Fattaheian-Dehkordi, Sajjad; Abbaspour, Ali; Fotuhi-Firuzabad, Mahmud; Lehtonen, Matti

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A Distributed Framework for Intense Ramping Management in Distribution Networks

Sajjad Fattaheian-Dehkordi, *Graduate Student Member*, *IEEE*, Ali Abbaspour, Mahmud Fotuhi-Firuzabad, *Fellow*, *IEEE*, and Matti Lehtonen

***Abstract*—High-penetration of renewable energy sources (RESs) in power networks has resulted in new operational challenges in the system. Accordingly, due to the uncertainty as well as variability of power-outputs of RESs, the flexibility ramping capacity of the system should be improved. Accordingly, system operators would rely on local responsive resources (LRSs) in distribution networks (DNs) to guarantee the demand-supply balance in each area of the system and minimize its associated ramping requirements. Nevertheless, the introduction of multi-microgrid (multi-MG) structures would limit the direct-access of system operators over the LRSs scheduling. As a result, this paper aims to develop a novel framework for intense-ramping management in multi-MG systems to settle the demand-supply gap in the system while addressing the distributed nature of the network. Respectively, alternating direction method of multipliers (ADMM) is employed to develop a decentralized coordination scheme in the system. Moreover, transactive energy control signals are utilized in the context of the ADMM-algorithm in order to exploit the LRSs scheduling to address the ramping constraints of the overall system. Lastly, the scheme is simulated on 37-bus and 123-bus DNs to analyze its efficacy in the management of intense ramping conditions in multi-MG DNs.**

***Index Terms*—Ramping management, Transactive control, Multi-microgrid system, Distributed Management, Renewable energy, Responsive resources.**

NOMENCLATURE

Acronyms

ADMM	Alternating direction method of multipliers
CDG	Conventional distributed generation
CVaR	Conditional Value at Risk
DLMP	Distribution local marginal price
DN	Distribution network
DNA	Distribution network agent
DSO	Distribution system operator
ESS	Energy Storage System
LRSs	Local responsive sources
MCU	Microgrid control unit
MG	Microgrid
RESs	Renewable energy sources
TN	Transmission network
TE	Transactive energy
TECS	Transactive energy control signal

Indices

i	Nodes of the DN.
n	Nodes of the MG's grid.
t	Time intervals
st	Operational scenarios.
Ω_n^{CDG}, Ω_n^{RES}	Set of CDGs/RESs at n_{th} node of the respective MG.
T	Operational-horizon.
Π^{MG_i}, Π_{Node}^{Grid}	Set of nodes in MG i and the DN.
Π_i^{Grid}	Set of adjacent agent of node i in the DN.

Parameters

r_n / x_n	Resistance/Reactance of line n.
$Cost_n^{h,CDG}$	Cost of power-output by CDG unit h at node n.
$Cost_n^{LoadShed}$	Cost of load shedding at node n.
$p_{n,st,t}^{Demand,Max}$ / $p_{n,st,t}^{Demand,Min}$	Load demand bounding at time t in scenario st in node n.
$EDemand_n$	Required energy consumption of demand in node n over the operational-horizon.
$\eta_n^{ESS,Ch}$ / $\eta_n^{ESS,Dis}$	Charging/Discharging efficiency of the ESS unit at node n.
$p_n^{ESS,Ch,Max}$ / $p_n^{ESS,Ch,Min}$	Charging rate bounding of the ESS at node n.
$p_n^{ESS,Dis,Max}$ / $p_n^{ESS,Dis,Min}$	Discharging rate bounding of the ESS in node n.
$E_n^{ESS,Max}$	Energy capacity bounding of ESS at node n.
$p_n^{h,CDG,Max}$ / $p_n^{h,CDG,Min}$	Power-output bounding of h $_{th}$ CDG unit at node n.
$q_{n,st,t}^{Max}$ / $q_{n,st,t}^{Min}$	Reactive injected power bounding at time t in scenario st in node n.
τ_{st}	Probability of scenario st.
α^{MG_i}	Confidence level considered in MG i in case of deployment of CVaR index.
β^{MG_i}	Risk constant considered in MG i in case of deployment of CVaR index
LMP_t	Locational marginal price at common coupling point of the DN and the TN.

S. Fattaheian-Dehkordi, A. Abbaspour, and M. Fotuhi-Firuzabad are with the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran. (e-mail: sajjad.fattaheiandehkordi@aalto.fi; abbaspour@sharif.edu; fotuhi@sharif.edu).

S. Fattaheian-Dehkordi, and M. Lehtonen are with Department of Electrical Engineering and Automation, Aalto University, Espoo, Finland. (e-mail: sajjad.fattaheiandehkordi@aalto.fi; matti.lehtonen@aalto.fi).

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$R^{Max,Down}$ / $R^{Max,Up}$	Maximum allowable ramping-down/up in net-load of the DN.
$v^{Min}_{n,st,t}, v^{Max}_{n,st,t}$	Voltage magnitude bounding at time *t* in scenario *st* in node *n*.
$L^{Max}_{n,st,t}$	Maximum amount of the squared current in line *n* at time *t* in scenario *st* in node *n*.

Variables

v_n	Squared value of the voltage magnitude of node *n*.
L_n	Squared value of the line current magnitude of line *n*.
Pl_n / Ql_n	Active/reactive power flow in line *n*.
p_n / q_n	Active/reactive injected power at node *n*.
$p^{h,CDG}_{n,st,t}$	Power-output by h_{th} CDG unit at time *t* in scenario *st* in node *n*.
$p^{ESS,Ch}_{n,st,t}$ / $p^{ESS,Dis}_{n,st,t}$	Charging/discharging of ESS unit at time *t* in scenario *st* in node *n*.
$\theta^{ESS,Ch}_{n,st,t}, \theta^{ESS,Dis}_{n,st,t}$	Binary variables to show the charging/discharging state of ESS at time *t* in scenario *st* in node *n*.
$SOC^{ESS}_{n,st,t}$	State of the charge of ESS unit at time *t* in scenario *st* in node *n*.
$p^{Demand}_{n,st,t}$	Power consumption by demands at time *t* in scenario *st* in node *n*.
$p^{LoadShed}_{n,st,t}$	Load shedding at time *t* in scenario *st* in node *n*.
$p^{h,RES}_{n,st,t}$	Power-output by renewable sources *h* at time *t* in scenario *st* in node *n*.
$p^{MG_i}_{st,t}$	Determined optimal power-exchanging between MG *i* and the DN at time *t* in scenario *st*.
$p^{DNA_i}_{i,t}$	Announced value of power-exchanging between the MG *i* and the grid to DNA *i* at time *t*
$TE^{DNA_i}_{t}$	Transactive energy control signal (TECS) that is determined by DNA *i* and announced to MG *i* at time *t*
$P^{Loss}_{i,t}$	Amount of power-loss in line *i* at time *t*
$\zeta^{MG_i}_{i}$	Auxiliary variable for deployment of CVaR method.
$\psi^{MG_i}_{i,sc}$	Auxiliary variable in CVaR method.

I. INTRODUCTION

Renewable energy sources (RESs) as prospective power sources in future systems have obtained significant attention in recent years. High penetration of RESs based on the governmental and environmental supports in power systems has caused the primary transformations in managing the system [1]. In this regard, RESs uncertainties could result in the intense-ramping in the system's net-load which could engender the supply-demand gap in the system [2]-[3]. As a result, system operators would require a significant amount of flexibility ramping capacity to settle the intense-ramping in the system, which would enhance the flexibility and reliability of the network [4].

Power systems traditionally rely on bulk generation units connected to transmission networks (TNs) to settle the intense-ramping issue in the system. However, the investment and operational costs of these systems as well as the potential over-loading conditions in the TN would limit the flexibility ramping capacity that could be provided by these generation units [4], [5], [6]. System operators should incorporate the local responsive sources (LRSs) to settle the intense-ramping in the system. Net-loads of distribution networks (DNs) in modern power networks should be managed in a way that ensures the required ramping capacity could be provided by generation units in the TN [7]. This management idea is similar to the zonal flexibility management concept where system operators aim to activate operational service from LRSs to manage the intense-ramping in the system [4]. As a result, distribution system operators (DSOs) as mediator entities between DNs and TNs should exploit the LRSs scheduling in DNs with high RESs penetration in order to manage the intense-ramping in the DN's net-load.

Introduction of privatization has resulted in the development of multi-microgrid (multi-MG) structures in DNs which could facilitates integrating LRSs into the network. However, the development of multi-MG DNs would limit the direct access of the DSO over the LRSs scheduling in the network [8], [9]. In this regard, the developed centralized approach in [1] for intense-ramping management in DN may not be applicable in decentralized DNs. In other words, in [1], the operational data of LRSs would be sent to DSO to centrally optimize the intense-ramping in the DN. Consequently, new coordination schemes should be deployed in Multi-MG DNs in order to enable the DSO to exploit the LRSs scheduling with the aim of managing the intense-ramping in the DN's net-load. In these structures, the procedure of gathering and analyzing all of the local operational data in a central manner could be avoided, which would also decrease the security risks in the system.

Recently, several research works are conducted on activating flexibility ramp service from LRSs in DNs. In this regard, [5, 7, 10] have developed an optimization model, in which a microgrid (MG) would provide the flexibility ramp service for the DN to settle the intense-ramping in the system. In these works, the LRSs are efficiently scheduled to minimize the intense-ramping of the overall DN. Furthermore, the application of exploiting the electric vehicles scheduling in a DN to activate the flexibility ramp service is investigated in [11]. Authors in [12] have organized a novel scheme to exploit the power-charging of electric vehicles in the DN in order to settle the intense-ramping issue in evening periods. In [13], a market model based on a bi-level optimization conducted by the DSO is developed to settle the intense-ramping issue in the DN. Based on the study conducted in [13], intense-ramping management in DNs would finally benefit the overall power system. In addition, the peak ramping-up minimization of a multi-MG is studied in [14], which shows the application of LRSs in addressing the intense-ramping in the DN. Moreover, a linear unit commitment model is proposed in [15] to supply the flexible ramp product in power systems. In this context, a review over the effects of flexible ramp products on the improvement of the operational flexibility of the system is conducted in [16]. In addition, an energy managing model is developed in [17] for a residential home while offering local operational services to DNs. Authors in [18] have modeled a flexibility optimization to measure the ability of a building with regard to the DN's requirements for operational services. Furthermore, a flexible product to alleviate the intense-ramping issue in PV-based DNs in multi-time scale operation conditions has been offered in [19]. In [3], investment planning in DNs based on the flexibility ramping requirements is studied in a central manner. The developed approach in this paper finally enables the DSO to settle the intense-ramping in the DN utilizing LRSs. While the previous research works have strived to provide an efficient model for intense-ramping management in DNs, the distributed nature of future DNs and the security

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concerns of the independent prosumers are not addressed in these research works [5-10, 12-13]. Moreover, the proposed model in [10] has merely considered optimizing the power-charging of electric vehicles in a DN in order to minimize the intense-ramping of DN's net-load. As a result, based on the multi-MG structure of future DNs, utilities should develop an effective methodology to manage the intense-ramping of the DN's net-load while considering their distributed structures.

Transactive energy (TE) concept is latterly taken into account in several works conducted by research groups to manage local electrical systems in an efficient way [9]-[20]. In TE-based schemes, a monetary control signal called TE control signal (TECS) is proposed based on an economic mechanism to exploit the management procedure by independent entities in the system [10], [21]. A transactive-based management model is proposed in [11] in order to enable the DSO to schedule the LRSs in the DN. Moreover, authors in [20] have developed a two-stage robust optimization model to optimize the MGs scheduling while modeling the RESs uncertainty. In this paper, the TECSs are employed to facilitate the energy exchange between the MGs as well as the power grid. Most of the TE-based schemes similar to [22, 23] rely on a central coordinator to manage the energy exchanges among all of the MGs in the system, which could cause scalability issues as well as privacy concerns in the proposed schemes. That is why distributed approaches have received significant attention in the operational scheduling of multiple entity energy systems. In this context, alternating direction method of multipliers (ADMM) [24] has been employed in several works developed recently to operate the electrical systems in a distributed manner [25], [26]. Authors in [27] have developed a distributed approach to address the congestion issue in the energy grid. Moreover, [28] has proposed an ADMM-robust-based energy management scheme to efficiently schedule the LRSs in a multi-agent DN. However, the optimization model of LRSs in each agent is included in the ADMM optimization to develop the robust optimization formulation, which could cause privacy issues in the DN. On the other hand, the authors in [29] have utilized the ADMM-algorithm to operate the DN in a distributed way. In this paper, the robust optimization technique is employed in the MGs scheduling to address the RESs uncertainty. However, providing ramping-up/down service to the power grid by exploiting the coordination of LRSs has not been studied in [29]. The ADMM-algorithm is taken into account in [30]-[31] to model the economic dispatch in islanded MGs. Nevertheless, the proposed approaches in [30]-[31] have focused on economic dispatch and overlooked the operational constraints of electrical networks. An ADMM-based framework is proposed in [32] to enable the DSO to optimize the energy imbalance in a multi-agent energy system. This paper has utilized TECSs to minimize the cost of the system associated with the energy imbalance between day-ahead and real-time operational planning of the system. As a result, in [32], the proposed TECSs are associated with the power request of agents at the real-time operation. However, [32] has not considered the intense-ramping management in local DNs, which is corresponding with the difference between the power request of entities at two sequential time-steps. On the other hand, [32] has not taken into account the stochastic programming and the conditional value at risk (CVaR) to model the resources uncertainties. Respectively, [32] aims to maximize the profit of the local DN in the real-time operation, while this paper strives to provide operational service to the power grid in case of intense-ramping happening in the DN. Moreover, energy management in future networked-MG systems is studied in [33] utilizing the ADMM-algorithm. In this paper, the robust optimization technique is employed for modeling the resources uncertainties, while ADMM-algorithm facilitates the coordination of MGs scheduling. Reference [34] has developed an ADMM-based scheme to coordinate the operation of MGs and the DN. Nevertheless, it is noteworthy that, in the proposed frameworks in [33] and [34], MGs exchange information directly with the system operator in which could impede its scalability. Authors in [35] have employed ADMM-algorithm to optimize the residential demand response programs in a distributed way. Similar to [33] and [34], all the aggregators of residential loads in [35] directly exchange the required data with the system utility.

The taxonomy of research works in the context of intense-ramping management in DNs is presented in Table I.

Table I. Taxonomy of research works on intense-ramping management of DNs.

Ref. Num.	Ramping Management	Central Optimization	Distributed Optimization	Uncertainty Modeling	Network Modeling	A General Model for Different Kinds of Responsive Resources
[1]	✓	✓			✓	✓
[3]	✓	✓			✓	✓
[4]	✓	✓				
[5], [6]	✓	✓		✓		✓
[7]	✓	✓		✓	✓	✓
[8]	✓	✓		✓		✓
[9]	✓	✓			✓	✓
[10]	✓	✓				✓
[12]	✓		✓			
[13]	✓	✓			✓	✓
[14]	✓		✓			✓
[17]	✓	✓		✓		
[23]	✓		✓			✓
This paper	✓		✓	✓	✓	✓

Despite various studies on flexibility ramping service in DNs as well as operational coordination of Multi-MGs; based on the previous discussions, distributed intense-ramping management in DNs with Multi-MG structures has not yet been investigated. This paper strives to avoid the centralized optimization model utilized in [4- 10, and 13] to activate the flexibility ramping service from LRSs as well as TE-based schemes in [15-18] to manage independent entities in the DN. The proposed approach in this paper dismantles the optimization associated with the MGs scheduling from the operational modeling of the DN. In this regard, ADMM-algorithm is deployed to facilitate the distributed management of the DN; while TECSs are taken into account to model the energy price and power-loss in the MGs scheduling as well as to enable the DSO to settle the intense-ramping in operational optimization of the multi-MG system in the day-ahead period. In this regard, unlike previous works which include the optimization formulation of local systems in the ADMM-optimization; operational optimization of MGs is separately conducted in this paper by the microgrid control unit (MCU) to facilitate incorporating new management models in MGs and address the privacy concerns in DNs. In this paper, distribution-network-agents (DNAs) are considered in the proposed scheme to conduct the ADMM-algorithm for the distributed operation of the DN as well as determining the TECSs associated with each MG. As a result, the information

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exchange of the MCU and its respective DNA is limited to the accumulated requesting power and the TECS, which ensures system privacy. Furthermore, DSO as the entity responsible for intense-ramping management in the DN would exploit the TECSs at the point of the common coupling (PCC) of the DN and the TN to ensure the ramping of the DN's net-load meet the available ramping capacity in the TN. Consequently, without direct control of LRSs, the developed approach enables ensuring the demand-supply balance, and avoid potential price spikes. The proposed management framework would also facilitate the high-penetration of RESs in DNs without engendering the intense-ramping in the system. Furthermore, without loss of generality, scenario-based stochastic programming is employed in the optimization model conducted by each MCU to deal with the RESs uncertainties, while the CVaR method is deployed to model the risk associated with the uncertain parameters. Finally, the proposed framework facilitates decentralized intense-ramping management in DNs with high RESs penetration.

The below points could be pointed out:

- Previous researches on activating operational services from LRSs have considered the power-output while the ramping is associated with the difference between power requests of the system in two consecutive time steps. As a result, in this paper, a new approach is developed to enable the DSO to settle the intense-ramping in the DN.
- This paper has proposed a new formulation to facilitate modeling the ramping management constraints with TECSs, which enables distributed optimization of the DN. It is noteworthy that unlike previous research works in a similar context [4- 10, 11- 15, and 23] which were relied on the direct exchange of information between local MGs/agents/LRSs and the DSO, the proposed scheme in this paper is not dependent on the direct information exchange of MGs and DSO.
- Several research works in this context have merely focused on one type of LRSs, e.g. [36], or overlooked the operational modeling of the DN, e.g. [4, 8]. However, this paper strives to develop a general scheme considering the operational modeling of the DN and different kinds of LRSs. In other words, the proposed structure for intense-ramping management is general and different kinds of LRSs could effortlessly be integrated into MGs and considered in the optimization model.
- The proposed approach copes with the distributed structure of the DN by dismantling the operational modeling of the DN from the operational optimization of LRSs in each MG. In other words, combining the transactive control concept with the ADMM-algorithm enables the distributed operation of the decentralized DNs, which would also facilitate the security of the proposed scheme for intense-ramping management in multi-MGs.
- Stochastic programming is employed by MCUs to deal with the RESs uncertainties, while the CVaR index is deployed to model its associated operational risk.

In Section II, the DN modeling, and the developed intense-ramping management scheme are illustrated. In this section, the optimization conducted by each MG, as well as the mathematical model associated with operating the DN utilizing the ADMM-algorithm are presented. Furthermore, the procedure of calculating the TECSs is illustrated in this section. Finally, Section III represents the results associated with implementing the proposed framework on the IEEE 37-bus DN, followed by the conclusion in Section IV.

II. METHODOLOGY

A. System Modeling

Restructuring and privatization in DNs have resulted in the development of Multi-MGs, where each MG independently operates its respective energy sources. Respectively, in this paper, MCU agents are conceived responsible for optimizing the resources scheduling in their corresponding MGs. Furthermore, DNA agents are modeled to operate the DN and coordination of MGs in the ADMM-algorithm utilizing the TECSs. In this respect, each MCU optimizes the LRSs day-ahead scheduling in the corresponding MG based on the received TECS from the respective DNA agent. In this regard, the TECS associated with each MCU models the price of power-exchanging with the TN and the power-loss in the DN. As a result, in each iteration, MCUs determine the power-exchanging of the MGs with the DN at the received TECSs and announce them to the DNAs, which run the ADMM-algorithm and update the TECSs. Moreover, DSO based on the results of the network scheduling strives to settle the potential intense-ramping in the multi-MG's net-load by exploiting the MGs scheduling. In this regard, considering the TECS at the PCC of the DN and the TN to be $TE_t^{DNA_0}$, DSO would be able to exploit the $TE_t^{DNA_0}$ and announce it to DNA 0 to decrease the intense-ramping associated with the net-load of the DN. The model of the Multi-MG DN is presented in Fig. 1.

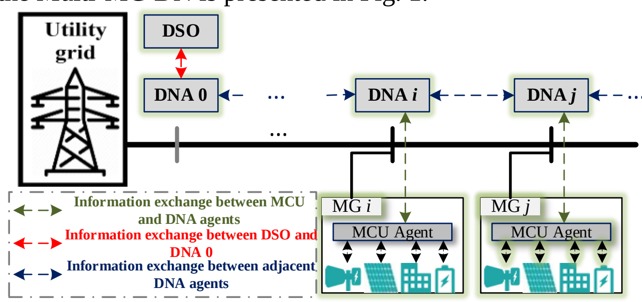

Fig. 1 The simplified structure for managing the intense-ramping in a multi-MG DN.

B. The Suggested Transactive-based Ramping Management Scheme in Multi-MG DNs

In this paper, the decentralized framework settles the intense-ramping issue while optimizing the operation of multi-MG DNs. In the scheme, DNA entities operate the DN based on the ADMM-algorithm, while providing their associated MCUs with TECSs to optimize the LRSs scheduling. MCU agents independently schedule the LRSs in their corresponding MGs considering the received TECSs from the related DNA agents. Note that the TECSs which model the energy price and power-loss in the DN would be determined considering the information-exchange between DNA agents in the ADMM-algorithm. Furthermore, without loss of generality, the stochastic-optimization model and the CVaR index are taken into account in modeling the MGs optimization to deal with the RESs uncertainties and their associated operational risks. Finally, MCUs would send the accumulated requesting power by MGs to DNA agents to run the ADMM-algorithm.

As mentioned, in the proposed scheme, DSO strives to settle the intense-ramping of the Multi-MG DN. In this regard, it is considered that DSO would define the TECS at the PCC of the TN and the DN, which models the value of the ramping service based on the cost of power-exchanging between the DN and the TN; i.e. locational marginal price (LMP). Consequently, TECSs associated with the MGs would be revised by their DNA agents while running the ADMM-based OPF-optimization. In this regard, the proposed iterative-based ADMM-algorithm would be continued until the step that the intense-ramping issue in the DN is resolved. It is noteworthy that information exchanges in the proposed structure between different agents are limited to non-critical information, which settles the privacy concerns of LRSs operated independently. Based on the above descriptions, a simplified model of the iterative algorithm for intense-ramping management in multi-MG DNs is shown in Fig. 2.

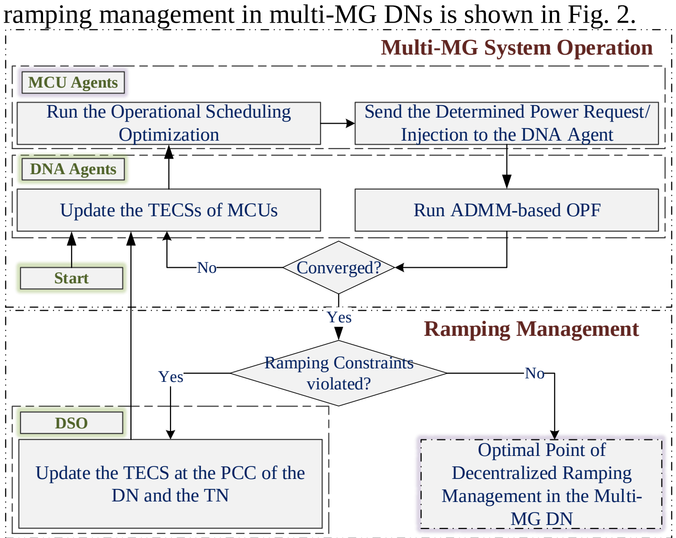

Fig. 2 The recommended intense-ramping management scheme in multi-MG DNs.

The proposed approach facilitates considering a hierarchical model of the system by considering network modeling in the operational optimization of MGs. In other words, the proposed approach is formed in a general manner that facilitates adapting the scheme based on the structure of DNs to settle the intense-ramping issue in the system. Moreover, the developed approach relies on the information exchange of the neighbor DNA agents, while the central optimization model depends on collecting and analysis of the local information in a central manner. In this regard, the proposed scheme would not be limited by the communication infrastructures and could be expanded to DNs with different structures, which would also facilitate its scalability.

C. Optimizing Microgrids Scheduling

In the proposed scheme, MCUs are the responsible entities for optimizing the MGs scheduling considering the operational constraints associated with their RESs/LRSs as well as the received TECSs from the DNA agents. Furthermore, scenario-based stochastic programming as well as the CVaR are taken into account to deal with the RESs uncertainties and their respective risks.

In this regard, the day-ahead operational optimization of MG *i* utilizing the DistFlow formulation [7, 24, 25] is modeled as follows:

$$F^{MG_i} = \left(1-\beta^{MG_i}\right)\cdot F^{MG_i,1} + \beta^{MG_i}\cdot F^{MG_i,2} \tag{1}$$

subject to

$$F^{MG_i,1} = \sum_{st}\tau_{st}^{MG_i}\cdot\left(\begin{array}{l}\sum_{t\in T}\left(p_{st,t}^{MG_i}\cdot TE_t^{DNA_i}\right)+\\ \sum_{t\in T}\sum_{n}\left[\sum_{h\in\Omega_n^{CDG}}\left(\mathrm{Cos}\,t_n^{h,CDG}\cdot p_{n,st,t}^{h,CDG}\right)\right]+\\ \sum_{t\in T}\sum_{n}\left(\mathrm{Cos}\,t_n^{LoadShed}\cdot p_{n,st,t}^{LoadShed}\right)\end{array}\right) \tag{2}$$

$$F^{MG_i,2} = \zeta^{MG_i} + \left(\frac{1}{1-\alpha^{MG_i}}\right)\cdot\sum_{st}\left(\tau_{st}^{MG_i}\psi_{st}^{MG_i}\right) \tag{3}$$

$$\begin{array}{l}-\zeta^{MG_i} + \sum_{t\in T}\left(p_{st,t}^{MG_i}\cdot TE_t^{DNA_i}\right) + \sum_{t\in T}\sum_{n}\left[\sum_{h\in\Omega_n^{CDG}}\left(\mathrm{Cos}\,t_n^{h,CDG}\cdot p_{n,st,t}^{h,CDG}\right)\right]+\\ \sum_{t\in T}\sum_{n}\left(\mathrm{Cos}\,t_n^{LoadShed}\cdot p_{n,st,t}^{LoadShed}\right)\leq\psi_{st}^{MG_i}\end{array} \tag{4}$$

$$\begin{array}{l}p_{n,st,t} = \sum_{h\in\Omega_n^{RES}} p_{n,st,t}^{h,RES} + \sum_{h\in\Omega_n^{CDG}} p_{n,st,t}^{h,CDG} - p_{n,st,t}^{Demand}\\ -p_{n,st,t}^{ESS,Ch} + p_{n,st,t}^{ESS,Dis}\quad,\quad n\in\Pi^{MG_i}\end{array} \tag{5}$$

$$p_{n,st,t} = p_{st,t}^{MG_i}\qquad, n = PCC^{MG_i} \tag{6}$$

$$\sum_{st}\left(\tau_{st}\cdot p_{st,t}^{MG_i}\right) = p_{i,t}^{DNA_i}\ \ , i = PCC^{MG_i} \tag{7}$$

$$v_{A_n,st,t} = v_{n,st,t} + 2\left[r_n Pl_{n,st,t} + x_n Ql_{n,st,t}\right] + z_n L_{n,st,t},\quad n\in\Pi^{MG_i} \tag{8}$$

$$\sum_{j}\left(-Ql_{j,st,t} - x_j L_{j,st,t}\right) + q_{n,st,t} = -Ql_{n,st,t},\quad n\in\Pi^{MG_i} \tag{9}$$

$$\sum_{j}\left(-Pl_{j,st,t} - r_j L_{j,st,t}\right) + p_{n,st,t} = -Pl_{n,st,t},\quad n\in\Pi^{MG_i} \tag{10}$$

$$Pl_{n,st,t}\cdot Pl_{n,st,t} + Ql_{n,st,t}\cdot Ql_{n,st,t} \leq v_{n,st,t}\cdot L_{n,st,t},\quad n\in\Pi^{MG_i} \tag{11}$$

$$q_{n,st,t}^{Min} \leq q_{n,st,t} \leq q_{n,st,t}^{Max},\quad n\in\Pi^{MG_i} \tag{12}$$

$$\sum_{t\in T}\left(p_{n,st,t}^{LoadShed} + p_{n,st,t}^{Demand}\right) = EDemand_{n,st}\ ,\quad n\in\Pi^{MG_i} \tag{13}$$

$$p_{n,st,t}^{Demand,Min} \leq p_{n,st,t}^{LoadShed} + p_{n,st,t}^{Demand} \leq p_{n,st,t}^{Demand,Max},\quad n\in\Pi^{MG_i} \tag{14}$$

$$p_{n,st,t}^{h,CDG,Min} \leq p_{n,st,t}^{h,CDG} \leq p_{n,st,t}^{h,CDG,Max},\quad h\in\Omega_n^{CDG}, n\in\Pi^{MG_i} \tag{15}$$

$$0 \leq p_{n,st,t}^{ESS,Ch} \leq p_{n,st,t}^{ESS,Ch,Max}\cdot\theta_{n,st,t}^{ESS,Ch},\quad n\in\Pi^{MG_i} \tag{16}$$

$$0 \leq p_{n,st,t}^{ESS,Dis} \leq p_{n,st,t}^{ESS,Dis,Max}\cdot\theta_{n,st,t}^{ESS,Dis},\quad n\in\Pi^{MG_i} \tag{17}$$

$$\theta_{n,st,t}^{ESS,Ch} + \theta_{n,st,t}^{ESS,Dis} \leq 1,\quad n\in\Pi^{MG_i} \tag{18}$$

$$SOC_{n,st,t+1}^{ESS} = SOC_{n,st,t}^{ESS} + \left.\left(\begin{array}{l}p_{n,st,t}^{ESS,Ch}\cdot\eta_n^{ESS,Ch} - \\ p_{n,st,t}^{ESS,Dis}/\eta_n^{ESS,Dis}\end{array}\right)\right/E_n^{ESS,Max},\ n\in\Pi^{MG_i} \tag{19}$$

$$SOC_{n,st,t}^{ESS,Min} \leq SOC_{n,st,t}^{ESS} \leq SOC_{n,st,t}^{ESS,Max},\quad n\in\Pi^{MG_i} \tag{20}$$

$$v_{n,st,t}^{Min} \leq v_{n,st,t} \leq v_{n,st,t}^{Max},\quad n\in\Pi^{MG_i} \tag{21}$$

$$L_{n,st,t} \leq L_{n,st,t}^{Max},\quad n\in\Pi^{MG_i} \tag{22}$$

In the proposed formulation, the objective function (1) strives to minimize the cost of the MG considering the viewpoint of the MCU towards risk. The terms of the objective are presented in (2) and (3). Furthermore, (3) and (4) are utilized to model the linear format of the CVaR index. $TE_t^{DNA_i}$ presents the TECS announced by the DNA_i to the MG_i, which is considered as the price associated with the power-exchanging at the PCC of the i_{th} MG and the main network of the Multi-MG system. Note that, in this optimization model, $\psi_{st}^{MG_i}$ should be considered as a positive variable. Moreover, the nodal power balance is shown in (5) and (6). In this regard, the announced power request to the DNA *i* is represented in (7). It is noteworthy that, in this paper, the nodes of the MG's grid are presented by index *n*, while the main grid's nodes are modeled by *i* in the formulation.

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PCC^{MG_i} presents the common coupling point of the DN and the MG i. In addition, the operational constraints of the MG's grid are shown in (7) – (12). It is noteworthy that, in the developed formulation, it is assumed that the grid is radially operated [7, 24, 25]; in which the node A_n is considered as the ancestor node of the node n. Furthermore, (13) - (14) impose the operational constraints of the demand in each node of the MG, while the limitation over the power-output by conventional distributed generation (CDG) units is enforced by (15). In addition, (16) – (20) show the operational constraints of the electrical storage systems (ESSs) in each node of the i_{th} MG's grid. Finally, the constraints of voltage and current magnitudes in network are presented by (21) and (22). While running the ADMM-algorithm, each MCU would schedule the RESs/LRSs in the respective MG without considering the formulation of the ADMM-algorithm, which benefits the system from security and scalability perspectives.

D. Operational Modeling of DNs

Based on the suggested structure, DNA agents are responsible for operating the DN. In this regard, the ADMM-algorithm is applied to operate the grid in a decentralized-manner. In this section, the optimal power flow (OPF) is presented to operate the DN in a central manner, which is finally re-cast into a decentralized operational model utilizing the ADMM-algorithm.

1) Central OPF Formulation

The DN enables the power-exchanging among MGs as well as the TN. In this regard, it is assumed that the DN consists of a set of nodes presented by Π_{Node}^{Grid}, which models the PCC of the TN and the DN as well as the PCC of the MGs and DN. Moreover, the set of lines is presented by Π_{Line}^{Grid} models distribution lines. Note that, as shown in Fig. 1, the PCC of the TN and the DN is considered as Node 0. Accordingly, in this paper, it is considered that the cost of power-exchanging with the TN is presented by $TE_t^{DNA_0}$. Consequently, the OPF model of the DN [7, 24] is modeled as below:

$$\text{Min} \sum_i F_{i,t} \tag{23}$$

Subject to

$$v_{A_i,t} = v_{i,t} + 2\left[r_i\, Pl_{i,t} + x_i\, Ql_{i,t}\right] + z_i L_{i,t}, \qquad i \in \Pi_{Node}^{Grid} \tag{24}$$

$$\sum_j \left(-Ql_{j,t} - x_j L_{j,t}\right) + q_{i,t} = -Ql_{i,t}, \qquad i \in \Pi_{Node}^{Grid} \tag{25}$$

$$\sum_j \left(-Pl_{j,t} - r_j L_{j,t}\right) + p_{i,t} = -Pl_{i,t}, \qquad i \in \Pi_{Node}^{Grid} \tag{26}$$

$$Pl_{i,t} \cdot Pl_{i,t} + Ql_{i,t} \cdot Ql_{i,t} \le v_{i,t} \cdot L_{i,t}, \qquad i \in \Pi_{Node}^{Grid} \tag{27}$$

In the developed formulation, the objective function (23) minimizes the associated cost with the power-exchanging of the DN and the TN at Node 0 (i.e. the PCC of the DN and the TN), which would be associated with the $TE_t^{DNA_0}$. Moreover, the operational constraints of the grid are presented by (24) – (27). Note that $p_{i,t}$ at the PCC of MGs and the DN equals to $p_{i,t}^{DNA_i}$, which would be determined by (7) and sent to DNA i by MCU i. Furthermore, as the energy-limited LRSs such as storage units are operated independently by MCUs, the OPF-model in the DN could be independently conducted in each time-step. This characteristic would finally facilitate the utilization of parallel processing in modern processors with multi-core structures.

2) ADMM-based OPF Mathematical Formulation

As mentioned, the ADMM-algorithm facilitates the decentralized operation of the DN. In this paper, the ADMM facilitates decentralized operating of the DN by DNAs. Consequently, the OPF-optimization model, i.e. (23) – (27), could be modeled in a simplified format as follows:

$$\min_u \sum_i f_i\left(u_i\right) \tag{28}$$

$$\text{Subject to} \quad \sum_{j \in \Pi_i^{Grid}} B_{i,j} u_j = 0, \;\; i \in \Pi_{Node}^{Grid} \tag{29}$$

In this formulation, Π_i^{Grid} shows the set of neighbor nodes of $i \in \Pi_{Node}^{Grid}$. Moreover, u_i presents the decision variables including $\{v_i, \ell_i, PL_i, QL_i, p_i, q_i\}$. Furthermore, $B_{i,j}$ is a matrix associated with the operational constraints of the DN. In the ADMM-algorithm, the optimization model of each DNA agent would be separated from the adjacent DNAs, which are related in the central OPF-model due to network operating constraints. In this regard, a new set of variables called auxiliary variables are taken into account to show the duplicate of the variables of the adjacent agents (i.e. u_j) in the optimization of DNA agent i. Accordingly, the optimization model (28)-(29) could be reformulated as follows:

$$\min_{u,z} \sum_i f_i\left(u_i\right) \tag{30}$$

$$\text{s.t.} \quad \sum_{j \in \Pi_i^{Grid}} B_{i,j} z_{j,i} = 0, \; i \in \Pi_{Node}^{Grid} \tag{31}$$

$$z_{j,i} = u_j, \;\; i \in \Pi_{Node}^{Grid}, j \in \Pi_i^{Grid} \tag{32}$$

In this regard, constraint (32) could be added to the objective function utilizing the augmented Lagrangian concept. Respectively, the augmented Lagrangian model of the problem could be formulated as below:

$$f(u,z,\lambda) := \sum_{i \in \Pi_{Node}^{Grid}} \left(f_i\left(u_i\right) + \sum_{j \in \Pi_i^{Grid}} \lambda_{i,j}\left(u_i - z_{j,i}\right) + \frac{\rho}{2}\left\|u_i - z_{j,i}\right\|_2^2 \right) \tag{33}$$

Where, $\lambda_{i,j}$ is a Lagrangian-multiplier, and ρ is a constant positive parameter. As a result, considering the developed formulation, each iteration of running the ADMM-algorithm includes three steps, where local variables, auxiliary variables, and Lagrangian-multipliers would be updated. The procedures of updating the local, auxiliary, and the Lagrangian-multiplier in the iteration k of running the ADMM-algorithm are formulated as follows:

$$u^{k+1} = \arg\min_u f(u, z^k, \lambda^k) \tag{34}$$

$$z^{k+1} = \arg\min_z f(u^{k+1}, z, \lambda^k) \tag{35}$$

$$\lambda^{k+1} = \lambda^k + \rho(u^{k+1} - z^{k+1}) \tag{36}$$

Furthermore, in the ADMM-algorithm conducted in the DN, the criteria defined in (37) and (38) are employed to determine the convergence of the algorithm.

$$r^k := \left\|u^k - z^k\right\| \tag{37}$$

$$s^k := \rho\left\|(u^k - z^{k-1})\right\| \tag{38}$$

In (37) and (38), r^k and s^k show the primal and dual residuals, which are deployed to ensure convergence of the proposed algorithm. Note that as the ADMM-algorithm is well-defined in previous works, the general algorithm and formulation are merely presented in this section. However, the detailed formulation of the ADMM-based-OPF in DNs could be found in [24].

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E. The Developed TECSs

In this framework, DNA agents in the DN would measure the TECSs of MCUs; which model the price of power-exchanging at the PCC of the respective MG and the DN. Consequently, a procedure has to be defined to enable the DNAs to determine the TECSs while operating the DN based on the developed ADMM-algorithm. The proposed TECSs should be calculated while running the ADMM-algorithm in the DN. As a result, here, TECSs are calculated considering the cost of power-exchanging with the TN and the power-loss in the DN in a fully decentralized way. Note that, as previously discussed, the TECS at the PCC of the Multi-MG DN and the TN is shown by $TE_t^{DNA_0}$ which presents the cost of exchanging power with the TN.

The developed approach in this paper aims to settle the intense-ramping management in Multi-MG DNs. In this regard, a new formulation is developed in the following subsection to enable the DSO to exploit the $TE_t^{DNA_0}$ in order to incentivize the LRSs to provide the ramping service to the DN. In other words, DSO strives to update the $TE_t^{DNA_0}$ with the aim of minimizing the intense-ramping in the DN. Furthermore, the system operator would compensate the cost of LRSs for providing the operational service to settle the intense-ramping in the DN [5, 7].

1) Calculating TECSs in DN

In the developed framework, DNAs calculate TECSs. Accordingly, the distribution local marginal price (DLMP) concept is employed to calculate the energy cost in each node of the grid considering the power-loss in the connecting lines. As a result, the TECSs in each node of the grid could be related to each other as follows:

$$TE_t^{DNA_i} = TE_t^{DNA_{A_i}} \cdot \left(1 + \partial P_{i,t}^{Loss} \big/ \partial Pl_{i,t}\right) \tag{39}$$

where $\partial P_{i,t}^{Loss} \big/ \partial PL_{i,t}$ presents the extra power-loss in the line connecting nodes i and A_i due to the marginal growth in the injected power at i_{th} node. Note that DNA_i and DNA_{A_i} are the DNA agents associated with nodes i and A_i, respectively. In this regard, this term could be calculated based on the power-loss formulation at line i that connects nodes i and A_i. Accordingly, the power-loss in line i could be measured as presented in (40).

$$P_{i,t}^{Loss} = \frac{r_i \cdot \left(Pl_{i,t}^2 + Ql_{i,t}^2\right)}{v_{i,t}} \tag{40}$$

Based on (40), a marginal growth in power flow Pl_i would change the power-loss as follows:

$$\Delta P_{i,t}^{Loss}\Big|_{Pl_{i,t} \to Pl_{i,t} + \Delta Pl_{i,t}} = \frac{2 \cdot r_i \cdot Pl_{i,t} \cdot \Delta Pl_{i,t}}{v_{i,t}} \tag{41}$$

In this regard, considering (40) for modeling the increase in the power-loss in case of changes in the injected power at node i, the primary equation (39) which models the decentralized relation between the TECSs of adjacent DNA agents could be reformulated as follows:

$$TE_t^{DNA_i} = TE_t^{DNA_{A_i}} \cdot \left(1 + \frac{2 \cdot r_i \cdot Pl_{i,t}}{v_{i,t}}\right) \tag{42}$$

Based on the developed formulation, DNA agents would be able to calculate the TECSs in a decentralized-way. In this regard, along with the conventional information-exchange between adjacent agents in the DN, DNA agents would receive the TECSs from their ancestor node in the DN. Consequently, while the TECS at the PCC of the DN and the TN is determined, the TECSs in each node of the DN could be distributedly calculated by DNA agents based on the ADMM-algorithm.

2) TECSs for Ramping Management

In the proposed scheme, DSO as the intermediary entity between the DN and the TN is considered to be responsible for intense-ramping management in the system. Note that activating operational service in Multi-MG systems could decrease the intense-ramping in the DN. Moreover, alleviating the intense-ramping in the net-load of the DN by incorporating the LRSs would facilitate the increase in integration of RESs in the DN without engendering operational issues. The centralized operational optimization of the DN considering the ramping constraints could be formulated as follows:

$$\text{Min Cost} = \sum_t p_{0,t} \cdot LMP_t \tag{43}$$

Subject to (24) – (27) and

$$p_{0,t} - p_{0,t-1} \le R^{Max,Up} \tag{44}$$

$$p_{0,t-1} - p_{0,t} \le R^{Max,Down} \tag{45}$$

Note that $p_{0,t}$ equals to $p_{0,t}^{DNA_0}$ in the developed formulation, which shows the exchanging power with the TN. In the developed formulation, the objective function (43) aims to minimize the cost of power-exchanging with the TN, while (44) and (45) impose the ramping-up/down constraints, respectively. In this regard, (44) and (45) could be included in the objective function utilizing the Lagrangian-multiplier concept as follows:

$$\text{Min Cost} = \sum_t \left\{ \begin{array}{l} p_{0,t} \cdot LMP_t + \lambda_t^{Ramp-Up} \cdot (p_{0,t} - p_{0,t-1} - R^{Max,Up}) \\ + \lambda_t^{Ramp-Down} \cdot (p_{0,t-1} - p_{0,t} - R^{Max,Down}) \end{array} \right\} \tag{46}$$

Where $\lambda_t^{Ramp-Up}$ and $\lambda_t^{Ramp-Down}$ present the Lagrangian-multipliers associated with ramping-up/down constraints. As a result, updating the Lagrangian-multipliers according to the intense-ramping issue would result in alleviating the intense-ramping in the DN. In other words, it is assumed that, in (46), Lagrangian-multipliers similar to constant parameters could be updated based on the ramping-up/down of the DN's net-load in order to exploit the LRSs scheduling to settle the ramping constraints in the system. Moreover, the terms $R^{Max,Up}$ and $R^{Max,Down}$ are considered as positive constant parameters that could be removed from the objective function. By removing the constant variables, the objective function could be reformulated as follows:

$$\text{Min Cost} = \sum_t \left\{ \begin{array}{l} p_{0,t} \cdot LMP_t + \lambda_t^{Ramp-Up} \cdot (p_{0,t} - p_{0,t-1}) \\ + \lambda_t^{Ramp-Down} \cdot (p_{0,t-1} - p_{0,t}) \end{array} \right\} \tag{47}$$

Furthermore, as the objective function of the operational optimization considers the overall operational-horizon, ramping terms in (47) could be reformulated as follows:

$$\begin{aligned} & \sum_t \left\{ \lambda_t^{Ramp-Up} \cdot (p_{0,t} - p_{0,t-1}) + \lambda_t^{Ramp-Down} \cdot (p_{0,t-1} - p_{0,t}) \right\} \\ & = \sum_t \left\{ \left(\lambda_t^{Ramp-Up} - \lambda_{t+1}^{Ramp-Up}\right) \cdot p_{0,t} + \left(\lambda_{t+1}^{Ramp-Down} - \lambda_t^{Ramp-Down}\right) \cdot p_{0,t} \right\} \end{aligned} \tag{48}$$

Consequently, considering (48), the objective function could be reformulated as below:

$$\text{Min Cost} = \sum_t \left\{ p_{0,t} \cdot \left(\begin{array}{l} LMP_t + \left(\lambda_t^{Ramp-Up} - \lambda_{t+1}^{Ramp-Up}\right) \\ + \left(\lambda_{t+1}^{Ramp-Down} - \lambda_t^{Ramp-Down}\right) \end{array} \right) \right\} \tag{49}$$

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As a result, the employed procedure results in a simplified formulation, where the term $\begin{pmatrix} LMP_t + \left(\lambda_t^{Ramp-Up} - \lambda_{t+1}^{Ramp-Up}\right) + \\ \left(\lambda_{t+1}^{Ramp-Down} - \lambda_t^{Ramp-Down}\right) \end{pmatrix}$ could be considered as $TE_t^{DNA_0}$. In this regard, as presented in (50)-(53), DSO could update $TE_t^{DNA_0}$ associated with DNA_0 to exploit the MGs scheduling in the context of the developed ADMM-algorithm in the DN.

$$TE_t^{DNA_0} = \begin{pmatrix} LMP_t + \left(\lambda_t^{Ramp-Up} - \lambda_{t+1}^{Ramp-Up}\right) + \\ \left(\lambda_{t+1}^{Ramp-Down} - \lambda_t^{Ramp-Down}\right) \end{pmatrix} \tag{50}$$

$$TE_t^{Ramp-DNA_0} = \begin{pmatrix} \left(\lambda_t^{Ramp-Up} - \lambda_{t+1}^{Ramp-Up}\right) + \\ \left(\lambda_{t+1}^{Ramp-Down} - \lambda_t^{Ramp-Down}\right) \end{pmatrix} \tag{51}$$

$$\lambda_t^{Ramp-Up} = \lambda_t^{Ramp-Up,old} + \rho^{Ramp-Up} \cdot (p_{0,t} - p_{0,t-1} - R^{Max,Up}) \tag{52}$$

$$\lambda_t^{Ramp-Down} = \lambda_t^{Ramp-Down,old} + \rho^{Ramp-Down} \cdot (p_{0,t-1} - p_{0,t} - R^{Max,Down}) \tag{53}$$

Where $\lambda_t^{Ramp-Up,old}$ and $\lambda_t^{Ramp-Down,old}$ present the Lagrangian-multipliers of ramping-up/down in the previous step. Moreover, $\rho^{Ramp-Up}$ and $\rho^{Ramp-Down}$ are positive constant parameters that would be determined by DSO to update the TECS based on the ramping condition of the network. Moreover, $TE_t^{Ramp-DNA_0}$ shows the change in the $TE_t^{DNA_0}$ due the developed intense-ramping management procedure to incentivize the contribution of LRSs in the intense-ramping alleviation. Note that the updating procedure for Lagrangian-multipliers in (52) and (53) would be merely conducted in case that the ramping-up/down constraints are violated, respectively. Based on the developed formulation, in case of intense-ramping-up/down in the net-load of the DN at time *t*, the operator increases/decreases the $TE_t^{DNA_0}$ in order to motivate the MGs to decrease/increase their power request at *t*; while decreases/increases $TE_{t-1}^{DNA_0}$ with the aim of incentivizing MGs to increase/decrease their requesting power at *t-1*. This procedure would finally result in alleviating the intense-ramping-up/down in the system. In other words, the defined procedure in this section facilitates the re-cast of the ramping issue in the DN into monetary TECSs that would incentivize independent LRSs to participate in the procedure of decreasing the intense-ramping-up/down associated with the net-load of the Multi-MG DN.

III. Numerical Results

The scheme for decentralized intense-ramping management in multi-MG DNs is simulated considering the 37-bus and 123-bus DNs using CPLEX solver in GAMS.

A. 37-bus Test System

The 37-bus test network is structured as a multi-MG DN shown in Fig. 3. Furthermore, MGs are termed based on their PCC node with the DN. Moreover, similar to previous research works in this context, it is considered that system is balanced and the operational characteristics of LRSs are adapted from [6-8] to facilitate the study of the intense-ramping management in the test network. However, it is noteworthy that while previous intense-ramping management models in DNs [2-9, and 12] have considered the centralized modeling; this paper has considered a multi-MG structure and aims to settle the intense-ramping issue in a distributed structure. In addition, it is considered that each MCU considers 20 scenarios for modeling their resources uncertainties, which are presented in [37]. Finally, in the operational optimization of each MG, the risk parameter (β) of the CVaR index is considered to be 0.4.

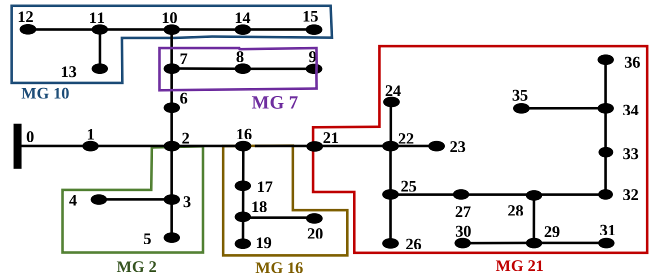

Fig. 3. The considered multi-MG test network.

The proposed scheme aims to optimize the day-ahead operation of the test system considering the ramping-up/down constraints (i.e. 500 kW/h). The developed approach in Fig. 2 would facilitate the distributed operation of the Multi-MG DN, while addressing the ramping constraints. In this context, the power-exchanging of the Multi-MG DN and the TN per-iteration of running the ADMM-algorithm is presented in Fig. 4. These results show the provided ramping service to the grid.

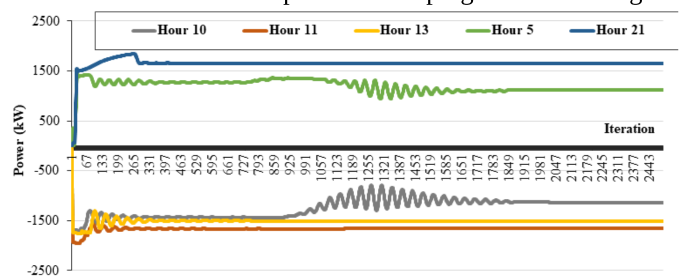

Fig. 4. Power-exchanging of the Multi-MG DN and the TN per-iteration of running the ADMM-algorithm.

The value of the TECSs associated with MGs 10 and 21 per-iteration of running the proposed algorithm at hours 10, 17, and 21 are presented in Fig. 5. Moreover, the converged TECSs associated with nodes 0, 10, 21 (i.e. $TE_t^{DNA_0}$, $TE_t^{DNA_{10}}$, $TE_t^{DNA_{21}}$) over the operational-horizon are shown in Fig. 6. These results present the strong performance of the proposed scheme to operate the Multi-MG DN, while exploiting the LRSs scheduling to manage intense-ramping in the DN. As mentioned, in the developed scheme, TECSs model the price of power-exchanging with the TN, power-loss, and ramping issues in the DN. In this regard, the difference between the TECSs in different nodes of the DN is associated with the power-loss in the grid.

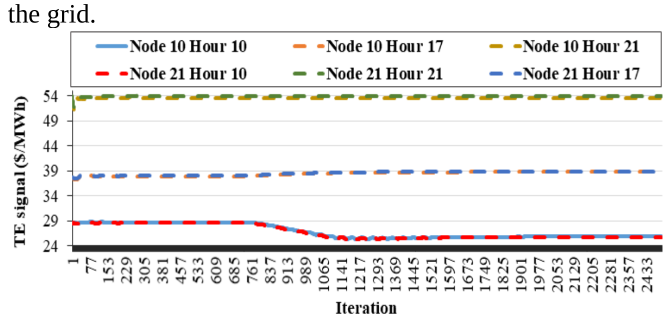

Fig. 5. TECSs of MGs 10 and 21 at hours 10, 17, and 21 per-iteration.

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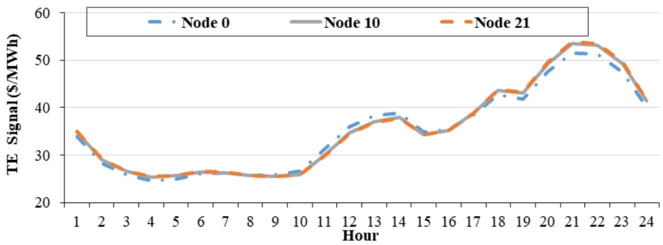

Fig. 6. The converged TECSs associated with nodes 0, 10, and 21 over the operational-horizon.

The ramping associated with the DN's net-load at hours 9, 13, and 17 per-iteration of running the proposed algorithm are shown in Fig. 7. The results show that the approach facilitates decreasing the intense-ramping of the DN in a decentralized-manner. In this context, the ramping of the net-load of the Multi-MG DN during the operational-horizon with/without implementing the proposed intense-ramping management framework is presented in Fig. 8. The obtained results indicate that absolute values of up-ramping and down-ramping are decreased from more than 600 kW/h and 800 kW/h to 500 kW/h, which shows the 40% decrease in the intense-ramping of the Multi-MG DN. Respectively, the proposed model enables managing the intense-ramping in DNs with distributed structures. As discussed in the proposed scheme, DSO exploits $TE_t^{DNA_0}$ to settle the intense-ramping in the Multi-MG DN in an iterative-manner. Consequently, the converged value of the $TE_t^{DNA_0}$ as well as its value without implementing the proposed intense-ramping management scheme (i.e. LMP_t) are shown in Fig. 9. The costs of power-exchanging with the grid associated with each MG are shown in Fig. 10. Moreover, based on the developed approach, the cost of power-exchanging with the grid for each MG is associated with the announced TECS, which includes the cost of power-exchanging with the TN as well as the power-loss and intense-ramping alleviation procedure. In this regard, the cost associated with the intense-ramping procedure (i.e. $TE_t^{Ramp-DNA_0}$) is presented in Fig. 11. The total cost associated with the $TE_t^{Ramp-DNA_0}$ is less than 5% of the total costs of the MGs power-exchanging with the grid (presented in Fig. 10), which shows the benefit of intense-ramping management in DNs utilizing LRSs.

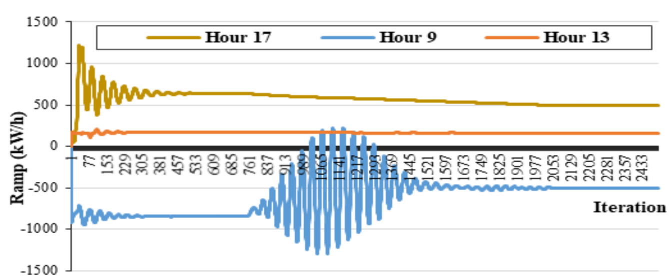

Fig. 7. Ramping of the DN's net-load at hours 9, 13, and 17 per-iteration.

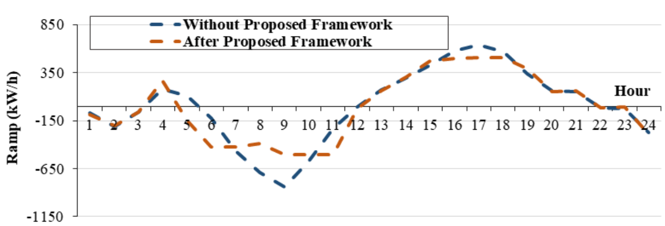

Fig. 8. Ramping of the DN's net-load with/without implementing the proposed intense-ramping management scheme.

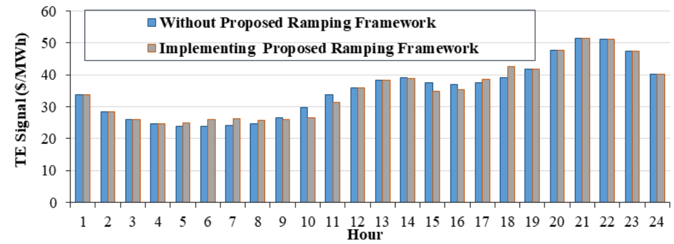

Fig. 9. TECS at the PCC of the Multi-MG and the TN (i.e. $TE_t^{DNA_0}$) with/without implementing the proposed intense-ramping management scheme.

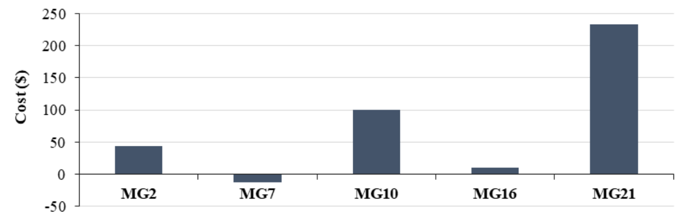

Fig. 10. The total cost of power-exchanging with the grid over the operational-horizon for each MG in the DN.

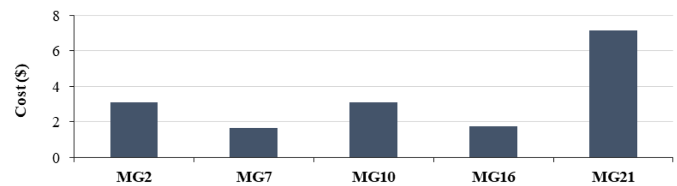

Fig. 11. The total cost associated with $TE_t^{Ramp-DNA_0}$ for each MG in the DN.

Furthermore, the changes in the power-exchanging of the MGs 10 and 21 with the DN in the case of implementing the proposed intense-ramping management technique are investigated in Fig. 12, which shows that the scheme enables the utilities to exploit the MGs scheduling without compromising their privacy. Note that the sum of power-output/consumption by each kinds of resources in MGs 10 and 21 are also presented in Figs. 13- 14. Moreover, the changes in the LRSs scheduling in MG 10 in the case of implementing the proposed intense-ramping management scheme are studied in Figs. 15-17, which show the ability of the developed approach in exploiting the independently operated LRSs scheduling. Note that, the developed algorithm in this paper enables the decentralized operation and intense-ramping management in Multi-MG DNs, which facilitates its flexibility and security.

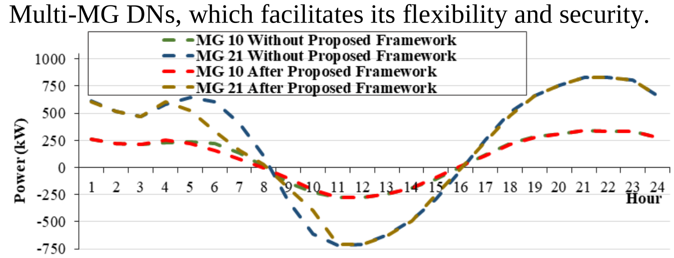

Fig. 12. Requesting power of the MGs 10 and 21 during the operational-horizon with/without implementing the proposed scheme.

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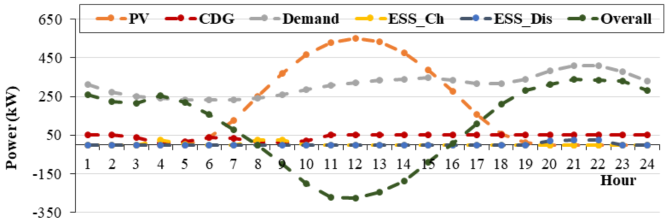

Fig. 13. Detailed scheduling in MG 10 during the operational-horizon while implementing the proposed scheme.

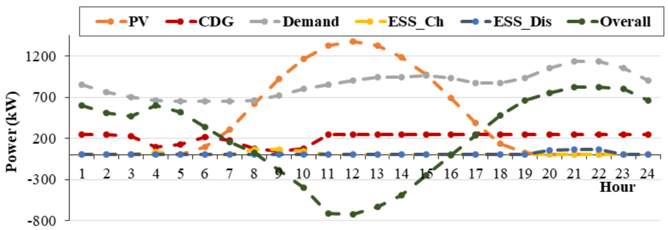

Fig. 14. Detailed scheduling in MG 21 during the operational-horizon while implementing the proposed scheme.

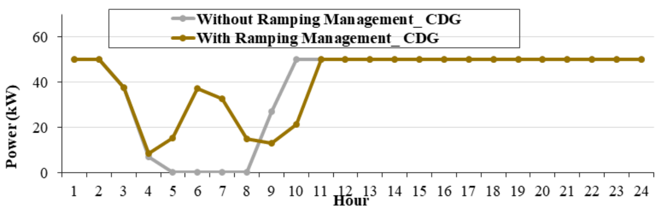

Fig. 15. Scheduling of CDGs in MG 10 during the operational-horizon with/without implementing the proposed intense-ramping management scheme.

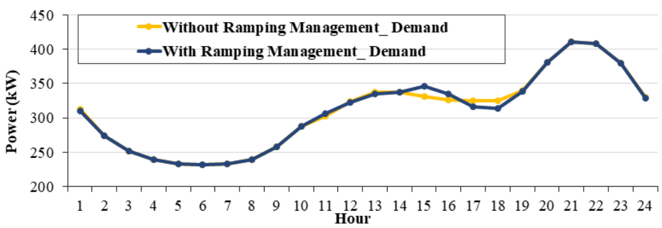

Fig. 16. Scheduling of load demands in MG 10 during the operational-horizon with/without implementing the proposed scheme.

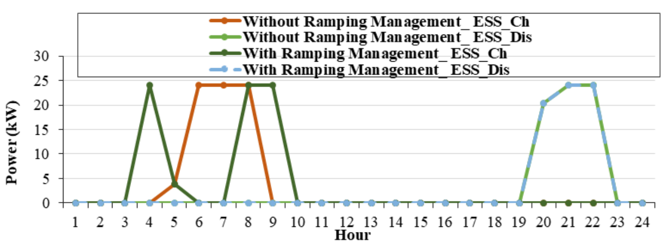

Fig. 17. Scheduling of ESSs in MG 10 during the operational-horizon with/without implementing the proposed intense-ramping management scheme.

B. 123-bus Test System

The proposed scheme is also applied on a 123-bus test system which is structure as a multi-MG DN shown in Fig. 18. Each MG operates its resources while cooperating in minimizing the intense-ramping in the DN.

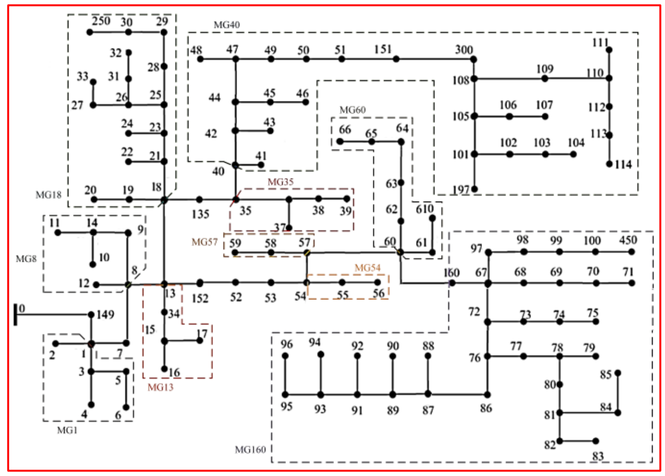

Fig.18. The considered multi-MG DN.

In this study, we consider the ramping-up/down constraints (i.e. 1400 kW/h) in the Multi-MG DN. The ramping associated with the DN's net-load at hours 1, 9, and 18 per-iteration of running the proposed algorithm are shown in Fig. 19. Respectively, the proposed scheme could appropriately limit the ramping of the system within the considered constraint.

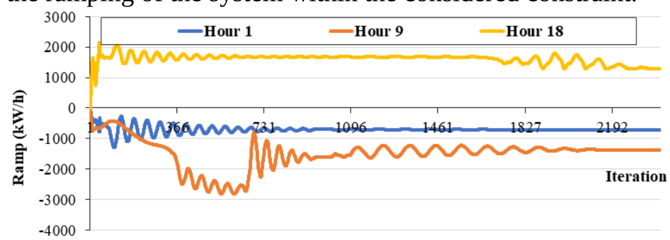

Fig. 19. Ramping of the DN's net-load at hours 1, 9, and 18 per-iteration.

As mentioned, the $TE_t^{DNA_0}$ would be updated to address the intense-ramping in the DN. Respectively, the value of $TE_t^{DNA_0}$ per iteration of running the proposed scheme at hours 1, 9, and 18 is shown in Fig. 20. Based on the results, the TE signal at hours 9 and 18 is updated to address the intense ramping; however, the $TE_t^{DNA_0}$ remains constant at hour 1 that does not violate the ramping constraint. In other words, $TE_t^{DNA_0}$ is exploited to settle the intense-ramping in the Multi-MG DN in an iterative-manner. The converged value of the $TE_t^{DNA_0}$ as well as its value without implementing the proposed intense-ramping management scheme (i.e. LMP_t) are presented in Fig. 21.

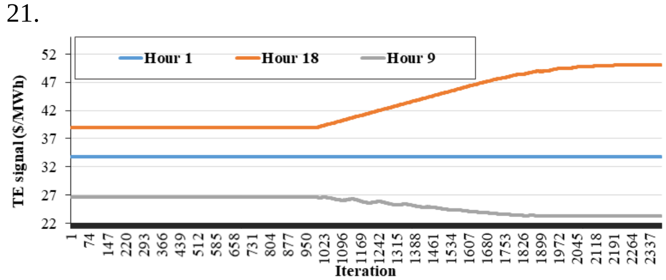

Fig. 20. $TE_t^{DNA_0}$ at hours 1, 9, and 18 per-iteration.

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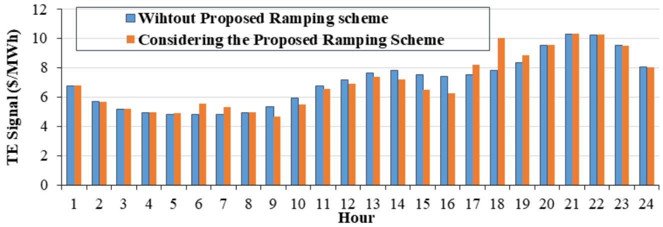

Fig. 21. TECS (i.e. $TE_t^{DNA_0}$) with/without implementing the proposed intense-ramping management scheme.

The power-exchanging of the Multi-MG DN and the TN per-iteration of running the ADMM-algorithm at hours 1, 9 ,and 18 is presented in Fig. 22. The results show the performance of the system while providing the operational service address the intense-ramping issue. Finally, the converged results associated with the power exchanging of the test system and the TN during the operational horizon with/without implementing the proposed intense-ramping scheme are shown in Fig. 23. The obtained results in this section show that the developed approach would facilitate the distributed operation of the Multi-MG DN, while addressing the ramping constraints. Note that the proposed scheme improves the reliability and flexibility of the system by addressing the potential intense-ramping issue in Multi-MG DNs with high penetration of RESs as well as its associated power price spikes, which eventually facilitates installation of independently operated energy sources in the DN.

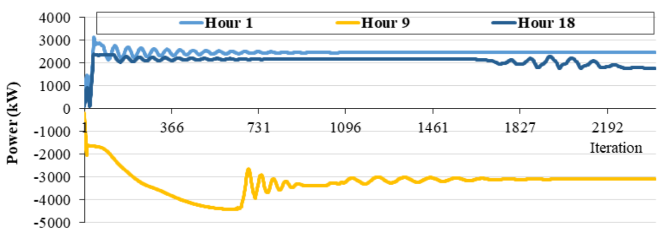

Fig. 22. Power-exchanging of the Multi-MG DN and the TN per-iteration of running the ADMM-algorithm.

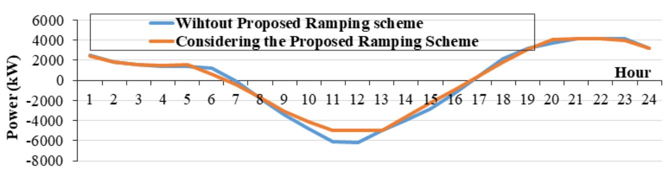

Fig. 23. Power-exchanging of the Multi-MG DN and the TN with/without implementing the proposed intense-ramping management scheme.

IV. Discussion

As discussed in the proposed formulation, the MCUs would consider stochastic-programming to model the local resources uncertainty (e.g. RESs). In this regard, as the power-output by RESs are related to the meteorological characteristics, the MCUs could consider correlation between the power-output of RESs to generate their respective operational scenarios for conducting the optimization problem. This concept could also be expanded for other resources. In this regard, control units could employ Copula functions to demonstrate the correlation between the stochastic variables in their systems. Respectively, the proposed approach in [7] could be utilized to develop the operational scenario for implementing the proposed scheme. Nevertheless, it is noteworthy that, in this paper, the developed scheme for intense-ramping management is formed in a general manner, where the operational optimization conducted in MGs as well as the uncertainty modeling would not change the proposed procedure for updating the TECS associated with the intense-ramping issue.

V. Conclusion

This paper strives to provide an efficient decentralized intense-ramping management scheme for operation of multi-MG DNs. In this regard, ADMM-algorithm is deployed for distributed operation of the DNs, while, optimizing the RESs/LRSs scheduling in each MG is directed independently. Furthermore, stochastic programming and CVaR index are employed in the operational scheduling of MGs to deal with the RESs uncertainty. Note that, in this paper, a procedure is developed based on the ADMM-algorithm in order to calculate the TECSs associated with each of MGs to optimize their resource scheduling. In this context, the developed TE-based approach enables the DSO to change the resource scheduling of MGs in order to settle the intense-ramping-up/down in the net-load of the Multi-MG DN. As a result, the proposed TECSs model the price of the power-exchanging with the TN, power-loss, and the intense-ramping issue in the DN. Respectively, the proposed scheme facilitates intense-ramping management in DNs while addressing the privacy concerns of LRSs. Finally, the planned scheme is simulated on 37-bus and 123-bus DNs to study its effectiveness in intense-ramping management in DNs, which shows its application in improving the reliability and flexibility of the system.

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