Decentralized Controls and Communications for Autonomous Distribution Networks in Smart Grid

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***Abstract*—The traditional power grid system was constructed in a centralized and radial topology where power is generated and delivered from one end to the other. Conventional methods for *unidirectional* power flow analysis will no longer be effective to control renewable energy sources implemented at the consumption sector efficiently; new strategies are called for to facilitate the *bidirectional* flow incurred by power production of the distributed energy resource units. The transformation will require intelligent distribution automation by means of decentralized power management as well as information and communications technologies to actualize smart grid modernization. In this paper, we design autonomous distribution networks that take scalability into account by dividing the legacy distribution network into a set of subnetworks. We tackle the power flow and power balance issues individually in parallel to optimize the global distribution operation by our proposed power-control method. Meanwhile, we propose an overlay multi-tier communications infrastructure for the underlying power network to analyze the traffic of data information and control message required for associated power flow operation. Based on the proposed schemes, we show that we can potentially improve the utilization of renewable energy production and achieve data traffic reduction under decentralized operations as compared to legacy centralized management.**

***Index Terms*—Autonomous distribution network, bidirectional power flow, distributed control, distributed generation, graph theory, micro grids, network traffic, partitioning, scalability, power sharing, smart grid.**

I. INTRODUCTION

In recent years, the amount of research on smart grid has been growing rapidly. Various fields such as power engineering, information science, and computer/communications engineering are now incorporated to develop the next-generation electric power system. Owing to the global warming and rising demand for energy, the fuel-based power system has been called to accommodate renewable-based resources to support its system loads. On the other hand, the high-voltage (HV) transmission network of the centralized and radial power grid is vulnerable to cascading failures with low efficiency and poor resource utilization, despite it is claimed to be reliable and controllable [1]. In order to enhance system efficiency and alleviate power congestion in the medium-voltage (MV) and low-voltage (LV) distribution networks incurred by rising demands, a high penetration level of renewable energy sources (RESs) to be located near customers' sites will be enabled to provide distributed generation to local loads. Such transformation results in the construction of microgrids (MGs) in the distribution system consisting of interconnected loads, energy storage, and distributed energy resource (DER) units such as photovoltaic (PV) solar-power and small wind-power systems. Each MG with a smart interface switch acts as a subsystem which can operate intelligently in parallel with the macro grid or in an island mode. Furthermore, every MG can be considered as a generating-resource or consuming-resource region/entity depending on the status of power generation and consumption in its local area at certain time periods; customers are not solely the electricity buyers but will become *prosumers*.

Smart distribution of the smart grid introduces the concept of active/autonomous distribution networks (ADNs) in cooperation with distributed grid intelligence [2], multi-agent systems [3]–[6], and active network management [7], [8]. ADNs, which are composed of multiple MGs, smart inverters, and intelligent distribution transformers, embody system (re)configuration management, power management, and fault detection management. Local controls for these key components can be achieved through fast control and communications, and need to be coordinated with the overall system controls. From the power network perspective, the primary issue for the power distribution operation with high penetration levels of DER units is voltage control as well as power flow management [5], [9]–[15]. In voltage control, for example, the variability of outputs of PV power generation subject to cloud transients would incur voltage harmonics and fluctuations, which could be detrimental to the distribution system. Smart inverters with PV and distributed storage systems can possibly control the voltage on the distribution system by providing power when the voltage is low and by absorbing power when the voltage is high [16]. In power flow management, surpluses of power produced by DERs can be shared among the households as well as delivered to the neighboring distribution networks; this provision requires bidirectional power flows. Notably, in some countries, the reverse power flow from the distribution network back to the transmission network is prohibited, e.g., Japan [12].

While customers' houses and line feeders with electric poles will be implemented with smart meters and smart actuators/sensors, respectively, the distribution system can be seen as a large version of wireless sensor networks (WSNs) in which the nodes are strategically and statically deployed. Smart sensors can integrate communications with control functions in order to optimize system performance. From the communications network design standpoint, the centralized schemes (i.e., master-slaves relationship) applied in the legacy power system will become impractical once the size of distribution networks grows to a

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certain extent. Scalability has been extensively studied in wireless ad hoc and sensor networks [17] as well as addressed in the context of smart grid applications [18], [19]. Clustering is one of primary techniques that is adopted in a WSN by breaking its network into multiple subnetworks to improve network performance and efficiency. Similar strategies such as partitioning [20], [21] and multilevel partitioning [22] tactics may also be applied to the distribution network and its overlay communications network in order to perform load balancing and to reduce power and communications costs in a decentralized and distributed manner. The power costs may refer to power disturbance, power congestion, and power loss, whereas the communications costs may indicate control overheads, signal interference, and data packet loss. In comparison with the conventional methods, several studies [21], [23], [24] have shown that distributed control and management is a preferable approach to the designs of both power and communications networks for the future smart grid. The main contributions of this paper are summarized in the following:

- The bidirectional power flow incurred by renewable energy production of PV systems in residential networks or MGs is defined and formulated into a power balance problem using graph theory.
- The design of an ADN based on the practical power distribution structure (i.e., radial tree-like topology) is proposed to solve power balance efficiently. An algorithm for control of power flow direction (COPE) is proposed to perform power sharing between PV generation and households' loads throughout the ADN.
- An overlay multi-tier communications network infrastructure (OCNI) for the underlying ADN is developed to facilitate power management, along with a methodology designed for interactive power control and communications operations to reduce the overall data traffic in exchange of data information and control messages.
- Simulations for determining the outcomes of the COPE algorithm as well as uplink and downlink data traffic throughout of the decentralized OCNI and centralized legacy system are conducted, compared, and discussed.

The remainder of this paper is structured as follows: Section II introduces voltage control and power sharing in the power system, and addresses the challenging issues for such operations. Meanwhile, recent research on communications and network designs for the power system will be presented. Section III provides a typical power distribution system model for our investigation into the power network operation. It further develops an overlay multi-tier communications infrastructure to support its underlying active distribution network. Section IV defines the power balance problem in the distribution system, and adopts the graph theory tool to solve the associated power flow issue in a residential network. Section V analyzes the simulation results of the proposed methodology and discusses the findings. Finally, Section VI summarizes the focal points, draws a conclusion, and presents the future work.

II. BACKGROUND AND RELATED WORKS

Electric power grid exhibits the characteristics of a small-world network [25]; however, Wang *et al.* [26] discovered that its grid topology is in fact very sparsely connected with a very low average nodal degree (2–5), and Hines *et al.* [27] indicated that electrical and physical distances can be influential factors which have not been extensively studied in the context of structural network analysis, e.g., voltage drop [11], [28]. As an example shown in Fig. 1(a), HV power is generated from the macro grid and ramped down to LV power to serve loads of customer 1, 2, and 3 in the distribution network. Voltage is decreased along the feeder as the distance increases. Voltage drop is discovered explicitly for customer 1 and 3 due to the increased current flow on the feeder while customers' power consumption (or loads) increase. The consequence causes decreased voltage for customers approaching the end of the feeder from the substation; nevertheless, voltage has to be maintained within an acceptable range (e.g., $120\text{V}\pm 5\%$) along the feeder by utilizing capacitor banks. The control of voltage and active/reactive power becomes more challenging for the operation of power distribution systems when the penetration level of DER units rises, with inclusion of plug-in electric vehicles (EVs) [15]. Voltage control involves voltage regulating devices such as load tap changer (LTC) at the substation transformer, distribution sensors/supplementary regulators and capacitor banks along the feeder (on or close to electric poles), and smart meters with PV inverters at houses from which voltage information is collected in real time. Coordination by means of integrated control and communications along with the distribution equipment controllers can efficiently regulate voltage, reduce losses, conserve energy, and optimize utilization of system resources. Reference [28] introduces the smart distribution integrated Volt-VAR control and optimization as shown in Fig. 1(b).

The direction and amount of power flow in distribution networks require flexible and dynamic control operation [29]. The existing distribution networks were not designed to operate with bidirectional power flow; nonetheless, introducing appropriately specific loops techniques and developing a hybrid structure to enable meshed operation in the legacy radial system with intelligent circuit breakers and switches are potential approaches to provision the two-way power system in the future [30]. Nguyen *et al.* [6] proposed a distributed optimal routing algorithm with a power router interface to manage the power flow in the active distribution network. Moreover, the so-called contactless and bidirectional power transfer system compensated by an inductor-capacitor-inductor circuit has been proposed in [31], [32] and claimed to be a viable solution for smart grid applications, e.g., DERs, EVs.

There has been substantial research on integrating information and communications technologies (ICTs) into power systems [4]–[6], [8]–[10], [12], [14], [33]–[35], including consideration of secure communications [36]. Particularly, Yang *et al.* [8] proposed communications infrastructures for MV and LV distribution networks. By using microwave/T1 for MV network and satellite/T1 for LV network, the authors showed that these technologies can coexist and meet the delay requirement for data delivery. Majumder *et al.* [14] also designed communications systems using WSN to manage power flow within MGs and adopting wired network to support data exchange among MGs or communities. The low-cost and low-bandwidth WSN was proved to be sufficient to deliver local data measurements, and at the same time was able to improve the system reliability and operation accuracy. Furthermore, Erol-Kantarci *et al.* [34] considered multiple MGs throughout the distribution network where each MG can represent residential, commercial, and campus entities. Every MG may or may not have power surplus at different times during the day. A number of MGs are grouped together as long as their outputs are balanced, i.e., power surplus is equal to consumption. In order to achieve survivability, the method is to form a ring topology (i.e., at least three MGs must be grouped) so that the grouped MGs can support each other. Because of varying power usage and production in geographical regions, group formation changes during different time periods. Meanwhile, partitioning MGs in distribution networks based on coalition game theory was introduced in [35]. Coalitions of MGs are formed according to the coalition formation algorithm incorporated with merge-split rules in which the tradeoff (i.e., power loss) value is determined for each MG whether to merge with other coalitions (or split from its coalition), until the network converges to a number of disjoint coalitions where there is no more incentive to further merge or split. Unlike [34] and [35], we propose a communications infrastructure for the WSN-based distribution grids with consideration of the underlying power system structure and constraints in order to make the designed methodology more practical.

III. SYSTEM MODELS

A. Underlying Autonomous Distribution Network (ADN)

We consider a distribution system model (a modified model of [15]), as shown in Fig. 2, in order for us to investigate the operation of the power system. The model consists of *one* power source (which can be a group of conventional power plants) in the macro grid, *four* distribution networks, and *nine* buses (i.e., Bus 1–6, 8, 10, 14, depicted by the thick lines). Note that we only show the distribution network that is connected to Bus 4 and assume that other networks (which are connected to Bus 1–3) also possess the same structure properties for simplicity. The typical distribution network is composed of *eight* neighborhoods (i.e., Block 7, 9, 11–13,15–17), and each neighborhood which is constructed with *fifteen* households forms a MG.

Traditionally, power is generated by fuel-based power plants in remote locations, routed or switched through the HV transmission system, and delivered to the residential sites in the distribution network; power flow is unidirectional. With customers' capability to install DER units on their premises, contributing power back to the grid incurs bidirectional power flow in the power system. Each MG is a grid entity that sometimes can provide or absorb a range of real and reactive power to or from other MGs, before requesting power from the macro grid. The overall distribution system can be interpreted by node representation from graph theory (shown in Fig. 3(a)); each bus represents a node where power can be injected, extracted, or injected and extracted simultaneously by cumulative generation and loads during different time periods. Note that node 5, 6, 8, 10, 14 are not directly connected to households but to the associated residential networks.

Each distribution network is designed as a cluster, $\{c_1, c_2, \ldots, c_s\} \in C$, where $s = |C| = 4$, the cardinality of A, in our case. Cluster $c_i, i = 1, 2, \ldots, s$, is partitioned into a number of groups, $\{g_1, g_2, \ldots, g_k\} \in c, \forall c \in C$, where $g_1 \cap g_2 \cap \ldots \cap g_k = \emptyset$ (i.e., groups are not overlapping), and all clusters are assumed to have the same group size k $(= 3$ in our case). Each group, $g_i, i = 1, 2, \ldots, k$, is composed of multiple MGs, $\{h_1, h_2, \ldots, h_j\} \in g, \forall g \in c$. All groups are assumed to have the same MG size j except the third group $(i = 3)$ which has MG size $j - 1$; from our example, MG 7, 12, 13 are merged into Group g_1; MG 9, 11, 15 are merged into Group g_2; and MG 16, 17 are merged into Group g_3. The grouping method assumes that each distribution transformer in residential networks is connected to the same number of households; meanwhile, for the network balancing purpose, the number of MGs in the groups keeps the same as much as possible. The balance of power in the power system can be interpreted as follows:

$$P = \sum_{c \in C} P_c + P_{\mathrm{GEN}} + P_{\mathrm{LOSS}} \approx 0 \tag{1}$$

where $P_c \in \mathbb{Z}, \forall c \in C$, is the output power of cluster c, P_{GEN} is the total power generated in the macro grid and delivered to the clusters, and P_{LOSS} is the total power loss during power transmission. Since power sharing is possible among MGs [10], [13], it is also possible among groups as well as among clusters. In this way, renewable energy production can be utilized whenever it is available through power sharing among entities in order to minimize the amount of power requested from the macro grid, i.e., $P_{\mathrm{GEN}} = 0$; this can be done by effectively controlling the output power P_c as much as possible subject to P_{LOSS}, which is not considered in this paper. The output power of cluster c is the summation of the output power of groups, $P_c = \sum_{i=1}^{k} P_{g_i}, \forall c \in C$; the output power of each group g is the summation of the output power of MGs, $P_g = \sum_{i=1}^{j} P_{h_i}, \forall g \in c, P_g \in \mathbb{Z}$; the output power of each MG h is the summation of the output power of households, $P_h = \sum_{i=1}^{n} P_{v_i}, \forall h \in g, P_h, P_v \in \mathbb{Z}$, where $\{v_1, v_2, \ldots, v_n\} \in V_h, \forall h \in g$ denote the buses connected with associated households in the residential networks. Note that each MG is assumed to have the same household size n, as mentioned earlier. Consequently, Fig. 3(a) can be coarsened to the graph shown in Fig. 3(b) where each decentralized group governs its voltage control and power flow in its corresponding cluster. The nonoverlapping groups constitute an ADN, which is able to perform power control management internally and interact with neighboring ADNs externally to sell or buy renewable power before requesting power from the conventional power pants.

B. Overlay Communications Network Infrastructure (OCNI)

We assume that *power nodes* with communications interfaces (e.g., smart meters with PV inverters, circuit breakers, line sensors, convertors, voltage regulators, capacitor banks) in MGs are strategically deployed in positions so that their connectivity is ensured; relay nodes are placed to mitigate constraints such as transceivers' transmit-power level, MAC (medium access

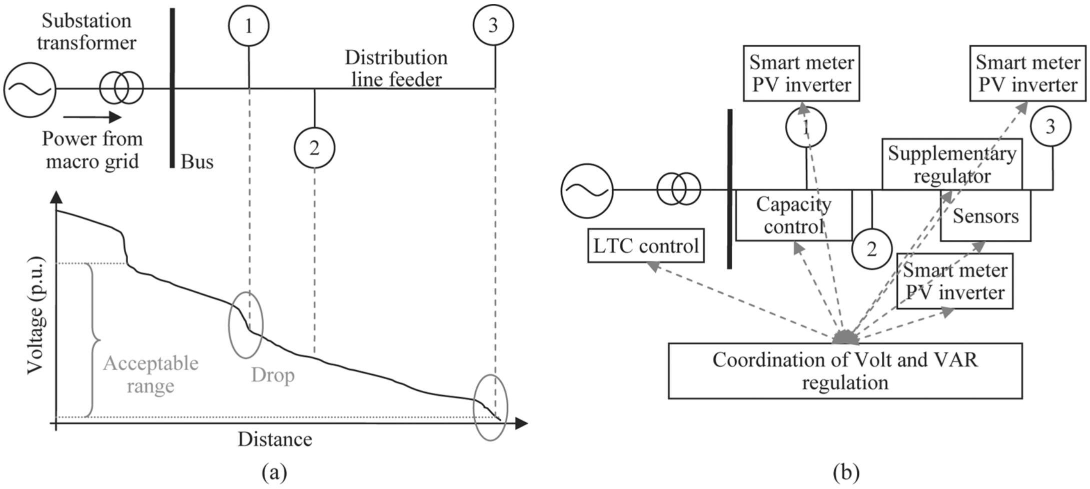


Fig. 1. (a) Voltage profile for a typical distribution feeder; and (b) coordination via communications and control in the distribution network.

control), routing issues [17], [37]. The positions of nodes in the system are fixed, and therefore our OCNI model for the power system is developed practically based on its underlying power network to facilitate both power flow and communications traffic management.

The OCNI model, illustrated in Fig. 4, is structured into *four* tiers (from the bottom to the top): 1) entire households grouped into a number of MGs at Tier 4; 2) sets of MGs forming neighborhood/field area networks (N/FANs) such that each MG belongs to a corresponding control center (CC) at Tier 3; 3) coupled or consolidated MGs managed by an associated subsystem CC at Tier 2; and 4) overall ADNs at Tier 1 such that each ADN consisting of a number of subsystems is under control of its distribution control center (DCC). The CCs at Tier 2 and 3 govern the corresponding networks below them. The DCCs owned by distribution system operators (DSOs) at Tier 1 monitor and control power flow for the corresponding ADNs. The central control center (CCC) owned by transmission system operators (TSOs) in the transmission network is in charge of delivering power to the distribution system upon ADNs' requests. Power nodes at Tier 4 are associated with the CCs at Tier 3 (using WSNs based on IEEE 802.15.4) via one-hop or multihop transmissions; the CCs at Tier 3 are associated with the CCs at Tier 2 using technologies such as 3 G and WiFi; and the CCs at Tier 2 are associated with the DCCs at Tier 1 using technologies such as 4 G and fiber optics, as well as communications between the DCCs and CCC using broadband technologies.

The operation of each ADN is to collect voltage profile and associated data measurements from the power nodes at Tier 4, and deliver this data information through *uplink* transmission to the CCs at the upper tiers for the local power flow analysis. In the *downlink*, the associated CCs send control signals to the power nodes to adjust power output in order to optimize the network resources while maintaining the system reliability. Since the size of data packet generated by the power nodes is relatively small (e.g., tens to few hundreds of bytes), using aggregation technique can improve bandwidth utilization at upper tiers. In MGs at Tier 4, fast control of individual power units requires real-time and detailed information on DERs and loads. Fortunately, the study [1] has demonstrated that the control complexity can be greatly reduced when using coupled MGs: 1) A system consisting of many MGs does not need fast communication, and 2) Redispatching power among MGs does not need detailed information on individual power units for the corresponding communications systems to deliver. Therefore, the hierarchical OCNI with the grouping technique for ADNs can potentially simplify control complexity and economize communications bandwidth at the upper tiers; this benefits both power control and communications management.

IV. PROBLEM DEFINITION AND FORMULATION

Bidirectional power flow due to renewable power generation contributed from the residential networks requires an effective mechanism to manage power flow in the distribution system, in which the system reliability is maintained, and at the same time instant renewable production is consumed in order to maximize energy utilization. Balancing power generation and loads is the fundamental rule to stabilize the power system, i.e., the quantity of total generation matches that of total loads. Hence, our objective is to balance (1), which is rewritten as $P = \sum_{c \in C} P_c \approx 0$; that is, we only focus on balancing the energy generated by households while the power loss is assumed negligible as mentioned earlier. We ignore energy from macro grid because we prioritize renewable power sharing within MGs, among MGs in a group, among groups, and among ADNs in bottom-up order, to balance the power distribution system whenever possible.

Determination of the cumulative output power of an ADN at Tier 1 (shown in Fig. 4) is first to discover the cumulative output power of MGs at Tier 4, i.e., $P_h, \forall h \in g$. Given the residential network for every MG as depicted in Fig. 2, we can also interpret it by using node representation (shown in Fig. 5): a connected, undirected tree graph $G = (V, E)$ with a set of vertices $v_1, v_2, \ldots, v_n \in V$ and a set of edges E. The vertices represent buses, and edges represent line feeders between two buses. Each household has a smart meter installed with a grid-tie PV system mounted on the rooftop. Each PV unit generates a certain amount of power (in kW) during a certain time period based on

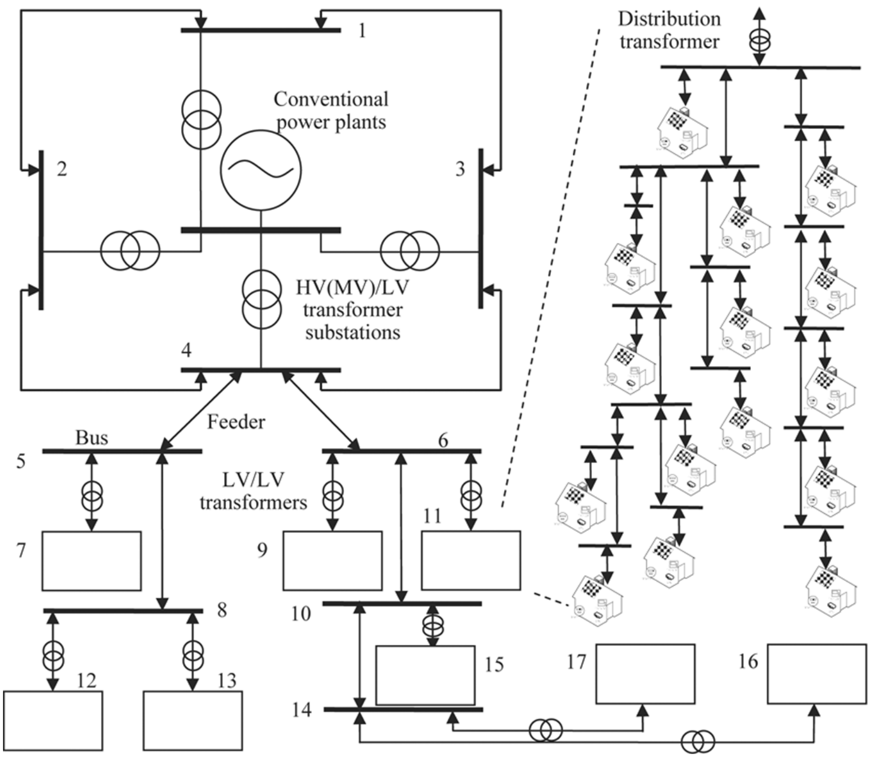


Fig. 2. The systematic model of a power distribution system and associated residential network.

sun radiation. Note that the stochastic nature of renewable energy production may be tackled by means of weather forecasts, historical records, smart inverters, as well as data collection and coordination via communications. When the amount of generated power is sufficient to support its household's load, there is either a surplus or no surplus to flow into the bus. On the other hand, when PV generation is insufficient to support its household's load, power is drawn from the bus. Hence, each vertex (bus) is injected or extracted with positive or negative power $P_{v_i} \in \mathbb{Z}$, respectively, by household v_i. During different time periods, household v_i can be a generating or consuming unit; household v_i can also be an idle unit when its generation and load are balanced. Note that power is injected to the bus with PV generation that is unused by a household; the term *generation* refers to *surplus* power instead of purely total generation. For a connected, tree digraph G, each edge is an ordered pair (v, w) of vertices.

Definition 1: In a rooted tree, the parent of vertex v is vertex w on the path to the root; the child of vertex v is vertex u on the path to the leaf.

Definition 2: A forward edge refers to edge (v, u) that connects vertex v to vertex u, whereas a reverse edge refers to edge (v, w) that connects vertex v to vertex w, e.g., edge (v_1, v_2) represents a forward flow, whereas edge (v_2, v_1) represents a reverse flow, see Fig. 5.

Definition 3: A graph contains a set of parent vertices $w_1, w_2, \ldots, w_l \in W \subset V$, e.g., $w(v_4) = w(v_5) = w(v_6) = v_2$.

Definition 4: The capacity of edge $(v, w), \mathrm{cap}(v, w)$, is a mapping, $\mathrm{cap} : E \to \mathbb{N}\backslash\{0\}$, which represents the maximum amount of flow that can pass through edge (v, w) and is a positive integer.

For a feasible flow $f : E \to \mathbb{N}$, the following three types of constraints must be obeyed [38]:

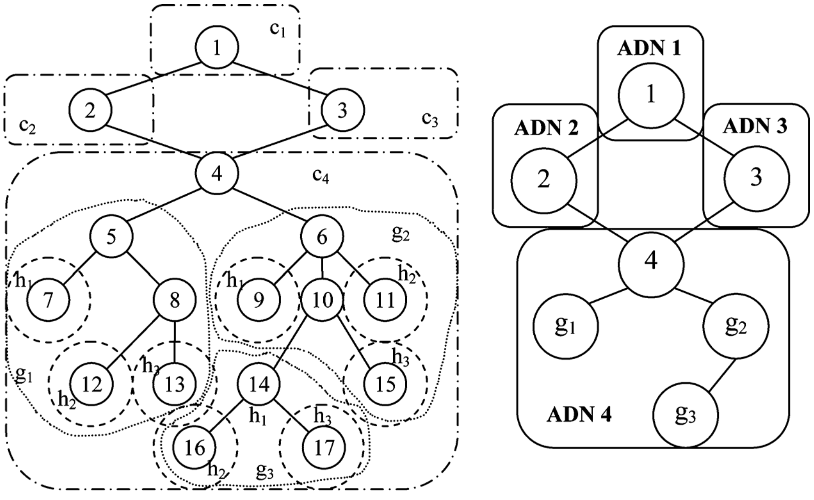
$$f(v,w) \le \mathrm{cap}\,(v,w), \quad \forall (v,w) \in E \tag{2}$$

$$\sum_{(w,v)\in E} f(w,v) = \sum_{(v,w)\in E} f(v,w), \quad \forall v \in V \tag{3}$$

$$f(v,w) \ge 0, \quad \forall (v,w) \in E \tag{4}$$

The constraint in (2) specifies the *capacity limit* of edge (v, w) where the amount of power delivered during a certain time period from vertex v to vertex w is subject to the capacity of distribution line feeders. When generated power to be delivered for the nodes in need is greater than the line can hold, some power may not be delivered. The constraint in (3) introduces *conservation of flows* such that accumulated power flow into vertex v is equal to the amount of power flow out of vertex v. Finally, the constraint in (4) is to satisfy the *nonnegativity* requirement such that the value of flow must be nonnegative regardless of the flow direction. Without loss of generality, we have considered the following primary assumptions:

1) Renewable energy is sufficient in the distribution network during daylight with high penetration of PV systems, especially in the summer season and when consumption is low in some regions.
2) No large energy storage is available; when renewable energy is produced, it needs to be consumed immediately for high energy utilization.
3) No reverse power flows back to the transmission grid.



(a) (b)

Fig. 3. (a) A connected, undirected graph for the distribution system model in Fig. 2; and (b) contraction of the graph and formation of ADNs.

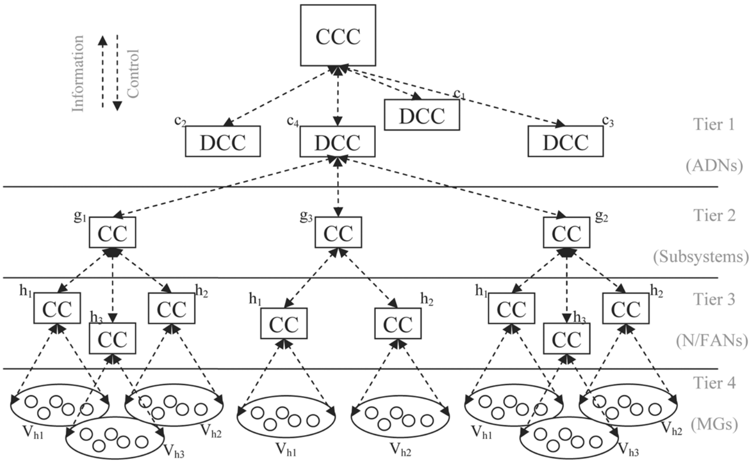


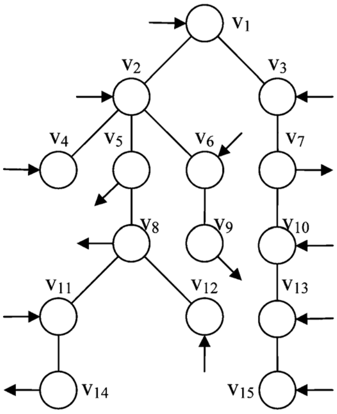
Fig. 4. The 4-tier communications infrastructure for the ADN.

4) Voltage, current, frequency for active and reactive power are managed via coordination by means of control and communications.
5) Distance among households is small enough such that power loss in transmission can be neglected or tolerated.
6) Power flow delivered along the feeders is always under the transfer capacity; power congestion is not considered. (See [39] for a power congestion case.)

A. Power Flow in the Distribution Networks

In normal operation, power flows from a higher to a lower voltage level, as in the conventional passive power network from HV transmission to MV/LV distribution. Similar to the active distribution network, the variability of PV generation and loads will fluctuate the voltage profiles of MGs. As an example illustarted in Fig. 5, some have positive power (available surplus) injected into the node while others have negative power (loads) extracted from the node. Note that v_0 (which is not shown in Fig. 5) may refer to node 5, 6, 8, 10, 14. In this example, the cumulative output power is 24 (without considering power loss) which we may know by collecting the measured data from the power nodes at the instant via communications; the surplus induced by the cumulative output power at v_1 should be exported to other MGs. However, power may flow in a direction which is not preferred due to power laws. For instance, one power unit injected into v_3 can compensate for the load at v_7 that results in a forward direction. Similar to v_2, two power unit can compensate for the load at v_5 causing another forward direction. Without global information on each node, the system resource cannot be efficiently utilized. Therefore, we have to determine how power should flow so that the utilization of energy is enhanced and system reliability is ensured; meanwhile, some voltage control algorithms using reactive power regulation proposed in power engineering research can be used to support our design, e.g., [10], [11], [13], [14].

In order to control the power flow given graph properties, we propose a *bottom-up* approach by taking the *depth* information (denoted by $D = (1, 2, \ldots, d)$) and start with the largest depth d in the tree since the leaf nodes are positioned at the end of the tree. In the right branch of the given example, v_{15} has positive power of 2, which should be flowed in a reverse direction, i.e., from v_{15} to v_{13}. The cumulative output power of v_{13} is a



(a)

Input				Output	
V^T	D^T	W^T	P_V^T **(kW)**	E	$f(v,w)$ **(kW)**
v_1	1	v_0	6	(v_1,v_0)	24
v_2	2	v_1	2	(v_2,v_1)	7
v_3	2	v_1	1	(v_3,v_1)	11
v_4	3	v_2	3	(v_4,v_2)	3
v_5	3	v_2	-1	--	0
v_6	3	v_2	4	(v_6,v_2)	2
v_7	3	v_3	-3	(v_7,v_3)	10
v_8	4	v_5	-6	(v_8,v_5)	1
v_9	4	v_6	-2	(v_6,v_9)	*2*
v_{10}	4	v_7	6	(v_{10},v_7)	13
v_{11}	5	v_8	8	(v_{11},v_8)	4
v_{12}	5	v_8	3	(v_{12},v_8)	3
v_{13}	5	v_{10}	5	(v_{13},v_{10})	7
v_{14}	6	v_{11}	-4	(v_{11},v_{14})	*4*
v_{15}	6	v_{13}	2	(v_{15},v_{13})	2

(b)

Fig. 5. (a) A connected, undirected graph for the residential network model in Fig. 2 with a set of injection of power generation and extraction of power loads; and (b) the digraph information table.

summation of reverse power from v_{15} and power generation by the associated household. Similarly, in the left branch, v_{14} has negative power of 4 that requires its parent v_{11} to support its load in a forward direction, while v_{11} compensates its residual power of 4 for the load at v_8. The process is repeated until the cumulative output of v_1 is derived. Note that power is balanced at v_5, and v_3 has an aggregate of power 11 flowed in a reverse direction to v_1; these result in different outcomes than what was discussed above. The proposed scheme COPE is shown in Algorithm 1, which is operated in each MG in parallel at Tier 4 as well as applied to operations at the upper tiers.

Algorithm 1 Control Of Power flow dirEction (COPE)

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Initiation: Perform breadth-first search or depth-first search to obtain the characteristics of an undirected graph $G$.
Input: A table containing $(V^{\mathrm{T}}, D^{\mathrm{T}}, W^{\mathrm{T}}, P_V^{\mathrm{T}})$ information is sorted in descending order of $D^{\mathrm{T}}$.
Output: A digraph $G$ presenting the direction and amount of power flow, i.e., $E$ and $f(v,w)$.
$P_{W(V[n])} = 0$
for $i = 1$ to $n$ do
    $P_{W(V[i])} \leftarrow P_{V[i]} + P_{W(V[i])}$
    if $P_{V[i]} > 0$ then
        $f(V[i], W(V[i])) = P_{V[i]}$ {reverse flow}
        $E \leftarrow (V[i], W(V[i]))$
    end if
    if $P_{V[i]} < 0$ then
        $f(W(V[i]), V[i]) = P_{V[i]}$ {forward flow}
        $E \leftarrow (W(V[i]), V[i])$
    end if
end for
```

Theorem 1: Given a radial tree-like topology G, the proposed bottom-up approach for calculating the paths of power flow is the shortest path.

Proof: The directed distance from a vertex u to a vertex v in a tree digraph is the length of the shortest directed walk from u to v. Since the digraph G contains no loops, the power flow from each vertex passes through or flows into other vertices at most once. Therefore, the shortest path is obtained. ■

The given example shows an unbalanced situation in a MG $(P_h > 0)$; a reduction in power injection is required by increasing households' loads, e.g., using heat pump water heaters to store thermal energy [12]. Conversely, when a MG has greater consumption than generated solar power $(P_h < 0)$, solutions such as demand response and conservation programs introduced in smart grid applications can be applied, e.g., raising energy costs and delaying appliances operations. For market business and utility operation reasons, importing or exporting renewable power from or to other regions can be done by using the proposed power sharing scheme in descending order of the tier number throughout the ADNs.

B. Traffic Loads in the Overlay Communications Networks

1) The Centralized Scheme: Traditionally, power systems are regulated under a two-tier hierarchical master-slave architecture. System control devices such as remote terminal units (RTUs) located at Tier 2 act as slave data concentrators and periodically report their measurements (on relays, current, breakers) via a hard-wired connection to a master RTU along with associated DCC at Tier 1 [29]. According to Little's Theorem [40], if a total set of RTUs $\mathcal{M}$ generate average traffic at a rate of $\overline{\lambda}_{\mathcal{M}}$ and an additional set of emerging smart meters $\mathcal{V}$ generate average traffic at a rate of $\overline{\lambda}_{\mathcal{V}}$, the overall system throughput is derived as $L = L_{\mathcal{M}} + L_{\mathcal{V}}$, where $L_{\mathcal{M}} = \overline{\lambda}_{\mathcal{M}}\mathcal{M}$ and $L_{\mathcal{V}} = \overline{\lambda}_{\mathcal{V}}\mathcal{V}$; the single DCC will be required to upgrade its processing capacity in order to accommodate the aggregate traffic of the measuring nodes $(N = \mathcal{M} + \mathcal{V})$. For example, if the execution time of an operation for power quantity analysis of the DCC takes t_{proc} seconds on average, the DCC cannot process more than $1/t_{\mathrm{proc}}$ operations/sec in the long run, i.e., $L_a \leq 1/t_{\mathrm{proc}}$; the maximum attainable throughput L_a is an upper bound determined by the processing capacity of the DCC that could queue up the unprocessed operations and cause the system to enter an unsteady state when $L > L_a$. In addition to the processing time t_{proc}, considering other delay factors that compose the overall end-to-end delay T spent in a data communications network system is also critical: $T = (t_{\mathrm{trans}} + t_{\mathrm{prop}} + t_{\mathrm{proc}} + t_{\mathrm{queu}})\chi$, where t_{trans} is the transmission delay, t_{prop} is the propagation delay, t_{queu} is the queuing delay, and χ is the number of hops in a multi-hop network environment. Despite the fact that the centralization of legacy operation allows the DCC to obtain a global knowledge of its corresponding distribution network status at each certain time period, it can degrade the system performance due to the limitation of L_a and the requirement of T being directly proportional to N, as well as single-point failures. The centralized scheme is essentially delivering *fine-grained* information from each individual measuring node to the DCC due to the simplicity of legacy one-way power delivery architecture.

2) The Decentralized Approach: In order to relieve the computational complexity and bandwidth capacity at the DCC, decentralization of power-communications operations in OCNI is proposed to achieve a number of merits: 1) *local processing for quick decision making*: a set of sub-CCs are added in the middle tiers as multi-agent coordinators in order to perform local power flow optimization at both LV (e.g., 240/120 V at Tier 3) and MV/LV (e.g., 26/13/4 kV at Tier 2) levels to obtain global optimization; 2) *end-to-end delay reduction*: the addition of sub-CCs decreases the distances between the power nodes and operation centers to operate power sharing by cooperatively compensating for power within and among MGs; 3) *traffic load deduction*: a) when power balance can be fulfilled at one tier, transmitting data to upper tiers is not necessary (unless the upper-tier CCs request it for other purposes), and b) the original amount of data containing detailed information on the power nodes is not required to be transmitted completely to the upper-tier CCs when power sharing among MGs and ADNs is activated; and 4) *scalable*: the network scalability does not have to depend upon the quantity of power nodes but upon the scale of added sub-CCs at Tier 3 and Tier 2 from the entire distribution network perspective. In contrast to the centralized scheme, the multi-tier OCNI for ADNs is designed to mitigate heavy traffic loads by means of *coarse-grained* information delivered in the uplink transmission:

$$\alpha_i = \frac{L_{i\_(i-1)}}{L_{(i+1)\_i}}, \quad i \in \{1, 2, 3\} \tag{5}$$

where α_i is the *abstraction* ratio which depends on the operation requirement of the CCs at Tier i (i.e., $0 < \alpha_i \leq 1$); $L_{(i+1)\_i}$ is the total amount of data received from Tier $(i+1)$, and $L_{i\_(i-1)}$ is the amount of data to be transmitted to the CC at Tier $(i-1)$. For example, in the process of power balancing, the CC at Tier 3 will need to acquire L_{4_3} amount of data from its associated power nodes in the MG in order to have a local knowledge of the network status while performing its operation. When the support of power sharing with neighboring MGs is required (either power import or export), the CC at Tier 3 will contact the associated CC at Tier 2 by sending correlated information regarding its lower-tier network condition with its L_{3_2} amount of data, which is usually smaller than what it received, i.e., $L_{3\_2} < L_{4\_3}$; this is because the Tier-2 CC does not need to know everything about the network condition of Tier-3 fully supervised by the Tier-3 CC, and interestingly, it may be possible for the Tier-3 CC to send only a notification message (even abstract data are not required) to the Tier-2 CC indicating how much power in total it has to export/import to/from the other MGs in order to support its power balance. The methodology of power and communications network operations is illustrated in Algorithm 2.

Algorithm 2 Power control and communications in ADNs

```
Require: All units are connected to the grid (in both power and communications perspectives).
Ensure: Periodic uplink and downlink data transmission between Tier 4 and Tier 3.
  while unbalanced power is discovered in a MG do
    if solutions provided in SectionIV.A mitigate the problem then
      Power control and data communications remain in Tier 4 and Tier 3.
    else {solutions do not effectively work}
      Power sharing with other MGs is necessary.
      Communications with CC at Tier 2 takes place.
      if unbalanced problem is still unsolved then
        Power sharing with other groups is necessary.
        Communications with DCC at Tier 1 takes place.
        if unbalanced problem still remains then
          Power sharing with other ADNs is necessary.
          Communications with CCC takes place.
          Power from macro grid is granted if needed;
          otherwise, disconnecting PV systems is required.
        end if
      end if
    end if
  end while
```

We investigate the data traffic loads in both uplink and downlink transmission involved at each tier of the distribution network. At a given time period, the uplink traffic loads performing information collection and downlink traffic loads administering control processes (which are often broadcasts in nature) are described in Tables I and II, respectively.

V. SIMULATION RESULTS AND ANALYSES

We investigate the performance of the proposed OCNI design in comparison with that of the traditional system operation by

TABLE I
DESCRIPTION OF PRESUMPTIVE TRAFFIC LOADS VIA **UPLINK TRANSMISSIONS** BETWEEN ADJACENT TIERS IN OCNI

Tier Index	Amount of Traffic Load	Description
4 to 3	$L_{4\_3} = \overline{\lambda}_{N_h} N_h,$ $\forall h \in g,$ $\forall g \in c, \forall c \in C$	This is where the fundamental power control and communications operations take place while each MG is governed by its associated Tier-3 CC simultaneously to monitor and control power flow individually. The number of households $\|V_h\|$ and other nodes M_h (e.g., sensors along the feeders) that make the total power nodes $N_h = \|V_h\| + M_h$ in the corresponding MG are considered; the expected traffic arrival rate of these nodes is $\overline{\lambda}_{N_h}$.
3 to 2	$L_{3\_2} = \alpha_3 \sum_{j=1}^{\|g\|} \left(\overline{\lambda}_{N_{h_j}} N_{h_j}\right) +$ $+\overline{\lambda}_{M_g} M_g, \forall g \in c, \forall c \in C$	This is where an aggregate of data traffic is collected from Tier-3 CCs and other measuring nodes M_g in the corresponding group. The Tier-3 CCs will generate abstract data containing sufficient information on $\|g\|$ MGs status with α_3 and transmit to the corresponding CC at Tier 2.
2 to 1	$L_{2\_1} = \alpha_2 \sum_{k=1}^{\|c\|} L_{3\_2,k} +$ $+\overline{\lambda}_{M_c} M_c, \forall c \in C$	Similar to the above, an aggregate of data traffic is collected from Tier-2 CCs and other measuring nodes M_c in the corresponding ADN. The Tier-2 CCs will generate abstract data containing sufficient information on $\|c\|$ groups status with α_2 and transmit to the corresponding DCC.
1	$L_{1\_ccc} = \alpha_1 \sum_{s=1}^{\|C\|} L_{2\_1,s}$	Similar to the above, an aggregate of data traffic is collected from Tier-1 DCCs. The Tier-1 DCCs will generate abstract data containing sufficient information on $\|C\|$ ADNs status with α_1 and transmit to the CCC.

TABLE II
DESCRIPTION OF PRESUMPTIVE TRAFFIC LOADS VIA **DOWNLINK TRANSMISSIONS** BETWEEN ADJACENT TIERS IN OCNI

Tier Index	Amount of Traffic Load	Description
3 to 4	$L_{3\_4} = \overline{\lambda}_{3\_4} N_h,$ $\forall h \in g, \forall g \in c, \forall c \in C$	The fundamental level requires the CCs of N/FANs to send control messages to all the power nodes in the corresponding MGs; the expected traffic arrival rate of the CCs is $\overline{\lambda}_{3\_4}$.
2 to 3	$L_{2\_3} = \overline{\lambda}_{2\_3} \left(\|g\| + M_g\right),$ $\forall g \in c, \forall c \in C$	Similar to the above, the CCs of subsystems send control messages to all the CCs and other measuring nodes M_g in the corresponding N/FANs with the expected traffic arrival rate $\overline{\lambda}_{2\_3}$.
1 to 2	$L_{1\_2} = \overline{\lambda}_{1\_2} \left(\|c\| + M_c\right),$ $\forall c \in C$	Similar to the above, the DCCs of ADNs send control messages to all the CCs and other measuring nodes M_c in the corresponding subsystems with the expected traffic arrival rate $\overline{\lambda}_{1\_2}$.
1	$L_{ccc\_1} = \overline{\lambda}_{ccc\_1} \|C\|$	Similar to the above, the CCC sends control messages to all the DCCs with the expected traffic arrival rate $\overline{\lambda}_{ccc\_1}$.

considering the four cases shown in Table III. In reality, on the one hand the amount of data traffic in the network can be reduced by the intermediate aggregation or concentration nodes to improve payload efficiencies for the small packets generated by the measuring devices; on the other hand, the traffic can also be escalated by necessary retransmissions due to signal interference and packet collisions especially in unscalable and crowded network environments. Here, our goal is to discriminate the outcomes between our proposed OCNI and the legacy operation, and demonstrate that our methodology aims to alleviate abundant data transmissions across the distribution network in the context of smart grid applications. In the simulations, the average data traffic of each power node transmitted in uplink is set identical, i.e., $\overline{\lambda}_{N_h} = \overline{\lambda}_{M_g} = \overline{\lambda}_{M_c} = \overline{\lambda}_{\mathcal{V}} = \overline{\lambda}_{\mathcal{M}} = 160$ bps; the average control traffic of each CC responded in downlink is also set identical, i.e., $\overline{\lambda}_{3\_4} = \overline{\lambda}_{2\_3} = \overline{\lambda}_{1\_2} = \overline{\lambda}_{ccc\_1} = \overline{\lambda}_{cen} = 80$ bps; the number of the measuring nodes M_g and M_c in the corresponding N/FAN and subsystem are set to 50 and 100, respectively. We assume all the CCs at the same tier apply the same α. Three demonstrations are undertaken to quantitatively analyze the outcomes of adjusting the abstraction ratios and the number of power nodes in the MGs while determining the amount of traffic involved at each tier categorized into cases: 1) $N_h = 100$ and $\alpha = 0.2, 0.6, 1$ in which all of CCs in the network operate with the same abstraction ratio, e.g., $\alpha_3 = \alpha_2 = \alpha_1 = 0.2$ in Fig. 6(a); 2) $N_h = 500$ and CCs at different tiers have distinct α values for their operations (Fig. 6(b)); and 3) $N_h = 500, 1000, 2000$ while $\alpha_3 = \alpha_2 = \alpha_1 = 0.6$ (Fig. 6(c)). We discovered that balancing power flow via coordination within each MG in parallel shown in case 1 generates the least traffic loads, whereas case 4 conveys the most traffic throughout the network because power balance cannot be achieved at the lower tiers and requires involvement of CCs at the upper tiers to resolve the problem; meanwhile, the legacy centralized scheme demands all the data transmission and traffic in order to perform its power flow management. In Fig. 6(a), if the upper-tier CCs are able to manage the unbalanced network with much less information (interpreted by smaller α) received from the lower-tier CCs, much more data traffic can be reduced; conversely, if fine-grained information (interpreted by $\alpha = 1$) is desired for the upper-tier CCs to do the job, the traffic loads considered in case 4 will reach an approximate same amount produced by the centralized scheme.

More interestingly, applying different α at CCs of different tiers has great impacts on the amount of traffic loads traversed at the upper tiers. Given the same amount of measuring nodes and traffic arrival rates in the network, Fig. 6(b) shows that the mid-gray line is greater than the dark-gray line in case 3 but they become opposite in case 4; this is because the DCC requires most of information its lower-tier CCs have in hand while the CCC only needs information from the DCCs to a certain degree in the case of $\alpha_2 = 0.9, \alpha_1 = 0.5$, whereas the dark-gray line depicts the opposite case. We further noticed that an increase in the number of power nodes of MGs barely changes the normalized rates of data traffic loads among the four cases because the aggregate data rate is directly proportional to the number of nodes, given the fixed traffic arrival rates and abstraction ratios, as illustrated in Fig. 6(c). In summary, the demerits of the decentralized OCNI operation are twofold: 1) CCs at Tier 3 only have their own local network knowledge while other CCs at upper tiers may have limited knowledge of the lower-tier network, and 2) OCNI may generate more traffic than the centralized scheme owing to the negotiation messages exchange among CCs, when case 4 is taken place (i.e., contacting CCC is required) and the

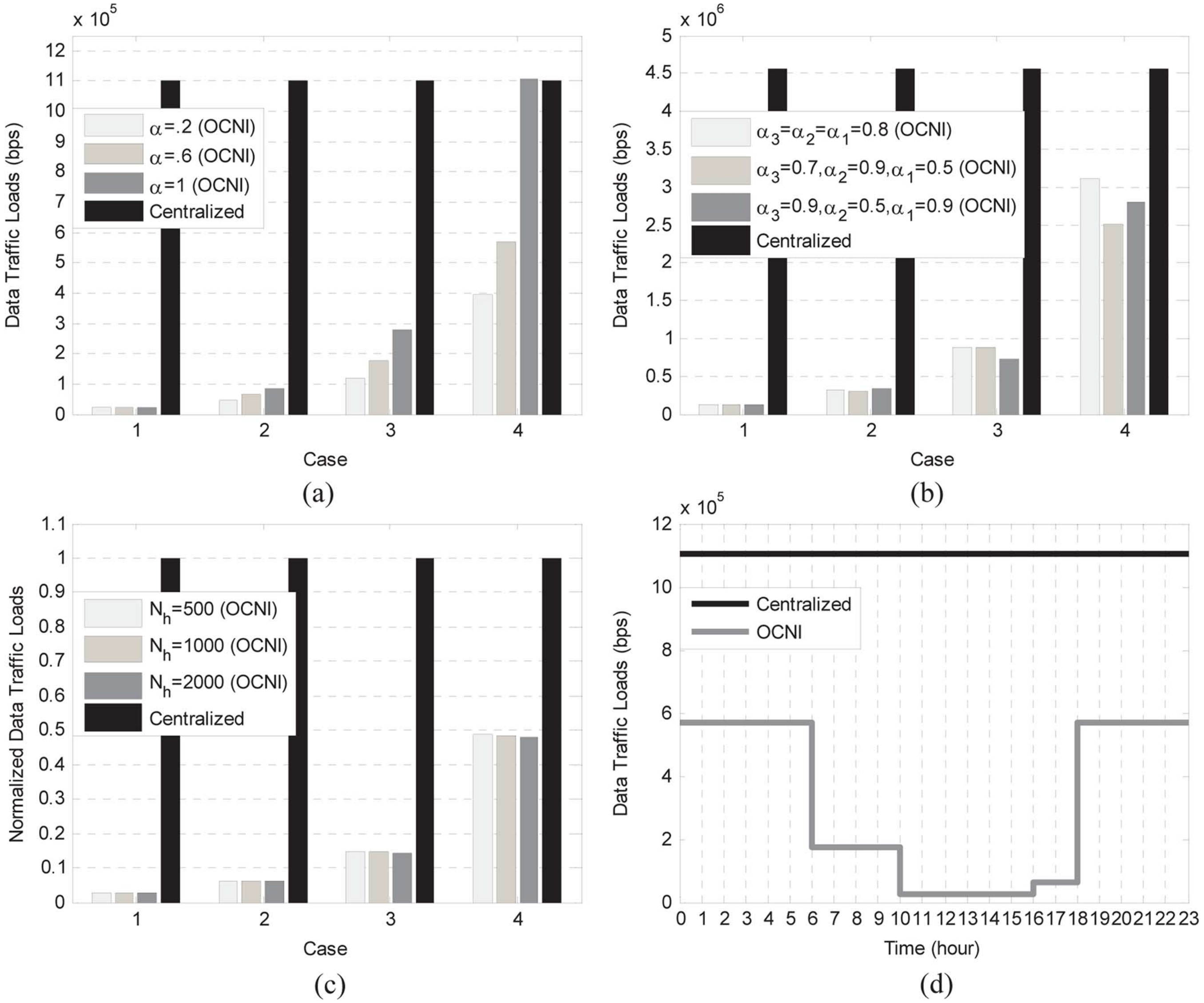

Fig. 6. Analysis of data traffic under OCNI and legacy system when (a) coarse-grained information is applied; (b) abstraction values are varying; (c) quantity of power nodes in a MG is varying; and (d) both operations are tested throughout the day.

abstraction ratio is 1 (i.e., fine-grained information is required, see case 4 in Fig. 6(a)). Nevertheless, OCNI is able to efficiently control the traffic of data loads based on its underlying power operation from LV to MV/LV levels in terms of network delay, and at the same time the amount of uplink data traffic will be essentially determined by 1) how often data are collected from the measuring nodes so that the granularity of content collection is satisfied in order to maintain the system reliability, 2) the volume of information of the lower-tier CCs required by the upper-tier operators who are then able to conduct power balancing operations at their level, and 3) the amount of renewable energy produced and consumed in regard to the pattern of customers' energy profiles, as well as the allocation of energy storage. Fig. 6(d) demonstrates the amount of data traffic conveyed in the network throughout the day when $N_h = 100$ and $\alpha = 0.6$. While the legacy operation involves all the data transmission as expected, traffic in OCNI shows a pattern in accordance with energy profiles. The pattern can be categorized into four phases; for example, in phase 1 (0–6 hour), people are asleep and PV units are not generating power, and therefore macro grid power is needed; in phase 2 (6–10 hour), people get up and go to work at sunrise, and therefore power sharing among ADNs using solar power may be possible; in phase 3 (10–16 hour), solar power is generated at the maximum while most of people are not at home, and therefore power balance may be achieved within the MGs; in phase 4 (16–18 hour), more people are coming home from work at sunset and start using appliances (e.g., oven, TV, dishwasher) that require macro grid power again, i.e., back to phase 1. To further decrease the traffic loads towards the CCC, implementing energy storage and other RESs such as micro wind turbines to support power during the nights is also a feasible solution. Notably, balancing power generation and loads within the MG has great potentials to reduce traffic loads transmitted to the upper tiers; however, it may be an unlikely case due to a small quantity of participating power nodes. Increasing the node quantity in a MG may ease power balance, but at the same time increases both control and communications complexities. Both case 2 and case 3 show a more

TABLE III

Data Traffic for Power Balance Conveyed in the **Decentralized** (OCNI) and **Centralized** (Cen.) Operations

Scheme	Case	Total Amount of Traffic	Description
OCNI	1	$L_{4\_3} + L_{3\_4}$	Power balance (PB) is possible within MGs.
	2	$L_{3\_2} + L_{2\_3} + L_{3\_4}\lvert g\rvert$	PB is not possible within MGs, but possible among MGs in N/FANs.
	3	$L_{2\_1} + L_{1\_2} + (L_{2\_3} + {} + L_{3\_4}\lvert g\rvert)\lvert c\rvert$	PB is neither possible within MGs nor in N/FANs, but possible among groups in subsystems.
	4	$L_{1\_ccc} + L_{ccc\_1} + [L_{1\_2} + {} + (L_{2\_3} + L_{3\_4}\lvert g\rvert)\lvert c\rvert]\lvert C\rvert$	PB is not possible within MGs, N/FANs, subsystems, but possible among ADNs; if not possible among ADNs, either macro grid power or PV unit disconnection is required.
Cen.	–	$(\bar{\lambda}_{\mathcal{M}}\mathcal{M} + \bar{\lambda}_{\mathcal{V}}\mathcal{V}) + {} + \bar{\lambda}_{cen}(\mathcal{M} + \mathcal{V})$	PB is performed throughout the distribution networks with DCCs. $\mathcal{M} = \sum_{k=1}^{\lvert c\rvert} M_{g_k} + \sum_{s=1}^{\lvert C\rvert} M_{c_s}, \forall g \in c, \forall c \in C$ and $\mathcal{V} = \sum_{\forall h \in g, \forall g \in c, \forall c \in C} (V_h + M_h)$.

practical phenomenon that is likely to occur in the future distribution system when renewable power and customer loads can be balanced.

VI. Conclusion and Future Work

In this paper, we have investigated a typical power system model which possesses the radial tree-like topology feature we have today; a multi-tier communications infrastructure is developed to facilitate active operations of the underlying autonomous distribution networks. Power balance is one primary issue in the power system that can be more challenging with higher penetration of distributed energy resources in terms of control and communications complexities. We consider a micro grid consisting of households with installed PV systems in a residential network. The objective is to enhance the utilization of renewable energy generated by PV systems without energy storage in the distribution system. We initially tackle the balance of PV generation and household loads within the micro grid by proposing an algorithm to derive the shortest paths for power sharing among households by means of voltage control and communications in coordination. The proposed autonomous distribution network with the multi-tier overlay communications infrastructure is constructed such that power sharing and associated communications are initially performed in each individual micro grid at the lower tier. Our simulation results show that not only this methodology has great potentials to save considerable bandwidth owing to the reduction of data traffic loads at the upper tiers, but also power balancing through power sharing at the upper tiers is a more practical condition due to higher chances of power compensation among micro girds at the cost of greater involvement of information exchange among subnetworks.

The novel methodology of power control and communications operation proposed in this research will have impacts on the legacy power distribution system. For future works, we will improve the proposed algorithms, COPE, by incorporating weights to the link attributed to power loss and physical distance, as well as OCNI by considering delays in heterogeneous topologies with respect to varying sizes of households and occurrence of faults in the power distribution system. The associated communications design for resource allocation to tackle signal interference incurred in the networks of micro grids will also be investigated.

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