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Published in:
I E E E Transactions on Energy Conversion

DOI (link to publication from Publisher):
10.1109/TEC.2015.2505358

Publication date:
2016

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Marzband, M., Parhizi, N., Savaghebi, M., & Guerrero, J. M. (2016). Distributed Smart Decision-Making for a Multimicrogrid System Based on a Hierarchical Interactive Architecture. *I E E E Transactions on Energy Conversion*, *31*(2), 637 - 648. https://doi.org/10.1109/TEC.2015.2505358

Distributed Smart Decision-Making for a Multi-Microgrid System Based on a Hierarchical Interactive Architecture

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***Abstract*—In this paper, a comprehensive real-time interactive EMS framework for the utility and multiple electrically-coupled MGs is proposed. A hierarchical bi-level control scheme-BLCS with primary and secondary level controllers is applied in this regard. The proposed hierarchical architecture consists of sub-components of load demand prediction, renewable generation resource integration, electrical power-load balancing and responsive load demand-RLD. In the primary-level, EMSs are operating separately for each MG by considering the problem constraints, power set-points of generation resources and possible shortage or surplus of power generation in the MGs. In the proposed framework, minimum information exchange is required among MGs and the distribution system operator. It is a highly desirable feature in future distributed EMS. Various parameters such as load demand and renewable power generation are treated as uncertainties in the proposed structure. In order to handle the uncertainties, Taguchi′s orthogonal array testing-TOAT approach is utilized. Then, the shortage or surplus of the MGs power should be submitted to a central EMS-CEMS in the secondary-level. In order to validate the proposed control structure, a test system is simulated and optimized based on multi-period imperialist competition algorithm- MICA. The obtained results clearly show that the proposed BLCS is effective in achieving optimal dispatch of generation resources in systems with multiple MGs.**

***Index Terms*—bi-level stochastic programming, Imperialist competition algorithm, demand response, multiple Microgrid, optimal energy management system, optimal scheduling, responsive load demand, Tagochi algorithm.**

NOMENCLATURE

Acronyms

CEMS	central energy management system
DER	distributed energy resources
DGU	dispatchable generation unit
BLCS	bi-level control scheme
DR	demand response
EMS	energy management system
ES	energy storage
ES+	ES during charging mode
ES-	ES during discharging mode
GRID+	power surplus of upstream grid
GRID-	power deficiency of upstream grid
ICA	imperialist competition algorithm
LL	lumped load
MG	Microgrid
MICA	multi-period ICA
MT	micro-turbine
NDU	non-dispatchable unit
PV	photovoltaic
SOC	state-of-charge
TCP	total consumed power
TGP	total generated power
TOAT	Taguchi′s orthogonal array testing
UP	undelivered power
VG	virtual generation
VL	virtual load
WT	wind turbine

Parameters

$\pi_t^{A,n}$	price of A in the MG #n during the time period t (€/kWh)

A $\in$ {DGU, ES-, ES+, GRID-, GRID+, LL, MT, MG-, MG+ NDU, NRL, PV, RLD, UP, VL, VG, WT}

$\overline{P}$, $\underline{P}$	limit of power (kW)

Variables

$P_{s,t}^{\mathrm{A,n}}$	the powers generated by resource A under scenario s in the MG #n (kW)
μ_s^{B}	the probability of scenario #s of non-dispatchable generation

B $\in$ {WT, PV}

$P_t^{\mathrm{UP},n}$	the amount of UP that has not been supplied by MG #n (kW)
$P_t^{\mathrm{LL,n}}$	the electricity needed by LL from MG #n (kW)
$P_t^{\mathrm{TCP,n}}$, $P_t^{\mathrm{TGP,n}}$	the total consumed/generated power in the MG #n (kW)
$P_{\mathrm{Tot},t}^{\mathrm{MG+,n}}$, $P_{\mathrm{Tot},t}^{\mathrm{MG-,n}}$	the total sold/bought power by MG #n (kW)
SOC_t	ES SOC (%)
μ_s^C	probability of the sth scenario of C

C $\in$ {WT, PV, NRL}

s	index of scenarios of WT, PV generation, and NRL

This work was supported by the Energy Technology Development and Demonstration Program (EUDP) through the Sino-Danish Project “Microgrid Technology Research and Demonstration” (meter.et.aau.dk).

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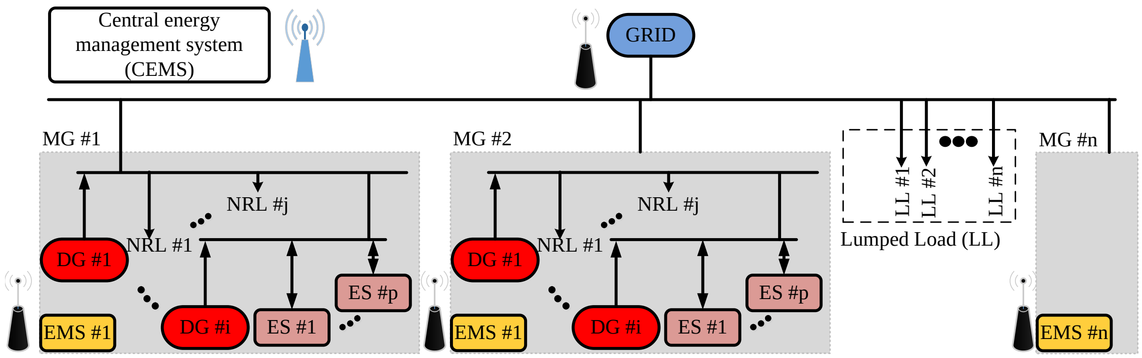


Fig. 1: Schematic diagram of a generic multi-microgrid system

s ∈ {swt, spv, snrl}

$X_t^{\mathrm{DGU,n}}$ decision making variable of the controllable resources (i.e. 1 if the request is in service and 0 otherwise)

I. Introduction

A Microgrid-MG is a combination of different distributed energy resource-DER resources at distribution level which supply local electrical and/or thermal load demands [1]–[5]. Proper control and management of MGs is a prerequisite for continued stable and economically efficient operation of these systems [6]–[8]. Intelligent distribution management can be achieved through real-time dispatch of dynamic DER resources [9], [10].

In addition, the complexity of the proper energy management system-EMS applicable under different conditions will significantly increase, especially when the system can be configured as an interconnection of multiple MGs with different owners [11]. In these systems, islanded MGs can be interconnected with each other in order to maximize the own social-welfare or profit as well as to reduce the number of load shedding occurrences in MGs [12], [13]. This condition can be met during islanded operation if there is an extra available generation capacity in DERs of at least one of the MGs [14]. In this structure, the total load demand in the interconnected MGs can be supplied by all the DERs within those MGs taking into account the maximization of social-welfare in each individual MG [15]. This duty can be fulfilled and coordinated by each local EMS installed for each MG. Eventually, a central EMS-CEMS is responsible for the overall coordination of local EMSs with the objective of fulfilling the total load demand in the interconnected MGs by minimizing the total cost.

Economic dispatch and unit commitment problem with various non-convex objective function considering generation, storage and responsive load offers is presented in the previous literature [4], [16], [17]. However, previously published works have been mainly concentrated on the control and operation problem of individual MGs [18], and thus, coupled operation in systems based on multiple MGs with different owners is still considered as an emerging area of research. Furthermore, it is time-consuming to solve optimization problems with large dimensions in large-scale tracking experiments by use of deterministic and stochastic algorithms. Therefore, in such applications, it is recommended to use heuristic algorithms that do not return the exact solution, but have an obvious advantage of reducing the time required, and making the analysis of larger systems feasible.

Concept of hierarchical control for power electronic interfaces in MGs is presented in [19]–[21]. In [19], the design of a hierarchical control system is developed in order to adjust the main control parameters and study the system stability. However, no optimization approach was used in that work. Furthermore, the research work presented in this paper is a continuation of the work by the authors [4], [22]–[24], where a comprehensive framework for neighborhood systems with multiple-MG interconnection is needed.

In the present paper, a hierarchical bi-level control scheme-BLCS is provided for interconnecting the neighbor grid-tied MGs with the goal of delivering scalable generation resource management. This paper is motivated by the eminent need of intuitive and flexible manipulation systems able to deal with assembly tasks on modelling, monitoring and control of systems based on multiple-MG interconnection.

Through the developed primary control level, this study examines how the parallel DERs in the system of multiple interconnected MGs can help to properly share the load of the system as a whole. This controller is decentralized and based on the imperialist competition algorithm- ICA algorithm that determines the shortage or surplus of each MGs with respect to maximizing the social-welfare in the primary-level and total cost minimization in the secondary-level. Unit commitment solution space can include many local optima and thus a stochastic search technique, starting from random initial points, may be trapped in a poor local minimum leading to a low-quality result or even infeasible solution for the problem. However, the proposed bi-level approach can escape from such local minima based on an enhanced version of ICA which provides an effective initial population and high exploration capability. This method presents several advantages such as simplicity, accuracy and short calculation time [25]. It can also reach economic results with high reliability because of its high convergence speed and ability of finding general optimum solution compared with other innovative optimum methods [25].

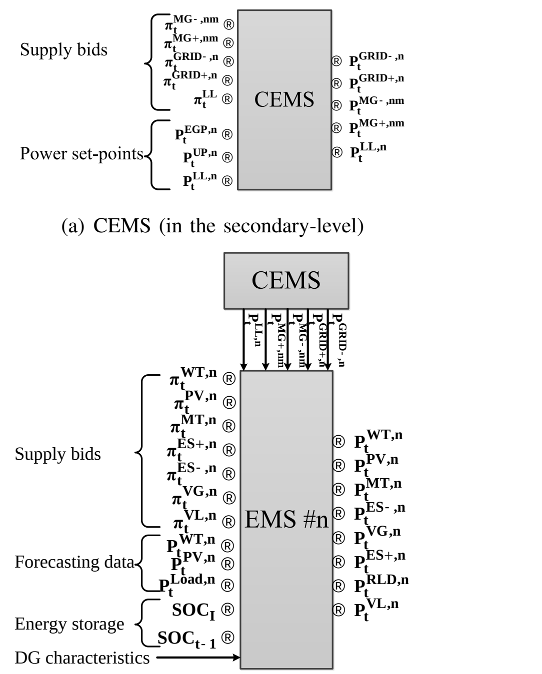
The proposed structure aims to present a general framework for the optimal management of multi-MG systems, demand side management, and proper power exchange and interaction among MGs themselves and among them and the upstream grid. In this structure, each of the MG elements is considered as an agent and the coordinated behavior of the agents inside the MG causes the minimization of generation cost. An agent is an object that can be characterized as a DER and/or responsive load demand- RLD operating as a single controllable unit or connected with other units in a system. This is while different MGs compete with each other for maximizing their profit and/or social-welfare. On the other hand, the operation and management of the corresponding MG are controlled and monitored by local EMSs. The main objective of these EMSs is minimizing the mismatch between fed power and load demand during consumption peak by changing the system load curve and demand response-DR mechanism. Moreover, a CEMS placed at the top level of the hierarchy is responsible for parameter-tracking and overall coordination, greatly reducing the generation cost. The main task for this controller is to control the power exchange between MGs and upstream grid if there is insufficiency or excess generations in either side. It can help to verify the possibility of a power sharing optimization between these parties.

Based on the aforementioned points, the main contributions of this paper are summarized below

- A bi-level optimisation approach is proposed to solve energy management problem in a multi-MG system. Economic dispatch is solved for each MG in the primary-level of the proposed approach which is decided by the consumers based on the prices offered by all available DERs and load-shifting mechanism. Based on the results of economic dispatch, the proposed algorithm is run in the secondary-level to seek the minimum operation cost for all MGs considering the capacity limitations of transmission lines among them.
- A stochastic search technique with high exploration and exploitation capabilities is developed with much less computation time and higher convergence rate and used as the optimisation tool in both levels. The proposed technique is an enhanced version of ICA, called hereafter multi-period ICA (MICA).

II. Interfacing control strategy for multi-microgrid systems

The schematic diagram of a distribution system configured as interconnected MGs is shown in Fig. 1. In this configuration, dispatchable/non-dispatchable DER units, storage devices and associated RLDs are configured in each MG. Non-dispatchable DERs (such as wind and photovoltaic units) are based on renewable energy resources which inherently suffer from a lack of the dispatch capability due to inherent stochastic behaviours of these resources. Each MG can exchange power with the main electric grid. The operation and management of each MG in different modes can be controlled by the local EMS in the primary-level. A CEMS is embedded in the secondary-level and it is responsible for the overall coordination of these EMSs. Furthermore, it decides the bids of MGs in power market, collects operation information of MGs (e.g. virtual load-VL and virtual generation-VG power) and allocates power exchange between MGs and electric grid. VL is the sum of power sold to the grid, to the other MGs, and supplied to the lump load- LL. VG is also the sum of power bought from the grid and other MGs. On the other hand, VL and VG are the probabilities of the excess and shortage generation, respectively. All these MGs are connected in parallel with the main grid and they can operate independently and in a group to deliver optimally the generated power in a timely manner. A set of LL is connected to the grid through distribution lines. An LL demand is formed by a set of consumers who do not belong to none of the MGs or grid. The input and output signals of EMS and CEMS framework are shown in Figs. 2(a) and 2(b).



(a) CEMS (in the secondary-level)

(b) EMS #n (in the primary-level)

Fig. 2: Input and output of parameters of the a) CEMS framework b) EMS #n

The EMS and CEMS controllers assign priorities to overcome the shortage of electricity or offers to decrease production or increase consumption in situations when there is a surplus of electricity in the system based on offer prices associated with parties. Furthermore, offers of generation units or consumers in some of the time intervals have conflict with each other, whereas continuous random variables can take any numeric value within its range (which should be bounded by upper and lower limits). As a result, the proposed EMS and CEMS must have the ability of selecting the best power generation sources and the requirement of the consumers by considering the minimum generation cost. Communication in coupled MG systems is required in order to exchange data reliable between control centres, substation automation systems or MG management systems in geographically widespread installations. This communication system is implemented so that network information, e.g., the price signal, power generated by each generation units and power demand, can be exchanged among the MGs, power grid, and energy management system, consisting of the EMSs and CEMS. Explaining in detail about communication system is out of scope for this paper, but is addressed in detail in [16].

III. Model and problem formulation

The system under study has n MGs and each of them has renewable (non-dispatchable) resources (wind turbine-WT and photovoltaic-PV), dispatchable resources as spinning reserve (micro-turbine-MT), energy storage-ES resources and several types of loads including non-responsive loads-NRL and responsive load demands, that are connected to the grid with several LL. The mathematical formulation for implementing EMSs and CEMS are presented in the following sections.

A. Assumptions

The simplifications are performed in this paper based on the following assumptions to improve the computation time and the convergence of the optimization:

- In the proposed EMS, the power scheduled by DER resources does not depend on the characteristics of the loads. It simply means that it is not important whether the loads are active or passive. In fact, both DER resources and consumers′ assets are modelled as power resources and the designed EMS is able to properly control and monitor them. In addition, EMS update interval is in the order of minutes, and DERs dynamics are in the order of seconds, thus, too fast to be taken care by EMS. As a result, detailed modelling of DERs and loads is not investigated here.
- The dynamics of voltage and current controllers used by DER controllers are much faster than those of EMS (primary controller). So, as it is explained in [21], the primary controller can be designed independently from those controllers. In addition, the design of the local controllers in inverter-based MGs can be assumed independent from the EMS design. In the other words, interaction between different control levels can be neglected. The stability and design of droop-controlled MGs has been already addressed in [26] and hence the stability of MG is not discussed here.

B. EMS #n mathematical implementation

Two types of objective functions have been defined for the optimization problem. A cost function has been defined for all EMSs with the aim of minimizing objective function and managing generation resources and the consumption in each MG. The aim of the proposed EMS is to maximize the use of non-dispatchable resources and to increase the energy stored in ES to enhance the system reliability. The defined cost function for the MG #n EMS (i.e.$Z^{\mathrm{EMS,n}}$) has been modeled as follows:

$$Z^{\mathrm{EMS,n}} = \min \sum_{t=1}^{24} \sum_{k=1}^{n} \left(\begin{array}{l} \sum_{s=1}^{\mathrm{S}} \mu_{\mathrm{s}}^{\mathrm{NDU}} \times P_{\mathrm{s},t}^{\mathrm{NDU,k}} \times \pi_{t}^{\mathrm{NDU,k}} \\ +P_{t}^{\mathrm{DGU,k}} \times \pi_{t}^{\mathrm{DGU,k}} \\ +P_{t}^{\mathrm{VG,k}} \times \pi_{t}^{\mathrm{VG,k}} \\ +P_{t}^{\mathrm{ES\text{-},k}} \times \pi_{t}^{\mathrm{ES\text{-},k}} \\ -P_{t}^{\mathrm{ES+,k}} \times \pi_{t}^{\mathrm{ES+,k}} \\ -P_{t}^{\mathrm{RLD,k}} \times \pi_{t}^{\mathrm{RLD,k}} \\ -P_{t}^{\mathrm{VL,k}} \times \pi_{t}^{\mathrm{VL,k}} \\ +P_{t}^{\mathrm{UP,k}} \times \pi_{t}^{\mathrm{UP,k}} \end{array} \right) \times \Delta t \tag{1}$$

The objective function in (1) allows decision making in both isolated (islanded) and grid connected operation modes of MGs to determine the hourly optimal dispatch of generators depending on system technical and economic constraints. The objective of EMS problem is carried out by minimizing the minus of the social-welfare while satisfying the generation resources′ constraints. The first five items in (1) represent costs relative to the base generation schedule made based on the forecasts of non-dispatchable/ dispatchable resources, and the excess generation by MG #n. The remaining items except the last one are the revenues obtained from consumers. The last item is included in the objective function as a penalty cost for the MG operator to avoid the undelivered power- UP to the NRL. At each time interval, firstly, the EMSs receive the proposed prices of all generation resources and the consumers of corresponding MG. After that, depending on the offered values, the algorithm decides applying generation resources and feeding the consumers with the aim of minimizing the generation cost. During daily operation of the system, MGs might have shortage in generation (i.e.,$\pi_{t}^{\mathrm{VG},n}$) or excess available generation (i.e.,$\pi_{t}^{\mathrm{VL},n}$) according to the bid from resource and virtual loads. The power allocated to the generation resources and the virtual load by the MG #n can be obtained from the following equation:

$$P_{t}^{\mathrm{n}} = P_{t}^{\mathrm{NDU,n}} + P_{t}^{\mathrm{DGU,n}} + P_{t}^{\mathrm{ES\text{-},n}} - P_{t}^{\mathrm{NRL,n}} - P_{t}^{\mathrm{ES+,n}} - P_{t}^{\mathrm{RLD,n}} \tag{2}$$

where $P_{t}^{\mathrm{NRL,n}}$ is NRL demand in the MG #n during the time period t. In the case of positive $P_{t}^{\mathrm{VG,n}}$ (i.e. the excess generation), the MG has the ability of selling power to other MGs and the grid and this excess power is allocated to the VL. But, when $P_{t}^{\mathrm{VG,n}}$ is negative (which means the generation shortage) the MG does not have the ability of supplying its internal demand and must import power from other MGs and the grid. Because of this, this power shortage is considered as a VG resource.

C. CEMS mathematical implementation

After determining the surplus and shortage power of each MG, the CEMS unit receives the information related to all the EMSs of the system and tries to provide the best conditions for supplying these values with the least operational cost. The cost function for the CEMS unit (i.e. Z^{CEMS}) can be defined as follows:

$$Z^{\text{CEMS}} = \min \sum_{t=1}^{24} \sum_{k=1}^{n} \left(\begin{array}{l} P_t^{\text{VL,k}} \times \pi_t^{\text{VL,k}} \\ -P_t^{\text{VG,k}} \times \pi_t^{\text{VG,k}} \\ -P_t^{\text{LL,k}} \times \pi_t^{\text{LL,k}} \\ +P_t^{\text{GRID-,k}} \times \pi_t^{\text{GRID-,k}} \\ -P_t^{\text{GRID+,k}} \times \pi_t^{\text{GRID+,k}} \\ -\sum_{m=1}^{q} P_t^{\text{MG+,mk}} \times \pi_t^{\text{MG+,mk}} \\ +\sum_{m=1}^{q} P_t^{\text{MG-,mk}} \times \pi_t^{\text{MG-,mk}} \end{array} \right) \times \Delta t \tag{3}$$

where q is required to be not equal to n in this relation. The objectives of CEMS controller are to minimize mismatch between feed power by MGs and load demand as well as to maximize utilization of the available power generated by MGs based on cheapest price. The objective function in (3) consists of cost and revenue of the MG. It can be divided into four parts: the first two items represent cost and revenue relative to VL and VG, respectively. The third one is the revenue obtained from LL load. The two next items are the cost and revenue due to selling/buying electricity to/from upstream grid. Two last items are also associated to the cost and revenue with obtaining the power exchanges between MGs.

$P_t^{\text{VL,n}}$ is the summation of power sold to the MG #k, electric grid and LL during the time period t. It can be defined by

$$P_t^{\text{VL,n}} = \sum_{m=1,q\neq n}^{q} P_t^{\text{MG+,mn}} + P_t^{\text{GRID+,n}} + P_t^{\text{LL,n}} \tag{4}$$

Also, $P_t^{\text{VG,n}}$ can be stated as the following equation:

$$P_t^{\text{VG,n}} = \sum_{m=1,q\neq n}^{q} P_t^{\text{MG-,qn}} + P_t^{\text{GRID-,n}} \tag{5}$$

D. Problem constraints

Other constraints defined for the optimization problem are as follows:

1) Power balance

This constraint means that in each MG, the value of the total power generated-TGP by the generators in each time interval must be equal to the total consumed power-TCP.

$$P_t^{\text{TCP,n}} = P_t^{\text{TGP,n}} \tag{6}$$

$$P_t^{\text{TCP,n}} = P_{\text{Tot},t}^{\text{MG+,n}} + \sum_{m=1,q\neq n}^{q} P_t^{\text{MG+,mn}} + P_t^{\text{GRID+,n}} + P_t^{\text{LL,n}} \tag{7}$$

$$P_t^{\text{TGP,n}} = P_{\text{Tot},t}^{\text{MG-,n}} + \sum_{m=1,q\neq n}^{q} P_t^{\text{MG-,mn}} + P_t^{\text{GRID-,n}} \tag{8}$$

where $P_{\text{Tot},t}^{\text{MG+,n}}$ and $P_{\text{Tot},t}^{\text{MG-,n}}$ can respectively be calculated by

$$P_{\text{Tot},t}^{\text{MG+,n}} = P_t^{\text{NRL,n}} + P_t^{\text{ES+,n}} + P_t^{\text{RLD,n}} \tag{9}$$

$$P_{\text{Tot},t}^{\text{MG-,n}} = P_t^{\text{NDU,n}} + P_t^{\text{DGU,n}} + P_t^{\text{ES-,n}} \tag{10}$$

2) ES constraints (Battery in this study) [25]

✓energy storage limits;
✓maximum charge/discharge power limit;
✓maximum charge/discharge energy stored limit;
✓energy balance in ES;
✓state-of-charge- SOC limit;
✓ES limit.

3) Dispatchable resources constraints (MT in this study)

$$X_t^{\text{DGU,n}} \cdot \underline{P}^{\text{DGU,n}} \leq P_t^{\text{DGU,n}} \leq X_t^{\text{DGU,n}} \cdot \overline{P}^{\text{DGU,n}} \tag{11}$$

4) Non-dispatchable resources constraints (WT and PV in this study)

$$\underline{P}^{\text{NDU,n}} \leq P_t^{\text{NDU,n}} \leq \overline{P}^{\text{NDU,n}} \tag{12}$$

5) Responsive load demand

$$\sum_{t=1}^{\text{NT}} \sum_{l=1}^{N_{\text{RLD}}} P_t^l \leq \overline{P}^{\text{RLD,n}} \tag{13}$$

$$\overline{P}^{\text{RLD,n}} \leq \xi \times \sum_{t=1}^{\text{NT}} P_t^{\text{NRL,n}} \tag{14}$$

where ξ is a part of the total consumed NRL during the daily operation.

6) The exchange power between MGs and the grid

As it is already mentioned, if the MG is connected to the grid, it can have interaction with the grid and other MGs. But, these interactions are limited to the following constraints

$$P^{\text{GRID+,n}} \leq X_t^{\text{GRID}} \cdot \overline{P}^{\text{GRID+}} \tag{15}$$

$$P^{\text{GRID-,n}} \leq (1 - X_t^{\text{GRID}}) \cdot \overline{P}^{\text{GRID-}} \tag{16}$$

These two inequalities mean that the MG #n cannot purchase power more than $\overline{P}^{\text{GRID+}}$ from the grid and other MGs and/or sell power more than $\overline{P}^{\text{GRID-}}$ to the grid, other MGs and LL load. For limiting the exchanges with the grid and better use of the resources existing in the MG, the following constraint is considered:

$$\overline{P}^{\text{GRID-}} = \overline{P}^{\text{GRID+}} \leq \zeta \times (\sum_{i=1}^{N_{\text{NDU}}} P_t^i + X_t^{\text{DGU}} \cdot \sum_{j=1}^{N_{\text{DGU}}} P_t^j + X_t^{\text{ES}} \cdot \sum_{k=1}^{N_{\text{ES}}} P_t^{k-}) \tag{17}$$

where ζ can control the exchange of power between MGs and upstream grid.

IV. Hierarchical control for energy management

The energy management structure proposed in this paper has a bi-level control structure consisting of primary and secondary levels and is applied to an MG cluster with multiple ownership. Fig. 4 shows the proposed algorithm for implementing bi-level

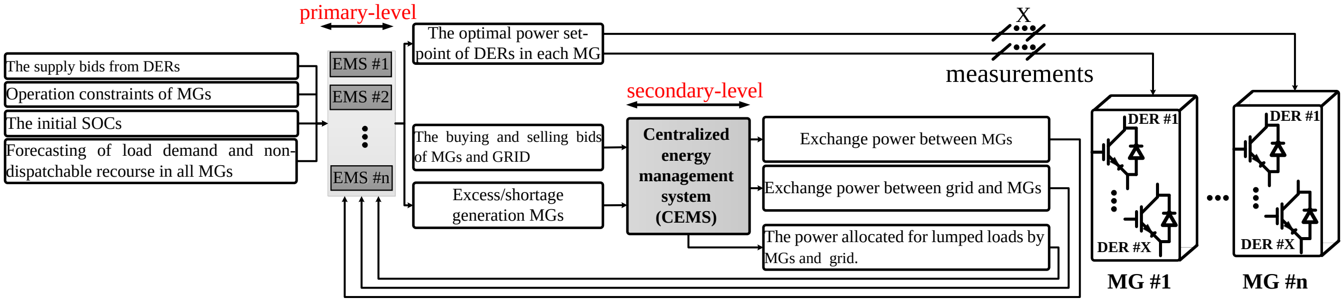


Fig. 3: Trade-offs between primary and secondary control levels

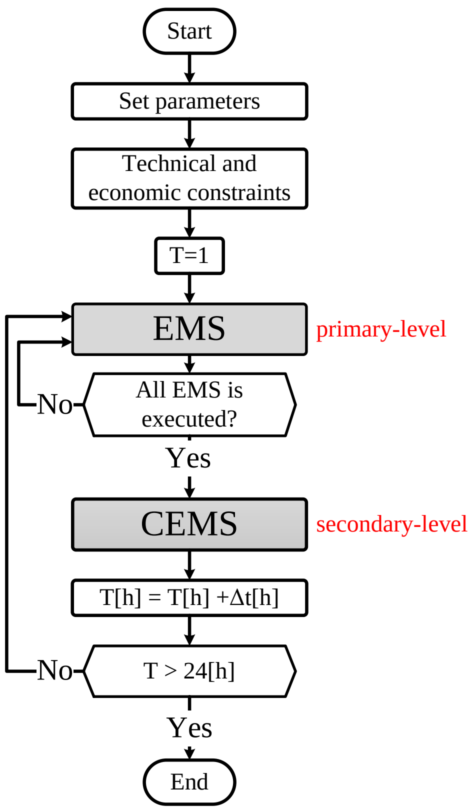


Fig. 4: Algorithm proposed for hierarchical energy management system

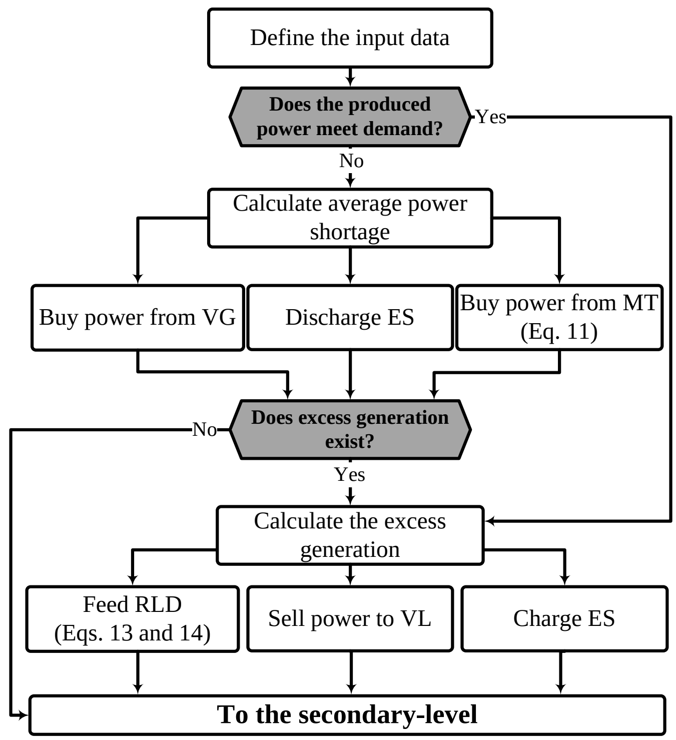


Fig. 5: Proposed flowchart for implementing the EMS unit in the primary-level control

control. As mentioned before, this architecture has two main units called EMS and CEMS.

The relationship between the EMSs in primary-level and CEMS in secondary-level is shown in Fig. 3. As observed, information such as the technical constraints of the devices involved in the MGs, prediction of the loads and the non-dispatchable generation resources and offers of each existing resources in the MGs are sent to the EMSs in the primary-level. After determining the optimum set-point powers of each MG and the value of surplus and shortage powers, this information are sent to the CEMS in the secondary-level.

A. *primary-level*

The proposed flowchart for implementing the EMS unit in the primary-level control has been shown in Fig. 5.

As depicted in Fig. 4, after selecting the MGs operation mode (islanded or grid-connected) in the primary-level control by introducing a binary variable, EMS of each MG is executed completely independent noting to the constraints considered for the problem including the optimum power values of the existing generation and consumption units. It is obvious that if the MG is in islanded mode; it will have no exchanges with the grid. On the other hand, the grid connected MG can also feed the external LL. In other words, in the energy management of grid connected MG, in addition to determining the optimum powers for the units existing in the MG, as stated before, two other variables called VG resources (i.e.$P_t^{\mathrm{VG,n}}$) and VL (i.e.$P_t^{\mathrm{VL,n}}$) are determined. These two variables are sum of the powers allocated for selling to the grid and other MGs and feeding external LL as a VL and the sum of the powers for purchasing from the grid and from other MGs as a VG resource. In other words, VL and VG are respectively the amount of possible power generation surplus and shortage. Noting the objective function and offers of the existing units in the MG and also offer of the LLs, that can be the grid and other MGs, EMS of each MG specifies whether power exchange with the outside is beneficial for the MG owner or not. On the other hand, the amount of power allocated for the load and the resources of VG is specified by EMS of each MG noting to the technical and economic constraints. Determining that what amount of this load and VG is allocated to which component is outside the duty scope of MG energy management at the primary control level. Thus, the MGs shortage and/or excess generation enters the CEMS at the secondary-level in each time interval to minimize the overall production cost

1) Taguchi′s orthogonal array testing algorithm (TOAT): One of the advantages of using MGs is the increase of the generation of renewable resources in the grid. However, a big problem of these types of devices is their intermittent nature due to dependence on weather parameters such as wind speed and solar radiation. However, despite uncertainty, the obtained optimal solution may be desired and or even feasible. Several widely different methods are used to represent the probability distribution of the intermittent supply from renewable resources and load flow. These techniques can be classified to analytical methods, approximate techniques and Monte-carlo simulation-MCS. MCS is the most straightforward, promising and accurate one having computational procedure and cumbersome efforts are its shortcoming that limits its range of practical applicability for large-scale plants. Analytical methods use convolution techniques which result in some simplifications such as independency or linear dependency of different random variables, linearization of the power system equations and losing accuracy [27], [28]. Approximate techniques have an intermittent characteristic and can provide a balance between speed and precision. Among the examples of these methods, TOAT is well established and widely-used in solving economic load dispatch in MG based systems [29]. TOAT ensures that the testing scenarios providing good statistical information with a minimum number in the uncertain operating space, which significantly reduces the testing burden. TOAT has been proven to have the ability to select optimally representative scenarios for testing from all possible combinations [28]. Compared with MCS, TOAT provides much smaller testing scenarios and leads to shorter computing time. The existing uncertainties in the discussed problem have been implemented with the scenarios formed according to Fig. 6.

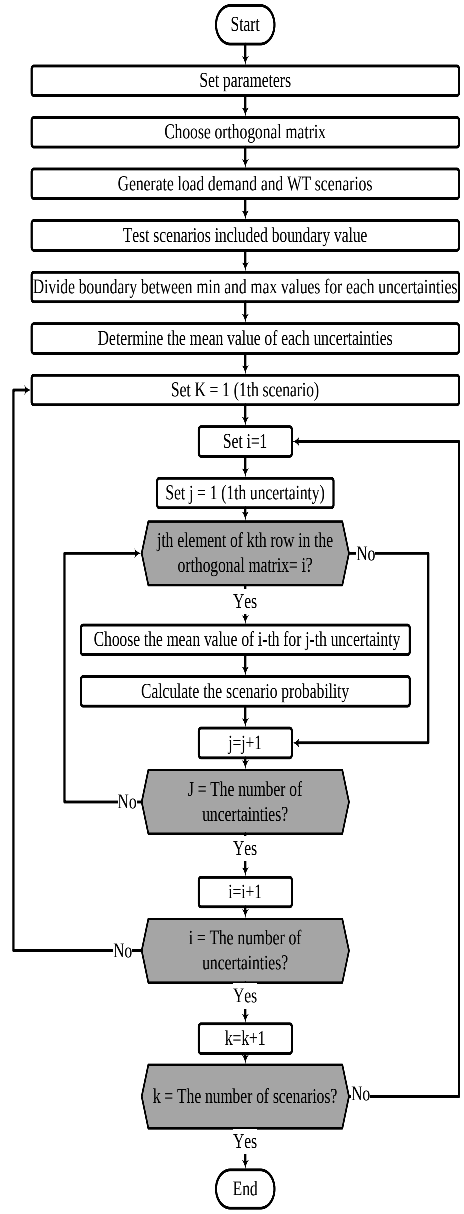


Fig. 6: Proposed flowchart for TOAT

B. secondary-level

The proposed flowchart for implementing CEMS unit in the secondary-level is presented in Fig. 7. As it is observed, the process of energy management at secondary-level control starts upon receipt of the information from EMS unit of all MGs. It is necessary to mention that if an MG is in islanded operation mode; secondary-level control will not apply for that. Thus, only the grid connected MGs send their possible generation shortage or excess generation to the CEMS and this system will specify the condition of the loads and VG at primary-level.

If all MGs have generation shortage, it means that the independent EMS of the MGs has considered a power for the VG resources. Because all the MGs have generation shortage, it is obvious that they cannot allocate any power for selling and they will compensate their generation shortage only from the grid. In this scenario, none of the MGs will have the ability of feeding LL and this load will completely be fed by the grid. When all the MGs have excess generation, this excess will be spent for feeding LL and selling to the grid. In this scenario, first the MGs compete with each other for feeding LL and the MG with fewer offers will win this competition. It should be noted that the wining MG may not be able to feed LL, completely. Under such conditions, other MGs will participate in feeding this load according to their price with priority given to trades entered first. If external LL is still not supplied with the appliance, it can be purchased from the grid. On the other hand, if there is excess generation in the MGs, it will be sold to the grid. In addition, it is possible that some MGs have generation shortage and others have surplus. In this case, the MGs with less offered prices are selected and their excess generations can be applied for compensating generation

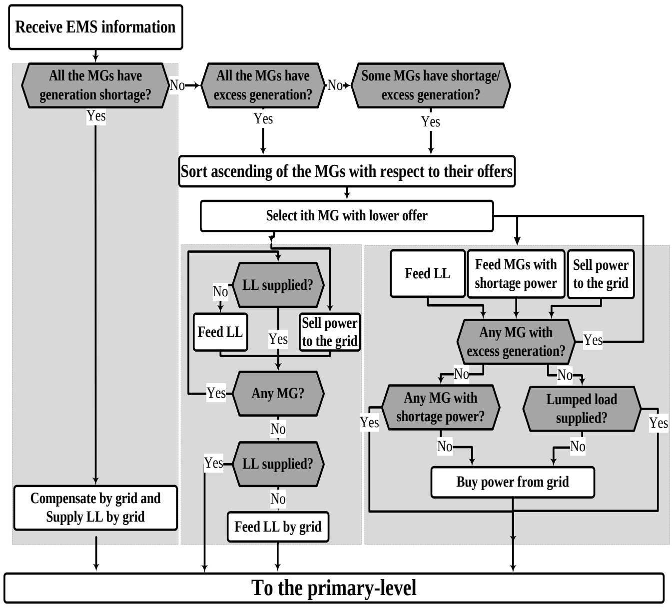


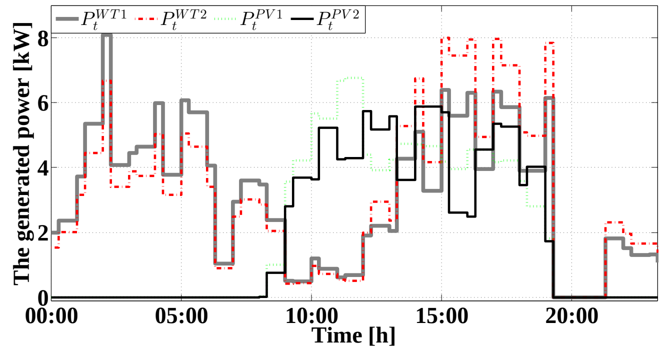
Fig. 7: Proposed flowchart for implementing CEMS unit in the secondary-level

shortage of other MGs, feeding external LL and selling to the grid. Under such conditions, firstly, the generation shortages of MGs with higher offer is compensated. CEMS decides what amount of excess generation shall be allocated to these three components. This process will continue until running out of the MGs excess generation and finally if the MGs with generation shortage or external LL are not supplied completely, the grid will cover the shortage to establish the power balance.

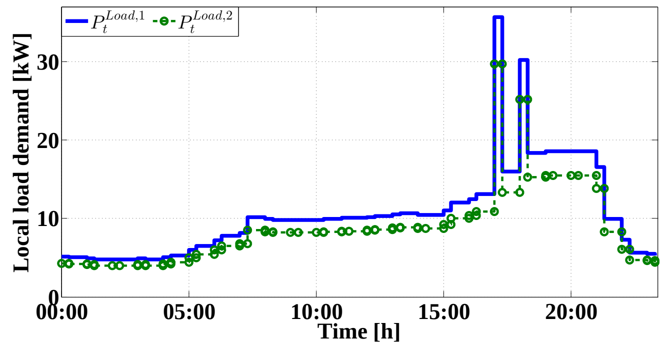
V. Results and Discussion

The proposed structure is validated over a case study which contains two MGs with different type of generation and consumer units. For this study, each of MG #1 and MG #2 has been configured by one PV (6.3kW) , one WT (8.2kW), one MT (12kW), one ES (2kWh), and responsive/non-responsive load demand. Non-dispatchable DERs and non-responsive load demand profiles in the MGs are extracted from [16], [17], [23] and shown in Figs. 8(a) and 8(b). Due to limitation of space, the details of the DER resources, the characteristic of each MG, communication details and settings are not presented in this paper, but are fully reported in [16]. The offers by each one of the generation resources of the MGs and exchanged power between them and the grid are also summarized in Table I.

Energy resources scheduling for MG #1 and MG #2 obtained by using the proposed algorithm has been shown respectively in Figs. 9(a) and 9(b). In addition, the power sold to the grid and to LL by each MG, the power sold to the other MG, RLD feeding power and ES charging power has been shown in Figs. 10(a) and 10(b). Power generation by PV and WT is affected by weather conditions and on the other hand, these resources have participated in supplying the consumers more than the other resources, because they have presented lower offers that are more competitive. As it can be seen in Fig. 9(a), MG #1 provided a part of the required power of MG #2 as well as the RLD and ES in MG #1 during



(a) non-dispatchable DERs



(b) non-responsive load demand

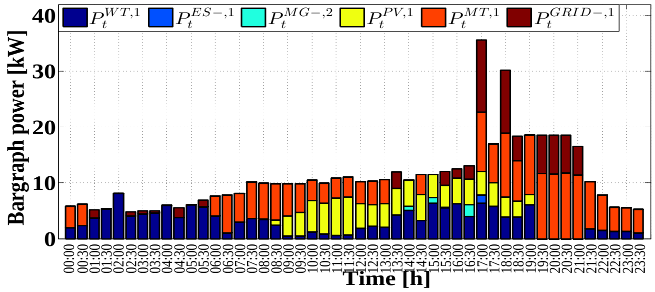
Fig. 8: Forecasted power curves of a) non-dispatchable DERs b) non-responsive load demand in MGs

TABLE I: Supply bids by generation and consumers units into EMS [€/kWh] [4], [17]

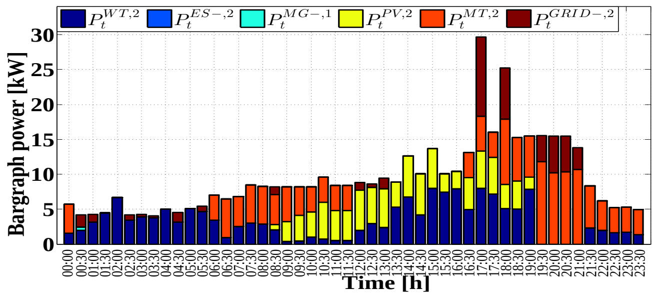
Symbol	Min	Max	Symbol	Min	Max
$\pi_t^{\text{UP},n}$	1.5		$\pi_t^{\text{RLD},n}$	0.08	0.15
$\pi_t^{\text{WT},n}$	0.03	0.09	$\pi_t^{\text{PV},n}$	0.08	0.11
$\pi_t^{\text{MT},n}$	0.14	0.16	$\pi_t^{\text{ES+},n}$	0.1	0.16
$\pi_t^{\text{ES-},n}$	0.1	0.15	$\pi_t^{\text{LL},n}$	0.06	0.12
$\pi_t^{\text{MG-},nm}$	0.07	0.17	$\pi_t^{\text{MG+},nm}$	0.15	0.17
$\pi_t^{\text{GRID-},n}$	0.16	0.18	$\pi_t^{\text{GRID+},n}$	0.05	0.115
$\pi_t^{\text{VG},n}$	0.135	0.15	$\pi_t^{\text{VL},n}$	0.09	0.17

00:30 to 01:00, because of the lower bid from MT. During the next hour, despite the higher value of $\pi_t^{\text{GRID-},1}$, EMS #1 has decided to supply a part of RLD by purchasing from the grid. At 02:00 pm more $P_t^{\text{EGP},1}$ is generated since the local load demand decreases and this power is mainly spent feeding the grid noting that $\pi_t^{\text{GRID+},1}$ offer is higher. EMS has reduced the consumed load in both of the MGs for preventing the penalty cost during the consumption peak when load diagram reaches maximum consumption or as in the Scenarios #2 and #3, the generation of all resources is not enough for feeding the load. ES charging has only occurred during three hours at both MGs and does not have a noticeable effect on the total power consumed. After these time periods, SOC at both MGs has reached the value $\overline{\text{SOC}}$ and ES is kept in the standby mode so that during MGs islanded operation, ES can support them.

In Fig. 11(a), the percentage of production on each

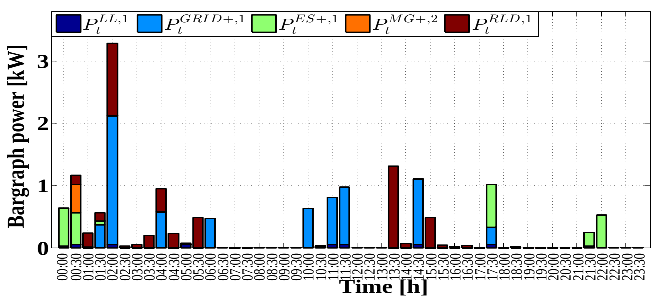


(a) MG #1

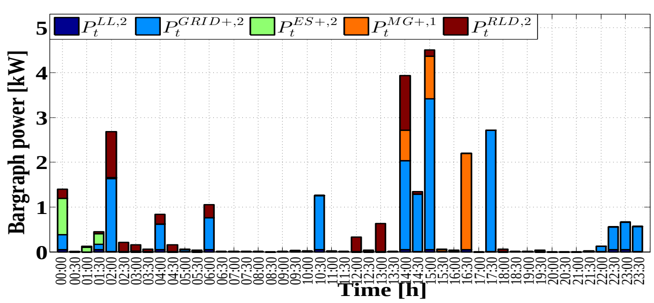


(b) MG #2

Fig. 9: Power setting of DERs in a) MG #1 b) MG #2



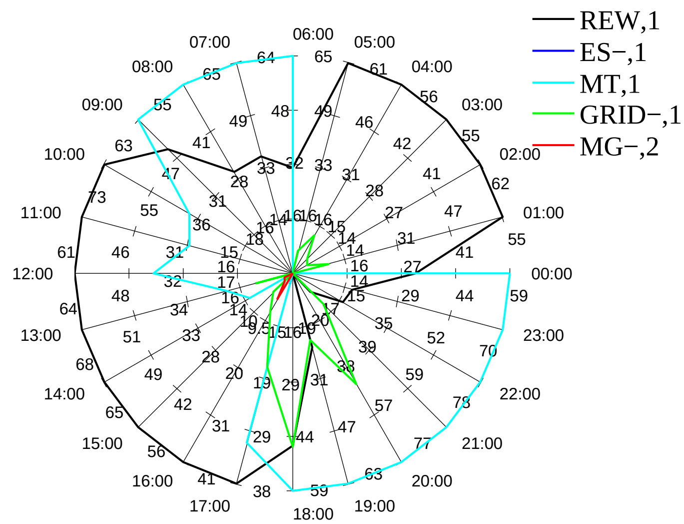
(a) MG #1



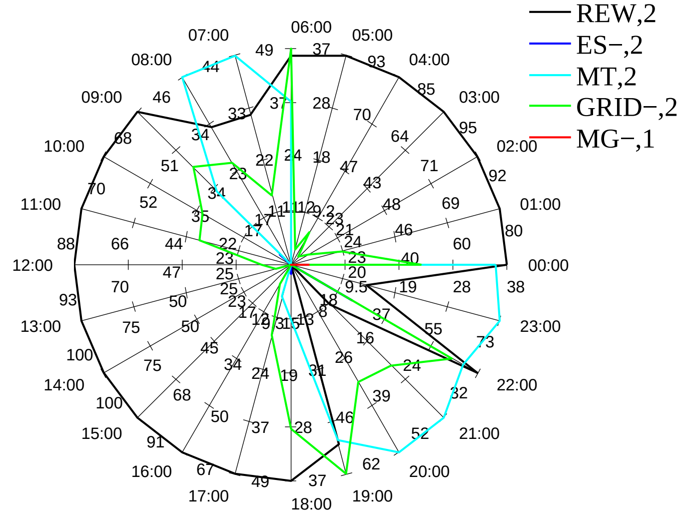
(b) MG #2

Fig. 10: Consumed power in a) MG #1 b) MG #2

generation resource is shown for MG #1 during a daily operation system. Additionally, the percentage of each responsive load demand in consuming excess available power during a daily operation system is depicted in Fig. 11(b). The number around the graph indicates a time period of a day. The numbers between the centre and the perimeter of the graph represent scale of energy generated by these resources. As it is observed, during the first hours of the day when the consumed load is low, the non-dispatchable resources have mainly fed it and in some cases power has been purchased from the grid. During the first hours of the morning, with the increase of load, demand is mainly fed by MT, because of the decrease of WT output power, and gradually when PV comes into operation, the participation of MT has decreased, gradually. As it can be seen from Fig. 11(b), a portion of the generated power is buffered in the ES by EMS #1 at the beginning of the day when load demand is relatively low. Since a maximum limit of charging power is included in the optimization for ES units (i.e., $\overline{P}^{ES}$), excess available power (i.e.,$P_t^{EGP,1}$) is stored in RLD as a part of DR program. If there is still excess power available, it will be directed to the next higher priority queue referred to as a highest bid price (MG #2 or upstream grid)



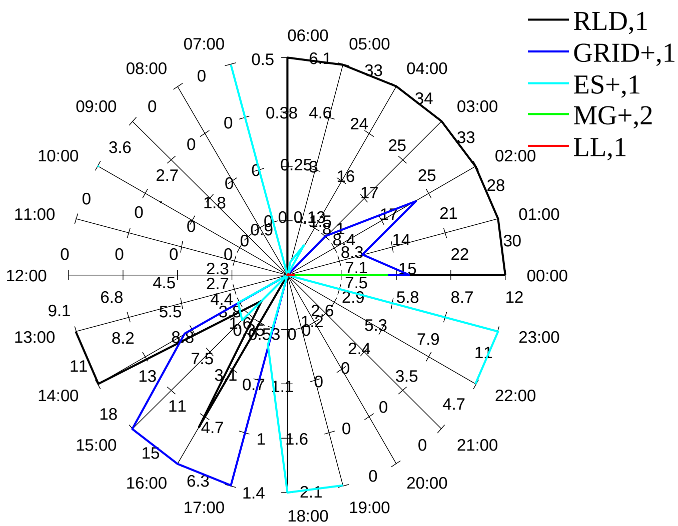
(a) MG #1



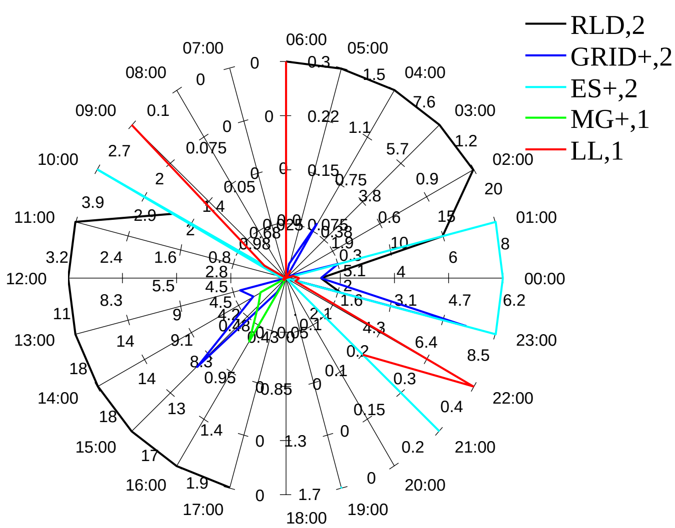
(b) MG #2

Fig. 11: Percentage of the electricity generation accounted by all DER resources in a) MG #1 b) MG #2

The value of power generation daily percentage and the share of each consumer of generated excess power have been shown respectively in Fig. 12(a) and 12(b) for MG #2. In addition, MG #2 similar to MG #1 has used MT and grid resources during some hours of the day. For instance, in the early morning hours when local load has started increasing before PV coming into operation, at the time of consumption peek, and the occurrence of Scenarios #2 and #3. Except during one hour, EMS #2 has not purchased any power from MG #1. During this period, ES, RLD and MG #2 have respectively been supplied considering the submitted offers. Despite the higher offer of MT relative to grid, MT is generated around the maximum capacity (i.e.$\overline{P}^{\mathrm{MT}}$) during evening and the rest of the required power is purchased from the grid.



(a) MG #1



(b) MG #2

Fig. 12: Percentage of the electricity consumption accounted by all DER resources in a) MG #1 b) MG #2

VI. Conclusions

The coordination control among multiple MGs including an active cluster of DER resources, ES devices and RLD is implemented using an innovative hierarchical control technique. The introduced distributed economic dispatch strategy can be easily configured in systems with multiple MGs interconnection having different owners. The proposed CEMS can import the excess generation by one MG toward consumption at other MGs which have suffered from shortage of power supply. Eventually, the feasibility and effectiveness of the presented hierarchical control technique for reliable and effective operations of the grid-tied multi-MGs have been verified using an optimization algorithm. This strategy was developed to overcome most of the challenges encountered by the coupling of non-fixed number of stochastic variables and decision variables in a system having a huge number of constraints.

The principal benefits of the proposed hierarchical controlled multi-MG interaction can be summarized as follows: 1) maximal usage of non-dispatchable resources 2) prioritization for the charging/discharging of the ES devices inside each MG with different SOC as a result reliability enhancement which can be coordinated by EMSs 3) preparedness for emergency conditions which can be managed by CEMS. Numerical results indicate that this dispatching approach can be successfully applied to deal with systems with multiple-MGs achieving the minimum cost of operation. However, the proposed mathematical formulation has a much simplified formulation with multiple smaller problems and less computational complexity. Furthermore, it can identify possible capability in the distributed economic dispatch strategy, where additional EMS with extending the system and load sharing functions can be exploited without accordant modification in design/requirement models. This can bring both technical and economic benefits for real-time EMS in the systems with distributed MG.

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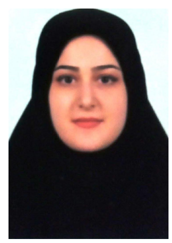

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