A Rudiment of Energy Internet: Coordinated Power Dispatching of Intra- and Inter-Local Area Packetized-Power Networks

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Abstract—Local area packetized-power network (LAPPN) provides flexible local power dispatching in the future Energy Internet. With interconnections among multiple LAPPNs, power dispatching can be further extended to intra- and inter-LAPPN power interchanges. It becomes a significant issue to schedule the two kinds of power interchanges as, from a system perspective high utilization of available scheduling time slots and low overall transmission loss should be guaranteed, and from a subscriber perspective a high scheduled ratio of transmission requests with a fair transmission sequence in terms of transmission urgency are expected. To this end, we propose a cooperative power dispatching framework for connected LAPPNs, including subscriber matching and two-layer power transmission scheduling. The former matches subscribers from different LAPPNs, considering both subscriber preferences and power transmission loss. The latter coordinates the intra- and inter-LAPPN power packet transmission to maximize the amount of energy delivered with a guaranteed fairness on user urgency. Simulation results of a two-LAPPN system are provided, which demonstrate that the proposed framework can achieve effective and efficient power dispatching in terms of the mentioned concerns, and reveal facts on ideal system capacity and how to manipulate the proportions of the two kinds of transmissions according to network status.

Index Terms—DC packetized-power network, power dispatching, networking, scheduling.

I. INTRODUCTION

Composition and function of power distribution networks have been continually renovated since the emergence and commercialization of renewable energy [11–13]. As a paradigm of the renovation, micro-grid [2] incorporates a certain size of renewable energy generation such as wind farm and photovoltaic (PV) farm, with a cluster of equivalent residential loads, which can realize an independent local operation with power self-sufficiency. Correspondingly, energy storage technology [4–8] has also been evolving to support the integration of renewable energy and plug-in electric vehicles (PEVs) [9], promoting an increasing penetration of distributed energy resources (DERs) to the grid. They are together making it a bidirectional-energy-flow power system.

A bright future of household energy storage can be deduced from the popularization of PEVs, as the capacity of a PEV battery system is more than sufficient for household usage, e.g., Tesla Model S 85D’s battery capacity is 85kWh, while the cost of battery packs for PEV is rapidly falling [10]. With PV generation experiencing a similar decrease in cost and an increase in efficiency, downsized distributed energy generation and storage system has a high potential to be widely deployed at residential house level [7], [8] where renewable energy resource is in abundance. We can foresee a common scene where every family can independently manage the production, consumption and storage of electricity, creating a strong incentive for people to establish and participate in a local electricity market to trade surplus energy with their neighbors in need.

The increasing penetration of DERs and the residential energy cooperations will significantly contribute to the load balancing in local area and thus reduce system’s excessive workload of bulk generation and power dispatching. But to fully achieve the benefits, the future power system has to tackle challenges such as stable and efficient operation under large penetration of DERs, flexible power dispatching for distribution networks where energy subscribers (ESs) can trade energy with each other, and incorporation of heterogeneous power transmission specifications, e.g., electric energy at different voltage or power levels [11]. The current AC power system is an on-demand system operating at a unified frequency and with a stable phase distribution. It is compulsorily required to maintain the balance between generation and load, as a failure will lead to frequency deviation in the network, decrease of voltage at the demand side, or even blackout. The injection of energy into the grid should be at a predetermined phase and power level with frequency synchronization. For DERs, the penetration even requires more complex operations such as power conversion and stabilization, frequency synchronization and phase control [12], [13]. A large penetration of DERs can pose critical challenges on steady, efficient and economic operation to the current system [14]. Besides, limited by its operating regime, the AC system may also be inefficient in supporting flexible power dispatching.

To achieve the expected functions of residential power distribution, recent studies have proposed a DC packetized-power distribution technology [15], [16]. Distinguished from the AC power system, the DC packetized-power system is a routing system, where power is delivered from a supplier to a demander via power routers [16], in the form of power packet that includes address information and payload. The power transmitted between the supplier-demander pair becomes a distinctive energy packet, of which the specification of the payload can be determined by the pair according to their preferences [15], [16]. This achieves flexible power dispatching and also supports a large penetration of DERs, as power con-
version, frequency synchronization and phase control can be substantially reduced. An in-home DC packetized-power distribution system by circuit switching has been proposed in [13] to coordinate the power consumption of electric appliances. A power packet distribution system with a schematic of power router as the key component of power packet dispatching has been further proposed and experimentally verified in [16] by a prototype with two power sources and two loads.

The transmission of the power packet requires an independent electrical path from the supplier to the demander, during which all the other applicants for the engaged public electric path are suspended. This time-division-multiplexing (TDM) manner will change how people consume electricity as they cannot receive electricity from the network at all time. The power of payload of power packet would be considerably enlarged, so as to deliver enough energy in a limited time length for user’s usage in a long duration. Therefore, it requires an efficient network structure and power dispatching scheme to schedule the transmission of power packets to meet energy users’ requirements. A simple algorithm proposed for a pulsed power network [17] similar to the DC packetized-power network, realizes a first-come-first-serve transmission. The preliminary work of Ma et al. [18] first proposed an local area packetized-power network (LAPPN) to serve tens of residential ESs. A packetized-power dispatching protocol has also been proposed for intra-LAPPN power dispatching, where the involved subscribers are matched into demander-supplier pairs first, and the matched pairs’ transmission tasks are then orderly scheduled over multiple power channels (independent electric paths) of the power router.

As a further step, this study extends the scenario of single LAPPN operation to a larger regional area consisting of multiple LAPPNs. By connecting the neighbouring LAPPNs, inter-LAPPN power distributions can also be achieved. This leads to an escalated power dispatching problem from intra-network layer to inter-network layer, with an intensified significance for global balance of demand and generation. The inter-LAPPN power transmission, on the other hand, generally takes a longer path that potentially incurs a larger transmission loss. The pros and cons suggest that supporting inter-LAPPN power transmission and reducing senseless transmission loss be equally considered upon power dispatching. In addition, the transmission scheduling also becomes more complex to coordinate intra-LAPPN power transmissions with inter-LAPPN ones that will simultaneously occupy the power routers of the corresponding LAPPNs. To this end, we propose a cooperative framework for packetized-power dispatching among multiple LAPPNs. The contributions are summarized as follows.

- As an operational regulation, the cooperative framework defines procedures such as subscriber matching, two-layer transmission scheduling and power packet transmission. It cyclically manages the packetized-power distribution, and can effectively coordinate both the intra- and inter-LAPPN power packet transmissions.
- The subscriber matching is formulated as a one-to-one stable matching problem, where the design of ES’s preference relation considers both the ES’s interest to maximize its utility and the controller’s concern on reducing senseless transmission loss and manipulating the outcome to balance the intra- and inter-LAPPN power packet transmissions.
- The transmission scheduling is formulated from the system perspective to maximize the amount of energy delivered while ensuring higher priorities for ESs with urgent requirement on energy delivery, and effectively coordinate intra- and inter-LAPPN transmissions. We develop a heuristic scheduling algorithm to achieve a fair and orderly transmission at a high scheduled ratio of the energy required to be transmitted.
- Simulations demonstrate effectiveness of the proposed cooperative framework and algorithms in achieving an efficient power dispatching with high utilization. Based on the results, we study the ideal capacity a two-LAPPN power system and discuss how to wisely and effectively operate the system.

The remainder of this paper is organized as follows. In Section [II] we introduce the system model. In Section [III] we present the cooperative framework, where the problem formulations and proposed solutions for the subscriber matching and transmission scheduling are also separately introduced. Simulation results and analyses are provided in Section [IV] and concluding remarks are drawn in Section [V].

II. System Model

We consider a regional DC packetized-power distribution network composed of residential LAPPNs and large-scale DERs, as illustrated in Fig. I. In each LAPPN, a core power router links a number of neighboring ESs and connects to the other power routers. Each ES in the LAPPN possesses a smart meter to manage the power exchange and consumption, and a battery system as a buffer. ESs are allowed to equip small-scale DERs, which enable them to sell energy in the local
electricity trading. All the LAPPNs are connected to the power utility’s power router, while there can be, but not necessarily, a connection between two arbitrary LAPPNs’ power routers.

**LAPPN power router:** A router provides interfaces for all the ESs and exterior interfaces to other regional network components. It is embedded with LAPPN management system to centrally manage the trading and the power dispatching. Each ES communicates with the router independently and trades on the management platform. A power channel, i.e., the electric path that carries the power transmission [18], has a maximum power capacity \( p_{\text{max}} \). Each power channel operates in a TDM manner, i.e., only one power packet can be delivered at a time. Similar to the preliminary work [18] and shown in Fig. 2, each LAPPN router equips multiple power channels to simultaneously support multiple power packet transmissions.

**Power packet:** As defined in [18], the time duration of a power packet is \( l = nh \), where \( h \) is the time length of an intended minimum time slot, and \( n \) is a positive integer. In terms of delivered energy, we assume the duration of the payload of a packet approximately equals \( l \), since the time lengths of header and footer are about tens of microseconds [16], negligible compared with the payload at the scale of minutes.

**Power transmission specification:** An arbitrary ES denoted by \( a \), can participate in the trading either as a demander further denoted by \( i \), or a supplier further denoted by \( j \). \( L(a) \) denotes the LAPPN that \( a \) belongs to. We assume a demander \( i \) in LAPPN \( A \), i.e., \( L(i) = A \), and a supplier \( j \) in LAPPN \( B \). Let \( p^i \) and \( p^j \) respectively denote the export power of the supplier, and the received power of the demander, satisfying

\[
  p^j = p^i (1 - \epsilon^i), \quad p^j \leq p_{\text{max}}^i.
\]

where \( \epsilon^i \in [0, 1] \) denote the transmission loss factor between the supplier and the demander. For simplicity, we do not consider the power loss due to router forwarding, and assume \( \epsilon^i \) as a linear function of the distance between the supplier and the demander [19]. \( \epsilon^i \) can be expressed as

\[
  \epsilon^i = \epsilon^i + \epsilon^{L(j)L(i)} + \epsilon^i,
\]

where \( \epsilon^i \) indicates the transmission loss between \( j \) and the router of LAPPN \( B \), \( \epsilon^{L(j)L(i)} \) the loss between the two routers and \( \epsilon^i \) the loss between the router of LAPPN \( A \) and \( i \). \( \epsilon^{L(j)L(i)} = 0 \), if \( B = A \). Given export energy \( E^i \) and energy demand \( D^i \), the balance of demand and supply can be mathematically expressed as:

\[
  D^i = E^i (1 - \epsilon^i).
\]

**III. COOPERATIVE FRAMEWORK**

As a generalization of the intra-LAPPN packetized power dispatching protocol [18], the multi-LAPPN power dispatching is also divided into three sequential event cycles. As shown in Fig. 2 a centralized regional controller first makes ESs pair up, then allocates power channels of each LAPPN router for intra- and inter-LAPPN power packet transmissions and schedules the power transmission tasks orderly. Finally, power interchanges are conducted as scheduled.

**A. Subscriber Matching**

1) **Registration:** Controller releases the information on power router availability and requires ESs to report their requests via the smart meters. Consider a set of available power routers \( \mathcal{R} \), where \( K \in \mathcal{R} \) denotes an arbitrary power router, and also its corresponding LAPPN. We assume \( M^K \) available channels for router \( K \in \mathcal{R} \). Let \( C^K = \{1, 2, \ldots, m^K, \ldots, M^K\} \) denote the set of available power channels. The available transmission capacity of \( m^K \) for scheduling is given by:

\[
  S_{\text{m}} = N_{\text{m}}^K h p_{\text{max}}^i.
\]

where \( N_{\text{m}}^K \) is the number of available time slots for the current event cycle. As shown in Fig. 2 upon a time for scheduling the upcoming transmissions, Channel 2 is already idle while the others are still busy. We assume the same time boundary for all the channels in current scheduling. ES with request should register on the trading platform as a demander or a supplier. Let \( S_d = \{1, \ldots, i, \ldots, I\} \) and \( S_s = \{1, \ldots, j, \ldots, J\} \) respectively denote the set of demander ESs, and that of the supplier ESs. Demander ES \( i \) has to report its energy demand range \( [D_{\text{min}}^i, D_{\text{max}}^i] \) and the bidding factor \( \iota^i \geq 1 \) representing its urgency on buying energy. Supplier ES \( j \) has to report its available energy range \( [E_{\text{min}}^j, E_{\text{max}}^j] \), and the discount factor \( 0 < \kappa^j \leq 1 \) representing its urgency on selling energy. Moreover, each ES \( a \) should also report its feasible generating or receiving power range \( [p_{\text{min}}^a, p_{\text{max}}^a] \).

2) **ES Preferences:** Next, ESs can check the availability of power routers and the other ESs’ requests. Based on the released information, each ES uploads a preference list (PL) on cooperators (i.e., the trading partners) before a deadline. Transmission requests with large-scale DERs and the power utility as special cooperators, will be dealt with after the scheduling for normal matched pairs. Practical pre-conditions should be addressed before the ESs select potential cooperators:

\[
  E_{\text{min}}^j \leq \frac{D_{\text{min}}^i}{1 - \epsilon^i} \leq E_{\text{max}}^j, \quad \frac{p_{\text{min}}^a p_{\text{max}}^a}{1 - \epsilon^i} \cap [p_{\text{min}}^a, p_{\text{max}}^a] \neq \emptyset,
\]

i.e., the energy demand and supply should be roughly matched, and so do the generating power and received power. Let \( \mu(a) \) denote the cooperater of \( a \) by matching \( \mu \). We define the maximal matchable energy of \( a \) and \( \mu(a) \) as:
require its power channels, the unscheduled pairs will have to be matched. 

Definition 2. A matching \( \mu \) is improved upon by any individual or any pair of ESs, if it cannot be improved

Each ES is considered to maximize its utility \( U^\mu(a) \) of energy cooperation, where

\[
U^\mu(a) = \begin{cases} 
0, & \mu(a) = a, \\
E^\mu(a)/\mu(a), & \mu(a) \neq a, a \in S_d, \\
\min \left\{ (1 - \epsilon^\mu(a))E^\mu_{\max}, \mu(a) \neq a, a \in S_s \right\}, & \mu(a) \neq a, a \in S_s.
\end{cases}
\]  

(5)

On the other hand, the centralized controller from a system perspective, tends to minimize transmission losses. Hence, the preference relation function, denoted by \( f(a, \mu(a)) \), is designed as a coordination of ES utility and transmission loss:

\[
f(a, \mu(a)) = U^\mu(a) - \left( \eta_i(e^a + e^{\mu(a)}) + \eta_j(e^{L(a)(\mu(a))}) \right) E^{\mu(a)},
\]

where \( e^a, e^{\mu(a)} \) and \( e^{L(a)(\mu(a))} \) respectively indicate \( a \)'s intra-transmission loss, \( \mu(a) \)'s intra-transmission loss, and the inter-transmission loss between the two LAPPN. \( \eta_0 \) is a weight factor predetermined by the controller to adjust the impact of intra-transmission loss, and \( \eta_l \) to adjust the impact of inter-transmission loss. The preference relation \( >_a \) is thus given by:

\[
\forall b_j > a \iff f(a, b_j) > f(a, b_j).
\]

(8)

Let \( \mathcal{P} \) denote the set of all ESs' preference relations.

3) Matching: Receiving all the PLs, the controller determines the subscriber matching and the power transmission specification of power packets.

Definition 1. A subscriber matching problem is defined over \( S_d \) and \( S_s \) by \( \mathcal{P} \), where each ES tries to get matched to at most one ES on the other side according to its PL. The problem is denoted by the triple: \((S_d, S_s, \mathcal{P})\).

A matching \( \mu \) can be improved upon by some pair consisting of \( i \in S_d \) and \( j \in S_s \), if \( i \) and \( j \) are not matched to one another at \( \mu \), but prefer each other to their assignments at \( \mu \), i.e. if \( i > j \mu(j) \) and \( j > i \mu(i) \).

Definition 2. A matching \( \mu^* \) is stable if it cannot be improved upon by any individual or any pair of ESs.

It has been proved in [21] that there always exists a nonempty set of one-to-one stable matchings. We use the deferred acceptance (DA) algorithm [21] to achieve a stable subscriber matching. Given all the ESs' PLs, the controller will centrally proceed the matching process for the ESs, and generate a set of matched demand-supply pairs, denoted by \( Q(\mu^*) \), where an arbitrary pair is denoted by \( (i, j) \).

B. Two-layer Transmission Scheduling

The controller first schedules the power packet transmission of matched ESs, then the power packet transmission between the unmatched ESs and large-scale DERs or the power utility if applicable. The available capacity \( E_{\max}^K \) of routing channel \( K \) is

\[
E_{\max}^K = \sum_{m \in C^K} E_{\max}^m.
\]

(9)

For any router, if \( E_{\max}^K \) is not enough for all the pairs that require its power channels, the unscheduled pairs will have to wait for the next scheduling. If there is still available capacity after all the pairs are arranged, the controller will schedule the channels for the unmatched ESs.

1) Matched Pair Scheduling: The controller aims to maximize the scheduled amount of matched demand-supply energy while guaranteeing a fair order of power packet transmission in accordance with ESs’ different urgency degrees. We design a utility model to characterize the concern. Let \( Q(\mu) = \{1, 2, ..., Q\} \) denote the set of \( Q \) matched demand-supply pairs by matching \( \mu \), and \( q \) denote \( q \)-th demand-supply pair. For pair \( q = (i, j) \), we define an utility function \( \omega^q \) as

\[
\omega^q = \frac{t^i_{K}}{K^j} E^{ij},
\]

where \( E^{ij} \) is the matched and scheduled energy of pair \( q \), \( t^i \) represents \( i \)'s urgency on buying energy, and \( 0 < \kappa^j \leq 1 \) represents \( j \)'s urgency on selling energy. We use a binary indicator \( W^q \) to indicate whether pair \( q \) has been scheduled for transmission. To indicate the power channel(s) that each pair is assigned to, we define an assignment matrix for each pair as

\[
w^q = [w^q_{K,m}]_{K \times m},
\]

(11)

where \( w^q_{K,m} \in \{0, 1\} \) indicates whether channel \( m \) of LAPPN \( K \) has been assigned to pair \( q \). \( 1_{1,K}w^q_{1,M,K} \) indicates intra-LAPPN transmission, and \( 1_{1,K}w^q_{1,M,K} > 1 \) indicates inter-LAPPN transmission. Since multi-hop power packet delivery takes up too many router channels and cause high transmission loss, we only assume inter-LAPPN transmissions between neighboring connected LAPPNs, i.e., \( 1_{1,K}w^q_{1,M,K} \leq 2 \). Let \( \lambda^q \) denote the scheduling order of pair \( p \). The scheduling problem can be formulated as finding an assignment matrix and determining the transmitted energy for each pair to maximize the total utility weighted by \( \frac{1}{\lambda^q}\):

\[
\max_{w^q, E^{ij}} \sum_{q \in Q(\mu)} W^q \omega^q \lambda^q,
\]

s.t.

\[
C_1 : \sum_{q \in Q(\mu)} w^q_{K,m} E^{ij} \leq E_{\max}^K, \forall m \in C^K, K \in \mathcal{R},

\]

\[
C_2 : \lambda^q \neq \lambda^{q'}, \forall q_1, q_2 \in Q(\mu),
\]

\[
C_3 : \lambda^q > \lambda^{q'}, \forall q_1, q_2 \in Q(\mu)
\]

\[
C_4 : \frac{1}{1 - \epsilon} \leq E^{ij} \leq E_{\max}^K, \forall q \in Q(\mu)
\]

(12)

where \( C_1 \) ensures that the transmission power on each power channel does not exceed the capacity of the channel in the current scheduling, \( C_2 \) states that \( \{\lambda^q\}_{q \in 1,2,...,Q} \) is a rearrangement of \( \{1, 2, ..., Q\} \), \( C_3 \) ensures the fairness that a pair with higher utility value gets a higher priority to be scheduled, and \( C_4 \) is the constraint on the carried energy of the packet. Moreover, for inter-LAPPN transmissions, the controller has to respectively specify a power channel from each of the involved LAPPNs and synchronize the transmission period of the two channels.

To solve such a complex problem, we design a heuristic scheduling algorithm. After \( Q(\mu^*) \) is determined in the subscriber matching, the controller initializes a set of power transmission specifications \( S^q \) for each pair, defined as:

\[
S^q = ((i, j), w^q, E^{ij}, t^i, p^j, \lambda^q, \omega^q, w^q, W^q),
\]

(13)

where \( t^i \) is the time length of the power packet, \( p^j \) is \( j \)'s
Table I

| Step | Description |
|------|-------------|
| 01   | \( n \mapsto 1 \); initialize \( w_0 \). |
| 02   | Initialize \( C_K^K(n) \); \( C_f^K \forall K \in S \). |
| 03   | while \( \bigcup \{ C_f^K(n) \neq 0 \} \) do, and \( C_f^K(n) 
eq 0 \) for \( K \in \mathcal{S} \). |
| 04   | select the first pair \( q_1(n) = (i,j) \) in \( \mathcal{Q}^* \). |
| 05   | if \( i, j \in K \) then, |
| 06   | select the first power channel \( N_i^k \) in \( C_f^K(n) \). |
| 07   | if \( \frac{D_{\text{min}}}{1 - \epsilon h_i} \leq N_i^k \) then, |
| 08   | \( T_{\text{temp}} \) is the earliest \( \lfloor N_f^k \rfloor \) satisfying \( m \). |
| 09   | else set \( S^* \) accordingly. |
| 10   | set \( C_f^K(n) \) accordingly. |
| 11   | \( \{ N_j^k \} = \{ N_j^k \} - \frac{l_j^i}{h_i} \). |
| 12   | if \( \{ N_j^k \} = 0 \) then, |
| 13   | delete \( \{ N_j^k \} \) from \( C_f^K(n) \). |
| 14   | end if |
| 15   | else set \( \{ S^* \} \). |
| 16   | set \( C_f^K(n) \) accordingly. |
| 17   | \( N_j^k(n) = N_j^k(n) - \frac{l_j^i}{h_i} \). |
| 18   | if \( N_j^k(n) = 0 \) then, |
| 19   | delete \( N_j^k(n) \) from \( C_f^K(n) \) or. |
| 20   | end if |
| 21   | end if |
| 22   | end if |
| 23   | end while |
| 24   | end while |

Export power, and \( t_{\text{start}}^i \) is the start time of the power packet’s transmission. Next, for each LAPPN the controller sorts the power channels in a descending order of the available time slots \( N_i^m \), and also sorts the matched pairs in a descending order of \( \omega^j \). For LAPPN \( K \), let \( C_f^K \) denote the sorted set of power channels in which each power channel is represented by its \( N_i^m \), and \( C_f^K \) denote the set of flexible time periods of the power channels (to be introduced later with an example), of which an element is denoted by \( N_j^m \). Let \( Q^* \) denote the sorted set of demand-supply pairs where each pair is represented by its \( \omega^j \). Then, the scheduling iteration begins. In the \( n \)-th iteration, the controller selects the currently first ranked pair \( q_1(n) = (i,j) \in \mathcal{Q}^*(n) \). If \( i \) and \( j \) belong to the same LAPPN \( K \), the controller will try to assign the packet to the currently first ranked power channel \( N_i^m \in \mathcal{C}_f^K(n) \). The assignment will succeed if

\[
\frac{D_{\text{min}}}{1 - \epsilon h_i} \leq N_i^m \quad \text{(14)}
\]

If \( i \) and \( j \) respectively belong to \( K_1 \) and \( K_2 \), the controller will choose the smaller between \( N_{i_1}^m \) \( (n) \in \mathcal{C}_f^K(n) \) and \( N_{i_2}^m \) \( (n) \in \mathcal{C}_f^K(n) \). We suppose that \( N_{i_1}^m \) \( (n) \) is smaller. The assignment will succeed if

\[
\frac{D_{\text{min}}}{1 - \epsilon h_i} \leq N_{i_1}^m \quad \text{(15)}
\]

To better understand this operation, we refer to scheduling 6 in Fig. 2. Before scheduling, LAPPN 1 Channel 2 (L1C2) and L2C3 are respectively the first ranked channels while L1C2 has less available time slots and is chosen. For the other LAPPN, namely \( K_2 \), the controller will choose the channel \( N_{i_2}^m \) \( (n) \in \mathcal{C}_f^K(n) \) according to

\[
\min N_{i_2}^m \quad (n) - N_{i_1}^m \quad (n) \geq 0, \quad \text{(16)}
\]

which ensures that the following intra-LAPPN power packet of \( K_2 \) can be scheduled to an earlier time. In the example, only L2C3 satisfies (16) and is chosen.

Now a number of flexible time slots have been created, denoted by \( (N_f^m) \), where \( k \) indicates it is the \( k \)-th created flexible time slots in \( \mathcal{C}_f^K(n) \) due to inter-LAPPN transmission scheduling (e.g., the first 3 slots of L2C3 in Fig. 2). Flexible time slots can be used to carry the latter intra-LAPPN power packets if the time lengths fit. When there are flexible periods, the controller will first try to assign the intra-LAPPN packet to a flexible period before to the currently first ranked power channel. The earliest flexible period \( (N_f^m) \) that is prior to \( N_{i_1}^m \) \( (n) \) and satisfies

\[
\frac{D_{\text{min}}}{1 - \epsilon h_i} \leq (N_f^m), \quad \text{(17)}
\]

will be used to carry the intra-LAPPN transmission of \( K \) (example: scheduling 7 in Fig. 2).

Upon successful scheduling, the transmission specifications are determined by the following equations:

\[
E^{ij} = \min \left\{ \begin{array}{ll}
N_{i_1}^m (n) h, & \text{if intra-LAPPN,} \\
(N_f^m) h, & \text{if inter-LAPPN,}
\end{array} \right. \quad \text{(18)}
\]

\[
\min E_{\text{max}}, \quad \text{(19)}
\]

\[
\frac{E^{ij}}{1 - \epsilon h_i} \leq h_i, \quad p^{ij} = \frac{E^{ij}}{1 - \epsilon h_i}, \quad \lambda q^1(n) = n, \quad \text{and} \quad q_1(n) \text{ is set accordingly.}
\]

For each scheduled power channel, the number of available time slots \( N_{i_1}^m \) \( (n) \) is updated as \( N_{i_1}^m \) \( (n) = N_{i_1}^m \) \( (n) - \frac{l_j^i}{h_i} \). If \( N_{i_1}^m \) \( (n) = 0 \), the controller deletes it from \( C_f^K \). Otherwise, the controller puts \( N_{i_1}^m \) \( (n) \) back to \( C_f^K \) obeying the descending order. For each scheduled flexible period, \( (N_f^m) \) is similarly updated or deleted. If \( (14) \) or \( (15) \) is unsatisfied, the controller only has to delete \( q_1(n) \) from \( Q^* \). The algorithm terminates if there is no available channel or demand-supply pair. The detailed procedure is presented in TABLE I.

2) Unmatched ES Scheduling: It schedules the LAPPNs that still have available time slots after the matched pair scheduling. The unmatched ESS can buy power from the large-scale DERs or the power utility, or sell power to the power utility. Similarly, we use a modified utility model to evaluate the transmission, where the large-scale DERs and the power utility
are regarded as special subscribers. Let \( S_u \) denote the set of unmatched ESs, and \( S_{SS} = \{0, 1, ..., J, \ldots \} \) the set of special subscribers where \( J = 0 \) is the power utility and the others are large-scale DERS. For demander ES \( i \in S_u \), the utility function \( \omega^{ij} \) is expressed as \( \omega^{ij} = \frac{1 - e^{\alpha(i)}}{\kappa(i)} \cdot D^{ij} \). For supplier ES \( j \in S_u \), \( \omega^{jo} \) is defined as \( \omega^{jo} = \frac{1 - e^{\alpha(j)}}{\kappa(j)} \cdot E^{jo} \).

The scheduling indicator of an arbitrary unmatched ES \( \alpha \) is denoted by \( W^\alpha \), and the assignment matrix for \( a \) is \( w^a = [w^a_{K,m,n}] \), where \( \sum_{K \in S} \kappa \in \mathbb{C} w^a_{K,m,n} \leq 1 \). Let \( \lambda^\alpha \) denote the order of \( a \) to be arranged in the transmission scheduling. The unmatched ES scheduling problem and solution can be obtained with the modified variables replacing those in the former scheduling problem, which is not presented in detail.

C. Power Packet Transmission

Being notified with the power transmission schedule, each ES sends a confirmation to the controller and prepares to export or receive power packet at the scheduled time. If the controller does not receive the confirmation from either of an authorized demand-and-supply pair before the scheduled time, the scheduled transmission will be cancelled and the supplier ES will not be permitted to export energy.

IV. Simulation Results and Analyses

We consider a two-LAPPN case, where each LAPPN’s power router has 3 power channels. The maximum capacity of a power channel and a cable core \( p_{max} \) is set as 50KW [13].

The power cable linking the two LAPPN routers has 3 cores that can simultaneously support at most 3 inter-LAPPN power packets’ transmission. The time length of a time slot is equal to 1 minute [18], while the time lengths of header and footer are disregarded. The time slot is about tens of microseconds (tens) compared with a time slot. The maximum available time slots for each scheduling procedure is set as 20. Such that the scheduling capacity is \( 3 \times 50 \times 20 = 500 \text{KWh} \). As the percentage of transmission loss is at \( 10^{-4} \) to \( 10^{-3} \)[19], for this distribution system, we assume a 0% – 5% intra-transmission loss and a 0% – 15% inter-transmission loss, i.e., \( \epsilon^{ad} \in [0, 0.05] \), and \( \epsilon^{AB} \in [0.015] \). Weight factor \( \eta_0 \) is fixed at 2 while \( \eta_1 \) is between 0 and 4.

As described in [18], each ES equips an application program interface (API) that connects to the LAPPN power router and manages household storage, generation and consumption. We assume ES’s load and generation power vary over time independently, causing the fluctuation of stored energy. The capacity of energy storage system is assumed to be 10kWh referring to [5].

Still, we characterize two types of behavior patterns: when an ES’s stored energy is running out, it becomes a demander-type ES willing to buy electricity; when an ES’s stored energy is nearly fully charged by its distributed generation, it becomes a supplier-type ES willing to sell electricity. We assume that the demander-type ESs are with 2.5kWh average demand energy ranging from 0kWh to 5kWh, the supplier-type ESs are with 2.5kWh average selling capacity ranging from 0kWh to 5kWh. The settings of parameters and variables are summarized in Table 1.

![Table 1](image)

A. Performance of ES Matching

To evaluate the performance of ES matching, we compare the matched ratio \( \alpha_0 \) is defined as \( \alpha_0 = \frac{\sum_{i,j \in S} (1 - 1 - e^{\alpha(j)}) \text{E}_{max}}{\sum_{i,j \in S} \text{D}_{max} + \sum_{i,j \in S} \text{E}_{max}} \), i.e. the total matched energy over the total potential energy to be transmitted. Each LAPPN is assumed to have 30 ESs, while the proportions of the two types of ESs in each LAPPN vary. Let \( S_d \) and \( S_s \) respectively denote the number of demander ESs in LAPPN 1 and that in LAPPN 2. Each \( \{S_d, S_s\} \) stands for an independent simulated case and both \( S_d \) and \( S_s \) independently vary from 1 to 29. All \( \epsilon^{ad} \) is within \([0, 0.05]\) and \( \epsilon^{AB} \) is fixed at 0.05. For each \( \{S_d, S_s\} \), we run 200 simulations to obtain an average \( \alpha_0(\{S_d, S_s\}) \). Fig. 1(a) shows the results of all the ES matching cases, where the noncooperative scheme (no inter-transmission) is used for comparison. In most cases, the cooperative scheme outperforms the noncooperative one and equally in the other cases.

For further analysis, we select 4 typical cases and record their datum in Table 2.

![Table 2](image)

To better demonstrate the effectiveness of ES match-
expressed as: 

$$\text{CASE D}, \text{i.e., inter-LAPPN transmission requests grow dramatically,}$$

B. Transmission Scheduling and Overall Performance

We define a scheduled ratio of matched pairs by $\beta_0$, expressed as: $\beta_0 = \frac{\sum_{s \in S} \mu_s (1 - \epsilon_{ij}) E_{ij}^\mu}{\min(\sum_{s \in S} D_{max}^s + \sum_{j \in S_s} E_{max})}$, where the numerator is the total scheduled energy of matched ESs and the denominator is the total matched energy of matched ESs. This simulation is based on the outcome of ES matching in the former subsection. As shown in Fig. 4(b), in most cases, both scheduling algorithms maintain a high $\beta_0$ at nearly 100%. However, when it comes to extreme complementary case (CASE D), i.e., inter-LAPPN transmission requests grow dramatically, $\beta_0$ of cooperative scheduling algorithm decreases to 72.8%. This is due to both the limited scheduling capacity of power channels and power lines, and the synchronization of inter-LAPPN transmission. As calculated in the setting-up, a router and a 3-core inter-LAPPN power line both have a maximum scheduling capacity of 50kWh. In CASE D, 28 demander ESs in LAPPN 1 with average 2.5kWh demand, want to cooperate with 28 supplier ESs in LAPPN 2 with average 2.5kWh capacity. The average matched energy is $\text{min}(\sum_{s \in S} D_{max}^s + \sum_{j \in S_s} E_{max}^j) \cdot \alpha_0 = 2.5kWh \cdot 28 \cdot 85.6\% = 59.85kWh$, which is larger than the available scheduling capacity 47.5kWh (the only intra-LAPPN pair assumed scheduled). Therefore, the current scheduling capacity cannot meet the requirements of inter-LAPPN transmission. Nevertheless, the scheduled energy $\sum_{\mu \in \mathcal{Q}} E_{ij}^\mu = 59.85kWh \cdot 72.8\% = 43.57kWh < 47.5kWh$, indicating the available inter-LAPPN transmission capacity is not fully utilized. This is because the synchronization of inter-LAPPN transmissions create some flexible idle time zones which can no more be used for inter-LAPPN transmission.

For the overall performance, we define a utilization ratio by $\nu$ as the number of occupied time slots over the maximum available time slots to evaluate the utilization of the system. We define an overall scheduled ratio by $\gamma$ as the scheduled energy of all ESs over the total potential energy to be transmitted, given by: $\gamma = \frac{\sum_{\mu \in \mathcal{Q}} (2 - \epsilon_{ij}) E_{ij}^\mu + \sum_{s \in S_{uns}} (1 - \epsilon_{ij}) E_{ij}^s + \sum_{s \in S_{uns}} E_{max}^s}{\sum_{s \in S} D_{max}^s + \sum_{j \in S_s} E_{max}^j}$, where $S_{uns}$ is the set of scheduled unmatched demander ESs and $S_{uns}$ that of scheduled unmatched supplier ESs. This simulation uses the datum generated by the former transmission scheduling simulation. As shown in Fig. 4(c), both schemes obtain a high utilization of the system as in all cases the $\nu$ are close to 100%. This indicates that the proposed scheme is effective in allocating the power channel resource for energy cooperation. Fig. 4(e) suggests that both scheduling algorithms manage to maintain a high overall scheduled ratio over a restrained scheduling capability of 50kWh.

To further evaluate the cooperative scheduling, we compare the proportion of scheduled matched pairs with that of the scheduled unmatched ESs. Let $\gamma_0$ denote the ratio of scheduled matched energy over the total potential energy to be transmitted, given by $\gamma_0 = \frac{\sum_{\mu \in \mathcal{Q}} (2 - \epsilon_{ij}) E_{ij}^\mu}{\sum_{s \in S} D_{max}^s + \sum_{j \in S_s} E_{max}^j}$. In Fig. 4(d), the gap between the two surfaces equals to the proportion of scheduled unmatched energy. In CASE A, it is impossible for most of the supplier ESs to match demander ESs. Thus, the scheduling let them deal with the power utility. Once the LAPPNs become more complementary, i.e., CASES B, C, and D, the cooperative scheme can effectively increases the proportion of scheduled matched energy.
Fig. 5. Performance of the scheme II.

C. Priority of Transmission and Ideal LAPPN Capacity

To verify the fairness of transmission priority, we test CASE B for 10000 times and observe the outcome of scheduling matched pairs. As presented in Fig. 5(a) on average, a demander ES with higher bidding factor will have a higher priority to buy electricity, a supplier ES with smaller \( \kappa \), i.e., larger discount will have a higher priority to sell electricity, and a power packet with larger payload has a higher priority to be delivered. The result is in accordance with with the definition of \( \omega^q \) in (10), conveying the regulation in the scheme that those with higher urgency in buying or selling electricity have to offer higher prices or larger discount, and will on average get a higher priority of transmission. It also suggests that the proposed scheduling algorithm can maximize the scheduled amount of matched demand-supply energy.

Based on the cooperative framework, we study the optimal LAPPN capacity. An efficient operation should obtain both a high scheduled ratio \( \gamma \) and a high utilization of the system \( \nu \). We define an ideal LAPPN capacity as one corresponding to the case when both \( \bar{\gamma} \) and \( \bar{\nu} \) are no less than 90%. We assume two homogeneous LAPPNs that both have 50% demander ESs and 50% supplier ESs. The number of ESs in an LAPPN will increase from 2 to 60. For each fixed number of ESs, we test the case for 1000 times. As presented in Fig. 5(b) with a restrained scheduling capability of 50kWh in 20 minutes, the ideal capacity of an LAPPN for the cooperative scheme is between 26 to 30 ESs. Moreover, with an increase in number of ESs before saturation, the cooperative scheme has a higher \( \bar{\nu} \) than the noncooperative one. This is because the power channel resource to support an inter-LAPPN transmission is about two fold of that to support an equal intra-LAPPN transmission. When the LAPPN comes to saturation, the average scheduled ratio of cooperative scheme becomes lower than the noncooperative scheme. This is because in the cooperative case, all flexible time zones created by inter-LAPPN transmission will finally be cut down to smallest time slots that are not applicable after all scheduling procedures. But at least, the cooperative scheme can utilize those flexible time zones as many as possible.

D. Impact of \( \epsilon^{AB} \) and \( \eta_1 \) on Power Packet Transmission

We study under what conditions ESs would prefer inter-LAPPN transmission to intra-LAPPN transmission. Two variables can be the incentives to affect their preferences: the transmission loss factor between the two LAPPNs \( \epsilon^{AB} \) and the ratio \( \eta_1 \). We choose a balanced scenario, i.e., CASE B to study the impacts. Let \( \epsilon^{AB} \) vary from 0 to 0.15 at an interval of 0.01. Instead of directly determining \( \bar{\eta}_0 \), we fixed \( \eta_0 \) at 2 and let \( \eta_1 \) vary from 0 to 8 at an interval of 0.2. For each \( \epsilon^{AB}, \eta_1 \) we test 300 times. Fig. 5(c) shows that, for a fixed \( \epsilon^{AB} \), the proportion of inter-LAPPN transmission decreases over an increasing \( \eta_1 \). That is, when \( \bar{\eta}_1 \) decreases, the inter-LAPPN transmission loss will have a stronger effect on the decrease of preference value in (7). For a fixed \( \eta_1 \), the proportion of inter-LAPPN transmission decreases over an increasing \( \epsilon^{AB} \). That is, an increasing inter-LAPPN transmission loss will weaken the necessity of inter-LAPPN energy cooperation. \( \epsilon^{AB} \) corresponds the special case when the two LAPPNs actually become one, in which the inter-LAPPN transmission is the same as the intra-LAPPN one, though these two portions appear to be equal in the figure. We can conclude from the result that it becomes less necessary for two LAPPNs at a long distance to cooperate, while to encourage the inter-LAPPN energy cooperation between two complementary LAPPNs at a distance, the controller can increase \( \bar{\eta}_1 \).

V. CONCLUDING REMARKS

We proposed a cooperative framework with corresponding algorithms to match a major portion of the ESs into stable demander-supplier pairs, and fairly and efficiently schedule the intra- and inter-LAPPN power packet transmission. Simulation verifies the effectiveness of the proposed scheme in achieving a highly utilized and efficient multi-LAPPN system, also suggests a necessity to conduct inter-LAPPN transmission when the neighboring LAPPNs have complementary types of ESs. It indicates the tradeoff between system utilization and scheduled ratio, providing an ideal LAPPN capacity setting for highly effective operation. In certain cases when promoting inter-LAPPN transmission is above the concern of reducing power transmission loss, the controller can manipulate weight factors \( \eta_0 \) and \( \eta_1 \) to encourage changes to the intended goals.

REFERENCES

[1] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. C. P. Guisado, A. M. Prats, J. I. Leon, and N. Moreno-Alfonso, “Power-electronic systems for the grid integration of renewable energy sources: A survey,” IEEE Trans. Ind. Electron., vol. 53, no. 4, pp. 1002-1016, Aug. 2006.
[2] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. De Vicuna, and M. Castilla, “Hierarchical control of droop-controlled ac and dc microgrids-A general approach toward standardization,” IEEE Trans. Ind. Electron., vol. 58, no. 1, pp. 158-172, Jan. 2011.
[3] E. D’Al Anese, S. V. Dhople, and G. B. Giannakis, “Optimal dispatch of photovoltaic inverters in residential distribution systems”, IEEE Trans. Sustain. Energy, vol. 5, no. 2, pp. 487-497, Apr. 2014.
[4] M. T. Lawder et al., “Battery energy storage system (BESS) and battery management system (BMS) for grid-scale applications”, Proc. IEEE, vol. 102, no. 6, pp. 1014-1030, Jun. 2014.

[5] J. Tant, F. Geth, D. Six, P. Tant, and J. Driesen, “Multiobjective battery storage to improve PV integration in residential distribution grids”, IEEE Trans. Sustain. Energy, vol. 4, pp. 182-191, Jan. 2013.

[6] H. Zhao, Q. Wu, S. Hu, H. Xu, and C. N. Rasmussen, “Review of energy storage system for wind power integration support”, Appl. Energy, vol. 137, pp. 545-553, Jan. 2015.

[7] M. N. Kabir, Y. Mishra, G. Ledwich, Z. Y. Dong, and K. P. Wong, “Coordinated control of grid-connected photovoltaic reactive power and battery energy storage systems to improve the voltage profile of a residential distribution feeder”, IEEE Trans. Ind. Inform., vol. 10, no. 2, pp. 967-977, May 2014.

[8] J. Rajasekharan and V. Koivunen, “Optimal energy consumption model for smart grid households with energy storage,” IEEE Journal of Selected Topics in Signal Processing, vol. 8, no. 6, pp. 1154-1166, Dec. 2014.

[9] S. Carley, R.M. Krause, B.W. Lane, and J.D. Graham, “Intent to purchase a plug-in electric vehicle: a survey of early impressions in large U.S. cites”, Transport. Res. Part D: Transp. Environ., vol. 18, pp. 39-45, Jan. 2013.

[10] B. Nykvist, and M. Nilsson, “Rapidly falling costs of battery packs for electric vehicles”, Nature Climate Change, vol. 5, pp. 329-332, 2015.

[11] A. Q. Huang, M. L. Crow, G. T. Heydt, J. P. Zheng and S. J. Dale, “The future renewable electricity delivery and management (FREEDM) system: The energy internet,” Proc. IEEE, vol. 99, no. 1, pp. 133-148, Jan. 2011.

[12] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, “Overview of control and grid synchrononization for distributed power generation systems,” IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1398-1409, Oct. 2006.

[13] N. Eghtedarpour and E. Farjah, “Power control and management in a hybrid AC/DC microgrid,” IEEE Trans. Smart Grid, vol. 5, no. 3, pp. 1494-1505, May 2014.

[14] P. Ferreira, P. Carvalho, L. A. Ferreira, and M. Ilic, “Distributed energy resources integration challenges in low-voltage networks: Voltage control limitations and risk of cascading”, IEEE Trans. Sustain. Energy, vol. 4, no. 1, pp. 82-88, Jan. 2013.

[15] T. Takuno, M. Koyama, and T. Hikihara, “In-home power distribution systems by circuit switching and power packet dispatching,” in Proc. 1st IEEE Int. Conf. Smart Grid Commun., Gaithersburg, MD, Oct. 2010.

[16] R. Takahashi, K. Tashiro, and T. Hikihara, “Router for power packet distribution network: Design and experimental verification,” IEEE Trans. Smart Grid, vol. 6, no. 2, pp. 618-626, Mar. 2015.

[17] H. Sugiyama, “Pulsed power network based on decentralized intelligence for reliable and low loss electrical power distribution,” in Proc. Computational Intelligence Applications in Smart Grid (CIASG), 2014 IEEE Symposium on, Orlando, FL, Dec. 2014.

[18] J. Ma, L. Song, and Y. Li, “Optimal power dispatching for local area packetized power network,” IEEE Transactions on Smart Grid, online published.

[19] J. Machowski, J. W. Bialek, and J. R. Bumby, Power Systems Dynamics: Stability and Control. New York, USA: Wiley, 2008.

[20] A. Roth, and M. Sotomayor, Two-Sided Matching: A Study in Game-Theoretic Modeling and Analysis, Cambridge University Press, 1992.

[21] D. Gale and L. S. Shapley, “College admissions and the stability of marriage,” Amer. Math. Monthly, vol. 69, no. 1, pp. 9-15, Jan. 1962.

[22] METERING SPECIFICATIONS, WATERLOO NORTH HYDRO INC., Waterloo, ON, Canada. Available: https://www.wnhydro.com/en/your-business/resources/Developers%20and%20Contractors/wnhimeteringspecifications20090521.pdf