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Elastic Energy Distribution of Local Area Packetized Power Networks to Mitigate Distribution Level Load Fluctuation

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ABSTRACT Featured by distributed energy storing and time division multiplexing transmission, dc packetized-power distribution has great potential in compensating inelastic load fluctuations at the demand side. In this paper, we investigate an ac distribution grid integrated with local area packetized-power networks (LAPPNs). LAPPNs, as the dc sector, enable a store-then-consume mechanism, whereby the sectoral loads characterized as elastic ones, can be manipulated to reduce the distribution level load fluctuation. A multi-mode energy distribution is proposed for the dc sector, including an advanced energy distribution as the 'storing' phase utilizing conventionally non-peak hours, and an open energy distribution as the 'consumption' phase to further compensate the ac sector load fluctuation on real-time basis. We develop a cross-time hierarchical energy distribution scheme to coordinate energy distribution of dc sector and ac sector and exploit the elasticity of dc sector loads on both day-ahead basis and real-time basis, jointly resulting in a significant mitigation of distribution load fluctuation. Power distribution optimizations are separately formulated and solved for different procedures of the scheme. Simulations have been conducted to demonstrate the effectiveness of the scheme in reducing distribution level load fluctuation and to reveal facts on how much dc elastic loads is needed for fluctuation reduction in a scenario in North America.

INDEX TERMS DC packetized-power network, demand side management, load shaping.

I. INTRODUCTION

Power-on-demand, as the most essential feature of conventional power systems [1], can date back to the very beginning of power industry, and has been ruling the planning, construction, operation and development of global power grids ever since. The reason to choose, accept or be subjected to this feature is simply because electric energy has been difficult to store at a scale at a low cost. In terms of operation, it has made the power generation and dispatching a strict obedience to human's living and productive activities, which is characterized by a high dynamism of demand profile on a real-time scope and a regular demand fluctuation on a daily time basis.

These characteristics have led to issues such as (1) excessive generation cost, e.g. standing-by and higher operation costs of fast-responding generators, (2) a passive energy consumption, e.g. mandatory lighting of commercial and public buildings in off-peak hours to complement the minimum required load of economic operation, and (3) a wastage of energy surplus, e.g., unused power surplus due to load drop. To alleviate the tension between generation and demand, it has been a dominant view to take measures at the demand side to weaken the dynamism and fluctuation of demand profile [2], [3]. Although functioning to some extent by taking advantage of the elasticity of human activities, they do not manage to dispense with the constraints by that very feature. What if the elasticity has been exhausted?

Alternatively, we can consider power-on-demand may be slacked. Mathematically, we use g, l, and d to respectively denote real-time generated power, load and consumers' demand. Generation-on-load, i.e. $g = l$, is an inherent request of power system operation. With a permanent guarantee of power-on-demand by the conventional system, the consumers have been with a purchase-on-demand habit. Thus, the load have been always equal to their demand, i.e., $l \equiv d$. Power on demand then can be expressed as $g = d$. Now, the issue is to decouple the equation between generation and demand on real-time basis. To do this, we could replace $l \equiv d$ with $\int ldt = \int ddt$, and achieve

$$\int gdt = \int ddt,$$

i.e., to maintain the balance between supply and demand in terms of energy instead of power.

Inspiring has been the breakthrough in electric energy storage [4]–[8]. Electric battery systems of hundred-kwh capacity and with advanced battery management have been applied in commercialized plug-in electric vehicles [9] and functioning efficiently, such as the Tesla Model S 100D that has an 100kWh battery system. The costs of battery packs for electric vehicles is also rapidly falling [10]. They are more than sufficient for household deployment, and have a potential to support larger commercial usage by upgrade in the size. With the deployment of distributed energy storages, it is feasible to promote a store-then-consume habit at the demand side with negligible effect on people's living habits indeed. Moreover, an emerging DC packetized-power distribution technology [11], [12] can achieve a time division multiplexing (TDM) power dispatching among residential consumers [13], where power is transmitted in the form of power packet including address information and payload, from a supplier to a power router(s), and forwarded by the router(s) to a demander. This not only frees some sub-networks from power-on-demand, but also provides an effective solution to incorporate large penetration of distributed energy resources (DERs) [14] and supports local energy trading among neighboring subscribers. These advancements together conduce greatly to the intended goal of slacked energy balance.

In this paper, as a preliminary attempt to alleviate the tension by power-on-demand, we separate what can be converted into elastic loads with the assistance by distributed energy storages, e.g. residential loads, from inelastic loads in the conventional power system, e.g. industrial loads, and place them in local area packetized-power networks (LAPPNs). By this, an integrated local power distribution network is established, composed of both AC sector conducting conventional AC distribution, and DC sector adopting elastic energy distribution to realize energy-on-demand, which can be used to compensate load fluctuation of the AC sector.

To effectively achieve reduction of load fluctuation, it is significant to apply a more suitable power distribution mechanism in the DC sector to match characteristics of the novel DC packetized-power distribution technique. Therefore, we divide the DC sector energy distribution into two stages. An advanced energy distribution in what conventionally used to be off-peak hours, e.g., from 12 am to 8 am, is used to distribute the main portion of consumer's daily required energy to be stored prior to consumption, under a bus-feeder DC distribution mode. An open energy distribution is conducted in the other time under the DC-packetized power distribution mode, where the consumers can purchase complementary energy or sell surplus energy in a flexible local energy trading.

Consequently, we propose a cross-time hierarchical energy distribution scheme to accommodatively regulate energy distribution in the DC sector and coordinate the two sectors from an overall perspective. In the day-ahead top-down scheduling, a distribution level load shaping is first conducted based on collected demand information and estimations, by which the reference load profile for DC sector is obtained. Based on the reference, a DC intra-sector advanced distribution scheduling is further performed. In the real-time energy distribution, the operator coordinates the loads of the DC sector with that of the AC sector and the state of bulk generation, in order to reduce the deviation of distribution level aggregate loads from an economic bulk generation capacity.

Optimization problems are developed based on the scheme, respectively on the day-ahead basis and the real-time basis, both at the distribution level and the intra-sector level. In the day-ahead scheduling, the distribution level load shaping is formulated as a peak-to-average ratio (PAR) minimization to reduce distribution level load fluctuation, and the DC intra-sector advanced distribution scheduling as a PAR minimization to reduce the load fluctuation at each DC sector energy subscriber and the utility router. They both can be converted into linear programming problems and effectively solved. The real-time distribution level load management is formulated as a cost minimization problem to reduce the cost of bulk generation deviation and enlarge the profit by inter-sector energy interchange, which is a binary quadratic optimization and can be effectively tackled.

Simulations are conducted on both day-ahead basis and real-time basis to demonstrate the effectiveness of the scheme in load fluctuation reduction, and reveal facts on how much DC sector loads is needed for fluctuation compensation and how the severity of load fluctuation affects the requisite proportion of elastic loads in terms of reducing PAR to a certain level.

The remainder of this paper is organized as follows. In Section II, related work is provided. In Section III, system model is introduced. The proposed cross-time hierarchical energy distribution scheme is presented in IV, and the corresponding optimization formulation and solution are given in V. Simulation results and analyses are provided in Section VI, and conclusion are drawn in Section VII.

II. RELATED WORK

Existing works on load shaping, or demand side management, can be classified according to the load pattern analyzed, or the scale of the scenario.

For residential loads, studies have been conducted respectively at house level, e.g., [15]–[17], and cluster of houses level, e.g., [18]–[20]. By taking advantage of consumers' rationality in terms of economic incentive, pricing strategies and game theory have been applied in the management to motivate users shift on-peak loads to off-peak hours [16], [17], [19], [20]. To address an increasing penetration of DERs

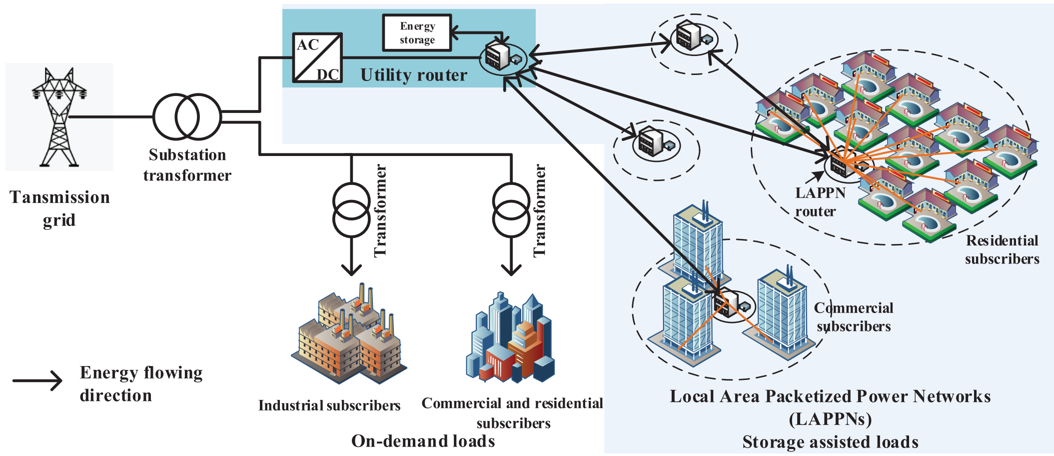

FIGURE 1. **Abstraction of a distribution network.**

to power system, studies have also considered the affect of DERs on load shaping in the schemes, e.g., [15]. To further enhance the practicability of load management, recent works have applied tools such as stochastic approximation to deal with the information uncertainty in energy trading [19], and the machine learning to better capture users behavioral characteristics [18].

For commercial and industrial loads, studies have been conducted respectively at building level, e.g. [21] and [22], and sector level, e.g., [23] and [24]. The work in [21] has studied respectively, the load reduction and load shifting strategies of different types of commercial buildings and industrial buildings under dynamic electricity pricing schedules. A physically based model and corresponding scheduling is proposed in [22] for industrial load management using integer linear programming to minimize the electricity cost. The work in [23] has proposed optimal load control strategies under different electricity pricing schemes, while considering the distinct demand patterns of industrial users. The work in [24] has simulated an electricity market with demand response from different types of commercial buildings by using agent-based modeling and simulation techniques.

Compared with the existing works, the novelty of the proposed work is to study the load shaping problem in a comprehensive power distribution grid composed of different load patterns. Based on the characteristics of different load patterns' load profiles, we utilize distributed energy storages and DC packetized-power distribution to convert a portion of the conventional AC loads into elastic DC loads, realizing a load elasticity at sector level that enables a stronger ability to mitigate load fluctuation at the distribution level. Strong restrains to the power system posed by power-on-demand can thus be effectively slacked.

III. SYSTEM MODEL

An integrated local power distribution grid composed of both AC distribution and DC distribution is considered in this study. As shown in Fig. 1, electric energy from a transmission grid is assumed to be delivered in the form of AC and distributed via an AC substation. In this cyber-physical system, robust communications are assumed to guarantee monitoring and control of the operation, and management and participation of the energy trading.

A. SYSTEMATIC DESCRIPTION

1) AGGREGATE LOADS

The time basis of day-ahead distribution scheduling is characterized by $\mathcal{K} = \{1, \ldots k, \ldots 24\}$, where k denotes the k-th hour of a cycle. Let L^k denote the aggregate loads of the distribution grid in the k-th hour, and $\mathbf{L} = (L^k)_{k=1}^{24}$ the grid's daily load profile. L^k is expressed as:

$$L^k = L^k_{AC} + L^k_{DC}, \tag{1}$$

where L^k_{AC} denotes aggregate loads of the AC sector, and L^k_{DC} aggregate loads of the DC sector.

2) BULK GENERATION DEVIATION COST

Bulk generation deviation is defined in the real-time energy distribution, as the difference between a short-term estimated loads and its corresponding planned bulk generation capacity. The planned bulk generation capacity is characterized as an economic bulk generation capacity that can be obtained without extra costly adjustment to the bulk generators, denoted by G_{eco}. This mismatch, either an overload or underload at the distribution level, can cause a deviation of the bulk generation from G_{eco}, resulting in an increasing unit cost of generation or waste of power surplus. We define a deviation cost C to characterize the cost and waste, by which we consider the waste of power surplus equal to a kind of cost. The real-time energy distribution management is cyclically conducted on an independent time basis denoted by τ.[1] We adopt the

[1] τ can be determined practically, e.g. equal to hourly basis, 30-min basis or 15-min basis. In this work's simulation, however, τ is still set as a hourly basis due to an incapability to access sub-hour electric load datum.

quadratic cost function for thermal generators [1]:

$$\alpha_1 x^2 + \alpha_2 x + \alpha_3. \tag{2}$$

Let $x = L^\tau - G^\tau_{eco}$ denote the difference between the estimated loads and the economic generation in τ. The cost of deviation, denoted by $C(x)$, is characterized as:

$$C(x) = \begin{cases} \alpha_1^\tau x^2 + \alpha_2^\tau x & x \geq 0, \\ -\alpha_3^\tau x^2 - \alpha_4^\tau x & x < 0, \end{cases} \tag{3}$$

where $\alpha_1^\tau, \alpha_2^\tau, \alpha_3^\tau$ and α_4^τ are positive characteristic factors.

B. AC SECTOR

1) SUBSCRIBER BEHAVIORAL PATTERN

The AC sector provides uninterruptible power for large industrial and commercial energy subscribers (ESs) and conventional residential ESs that require on-demand power supply. Let $\mathcal{S}_{AC}$ denote the set of AC subscribers. For an ES $u \in \mathcal{S}_{AC}$, let E_u^k denote its hourly loads and $E_u = (E_u^k)_{k=1}^{24}$ the load profile. L_{AC}^k is given by

$$L_{AC}^k = \sum_{u \in \mathcal{S}_{AC}} E_u^k. \tag{4}$$

The load profile of AC sector is expressed by $\mathbf{L}_{AC} = (L_{AC}^k)_{k=1}^{24}$. It can be characterized as inelastic loads in the day-ahead scheduling based on planned or estimated load profiles.

C. DC MULTI-LAPPN SECTOR

The DC sector is designed as a packetized power distribution network composed of multiple LAPPNs to serve the commercial and residential subscribers equipped with energy storages. L_{DC}^k is aggregated at a utility router that is assumed as the distributer of the sector.

1) INTER-LAPPN CONNECTIONS

Let $\mathcal{R}_+ = \{0\} \cup \mathcal{R}$ denote the set of power routers, where 0 denotes the utility router and $\mathcal{R} = \{1, \ldots R, \ldots\}$ represents the set of LAPPN routers. A power line between two routers is denoted by $(R_1, R_2), R_1, R_2 \in \mathcal{R}_+$. For inter-LAPPN energy cooperation, we assume there can be, but not necessarily, a connection between two arbitrary LAPPN routers. As is assumed in the previous work [13], the inter-LAPPN power lines have multiple cores adapted to the structure of LAPPN routers. Let $\mathcal{C}_{R_1R_2}$ denote the set of cores of line (R_1, R_2). The utility router provides independent interfaces for all cores of the connected power lines, and has a single core that connects the installed energy storage for its potential in reducing load fluctuations, the connection between which and the utility router is denoted by $(0, 0)$. The capacity and the loads in hour k of the storage is respectively denoted by E_{0_max} and E_0^k. An ideal daily operation of the utility storage satisfies: $\sum_{k \in \mathcal{K}} E_0^k = 0$.

2) INTRA-LAPPN CONNECTIONS

Let $\mathcal{S}_R = \{1, \ldots, a, \ldots\}$ denote the set of subscribers in LAPPN R, and (R, a) the power line linking router R and ES a. All intra-LAPPN power lines are single-core. An LAPPN router is embedded with multiple power channels [13], i.e., electric paths with variable connectivity to deliver power packets according to subscriber matching. Let $\mathcal{C}_R$ denote the set of power channels of LAPPN router R, and $m \in \mathcal{C}_R$ denote an arbitrary power channel.

3) POWER DISTRIBUTION SPECIFICATION

We assume the power capacity of a core in an inter-LAPPN power line equals that of a power channel in an LAPPN router, denoted by P_{CHN}^{MAX}, and $|\mathcal{C}_R| = |\mathcal{C}_{R_1R_2}|, \forall R \in \mathcal{R}, \forall R_1, R_2 \in \mathcal{R}_+$. An inter-LAPPN power line or LAPPN router's capacity is $|\mathcal{C}_R|P_{CHN}^{MAX}$. The utility router's power capacity, denoted by P^{MAX}, is:

$$P^{MAX} = (|\mathcal{R}||\mathcal{C}_R| + 1)P_{CHN}^{MAX}. \tag{5}$$

For simplicity, we do not consider power transmission loss in scheduling hourly load profile. The DC sector are assumed with two distributing modes:

a: BUS-FEEDER MODE

the utility router and LAPPN routers operate as DC buses to distribute continuous power to all the subordinates, and all the power lines become feeders of the superior routers. In this mode, L_{DC}^k is calculated by:

$$L_{DC}^k = \int_k p_{DC}\, dt, \tag{6}$$

where p_{DC} denote the aggregate power at the utility router, and $\int_k \cdot dt$ denote the time integration in hour k.

b: POWER PACKET MODE

the DC sector operates on a time-slot basis with h denoting time length of the intended minimum slot. All LAPPN routers operate by the time division multiplexing (TDM) manner [13], i.e., each power channel of the LAPPN can only deliver a power packet at a time. The time length of a power packet, denoted by l, is an integral multiple of h, i.e., $l = nh, n \in \mathbb{Z}_+$. The utility router can simultaneously distributes multiple power packets to specific subscribers in different LAPPNs as long as there are available power channels in the LAPPN routers. Let $\mathcal{W}_{0R}^k$ denote the set of power packets delivered from the utility router to LAPPN R in the k-th hour. Let p_{0R_i} and l_{0R_i} respectively denote the utility router's output power and the time length of power packet $i \in \mathcal{W}_{0R}^k$. L_{DC}^k is calculated by:

$$L_{DC}^k = \sum_{R \in \mathcal{R}} \sum_{i \in \mathcal{W}_{0R}^k} p_{0R\_i} l_{0R\_i}. \tag{7}$$

4) SUBSCRIBER BEHAVIORAL PATTERN

The LAPPN subscribers adopt a store-then-consume pattern. A portion of their daily required energy can be delivered and stored in the storages any time before consumption, which can be scheduled to compensate the fluctuation of the inelastic ones. For $a \in R$, let E_a E_{a_adv} and E_{a_comp} respectively denote the daily loads, the energy delivered in advance and the complementary energy of a. They satisfy:

$$E_a = E_{a\_\mathrm{adv}} + E_{a\_comp}. \tag{8}$$

E_{a_adv} is expected to be delivered in what conventionally used to be off-peak hours, e.g., from 12 am to 8 am, under the bus-feeder mode, named the *advanced energy distribution*. In the other time, the ES can purchase complementary energy if the stored one is running out ($E_{a\_comp} \geq 0$) or sell surplus energy to those in demand ($E_{a\_comp} < 0$), which is conducted under the power packet distribution mode, named the *open energy distribution*. The daily DC sector energy distribution satisfies:

$$E_{DC} = \sum_{k\in\mathcal{K}} L_{DC}^k = \sum_{R\in\mathcal{R}} \sum_{a\in R} E_a + \sum_{k\in\mathcal{K}} E_0^k, \tag{9}$$

where E_{DC} denotes the DC sector's daily required energy.

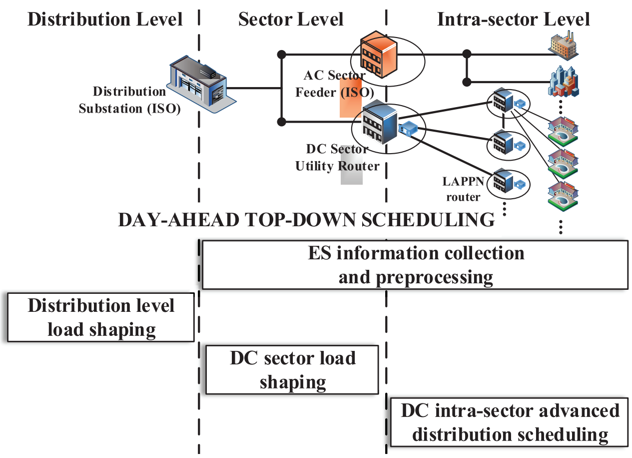

FIGURE 2. System topology and day-ahead top-down load scheduling.

IV. CROSS-TIME HIERARCHICAL ENERGY DISTRIBUTION

As shown in Fig. 2, an independent system operator (ISO) is assumed as the centralized controller that controls the distribution and sector level distribution and also the intra-AC-sector distribution. The utility router acts as a subordinate of the ISO that controls the intra-DC-sector distribution. The LAPPN routers as subordinates of the utility router, control the intra-LAPPN distributions.

The energy distribution scheme includes a day-ahead top-down load scheduling that hierarchically shapes the load profiles at the distribution level, the sector level and the intra-sector level, and a and real-time multi-mode energy distribution to regulate real-time grid operation.

A. DAY-AHEAD TOP-DOWN SCHEDULING

Hierarchical relationship of the procedures are shown in Fig. 2. The scheduling is conducted on a hourly time basis.

1) ES INFORMATION COLLECTION AND PREPROCESSING

AC ES $u \in \mathcal{S}_{AC}$ reports its planned load profile E_u or planned daily loads $E_u = \sum_{k\in\mathcal{K}} E_u^k$ to the ISO. Based on E_u and $E_u = \sum_{k\in\mathcal{K}} E_u^k$, the ISO estimates the inelastic load profile of the AC sector $\mathbf{L}_{AC}$. DC ES $a \in R$ uploads its required energy delivered in advanced E_{a_adv}, and the feasible time interval for its advanced energy distribution, denoted by $[k_{a\_sta}, k_{a\_end}]$, to the LAPPN router. The utility router aggregates the demand information from the LAPPN routers, calculates subscriber's total required energy delivered in advance $\sum_{R\in\mathcal{R}} \sum_{a\in R} E_{a\_\mathrm{adv}}$, estimates the total required energy E_{DC}, determines the minimum energy stored in advance in the utility storage $\underline{E}_{0\_\mathrm{adv}}$, and report to the ISO.

2) DISTRIBUTION LEVEL LOAD SHAPING

By aggregating the uploaded information, e.g., $\mathbf{L}_{AC}$, E_{DC_adv} and E_{DC}, the ISO shapes the distribution level load profile $\mathbf{L}$.

3) DC SECTOR LOAD SHAPING

The ISO obtains the DC sector load profile by $\mathbf{L}_{DC} = \mathbf{L} - \mathbf{L}_{AC}$, determines the time proportion of advanced energy distribution and that of the open energy distribution, and sets the loads boundaries of the DC sector in the open energy distribution.

4) DC INTRA-SECTOR ADVANCED DISTRIBUTION SCHEDULING

Based on the sector-layer schedule and the subscribers' preference information $[k_{a\_sta}, k_{a\_end}]$, the utility router schedules the advanced energy distribution of all the subscribers and the utility storage.

B. REAL-TIME MULTI-MODE ENERGY DISTRIBUTION

1) DISTRIBUTION LEVEL LOAD MANAGEMENT

In the real-time scope, the AC sector conducts a conventional AC distribution with primary power supply by the bulk generation. The distribution level load management aims at the period when the DC sector is in the open energy distribution and is conducted on a τ-time basis. The ISO coordinates the loads of the DC sector with that of the AC sector and the state of the bulk generation, to reduce the deviation of distribution level aggregate loads from the economic bulk generation capacity.

2) DC SECTOR LOAD MANAGEMENT

The DC sector first conducts the advanced energy distribution under the bus-feeder mode to distribute the bulk required energy. After this, it changes into the open energy distribution under the power packet mode, by which the DC intra-sector energy cooperation is promoted and the DC sector aggregate loads are bounded. The open distribution applies the inter- and intra- LAPPN packetized power distribution dispatching mechanism proposed in our previous work [25]. With the stored capacity of the utility router and the energy surplus of some DC subscribers, the DC sector provides opportunistic power supply to compensate the instantaneous load fluctuation of AC sector, under the control of ISO.

An illustration of the energy distribution is shown in Fig. 3.

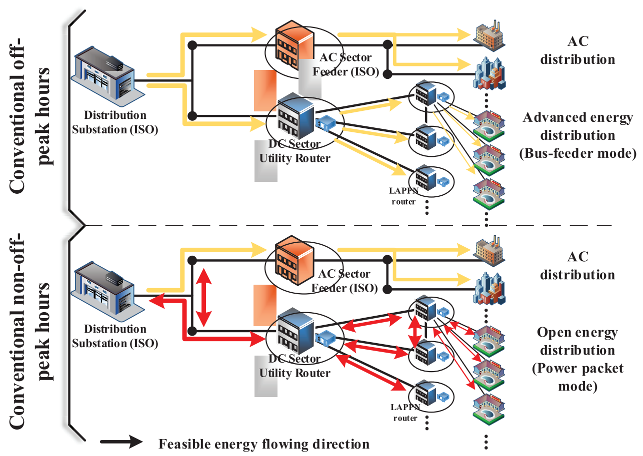

FIGURE 3. Illustration of real-time multi-mode energy distribution.

V. ENERGY DISTRIBUTION OPTIMIZATION: PROBLEM FORMULATION AND SOLUTION

Problems and solutions are presented in accordance with the description of the proposed energy distribution scheme.

A. DAY-AHEAD DISTRIBUTION AND SECTOR LEVEL LOAD SHAPING

To measure load fluctuation, we adopt the peak-to-average ratio (PAR) [26], denoted by Ω, which is defined as the maximum hourly loads over the average hourly loads in the day:

$$\Omega = \frac{\max_{k\in\mathcal{K}} L^k}{\frac{1}{24}\sum_{k\in\mathcal{K}} L^k}. \tag{10}$$

1) PROBLEM FORMULATION

Based on the inelastic loads of AC sector, the ISO minimizes the distribution level PAR by shaping the DC sector load profile and determining the energy stored in the utility router in advance E_{0_adv}, expressed as:

$$\begin{aligned}
\underset{\mathbf{L}_{DC}, E_{0_\mathrm{adv}}}{\text{minimize}} \quad & \Omega = \frac{\max_{k\in\mathcal{K}}(L^k_{DC} + L^k_{AC})}{\frac{1}{24}\sum_{k\in\mathcal{K}}(L^k_{DC} + L^k_{AC})}, \\
\text{subject to } C1: & \sum_{k\in\mathcal{K}} L^k_{DC} = E_{DC}, \\
C2: & \sum_{k\in\mathcal{K}_{\mathrm{adv}}} L^k_{DC} = \sum_{R\in\mathcal{R}}\sum_{a\in R} E_{a_\mathrm{adv}} + E_{0_\mathrm{adv}}, \\
C3: & \underline{E}_{0_\mathrm{adv}} \le E_{0_\mathrm{adv}} \le E_{0_max} - E_{0_rm}, \\
C4: & \underline{L}_{DC_out} \le L^k_{DC} \le P^{MAX}\cdot 1h,\ k\in\mathcal{K}, \\
C5: & 0 \le L^k_{DC},\ k\in\mathcal{K}_{\mathrm{adv}},
\end{aligned} \tag{11}$$

where C1 is the constraint on DC sector daily energy satisfaction, C2 ensures a satisfactory amount of energy delivered in advance and $\mathcal{K}_{\mathrm{adv}}$ represents the set of hours for advanced energy distribution, C3 is the constraint on the utility storage' advanced charging and E_{0_rm} denotes the storage's remained energy after the last cycle. C4 and C5 together are the boundaries of the aggregate loads of DC sector, where $\underline{L}_{DC\_out} \le 0$ denotes the boundary of output energy in the open energy distribution and C5 suggests that the advanced energy distribution is only for 'charging' the DC sector. $\underline{L}_{DC\_out}$ is to guarantee that the DC sector can export energy to compensate the load fluctuation of AC sector. Since $\frac{1}{24}\sum_{k\in\mathcal{K}}(L^k_{DC}+L^k_{AC})$ is fixed, problem (11) equals:

$$\begin{aligned}
\underset{\mathbf{L}_{DC}, E_{0_\mathrm{adv}}}{\text{minimize}} \quad & \max_{k\in\mathcal{K}}(L^k_{DC} + L^k_{AC}), \\
\text{subject to} \quad & C1,\ C2,\ C3,\ C4,\ C5.
\end{aligned} \tag{12}$$

Problem (12) is not differentiable but can be converted into a linear programming (LP) problem [27], expressed as:

$$\begin{aligned}
\underset{\gamma, \mathbf{L}_{DC}, E_{0_\mathrm{adv}}}{\text{minimize}} \quad & \gamma, \\
\text{subject to} \quad & C1,\ C2,\ C3,\ C4,\ C5, \\
& C6: \ L^k_{DC} + L^k_{AC} \le \gamma,\ k\in\mathcal{K},
\end{aligned} \tag{13}$$

where γ is an auxiliary variable. Problem (13) can be effectively solved by LP solvers such as the interior point method (IPM) [27].

2) PROPOSED SOLUTION

The ISO first sets $\underline{L}_{DC\_out}$ and $\mathcal{K}_{\mathrm{adv}}$ according to the collected and historical information. We assume that $\underline{L}_{DC\_out}$ is set as the DC sector's maximum hourly export energy in the last cycle, denoted by $\mathcal{K}_{-1}$, i.e.,

$$\underline{L}_{DC\_out} = \min\left(\min_{k\in\mathcal{K}_{-1}} L^k_{DC}, 0\right). \tag{14}$$

Let k_{adv_sta} and k_{adv_end} respectively denote the start and end time of the advanced energy distribution. To exploit the potential of the elastic loads to compensate load fluctuation, we develop a heuristic algorithm to determine $\mathcal{K}_{\mathrm{adv}}$ as presented in TABLE 1. $\mathcal{K}_{\mathrm{adv}}$ is originally set as the hour with the least AC aggregate loads. If the average advanced distribution loads, denoted by L_{adv_avg}, exceeds the hourly average loads $\bar{L}$, $\mathcal{K}_{\mathrm{adv}}$ will incorporate one of its adjacent hours for the DC advanced distribution, while $\mathcal{K}_{\mathrm{adv}}$ can at most have K_{max} hours. Then the ISO solves problem (13) via the IPM to obtain $\mathbf{L}$, $\mathbf{L}_{DC}$ and E_{0_adv}.

B. DC INTRA-SECTOR ADVANCED DISTRIBUTION SCHEDULING

For ES $a \in$ LAPPN R, let $\mathcal{K}_{a\_adv}$ denote its advanced energy distribution interval in the scheduling, which is determined by $\mathcal{K}_{a\_adv} = [k_{a\_sta}, k_{a\_end}] \bigcap \mathcal{K}_{\mathrm{adv}}$. The utility router aims to minimize the load fluctuation of each ES and the utility router, which can be expressed as:

$$\begin{aligned}
\underset{\substack{E_{a_adv}, a\in R,\\ R\in\mathcal{R}; E_{0_\mathrm{adv}}}}{\text{minimize}} \quad & \max_{k\in\mathcal{K}_{\mathrm{adv}}} E^k_{0_adv} + \sum_{a\in R, R\in\mathcal{R}} \max_{k\in\mathcal{K}_{a_adv}} E^k_{a_adv}, \\
\text{s.t.} \quad C7: & \sum_{k\in\mathcal{K}_{\mathrm{adv}}} E^k_{0_adv} = E_{0_adv},
\end{aligned}$$

TABLE 1. Heuristic algorithm to determine $\mathcal{K}_{\text{adv}}$.

$n=1$, find κ such that $L_{\text{AC}}^{\kappa}=\min_{k\in\mathcal{K}} L_{\text{AC}}^{k}$;
$k_{\text{adv\_sta}}(n)=k_{\text{adv\_end}}(n)=\kappa$;
$L_{\text{adv\_avg}}(n)=\frac{\sum_{R\in\mathcal{R}}\sum_{a\in R}E_{a\text{\_adv}}+E_{0\text{\_max}}+\sum_{k\in\mathcal{K}_{\text{adv}}(n)}L_{\text{AC}}^{k}}{|\mathcal{K}_{\text{adv}}(n)|}$;
$\bar{L}=\sum_{k\in\mathcal{K}}L_{\text{AC}}^{k}+E_{\text{DC}}$;
while $(L_{\text{adv\_avg}}(n)>\bar{L}$ **or** $L_{\text{adv\_avg}}(n)>\text{P}^{\text{MAX}}\cdot 1\text{h})$ **and** $|\mathcal{K}_{\text{adv}}(n)|<K_{max}$ **do**
    $n++$;
    if $L_{\text{AC}}^{k_{\text{adv\_sta}}(n-1)-1}<L_{\text{AC}}^{k_{\text{adv\_end}}(n-1)+1}$ **then**
        $k_{\text{adv\_sta}}(n)=k_{\text{adv\_sta}}(n-1)-1$;
        $k_{\text{adv\_end}}(n)=k_{\text{adv\_end}}(n-1)$;
    else
        $k_{\text{adv\_sta}}(n)=k_{\text{adv\_sta}}(n-1)$;
        $k_{\text{adv\_end}}(n)=k_{\text{adv\_end}}(n-1)+1$;
    end if
    $L_{\text{adv\_avg}}(n)=\frac{\sum_{R\in\mathcal{R}}\sum_{a\in R}E_{a\text{\_adv}}+E_{0\text{\_max}}+\sum_{k\in\mathcal{K}_{\text{adv}}(n)}L_{\text{AC}}^{k}}{|\mathcal{K}_{\text{adv}}(n)|}$;
end while

$$C8:\ \sum_{k\in\mathcal{K}_{a\_adv}}E_{a\_adv}^{k}=E_{a\_adv},\ \ a\in R,R\in\mathcal{R},$$
$$C9:\ E_{0\_adv}^{k}+\sum_{a\in R,R\in\mathcal{R}}E_{a\_adv}^{k}=L_{DC}^{k},\ \ k\in\mathcal{K}_{\text{adv}},$$
$$C10:\ 0\le E_{a\_adv}^{k}\le P_{CHN}^{MAX},\ \ k\in\mathcal{K}_{\text{adv}},a\in R,R\in\mathcal{R}$$
$$C11:\ 0\le E_{0\_adv}^{k}\le P_{CHN}^{MAX},\ \ k\in\mathcal{K}_{\text{adv}}, \tag{15}$$

where C7 and C8 are the constraints on total delivered energy of the utility storage and those of the subscribers, C9 is the constraint on the hourly distribution capacity, C10 and C11 are the constraints on power line capacity. Problem (27) can also be converted into a LP problem as

$$\begin{aligned}\underset{\gamma_a,E_{a\_adv},a\in R,R\in\mathcal{R};\ \gamma_0;E_{0\_\text{adv}}}{\text{minimize}}\quad & \gamma_1+\sum_{a\in R,R\in\mathcal{R}}\gamma_a,\\ \text{s.t.}\quad & C7,\ C8,\ C9,\ C10,C11,\\ & C12:\ \ E_{0\_adv}^{k}\le\gamma_1,\ \ k\in\mathcal{K}_{\text{adv}},\\ & C13:\ \ E_{a\_adv}^{k}\le\gamma_a,\ \ k\in\mathcal{K}_{\text{adv}},a\in R,R\in\mathcal{R},\end{aligned}\tag{16}$$

and be solved by the IPM. Thus, the utility router completes the daily ahead scheduling by solving problem (16) to obtain E_{a_adv} and E_{0_adv}.

C. REAL-TIME DISTRIBUTION LEVEL LOAD MANAGEMENT

The goal is formulated as a global cost minimization problem. To characterize the global cost, an income/cost of energy interchange between the sectors is first introduced.

1) INCOME/COST OF ENERGY INTERCHANGE

For a coming management cycle τ, the ISO characterizes the aggregate loads at the DC sector L_{DC}^{τ} by:

$$L_{DC}^{\tau}=D^{\tau}+E_0^{\tau}, \tag{17}$$

where D^{τ} denotes the unmatched loads under the power packet mode, and E_0^{τ} denotes the loads of the utility storage. $D^{\tau}\geq 0$ refers to subscribers' unmatched demand and $D^{\tau}<0$ refers to the unmatched energy surplus. $E_0^{\tau}\geq 0$ suggests the utility storage is going to be charged and $E_0^{\tau}<0$ refers to its being discharged. In the proposed LAPPN packetized power dispatching framework [13], the utility is regarded as a special ES that has not been assumed to provide economic incentives affecting subscribers' behavioral. To realize a joint management of the two layers, we assume a buying/selling price β^{τ} for the utility, on behalf of the AC sector to affect subscribers' behavioral. Specifically, β^{τ} is designed as

$$\beta^{\tau}=\beta_0^{\tau}+y, \tag{18}$$

where β_0^{τ} is fixed and y is adjustable.

Property 1: By a practical consideration, the relation between D^{τ} and y is characterized by:

$$\frac{\partial D^{\tau}}{\partial y}<0. \tag{19}$$

That is, a higher price restrains the willingness to buy energy and motivate those who want to sell energy.
We assume D^{τ} linearly decreases over y, i.e.,

$$D^{\tau}=(D^{\tau})_0-e^{\tau}y. \tag{20}$$

The income/cost in terms of energy interchange with DC subscribers is characterized by:

$$C_{comp}=\beta^{\tau}D^{\tau}=(\beta_0^{\tau}+y)\left((D^{\tau})_0-e^{\tau}y\right), \tag{21}$$

where $C_{comp}>0$ indicates an income and $C_{comp}<0$ a cost.

2) MANAGEMENT OBJECTIVE

Based on the estimated economic bulk generation capacity G_{eco}^{τ}, and the AC sector aggregate loads L_{AC}^{τ}, the global cost, denoted by f, is expressed as:

$$f(x)=C(x)-C_{comp}, \tag{22}$$

where $x=L_{AC}^{\tau}+D^{\tau}+E_0^{\tau}-G_{eco}^{\tau}$, and $C(x)$ is the deviation cost defined in (3). Note that f actually is a function of E_0^{τ} and y. But to better demonstrate and discuss its property, we use x as an auxiliary variable.

Property 2: When $L_{AC}^{\tau}+(D^{\tau})_0>G_{eco}^{\tau}$, $\forall x<0$,

$$f(x)\geq f(0). \tag{23}$$

When $L_{AC}^{\tau}+(D^{\tau})_0<G_{eco}^{\tau}$, $\forall x>0$

$$f(x)\geq f(0). \tag{24}$$

That is, in practice, the best compensation is when the difference between L^{τ} and G_{eco}^{τ} is fully compensated, i.e., $x=0$, while an over compensation shall be avoided. Therefore, when $L_{AC}^{\tau}+(D^{\tau})_0>G_{eco}^{\tau}$, a theoretical minimal global cost shall never locate below $x=0$. $L_{AC}^{\tau}+(D^{\tau})_0<G_{eco}^{\tau}$, a theoretical minimal global cost shall never locate beyond $x=0$. This leads to the proposition:

Proposition 1: When $L_{AC}^{\tau}+(D^{\tau})_0>G_{eco}^{\tau}$, E_0^{τ} is bounded by

$$E_0^{\tau}\geq(G_{eco}^{\tau}-L_{AC}^{\tau})-\frac{(D^{\tau})_0+e^{\tau}(\beta_0^{\tau}+\alpha_4)}{2} \tag{25}$$

to guarantee a feasible global cost function. When $L_{AC}^{\tau} + (D^{\tau})_0 < G_{eco}^{\tau}$, E_0^{τ} is bounded by

$$E_0^{\tau} \leq (G_{eco}^{\tau} - L_{AC}^{\tau}) - \frac{(D^{\tau})_0 + e^{\tau}(\beta_0^{\tau} - \alpha_2)}{2}. \tag{26}$$

to guarantee a feasible global cost function.

Proof: Refer to Appendix. ■

3) PROBLEM FORMULATION

The ISO aims to minimizes the global cost of energy distribution, which is expressed as:

$$\begin{aligned} \underset{E_0^{\tau},y}{\text{minimize}} \quad & f(E_0^{\tau}, y) \\ \text{s.t.} \quad & C12: D^{\tau} \in [D_{-}^{\tau}, D_{+}^{\tau}], \\ & C13: E_0^{\tau} \in [-S_0^{\tau-1}, E_{0\_max} - S_0^{\tau-1}], \\ & C14: (25) \text{ if } x \geq 0, \\ & C15: (26) \text{ if } x \leq 0, \\ & C16: \beta^{\tau} \in [\beta_{-}^{\tau}, \beta_{+}^{\tau}], \end{aligned} \tag{27}$$

where the constraints on y is indicated by the feasible range of unmatched loads $[D_{-}^{\tau}, D_{+}^{\tau}]$, $S_0^{\tau-1}$ is the energy remained in the utility storage before the scheduling cycle.

4) SOLUTION

To solve the piecewise binary quadric optimization problem (27), a solution based on classified discussion is introduced. Each optimization problem is classified into 2 sub-problems by determining the feasible range of x and the optimal point is chosen as the better results between the two sub-problems. The first sub-problem is expressed as:

$$\begin{aligned} \underset{E_0^{\tau},y}{\text{minimize}} \quad & \alpha_1^{\tau} x^2(E_0^{\tau}, y) + \alpha_2^{\tau} x(E_0^{\tau}, y) - \beta^{\tau} D^{\tau}, \\ \text{s.t.} \quad & C12,\ C13,\ C16,\ (25), \quad x \geq 0. \end{aligned} \tag{28}$$

We examine whether the extreme point is in the range. By

$$\begin{cases} \dfrac{\partial f}{\partial E_0^{\tau}} = 0, \\ \dfrac{\partial f}{\partial y} = 0, \end{cases} \tag{29}$$

we have

$$\begin{cases} E_0^{\tau} = G_{eco}^{\tau} - L_{AC}^{\tau} - \dfrac{1}{2}\left((D^{\tau})_0 + \beta_0^{\tau} + \dfrac{\alpha_2}{\alpha_1}\right), \\ y = \dfrac{(D^{\tau})_0}{2e^{\tau}} - \dfrac{\beta_0^{\tau}}{2}. \end{cases} \tag{30}$$

At this point, $\frac{\partial^2 f}{\partial E_0^{\tau} \partial E_0^{\tau}} = 2\alpha_1$ and $\frac{\partial^2 f}{\partial y \partial E_0^{\tau}} - \frac{\partial^2 f}{\partial E_0^{\tau} \partial E_0^{\tau}} \frac{\partial^2 f}{\partial y \partial y} = -4\alpha_1\, e^{\tau}$ indicate that it is a minimum point. However, $x = -\frac{\alpha_2}{\alpha_1} < 0$ indicates it is out of range. Now we have to obtain the optimal point by analyzing the monotonicity of the objective function in the feasible range. Since the algebraic solution is too complex as it requires further classified discussions on those undetermined constants, we do not present the detailed procedure. Instead, we will present an example of the solution in the simulation section with all the values of the constants determined. The other sub-problem is expressed as:

$$\begin{aligned} \underset{E_0^{\tau},y}{\text{minimize}} \quad & -\alpha_3^{\tau} x^2(E_0^{\tau}, y) - \alpha_4^{\tau} x(E_0^{\tau}, y) - \beta^{\tau} D^{\tau}, \\ \text{s.t.} \quad & C12,\ C13,\ C16,\ (26), \quad x \leq 0. \end{aligned} \tag{31}$$

In this case, (29) does not lead to an extreme point since at the point $\frac{\partial^2 f}{\partial y \partial E_0^{\tau}} - \frac{\partial^2 f}{\partial E_0^{\tau} \partial E_0^{\tau}} \frac{\partial^2 f}{\partial y \partial y} = 4\alpha_3\, e^{\tau} > 0$. We also have to obtain the optimal point by analyzing the monotonicity of the objective function in the feasible range.

VI. SIMULATION RESULTS AND ANALYSES

A simulated distribution grid is established based on the living and productive activities in North America.

A. DAY-AHEAD SETTINGS

1) DISTRIBUTION GRID SCALE

We assume 300 residential houses as residential loads in the simulations, of which the average daily loads per house is around $31KWh$ [28]. Hence the average daily aggregate residential loads is $9300kWh$. The average daily commercial loads and industrial loads are respectively set as $9055KWh$ and $6120KWh$ according to the shares of U.S. retail sales of electricity released by the U.S. Energy Information Administration [29], where residential loads accounts for 38%, commercial loads accounts for 37%, and industrial loads accounts for 25%. Characteristics of the three kinds of load profiles, e.g., feature of the load shapes, are based on [21] and [30] and the datum provided by the U.S. Department of Energy, available on OpenEI [28].

2) PROPORTION OF DC SECTOR LOADS

We assume only residential and commercial loads can be converted into DC sector loads, and fix the ratio of the two kinds of loads at 3 : 1 in the DC sector. For example, if 100 residential houses with $3100KWh$ loads are in the DC sector, elastic commercial loads in the DC sector is correspondingly $1033KWh$, whereby the DC sector accounts for 16.9% of the total loads. In some simulations, the number of houses in the DC sector is set to vary from 0 to 300, with which the proportion of DC sector loads varies from 0 to about 50%.

3) FACILITIES' CAPACITIES

The maximum transmit power to a single house P_{MAX}^{CHN} is set as $50KW$.[2] The maximum transmit power between the utility router and its storage P_{STR}^{MAX} is set as $500KWh$. The maximum transmit power between the utility router and the DC commercial loads equals P_{STR}^{MAX}. The storage capacity of a DC sector house is set as $40KWh$, that of the utility storage E_{0_max} is set as 500 KWh, and that of the DC commercial loads is set flexibly in accordance with the loads.

[2] Capacity of a Canadian house meter can be $22KW$ $(200A,\ 110V)$ [31]. Considering the DC transmission, the capacity is set to be doubled.

4) DATA GENERATION

All subscribers' original load profiles or daily demands are generated based on the hourly profiles provided in [28]. DC subscriber a' required energy delivered in advanced E_{a_adv} is set as 90% of its estimated daily demand. Each feasible time interval for advanced energy distribution $[k_{a\_sta}, k_{a\_end}]$ is randomly generated, falling into the region between the 21th hour today to the 12th hour tomorrow.

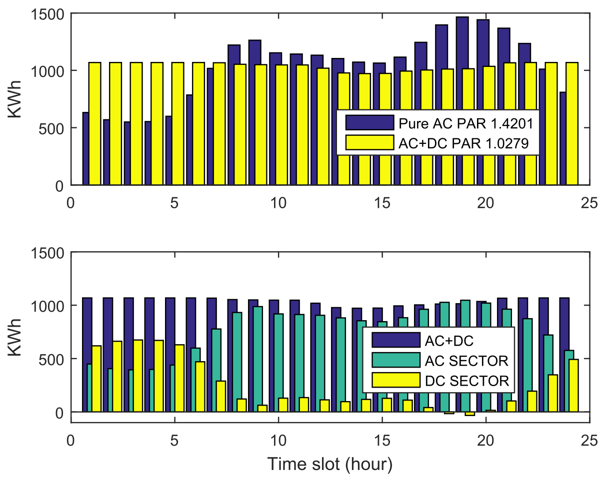

FIGURE 4. Distribution level and sector level scheduled load profiles.

B. DAY-AHEAD SCHEDULING WITH FIXED DC SECTOR LOADS

We consider 5 residential LAPPNs (LAPPNs 1-5) that each has 30 residential houses. The DC commercial industrial loads forms an independent LAPPN (LAPPN 6), with average 1550KWh daily demand and a 1500KWh storage. The average proportion of DC sector loads is $\frac{6200}{24475} = 25.3\%$. The minimum energy stored in advance in the utility storage $\underline{E}_{0\_\text{adv}}$ is set as 300KWh. The scheduling result is demonstrated by Fig. 4 and Fig. 5 together. From Fig. 5 we can check that the time region for advanced distribution determined by the algorithm is from the 21th hour today to the 12th hour tomorrow. At the distribution level shown by Fig. 4, the proposed scheme can effectively allocate the majority of DC sectoral loads in the time region for DC advanced distribution, corresponding to the non-peak hours of inelastic AC load profile. It can reduce the PAR to 1.0279 compared with the case when no loads are converted to the DC sector with PAR at 1.4201. At the DC intra-sector level shown by Fig. 5, despite the diversity of ESs' feasible advanced distribution time intervals in terms of length and starting time, the proposed scheme can effectively allocate the loads by successfully coordinating all participators' expected transmission time intervals. Moreover, because of the smoothness of charging power of the electric storages, the DC sector advanced energy distribution can be highly steady and controllable.

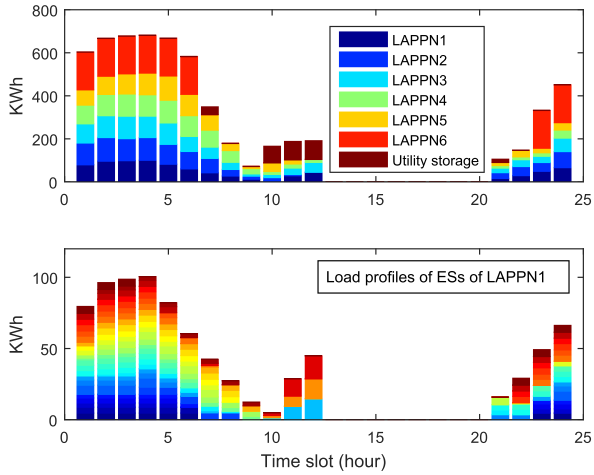

FIGURE 5. LAPPNs scheduled profiles and LAPPN 1 ES scheduled profiles.

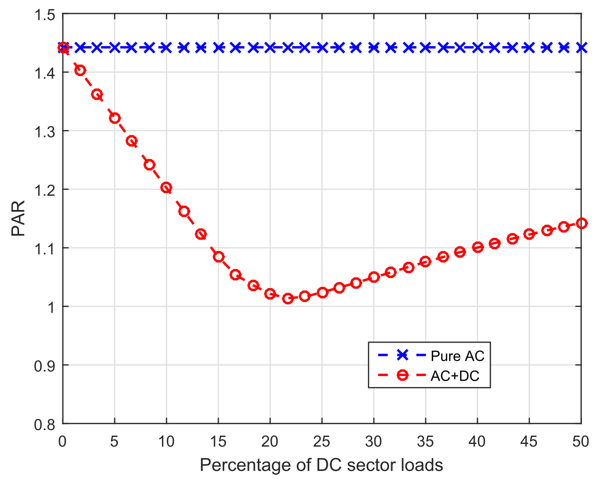

FIGURE 6. PAR versus proportion of DC sector loads.

C. IMPACT OF PROPORTION OF DC SECTOR LOADS

In this day-ahead scheduling case, we let the proportion of DC sector loads increase from 0 to 50% by a gap of 1%. The DC commercial storage correspondingly increase from 0 to 3000KWh. E_{0_max} increases from 0 to 1000KWh, and $\underline{E}_{0\_\text{adv}}$ increases from 0 to 600KWh. As shown in Fig. 6, when the proportion of DC sector loads reaches about 22%, the PAR can be reduced to nearly 1. On the other hand, with a further increase in the proportion, the PAR starts to increase slowly. This is due to the constraint on time length of the DC sector advanced energy distribution, i.e., we only allow maximal 12 hours for the DC sector advanced distribution. However, with the increase of DC sector loads, it no longer plays a complementary rule to the AC sector, but a dominant one over the AC sector. We may develop a more flexible distribution mechanism to regulate the operation when DC packetized-power distribution becomes dominant. For example, we can use a portion of the DC sector loads to compensate the AC sector load fluctuation, and schedule the rest of the loads to get charged sequentially, making them mutually complementary within the DC sector.

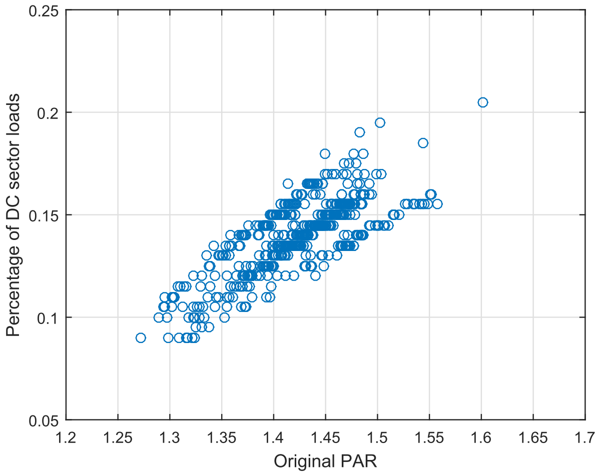

FIGURE 7. Proportion of DC sector loads versus original PAR.

D. REQUISITE DC SECTOR LOADS VERSUS LEVEL OF FLUCTUATION

Given a pure AC distribution grid load profile with high PAR, a requisite DC sector loads is defined as the amount of loads converted into DC sector loads that can be utilized to reduce the PAR to a certain level by scheduling. We want to know if, in general, an AC load profile with higher level of fluctuation, indicated by a higher PAR, requires a larger proportion of necessary DC sector loads to obtain a target PAR. In the simulation, the target PAR is set as 1.10. We have examined 500 different AC load profiles and obtain a distribution of proportion of DC sector loads versus original PAR, as shown in Fig. 7. The result is in accordance with our presumption, suggesting that when deploying LAPPNs, distribution grid with a higher level of load fluctuation needs a larger proportion of LAPPN loads, since a higher capacity of elasticity is required to compensate the fluctuation.

E. REAL-TIME SETTINGS

The simulation is set based on the day-ahead scheduling in Subsection VI-B, conducted on the hours except $\mathcal{K}_{\text{adv}}$.

1) GENERATION AND LOADS

The economic bulk generation capacity G^{τ}_{eco} is set equal to the distribution level scheduled loads. Short-term estimated DC sector unmatched loads $(D^{\tau})_0$ are set as Gaussian random variables of the DC sector scheduled loads, satisfying $N(L^k_{DC}, \frac{|L^k_{DC}|}{20})$. The feasible range of DC unmatched loads $[D^{\tau}_{-}, D^{\tau}_{+}]$ is set as $[(D^{\tau})_0 - 150KWh, (D^{\tau})_0 + 150KWh]$ Short-term estimated AC sector loads L^{τ}_{AC} are set as Gaussian random variables of the day-ahead planned loads, satisfying $N(L^k_{AC}, \frac{|L^k_{AC}|}{20})$.

2) PRICE AND COST

The basic buying/selling prices β^{τ}_0 are set to use the *Global Adjustment 1st Estimate* price [32] which are usually at $\$0.085/KWh$ to $\$0.250/KWh$, based on the *Hourly Ontario Energy Price* provided by the Independent Electricity System Operator, Ontario [32]. The feasible price range $[\beta^{\tau}_{-}, \beta^{\tau}_{+}]$ is set as $[0.05, 0.3]\$/KWh$. The price sensitivity factor e^{τ} in (20) is set as $1000(KWh)^2/\$$, i.e., if the price increases $\$0.01/KWh$ the DC sector unmatched loads is assumed to decrease $10KWh$. The deviation cost factors in (3) are respectively set as $\alpha^{\tau}_1 = \frac{\beta^{\tau}_0}{50}, \alpha^{\tau}_2 = 2\beta^{\tau}_0, \alpha^{\tau}_3 = \frac{\beta^{\tau}_0}{40}$ and $\alpha^{\tau}_4 = 5\beta^{\tau}_0$. That is, if $x > 0$, the marginal deviation cost at $x = 0KWh$ is critically set as $2\beta^{\tau}_0$, and that at $x = 100KWh$ is $6\beta^{\tau}_0$; if $x < 0$, the marginal deviation cost at $x = 0KWh$ is critically set as $-5\beta^{\tau}_0$, and at $x = -100KWh$ the total deviation cost reaches the peak.

F. COST MINIMIZATION CASE STUDY

We present the solution of cost minimization by an example based on a series of determined constants: $L^{\tau}_{AC} = 900$, $(D^{\tau})_0 = 200$, $G^{\tau}_{eco} = 1050$, $\beta^{\tau}_0 = 0.1$, and $S^{\tau-1}_0 = 150$.

Sub-problem (28) is expressed as:

$$\begin{aligned} \underset{(E^{\tau}_0, y)}{\text{minimize}} \quad & -5+\frac{2}{5}E^{\tau}_0+\frac{1}{500}(E^{\tau}_0)^2 - 4E^{\tau}_0 y - 500y+3000y^2 \\ \text{s.t.} \quad & E^{\tau}_0 \in [-150, 350], \quad y \in [-0.05, 0.15], \\ & 50 + E^{\tau}_0 - 1000y \geq 0. \end{aligned} \tag{32}$$

By $50 + E^{\tau}_0 - 1000y \geq 0$ and $y \in [-0.05, 0.15]$, E^{τ}_0 is further restrained to $[-100, 350]$. We have $\frac{\partial f}{\partial E^{\tau}_0} = \frac{2}{5} + \frac{1}{250}(E^{\tau}_0 - 1000y) \geq \frac{1}{5}$. Thus, f is an increasing function of E^{τ}_0, based on which we let $E^{\tau}_0 = -100$. Next, $\frac{\partial f}{\partial y} = 6000y - 100$, $y \leq -0.05$. Hence, the minimum cost -12.5 is obtain at $(-100, -0.05)$.

Sub-problem (31) is expressed as:

$$\begin{aligned} \underset{(E^{\tau}_0, y)}{\text{minimize}} \quad & -51.25-\frac{3}{4}E^{\tau}_0-\frac{1}{400}(E^{\tau}_0)^2+5E^{\tau}_0 y+650y-1500y^2 \\ \text{s.t.} \quad & E^{\tau}_0 \in [-150, 100], \quad y \in [-0.05, 0.15], \\ & 50 + E^{\tau}_0 - 1000y \leq 0. \end{aligned} \tag{33}$$

We have $\frac{\partial f}{\partial E^{\tau}_0} = -\frac{3}{4} - \frac{1}{200}E^{\tau}_0 + 5y \in [-\frac{5}{4} + 5y, 5y]$ and $\frac{\partial f}{\partial y} = 5\,E^{\tau}_0 + 650 - 3000y \in [200 + 5\,E^{\tau}_0, 800 + 5\,E^{\tau}_0]$. (1) assuming $y \leq 0$ by which E^{τ}_0 is further restrained by $[-150, -50]$, we have $\frac{\partial f}{\partial E^{\tau}_0} \leq 0$, i.e., f is a decreasing function of E^{τ}_0. Thus we let $E^{\tau}_0 = -50$ and get $y = -0.05$. However this point is out of range. (2) assuming $y \geq 0$, we let $\frac{\partial f}{\partial E^{\tau}_0} = 0$ and $\frac{\partial f}{\partial y} = 0$ to get the extreme point $(-100, 0.05)$ whose cost is 2.5. (3) assuming $E^{\tau}_0 \geq -40$, we have $\frac{\partial f}{\partial y} \geq 0$, i.e., f is an increasing function of y. Let $y = -0.05$, whereby E^{τ}_0 should satisfy $E^{\tau}_0 \leq -100$, in contradiction with the assumption. (4) assuming $E^{\tau}_0 \leq -40$, we let $\frac{\partial f}{\partial y} = 0$ and $\frac{\partial f}{\partial E^{\tau}_0} = 0$ to get the extreme point $(-100, -0.05)$ whose cost is -12.5.

In conclusion, both sup-problems get the optimal cost -12.5 at $(-100, -0.05)$.

G. REAL-TIME ENERGY DISTRIBUTION MANAGEMENT

Based on the settings, we test the real-time management in 1000 days. A single-day example is shown in Fig. 8.

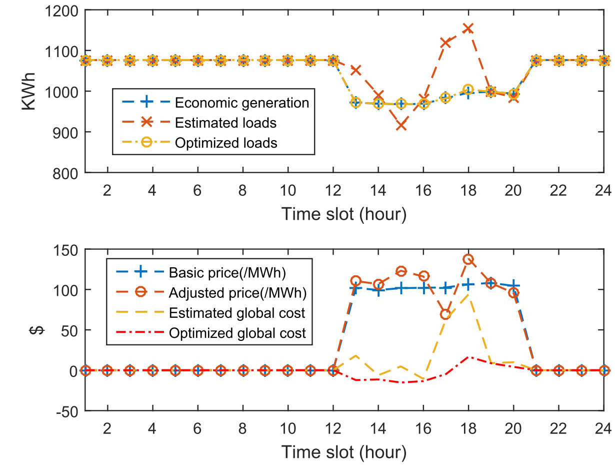

FIGURE 8. Realtime load profile.

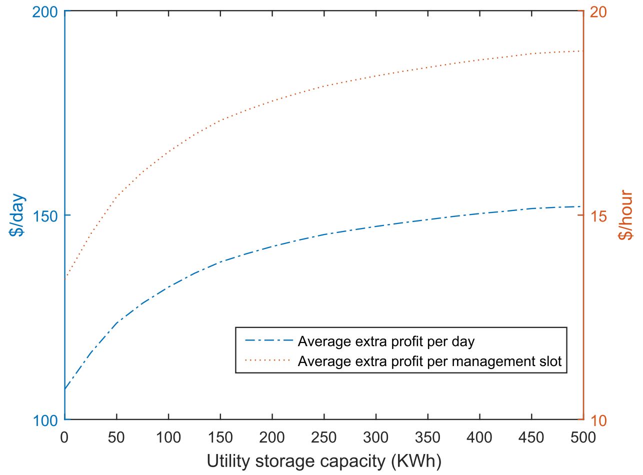

FIGURE 9. Extra profit versus utility storage capacity.

The original average hourly deviation loads is 43.6622KWh, while the optimized average hourly deviation loads is reduced to 0.2121KWh. The original average hourly global cost is \$13.1094 while the optimized average global cost is $\$-6.3222$. The proposed real-time energy distribution management can effectively manipulate the DC sector loads to compensate the distribution load fluctuation and create extra profit by utilizing the utility storage as a buffer and the energy interchanging price as an incentive to affect DC ESs' behaviors. In addition, we study the relationship between the extra profit, defined as the original global cost minus the optimized original cost, and the capacity of utility storage. As shown in Fig. 9, with the increase of storage capacity, higher extra profit is obtained by the proposed management. This suggests a higher utility storage capacity has enabled a higher management flexility for the controller to shape loads and thus create more benefits. On the other hand, the marginal extra profit is decreasing over the storage capacity, suggesting that it will be less cost efficient to deploy a storage of excessive capacity in terms of a distribution grid with a certain scale.

VII. CONCLUSION

In this paper, we have proposed an integrated power distribution network, encompassing conventional AC distribution sector, and DC distribution sector (i.e., LAPPNs). We have proposed a cross-time hierarchical scheduling scheme with corresponding optimizations and solutions to reduce the distribution level load fluctuation by manipulating the shape of elastic loads. Simulation results have demonstrated the effectiveness of the proposed scheme in reducing load fluctuation on both the day-ahead basis and the real-time basis, and further revealed important facts: for an average North American distribution grid, a flat load profile can be effectively obtained by converting about one-fifth of its total loads into elastic loads through energy storage devices (consider residential and commercial loads to be converted); a distribution grid with a higher level of load fluctuation generally requires a larger proportion of elastic loads for fluctuation compensation; and a centrally deployed DC sectoral storage with appropriate capacity can significantly contribute to smooth energy distribution of the system during on the real-time basis.

For further works, distribution mechanism can be further studied in a pure DC packetized-power distribution network, where conventional on-peak and off-peak concept no longer exists. LAPPNs can be divided into several complementary sectors being sequentially 'charged'. Moreover, the LAPPN networking and store-then-consume operation has potential in incorporating large plug-in electric vehicles (PEV) penetration in distribution networks while mitigating the distribution level load fluctuations.

APPENDIX

PROOF OF PROPOSITION 1

Based on (20) and the definition of x, the relation between y and x can be obtained as $y = \frac{(D^\tau)_0-(x-E_0^\tau-L_{AC}^\tau+G_{eco}^\tau)}{e^\tau}$. We rewrite f as a function of x and E_0^τ: $f = C(x) - (\beta_0^\tau + \frac{(D^\tau)_0-(x-E_0^\tau-L_{AC}^\tau+G_{eco}^\tau)}{e^\tau})(x - E_0^\tau - L_{AC}^\tau + G_{eco}^\tau)$. When $L_{AC}^\tau + (D^\tau)_0 > G_{eco}^\tau$, it is required that $\frac{\partial f}{\partial x}|_{x=0^-} \leq 0$ to satisfy Property 2. When $x < 0$, $\frac{\partial f}{\partial x} =$

$$-2\alpha_3 x - \alpha_4 - \beta_0^\tau + \frac{2(x - E_0^\tau - L_{AC}^\tau + G_{eco}^\tau) - (D^\tau)_0}{e^\tau}.$$

Hence, we have

$$-\alpha_4 - \beta_0^\tau + \frac{2(-E_0^\tau - L_{AC}^\tau + G_{eco}^\tau) - (D^\tau)_0}{e^\tau} \leq 0,$$

from which (25) is derived. When $L_{AC}^\tau + (D^\tau)_0 < G_{eco}^\tau$, it is required that $\frac{\partial f}{\partial x}|_{x=0^+} \geq 0$ to satisfy Property 2. When $x > 0$, $\frac{\partial f}{\partial x} =$

$$2\alpha_1 x + \alpha_2 - \beta_0^\tau + \frac{2(x - E_0^\tau - L_{AC}^\tau + G_{eco}^\tau) - (D^\tau)_0}{e^\tau}.$$

We have

$$\alpha_2 - \beta_0^\tau + \frac{2(-E_0^\tau - L_{AC}^\tau + G_{eco}^\tau) - (D^\tau)_0}{e^\tau} \geq 0,$$

from which (26) is derived.

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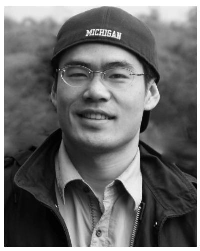

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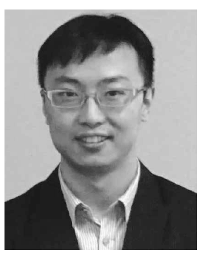

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