

A DER Management System for Distributing Power among Discretely and Continuously Controlled Devices within DER group

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SUMMARY

The integration of distributed energy resource (DER) poses new control challenges to distribution system which are originally comprised mainly of passive loads. To ensure harmonious operation, a software application capable of monitoring and controlling the distribution system in conjunction with the grid operator, must be developed to provide DERs with appropriate set points predetermined by a sophisticated control algorithm subject to grid requests and constraints.

Given DERs with diverse characteristics dispersed widely in distribution system, managing DERs in a collective and hierarchical way becomes increasingly important to address the large quantity and high complexity of DERs. Among the high numbers of DERs, there may be several devices of the same type or termed as DER group in IEC 61968-5, which can be generally categorized into continuously (termed as C-devices) and discretely controlled (termed as D-devices). The continuously controlled DERs can be adjusted continuously in a specific range, while the discretely controlled DERs can only be turned on or off. For this, the control system should not only dispatch the DER groups on higher-level, in light of the overall objectives such as cost minimization, high resilience and reliability, fuel consumption reduction, but also should ensure reasonable power distribution among C-devices and D-devices within the DER group by a lower-level control.

To meet this requirement, a DER management system capable of aggregating DERs as groups and then distributing power within DER group is proposed, which can serve as supplementary measures of utility distribution management system (DMS) or microgrid controller. For active power dispatch, a weighted and queuing (W&Q) method is employed to manage power distribution within DER group. For reactive power distribution, an iterative backtracking method is adopted for switching ON or OFF D-devices while weighted method is used for distribution among C-devices. Theoretical basis which interprets the power distribution as Knapsack problem from the perspective of computer engineering is also established. The proposed control strategy paves ways for developing advanced distribution management system with hierarchical architecture, by firstly generating dispatch command on aggregated DER group level and then distributing power among specific devices on DER device level.

KEYWORDS

DER Management System, Distributed Energy Resource Group, Discretely and Continuously Controlled Devices, Weighted and Queuing Approach, Knapsack Problem, Greedy Algorithm, Iterative Backtracking Algorithm

1. MICROGRID AND DER GROUP COMPOSITION

With common functions specified for inverter-interfaced DERs [1], standardization of grid code, device communication interface and test procedure of DERs [2], there is a growing need of transferring the numerous individual devices with complex settings and DER-type-specific interactions into DER groups with harmonious control actions [3]. One path to reach this objective is DER management system which can aggregate numerous DERs into several groups, thus simplifying the overall control actions. As per the imminent guide IEEE Std. 2030.11 entitled “Distributed Energy Resources Management Systems (DERMS) Functional Specification” and common function specifications for DER group [4], the basic control functions of DER group include real power and reactive power dispatch. Integrating DER group management with higher-level controller such as microgrid controller or DMS will make dispatch of distribution system with numerous DERs compact, modular and scalable.

One architecture of deployment of the DER management system is sketched in Fig. 1 where multiple DER groups are controlled. On the DER group level, the characteristics and interactions of each devices can be ignored but focus only needs to be given to the aggregated group behavior. Taking active power dispatch as an example, a general DER composition is shown in Fig. 1 where controllable devices are categorized into four types: dispatchable generators such as diesel generator and biomass, controllable loads such as continuous demand response (if allowed by contract), discretely sheddable load or load with hybrid control characteristics, energy storage system (ESS), and non-dispatchable generators (wind and photovoltaic (PV)). The conventional control system designed for individual DER dispatch can still be used for power dispatch among DER groups based on certain objectives [5].

On the device level, DER management system capable of aggregation and dissemination, is responsible for power distribution between C-devices and D-devices with general representation given in Fig 2. This is realized by a few control algorithms designed to distribute the total power command given by group level control. In this paper, control algorithms for both active and reactive power distribution between C-devices and D-devices are investigated and tested with controller hardware-in-the-loop approach.

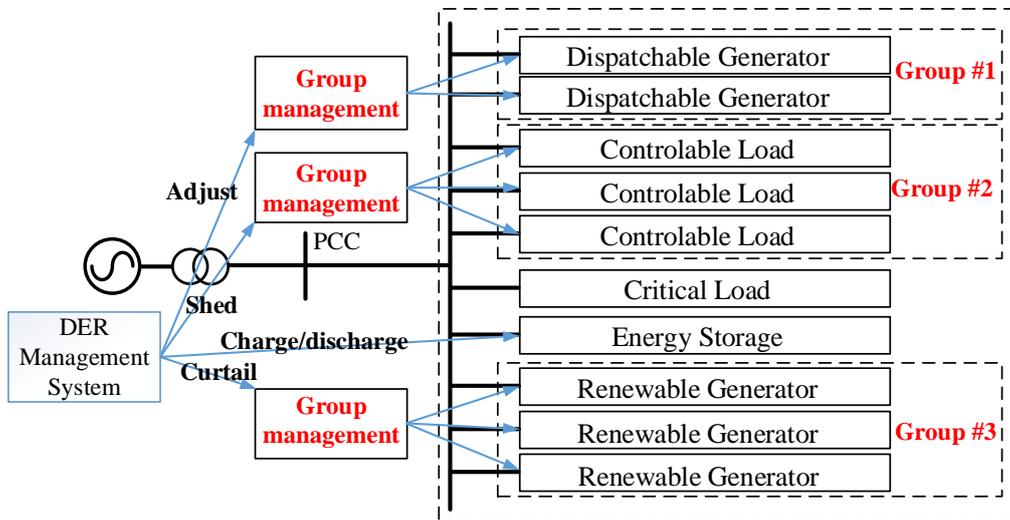


Fig. 1. DER management system for multiple DER groups

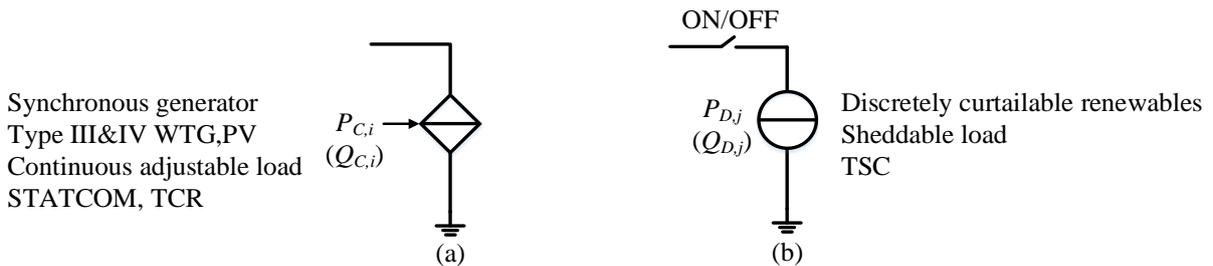


Fig. 2. General illustration of devices within DER group. (a) Continuous controlled. (b) Discretely controlled.

2. ACTIVE POWER DISTRIBUTION

2.1. Problem formulation

The power distribution within DER group should first meet power balance constraint. It is assumed that P_{plan} is the total planned power command for the considered DER group, which is specified on group level by optimization or rule (priority)-based control [5]. Let $P_{Ci,f}$ and $P_{Dj,f}$ be the forecasted power of the i^{th} C-device and the j^{th} D-device, P_{Ci} and P_{Dj} be the practical power of the i^{th} C-device and the j^{th} D-device after control, $P_{Ci,min}$ and $P_{Ci,max}$ be the minimum and maximum power of the i^{th} C-device, the power balance constraint can be formulated by (1) where variable x_i is the adjustment percentage of the i^{th} C-device, y_j is the ON/OFF command of the j^{th} D-device with $y_j=0$ denoting ON and $y_j=1$ denoting OFF.

$$\begin{aligned} \sum_{i=1}^m P_{C,i} + \sum_{j=1}^n P_{D,j} - P_{plan} &= 0 \\ P_{C,i} &= (1-x_i)P_{Ci,f}, P_{D,j} = y_j P_{Dj,f} \\ x_i &\in [P_{Ci,min} / P_{Ci,f}, 1] (\text{for decrease case}) \text{ or } [1, P_{Ci,max} / P_{Ci,f}] (\text{for increase case}) \\ y_j &\in \{0, 1\}, i = 1, 2, \dots, m; j = 1, 2, \dots, n \end{aligned} \quad (1)$$

The power distribution problem is to find x_i and y_j . Given (1) is an indefinite equation, other constraints and objectives should be included to narrow down the solution set. In reference to the principle of power curtailment within wind farm [6] and computer engineering algorithms to solve dispatch problem [7], an algorithm combining weighted and queuing (W&Q) method for power distribution within DER group is proposed to find power command P_{Ci} and P_{Di} . Notice that other algorithms such as dynamic programming or branch and bound method, can also be adopted for power distribution among D-devices, but higher computational capability is required [7].

2.2. Weighted method

For C-devices within DER group, weighted averaging based on certain criteria is employed for continuous power adjustment, as given in (2)-(6) where $P_{C,f} = \sum_{i=1}^m P_{Ci,f}$ and $P_{D,f} = \sum_{j=1}^n P_{Dj,f}$ are the total forecasted active power of C-devices and D-devices. Notice the value of x_i in (2) may exceed the ranges defined in (1). In that case, x_i will take the value at the terminal of the interval while the remaining devices will balance the power mismatch as per the same weighted criterion. In (5), the power margin $P_{marg,i}$ which represents the adjustable power range, is defined as $P_{Ci,min} - P_{Ci,f}$ or $P_{Ci,max} - P_{Ci,f}$, depending on power adjustment direction. A combined consideration of cost and power margin is given by (6) where λ_i is the incremental cost near the operating point $P_{Ci,f}$.

$$(a) \text{ Uniform (or even) distribution: } x_i = (P_{C,f} - P_{plan}) / (m * P_{Ci,f}) \quad (2)$$

$$(b) \text{ Nameplate capacity } (P_{name,i}) \text{ weighted averaging: } x_i = (P_{C,f} - P_{plan}) P_{name,i} / (\sum_{i=1}^m P_{name,i} P_{Ci,f}) \quad (3)$$

$$(c) \text{ Forecasted power } (P_{Ci,f}) \text{ weighted averaging: } x_i = (P_{C,f} - P_{plan}) / \sum_{i=1}^m P_{Ci,f} \quad (4)$$

$$(d) \text{ Capacity-margin } (P_{marg,i}) \text{ weighted averaging: } x_i = (P_{C,f} - P_{plan}) P_{marg,i} / (P_{Ci,f} \sum_{i=1}^m P_{marg,i}) \quad (5)$$

$$(e) \text{ Power-cost ratio weighted averaging: } x_i = (P_{C,f} - P_{plan}) (P_{marg,i} / \lambda_i) / (P_{Ci,f} \sum_{i=1}^m P_{marg,i} / \lambda_i) \quad (6)$$

2.3. Queuing method

For D-devices within DER group, a queuing method is adopted. Combining with weighted method, complete algorithm of the W&Q method to set power command P_{Ci} and P_{Di} of a hybrid DER group with C-devices and D-devices is developed. It is assumed that C-devices are prioritized over D-devices given the lower cost than D-devices ($\lambda_i < \lambda_j$). Objective of the algorithm is to minimize the total number of ON/OFF actions of D-devices ($\sum_{j=1}^n y_j$) while power curtailment of C-devices are weighted with their forecasted power ($P_{Ci,f}$). Procedure of the W&Q algorithm for power curtailment is described below.

Step (1): If $P_{D,f} + \sum_{i=1}^m P_{Ci,min} \leq P_{plan} < P_{D,f} + P_{C,f}$, set $P_{C,i} = \max\{P_{Ci,min}, P_{Ci,f} / P_{C,f} (P_{plan} - P_{D,f})\}$. The distribution ends and no ON/OFF actions of D-devices are needed.

Step (2): If the condition $P_{D,f} + \sum_{i=1}^m P_{Ci,min} \leq P_{plan}$ in (1) does not hold, the strategy is shown as below, by which the D-devices will be tripped off from large to small in a queuing manner to solve the problem (7) which is essentially a combinatorial optimization problem [8].

$$\begin{aligned} \min \quad & \sum_{j=1}^n y_j \\ \text{s.t.} \quad & \sum_{j=1}^n P_{D,j} \geq P_{plan} - \sum_{i=1}^m P_{Ci,min} \\ & P_{D,j} = y_j P_{Dj,f}, y_j \in \{0,1\}, j = 1, 2, \dots, n \end{aligned} \quad (7)$$

- 2.1) Find and trip off the h^{th} D-device that satisfies $P_{Dh,f} = \min\{P_{Dr,f} | P_{Dr,f} > (-P_{plan} + P_{D,f} + \sum_{i=1}^m P_{Ci,min})\}$ and recalculate $P_{D,f}$, then go to 2.3).
- 2.2) If no such D-device exists, find the k^{th} D-device that satisfies $P_{Dk,f} = \max\{P_{Ds,f} | P_{Ds,f} < (-P_{plan} + P_{D,f} + \sum_{i=1}^m P_{Ci,min})\}$. Trip it off and recalculate $P_{D,f}$. If $P_{plan} - P_{D,f} - \sum_{i=1}^m P_{Ci,min} > 0$, return to 2.1); otherwise stop tripping D-devices and go to 2.3).
- 2.3) The total remaining power of C-devices is calculated to be $P_{plan} - P_{D,f}$ where $P_{D,f}$ is the power of D-devices after tripping in 2.1) and 2.2). After 2.3), go to Step (3).

Step (3): For C-devices, the power in the next interval is $P_{Ci,f} = \max\{P_{Ci,min}, P_{Ci,f}/P_{C,f}(P_{plan} - P_{D,f})\}$ based on $P_{Ci,f}$ weighted averaging. After that, the algorithm of W&Q method ends.

The above procedure to solve (7) in W&Q algorithm is quite similar to the greedy algorithm to solve 0-1 Knapsack problem [8]. In the above process, it is assumed that all devices have the same incremental cost which may be different in practical situations. In that case, the power distribution problem will be reformulated as minimizing $\{\sum_{i=1}^m \lambda_i x_i P_{Ci,f} + \sum_{j=1}^n \lambda_j y_j P_{Di,f}\}$ with suboptimal problem changed to minimizing $\sum_{j=1}^n \lambda_j y_j P_{Di,f}$. A greedy algorithm with $\lambda_j P_{Di,f}$ queuing from small to large can be developed.

3. REACTIVE POWER DISTRIBUTION

For reactive power management, DER groups can be separated based on zone-division approach [9], which may be unnecessary for networks covering a small region only. The reactive power distribution within DER group can also be categorized into 0-1 Knapsack problem. However, the priority will be given to D-devices such as thyristor-controlled capacitor (TSC), for their lower incremental cost relative to C-devices such as inverter-interfaced generators. The objective here will be minimizing the use of C-devices for reactive power regulation while avoiding over-compensation by D-devices.

Replacing the symbol “P” with “Q”, removing “f” (the capacity of D-devices are known) and using the same label (i, j, m, n), the power distribution for D-devices can be formulated as (8), which can be interpreted as Container Loading problem and related algorithms can be leveraged [7]. With reactive power compensation for inductive load as an example, iterative backtracking algorithm based on Depth-First Search (DFS) principle is adopted here to determine the ON/OFF action of D-devices, while power of C-devices is weighted by their reactive power capability.

$$\begin{aligned} \max \quad & \sum_{j=1}^n Q_{D,j} z_j \\ \text{s.t.} \quad & \sum_{j=1}^n Q_{D,j} z_j \leq Q_{plan}, \\ & z_j \in \{0,1\}, j = 1, 2, \dots, n \end{aligned} \quad (8)$$

Step (1): If $\min\{Q_{D,j}\} \leq Q_{plan}$ holds, the power distribution is determined by the following two steps.

- 1.1) Iterative backtracking algorithm will be implemented to obtain the ON/OFF commands (z_j) of D-devices. The details of the algorithm can be found in [8] and are not given here for brevity. Calculate the total reactive power of D-devices $Q_D = \sum_{j=1}^n Q_{D,j} z_j$.
- 1.2) Set the total power command for C-devices as $Q_C = \min\{\sum_{i=1}^m Q_{Ci, capmax}, Q_{plan} - Q_D\}$ where Q_D is calculated from (1). $Q_{Ci, capmax}$ is the maximum adjustable capacitive power of C-devices, which can be determined from power capacity of C-devices. For STATCOM, $Q_{Ci, capmax}$ is equal to the inverter capacity. For renewable generators, $Q_{Ci, capmax}$ depends on the output active power and constraints of power factor and reactive power [2]. The reactive power

command of C-devices $Q_{C,i}$ is given by (9) where power margin weighting is considered.

$$Q_{C,i} = Q_C Q_{C_i, capmax} / \sum_{i=1}^m Q_{C_i, capmax} \quad (9)$$

Step (2): If the condition in (1) does not hold, two scenarios are considered.

- 2.1) If $Q_{plan} \leq \sum_{i=1}^m Q_{C_i, capmax}$, all D-devices will be OFF. $Q_{C,i}$ is calculated from 1.2).
- 2.2) If $Q_{plan} > \sum_{i=1}^m Q_{C_i, capmax}$, two sub-scenarios will be further considered.
 - 2.2.1) If $\min\{Q_{D,j}\} - Q_{plan} < \sum_{i=1}^m Q_{C_i, indmax}$, the D-device with reactive power equal to $\min\{Q_{D,j}\}$ will be ON and Q_C is set as $\min\{Q_{D,j}\} - Q_{plan}$. After that, $Q_{C,i}$ will be calculated by (9) with $Q_{C_i, capmax}$ replaced by $Q_{C_i, indmax}$ which represents the maximum adjustable inductive power of C-devices. Notice that reactive power is over-compensated in this case.
 - 2.2.2) If condition in 2.2.1) not rue, power is determined by the following steps.
 - 2.2.2.1) If $\min\{Q_{D,j}\} - Q_{plan} - \sum_{i=1}^m Q_{C_i, indmax} > Q_{plan} - \sum_{i=1}^m Q_{C_i, capmax}$, go to 2.1).
 - 2.2.2.2) If the condition in 2.2.2.1) does not hold, the D-device with reactive power equal to $\min\{Q_{D,j}\}$ will be ON, Q_C is set as $\sum_{i=1}^m Q_{C_i, indmax}$ and power will be distributed as per 2.2.1).

4. IMPLEMENTATION AND CASE STUDIES

4.1. CHIL testing platform

The DER management system for power distribution within DER group is tested with controller-hardware-in-the-loop (CHIL) approach. Simplified model of power network is run on real-time simulator (RTS) while control algorithm is implemented on microcomputer Raspberry Pi. Ethernet connection based on UDP/IP protocol is used for communication between RTS and Raspberry Pi.

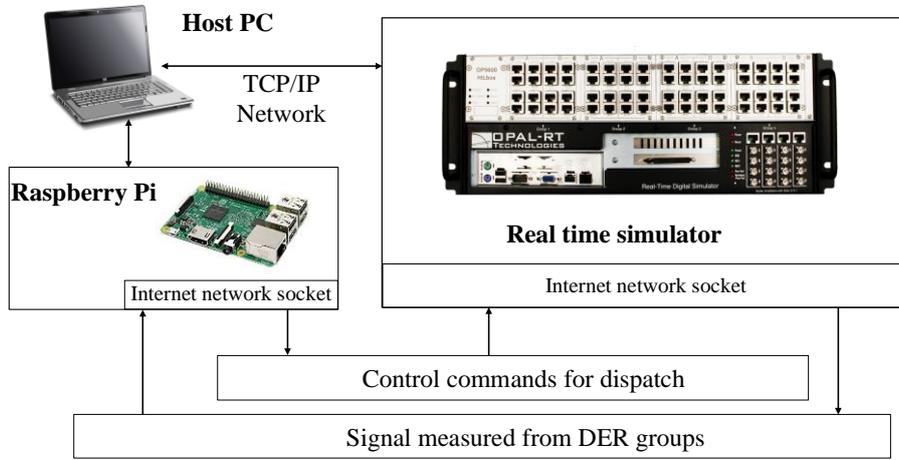


Fig. 3. CHIL test platform of DER management system

4.2. Active power management

To verify the effectiveness of W&Q method for active power management, power shedding for continuously controlled load (C-devices) and discretely controlled load (D-devices) is taken as an example. A simplified DER group model with two C-devices and three D-devices depicted in Fig. 4 is adopted for the test. For convenience, the original power outputs of the devices are assumed constant, as listed in Table. 1. The total shedding command P_{plan} increases incrementally from 0.1 to 1.5 p.u. The simulation results in Fig. 5 show that the practical power can closely track the desired profile. The continuously controlled loads (C#1-2) are shed in proportion to their original power, assuming the cost of C-devices are identical in the case study. The discretely controlled loads (D#1-3) are shed from small to large power in a queuing manner which meets power balance while avoiding unordered actions.

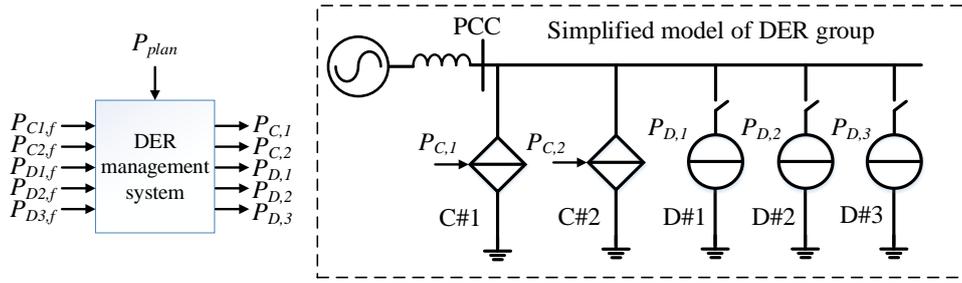


Fig. 4. Simplified model of DER group to test the DER management system

Table 1. Original forecasted load power

Devices	D-devices			C- devices	
	D#1	D#2	D#3	C#1	C#2
Forecasted Active Power	0.3	0.4	0.5	0.6	0.7
Constraints	ON/OFF			$P_{C_i,f} \geq P_{C_i} \geq \max\{P_{C_i,f}/2\}$	

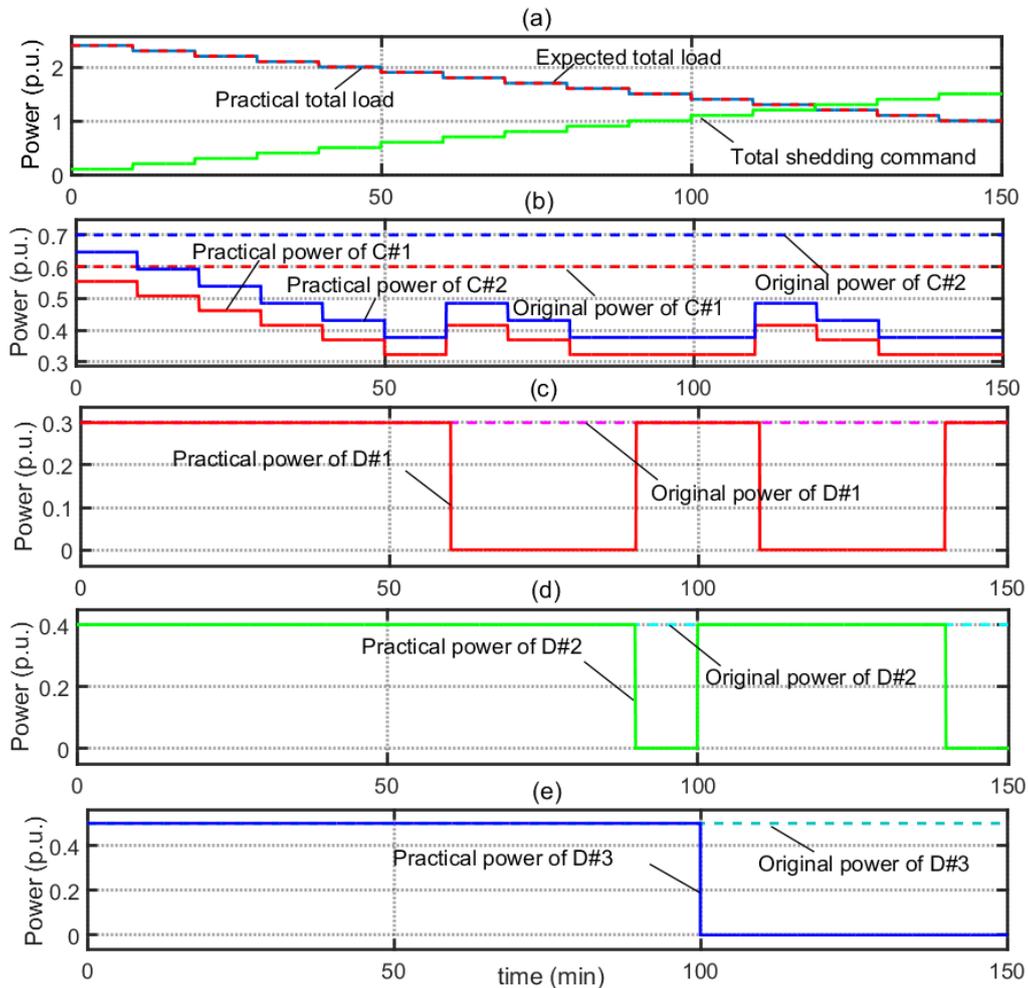


Fig. 5. Simulation results of DER management system for active power load shedding

4.3. Reactive power management

A similar model as in Fig. 4 with active power replaced by reactive power is adopted. The interconnecting impedance between PCC and the slack bus is $0.017+j0.1$ p.u. The power values are listed in Table 2. The total dispatch command to compensate for inductive load increases from 0.1 to 1.5 p.u. The D-devices (D#1-3) can be three TSCs, the first C-device (C#1) can be a PV generator which

has 0.44 p.u. reactive power capability while the second C-device (C#2) can be a STATCOM [2]. The practical reactive power closely matches the inductive load profile, as shown in Fig. 6. The priority of reactive power balance is given to D-devices which are added from small to large power based on iterative backtracking algorithm, while C-devices output power in proportion to their reactive power capability. In contrast to active power dispatch, the number of ON/OFF actions of D-devices is larger. The voltage profile improvement in Fig. 7 demonstrates the effectiveness of reactive power compensation.

Table 2. Parameters of reactive power devices

Assets	D-assets			C-assets	
Label	D#1	D#2	D#3	C#1	C#2
Reactive Power/p.u.	0.3	0.4	0.5	$Q_{c,1}$	$Q_{c,2}$
Constraints	ON/OFF			$Q_{c,1} \in [-0.44, 0.44]$	$Q_{c,2} \in [-1, 1]$

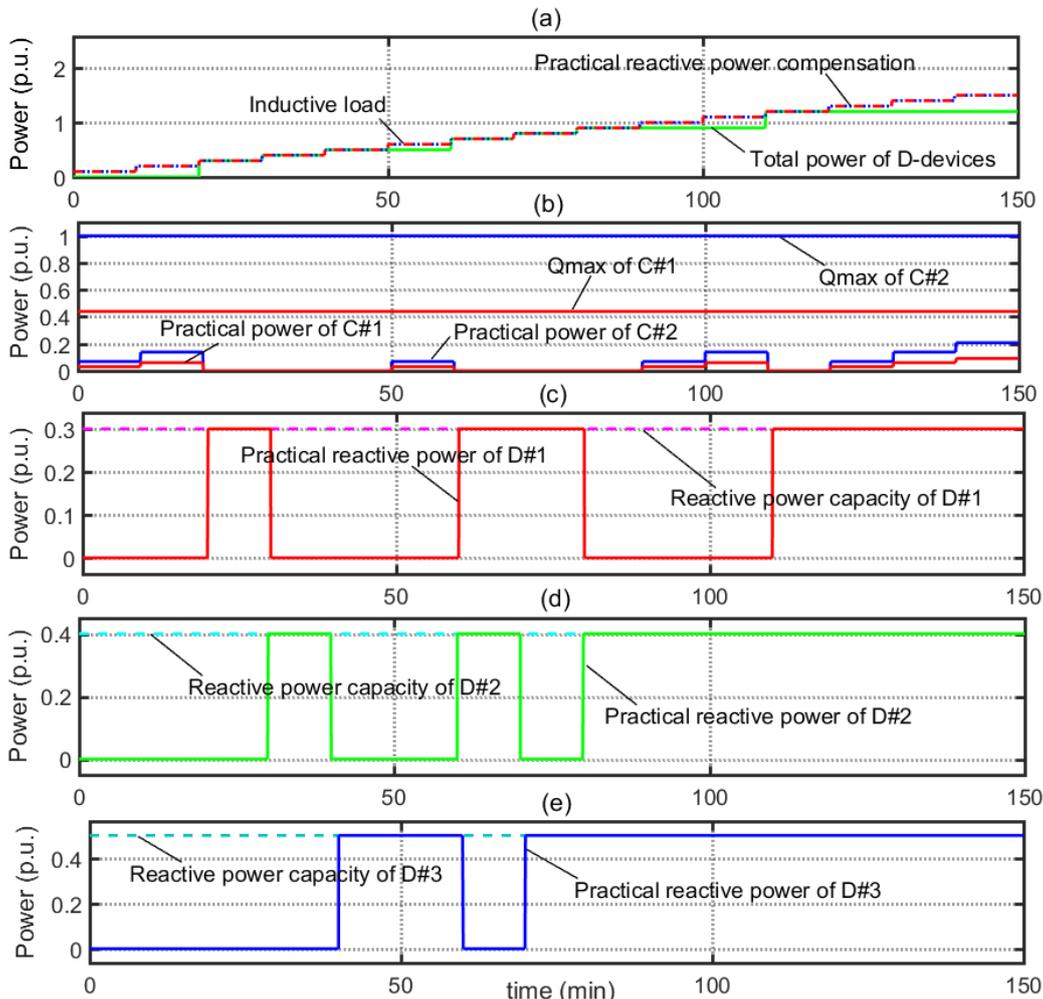


Fig. 6. Simulation results of DER management system for reactive power distribution

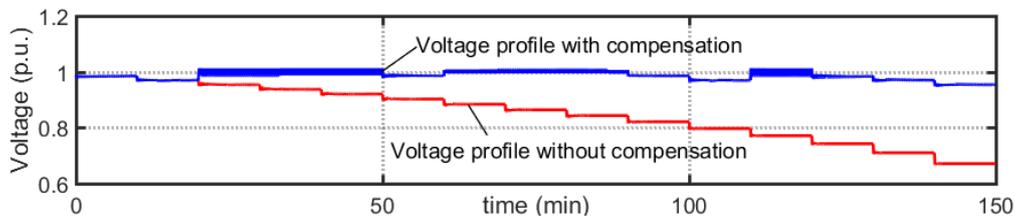


Fig. 7. Profiles of voltage amplitude at PCC with and without reactive power compensation

5. CONCLUDING REMARKS

This paper presented algorithms of DER management system to distribute power within aggregated DER group. For active power distribution, the proposed method sets weighting criteria for continuously controlled devices so that their power is shared based on power capacity, cost or other priority criteria, while the discretely controlled devices are controlled to reduce the total number of ON/OFF actions or the associated cost. For reactive power distribution, the discretely controlled devices are switched ON/OFF based on iterative backtracking algorithm while the remaining power is distributed among continuously controlled devices with weighted method. The proposed control algorithms provide a simple way to orchestrate devices within DER group including load shedding, renewable curtailment, diesel generator adjustment and reactive power management, which will be promising to embrace a future of digital grid with millions of DERs.

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