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A Resilient and Privacy-Preserving Energy Management Strategy for Networked Microgrids

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***Abstract*—This paper presents an energy management strategy for day-ahead scheduling of networked microgrids and is named as *nested energy management system*. In the proposed nested energy management strategy, the surplus power existing in the inner level microgrids is reflected as a resource and deficit as a load to the outer level microgrids. The operation cost of networked microgrids with nested energy management systems is lesser as compared to conventional decentralized or hybrid energy management strategies. Similarly, due to the inclusion of data (surplus/deficit) from inner level microgrids, customer privacy also increases. In islanded mode, the resilient performance of disconnected microgrids is enhanced due to their ability to form *subgroups*. The probability of subgrouping for L-layers of microgrids is given by (L-2)/L. In grid-connected mode, various cases with diverse generation costs at each microgrid level along with the time-of-use market price signals have been evaluated. In islanded mode, the effect of battery energy storage system and disconnection of microgrids from the network have been evaluated. Hybrid AC/DC microgrids have also been considered to evaluate the effectiveness of the proposed approach. Simulation results have proved the viability of the proposed approach.**

***Index Terms*— Customer privacy, hybrid microgrids, nested energy management systems, resiliency, time-of-use pricing.**

NOMENCLATURE

Abbreviations

BESS	Battery energy storage system
CDG	Controllable distributed generator
EMS	Energy management system
MG	Microgrid
MILP	Mixed integer linear programming
RDG	Renewable distributed generator

Sets

i	Set of generations, running from 1 to I.
l	Set of microgrids, running from 1 to L.
t	Set of time intervals, running from 1 to T.
ρ_l	Priority index for load of microgrid l.

Constants

$C_{l,i}^{CDG}$	Production cost of CDG unit i in MG l.
$C_{l,i}^{SU}$	Start-up cost of CDG unit i in MG l.
$C_{l,i}^{SD}$	Shut-down cost of CDG unit i in MG l.
$C_{l,t}^{Pen}$	Penalty cost for shedding load of MG l at time t.
$P_{l,t}^{PV}$	Forecasted photovoltaic cell power of MG l at time t.
$P_{l,t}^{WT}$	Forecasted output of wind turbine of MG l at time t.
$P_{l,t}^{L}$	Forecasted load of MG l at time t.
$P_{B,l}^{Cap}$	Capacity of BESS of MG l.
$P_{l,i}^{\min}$	Minimum production limit of CDG i of MG l.
$P_{l,i}^{\max}$	Maximum production limit of CDG i of MG l.
PR_t^{Buy}	Electricity buying price from utility grid at time t.
PR_t^{Sell}	Electricity selling price to utility grid at time t.
$PR_{l,t}^{Def}$	Price for buying power by MG l in islanded mode.
PR_l^{Sur}	Price for selling power by MG l in islanded mode.
L_l^{B+}	Charging loss of BESS in MG l.
L_l^{B-}	Discharging loss of BESS in MG l.
$P_{(l,l+1)}^{CON}$	Capacity of converter linking microgrids l and $l+1$

Variables

$P_{i,l,t}^{CDG}$	Generation amount of CDG unit i at time t in MG l.
$P_{l,t}^{Def}$	Proposed deficit amount of power at time t in MG l.
$P_{l,t}^{Sur}$	Proposed surplus amount of power at time t in MG l.
$P_{l,t}^{A\_Sur}$	Actual surplus amount of power at time t in MG l.
$P_{l,t}^{A\_Def}$	Actual deficit amount of power at time t in MG l.
$P_{(l,l+1),t}^{C\text{-}Loss}$	Loss of converter linking microgrids l and $l+1$
$P_{(l,l+1),t}^{L\text{-}Loss}$	Loss of line linking microgrids l and $l+1$
$P_{(l,l+1),t}^{Loss}$	Total loss to transfer power from microgrids l to $l+1$
$P_{l,t}^{B+}$	Power charged to BESS in MG l at time t.
$P_{l,t}^{B-}$	Power discharged from BESS in MG l at time t.
$P_{l,t}^{Shed}$	Amount of load shed from MG l at time t.
$P_{l,t}^{Rd}$	Amount of power ramp downed at MG l at time t.
$PRD_{l,t}^{\max}$	Maximum amount of power to be ramp downed in MG l at time t.
$PS_{l,t}^{\max}$	Maximum amount of load shed in MG l at time t.
$P_{l,t}^{RL}$	Amount of load restored in MG l at time t.
RI	Resilience index for networked microgrids
$RI^{\max}$	Maximum possible value of resilience index
RI^{acc}	Acceptable value of resilience index.
RI^{1}	Resilience index of level 1(most critical) microgrid.
$SOC_{l,t}^{B}$	State of charge for BESS at t in MG l.
$u_{l,i,t}$	Commitment state of CDG unit i at time t in MG l.

I. INTRODUCTION

MICROGRIDS have the potential to improve the economical, technical, environmental, and sustainable performances of conventional distribution systems. Microgrids have the ability to sustain the integration of controllable distributed generators (CDGs) and combined heat and power systems [1]. In addition, microgrids have the ability to operate both in grid-connected and islanded modes. Therefore, microgrids have the

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capability to improve the system resiliency, service reliability, and power quality for the end-users. In order to realize these benefits of microgrids, several challenging problems need to be addressed [2]-[5]. From the viewpoint of microgrid energy management, uncertainty management, customer privacy, and system resiliency are the major challenges [3]-[5].

Networking of various microgrids to form a network of microgrids has emerged in the literature as an advanced form and application of the microgrid concept [2]-[5]. Networked microgrids have potential to decrease the operation cost of the network in grid-connected mode operation. Similarly, the load-shedding amount could be reduced through sharing of energy in the islanded mode operation. Optimization algorithms and energy management strategies incorporated in the energy management system (EMS) of networked microgrids are considered as the major components of smart distribution management systems [6]. Numerous researches have been carried out for optimal energy management of networked/coupled microgrids as listed in Table I.

The computational burden on central EMS, [7]-[9], increases rapidly with increase in network size [10]. In order to reduce the computational burden on the central EMS, sequentially coordinated operations have been suggested by [11], [12] for scheduling of microgrids. The computational burden on the central EMS can be reduced by using hierarchical energy management strategies or sequentially coordinated operations. However, the operators in the central EMS need the private information about the energy consumption and generation patterns of consumers of each microgrid. The demand of such information may raise privacy concerns [13]-[15]. In addition, an intensive communication infrastructure is required for centralized EMSs [1]. Therefore, decentralized EMSs have been proposed [13]-[16]. Due to individual objectives of different units in distributed/decentralized EMSs, an equilibrium may exist. In that case, no entity can further optimize its objective by only changing its local decisions [17]. Additionally, the local controllers in decentralized/distributed EMSs are unaware of the system level parameters and hence are not able to utilize them optimally [18]. Centralized and decentralized EMSs are capable of fulfilling a set of objectives while fully comprising the contrary set. Therefore, the characteristics of both centralized and decentralized EMSs can be combined to form a hybrid EMS for networked microgrids [19].

Each of the EMS has its own merits and demerits. Merits of each EMS like minimum operation cost, customer privacy, resiliency, flexibility, diversification, reduction of computational burden, and reliability are usually contrary. It is a challenging task to develop a trade-off between them in a single energy management strategy. Hybrid EMSs have emerged in the literature as a trade-off solution for management of networked microgrids [17]-[23]. However, due to the parallel operation of individual microgrids with zero information of other microgrids of the network, operation cost is dependent on the load patterns of individual microgrids. Another drawback of hybrid EMSs is, in islanded mode when a microgrid disconnects from its network, it has to operate independently. This effect makes them less tolerant to faults and hence resiliency is reduced. Most of the hybrid EMSs are two level, which results in single level privacy. If the central EMS knows about the generation capacity of individual microgrids (by any way), the privacy of the customers will be fully compromised, as the surplus/deficit amount is already known to the central EMS.

TABLE I
LITERATURE REVIEW

EMS Type	Optimization Objective	Optimization Algorithm	Major Considerations	Ref.	Limitations
Centralized	Cost minimization	Particle swarm optimization	1. Uncertainties in load and renewable power 2. Grid-connected mode only	[7]	1. Increase in computational burden of central EMS 2. Failure to preserve customer privacy of microgrids 3. Requirement of extensive communication setup
	Cost minimization and reliability maximization	Imperialistic competitive algorithm	1. Load-generation uncertainties 2. Both grid-connected and islanded modes	[8]	
	System reliability maximization	Mixed integer linear programming (MILP)	1. Detailed modeling of unbalanced systems 2. Islanded mode only	[9]	
Centralized with Sequential Operation	Cost minimization		1. Distribution of computational burden 2. Grid-connected mode only	[11]	1. Failure to preserve customer privacy of microgrids 2. Requirement of extensive communication setup
	Cost minimization	Sequential quadratic programming	1. Demand bidding and three level control 2. Grid-connected mode only	[12]	
Decentralized	Cost minimization	Multi-agent system with contract net protocol	1. Autonomous operation & customer privacy 2. Grid-connected mode only	[13]	1. Unawareness of system level resources 2. Due to individual objectives, equilibrium may exist and further optimization may not be possible
	Minimization of load shedding		1. Competitive environment among suppliers 2. Islanded mode only	[14]	
	Cost minimization and reliability maximization	Stochastic optimization	1. 2-layered stochastic model & uncertainties 2. Both grid-connected and islanded modes	[15]	
	Supply adequacy maximization	Average consensus algorithm	1. Self-healing and autonomous operation 2. Both grid-connected and islanded modes	[16]	
Hybrid	Cost minimization and reliability maximization	MILP	1. Three-level control and dynamic conditions 2. Both grid-connected and islanded modes	[20]	1. Parallel operation of microgrids 2. Single-level privacy of customers, easy to reveal 3. Reduction in resiliency of disconnected microgrids 4. Central EMS failure results in autonomous operation
	Cost minimization		1. Control of voltage, frequency, and power 2. Both grid-connected and islanded modes	[21]	
	Cost minimization and reliability maximization		1. Hybrid microgrids and diversity gain 2. Both grid-connected and islanded modes	[22]	
	Cost minimization		1. Load smoothening & cooperative operation 2. Islanded mode only	[23]	

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In this paper, a novel energy management strategy has been proposed for scheduling of networked microgrids and is named as *Nested EMS*. In nested EMS, each lower EMS optimizes its local resources and informs the upper-level EMS about its status (surplus/deficit amount). Upper-level EMS uses this information during the optimization of its local resources, which reduces the operation cost of the network. If a microgrid is disconnected from the network in islanded mode, its resiliency is enhanced through subgrouping. The major contributions of this paper are listed as follows.

- Development of a novel EMS with following capabilities:
  a. Reduction of operation cost in grid-connected mode
  b. Provision of layered privacy to the customers
  c. Enhancement of resiliency in islanded mode
- Proposition of a privacy-preserving mechanism for information sharing with local EMS
- Consideration of hybrid microgrids and comparison of nested EMS with prevailing EMSs
- MILP-based problem formulation for both operation modes and formulation a resilience index

II. Prevailing EMSs

A. Centralized EMSs

In centralized EMSs, the function of the central EMS is to manage the energy balance of the entire network [13]. In islanded mode, the function of the central EMS is to shed the non-critical loads. It is also responsible for dealing with the external EMS as shown in Fig. 1.a. Centralized EMSs are well suited for optimization of those microgrid systems, which are owned by a single owner. Centralized EMSs are also useful for standalone microgrids with slow changing infrastructures [30]. Various centralized EMSs have been proposed and analyzed for AC, DC, and hybrid microgrids by [24]–[26].

B. Decentralized EMSs

In decentralized EMSs, each microgrid is an autonomous entity and possesses a local EMS with an objective to maximize its own profit. Each microgrid trades power with the utility grid individually as shown in Fig. 1.b. In some cases, the local EMSs can communicate with their neighbor microgrids [1], [29]. Multi-agent systems are commonly used for optimization of decentralized EMSs [13], [14], [30], [31]. Decentralized EMSs are well-suited for grid-connected microgrids comprising various fast changings distributed generators with different ownerships [29].

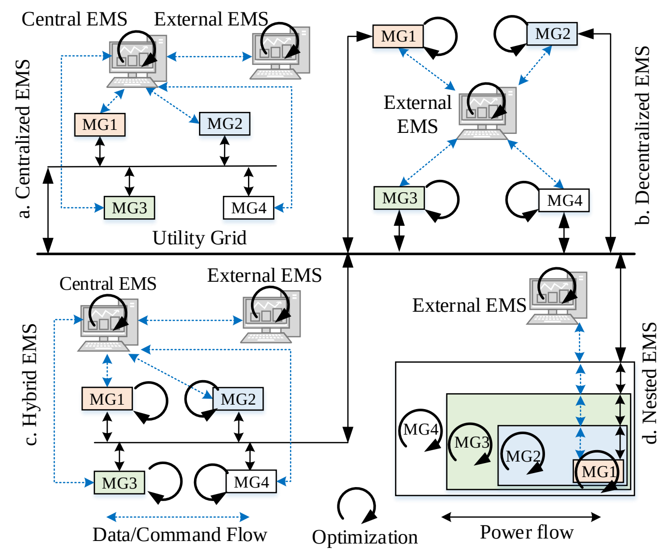

Fig. 1. Illustration of prevailing and proposed EMSs.

C. Hybrid EMSs

Hybrid EMSs have evolved to overcome the drawbacks of each of the centralized and the decentralized EMS and to exploit the merits of each EMS [18]-[20], [29]. In hybrid EMSs, each of the local EMS is responsible for optimization of local resources only, and it informs the central EMS about the surplus/deficit amount (Fig. 1. c). The central EMS is responsible for management of system level resources and enables trading between microgrids. Energy management schemes based on hybrid EMSs have been proposed by [19], [23].

The merits and demerits of all the three prevailing EMSs are summarized in Table II. Fig. 1 shows the information & power flow of the three prevailing EMSs and the proposed EMS.

TABLE II
MERITS AND DEMERITS OF PREVAILING EMSs

EMS Type	Merits	Demerits	Ref.
Centralized	• Reduced operation cost (global optimization) • Utilization of efficient components of each microgrid • Easy to standardize and easy to implement • Reduction in external trading • Higher reliability in islanded operation, only if central EMS is not compromised	• Requirement of an extensive communication infrastructure and computationally powerful central EMS • Weak plug-and-play functionality • Failure to preserve customer privacy • Onerous testing after even small modifications in the system • Lesser adaptability, flexibility, and propagation of forecasting errors	[1], [4], [6],
Decentralized	• Preserve customer privacy • Higher flexibility and ensures plug-and-play flexibility • Distribution of computational burden • Influence of forecasting errors on microgrid level only	• Increased operation cost and unawareness of the system level resources (local optimization) • Lesser resiliency in islanded mode • Excessive power trading with utility grid in grid-connected mode	[27], [28],
Hybrid	• Preserve customer privacy (single level) • Better flexibility as compared to centralized EMSs • Ensure plug-and-play flexibility • Distribution of computational burden • Lesser operation cost compared to decentralized EMSs	• Parallel operation of microgrids, unaware of other microgrids • Single level privacy, easy to reveal the privacy of consumers • Reduction in resilient performance of disconnected microgrids • If central EMS is compromised, all microgrids will operate in a decentralized way (autonomously)	[29], [32], [37]

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III. Proposed Nested EMS

A. Configuration of Nested EMSs

This section describes the configuration of the proposed model of a microgrid network of L microgrids as shown in Fig. 2. Each microgrid constitutes a level of the microgrid network. Nesting of microgrids could be based on load priority, voltage levels of microgrids, amount of loads, power source type (AC/DC), customer privacy, etc. However, in this study load priority-based nesting has been considered. Each microgrid contains CDGs, renewable distributed generators (RDGs), battery energy storage system (BESS), and electrical loads.

B. Information Flow in Nested EMSs

The sequential flow of information and commands in the proposed nested EMS is shown in Fig. 3. Firstly, the EMS of microgrid at $L=1$ performs its local optimization and informs the upper-level EMS ($L=2$) about the surplus/deficit amount. During informing the upper EMS, converter losses are considered by the inner level EMS. The EMS at $L=2$ considers the surplus as a resource and the deficit as a load and optimizes its resources. All the in-between EMSs optimize their resources in the same way. The topmost EMS ($L=3$ in this case) optimizes its local resources and decides the trading amount of power with the utility grid. In the case of selling, due profit is received by each microgrid in accordance to its share in the power sold to the utility grid. However, if the surplus from l^{th} microgrid is utilized by microgrid at $l+1$, $(l+1)^{th}$ microgrid will compensate the l^{th} microgrid with market selling price and vice-versa for the buying power. Surplus/deficit information from l^{th} microgrid is received by microgrid at $l+1$. When the surplus/deficit information of $(l+1)^{th}$ is received by microgrid at $l+2$, it will be very difficult for the operators at $l+2$ to unveil the load pattern of microgrid 1, since it is mixed with the data of microgrid 2. When the information reaches L^{th} microgrid, it will be very difficult to find microgrid 1's data. Fig. 3 shows the information flow in the proposed nested EMS.

Most of the times inside a microgrid there are various loads and each with different ownerships. In that case, each of the load owners may not want to disclose its load pattern [4], [34] to the local EMS. A privacy-preserving mechanism for information sharing inside a single microgrid with different load owners is proposed and is depicted by Fig. 4. Encrypted load information will be sent to the data aggregator by each load owning entity. Data aggregator will add all the encrypted loads and form a collective load. Encryption will be a simple addition of a random number to the actual data. This random number is considered as the key for the encrypted data. Keys from all the load owners will be sent to a key aggregator and key aggregator will sum all the keys to form a new key. Data aggregator will send the collective load and key aggregator will send the new key to its local EMS. The EMS will subtract the new key from the collective load to find the actual total load. In this way, the privacy of each load owner will be preserved. Generation units and BESS are owned by the local microgrid. Therefore, their data is directly sent to the local EMS.

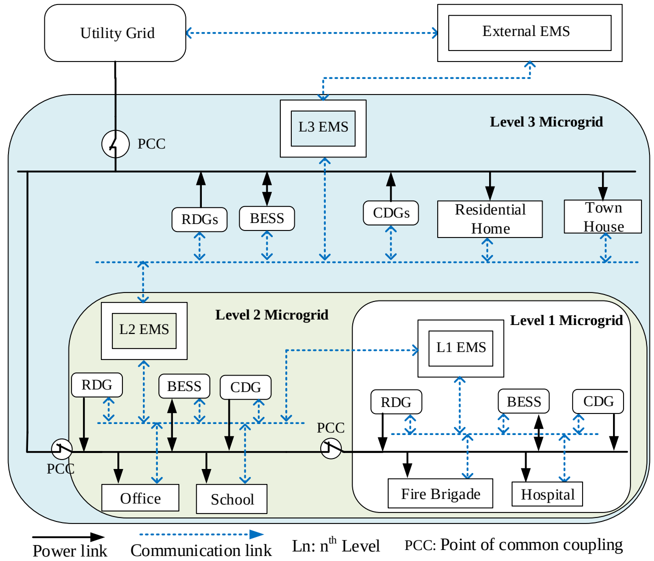

Fig. 2. Configuration of the proposed nested EMS.

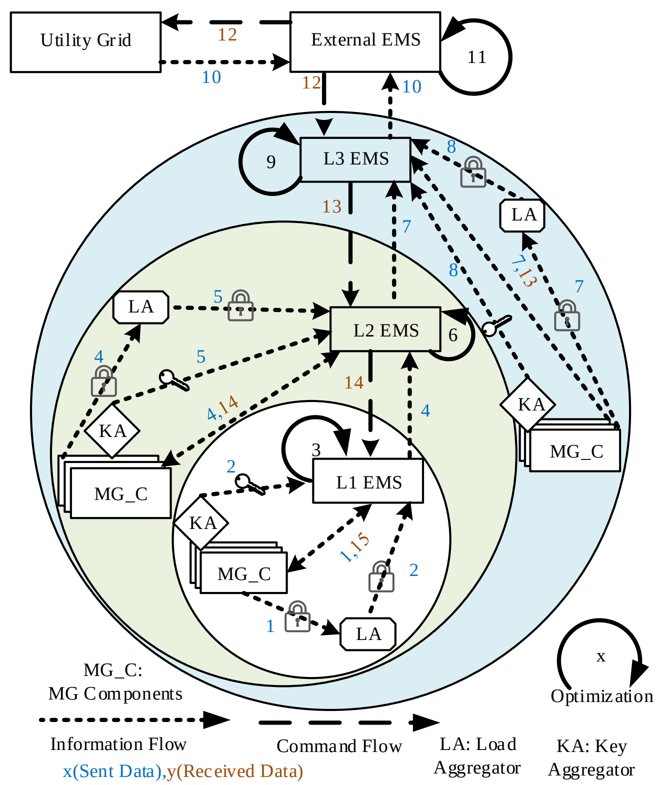

Fig. 3. Information flow in the proposed nested EMS.

The proposed approach is primarily for nested energy management of microgrids. It is defined by the way information is processed. However, in some cases, physical nesting of microgrids is also possible. Campus/institutional microgrids (universities, hospitals, industrial parks, etc.) and military microgrids could be considered as physically nested microgrids [34]. A university town, with several universities, could be the outermost level of microgrid with town level resources. Each university campus could be an inner level microgrid with campus resources. Similarly, a department/research center of a university could be an inner level microgrid of the university. A similar interpretation is valid for recreational complexes and

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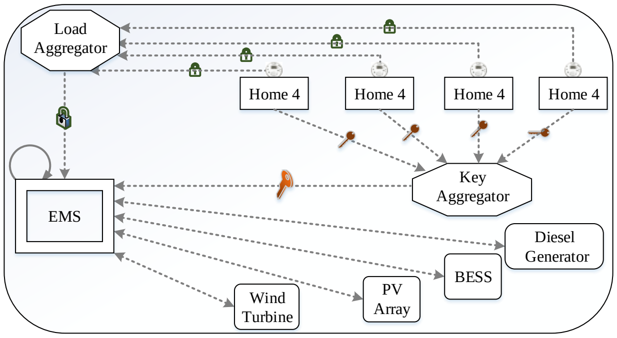

Fig. 4. Information sharing mechanism within a microgrid.

community health centers. Another example of physically nested microgrids is a village or a city town [35], i.e. a village could be the outermost level microgrid with village level resources. A division (administrative unit) of the village could be an inner level microgrid. An emergency service providing area of the division could be an inner level microgrid of the division. Similarly, physical nesting of microgrids has been considered for structured energy management by [36].

C. Benefits of Nested EMS over Hybrid EMS

Centralized and decentralized EMSs are capable of fulfilling a set of objectives while compromising the contrary set. Hybrid EMSs are considered as the trade-off EMSs [19]-[23]. Therefore, drawbacks of hybrid EMSs and potential benefits of the proposed nested EMS are elaborated in this section.

a) In hybrid EMSs, all the microgrids optimize their local resources in parallel (unaware of other microgrids), resulting in increased operation cost of the network. The proposed nested EMS uses the surplus/deficit information of lower level microgrids during optimizing its local resources and it reduces the operation cost of the network.

b) When a microgrid is disconnected from the network, in hybrid EMS it has to operate autonomously. In the case of nested EMS, it is more likely that it will form a subgroup. This subgrouping will improve the resiliency of the network and the disconnected microgrid. The probability of subgrouping for L-layers of microgrids is given by (L-2)/L.

c) The privacy of customers in the hybrid EMS is uniform and is of the single level while in nested EMS, customer privacy is layered (realistic). The privacy of the innermost microgrid is strongest while that of the outermost is weakest (although stronger than the hybrid EMS).

d) Hybrid EMS requires L local EMSs and one central EMS for optimizing L microgrids while nested EMSs only require L local EMSs. In case of hybrid EMSs, when the central EMS is compromised, all microgrids of the network will operate in a decentralized way. However, in case of nested EMSs, when the outermost EMS is compromised, all microgrids except the outermost microgrid will form a network.

IV. Problem Formulation

In this section, a day-ahead scheduling problem for the proposed nested EMS is formulated based on MILP. The objective of the formulated scheduling model is to minimize the operation cost of the microgrid network in grid-connected mode and to maximize the service reliability in islanded mode.

A. Grid-Connected Mode

The objective of nested EMS in grid-connected mode is to minimize the operation cost of the network while respecting some equality and inequality constraints. The objective function for a nested EMS of L microgrids is given by (1).

$$\min \sum_{l\in L}\sum_{i\in I}\sum_{t\in T}\left(C^{CDG}_{l,i}\left(P^{CDG}_{l,i,t}\right)+y_{l,i,t}.C^{SU}_{l,i}+z_{l,i,t}.C^{SD}_{l,i}\right)+ \sum_{l\in L}\sum_{t\in T}\left(PR^{Buy}_t\cdot\left(P^{Def}_{l,t}-P^{Def}_{l-1,t}\right)-PR^{Sell}_t\cdot\left(P^{Sur}_{l,t}-P^{Sur}_{l-1,t}\right)\right) \quad (1)$$

Subject to

$$u_{l,i,t}\cdot P^{\min}_{l,i}\le P^{CDG}_{l,i,t}\le u_{l,i,t}\cdot P^{\max}_{l,i} \qquad \forall l\in L, i\in I, t\in T \quad (2)$$

$$y_{l,i,t}=\max\left\{\left(u_{l,i,t}-u_{l,i,t-1}\right),0\right\},\ u_{l,i,t}\in\{0,1\}\ \ \forall l\in L, i\in I, t\in T \quad (3)$$

$$z_{l,i,t}=\max\left\{\left(u_{l,i,t-1}-u_{l,i,t}\right),0\right\},\ u_{l,i,t}\in\{0,1\}\ \ \forall l\in L, i\in I, t\in T \quad (4)$$

$$P^{PV}_{l,t}+P^{WT}_{l,t}+P^{CDG}_{l,i,t}+P^{Def}_{l,t}-P^{Sur}_{l,t}+P^{B-}_{l,t}-P^{B+}_{l,t}=P^{L}_{l,t}+P^{Def}_{l-1,t}-P^{Sur}_{l-1,t} \qquad \forall l\in L, i\in I, t\in T \quad (5)$$

$$0\le P^{Def}_{l,t},\ P^{Sur}_{l,t}\le P^{CON}_{(l,l+1)} \qquad \forall l\in L, i\in I, t\in T \quad (6)$$

$$P^{Sur}_{l,t}=P^{A\_Sur}_{l,t}-P^{Loss}_{(l,l+1),t} \qquad \forall l\in L, i\in I, t\in T \quad (7)$$

$$P^{Def}_{l,t}=P^{A\_Def}_{l,t}+P^{Loss}_{(l,l+1),t} \qquad \forall l\in L, i\in I, t\in T \quad (8)$$

$$P^{Loss}_{(l,l+1),t}=P^{C-Loss}_{(l,l+1),t}+P^{L-Loss}_{(l,l+1),t} \qquad \forall l\in L, i\in I, t\in T \quad (9)$$

$$0\le P^{B+}_{l,t}\le P^{Cap}_{B,l}\cdot\left(1-SOC^{B}_{l,t-1}\right)\cdot 1/1-L^{B+}_{l} \qquad \forall l\in L, t\in T \quad (10)$$

$$0\le P^{B-}_{l,t}\le P^{Cap}_{B,l}\cdot SOC^{B}_{l,t-1}\cdot(1-L^{B-}_{l}) \qquad \forall l\in L, t\in T \quad (11)$$

$$SOC^{B}_{l,t}=SOC^{B}_{l,t-1}-\frac{1}{P^{Cap}_{B,l}}\cdot\left(\frac{1}{1-L^{B-}_{l}}\cdot P^{B-}_{l,t}-P^{B+}_{l,t}\cdot(1-L^{B+}_{l})\right) \quad (12)$$

$$0\le SOC^{B}_{l,t}\le 1 \qquad \forall l\in L, t\in T \quad (13)$$

$$Case\ 1:\ When\ l=1 \quad P^{Def}_{l-1,t}=P^{Sur}_{l-1,t}=0 \qquad \forall l\in L, t\in T \quad (14)$$

$$Case\ 2:\ When\ l=L$$

$$P^{Def}_{l,t}=P^{Buy}_{l,t},\ P^{Sur}_{l,t}=P^{Sell}_{l,t} \qquad \forall l\in L, t\in T \quad (15)$$

The first line of equation (1) represents generation, startup, and shutdown costs of CDG generators. The second line contains the price for buying power from upper-level microgrid, the price for selling power to lower level microgrid, the price for buying power from lower level microgrid, and the price for selling power to upper-level microgrid, respectively. The inequality constraints associated with the CDG generators of level l are represented by (2)-(4). The equality constraint for power balance of l^{th} microgrid is given by (5). The constraint related to the capacity of the converter interconnecting microgrids l and $l+1$ is given by (6). Total loss is considered for proposing surplus/deficit amounts, as depicted by equations (7) and (8). Total loss is computed by summing the losses of converter and line connecting l^{th} microgrid with $(l+1)^{th}$ microgrid, as given by equation (9). The inequality constraints associated with the charging, discharging, and status-of-charge of BESS of l^{th} microgrid are given by (10)-(13). The specific equality constraints associated with the first ($l=1$) and the last ($l=L$) microgrids are given by (14), (15), respectively. The specific constraints depict that, 1^{st} microgrid can trade only with upper-

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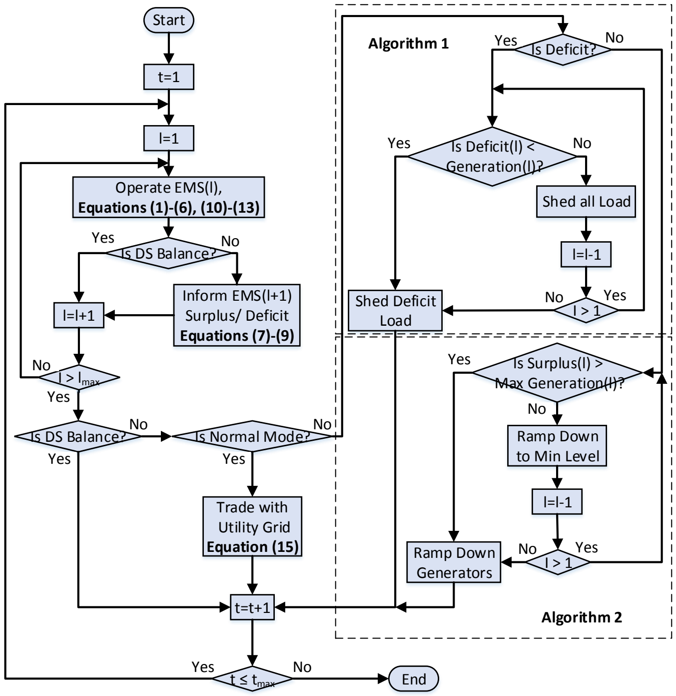

Fig. 5. Flow chart for information processing in the proposed nested EMS.

level microgrid and the last microgrid is responsible for trading with the utility grid. A flowchart for optimization of L nested EMSs is shown in Fig. 5. Scheduling of resources is started for the innermost microgrid, i.e. level 1 microgrid. If the demand and supply of the inner microgrid is balanced, the upper-level microgrid is selected for scheduling. Otherwise, inner microgrid sends its surplus/deficit information to the outer level microgrid. After scheduling the resources of the outermost microgrid, i.e. microgrid at level L, the operation mode of the microgrid network is assessed. If the microgrid network is in grid-connected mode, surplus/deficit amount from the microgrid network is balanced by trading with the utility grid. In the case of islanded mode, surplus amount is adjusted by ramping down the dispatchable generators. Similarly, a load shedding mechanism is used for adjusting the deficit amount. Algorithms 1 and 2 explain the detailed mechanisms for load shedding and ramping down, respectively.

B. Islanded Mode

The objective of the microgrid network in islanded mode is to minimize the operation cost of the network using the network resources only. The penalty cost for curtailing load is assumed to higher than the generation cost of CDGs, as shown in Fig. 7(c) and Table V. Due to this assumption, the priority of service reliability will be higher than the operation cost in the islanded mode. In this study, nesting of microgrid EMSs is based on load priority, i.e. load of the microgrid at level 1 is the most critical while that of L is the least critical. Equation (16) is the objective function of microgrid network in islanded mode. The first line contains generation, startup, and shutdown costs of CDG generators. The second line contains the price for buying power from upper-level microgrid, the price for selling power to lower level microgrid, the price for buying power from lower level microgrid, and the price for selling power to upper-level microgrid, respectively. Equation (17)-(19) shows the constraints for CDG generators. Power balancing of l^{th} microgrid is given by (20). The constraint related to the capacity of the converter interconnecting a pair of microgrids is given by (21). Surplus and shortage amounts after considering converter and line losses are given by equations (22) - (24). The constraints related to BESS are given by (25)-(28). Similar to grid-connected mode, the 1^{st} microgrid can trade only with upper-level microgrid as shown in equation (29). However, due to the absence of connection with the utility grid, trading with the utility grid is not possible. The maximum amount of load to be shed and the maximum amount of power to be ramped down at each time interval is represented by (30).

$$\min \sum_{l\in L}\sum_{i\in I}\sum_{t\in T}\left(C^{CDG}_{l,i,}\left(P^{CDG}_{l,i,t}\right)+y_{l,i,t}.C^{SU}_{l,i}+z_{l,i,t}.C^{SD}_{l,i}\right)+$$
$$\sum_{l\in L}\sum_{t\in T}\left(PR^{Def}_{l,t}.P^{Def}_{l,t}-PR^{Def}_{l-1,t}.P^{Def}_{l-1,t}+PR^{Sur}_{l-1,t}.P^{Sur}_{l-1,t}-PR^{Sur}_{l,t}.P^{Sur}_{l,t}\right) \quad (16)$$

Subject to

$$u_{l,i,t}\cdot P^{\min}_{l,i}\le P^{CDG}_{l,i,t}\le u_{l,i,t}\cdot P^{\max}_{l,i} \qquad \forall l\in L, i\in I, t\in T \quad (17)$$

$$y_{l,i,t}=\max\left\{\left(u_{l,i,t}-u_{l,i,t-1}\right),0\right\},\ u_{l,i,t}\in\{0,1\} \ \forall l\in L, i\in I, t\in T \quad (18)$$

$$z_{l,i,t}=\max\left\{\left(u_{l,i,t-1}-u_{l,i,t}\right),0\right\},\ u_{l,i,t}\in\{0,1\} \ \forall l\in L, i\in I, t\in T \quad (19)$$

$$P^{PV}_{l,t}+P^{WT}_{l,t}+P^{CDG}_{l,i,t}+P^{Def}_{l,t}-P^{Sur}_{l,t}+P^{B-}_{l,t}-P^{B+}_{l,t}=P^{L}_{l,t}+P^{Def}_{l-1,t}-P^{Sur}_{l-1,t}$$
$$\forall l\in L, i\in I, t\in T \quad (20)$$

$$0\le P^{Def}_{l,t},\ P^{Sur}_{l,t}\le P^{CON}_{(l,l+1)} \qquad \forall l\in L, i\in I, t\in T \quad (21)$$

$$P^{Sur}_{l,t}=P^{A\_Sur}_{l,t}-P^{Loss}_{(l,l+1),t} \qquad \forall l\in L, i\in I, t\in T \quad (22)$$

$$P^{Def}_{l,t}=P^{A\_Def}_{l,t}+P^{Loss}_{(l,l+1),t} \qquad \forall l\in L, i\in I, t\in T \quad (23)$$

$$P^{Loss}_{(l,l+1),t}=P^{C-Loss}_{(l,l+1),t}+P^{L-Loss}_{(l,l+1),t} \qquad \forall l\in L, i\in I, t\in T \quad (24)$$

$$0\le P^{B+}_{l,t}\le P^{Cap}_{B,l}\cdot\left(1-SOC^{B}_{l,t-1}\right)\cdot 1/1-L^{B+}_{l} \qquad \forall l\in L, t\in T \quad (25)$$

$$0\le P^{B-}_{l,t}\le P^{Cap}_{B,l}\cdot SOC^{B}_{l,t-1}\cdot(1-L^{B-}_{l}) \qquad \forall l\in L, t\in T \quad (26)$$

$$SOC^{B}_{l,t}=SOC^{B}_{l,t-1}-\frac{1}{P^{Cap}_{B,l}}\cdot\left(\frac{1}{1-L^{B-}_{l}}\cdot P^{B-}_{l,t}-P^{B+}_{l,t}\cdot(1-L^{B+}_{l})\right) \quad (27)$$

$$0\le SOC^{B}_{l,t}\le 1 \qquad \forall l\in L, t\in T \quad (28)$$

$$Case\ 1:\ When\ l=1 \quad P^{Def}_{l-1,t}=P^{Sur}_{l-1,t}=0 \qquad \forall l\in L, t\in T \quad (29)$$

$$Case\ 2: When\ l=L$$
$$P^{Def}_{l,t}=PS^{\max}_{l,t},\ P^{Sur}_{l,t}=PRD^{\max}_{l,t} \qquad \forall l\in L, t\in T \quad (30)$$

1) Load Shedding and Ramp-Down Algorithms: Due to load priority-based nesting, load shedding will start from the L^{th} microgrid. After shedding the maximum possible load by L^{th} microgrid, deficit amount of load will be updated. If the deficit amount of load is not zero, inner level microgrid (*L-1*) will shed its maximum possible load and update the deficit amount. In the worst-case scenario, this process will be repeated up to the innermost (level 1) microgrid. During the islanded mode operation, the price for buying the deficit amount is replaced with the penalty cost. The penalty cost for curtailing the load of the innermost microgrid is highest and is lowest for the outermost microgrid as shown in Algorithm 1.

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Algorithm 1 Load shedding algorithm

Initial values
Run local optimization for each microgrid
while $t < T$ **do**
  for all $l < L$ **do**
    if $l = L$ **then**
      $P^{Shed}_{l,t} \le PS^{\max}_{l,t}$, $P^{Def}_{l,t} := P^{Def}_{l,t} - P^{Shed}_{l,t}$
    else if $l = 1$ **then**
      $PS^{\max}_{l,t} = PS^{\max}_{l+1,t} - P^{Shed}_{l+1,t} - P^{C-Loss}_{(l,l+1),t}$
      $P^{Shed}_{l,t} = PS^{\max}_{l,t}$, $P^{Def}_{l,t} = 0$
    else
      $P^{Shed}_{l,t} \le PS^{\max}_{l+1,t} - P^{Shed}_{l+1,t} - P^{C\text{-}Loss}_{(l,l+1),t}$
      $P^{Def}_{l,t} := P^{Def}_{l,t} - P^{Shed}_{l,t}$
    end if
    $PR^{Def}_{l,t} = C^{Pen}_{l,t}$, $C^{Pen}_{l,t} > C^{Pen}_{l+1,t}$
  end for
  t++
end while

Algorithm 2 Ramp down algorithm

Initial values
Run local optimization for each microgrid
while $t < T$ **do**
  for all $l < L$ **do**
    if $l = L$ **then**
      $P^{Rd}_{l,t} \le PRD^{\max}_{l,t}$, $P^{Sur}_{l,t} := P^{Sur}_{l,t} - P^{Rd}_{l,t}$
    else if $l = 1$ **then**
      $PRD^{\max}_{l,t} = PRD^{\max}_{l+1,t} - P^{Rd}_{l+1,t} + P^{C\text{-}Loss}_{(l,l+1),t}$
      $P^{Rd}_{l,t} = PRD^{\max}_{l,t}$, $P^{Sur}_{l,t} = 0$
    else
      $P^{Rd}_{l,t} \le PRD^{\max}_{l,t} = PRD^{\max}_{l+1,t} - P^{Rd}_{l+1,t} + P^{C\text{-}Loss}_{(l,l+1),t}$
      $P^{Sur}_{l,t} := P^{Sur}_{l,t} - P^{Rd}_{l,t}$
    end if
    $PR^{Sur}_{l,t} = C^{CDG}_{l,i}$
end for
t++
end while

Similar to load shedding, ramping down of dispatchable generators will also be started from the outermost microgrid, i.e. L^{th} microgrid. After ramping down the maximum possible generation at the outermost microgrid, remaining amount of surplus amount is updated. Both converter and line losses are considered by the inner level microgrids while proposing surplus/shortage to the outer microgrids. Therefore, total losses will be adjusted while ramping down or load shedding by all microgrid. The selling price of surplus power is replaced with the generation cost of CDGs as depicted in Algorithm 2.

2) Resiliency Evaluation: In order to evaluate the resiliency of disconnected microgrids in islanded mode, a resilience index is formulated in this section. The resiliency of each microgrid can be computed by using the total available load and the amount of load restored during a particular event as given by equation (31). The priority of the innermost microgrid's load is the highest ($\rho_1 = 1$) and that of the outermost is the lowest as given by equation (32). The maximum and minimum possible values of the formulated resilience index are bounded by equation (33). Equation (34) depicts the acceptable range of the formulated resilience index. At least the most critical loads need to be restored to assure an acceptable resilience index as given by equation (34). The two conditions for an acceptable resilience index are $RI^{acc} \in [1/L, RI^{\max}]$ and $RI^1 = 1$.

$$RI = \frac{\left(\sum_{t\in T}\sum_{l\in L}\frac{P^{RL}_{l,t}}{P^{L}_{l,t}}.\rho_l\right)}{L} \qquad \forall l \in L, t \in T \qquad (31)$$

$$\rho_l \in [0,1],\ \rho_1 > \rho_2 ... > \rho_L \qquad \forall l \in L, t \in T \qquad (32)$$

$$RI^{\max} = \frac{\sum_{l\in L}\rho_l}{L},\ RI \in [0, RI^{\max}] \qquad \forall l \in L, t \in T \qquad (33)$$

$$RI^{acc} \in [{}^{1}\!/_{L}, RI^{\max}],\ \ RI^1 = \sum_{t\in T}\frac{P^{RL}_{1,t}}{P^{L}_{1,t}} \qquad \forall l \in L, t \in T \qquad (34)$$

This formulated resilience index has been used to evaluate the performance of the three prevailing EMSs and the nested EMS in islanded mode operation in section V-D.

V. Numerical Simulations

A. Simulation Environment and Assumptions

In order to illustrate the effectiveness of the proposed strategy, three microgrids have been considered in this study. Each microgrid comprises of RDGs (photovoltaic array and/or wind turbine), BESS, CDG units, and electric load. The load of microgrid 1 is the most critical while that of microgrid 2 is less critical and the load of microgrid 3 is assumed as the least critical. However, in order to analyze the resilient performance of disconnected microgrids through subgrouping, a network of six microgrids has also been considered in the islanded mode operation. Three new microgrids have been considered outside the initially selected three microgrids. Among the three newly added microgrids, two microgrids are DC microgrids and the remaining one (the outermost) is an AC microgrid. Optimization is performed by using CPLEX in visual studio environment for a scheduling horizon of 24h with 1h time steps.

The major assumptions made in this study for simulations are summarized in Fig. 6. The capacity of CDG & BESS, load, and microgrid size increases from level 1 to level L microgrid. On the other hand, load priority, resiliency, customer privacy, and service reliability increases from level L to level 1.

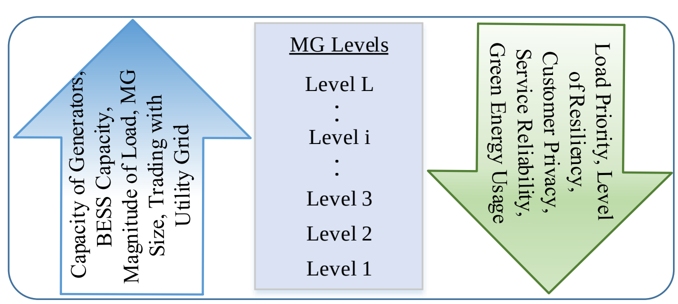

Fig. 6. Basic assumptions for simulations.

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B. Input Data and Network Parameters

Dispatchable generators play a key in optimizing the cost of microgrids. The parameters related to the dispatchable generators (CDGs) considered in each microgrid of the simulated network are tabulated in Table III. BESS can be used to minimize the operation cost of microgrids by storing excess power and by discharging it in high price/load intervals. Parameters related to BESSs of each microgrid of the simulated network are shown in Table IV. Microgrids trade power with other microgrids of the network to reduce trading with the utility grid. Prices for trading power among microgrids and penalty costs for curtailing loads at each level of microgrid in islanded mode are shown in Table V. Power trading among microgrids and with the utility grid are constrained by the capacities of converters connecting them. Losses and capacities of different converters and lines connecting each pair of microgrids of the simulated network are shown in Table VI. The forecasted values of loads, the output power of RDGs, and the day-ahead market price signals have been taken as inputs. Fig. 7(a) shows the hourly load profiles of the three innermost microgrids. The output power of RDGs in microgrids 1, 2, and 3 are shown in Fig. 7(b). Time-of-use price signals along with average per-unit generation costs for the CDGs at each level of the nested network are shown in Fig. 7(c).

In order to compare the results of the proposed nested EMS and the three prevailing EMSs, simulations of all the three prevailing EMSs have also been conducted. Mathematical models are different for each of the EMS. The energy-balancing model proposed by [7] has been used for centralized EMS. The model proposed for normal operation mode by [16] has been used for decentralized EMS. The two-stage model proposed by [37] has been used for hybrid EMS. Constraints related to BESS and CDGs are same for all EMSs. For the sake of comparison, BESS has been treated as a load during charging and as a source during discharging for all the EMSs.

TABLE III
PARAMETERS RELATED TO CDGs OF THE SIMULATED NETWORK

Parameters	MG1	MG2	MG3	MG4	MG5	MG6
Start-up Cost (Won)	200	195	192	187	185	178
Shut-down Cost (Won)	180	175	172	167	165	158
Minimum (KW)	0	0	0	0	0	0
Maximum (KW)	240	490	670	780	820	900

TABLE IV
PARAMETERS RELATED TO BESSs OF THE SIMULATED NETWORK

Parameters	MG1	MG2	MG3	MG4	MG5	MG6
Capacity (KWh)	50	100	150	180	230	300
Initial Charge (KWh)	0	0	0	0	0	0
Charging Loss (%)	5	5	5	4	4	5
Discharging Loss (%)	5	5	5	4	4	5

TABLE V
POWER TRADING PRICES & PENALTY COSTS IN ISLANDED MODE

Parameters (Won/kWh)	MG1	MG2	MG3	MG4	MG5	MG6
Buying Price	100	108	110	113	115	118
Selling Price	80	88	90	93	95	98
Penalty Cost	500	430	350	300	260	240

TABLE VI
EFFICIENCIES AND CAPACITIES OF LINKS BETWEEN MGs

Link	Line Loss (%)	Converter Loss (%)	Link Capacity (kW)
MG1↔MG2	3	2	300
MG2↔MG3	3	2	600
MG6↔Utility Grid	4	2	2000
MG3↔MG4	2	2	1000
MG5↔MG6	2	2	1700
MG4↔MG5	2	1	1300

C. Normal Mode Operation

The objective of the nested EMS in normal operation is to minimize the operation cost of the microgrid networks while assuring privacy to the customers. If the generation cost of a CDG is lesser than the market selling price, the CDG generates maximum power. Excess of electricity after serving loads is sold to the utility grid to maximize the profit. CDG1 shows this type of behavior during time intervals 7-22, while CDG2 and CDG3 show this behavior during time intervals 12-18. It can be verified from Fig. 6(c) that during those intervals generation costs of these CDGs is lesser than the market selling price. If the generation cost of a CDG is higher than the market buying price, the CDG generates minimum power. Electricity is bought from the utility grid to fulfill the load in order to minimize the operation cost. It can be observed from Fig. 8(b) and 8(c) that CDG2 and CDG3 have generated minimum power during time intervals 1-6 and 23-24. It can be verified from Fig. 7(c) that generation cost of CDG2 and CDG3 is higher than the market buying price during those intervals. If the generation cost of a CDG is sandwiched between the market buying and the market selling prices, trading with utility grid is not economically feasible. Therefore, during those intervals, the generation of the CDG is equal to the local load. This kind of behavior is shown by CDG1 during time intervals 1-6 and 23-24 as depicted in Fig. 7(a). The Same type of behavior is shown by CDG2 and CDG3 during time intervals 7-11 and 19-22. This behavior of CDGs can be justified from Fig. 7(c). BESS is charged during off-peak and/or shoulder intervals and utilized during peak intervals to maximize the profit.

By using the above-mentioned rules, each microgrid performs local optimization. Surplus/shortage is computed by

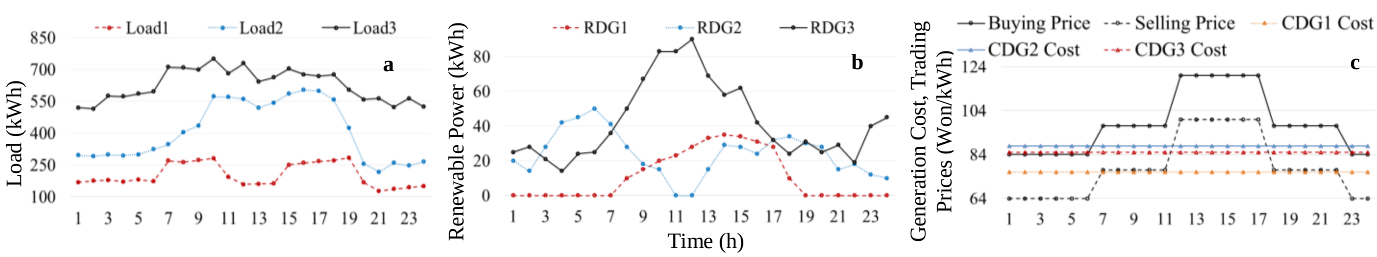

Fig. 7. Input data: (a) Forecasted load profiles of microgrids; (b) Renewable power output; (c) Market price signals and CDGs' generation cost.

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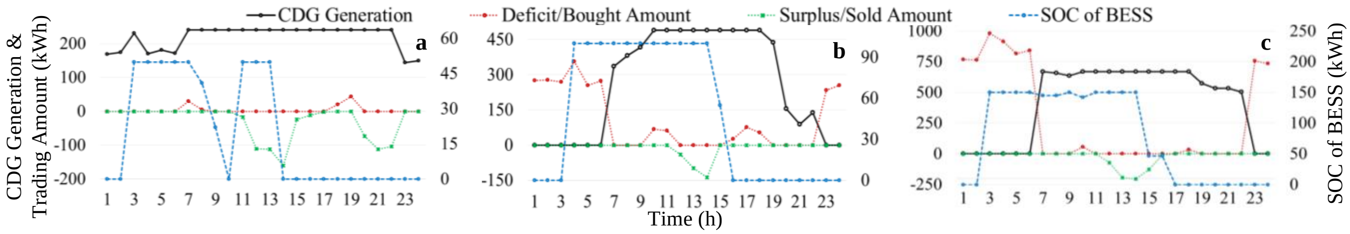

Fig. 8. Power generation and consumption profiles in normal mode: (a) Microgrid 1; (b) Microgrid 2; (c) Microgrid 3.

level 1 microgrid for each time interval and is sent to the level 2 microgrid as shown in Fig. 8(a). Level 2 microgrid uses this information during its local optimization and computes its surplus/shortage. This information is sent to level 3 microgrid as shown in Fig. 8(b). After optimization, level 3 microgrid decides the amount of power to be traded with the utility grid for each time interval as shown in Fig. 8(c).

In order to illustrate the effectiveness of the proposed nested energy management strategy, three extreme cases have been simulated. Operation costs of all other cases will lie within the boundaries set by these three extreme cases. Operation costs along with external trading amounts have been compared with prevailing EMSs for each case. Following are the three simulated cases in normal mode operation.

Case A: $C^{CDG}_{3,i\in I} < C^{CDG}_{2,i\in I} < C^{CDG}_{1,i\in I}$, ***Case B:*** $C^{CDG}_{3,i\in I} > C^{CDG}_{2,i\in I} > C^{CDG}_{1,i\in I}$, and ***Case C:*** $C^{CDG}_{3,i\in I} = C^{CDG}_{2,i\in I} = C^{CDG}_{1,i\in I}$.

Results of all the three cases are tabulated in Table VII. Centralized EMS being the most cost efficient EMS, has been taken as a reference while comparing the operation cost and the external trading. It can be observed from Table VII that the increase in operation cost for the proposed nested EMS is lower than both decentralized and hybrid EMSs in all the cases.

If only operation cost is considered, centralized EMS is the most favorable EMS. However, there are several issues associated with the centralized EMSs as listed in Table II. If both customer privacy and operation cost are considered, in grid-connected mode, the proposed nested EMS performs better than all the three prevailing EMSs.

TABLE VII
COMPARISON BETWEEN DIFFERENT EMSs IN NORMAL MODE

Parameters and Cases		Centralized EMS [7]	Decentralized EMS [13]	Hybrid EMS [37]	Nested EMS
Increase in Operation Cost (%age)	A	0	0.79	0.58	0.38
	B	0	1.06	0.71	0.33
	C	0	0.32	0.13	0.03
Increase in External Trading (%age)	A	0	22.03	14.94	7.52
	B	0	70.27	47.33	14.96
	C	0	8.24	3.08	1.72

D. Islanded Mode Operation

The objective of nested EMS in islanded mode operation is to increase the service reliability and system resiliency while reducing the operation cost. In order to illustrate the effectiveness of the nested EMS, two different scenarios have been simulated in islanded mode.

1) Microgrid Network of 3-AC Microgrids: In this scenario, the same network as that of the grid-connected mode has been considered. Three different cases have been considered for assessing the effectiveness of the proposed nested EMS in islanded mode. Following are the three simulated cases.

Case A: Islanded mode operation with BESS, **Case B**: Islanded mode operation without BESS, and **Case C**: Islanded mode operation when microgrid 2 is disconnected from the network in the absence of BESS.

In islanded mode, each inner level microgrid generates maximum power, due to its ability to sell the surplus power to the outer level microgrid. When the outermost microgrid schedules its resources, it decides either to ramp down the CDGs or to shed the loads. As described in Algorithm I and II, both ramping down of CDGs and load shedding is started from the outermost microgrid. This process is repeated for the inner level microgrids until load and supply are balanced. BESS is charged when the generation is higher than the load and is discharged during peak load interval, if BESS is available.

In **Case A**, both CDG1 and CDG2 being the inner level CDGs, have generated maximum power. In this case, the total supply of the network is greater than the total load. Therefore, load shedding is not required and ramping down has been carried out at level 3 microgrid only, as depicted in Fig. 9(a). BESS has been fully utilized by each microgrid to mitigate the load shedding as depicted in Fig. 9(c).

In **Case B**, the generation pattern of inner level CDGs (CDG1 & CDG2) is identical to that of the previous case. However, due to unavailability of BESS, limited load shedding has been carried out at level 3 microgrid. It can be observed from Fig 9(b) that during intervals 10, 15-18 all the three CDGs have generated maximum power and load shedding is

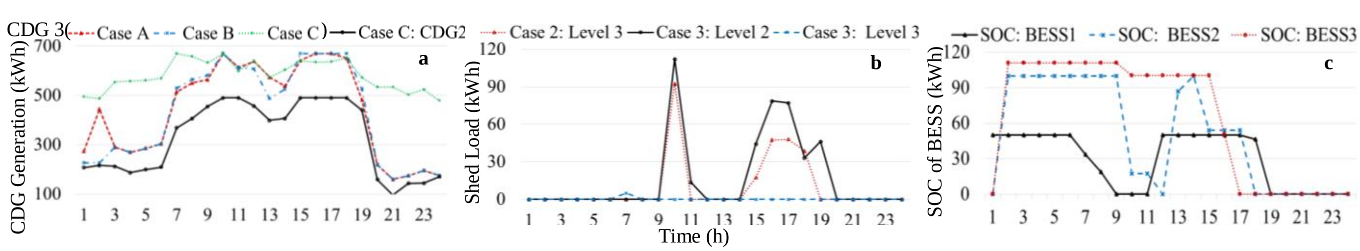

Fig. 9. (a) CDG generation in different cases; (b) Load shedding at different microgrids in different cases; (c) SOC of BESS in each microgrid in Case A.

carried out to balance the demand and supply. Due to the higher priority of loads, there is no load shedding at level 1 & 2 microgrids. In other intervals, ramping down is carried out at level 3 microgrid only, as depicted in Fig. 9(a). In this case, due to the absence of BESS excess power cannot be stored.

In **Case C**, the disconnected microgrid (microgrid 2) forms a subgroup with microgrid 1 while microgrid 3 is operating autonomously. There is no load shedding at level 1 microgrid due to higher load priority. There is some unavoidable load shedding at level 2 microgrid during time interval 10, 15-20, as depicted in Fig. 9(b). During these intervals, both CDG1 and CDG2 are generating maximum power and the amount of load that is beyond their capacities is shed. CDG2 being the outermost CDG for this subgroup, ramping down is carried out at CDG2 only, as depicted in Fig 9(a). In this case, microgrid 3 is operating autonomously. Therefore, during time interval 7, limited load shedding is carried out to balance the demand and supply, as depicted in Fig. 9(b). In the remaining intervals, CDG3 is ramped down to balance the demand and supply.

The behavior of the three prevailing EMSs and the proposed nested EMS has been compared under each of the three cases mentioned in this section. The amount of load shed in each level and the operation cost (cost of centralized EMS as a reference) is summarized in Table VIII. It can be observed from Table VIII that, the operation cost of nested EMS is even lower than the centralized EMS in case C. In all other cases, the operation of nested EMS is comparable with that of the centralized EMS. In all the cases, there is zero load shedding at level 1 microgrid due to the presence of higher priority loads. In the case of hybrid and decentralized EMSs, load shedding has been carried out at level 1 microgrid in all the three cases.

Load priorities (ρ_l) for level 1, 2, and 3 loads have been taken as 1.0, 0.80, and 0.65, respectively. Therefore, the acceptable range of resilience index will be 0.33-0.82. The acceptable value for resilience index of the innermost (level 1) microgrid will be 1.0. It can be observed from Table VIII that both the conditions for acceptable resilience index are fulfilled for the nested and centralized EMSs in all the three cases. However, the hybrid and the decentralized EMSs could not fulfill the second condition ($RI^1 = 1$) for all the three cases.

TABLE VIII
COMPARISON BETWEEN DIFFERENT EMSs IN ISLANDED MODE

EMS Type & Cases		Amount of Load Shed (kWh)			Increment in Cost (%)	Resilience Index, RI^1
		Level 1	Level 2	Level 3		
Centralized [7]	A	0	0	0	0	0.82, 1.00
	B	0	0	223	0	0.81, 1.00
	C	0	525	58	0	0.80, 1.00
De-centralized [16]	A	53	430	0	4.90	0.80, 0.98
	B	148	525	5	6.69	0.78, 0.96
	C	148	525	5	1.55	0.78, 0.96
Hybrid [37]	A	17.50	181	0	2.81	0.81, 0.99
	B	21	202	0	2.87	0.80, 0.99
	C	55	525	5	0.78	0.79, 0.98
Nested	A	0	0	0	0.06	0.82, 1.00
	B	0	0	223	0	0.81, 1.00
	C	0	393	5	-1.01	0.80, 1.00

2) Microgrid Network of 4-AC and 2-DC Microgrids: In this scenario, three additional microgrids are considered. The microgrids at level 1-3 are the same with those of the previous case. Microgrids 4 and 5 are the DC microgrids and microgrid 6 is an AC microgrid. The loads and RDG outputs of the microgrids 4, 5, and 6 are tabulated in Table IX. In order to illustrate the subgrouping ability and resilient performance of the proposed nested EMS, three different cases are considered in this section. In each case subgroups are formed. Both load shedding and ramping down of CDGs is carried out from the outermost microgrid according to Algorithms I and II.

In **case A**, microgrid 4 is assumed to be disconnected from the network. In this case, an AC subgroup (microgrids 1, 2, and 3) and a hybrid AC/DC subgroup (microgrids 4, 5, and 6) are formed. The load of microgrid 1 is the most important load in the AC subgroup. In the hybrid AC/DC subgroup, load of microgrid 4 is the most critical. In order to assure the service reliability to the most critical loads in each subgroup, load shedding has been carried out at level 3 of AC subgroup and level 6 of hybrid subgroup only, as depicted in Fig. 10.

TABLE IX
HOURLY LOAD AND RDG PROFILES OF ADDITIONAL MICROGRIDS

Time (h)	Load (kWh)			Renewable Power (kWh)		
	MG4	MG5	MG6	MG4	MG5	MG6
1	681	691	820	35	25	25
2	695	705	815	38	28	28
3	725	755	775	31	21	21
4	782	792	872	24	14	14
5	795	825	885	34	24	24
6	825	885	895	35	25	25
7	881	891	921	46	36	36
8	869	929	945	80	60	70
9	880	900	974	97	117	87
10	861	891	1051	113	133	103
11	892	942	1082	113	133	103
12	889	939	1029	120	140	110
13	843	953	943	99	119	89
14	822	922	962	88	108	78
15	823	923	903	92	122	82
16	887	887	897	72	92	52
17	849	879	889	62	42	42
18	795	895	875	34	24	24
19	784	884	804	41	31	31
20	787	797	789	35	25	25
21	683	783	763	39	29	29
22	627	727	723	29	19	19
23	668	768	764	50	40	40
24	678	758	744	55	45	45

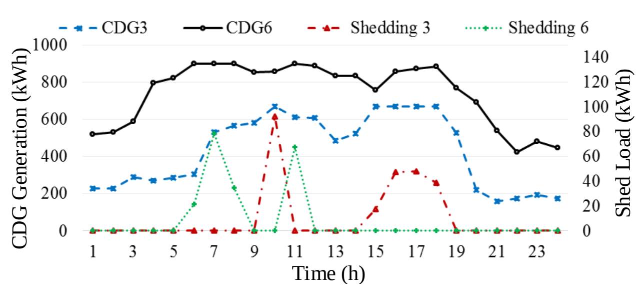

Fig. 10. Generation amounts of CDGs and load shedding for case A.

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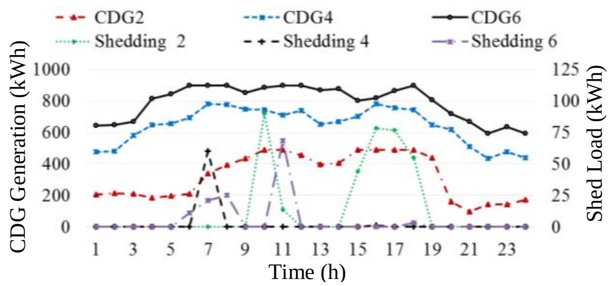

Fig. 11. Generation amounts of CDGs and load shedding for case B.

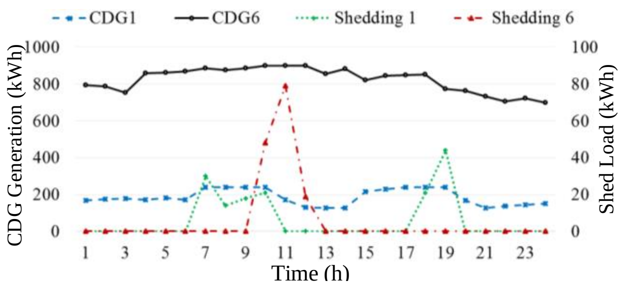

Fig. 12. (a) Generation & load shedding of autonomous MGs in case C.

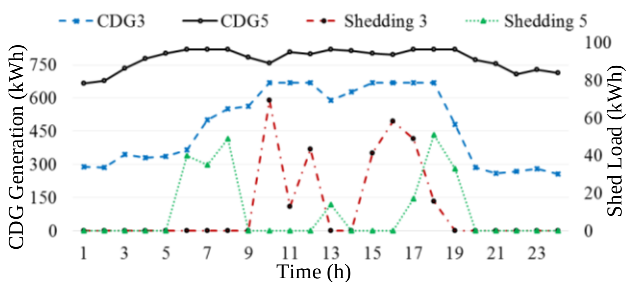

Fig. 12. (b) Generation & load shedding of sub-grouped MGs in case C.

In **case B**, simultaneous disconnection of microgrids 2 and 4 is considered. This simultaneous disconnection will transform the network into three subgroups. Microgrids 1 and 2 will form an AC subgroup. Microgrids 3 and 4 will form a hybrid AC/DC hybrid subgroup and microgrids 5 and 6 will form another hybrid subgroup. In each subgroup, the load priority of the inner level microgrid is higher. Therefore, In order to assure the service reliability to the most critical loads in each subgroup, load shedding has been carried out at the outermost level of microgrids only, as depicted in Fig. 11.

In **case C**, simultaneous disconnection of microgrids 1, 3, and 6 is considered. In this case, microgrids 1 and 6 will operate autonomously while an AC subgroup will be formed by microgrids 1 and 2, and a DC subgroup will be formed by microgrids 4 and 5. Due to the absence of subgrouping, microgrids 1 and 6 have balanced their demand and supply by either load shedding or by ramping down their respective CDGs, as depicted in Fig. 12(a). However, In order to assure the service reliability to the most critical loads of AC and DC subgroups, load shedding has been carried out at the outermost level of microgrids only, as depicted in Fig. 12(b).

E. Computation Time and Limitations of Nested EMSs

The problem formulation for both grid-connected and islanded modes is based on MILP and both the models are deterministic. Therefore, computation time is very less and solutions are convergent. The computation time is observed by varying the number of microgrids along with the BESS and CDG units in a microgrid from 1 to 10. It can be observed from Fig. 13 that computation time increases with increase in the number of microgrids. The computation time increases with increase in the number of BESS units also, but with a smaller slope. The increase in the number of CDG units has a minute effect on the computation time, as depicted by Fig. 13. The computation time of the developed MILP model is acceptable for day-ahead scheduling, the target scheduling horizon of this study.

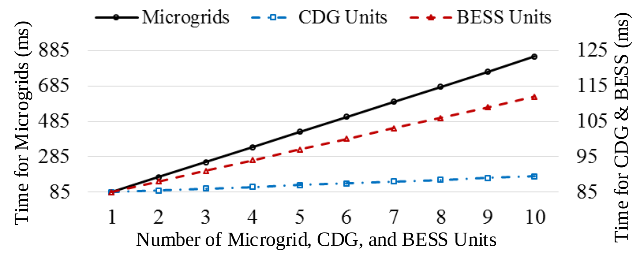

Fig. 13. Computation time variation with change in MGs, CDGs, and BESSs.

The limitation associated with the proposed nested EMS can be summarized as follows.

- When the innermost/outermost microgrid is separated from the network, the resiliency of the disconnected microgrid in nested EMS will be similar to that of hybrid EMS. On the other hand, when an intermediate microgrid disconnects from the network, the proposed EMS will increase the resiliency of the disconnected microgrid through subgrouping.
- Being an iterative optimization technique, global optimality of the solution cannot be guaranteed. Only centralized EMSs can guarantee the global optimality but there are several limitations of centralized EMSs as listed in Table II.
- Computation time increases with increases in the number of microgrids. However, for a day-ahead scheduling horizon, it is acceptable.

Future extension of this research could be comparison of network security, plug-and-play ability, and complexity analysis of the proposed nested EMS with prevailing EMSs. Another valuable extension could be impact analysis of uncertainties in both RDG outputs and loads on the proposed nested EMS.

VI. CONCLUSION

This paper has proposed a nested energy management strategy for day-ahead scheduling of networked microgrids. Due to layered privacy structure, customer privacy is preserved. At the same time, due to the ability to form subgroups in islanded mode, the resiliency of the disconnected microgrids is also improved in the proposed nested EMS. Average daily operation cost has been reduced to half as compared to hybrid EMSs. Operation cost of centralized EMSs is lesser. However, due to compromise on customer privacy, lesser flexibility, and requirement of computationally sound central EMS, its applications are restricted to specific scenarios and may not be acceptable for most of the users. It can be concluded that the proposed nested EMS is a trade-off between various contradictory objectives like operation cost, customer privacy, and network resiliency. The performance of proposed strategy has also been assessed for hybrid AC/DC microgrids.

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