Incentive-Based Flexible-Ramp-Up Management in Multi-Microgrid Distribution Systems

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***Abstract*—The increasing integration of renewable energy resources (RERs) and the expansion of multi-microgrid systems have transformed the operational condition of power systems. Respectively, the high-amount installation of RERs could result in the volatile changes exchanged-power of local systems, when their power generation drops suddenly. Nevertheless, the available ramp-up power for compensating the supply-demand gap in the power system could be limited due to the operational constraints of power networks and generation units. As a result, in this article, a transactive flexible-ramp-up-management-mechanism is offered in order to enable system operators to exploit the scheduling of microgrid systems with the aim of ensuring power requirements of the multi-microgrid system meet the flexible-ramp-up constraints. Therefore, the mechanism would result in the efficient rescheduling of local flexible resources in a multi-microgrid distribution system in order to address the ramp-up constraints in the system. The offered mechanism limits the information exchange between microgrids and the system operator to transactive control signals and accumulated power exchanges to impede privacy concerns of independently operated entities. Lastly, the recommended mechanism is implemented on the IEEE-37-bus test system, where, its effectiveness in addressing the overall system flexible-ramp-up limitations is investigated.**

***Index Terms*—Distributed energy resources (DERs), flexibility, flexible-ramp-up, multi-microgrid systems (MMSs), renewable energy, transactive energy management (TEM).**

NOMENCLATURE

A. Sets

$\Gamma^{Conventional-DG,h}$, $\Gamma^{ESS,h}$, $\Gamma^{RER,h}$, and $\Gamma^{D,h}$ Sets of all conventional distributed generations, energy storage systems, variable renewable energy sources, and loads in microgrid h.

Γ^{MG} Set of all microgrids in the multi-microgrid system.

t, T Index for time step and overall scheduling horizon.

h Index for microgrid.

Δt Duration of each time interval.

B. Constants

$PN_{h,i,t}^{RER}$ Power production of RER i in the hth microgrid at t.

$\widehat{PN_{h,i,t}^{RER}}$ Forecasted power generation by RER i in the hth microgrid at t.

$\Delta PN_{h,i,t}^{RER}$ Maximum forecast error of power generation by RER i in the hth microgrid at t.

$PN_{h,i}^{max,Conventional-DG}$, $PN_{h,i}^{min,Conventional-DG}$ Maximum and minimum capacity of conventional distributed generation i in the hth microgrid.

$RU_{h,i}^{Conventional-DG,\max}$, $RD_{h,i}^{Conventional-DG,\max}$ Maximum ramp-up and ramp-down of conventional distributed generation $i$in the hth microgrid.

$PN_{h,i}^{dch,max}$, $PN_{h,i}^{ch,max}$ Maximum possible discharging/charging of storage unit i in the hth microgrid.

$\eta_{h,i}^{ch}$, $\eta_{h,i}^{dch}$ Efficiency of power charging/discharging of storage unit i in the hth microgrid.

$E_{h,i}^{\max}$, $E_{h,i}^{\min}$ Maximum/minimum boundaries of the energy capacity of the storage unit i in the hth microgrid.

$LN_{h,i,t}^{non-adj}$ Non-adjustable load i in the hth microgrid at t.

$LN_{h,i,t}^{\max,adj}$, $LN_{h,i,t}^{\min,adj}$ Maximum/minimum boundaries of adjustable load i in the hth microgrid at t.

$NE_{h,i}^{adj}$ Considered required energy consumption by the adjustable load i in the hth microgrid.

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α, β	Starting and end points of the time period to calculate the energy consumption of the adjustable load.
$PS_t^{Ramp-up}$	Ramp-up constraint at *t*.
LMP_t	Price of power supplied by the main grid at *t*.
ρ	Penalty factor.

C. Variables

PS_t^{MMS}	Power request of the multi-microgrid system from the main grid at *t*.
$PS_{h,t}$	Power request of microgrid h from the main grid at *t*.
$PN_{h,i,t}^{Conventional-DG}$	Output power of conventional distributed generation i in the *h*th microgrid at *t*.
$PN_{h,i,t}^{ch}$, $PN_{h,i,t}^{dch}$	Amount of power charging/discharging of storage unit i in the *h*th microgrid at *t*.
$LSN_{h,i,t}$	Total shedding load i in the *h*th microgrid at *t*.
$LN_{h,i,t}$	Load i in the *h*th microgrid at *t*.
$LN_{h,i,t}^{adj}$	Adjustable load i in the *h*th microgrid at *t*.
$E_{h,i,t}$	Amount of energy stored in the storage unit i of *h*th microgrid at *t*.
$\alpha_{h,i}^{ch}$, $\alpha_{h,i}^{dch}$	Binary variables representing the charging/discharging of storage unit i in the *h*th microgrid.

D. Functions

$C_{h,i}^{LSN}$	Cost of shedding load i in *h*th microgrid.
$\mathrm{C}_{h,i}^{Conventional-DG}$	Generation cost of conventional distributed generation unit $i$of the microgrid *h*.
$\mathrm{C}_{h,i}^{RER}$	Operational cost of renewable energy unit i in the microgrid *h*.

I. Introduction

INTEGRATION of distributed energy resources (DERs) in distribution systems has significantly increased in recent years due to governmental, environmental, and economical inspirations. However, this has also initiated some new challenges in modern power systems, which should be taken into consideration by utilities in the planning and operational practices of the system. Accordingly, one of the matters that emerged by the high-amount installation of these resources would be the lack of flexible-ramp-up to meet the demand-supply gap in some hours of a day, when the power production of renewable energy resources (RERs) drops off suddenly [1], [2].

The intermittent and the stochastic nature of RERs (i.e., photovoltaic units (PVs) and wind turbines) resulted from their dependence on environmental features like solar-irradiance and wind-speed could cause abrupt changes in the exchanged-power of the system when the output power of RERs suddenly drops. In this context, based on the volatile-ramp-up in the California network, the decrease in the power production of PVs and the increase in load demands in the evening time periods could result in a considerable ramp-up in the exchanged-power of the system [3]. As a result, the energy systems in this operational condition would require a significant amount of flexible-ramp-up to impede the increasing gap between supply and demand [4].

Traditionally, fast-ramping bulk power generation resources are the primary sources that enable the system operators to provide the desired flexible-ramp-up capacity in the power grids. These generation units are connected to the transmission system and operated by the transmission system operator, which would limit the available flexibility capacity to impede the power mismatch in distribution networks due to the probable transmission system congestions. Moreover, decreasing investment and operational costs of RERs along with the investing requirements, construction time, and operational costs associated with bulk power generation resources have limited the available flexible-ramp-up that could be provided by generation resources connected to the transmission system [5], [6]. That is why, in modern power systems, distribution networks should be operated in a way that the variation in the exchanged-power of the system meets the available flexible-ramp-up that could be provided by the transmission system. Accordingly, local resources should be economically directed by the local coordinator entities to decrease the amount of flexible-ramp-up capacity that is required to be supplied by the transmission system. This idea is also aligned with the zonal flexibility service procurement concept, which aims to activate flexibility service in local areas of power systems [5], [7], [8]. In this regard, efficient scheduling of local flexible units should be taken into consideration to provide the flexibility capacity requirements in the grids with the high-amount installation of RERs.

As mentioned earlier, system operators would be dependent on local flexible resources to handle the volatile-ramp-up in modern power systems; however, access of distribution network operators (DNOs) on the operation of these resources have been restricted by the introduction of multi-microgrid architectures in distribution networks. Note that the complexity of collecting, assessment, and optimization of significant extents of measured data in distribution networks have resulted in the transformation of conventional distribution networks into multi-microgrid systems (MMSs). In this structure, microgrids could be organized and run independently with less data interaction to one another in order to secure the MMS from probable cyber-attacks. Despite these advantages, coordination of the operation of microgrids would be a challenge that could lead to low security of supply in distribution networks. In this regard, in recent years, various studies have been conducted in order to offer practical distributed control mechanisms to direct MMSs.

Recently, the transactive control model is utilized to offer new control mechanisms to be implemented in multi-agent systems [9]. Transactive energy management (TEM) model supports the contribution of local resources in the operation of power systems using a set of economic-based procedures [10],

[11]. Instead of specifying a central entity that could control all flexible energy resources as offered in [12] and [13], the decisions in transactive procedures are made based on values [14], i.e., economic transactions. Additionally, the full information regarding the preferences and characteristics of local resources required for the implementation of the method offered in [15] would not be necessary for a well-organized TEM mechanism. The TEM control technique is a promising mechanism that could incentivize the contribution of local resources in the operation of distribution networks, while facilitating the incorporation of autonomous agents that are reluctant to give up full control to the system operator [16]. In this regard, TEM-based arrangements could be established to coordinate the flexible resources in a multi-agent system, which would result in the system's security and reliability improvement.

Several pilot projects have been conducted for coordination of responsive resources in a smart grid, which show the application of the TEM concept to incentivize flexible resources to change their operational states. These mechanisms facilitate providing flexibility requirements without raising privacy concerns. TEM procedure is taken into account in REnnovates Project [17] to activate the contribution of flexible residential demands in the grid congestion alleviation process. In this project, the smart grid field test provides communication between DNO/aggregators with end-user prosumers equipped with PV units. In [17], the presented technique considers the decrease and increase of residential load demands to contribute to the controlling of the distribution network. This field study shows the effectiveness of TEM concept in activating flexibility service from local prosumers. Moreover, the TEM concept is taken into account in [18] in order to determine the power transactions among microgrids in MMSs. The authors in [19] have offered an energy controlling mechanism based on the TEM concept for commercial parking lots equipped with charging systems and rooftop PV systems in order to balance the demand and supply in the system. Furthermore, in [20], a TEM-based mechanism is offered in order to direct the DERs in distribution networks. Moreover, an iterative TEM model is offered in [21] in order to direct the power requests of microgrids in a community of microgrids. In this article, the operational controlling is modeled by a two-stage mechanism (i.e., microgrids-level and community-level) in order to efficiently activate demand response service in the system. Note that the offered techniques in [18]–[21] show the effectiveness and ability of the TEM concept in order to exploit the scheduling of independent entities in an energy system to address the designated operational objectives.

Application of local resources in a microgrid to reduce the volatile-ramp in a network has been investigated in [22] and [23]. In these papers, the microgrid's day-ahead operational optimization is conducted while taking into account the ramp-constraints determined by the DNO. However, the scheduling of flexible resources is centrally conducted and the application of the offered methodologies in MMSs is not investigated. Moghaddam *et al.* [1] propose a dynamic pricing mechanism for charging stations of electric vehicles to decrease their plausible effects on the volatile-ramp-up in the system. This study demonstrates the importance of dynamic pricing in impeding the volatile-ramp-up in distribution networks. Moreover, utilizing the flexibility capacity of local resources in microgrids in order to address the volatile-ramp in an MMS is investigated in [24]–[27]. Nevertheless, the offered models in [24]–[27] are relied on transferring the information associated with the operational characteristics of independent local resources to the central operator, which could cause privacy risks. It is noteworthy that the studies conducted on [22]–[28] show the key role that local flexible resources could play in impeding the volatile-ramp-up in distribution networks.

Despite several research works, which have been conducted in the context of the efficient operation of distribution networks, flexibility service activation of local resources [11], [16], [17], and ramp-up minimization [1], [4], [22]–[24]; to the best of the authors' knowledge, flexible-ramp-up controlling considering distributed nature of MMSs has not yet been thoroughly investigated in the previously offered methodologies. Motivated by the aforementioned facts, this article aims to propose a novel transactive technique to facilitate the contribution of local flexible resources directed by independent microgrids in decreasing the load variability seen by the transmission system. In other words, this article aims to minimize the volatile-ramp-up in the MMS, while taking into account its distributed nature. This could provide flexible-ramp-up service for the system operator and so would finally result in the system's security and reliability improvement. In this regard, while RERs specifically PV units are increasingly being integrated into distribution networks, local flexible resources (i.e., storage units, dispatchable generation units, and flexible demands) could enable the DNOs to impede volatile-ramp-up in the system. The offered mechanism enables the DNO to efficiently determine a transactive control signal to incentivize the contribution of local flexible resources in impeding the volatile-ramp-up in the system. Based on the offered mechanism, microgrids could take different agendas to schedule their resources, while the DNO strives to exploit their operational points to fulfill the ramp-up constraints. Furthermore, the robust optimization is taken into account by the microgrids to address the uncertainties associated with the operation of RERs. In this regard, the robust optimization algorithm aims to solve the local resources scheduling problem in each microgrid taking into consideration the worst-case realization of uncertain parameters.

Based upon the above-mentioned discussions, the offered TEM-based mechanism facilitates the contribution of the independently controlled local resources in providing the flexible-ramp-up service, which aims to address the volatile-ramp-up in MMSs. In this respect, the offered mechanism enables the DNOs to efficiently update the energy price as a TEM signal in order to motivate the microgrids/aggregators to reschedule their local resources. Since this control signal is based on an economic transition in the energy price, the offered mechanism could be easily adopted in the current resource scheduling optimization algorithms conducted by each entity. Moreover, the control signal could be transmitted to end-users to incentivize them to change their operational scheduling, which would decrease the operational risk of mediator control entities. Furthermore, it is noteworthy that the privacy and independence of the end-users are ensured in the offered mechanism by limiting the information exchange between the entities to accumulated energy requests and price signals. Moreover, the robust optimization is taken into account by independently operated microgrids to schedule

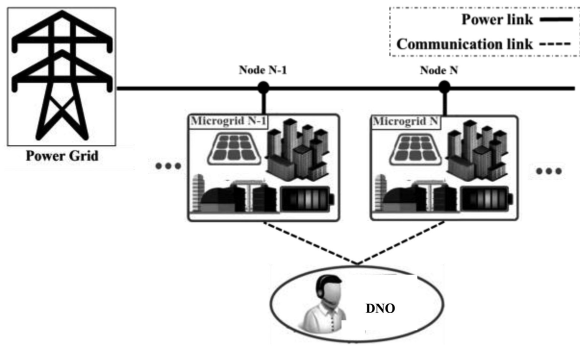

Fig. 1. Simple modeling of the considered MMS.

their respective local resources considering uncertainties associated with RERs. In this regard, the perspective of microgrids' operators toward risk would affect the ramp-up in the MMS and so influence the concluding TE control signals. Finally, it is noteworthy that the offered procedure for determining the TEM signal associated with activating ramp-up service in the MMSs could be straightforwardly adapted in controlling techniques offered in previous research works in order to ensure the ramp-up constraints of the MMS are addressed.

In this article, the MMS modeling and the offered technique for incentivizing microgrids to cooperate in the ramp-up minimization arrangement will be discussed in Section II-A and B, respectively. In this regard, interactions of microgrids with the DNO as well as the offered TEM mechanism are discussed in these sections. Furthermore, a mathematical formulation for providing the TEM signals in order to enable flexibility-based decentralized control of the MMS is offered and described in Section II-C and D. This formulation provides the mathematical modeling of the offered technique in Section II-B. Moreover, robust-based scheduling of local resources to address the uncertainty of RERs in a microgrid is offered in Section III-E. Finally, the results of implementing the offered mechanism on a 37-bus MMS and its effectiveness are demonstrated and analyzed in Section III, followed by the discussion and conclusion in Sections IV and V, respectively.

II. Methodology

A. MMS Modeling

Regarding the current trend, a distribution system could be modeled as an MMS, in which each microgrid is responsible for operational control of its local resources/demands. In this structure, the microgrid's control operator (MCO) performs as a mediator that could service the utility to operate the MMS (i.e., ramp-up minimization), while pursuing its objectives, i.e., cost minimization. In this regard, this MMS could address the privacy concerns at the expense of complicating the control strategies employed in distribution systems.

In this article, it is considered that a distribution system consists of a DNO as the system coordinator and *N* microgrids as independent entities scheduling their local resources, which is represented in Fig. 1. In this regard, microgrids independently schedule their local resources and their power exchange with the main grid to maximize their social welfare, while DNO is responsible for the efficient controlling of the MMS in a way that the variation in the exchanged-power of the MMS meets the flexibility ramp-up constraints.

B. Transactive Flexible-Ramp-Up Oriented Scheduling Framework

As noted earlier, DNO has to deploy a mechanism with the aim of motivating autonomously operated microgrids to modify their operational points in order to impede the volatile-ramp-up in the MMS. In the MMS, each microgrid optimizes its resource scheduling considering the price of energy exchange with the main grid designated as distribution local marginal price (DLMP) as well as its local resources operational constraints. In this regard, DLMP could be considered as a TEM signal that affects the resource scheduling conducted by each microgrid.

In order to conduct the operational controlling of an MMS, in a step-wise procedure, DNO determines the DLMP associated with each microgrid taking into account the price of energy exchange with the power grid, i.e., locational marginal price (LMP), and power losses in the distribution network. This iterative procedure is called the operational controlling of the MMS. After convergence of the preliminary operational controlling procedure, DNO revises the hourly costs of purchasing energy from the power grid (i.e., LMP) based on the ramp-up in the MMS. In this regard, the operational controlling procedure would be reconducted based on the updated LMP called LMP*. Subsequently, microgrids rerun their day-ahead operational optimization scheduling considering the revised energy prices and the determined requested power would be sent back to the DNO. This procedure would be continued until the targeted ramp-up limitations are justified. Consequently, the local resources would be efficiently directed in a way that the variation in the exchanged-power of the MMS at each hour meets the available flexible-ramp-up that could be provided by the power grid. As mentioned earlier, the offered procedure would be conducted for exploiting the preliminary scheduling of the local resources; that is why the power losses and ramp-up constraints are considered in the offered mechanism. Nevertheless, the offered mechanism for determining the TEM signals associated with ramp-up constraints is merely dependent on the energy costs and power exchanges at the common coupling point (CCP) of the MMS and the upper-level network, which facilitates its application in different mechanisms with the aim of decentralized operational controlling of MMSs.

The offered technique provides the possibility for the DNO to optimally direct local resources without any information exposure threat, which will result in a more secure and flexible system operation. The offered procedure is described in Fig. 2. It is noteworthy that this technique could be applied to similar systems with multi-agent arrangements to activate the flexibility service from each agent in order to impede the volatile-ramp-up in the MMS. In this respect, considering the existence of communication links and contracts with residential loads as considered in [17], the offered technique could be implemented to activate the end-users flexibility.

On one hand, the method for flexible-ramp-up minimization merely utilizes energy price as a control signal; therefore, the offered mechanism could easily be adopted in other mechanisms

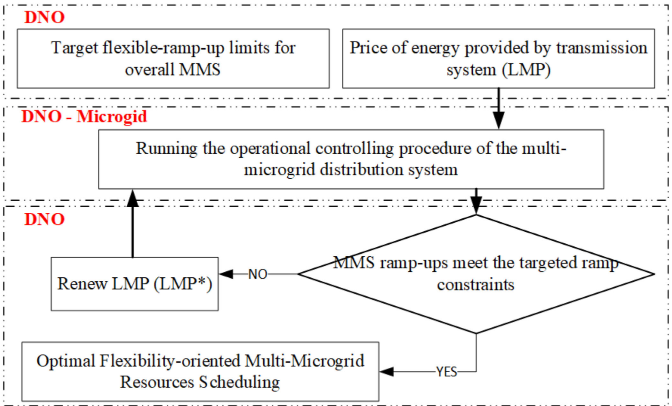

Fig. 2. Offered TEM-based flexible-ramp-up controlling mechanism in an MMS.

designated for the operational controlling of MMSs. On the other hand, the offered mechanism is independent of the operational optimization conducted by each microgrid. Consequently, the offered methodology could easily be combined with other evolved mechanisms for the operational scheduling of independent microgrids. The process of devising the TEM signals as well as the operational controlling procedure of MMSs is thoroughly discussed in the following sections.

C. Model Formulation

A simple centralized optimization model of resource scheduling in an MMS with the aim of minimizing the operational costs of microgrids is shown in (1)–(13).

$$\sum_{i\in\Gamma^{Conventional-DG,h}} PN^{Convnetional-DG}_{h,i,t} + \sum_{i\in\Gamma^{RER,h}} PN^{RER}_{h,i,t} + \sum_{i\in\Gamma^{ESS,h}} PN^{dch}_{h,i,t} + PS_{h,t} + LSN_{h,i,t} = \sum_{i\in\Gamma^{D,h}} LN_{h,i,t} + \sum_{i\in\Gamma^{ESS,h}} PN^{ch}_{h,i,t}, \mathrm{h}\in\Gamma^{MG}, t\in T \tag{2}$$

$$PN^{min,Conventional-DG}_{h,i} \leq PN^{Conventional-DG}_{h.i,t} \leq PN^{max,Conventional-DG}_{h,i}, h\in\Gamma^{MG}, i\in\Gamma^{Conventional-DG,h}, t\in T \tag{3}$$

$$lPN^{Conventional-DG}_{h,i,t} - PN^{Conventional-DG}_{h,i,t-1} \leq RU^{Conventional-DG,\max}_{h,i}, \in\Gamma^{MG}, i\in\Gamma^{Conventional-DG,h}, t\in T \tag{4}$$

$$PN^{Conventional-DG}_{h,i,t-1} - PN^{Conventional-DG}_{h,i,t} \leq RD^{Conventional-DG,\max}_{h,i}, \mathrm{h}\in\Gamma^{MG}, i\in\Gamma^{Conventional-DG,h}, t\in T \tag{5}$$

$$0 \leq PN^{dch}_{h,i,t} \leq PN^{dch,max}_{h,i}\cdot\alpha^{dch,max}_{h,i,t}, \mathrm{h}\in\Gamma^{MG}, i\in\Gamma^{ESS,h}, t\in T \tag{6}$$

$$0 \leq PN^{ch}_{h,i,t} \leq PN^{ch,max}_{h,i}\cdot\alpha^{ch,max}_{h,i,t}, \mathrm{h}\in\Gamma^{MG}, i\in\Gamma^{ESS,h}, t\in T \tag{7}$$

$$\alpha^{dch}_{h,i,t} + \alpha^{ch}_{h,i,t} \leq 1, \mathrm{h}\in\Gamma^{MG}, i\in\Gamma^{ESS,h}, t\in T \tag{8}$$

$$E_{h,i,t+1} = E_{h,i,t} + \begin{pmatrix} PN^{ch}_{h,i,t}.\eta^{ch}_{h,i}\cdot\Delta t \\ -\frac{PN^{dch}_{h,i,t}}{\eta^{dch}_{h,i}}\cdot\Delta t \end{pmatrix}, \mathrm{h}\in\Gamma^{MG}, i\in\Gamma^{ESS,h}, t\in T \tag{9}$$

$$E^{\min}_{h,i} \leq E_{h,i,t} \leq E^{\max}_{h,i}, \mathrm{h}\in\Gamma^{MG}, i\in\Gamma^{ESS,h}, t\in T \tag{10}$$

$$LN^{adj}_{h,i,t} + LN^{non-adj}_{h,i,t} = LN_{h,i,t}, \mathrm{h}\in\Gamma^{MG}, i\in\Gamma^{D,h}, t\in T \tag{11}$$

$$LN^{\min,adj}_{h,i,t} \leq LN^{adj}_{h,i,t} \leq LN^{\max,adj}_{h,i,t}, \mathrm{h}\in\Gamma^{MG}, i\in\Gamma^{D,h}, t\in T \tag{12}$$

$$\sum_{t\in[\alpha,\beta]} LN^{adj}_{h,i,t} = NE^{adj}_{h,i}, \mathrm{h}\in\Gamma^{MG}, i\in\Gamma^{D,h} \tag{13}$$

The objective function (1), shown at the bottom of this page, of the above-mentioned optimization formulation minimizes the total operational costs of the MMS over the operating scheduling horizon. Accordingly, the modeled operational costs include the cost of trading power with the main grid, operational costs of conventional distributed generations (conventional-DGs), costs of RERs, and the load shedding cost in each microgrid. Equation (2) models the balance of supply and demand in the MMS, in which the sum of the injected power by conventional-DGs, RERs, ESSs discharging, and the purchasing power from the main grid beside the load curtailment matches with the load demand and power charging of ESSs. The associated operational constraints of conventional-DGs are considered in (3)–(5). Constraint (3) imposes the power generation limit of each conventional-DG, while, (4) and (5) address the ramp-up and ramp-down limits, respectively. Operational limitations of ESSs are applied in (6)–(10). The operational restrictions of ESSs, while operating in the charging and discharging modes are presented in (6) and (7), accordingly. The amount of stored energy in ESSs in each time period is shown in (9), and (10)

$$\mathrm{MinCost} = \sum_{t\in T}\left(\sum_{h\in\Gamma^{MG}}\begin{pmatrix} LMP_t\cdot PS_{h,t} + \sum_{i\in\Gamma^{Conventional-DG,h}} \mathrm{C}^{Conventional-DG}_{h,i}(PN^{Conventional-DG}_{h,i,t}) \\ + \sum_{i\in\Gamma^{RER,h}} \mathrm{C}^{RER}_{h,i}(PN^{RER}_{h,i,t}) + C^{LSN}_{h,i}(LSN_{h,i,t}) \end{pmatrix}\right) \tag{1}$$

subject to (2)–(13)

imposes the capacity bounds of respective storages. Finally, (11)–(13) define the operating limits of adjustable loads.

The above-mentioned model optimizes the resource scheduling taking into account the microgrids' operational characteristics without considering overall ramp-up limitations. Therefore, the following constraints should be included in the model to ensure that the overall ramp-up requirements meet the available flexible-ramp-up that could be provided by the main grid.

$$PS_t^{MMS} = \sum_{h \in \Gamma^{MG}} PS_{h,t}, \mathrm{h} \in \Gamma^{MG}, t \in T \quad (14)$$

$$PS_t^{MMS} - PS_{t-1}^{MMS} \leq PS_t^{Ramp-up}, \mathrm{h} \in \Gamma^{MG}, t \in T \quad (15)$$

The above-mentioned optimization model is considered to be run by each microgrid, independently. However, this constraint links the optimization procedures of microgrids. In this regard, a novel technique is developed in this article to decouple the optimization procedure to be conducted by each microgrid, while considering the flexible-ramp-up constraints. This constraint is included in the objective function using a Lagrange multiplier (λ_t) shown in (16) at the bottom of this page.

Regarding the new formulation, in case the ramp-up constraint is violated, adjusting λ_t would be a potential way for the DNO in order to motivate microgrids to reschedule their respective flexible resources. In this regard, in finite steps, the procedure would result in a new operational point that meets the flexible-ramp-up constraint. The new objective function could be arranged as shown in (17) at the bottom of this page.

In this objective function, considering λ_t as a parameter defined by the DNO, the term $\lambda_t \times PS_t^{Ramp-up}$incorporates constant parameters. Consequently, the term $\lambda_t \times PS_t^{Ramp-up}$ could be omitted from the objective function as shown in (18) at the bottom of this page without affecting the final scheduling. In a decentralized mechanism, the offered procedure aims to dismantle the ramp-up controlling of the MMS from the scheduling optimization conducted by each microgrid. In this respect, λ_t would be a parameter that enables DNO to exploit operational rescheduling of microgrids to address the ramp-up constraint.

In order to provide a TEM signal, the terms associated with variables $PS_{h,t}$and $PS_{h,t-1}$in the objective function (18) at time periods *t* and *t*+*1* could be rearranged as follows:

$$\begin{aligned}&(LMP_t + \lambda_t) \times PS_{h,t} - \lambda_t \times PS_{h,t-1} + (LMP_{t+1} + \lambda_{t+1})\\ &\quad \times PS_{h,t+1} - \lambda_{t+1} \times PS_{h,t}\\ &= (LMP_t + \lambda_t - \lambda_{t+1}) \times PS_{h,t} - \lambda_t\\ &\quad \times PS_{h,t-1}(LMP_{t+1} + \lambda_{t+1}) \times PS_{h,t+1}. \quad (19)\end{aligned}$$

Regarding the above-mentioned discussions, the objective function could be rearranged based on (19) and the resulted optimization model could be defined as shown in (20) at the bottom of this page.

The objective function and the associated constraints of this optimization model are not coupled between microgrids; therefore, the optimization could be conducted autonomously by each microgrid to schedule its resources while fulfilling the MMS ramp-up constraints. It is noteworthy that the offered mechanism is not dependent on the type of flexible resources, which facilitates its utilization for activating flexible-ramp-up service from independent responsive entities.

Regarding the optimization model, λ_t could be adjusted as shown in (21) based on the difference between the overall MMS requested ramp-up and the targeted flexible-ramp-up in order to incentivize the microgrids to reschedule their local flexible resources. It is noteworthy that λ_t would merely be updated

$$\mathrm{Cost} = \sum_{t \in T} \left(\begin{array}{l} \lambda_t \times (PS_t^{MMS} - PS_{t-1}^{MMS} - PS_t^{Ramp-up}) + \\ \sum\limits_{h \in \Gamma^{MG}} \left(\begin{array}{l} LMP_t \cdot PS_{h,t} + \\ \sum\limits_{i \in \Gamma^{Conventional-DG,h}} \mathrm{C}_{h,i}^{Conventional-DG}(PN_{h,i,t}^{Conventional-DG}) \\ + \sum\limits_{i \in \Gamma^{RER,h}} \mathrm{C}_{h,i}^{RER}(PN_{h,i,t}^{RER}) + C_{h,i}^{LSN}(LSN_{h,i,t}) \end{array} \right) \end{array} \right) \quad (16)$$

$$\mathrm{Cost} = \sum_{t \in T} \left(\begin{array}{l} -\lambda_t \times PM_t^{Ramp-up} + \\ \sum\limits_{h \in \Gamma^{MG}} \left(\begin{array}{l} (LMP_t + \lambda_t) \times PS_{h,t} - \lambda_t \times PS_{h,t-1} + \\ \sum\limits_{i \in \Gamma^{Conventional-DG,h}} \mathrm{C}_{h,i}^{Conventional-DG}(PN_{h,i,t}^{Conventional-DG}) \\ + \sum\limits_{i \in \Gamma^{RER,h}} \mathrm{C}_{h,i}^{RER}(PN_{h,i,t}^{RER}) + C_{h,i}^{LSN}(LSN_{h,i,t}) \end{array} \right) \end{array} \right) \quad (17)$$

$$\mathrm{Cost} = \sum_{h \in \Gamma^{MG}} \left(\sum_{t \in T} \left(\begin{array}{l} (LMP_t + \lambda_t) \times PS_{h,t} - \lambda_t \times PS_{h,t-1} + \\ \sum\limits_{i \in \Gamma^{Conventional-DG,h}} \mathrm{C}_{h,i}^{Conventional-DG}(PN_{h,i,t}^{Conventional-DG}) \\ + \sum\limits_{i \in \Gamma^{RER,h}} \mathrm{C}_{h,i}^{RER}(PN_{h,i,t}^{RER}) + C_{h,i}^{LSN}(LSN_{h,i,t}) \end{array} \right) \right) \quad (18)$$

$$\begin{aligned}&\mathrm{MinCost} = \sum_{h \in \Gamma^{MG}} \left(\sum_{t \in T} \left(\begin{array}{l} (LMP_t + \lambda_t - \lambda_{t+1}) \times PS_{h,t} + \\ \sum\limits_{i \in \Gamma^{Conventional-DG,h}} \mathrm{C}_{h,i}^{Conventional-DG}(PN_{h,i,t}^{Conventional-DG}) \\ + \sum\limits_{i \in \Gamma^{RER,h}} \mathrm{C}_{h,i}^{RER}(PN_{h,i,t}^{RER}) + C_{h,i}^{LSN}(LSN_{h,i,t}) \end{array} \right) \right)\\ &\text{subject to (2)–(13)} \quad (20)\end{aligned}$$

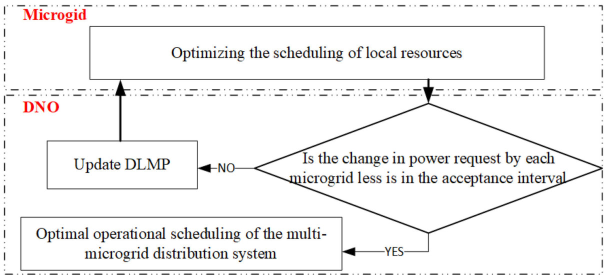

Fig. 3. Offered operational controlling procedure for MMSs.

based on (21) in cases that the ramp-up constraint is violated. However, at scheduling time intervals that the requested ramp-up is less than the ramp-up constraint, λ_t is considered as zero, which means the ramp-up constraint is not activated in the optimization.

$$\lambda_t^{new} = \lambda_t^{old} + \rho \times \left((PS_t - PS_{t-1}) - PS_t^{Ramp-up} \right) \quad (21)$$

In this regard, in the offered formulation, microgrids autonomously optimize resource scheduling, while analysis of the overall MMS flexibility constraint is conducted by DNO. Moreover, the term $\lambda_t - \lambda_{t+1}$ is a coefficient of the $PS_{h,t}$ similar to LMP_t; consequently, it could be considered that in each step the price of exchanging energy with the power grid is updated by the DNO. Accordingly, the offered technique, as shown in Fig. 3, is offered based upon this assumption that the price of exchanging energy with the power grid (i.e., LMP∗) is updated in each step as follows:

$$LMP_t^* = LMP_t + \lambda_t^{new} - \lambda_{t+1}^{new}. \quad (22)$$

Based on the obtained optimization model, at the time interval that the ramp-up constraint of the MMS is violated, increasing the energy price as a TEM signal motivates the entities to decrease their power consumption. Additionally, the energy price of the previous time interval is decreased with the aim of incentivizing the transition of energy consumption to this time period, which would increase the requested power at this time period and finally result in decreasing the ramp-up in the MMS. In this section, the TEM signals regarding the ramp-up constraints in the MMS are determined without considering the network modeling. In the following section, without loss of generality, the DLMP concept is taken into consideration to model the power losses associated with the distribution grid.

D. Operational Procedure of MMSs

As mentioned earlier, while each microgrid schedules its resources considering the price of exchanging the energy with the grid; DNO is responsible for coordinating the operation of the MMS. In this regard, the announced energy prices (i.e., DLMP) to each microgrid should also model the power losses associated with the power consumption/generation by each microgrid. Consequently, as shown in Fig. 3, it is considered that the announced DLMP would iteratively be updated to address the power losses in the distribution network. Finally, the operational controlling procedure of the MMS would be completed at the step that the proportional changes in the requested power by microgrids lay in a defined interval.

In order to update the DLMP in each step, DNO would first run the load-flow program [29] based on the received energy requests from microgrids to determine the power flow in each distribution line. In this regard, considering the radial operation of distribution networks, DLMP associated with each microgrid could be estimated utilizing the following formulation [30]:

$$DLMP_i = DLMP_j + DLMP_j \frac{\Delta PLoss_{i,j}}{\Delta P_{i,j}} \quad (23)$$

where *i* and *j* are the neighbor nodes of the MMS, which could present the CCP between the distribution grid and the power grid as well as the CCP of microgrids and the distribution network. Moreover, $\Delta PLoss_{i,j}/\Delta P_{i,j}$ represents the change in the power losses in the line between nodes *i* and *j,* while a marginal power increase is considered at the power request. In this regard, $PLoss_{i,j}$ and $\Delta PLoss_{i,j}$ by considering the resistance of the line between *i* and *j* (i.e., $r_{i,j}$) and the voltage of node *i* (i.e., V_i) could be estimated as follows:

$$PLoss_{i,j} = \frac{r_{i,j}(P_{i,j}^2 + Q_{i,j}^2)}{V_i^2} \quad (24)$$

$$\Delta PLoss_{i,j}|_{P_{i,j} \to P_{i,j} + \Delta P_{i,j}} = \frac{2r_{i,j}P_{i,j}\Delta P_{i,j}}{V_i^2}. \quad (25)$$

Consequently, by reformulating (25), the term $\Delta PLoss_{i,j}/\Delta P_{i,j}$ could be determined as follows:

$$\frac{\Delta PLoss_{i,j}}{\Delta P_{i,j}} = \frac{2r_{i,j}P_{i,j}}{V_i^2}. \quad (26)$$

In this regard, considering the LMP at the CCP of the distribution grid and the power grid, DLMP associated with all the nodes of the radially operated grid could be determined based on (23). In this regard, considering the updating procedure of LMP∗ for addressing the volatile-ramp-up in (22), DLMP associated with energy requests by each microgrid would also be updated. In other words, the LMP∗ as the price of power exchanges at the CCP of the distribution and transmission systems would be determined in (22), while the price of energy transactions at each node of the distribution network is defined in (23) in order to model the distribution grid's power losses in the offered ramp-up controlling mechanism. Consequently, the offered mechanism would finally enable the DNO to activate flexible-ramp-up services from local responsive resources while taking into account the power losses in the distribution grid. Respectively, the offered mechanism enables the DNO to motivate the microgrids to cooperate in decreasing the variation in the exchanged-power seen by the main grid.

E. Robust-Based Scheduling of Local Resources in Microgrids

RERs as potential energy resources in future energy grids would challenge the local operational scheduling regarding their uncertain characteristics. In this regard, the robust optimization algorithm could be taken into consideration by operators of microgrids to address the uncertainty of RERs. It is noteworthy that the robust optimization would merely influence the local optimization conducted by microgrids and so the offered TEM-based technique could as shown in Fig. 2 be employed by DNO to incentivize the participation of local resources in the provision of flexibility ramp-up service.

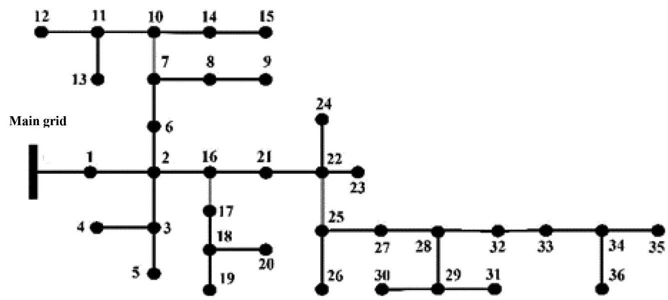

Fig. 4. Simplified model of the considered MMS for the simulation study.

Power generation by RERs considering their associated maximum forecast error could be modeled as follows:

$$PN_{h,i,t}^{VRER} \in \left[\widehat{PN_{h,i,t}^{VRER}} - \Delta PN_{h,i,t}^{VRER}, \widehat{PN_{h,i,t}^{VRER}} \right.$$
$$\left. + \Delta PN_{h,i,t}^{VRER}\right], h \in \Gamma^{MG}, i \in \Gamma^{VRER,h}. \quad (27)$$

In this regard, the operational optimization of each microgrid could be formulated as follows:

$$\max_{\widehat{P_{h,i,t}^{VRER}}} \min_{y} cost^{MG_h} \quad (28)$$

subject to

$$P_{h,i,t}^{VRER} = \widehat{P_{h,i,t}^{VRER}} + \varphi_{i,t}^{+} \Delta P_{h,i,t}^{VRER}]$$
$$- \varphi_{i,t}^{-} \Delta P_{h,i,t}^{VRER}, \quad i \in \Gamma^{VRER,h}, t \in T \quad (29)$$

$$0 \le \varphi_{i,t}^{+}, \varphi_{i,t}^{-} \le 1 \quad (30)$$

$$\sum_{i,t} \varphi_{i,t}^{+} + \varphi_{i,t}^{-} \le \Pi_h \quad (31)$$

and the operational constraints of resources for h_{th} microgrid.

The objective function (28) aims to minimize the operational costs of the h_{th} microgrid over the worst-case scenario of power generation by RERs. In this regard, (29)–(30) model the RERs' power production considering their associated uncertainties. Finally, a robustness budget (i.e., Π) as shown in (31) is taken into consideration to model the perspective of the MCO toward risk. In this context, the robustness budget limits the number of uncertain parameters deviating from their respective forecasted values.

The presented max–min optimization for robust-based scheduling of microgrids' local resources could be recast into a single maximization problem by deploying the duality theory. In this regard, the complete formulation of microgrids robust-based resource scheduling which enables regulating microgrids with respect to uncertainties of RERs is offered in [37].

III. Implementation

In this section, the offered technique is implemented on a 37-bus MMS as shown in Fig. 4 utilizing CPLEX solver in GAMS. In this regard, the study cases aim to analyze the efficiency of the offered mechanism in order to motivate local resources contribution in the flexibility ramp-up minimization. In this regard, each node of the test system is considered as a microgrid with high-amount installation of PV resources, which could cause volatile-ramp-up in the MMS. It is conceived that

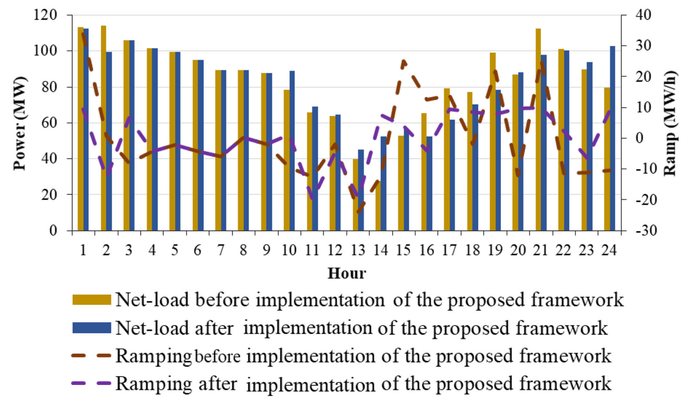

Fig. 5. Exchanged-power of the MMS and the transmission system in case of $\Pi = 0$.

the scheduling horizon is $T = 24$ h and scheduling intervals for microgrids' resource scheduling and ramp-up-rate evaluations are 1 h. Microgrids are responsible for the least-cost energy controlling of load demands, conventional-DG units, PVs, and storage units. Operational data of ESSs, conventional-DGs, load demands, and PVs are depicted in [37]. It is considered that the MMS provides the flexibility service to the main grid by keeping the ramp-up request below 10 MW/h. In other words, the main grid is considered to be able to provide up to 10 MW flexibility ramp-up in each hour; therefore, the ramp-up request of the MMS should be restricted to 10 MW/h. In this regard, this article provides a technique that enables DNO as an intermediate entity between microgrids and main grid operators to incentivize the microgrids to contribute to the ramp-up reduction.

In the first case study, it is considered that the operational scheduling of local resources in each microgrid is conducted considering $\Pi = 0$. In this respect, Fig. 5 illustrates that the power grid saw a dramatic increase in the flexible-ramp-up requirements of the MMS at 1, 15, 19, and 21 h, which mainly is resulted from the load demand increase and the drop of power generation by PV units. However, implementing the offered incentive mechanism as shown in Fig. 5 has resulted in decreasing the flexible-ramp-up requirements of the distribution network. In this regard, the maximum ramp-up request of the MMS was preliminary about 34 MW/h at 1 h, while the maximum ramp-up request of the MMS is less than 10 MW/h after deployment of the offered mechanism. Consequently, implementing the offered mechanism in an MMS with the high amount of RERs installation would inspire microgrids to change their operational point to fulfill the ramp-up-constraints, which finally results in the MMS flexibility improvement.

Regarding the offered methodology, the provided TEM signal (i.e., LMP$*$), which is based on the cost of energy purchased from the power grid (i.e., LMP), strives to activate the flexibility service from local responsive resources. In this regard, by revising the LMP$*$ and consequently updating DLMPs, microgrids would be motivated to reschedule their local flexible resources based on the distributed control mechanism. The hourly LMPs and LMP*s as the determined TEM signals are represented in Fig. 6. It is clear that the LMP* is higher than LMP at 19 and 21 h in order to point out that the purchasing power from

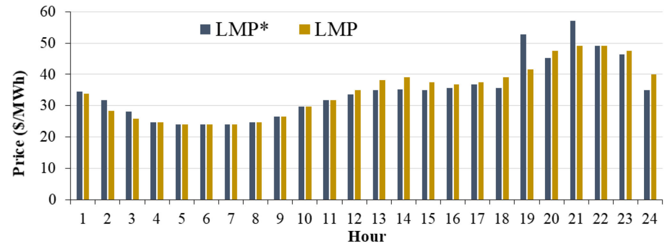

Fig. 6. Transactive control signals in case of $\Pi = 0$.

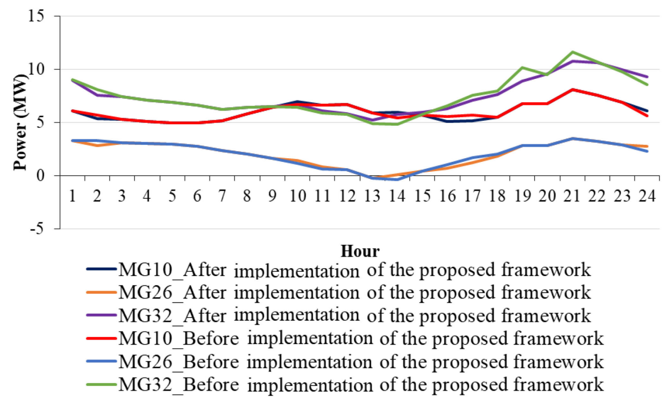

Fig. 7. Exchanged-power of microgrids 10, 26, and 32 in case of $\Pi = 0$.

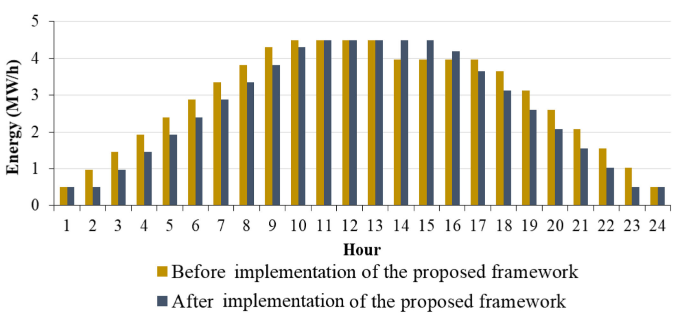

Fig. 8. Accumulated energy stored in ESS units of Microgrid-32 in case of $\Pi = 0$.

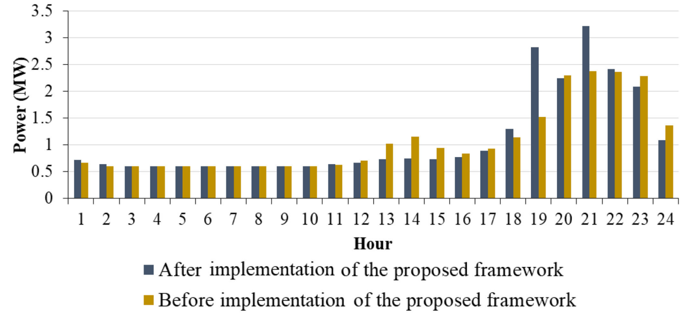

Fig. 9. Accumulated power production of local conventional-DG units in Microgrid-32 in case of $\Pi = 0$.

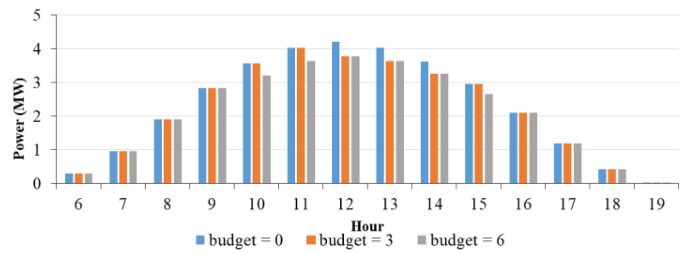

Fig. 10. Power output of PV units in Microgrid-32 for $\Pi = 0, 3,$ and 6.

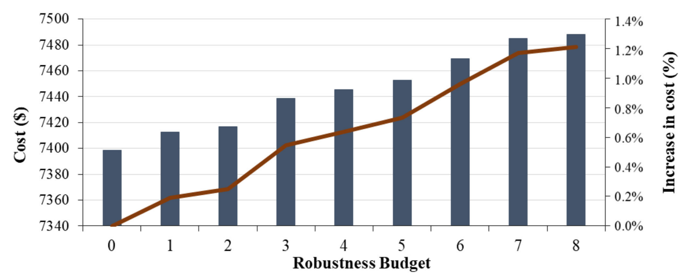

Fig. 11. Total operational cost of Microgrid-32 over 24 h considering ramp-up constraint of 10 MW/h.

the main grid is less profitable, and stimulates decreasing the exchanged-power and the volatile-ramp-up. Additionally, LMP is higher than LMP* at 12–14 h to inspire more power purchases from the main grid to compensate the PVs' power output drop in the afternoon.

The exchanged-power of microgrids 10, 26, and 32 of the MMS are presented in Fig. 7. It can be seen from Fig. 7 that while all the microgrids have contributed to the ramp-up minimization at 1 h by increasing their power requests at 24 h, Microgrid-32 has merely decreased its power request at 19 and 21 h to provide flexibility ramp-up service for minimizing the ramp-up of the MMS at these time intervals. Considering the operational controlling of ESSs and conventional-DGs in Micorgrid-32, the accumulated stored energy in ESSs and power generation by conventional-DGs are, respectively, presented in Figs. 8 and 9. In this regard, by changing the energy price associated with the power request of each microgrid as a result of updating LMP∗, the preliminary scheduling of the resources would be changed. Specifically, the increase in energy costs at 2, 19, and 21 h have resulted in increasing the power generation by conventional-DGs as well as decreasing the charging of ESSs at 2 h. Moreover, the decrease in energy prices at 13–15 h has resulted in decreasing the power generation by conventional-DGs as well as increasing the charging of ESSs at 14 h.

As mentioned earlier, operators of microgrids could employ different levels of robustness budget based upon their preferences toward risk-seeking or risk-aversion. In this regard, Fig. 10 presents the determined output power of PV units in Microgrid-32 considering the robustness budget to be 0, 3, and 6, while the maximum forecast deviation (ΔPN^{RER}) is taken into account to be 10% for all microgrids. In the selected worst-case scenario, the power output of PV units is reduced at time intervals that the forecasted power production by PV units and the energy prices are relatively high. Furthermore, the total operational costs of Microgrid-32 over 24 h in different case studies are presented in Fig. 11, which shows the increase in the operational cost of Microgrid-32 as it becomes more risk aversion. In other words, this would be the cost of minimizing the risk associated with the uncertainty of RERs.

Furthermore, the application of the offered mechanism for updating the price of energy exchange with the main grid in order

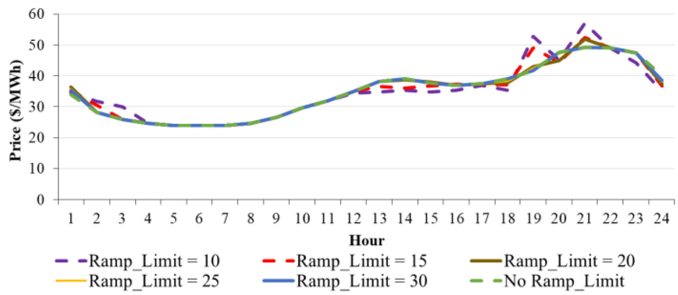

Fig. 12. Determined TEM signal associated with the price of energy exchange with the main grid (i.e., LMP∗) in different case studies.

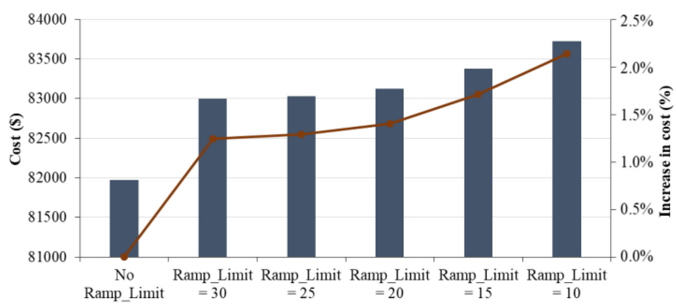

Fig. 13. Total operational cost of the MMS over 24 h in different case studies.

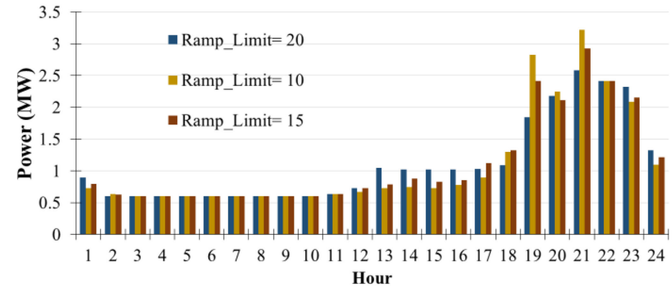

Fig. 14. Accumulated power production of local conventional-DGs in Microgrid-32 considering different ramp-limits in case of $\Pi = 0$.

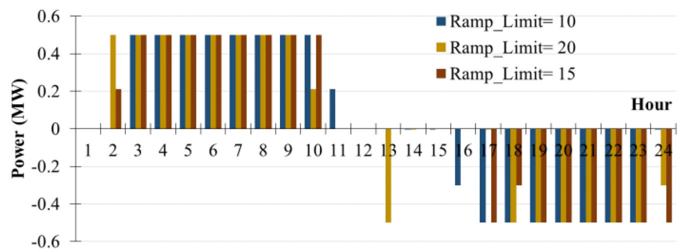

Fig. 15. Power charging/discharging of ESS unit in Microgrid-32 considering different ramp-limits in case of $\Pi = 0$.

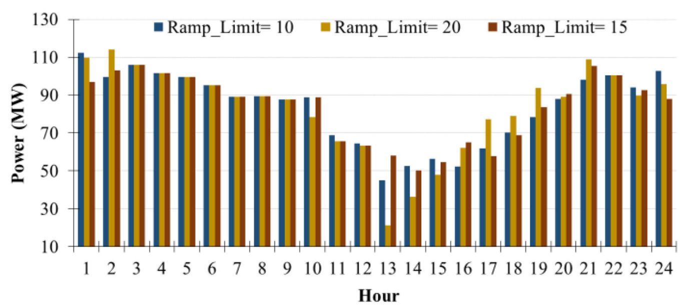

Fig. 16. Exchanged-power of the MMS and the transmission system considering different ramp-limits in case of $\Pi = 0$.

to activate flexible-ramp-up service from the local resources is investigated considering different ramp-up limits in the MMS, while the robustness budget is considered to be 6 for all microgrids. In this regard, the TEM signal (i.e., LMP∗) associated with the price of energy exchange with the power grid is presented in Fig. 12. It is clear that while the differences between the LMPs and LMP∗s are merely at 1 and 24 h considering ramp-up limits of 25 and 30 MW/h; their differences increase by minimizing the ramp-up constraint of the MMS. Besides, as shown in Fig. 13, the sum of operational costs of all the microgrids over 24 h is compared in the case of employing different ramp-up limits. Interestingly, the results show that while the overall operational costs of the MMS would be increased by decreasing the ramp-up limit; in all of the case studies, the proportional increase in operational costs of the MMS is small and below 2.1%. The results show the benefits of employing the offered technique: decreasing the volatile-ramp-up in the MMS, increasing the flexibility of the power grid, decreasing the potential price spikes in power systems due to flexibility ramp-up shortages [31], and finally delay investments for expanding bulk flexible resources in the transmission system.

Considering the different ramp-up limits, the accumulated power generation by conventional-DG units in Micorgrid-32 is shown in Fig. 14. Similarly, the power charging/discharging of storage units in Microgrid-32 is represented in Fig. 15. It is noteworthy that, in Fig. 15, the positive values indicate the power charging of the storage unit, while the negative values show the discharging values. Based on the obtained results, the power production of conventional-DGs at 12–16 h in case of considering ramp-up limit of 10 MW/h is lower than considering ramp-up limit of 15 MW/h and 20 MW/h. These results are admissible taking into account the TEM signals (i.e., LMP∗) shown in Fig. 12. Note that other obtained results could be similarly illustrated considering the TEM signals shown in Fig. 12. Finally, the exchanged-power of the MMS and the transmission system considering the ramp-up limits of 10 MW/h, 15 MW/h, and 20 MW/h is represented in Fig. 16.

In another case study, the capacity of RERs in the network is increased by 10%, 20%, and 50% in order to study the effectiveness of the offered mechanism for limiting the volatile-ramp-up in the MMS. In this regard, the accumulated power generation by conventional-DGs in Microgrid-32 considering the 110%RERs, 120%RERs, 150%RERs capacity is shown in Fig. 17. Moreover, the power charging/discharging of the storage units considering the 10%, 20%, and 50% increase in the RERs capacity is represented in Fig. 18. It is noteworthy that the obtained results for scheduling of conventional-DGs and ESSs are aligned with the determined transactive control signals shown in Fig. 19. Furthermore, the Exchanged-power of the MMS and the transmission system and its associated ramp-up before and after the implementation of the offered mechanism considering the ramp-up limit of 15 MW/h in different cases are shown in Figs. 20–23, respectively. The obtained results demonstrate

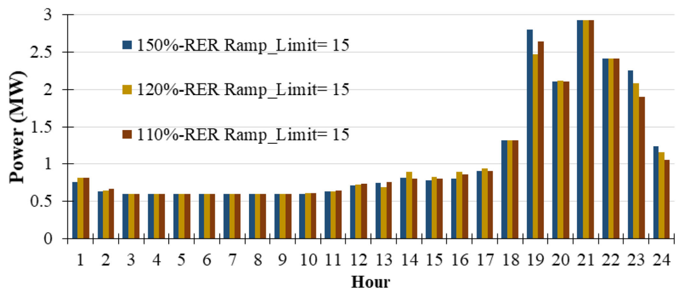

Fig. 17. Accumulated power production of local conventional-DGs in Microgrid-32 in different case studies considering $\Pi = 0$.

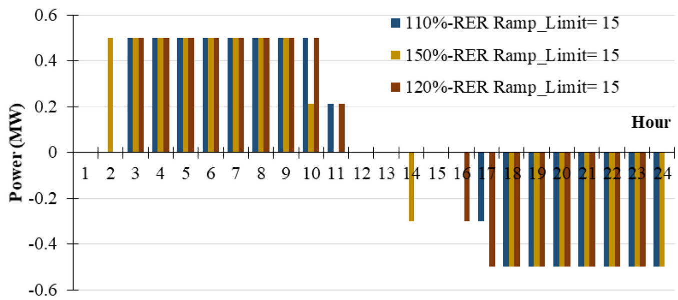

Fig. 18. Power charging/discharging of ESS unit in Microgrid-32 in different case studies considering $\Pi = 0$.

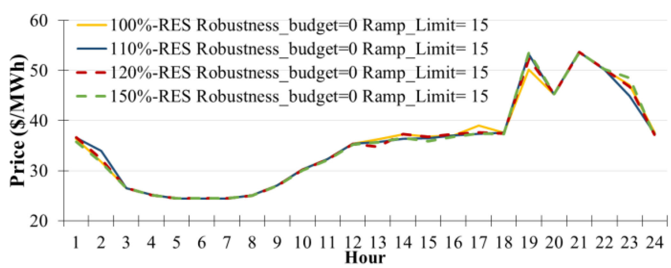

Fig. 19. Determined TEM signal associated with the price of energy exchange with the main grid (i.e., LMP$*$) in different case studies.

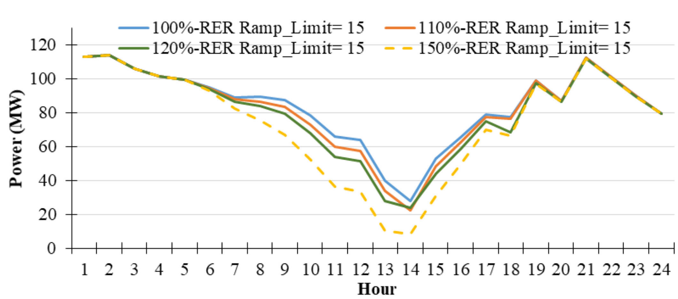

Fig. 20. Exchanged-power of the MMS and the transmission system before implementation of the offered technique in different case studies.

the ability of the offered technique in ramp-up controlling of MMSs utilizing the flexible local resources. Finally, the results indicate that the offered mechanism facilitates the high-amount installation of RERs without engendering the volatile-ramp-ups in the MMS.

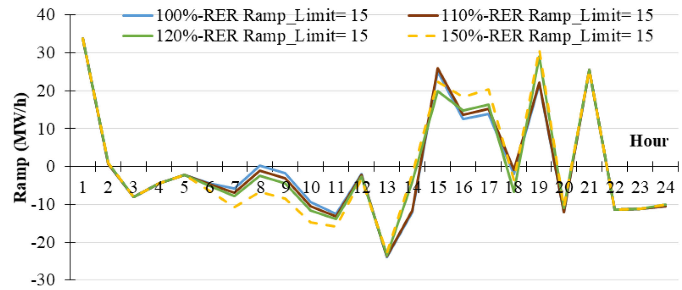

Fig. 21. Ramp-up associated with the exchanged-power of the MMS and the transmission system before implementation of the offered technique in different case studies.

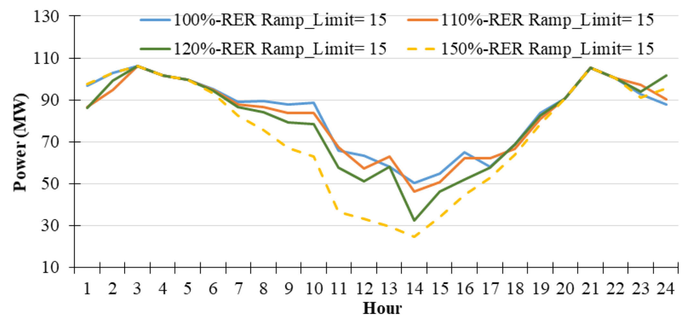

Fig. 22. Exchanged-power of the MMS and the transmission system after implementation of the offered technique in different case studies considering the ramp-up limit of 15 MW/h, and $\Pi = 0$.

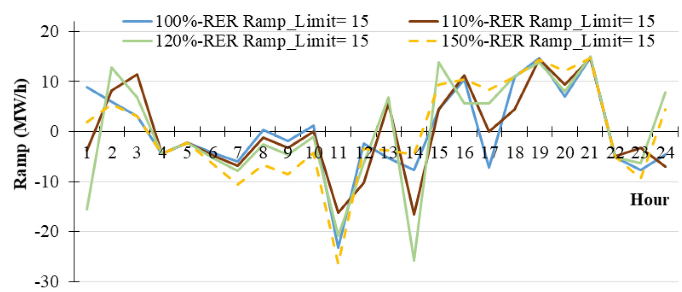

Fig. 23. Ramp-up associated with the exchanged-power of the MMS and the transmission system after implementation of the offered technique in different case studies considering the ramp-up limit of 15 MW/h and $\Pi = 0$.

IV. Discussion

In recent years, various algorithms have been offered to provide the interaction between networked microgrids. It is noteworthy that the offered technique for the provision of flexibility service could effortlessly be adopted in the previously offered methods (e.g., [32]–[36]) that facilitate the interaction of independent microgrids/agents in a distribution network. In other words, the offered technique for TEM-based flexible-ramp-up controlling exploits the LMP at the CCP of the MMS and the power grid to incentivize the contribution of local resources in the provision of flexibility ramp-up service for the power system. In this regard, DNOs could receive the flexibility service from local dispatchable resources of the distribution system to ensure the flexible operation of the MMS.

V. Conclusion

This article proposes an efficient distributed mechanism in order to motivate the local resources in an MMS to contribute to the system's flexibility improvement. In this regard, a TEM signal is designated based on the price of the energy purchased from the main grid and the difference of ramp-up requests and the targeted flexible-ramp-up in each scheduling interval. Respectively, the provided TEM signal results in updating the price associated with the power request of each microgrid to encourage their contribution in providing flexible-ramp-up service.

The offered mechanism is simulated on the IEEE-37 bust test network, which demonstrates the effectiveness and significance of the offered mechanism to enable the MMS to efficiently provide ramp-up reduction service with the aim of the system flexibility improvement. Finally, the results show that the mechanism can be applied to efficiently optimize the performance of an MMS with a more practical and efficient application in a real system.

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