulation-based case studies.

**Index Terms**—Convex optimization, AC microgrid, distributed energy resource (DER), distribution loss, Lagrange multiplier.

## I. INTRODUCTION

In modern smart grids, reducing power loss plays an important role in reducing carbon emissions and mitigating the global greenhouse effect. Since the heat generated is less, the heat that must be cooled is less [1]-[3], so energy saving can further save the cost and energy for the cooling system. In theory, the node voltage and distribution line resistance matrix can be used to simulate line losses. For these voltage-based models, the best reference voltage [4] and the optimal power flow [5], [6] for each der can be obtained to reduce online power loss. To reduce loss, an offline-optimization method [7] is proposed to find the best operating point of the load shedding machine. However, this offline solution only works under very ideal working conditions, with little or no change in parameters. In fact, line resistance is easily affected by ambient temperature and current levels, and the performance of offline solutions is always sub-optimal. In addition, only the line loss model can be optimized, while the power converter losses aren't considered. Actually, the converter loss may take part of over 50% of the overall distribution loss [8] in dc

microgrid. Therefore, having it taken into consideration in the control scheme would be important in minimizing the distribution power loss.

Converter losses cannot be directly expressed by voltage, while it is a function of output current by DER. In [9], the converter loss is further approximately fitted by a quadratic function of power. Then, the convex optimization is used to allocate the active power and reactive power of each converter. In [10], the proposed weight droop control method cannot easily consider both the converter loss and the line loss, which results in sub-optimal efficiency. In [11] and [12], a dynamic module-dropping strategy is proposed to improve the operation efficiency of paralleled inverters. The number and combination of activated inverters are determined by different load conditions. In [13], the converter loss is further approximately fitted by a function of active power and reactive power. Then, the convex optimization is used to allocate the active power and reactive power of each converter. The proposed centralized approach requires all DGs to communicate with the control center, which is sensitive to disturbances and faults in control centers and increases the system vulnerability.

As analyzed above, both converter loss and line loss are modelled as a quadratic function of the output currents of DER in this paper, which is a convex function. Besides, considering the balance of the current injection and consumption, the proposed distribution power loss model is an equality-constrained convex function. Therefore, the distribution loss minimization can be realized by adaptively adjusting the current coefficients of DER online. By collecting the global information, the optimal current coefficients can be obtained by solving one general Lagrange multiplier function for secondary current sharing control, as proposed in [14]. To increase reliability and efficiency, the distributed control structure requires only neighbor-to-neighbor interaction has been widely investigated. With exchanging information among neighboring units [15], [16], a distributed gradient descent algorithm for convex optimization is proposed for global distribution loss minimization. Furthermore, the proposed strategy is also developed to calculate the optimal allocation coefficients of active power and reactive power based on the general PQ control structure. Simulation results

validate the effectiveness of the proposed control strategy to reduce the distribution power loss of islanded AC microgrids.

## II. DISTRIBUTION LOSS MODELLING OF AC MICROGRID

Fig. 1 shows a typical configuration of an islanded three-phase AC microgrid with  $n$ -parallel inverters (only one phase is plotted). It comprises distributed generation (DG) units, loads, and power electronics interfaces. The wind turbine and solar PV panels serve as clean energy, and loads such as water heater, motor drive system can be directly connected to AC bus. The energy storage system is introduced to compensate power and alleviate bus voltage fluctuations.

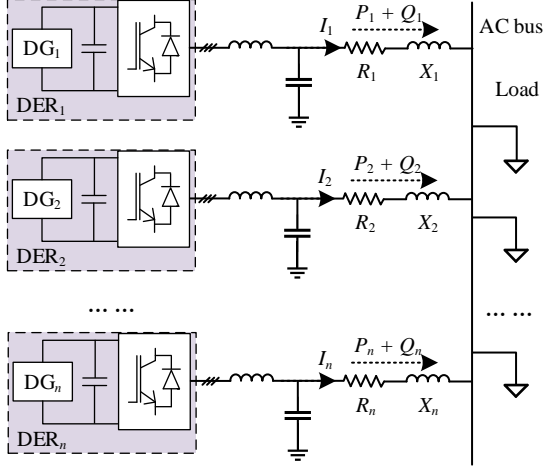


Fig. 1. Configuration of AC microgrid.

The distribution power loss contains two parts, namely the converter loss  $P_{loss}^{conv}$  and the line loss  $P_{loss}^{line}$ . The converter loss includes the average conduction loss of switches and bypass diodes, i.e.,  $P_{conS}$  and  $P_{conD}$ , average switching loss, i.e.,  $P_{sw}$ , average reverse recovery loss of bypass diodes, i.e.,  $P_{rec}$ , and power loss on resistive elements, i.e.,  $P_{res}$ ,

$$P_{loss}^{conv} = P_{conS} + P_{conD} + P_{sw} + P_{rec} + P_{res} \quad (1)$$

According to the analysis in [3], [4], and [7], the converter loss can be simplified as a quadratic function of the output currents of DER as

$$P_{lossi}^{conv} = a_i I_i^2 + b_i |I_i| + c_i \quad (2)$$

where  $a_i > 0$ ,  $b_i > 0$ , and  $c_i > 0$  are the conversion loss coefficients of the  $i$ -th converter;  $I_i$  are the sum of root-mean-square (RMS) values of the three-phase output currents of the  $i$ -th DER. These coefficients can be determined via the curve fitting of the measurements offline. Besides, the distribution line loss can be calculated based on the output currents and the line resistances as  $R_i I_i^2$ , where  $R_i$  indicate the equivalent line resistances in three-phase. Then, the total distribution power loss of the  $i$ -th DER system can be calculated based on

$$P_{lossi} = P_{lossi}^{conv} + P_{lossi}^{line} = R_i I_i^2 + a_i I_i^2 + b_i |I_i| + c_i \quad (3)$$

Based on (3), the distribution power loss of the entire three-phase islanded AC microgrid can be calculated based on

$$P_{loss}(N_i) = \sum_{i=1}^n P_{lossi} \quad (4.1)$$

$$= \sum_{i=1}^n [ (R_i + a_i)(N_i I_{tot})^2 + b_i |N_i I_{tot}| + c_i ] \quad (4.2)$$

where  $N_i$  is the current allocation coefficient of the  $i$ -th DER,  $I_{tot}$  is the sum of all the load currents. Therefore, the sum of RMS values of the three-phase output currents of the  $i$ -th DER, i.e.,  $I_i$ , can be calculated based on  $I_i = N_i I_{tot}$ . According to (4), the distribution power loss of the entire AC microgrid can be regulated by the current allocation coefficients. According to the Kirchhoff's current law, the constraint of the current allocation coefficient  $N_i$  satisfies

$$\sum_{i=1}^n I_i = \sum_{i=1}^n N_i I_{tot} = I_{tot} \Rightarrow g(N_i) = \sum_{i=1}^n N_i = 1 \quad (5)$$

By taking the first-order derivative and second partial derivative of  $P_{loss}(N_i)$  in (4) with respect to the  $i$ -th current allocation coefficient  $N_i$  gives

$$\partial P_{loss}(N_i) / \partial N_i = 2N_i (I_{tot})^2 (R_i + a_i) + b_i |I_{tot}| \geq 0 \quad (6.1)$$

$$\partial^2 P_{loss}(N_i) / \partial N_i^2 = 2(I_{tot})^2 (R_i + a_i) \geq 0 \quad (6.2)$$

The first-order derivative in (6.1) is continuous and differentiable. The second-order partial derivative is non-negative. Thus, the distribution power loss model in (4) is strictly convex. Then, the objective function and constraints of the proposed control strategy can be given as

$$\begin{aligned} & \text{minimize} && J = P_{loss}(N_i) \\ & \text{subject to} && \sum_{i=1}^n (N_i) = 1 \\ & && P_{mini} \leq P_i \leq P_{maxi} \end{aligned} \quad (7)$$

where  $P_{mini}$  and  $P_{maxi}$  are lower and upper bounds of the power generation capacities.

## III. PROPOSED CONTROL STRATEGY

### A. Distributed Gradient Descent Algorithm for Convex Optimization

As discussed above, the efficiency optimization problem is a convex optimization problem with equality constraint. Obviously, the problem (7) is to find an optimal combination of current allocation coefficients that minimizes the total power loss  $P_{loss}(N_i)$ . In this section, we are interested in distributed algorithms for solving (7), where each node is only allowed to communicate with its neighbors and conduct local computation. The communication network can be modeled as a directed graph  $(V, E)$  with node set  $V = \{1, \dots, n\}$  and edge set  $E \subseteq V \times V$ . Each edge  $(i, j)$  is a pair of distinct nodes with defining  $n_i = \{j | (i, j) \in E\}$  as the set of neighbors of node  $i$ . Assume that we have an initial allocation of the current allocation combination  $N(0)$  that satisfies  $\mathbf{1}^T N(0) = 1$ , where  $\mathbf{1}$  is the vector with all components one. Generally, if  $(i, j) \in E$ , the proposed distributed algorithm has the following iterative form:

$$N_i(k+1) = N_i(k) - W_{ii} P'_{lossi}(N_i(k)) - \sum_{j \in n_i} W_{ij} P'_{lossj}(N_j(k)) \quad (8.1)$$

for time sequences  $k = 0, 1$ ,  $W_{ii}$  is the self-weight at node  $i$ , and  $W_{ij}$  is the weight associated with the edge  $(i, j) \in E$ ,  $P'_{lossi}$  and  $P'_{lossj}$  are the gradient of the individual power loss. In other words, at each iteration, each node computes the derivative of its local function, queries the derivative values from its neighbors, and then updates its local variable by a weighted sum of the values of the derivatives. Defining  $W$  as the weight matrix, which is consisted by  $W_{ii}$  and  $W_{ij}$ . The equality constraint can be satisfied with two conditions:  $\mathbf{1}^T W = 0$  and  $W\mathbf{1} = 0$ . By substituting it to (8.1), it obtains

$$N_i(k+1) = N_i(k) - \sum_{j \in \eta_i} W_{ij} [P'_{lossj}(N_j(k)) - P'_{lossi}(N_i(k))] \quad (8.2)$$

Thus, the change in the local variable at each step is given by a weighted sum of the differences between its own derivative value and those of its neighbors. The equation (8) has a simple interpretation: at each iteration, each connected pair of nodes shifts currents from the node with higher marginal loss to the one with lower marginal loss, in proportion to the difference in marginal losses. More algorithm analysis will be given in the full paper.

### B. Improved Adaptive Droop Control for Distribution Power Loss Minimization

In general AC microgrids, the PQ control structure is mostly widely adopted. Hence, the control strategy to obtain the optimal active power and reactive power ratios for the minimization of distribution power loss in islanded three-phase AC microgrids are further proposed in this paper. In the equivalent circuit of the  $i$ -th DER system (as shown in Fig. 2),  $E_i \angle \phi_i$  is the converter open-circuit voltage,  $V_{bus} \angle 0^\circ$  is the common AC bus voltage,  $R_i + jX_i$  is the equivalent line impedance in three-phase.

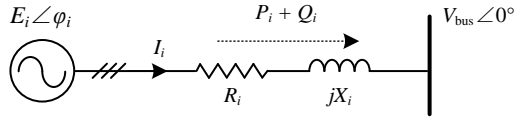


Fig. 2. Equivalent circuit of the  $i$ -th DER system.

For islanded low-voltage AC microgrids, the ratio of resistance over reactance of the line impedance is normally high (e.g.,  $R_i/X_i = 7.7$  [10]). Therefore, the formulas to calculate the active power and reactive power generation in the conventional power systems cannot be used. Based on the circuit laws, the generated active power and reactive power can be approximated as

$$P_i \approx \frac{V_{bus} E_i}{R_i} - \frac{V_{bus}^2}{R_i}, \quad Q_i \approx -\frac{V_{bus} E_i}{R_i} \phi_i \quad (9)$$

Based on (9), the droop control can be implemented as

$$E_{refi} = E_{nom} - m_i P_i, \quad m_i = (E_{max} - E_{min}) / P_{maxi} \quad (10.1)$$

$$\omega_{refi} = \omega_{nom} + n_i Q_i, \quad n_i = (\omega_{max} - \omega_{min}) / Q_{maxi} \quad (10.2)$$

where  $\omega_{refi}$  and  $E_{refi}$  are the references of angular frequency and voltage amplitude of the  $i$ -th DER.  $\omega_{nom}$  and  $E_{nom}$  are the nominal angular frequency and voltage amplitude.  $\omega_{max}$  and  $\omega_{min}$  are the maximum and minimum angular frequencies.  $E_{max}$  and  $E_{min}$  are the maximum and minimum voltage amplitudes.  $m_i$  and  $n_i$  are the power rating-dependent droop coefficients.

$Q_{maxi}$  is the maximum reactive power of the  $i$ -th DER.

The output current of the  $i$ -th DER system can be calculated based on

$$I_i = \sqrt{2} \sqrt{P_i^2 + Q_i^2} / E_i = \sqrt{P_i^2 + Q_i^2} / V_i \quad (11)$$

where  $E_i$  and  $V_i$  are the amplitude and RMS phase voltage of  $i$ -th DER. In (11), active power and reactive power are coupled in the output current. Therefore, the optimized current distribution coefficients cannot be directly adopted to derive the optimal allocation coefficients of the active power and reactive power for distribution power loss minimization. Based on (11),

$$(V_i)^2 (N_i I_{tol})^2 = (N_{Pi} P_{tol})^2 + (N_{Qi} Q_{tol})^2 \quad (12.1)$$

where  $P_{tol}$  and  $Q_{tol}$  are the total load active power and reactive power of the AC microgrid.  $N_{Pi}$  and  $N_{Qi}$  are the active power and reactive power allocation coefficients of  $i$ -th DER. To achieve frequency and phase angle synchronization, average reactive power sharing is adopted in this paper as

$$N_{Qi} = 1/n \quad (12.2)$$

where  $n$  is the number of DER in the AC microgrid.

By substituting (12.2) into (12.1), the active power allocation coefficient can be derived as

$$N_{Pi} = \begin{cases} P_{mini} / P_{tol} & P_i < P_{mini} \\ P_{maxi} / P_{tol} & P_i > P_{maxi} \\ \sqrt{(V_i)^2 (N_i I_{tol})^2 - (Q_{tol} / n)^2} / P_{tol} & \text{others} \end{cases} \quad (12.3)$$

where  $P_{mini}$  is the minimum active power of the  $i$ -th DER. Based on the convexity analysis in (6), if the active power of the  $i$ -th DER reaches the limits (i.e.,  $P_{maxi}$  or  $P_{mini}$ ), it can operate at the limited power while the power loss of rest DER systems is still a convex function such that the optimization control strategy in this paper can still be used to minimize the distribution power loss. To ensure accurate power sharing among the DER, a secondary control strategy is adopted. By defining  $x_{Pi} = P_i / N_{Pi}$  and  $x_{Qi} = Q_i / N_{Qi}$ , the power allocation errors can be written as

$$e_{Pi} = \sum_{i \neq j}^n (x_{Pi} - x_{Pj}) \quad (13)$$

$$e_{Qi} = \sum_{i \neq j}^n (x_{Qi} - x_{Qj})$$

Then, the adaptive voltage and frequency compensation can be obtained by proportional-integral (PI) controllers as

$$E_{adpi} = (k_{EPi} + k_{Eli} / s) e_{Pi} \quad (14)$$

$$\omega_{adpi} = (k_{\omega Pi} + k_{\omega li} / s) e_{Qi}$$

where  $k_{EPi}$  and  $k_{Eli}$  are the proportional and integral gains of  $i$ -th voltage compensation controller,  $k_{\omega Pi}$  and  $k_{\omega li}$  are the proportional and integral gains of  $i$ -th frequency compensation controller. By incorporating the adaptive terms (i.e.,  $E_{adpi}$  and  $\omega_{adpi}$ ) into (10), an adaptive droop control can be given as

$$E_{refi} = E_{nom} - m_i P_i + E_{adpi} \quad (15)$$

$$\omega_{refi} = \omega_{nom} + n_i Q_i - \omega_{adpi}$$

The schematic diagram of the proposed control strategy is presented in Fig. 3. The proposed  $P$ - $E$  and  $Q$ - $\omega$  droop control strategy is given in (a), schematic diagram is given in (b).

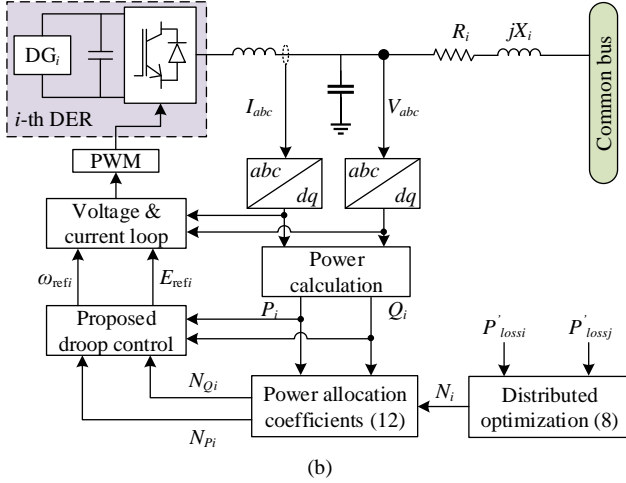
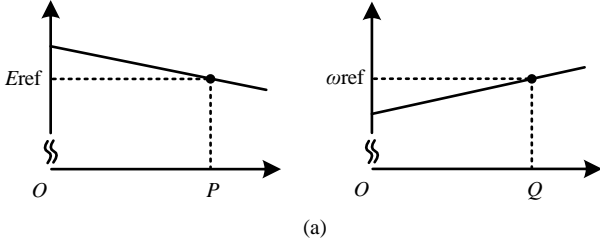


Fig. 3. (a) Proposed droop control, (b) Schematic diagram of the proposed control strategy.

#### IV. CASE STUDIES

Simulation-based case studies are carried out in Matlab/Simulink based on a 220 V AC microgrid with four DER systems being connected in parallel to an AC bus. The communication network of the AC microgrid in simulation is depicted in Fig. 4. Three-phase dc/ac converters are adopted as the grid-connected converters for the DER systems. Without losing the generality, non-dispatchable units and loads are modelled as a current sink, the current of which equals to the total output current of the DER systems to ensure the current balance in the AC microgrid. The main specifications of the AC microgrid are listed in Table I. The parameters of the four DER systems are identical, while the line resistances of the four DER systems are different. The AC bus voltage is allowed to deviate within 5% (i.e.,  $V_{\min}=209$  V and  $V_{\max}=231$  V). The generation capacity of the four DER systems are 4 kW. The switching frequency of the converters and sampling frequency of the controllers is 10 kHz. The algorithm execution period is set as 1 s. The proportional and integral gains of the PI controllers in the dual-loop control are kept constant for all the cases of the simulation. For DER systems 1, 2, 3, 4, the coefficients of their converter loss  $[a, b, c]$  are shown in Table II.

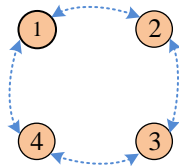


Fig. 4. Communication network of the AC microgrid in simulation.

TABLE I. PARAMETERS OF AC MICROGRIDS

Parameters	Value
Nominal bus voltage ( $E_{\text{nom}}$ )	$220\sqrt{2}$ V
Nominal angular frequency ( $\omega_{\text{nom}}$ )	$100\pi$ rad/s
Total load ( $S$ )	9.7 kW + 3.8 kVar
Generation capacity ( $P_{\text{max}}$ )	4 kW
Line impedance of DER <sub>1</sub> ( $R_1 + jX_1$ )	$0.642 + j0.0415 \Omega$
Line impedance of DER <sub>2</sub> ( $R_2 + jX_2$ )	$1.605 + j0.111 \Omega$
Line impedance of DER <sub>3</sub> ( $R_3 + jX_3$ )	$1.605 + j0.083 \Omega$
Line impedance of DER <sub>4</sub> ( $R_4 + jX_4$ )	$0.642 + j0.0553 \Omega$

TABLE II. CONVERTER LOSS COEFFICIENTS

Converter number	$a_i$	$b_i$	$c_i$
1	1.162	2.960	12.14
2	0.577	1.250	32.14
3	0.277	0.956	44.36
4	1.430	1.403	20.61

#### A. Convexity Verification of Distribution Loss Model

The convexity of the derived distribution power loss model in (6) is initially verified by the simulation. For the AC microgrid with three DER (i.e., DER1, DER2 and DER3, DER1, DER 2 and DER4, DER2, DER3 and DER4), the distribution power loss of the DER systems versus different values of current allocation coefficients are plotted in Fig. 5. The total output current of the three DER systems is 30 A and the sum of the current allocation coefficients for each case is 1. Obviously, the distribution power loss surfaces are convex with only one minimum point in each case.

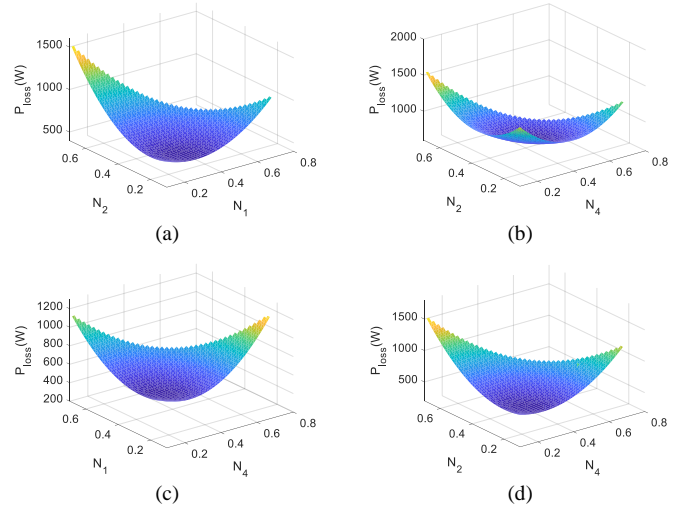


Fig. 5. Distribution loss with three DERs under variation of current allocation coefficients for load currents (a) DER1, DER2 and DER3, (b) DER1, DER2 and DER4, (c) DER1, DER3, and DER4, and (d) DER2, DER3, and DER4.

Furthermore, the distribution loss surfaces of the AC microgrid with four DER systems are plotted in Fig. 6. By fixing the one current allocation coefficient by 0.1, there are two adjustable variables for loss model, which is three-dimensional waveform. In the figures, the distribution loss model is smooth and has only one minimum point. Besides, the proposed loss model maintains the convexity regardless of the load power level or the range of current allocation

coefficients. For more DERs, the model's convexity cannot be graphically illustrated, while it is proven by (6).

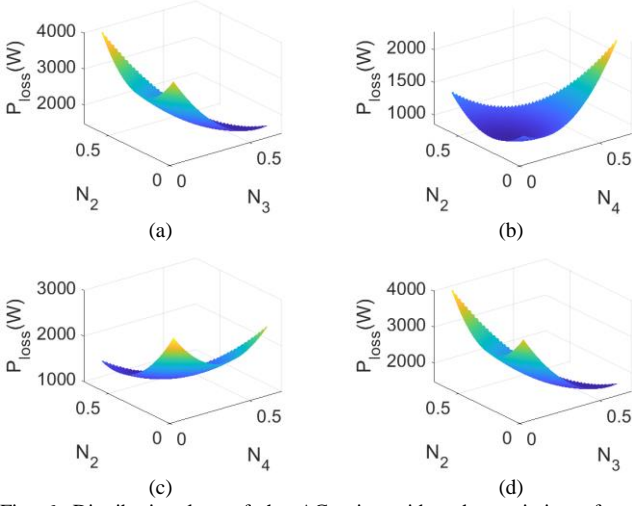


Fig. 6. Distribution loss of the AC microgrid under variation of current allocation coefficients for fixed (a)  $N_1$ , (b)  $N_2$ , (c)  $N_3$ , and (d)  $N_4$ .

### B. Case 1: Method Implementation

Fig. 7 show the waveforms of the voltages, output currents, active powers and reactive powers from the DER to the

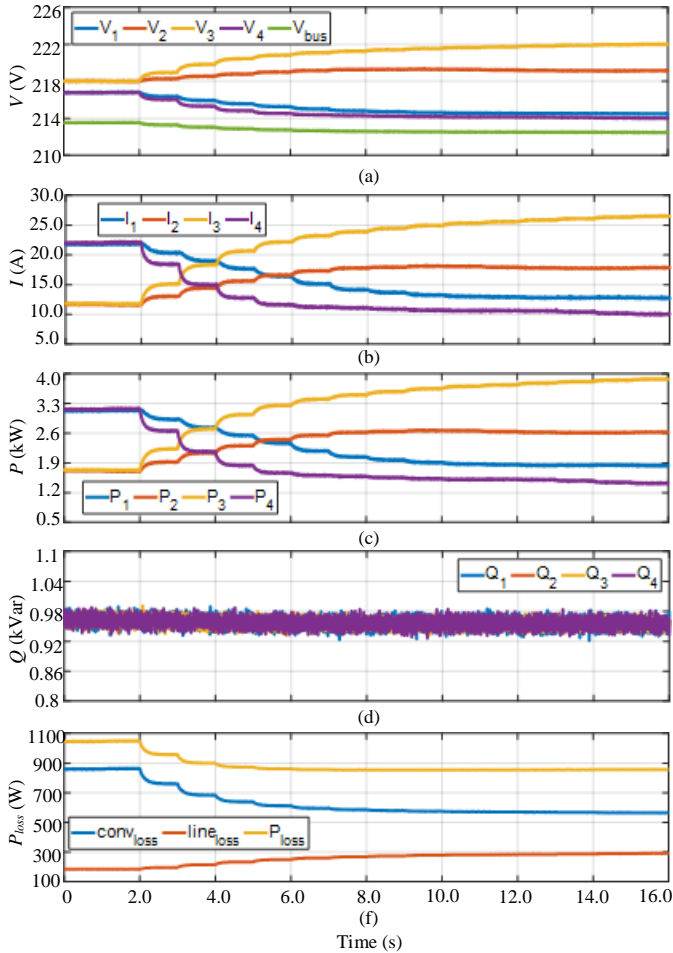


Fig. 7. Case1: (a) voltages, (b) output currents, (c) active powers, (d) reactive powers, and (f) power loss.

microgrid, and the distribution power loss of case 1. The proposed adaptive droop control is adopted for the four DER during the period from 0 to 2 s. It can be seen that the output currents, reactive and active powers of DERs can be allocated by the proportion of  $N_{Q1}: N_{Q2}: N_{Q3}: N_{Q4} = 1: 1: 1: 1$  and  $N_{P1}: N_{P2}: N_{P3}: N_{P4} = 2: 1: 1: 2$ . Without power loss optimization during the period from 0 to 2 s, the distribution power loss is about 1048 W (the corresponding conversion loss is 862 W and the line loss is 186 W). The proposed distributed convex optimization method is adopted at 2s (iteration period is 1s) for the coefficients updating of currents, reactive powers and active powers. During the period from 2 s to 16 s, the distribution loss is reduced step by step with by proposed adaptive droop control and distributed convex optimization. At 16s, the distribution power loss is further decreased to 855 W (the corresponding conversion loss is 564 W and the line loss is 291 W). Meanwhile, the bus voltages and output powers of DERs are within the limitations. Some control results of Case 1 are given in Table III. It is shown that the actual optimal current allocation coefficients are consistent with the theoretical optimal values. Some control results of Case 1 are given in Table III.

TABLE III. CONTROL RESULTS OF CASE 1

Current allocation coefficients	Optimal value	Active power allocation coefficients	Optimal value
$N_1$	0.193	$N_{P1}$	0.187
$N_2$	0.273	$N_{P2}$	0.273
$N_3$	0.389	$N_{P3}$	0.398
$N_4$	0.145	$N_{P4}$	0.142

### C. Case 2: Line Resistance Variation and Output Power Limitation

In case 2, the line resistance of DER<sub>1</sub> and DER<sub>4</sub> ( $R_1$  and  $R_4$ ) is changed to 0.963  $\Omega$  and 1.284  $\Omega$ , respectively. The waveforms of the voltages, output currents, active powers and reactive powers from the DER to the microgrid, and the distribution power loss are shown in Fig. 8. The proposed adaptive droop control is adopted for the four DER during the period from 0 to 2 s. It can be seen that the output currents, reactive and active powers of DERs can be allocated. During the period from 0 s~2 s, the proposed adaptive droop control is applied. The distribution power loss for the conventional droop control is 999W. During the period from 2 s to 16 s, the distribution loss is reduced step by step with by proposed adaptive droop control and distributed convex optimization. With considering the power generation constraints are used, the power loss can be reduced to 878 W. The power generated by DER<sub>3</sub> is limited within the boundary of 4 kW. Some control results of Case 1 are given in Table IV.

TABLE IV. CONTROL RESULTS OF CASE 2

Current allocation coefficients	Optimal value	Active power allocation coefficients	Optimal value
$N_1$	0.181	$N_{P1}$	0.172
$N_2$	0.281	$N_{P2}$	0.279
$N_3$	0.395	$N_{P3}$	0.402
$N_4$	0.143	$N_{P4}$	0.147



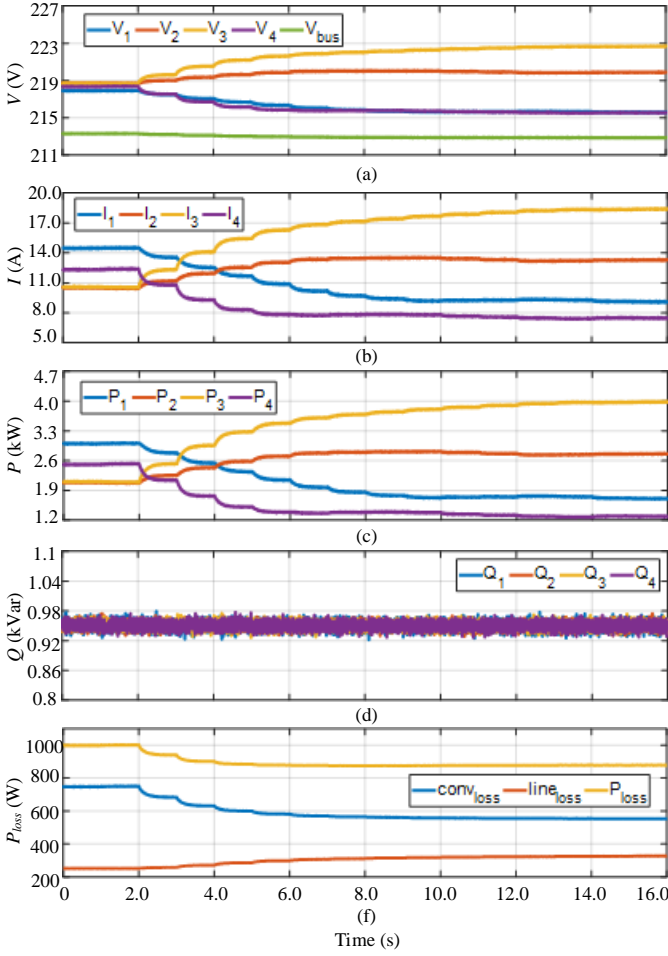


Fig. 8. Case2: (a) voltages, (b) output currents, (c) active powers, (d) reactive powers, and (e) power loss.

Fig. 9 shows the comparisons of the distribution power loss of the AC microgrid being controlled by the droop control, and the proposed control strategy. Compared to the conventional droop control, the proposed control can averagely reduce the distribution power loss about 18.42% in case 1 and 12.11% in case 2.

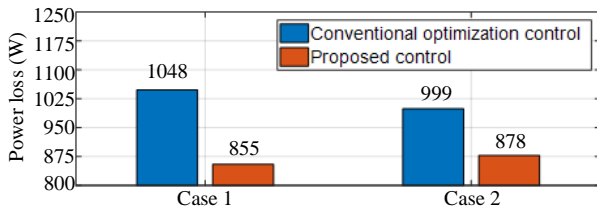


Fig. 9. Comparisons among the conventional droop control, and the proposed control.

## V. CONCLUSIONS

In this paper, distribution power loss of islanded three-phase AC microgrids is modelled as a quadratic function of current distribution coefficients, which is mathematically proved to be a constrained convex function, such that the distributed convex optimization method can be used to obtain the optimal current distribution coefficients in real time. The proposed distributed control strategy is designed to calculate the optimal

power allocation coefficients for the minimization of distribution power loss in AC microgrids. After current allocation coefficient iteration, optimal current and power sharing is achieved. Compared to the conventional droop control and average sharing power control, the proposed control strategy is validated to effectively reduce the distribution power loss of islanded three-phase AC microgrids in simulation-based case studies.

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