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Distributed Transactive Framework for Congestion Management of Multiple-Microgrid Distribution Systems

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***Abstract*—The privatization of distribution systems has resulted in the development of multiple-microgrid (multiple-MG) systems where each microgrid independently operates its local resources. Moreover, the high integration of independent distributed energy sources could lead to operational issues such as grid congestion in future distribution systems. Therefore, this paper provides a transactive-based energy management framework to operate multiple-MG distribution systems; while, alleviating grid congestion in a decentralized manner. In this respect, alternating direction method of multipliers (ADMM) is considered to develop an operational framework that copes with distributed nature of multiple-MG systems. In this context, a novel procedure in the context of ADMM is proposed to distributedly determine transactive coordinator signals which address energy prices as well as power losses and grid congestions. Furthermore, each MG takes into account stochastic programming and the conditional value-at-risk index to handle the uncertainty of its operational scheduling. At last, the proposed framework is applied on IEEE 37-bus and 123-bus test grids to investigate its efficacy in distributed energy management of multiple-MG systems.**

***Index Terms*—Congestion alleviation, transactive coordinator signal, multiple-microgrid system, responsive local resources, distribution grid.**

NOMENCLATURE

Indices and Sets

i	Distribution grid agents (DGAs)/ microgrid coordinator agents (MCAs)/nodes and lines in main grid.
n	Index of nodes/lines in MG.
A_n, C_n	Sets of parent and child nodes of node n.
A_i, C_i	Sets of parent and child nodes of node i.
t	Index for time period.
k	Index for iterations.
sc	Index for scenarios.
ess	Index for energy storage system (ESS).
pv	Index for photovoltaic (PV) units.
g	Index for conventional distributed generation (CDG).
sg	Index for piecewise linear segments.
Π_i^N, Π_i^L	Sets for nodes and lines in MG i.
Ω_n^{CDG}, Ω_n^{PV}, Ω_n^{ESS}	Sets for CDG units, PV units, and ESSs of node n in MG.
Λ_g	Set for discrete segments to linearize the cost of CDG g.
Ω_i^{Sc}	Set of scenarios for MG i.
T	Operational time horizon.

Parameters

r_n / x_n	Resistance/Reactance of line n.
v_n^{Max}/v_n^{Min}	Upper/Lower bound of squared voltage magnitude of node n.
$CS_{g,sg}^{CDG}$	Production cost of CDG g in segment sg.
CS_n^{DShed}	Cost associated with load shedding of node n.
$P_n^{Dem,Max}/P_n^{Dem,Min}$	Maximum/Minimum load demand for node n.
E_n^{Dem}	Required demand for node n over T.
$\eta_{ess}^{Ch}/\eta_{ess}^{DCh}$	Charging/Discharging efficiency of ESS.
$P_{ess,t}^{Ch,Max}/P_{ess,t}^{DCh,Max}$	Maximum charging/discharging rate of ESS.

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$P_{g,sg}^{CDG,Max}$	Maximum active power generation of CDG g for segment sg.
$Q_g^{CDG,Max}/Q_g^{CDG,Min}$	Maximum/Minimum reactive power generation of CDG g.
$P_{pv,sc}^{PV,Max/Min}$, $Q_{pv,sc}^{PV,Max/Min}$	Maximum/Minimum of active/reactive power output of PV units.
π_{sc}	Probability of scenario sc.
α_i^{MG}	Confidence level for employing MPC method in operational managements of MG i.
β_i^{MG}	Risk parameter for employing MPC method in operational managements of MG i.
LMP_t	Locational marginal price at substation node.

Variables

v_n	Voltage magnitude (squared) for node n.
PF_n / QF_n	Active/Reactive power flow of line n.
p_n / q_n	Active/Reactive power injection of node n.
L_n	Line current magnitude (squared) for line n.
$P_{g,sg,t}^{CDG}$	Active power production of CDG in segment sg.
$P_{ess}^{Ch}/P_{ess}^{DCh}$	Charging/Discharging rate of ESS.
$E_{ess,t}^{St}$	Stored energy of ESS.
$I_{ess,t}^{Ch}/I_{ess,t}^{DCh}$	Binary variable for charging/discharging mode of ESS.
$P_{n,t}^{Dem}/P_{n,t}^{DShed}$	Load demand/shedding of node n.
$P_{pv,t}^{PV}$	Active power output of PV unit.
$Q_{g,t}^{CDG}$	Reactive power production of CDG.
$Q_{pv,t}^{PV}$	Reactive power production of PV unit.
$P_{i,t,sc}^{MG}$	Power exchange of MG i at scenario sc.
$P_{i,t}^{DGA}$	Power exchange of MG i announced to DGA i.
$TES_{i,t}^{MG}$	Transactive coordinator signal associated with MG i.
$TES_{i,t}^{Congestion}$	Transactive coordinator signal associated with congestion in line i.
$LS_{i,t}$	Active power loss of line i.
$TES_{i,t'}^{MG}$	Transactive signal associated with MG i.
$TES_{i,t'}^{Congestion}$	Transactive signal associated with congestion in line-i.
ζ_i^{MG}	Auxiliary variable in MPC method for detecting the high-cost scenarios.
$\psi_{i,sc}^{MG}$	Auxiliary variable to help MPC for computing the expectation of detected scenarios.

I. INTRODUCTION

RAPID growth of distributed energy resources (DERs) has led to a fundamental transition of traditional power distribution systems to active power distribution systems with a large number of independent prosumers. In this regard, while the integration of DERs such as flexible demands, energy storage systems (EESs), and conventional distributed generation (CDG) units offers a level of flexibility to the system; non-coordinated operation of them could lead to severe operational problems in the future systems. In this context, the simultaneous charging/discharging of flexible DERs may result in congestion problems in the main grid [1]. Moreover, intermittency of renewable energy sources (RESs) such as photovoltaic (PV) units and variability of household demands would challenge the reliable operation of the system. Consequently, it seems a new organization is required to be applied in distribution systems, which addresses the independent operation of prosumers, congestion problems, and uncertainty of RESs.

Microgrids (MGs) are considered as an applicable and promising solution to securely and efficiently accommodate the proliferation of DERs and prosumers in distribution systems. With the increased integration of DERs and the advances in communication technologies, conventional distribution grids will be transformed into multiple-MG systems to further enhance the benefits of incorporating MGs in the power system [2]–[3]. Therefore, new practical organizations should be investigated to facilitate the coordination and cooperation of independently operated MGs while considering the operational characteristics of the distribution system. In this respect, an overview of the energy management systems for the operation of multiple-MG systems is pursued in [3].

Congestion management would be a crucially important topic in future distribution systems due to the high penetration of independently operated DERs. In this context, congestion management of distribution systems with high integration of electric vehicles and heat pumps is investigated in [4]–[5]. In [4], the distribution system operator (DSO) pays dynamic subsidies to the customers to solve congestion problems by shifting their energy consumption; whereas the suggested method in [5] relies on dynamic tariffs determined in an iterative way between DSO and aggregators. In [6], a congestion management methodology is suggested for distribution networks while taking into account the rebound effects of demand response units. In this methodology, DSO requests power-cost offers from flexible units in order to manage congestions of the grid after the day-ahead market is cleared. Stackelberg game is employed in [7] to model the cooperation of the system operator and responsive demands in congestion alleviation of the transmission system. Virtual prices are expanded based on the dual decomposition algorithm in [8] to exploit the potential flexibility of residential households in order to resolve congestion problems of the grid. It is noteworthy that the distributed coordination of independently operated MGs is not studied in [4]–[8], as all of the presented frameworks require a central operator in order to manage congestions of the grid. The suggested methodology in [9] has considered that all the aggregators would announce their power request to the distribution market operator, which is a central entity for clearing the 'pay-as-bid' market. As a result, in the suggested methodology in [9], the market-clearing price is conducted by a central entity. Furthermore, in [10], the DSO is considered responsible for alleviating the congestion issue. As a result, the DSO would conduct a robust optimization based on the prediction of local resources' power request to optimize the operation of the system during day-ahead scheduling. Moreover, the suggested organization in [10] has overlooked the power loss in the network and merely considered congestion alleviation utilizing the DC optimal power flow (OPF). In [11], the DSO utilizes tariffs in order to exploit the scheduling of local resources. As a result, all the resources and their respective agents should exchange information with a central coordinator. Furthermore, a hierarchical bi-level optimization is taken into account in [12] in order to alleviate congestion in a distribution system. Nevertheless, the optimization model is conducted by a central coordinator that could impede its scalability in distributed systems. On the other hand, the centralized optimization model could cause security risk while operating distribution grids with decentralized configurations.

In recent years, transactive energy (TE) is taken into account as a promising concept to enable the decentralized and reliable operation of independent agents [13]–[15]. TE employs economic signals and mechanisms in order to assure the dynamic balance between supply and demand across the power system [16]. Authors in [17], [18] have utilized transactive coordination signals in order to facilitate the participation of local resources in ramp markets. Reference [19] has suggested a TE management methodology for distribution networks; in which, DSO acts as a mediator by scheduling local energy resources of the distribution system and participating in the wholesale energy market of the transmission system. Yet, the presence of independent MGs in distribution systems is not considered the analyzed methodology. Authors in [20] have expanded a two-phase transactive organization to efficiently operate distribution systems with multiple-MG structures. In the primary phase, demand response and energy storage systems of MGs are utilized to manage the imbalances of the MGs; while, in the secondary phase, the remaining imbalances due to forecast errors are handled with the aid of an inter-MGs auction-based transactive market. In [21]–[22], coordination among the operation of networked MGs is achieved using the transactive energy concept; however, a central entity is considered to calculate the transactive coordinator signals. Moreover, in [22], the central coordinator requires the operational constraints of resources in each MG to transform the bi-level model into the final single-level optimization model. Wang *et al.* [23] have devised a bi-level programming framework in order to manage energy trading among MGs as well as the operational limits of the distribution system. Respectively, at the lower level of the expanded organization, a central operator clears the energy trading market among MGs; whereas, at the upper level, the DSO reconfigures the distribution network based on the MGs trades. In addition, in [24] a decentralized TE-based methodology is expanded for operational management of flexible resources in distribution systems. Nevertheless, this model has not considered the operational constraints of the grid as well as power loss in the distribution grid and networked MGs. Similarly, the optimization model for scheduling of DERs in [25] has not considered the operational modeling of distribution grids and has not studied alleviating the congestion issue in the main grid.

In all of the above mentioned operational management organizations [4]–[12], [19]–[23], [25], a central operator is considered to provide operational management of the system. This approach could result in privacy, communication, and scalability issues with the expansion of independent entities in the system [26]. Recently, distributed optimization methods, especially alternating direction method of multipliers (ADMM), are investigated to operate modern systems without considering a central operator. The authors in [27] have analyzed an ADMM-based methodology to solve the OPF problem for distribution systems by deriving closed-form solutions for the ADMM updates. Furthermore, robust scheduling of the distribution grids considering the ADMM is studied in [28]. In [26], a TE trading method is suggested based on the ADMM algorithm to enable bilateral energy trading among agents of the distribution system. In [29]–[30], a distributed methodology based on ADMM is suggested to solve the economic dispatch problem in islanded MGs. Although technical issues associated with the economic dispatch problem are addressed in [29]–[30], technical limits of the underlying grid is overlooked. Furthermore, the intermittent nature of RESs and randomness of demands are not taken into account in [20]–[21], [23]–[24]. In [31]–[32], ADMM algorithm is considered to operate distribution systems with different operational objective. However, the operational constraints of the main grid, risk associated with local resources, as well as the potential flexibility of local resources to manage congestion issues in the grid are not taken into consideration.

Although various methodologies are expanded for operation of multiple-MG systems; to the authors' best knowledge, the distributed transactive operational management of multiple-MG systems taking into account congestion in the grid has not yet been studied. The previously expanded methods for alleviation of congestion in the distribution system [4]–[12] rely on a central controller that determines the control signals associated with all entities of the system. Similarly, the previous TE-based methods [19]–[23] are expanded utilizing a central coordinator to manage independent agents of the system; while this paper aims to remove the central controller and provide a distributed operational management organization for multiple-MG systems. In this respect, the distributed algorithm expanded in this paper aims to dismantle the resource scheduling of each MG from the operational scheduling of the main grid in order to cope with the independent nature of MGs. Therefore, ADMM method is employed to operate the main grid in a distributed manner; whereas, TE is deployed to separate scheduling of each MG from the upper-level management as well as alleviating congestion of the main grid. Moreover, unlike the previous ADMM-based methods [20]–[21], [23]–[24] which include the resource scheduling of each MG within the ADMM-based operational optimization of the distribution system; the suggested framework in this paper facilitates the incorporation of novel operational management methodologies for MG scheduling. In addition, new agents are introduced in the distribution system to facilitate the distributed control of multiple-MG systems. In this regard, distribution grid agents (DGAs) are defined to enable operational management of the main grid in a distributed manner. Moreover, each DGA is responsible to provide TE coordinator signals for its respective MG coordinator agent (MCA) which is responsible for resource scheduling of the connected MG. It is noteworthy that in case of congestion occurrences in the main grid, DGAs accordingly updates TE signals during conducting ADMM algorithm to exploit the potential flexibility of resources in the MG. In this regard, while most of the previous researches in the context of congestion management of distribution systems have not considered congestion issues caused by over-generation of RESs; the TE-based model in this paper addresses the congestion issues engendered by over-consumption/over-generation of prosumers.

In general, the proposed transactive framework based on ADMM facilitates the distributed management of multiple-MG systems, while addressing potential congestion issues in the main grid. In this regard, DGAs are introduced to enable the distributed control of the system without considering a central coordinator. Furthermore, resource scheduling of MGs is conducted independently from the operational scheduling of the main grid by utilizing the TE coordinator signal announced by the DGA. In this respect, the communication between the DGA and the MCA is limited to overall power exchange and the TE coordinator signal, which improves the privacy of MGs. In addition, the operational constraints of local resources as well as the MG network are considered in the optimization model conducted by the MCA. In this regard, this paper aims to provide a comprehensive model for addressing congestion in the grid by modeling flexible load demands, CDGs, ESSs, and RESs; whereas, previous research works have mostly focused on single type of resources in order to alleviate congestion issue in the grid. Besides, stochastic programming is utilized to model uncertain parameters, e.g., real-time electricity prices. Correspondingly, the conditional value-at-risk (CVaR) index is utilized to manage the potential risks imposed on the MG by uncertain parameters. In this paper, without loss of generality, the hour-ahead operation of the main grid is managed by the DGAs; while each MCA carries out resource scheduling utilizing model predictive control (MPC) to account for future predictions of the MG scheduling.

The rest of this paper is organized as follows. Section II presents the system modeling, and the proposed framework. In this respect, mathematical modeling of the resource scheduling conducted by each MG, as well as the ADMM-based operation of the distribution system are presented. Moreover, the procedure of determining TE signals associated with each MG is illustrated in this section. Section III represents the study results of implementing the expanded scheme on test systems. Finally, Section IV presents the conclusions.

II. METHODOLOGY

In this section, first, the modeling of multiple-MG systems which is considered in this paper is discussed. In the next section, the proposed structure is illustrated, followed by mathematical modeling of resource scheduling in MGs, and operating the main grid utilizing the ADMM concept. Finally, the procedure defined to determine the transactive coordinator signals to alleviate congestion in the main grid is described.

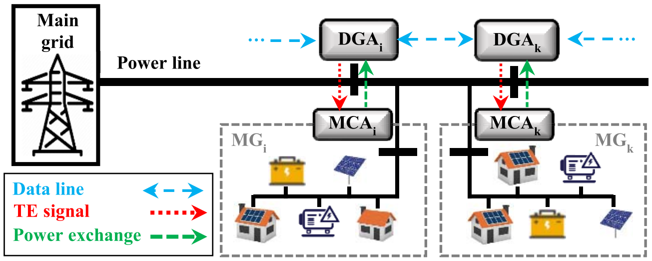

Fig. 1. The simplified management framework of a multiple-microgrid system.

A. Multiple-MG System Modeling

As mentioned, modern distribution systems will be operated as multiple-MG systems, where each MG independently operates and schedules its local resources. However, the independent and non-coordinated operation of these MGs could cause severe operational problems including congestion issues in distribution grids. In this regard, new agents, i.e., DGAs and MCAs, are introduced in this paper to coordinate the operation of MGs and alleviate congestions of the main grid while taking into account the independent operation of MGs. In this context, DGAs are responsible for the distributed coordination of MGs and operation of the network as well as congestion alleviation of the main grid; whereas, each MCA is responsible to economically schedule its local resources. Moreover, each DGA is responsible to compute the TE coordinator signal based on the available operational data and announce it to its corresponding MCA. Subsequently, the MCA runs an energy management algorithm and announces the power exchange with the main grid to the DGA. Figure 1 presents a simplified model of the multiple-MG system and the introduced agents in the analyzed energy management framework. In this structure, non-critical information is exchanged between adjacent agents to provide a distributed operational management methodology that is privacy-preserving and scalable. It is noteworthy that the transactive coordinator signals for alleviating congestion issue are not dependent on the operational modeling of sub-grids in this methodology; therefore, without loss of generality, the sub-grids in the considered distributed system are conceived as MGs in this paper.

B. Distributed Transactive-Based Management Framework for Multiple-Microgrid Distribution System

In this paper, a distributed TE-based framework is expanded to operate distribution systems with multiple-MG structures while alleviating congestions of the main grid. For this purpose, a TE coordinator signal is expanded to separate the operational management of the main grid from resource scheduling of MGs. Also, the ADMM method is employed by DGAs to operate the main grid in a fully distributed manner. In this respect, each DGA communicates the required data with its adjacent DGAs in order to run an ADMM-based OPF optimization. Moreover, based on the available data, each DGA is responsible to compute and announce the TE coordinator signal which represents the price of power

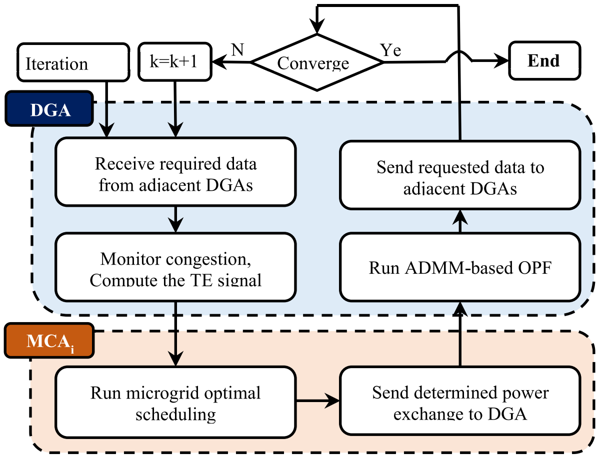

Fig. 2. The proposed management framework for multiple-MG distribution systems.

exchange at the point of common coupling (PCC) of the main grid and the respective MG. Furthermore, this method enables each DGA to update the TE signal in case of congestion occurrence in its corresponding line; which would finally incentivize local resources to contribute in the alleviation of congestion issues in the main grid. Without loss of generality, this organization is conducted to determine the hour-ahead operational management of the system. Within the organization, each MCA strives to optimize the resource scheduling at the current time dispatch while considering the received TE signal and the forecasted future of the MG scheduling. In addition, the MCA utilizes stochastic programming to model the uncertainty associated with the forecasted parameters of future time intervals. In this respect, the MCA utilizes stochastic programming and the CVaR index to immunize the operation of the MG against the uncertainty of forecasted parameters (i.e., real-time electricity prices and RESs power productions) of future time intervals. Finally, the MCA sends back the computed power exchange between MG and the main grid to its respective DGA. Fig. 2 presents the implementation procedure of the proposed methodology associated with DGA and MCA. As can be traced, the communication between the DGA and MCA is reduced to the computed TE signal and the power exchange at the PCC, which would preserve the privacy of MG's resources. It is noteworthy that this method does not require a central controller to calculate the TE signals, which facilitates the transition of conventional distribution grids to modern smart grids.

C. Microgrid Scheduling

As mentioned, MG scheduling is conducted by each MCA considering the announced TE coordinator signal and future uncertainties. In this respect, MPC is employed in order to model the operational condition of the MG in future time intervals, while optimizing the scheduling of local resources for the current time dispatch. Moreover, stochastic programming and CVaR index are utilized to manage the risk of future uncertain parameters. Furthermore, the convex OPF formulation is embraced form [33], [34] to model MG network's operational constraints. Finally, the resource scheduling of MG$_i$ for time interval t' while taking into account future T time periods is modeled as follows:

$$\min\ F_i^{MG} \tag{1a}$$

subject to:

$$\begin{aligned}&PF_{n,t,sc} + \sum_{g\in\Omega_n^{CDG}}\sum_{sg\in\Lambda_g} P_{g,sg,t,sc}^{CDG} + \sum_{ess\in\Omega_n^{ESS}}\left(P_{ess,t,sc}^{DCh} - P_{ess,t,sc}^{Ch}\right)\\&\quad + \sum_{pv\in\Omega_n^{PV}} P_{pv,t,sc}^{PV} - P_{n,t,sc}^{Dem} = \sum_{m\in C_n} PF_{m,t,sc}\,,\ n\in\Pi_i^N,\\&\quad t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc}\end{aligned} \tag{1b}$$

$$\begin{aligned}&QF_{n,t,sc} + \sum_{g\in\Omega_n^{CDG}} Q_{g,t,sc}^{CDG} + \sum_{pv\in\Omega_n^{PV}} Q_{pv,t,sc}^{PV} - Q_{n,t,sc}^{Dem} = \sum_{m\in C_n} QF_{m,t,sc}\\&\quad n\in\Pi_i^N,\ t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc}\end{aligned} \tag{1c}$$

$$\begin{aligned}&v_{A_n,t,sc} = v_{n,t,sc} + 2(r_n PF_{n,t,sc} + x_n QF_{n,t,sc}) + L_{n,t,sc}(r_n^2 + x_n^2),\\&\quad n\in\Pi_i^L,\ t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc}\end{aligned} \tag{1d}$$

$$PF_{n,t,sc}^2 + QF_{n,t,sc}^2 \le v_{n,t,sc}L_{n,t,sc},\ \ n\in\Pi_i^L,\ t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc} \tag{1e}$$

$$\begin{aligned}&P_{n,t}^{Dem,Min} \le P_{n,t,sc}^{Dem} + P_{n,t,sc}^{DShed} \le P_{n,t}^{Dem,Max},\ \ n\in\Pi_i^N,\ t\in\left[t', t'+T\right],\\&sc\in\Omega_i^{Sc}\end{aligned} \tag{1f}$$

$$\sum_{t'\le t}^{t'+T}\left(P_{n,t,sc}^{Dem} + P_{n,t,sc}^{DShed}\right) = E_{n,sc}^{Dem}\,,\ n\in\Pi_i^N,\ sc\in\Omega_i^{Sc} \tag{1g}$$

$$\begin{aligned}&E_{ess,t,sc}^{St} = E_{ess,t-1,sc}^{St} + \left(\eta_{ess}^{DCh}P_{ess,t,sc}^{DCh} - \eta_{ess}^{Ch}P_{ess,t,sc}^{Ch}\right),\ \ ess\in\Omega_n^{ESS},\\&\quad t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc}\end{aligned} \tag{1h}$$

$$0 \le P_{ess,t,sc}^{Ch} \le P_{ess}^{Ch,Max}.I_{ess,t,sc}^{Ch}\ ,\ \ ess\in\Omega_n^{ESS}, t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc} \tag{1i}$$

$$0 \le P_{ess,t,sc}^{DCh} \le P_{ess}^{DCh,Max}.I_{ess,t,sc}^{DCh},\ \ ess\in\Omega_n^{ESS}, t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc} \tag{1j}$$

$$I_{ess,t,sc}^{Ch} + I_{ess,t,sc}^{DCh} \le\ 1\ \ ,\ \ ess\in\Omega_n^{ESS}, t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc} \tag{1k}$$

$$E_{ess}^{St,Min} \le E_{ess,t,sc}^{St} \le E_{ess}^{St,Max},\ \ ess\in\Omega_n^{ESS}, t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc} \tag{1l}$$

$$PF_{n,t,sc} = P_{i,t,sc}^{MG}\ , n\in PCC_i,\ t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc} \tag{1m}$$

$$P_{i,t}^{DGA} = P_{i,t,sc}^{MG},\ \ \ t = t' \tag{1n}$$

$$\begin{aligned}&P_{g,sg}^{CDG,Min} \le P_{g,sg,t,sc}^{CDG} \le P_{g,sg}^{CDG,Max}\ \ g\in\Omega_n^{CDG}, sg\in\Lambda_g, t\in\left[t', t'+T\right],\\&\quad sc\in\Omega_i^{Sc}\end{aligned} \tag{1o}$$

$$Q_g^{CDG,Min} \le Q_{g,t,sc}^{CDG} \le Q_g^{CDG,Max}\ \ , g\in\Omega_n^{CDG}, t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc} \tag{1p}$$

$$P_{pv,sc}^{PV,Min} \le P_{pv,t,sc}^{PV} \le P_{pv,sc}^{PV,Max}\ \ , pv\in\Omega_n^{PV}, t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc} \tag{1q}$$

$$Q_{pv,sc}^{PV,Min} \le Q_{pv,t,sc}^{PV} \le Q_{pv,sc}^{PV,Max}\ \ , pv\in\Omega_n^{PV}, t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc} \tag{1r}$$

$$v_n^{Min} \le v_{n,t,sc} \le v_n^{Max}\ \ n\in\Pi_i^N, t\in\left[t', t'+T\right],\ sc\in\Omega_i^{Sc} \tag{1s}$$

$$\begin{aligned}&-\zeta_i^{MG} + P_{i,t',sc}^{MG}\cdot TES_{i,t'}^{MG} + \sum_{t'\le t}^{t'+T}\left(P_{i,t,sc}^{MG}\cdot\lambda_{i,t',sc}^{MG,FC}\right) + \sum_{t'<t}^{t'+T}\sum_{n\in\Pi_{MG_i}^N}\\&\quad (CS_n^{DShed}\cdot P_{n,t,sc}^{DShed} + \sum_{g\in\Omega_n^{CDG}}\left(CS_{g,sg}^{CDG}\cdot P_{g,sg,t,sc}^{CDG}\right)) \le \psi_{i,sc}^{MG}\ ,\ \ sc\in\Omega_i^{Sc}\end{aligned} \tag{1t}$$

$$\psi_{i,sc}^{MG} \ge 0,\ \ sc\in\Omega_i^{Sc} \tag{1u}$$

$$F_i^{MG,1} = \sum_{sc\in\Omega_i^{Sc}} \pi_{sc}\cdot\left(P_{i,t',sc}^{MG}\cdot TES_{i,t'}^{MG} + \sum_{t'<t}^{t'+T}\left(P_{i,t',sc}^{MG}\cdot\lambda_{i,t',sc}^{MG,FC}\right)\right.$$

$$+\sum_{t'\leq t}^{t'+T}\sum_{n\in\Pi_i^N}\left(CS_n^{DShed}\cdot P_{n,t,sc}^{DShed}+\sum_{g\in\Omega_n^{CDG}}\left(CS_{g,sg}^{CDG}\cdot P_{g,sg,t,sc}^{CDG}\right)\right)\Bigg)\Bigg) \tag{1v}$$

$$F_i^{MG,2}=\zeta_i^{MG}+\left(\frac{1}{1-\alpha_i^{MG}}\right)\cdot\sum_{sc\in\Omega_i^{Sc}}\left(\pi_{sc}\psi_{i,sc}^{MG}\right) \tag{1w}$$

$$F_i^{MG}=\left(1-\beta_i^{MG}\right)\cdot F_i^{MG,1}+\beta_i^{MG}\cdot F_i^{MG,2} \tag{1x}$$

where the operational cost of MG$_i$ at t' taking into account the future T time intervals is considered as the objective function in (1a). The MG's operational cost is comprised of power exchange with the main grid, CDGs, and load shedding. The active/reactive power balance in each node of the MG is presented in (1b)-(1c); while the relation between operational variables of each line is presented in (1d)-(1e). The operational constraints of the scheduled load and load shedding are represented in (1f)-(1g). Equations (1h)-(1l) respectively show the energy balance and charging/discharging/energy limits of each ESS. While the power exchange with the grid for each scenario is modeled in (1m), the final power exchange that is declared to DGA$_i$ is determined in (1n). Note that the power exchange with the main grid at t' (i.e., $P_{i,t'}^{DGA}$) is a here-and-now decision variable and would be sent to DGA. Operational constraints of active/reactive power production of each CDG, active/reactive power production of each PV unit, and nodal voltage magnitude are enforced in (1o)-(1s), respectively. Moreover, MG scheduling's risk is formulated in (1w) based on the CVaR index. Respectively, a linear formulation of the CVaR index is presented in (1t)-(1u) [27].

D. Distributed Operational Management of the Main Grid

DGAs are responsible to provide coordination among independent MGs and operate the main grid in a distributed manner. In this respect, an OPF optimization problem is formulated for the operation of the main grid. Furthermore, the ADMM algorithm [35] could be employed to solve the OPF problem in a distributed fashion by DGAs.

1) Optimal Power Flow Problem: The distribution system is considered to be composed of multiple MGs which are connected to the main grid at their PCC. A set of nodes $\mathbb{G}^N$ represents the PCC of MGs and the main grid; while a set of lines $\mathbb{G}^L$ represents the unique lines between nodes in a radial distribution system. Note that the main grid is connected to the transmission system at the substation node indexed as node 0. In order to balance supply and demand of MGs, the main grid could exchange power with the transmission system at the price of *LMP*, which is considered as a model input parameter. In this regard, the OPF problem presented in (2) is formulated using the convex-form of DistFlow [33]. In this regard, in the optimization formulation, it is considered that the main grid is operated radially; where the node A_i is the ancestor node of the node i.

$$\min\sum_{i\in\mathbb{G}}OF_{i,t'} \tag{2a}$$

subject to:

$$OF_{i,t'}=\begin{cases}LMP.p_{i,t'} & \text{if } i=\{0\}\\ 0 & i\in\mathbb{G}^N/\{0\}\end{cases} \tag{2b}$$

$$v_{A_i,t'}=v_{i,t'}+2(r_iPF_{i,t'}+x_iQF_{i,t'})+L_{i,t'}(r_i^2+x_i^2),\ i\in\mathbb{G}^L \tag{2c}$$

$$PF_{i,t'}+p_{i,t'}=\sum_{j\in\mathrm{C}_i}\left(PF_{j,t'}+r_jL_{j,t'}\right),\quad i\in\mathbb{G}^N \tag{2d}$$

$$QF_{i,t'}+q_{i,t'}=\sum_{j\in\mathrm{C}_i}\left(QF_{j,t'}+x_jL_{j,t'}\right),\quad i\in\mathbb{G}^N \tag{2e}$$

$$PF_{i,t'}^2+QF_{i,t'}^2\leq v_{i,t'}L_{i,t'}\ ,\quad i\in\mathbb{G}^L \tag{2f}$$

where (2a) minimizes the total cost of the power supplied from transmission system considering the operational limits of the system (2c)-(2f). Note that while the future T time intervals are considered in the MPC-based optimization problem conducted by each MCA$_i$; the optimization model (2) is merely conducted for the operation of the main grid in the next time interval (i.e., t'). Moreover, regarding the suggested organization, each MCA$_i$ is responsible to send the determined power exchange between the main grid and MG at t' to the respective DGA$_i$. In this regard, the power injection (i.e., $p_{i,t'}$) of the node $i\in\mathbb{G}^N/\{0\}$ is set to be equal to the declared power exchange with MG$_i$, i.e., $P_{i,t}^{DGA}$ at t'.

2) ADMM-Based OPF of Main Grid: In recent years, ADMM algorithm has been used by several research works to facilitate the distributed operation of power systems. A consensus-based ADMM approach is utilized in this paper to solve the optimization problem (2), which enables DGAs to operate the main grid in a distributed manner. In this respect, the following convex optimization problem is considered as the simplified model of the problem (2):

$$\min_{x}\sum_{i\in\mathbb{G}}OF_i(x_i) \tag{3a}$$

subject o:

$$\sum_{j\in\mathbb{G}_i}C_{i,j}x_j=0\quad i\in\mathbb{G} \tag{3b}$$

where for each $i\in\mathbb{G}$, $\mathbb{G}_i$ is a set of adjacent agents, x_i represents the vector of variables. The operational constraints of the main grid are presented in (3b). Local variables x_j are coupled together in (3b) by a constant matrix $C_{i,j}$. Note that in problem (2), $x_i:=\{v_i,L_i,PF_i,QF_i,p_i,q_i\}$. The consensus-based ADMM is applied by decoupling the variables of each agent from each other. For this purpose, auxiliary (duplicate) variables denoted by $y_{j,i}$ are considered as below:

$$\min_{x,y}\ \sum_{i\in\mathbb{G}}OF_i(x_i) \tag{4a}$$

subject to:

$$\sum_{j\in\mathbb{G}_i}C_{i,j}y_{j,i}=0\quad i\in\mathbb{G} \tag{4b}$$

$$y_{j,i}=x_j\quad i\in\mathbb{G},j\in\mathbb{G}_i \tag{4c}$$

Furthermore, the augmented Lagrangian of (4) is derived as below:

$$L_\rho(x,y,\lambda):=\sum_{i\in\mathbb{G}}\left(OF_i(x_i)+\sum_{j\in\mathbb{G}_i}\lambda_{i,j}\left(x_i-y_{j,i}\right)+\frac{\rho}{2}\left\|x_i-y_{j,i}\right\|_2^2\right) \tag{5}$$

where $\lambda_{i,j}$ and ρrepresent the Lagrangian multiplier of (4c) and a positive constant. Respectively, the ADMM algorithm runs in three steps to iteratively update variables at each iteration k as follows:

$$x^{k+1} = \arg\min_{x} L_\rho(x, y^k, \lambda^k) \tag{6a}$$

$$y^{k+1} = \arg\min_{z} L_\rho(x^{k+1}, y, \lambda^k) \tag{6b}$$

$$\lambda^{k+1} = \lambda^k + \rho(x^{k+1} - y^{k+1}) \tag{6c}$$

At last, stopping criteria could be utilized to ensure the convergence and stop the iterations of ADMM:

$$r^k := \left\| x^k - y^k \right\| \tag{7a}$$

$$s^k := \rho \left\| (y^k - y^{k-1}) \right\| \tag{7b}$$

where r^k and s^k present primal residual and dual residual, respectively. Note that an explicit formulation of the ADMM-based OPF problem discussed in this section is illustrated in [27].

E. Transactive Coordinator Signal

The TE coordinator signal is sent to MCA as the price of power at its PCC with the main grid. The MCA schedules the local resources according to the received TE coordinator signal. In this respect, a methodology within the ADMM algorithm is expanded in this paper, which enables DGAs to calculate the TE signal associated with their respective node in a fully distributed manner. It is noteworthy that, in addition to the cost of energy, the TE signal in this paper takes into account the cost incurred by active power losses and the cost associated with congestion in the grid. Note that LMP is considered as a base value of power exchange for the substation node. Respectively, the TE coordinator signals at other nodes are accordingly calculated by respective DGA entities within the ADMM process.

1) Modeling of Active Power Loss in the TE Signal: In order to model the induced cost of power loss in the TE signal, the concept of the distributional local marginal price (DLMP) associated with each node is taken into account. In this respect, the difference between the cost of energy at node i and its ancestor node would be proportional to the cost of power loss in the connecting line. In this regard, the TE signal of node $i \in \mathbb{G}^N/\{0\}$ could be calculated based on the value of the TE signal at its ancestor node A_i as follows:

$$TES^{MG}_{i,t'} = TES^{MG}_{A_i,t'}\left(1 + \partial LS_{i,t'} / \partial PF_{i,t'}\right), \quad i \in \mathbb{G}^N/\{0\} \tag{8}$$

where $\partial LS_{i,t'}/\partial PF_{i,t'}$ is the additional power loss of line i owing to a marginal increase of power in node i. Also, the power loss of line i could be determined as below:

$$LS_{i,t'} = \frac{r_i\left(PF^2_{i,t'} + QF^2_{i,t'}\right)}{v_{i,t'}}, \; i \in \mathbb{G}^L \tag{9}$$

Therefore, the additional power loss $\Delta LS_{i,t'}$ could be determined as follows:

$$\Delta LS_{i,t'}|_{PF_{i,t'} \rightarrow PF_{i,t'} + \Delta PF_{i,t'}} = \frac{2r_i.PF_{i,t'}.\Delta PF_{i,t'}}{v_{i,t'}}, \; i \in \mathbb{G}^L \tag{10}$$

Respectively, by substituting (10) in (8), the TE signal is determined as follows:

$$TES^{MG}_{i,t'} = TES^{MG}_{A_i,t'}\left(1 + \frac{2r_i.PF_{i,t'}}{v_{i,t'}}\right), \; i \in \mathbb{G}^N/\{0\} \tag{11}$$

Therefore, the TE signal of each node i of the main grid could be estimated by the respective DGA$_i$ according to the last available operational data that are being updated by the ADMM algorithm. Consequently, in the expanded methodology, the role of a central entity to determine TE signals is eliminated and DGAs could calculate the TE signal of their node in a distributed manner.

2) Modeling of Active Power Congestion in TE Signal: As mentioned, congestion in the main grid could be caused by over-power generation/consumption in the system. Furthermore, the suggested organization is expanded in a completely distributed manner; where the information connection between the DGAs is based on the ADMM process, and the communication between the DGA$_i$ and MCA$_i$ only consists of the TE signal and accumulated power exchange. In this regard, in order to develop a distributed operational management structure, DGA$_i$ is considered as the responsible entity for checking the congestion in the line connecting node i to its ancestor node A_i (i.e., line i). Respectively, DGA$_i$ would update the TE signal of node i in case of congestion occurrence in line i; which aims to incentivize the MGs in the system to collaborate in the congestion alleviation. Note that, as presented in (11), the TE signals of each node would be updated by the change in the TE signal of its ancestor node. In this regard, updating the TE signal of node i would accordingly affect the TE signals of the child nodes which affect the power flow in the line i. Consequently, for congestion alleviation in the system, the TE signal of the node i would be updated by DGA$_i$ as follows:

$$TES^{Congestion}_{i,t'} = TES^{Congestion}_{i,t'} \pm \tau^{Congestion}_{i,t'} \cdot \left|\Delta L^{overloading}_{line-i,t'}\right|, \; i \in \mathbb{G}^N/\{0\} \tag{12a}$$

$$TES^{MG}_{i,t'} = TES^{MG}_{i,t'} + TES^{Congestion}_{i,t'}, \; i \in \mathbb{G}^N/\{0\}(12b) \tag{12b}$$

where $\tau^{Congestion}_{i,t'}$ is a penalty factor to update the TE signal proportional to the overloading in the line i (i.e., $\Delta L^{overloading}_{line-i}$). Hence, the TE signals would be updated to incentivize the independently operated MGs in order to collaborate in congestion alleviation. Based on the formulation, at each iteration of the ADMM procedure, the TE signal of node i would be increased in case that the congestion of the line i is engendered by over-consumption in the system; while, the TE signal of node i would be decreased in case of over-generation by RESs. Note that, in case of congestion occurrences, each DGA entity would update the TE signal before sending it to its child nodes. Finally, in a distributed manner, this procedure enables the operational management framework to iteratively alleviate congestions in the main grid without modeling a central coordinator.

III. RESULTS

The TE-based congestion management methodology for multiple-MG systems is investigated in two test systems in

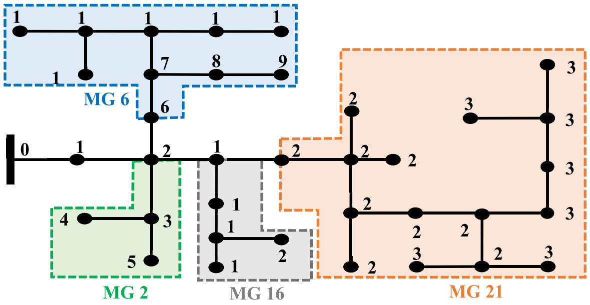

Fig. 3. The considered 37-bus multiple-MG test grid.

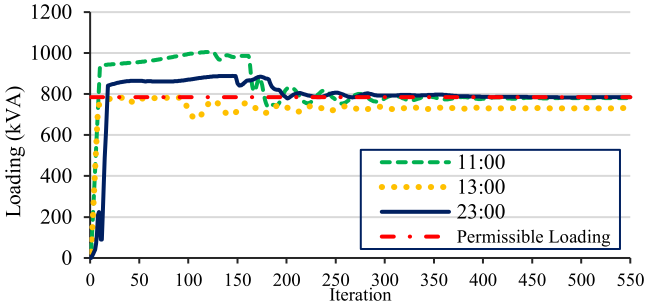

Fig. 4. Loading of line 16 at different time slots per iteration.

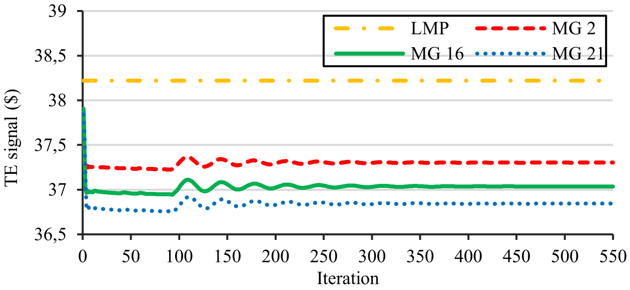

Fig. 5. TE signal of MGs at hour13:00 per iteration.

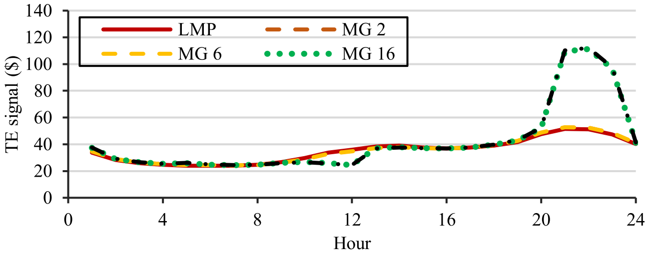

Fig. 6. The converged TE signal of MGs over the time horizon.

order to show its application in alleviating the congestion in the main grid in a decentralized manner.

A. 37-Bus Test Grid

In the first study, the framework is applied on the modified IEEE 37-bus test grid [12], [36]. The distribution system is structured as a multiple-MG system shown in Fig. 3. Respectively, each MG is identified by the parent node where the MG is connected to the main grid at its PCC. The operational characteristics of CDGs, ESSs, and flexible loads of each MG are adopted from [12], [19], [26], and [36]–[37]. A time resolution of 1 hour is considered for the total operational time horizon of 24 hours. Based upon the distributed nature of the multiple-MG test system, several case studies are taken into account to investigate the performance of the ADMM algorithm and the TE signal in congestion management of the system. The rated capacity of the line connecting node 16 and node 2 (i.e., line 16) is considered to be 85% of its maximum loading while operating the system without considering loading constraints in the distribution grid. Furthermore, the rated capacities of other lines of the distribution grid are considered to be 1.5 times of their maximum loading while operating the system without considering loading constraints in the distribution grid. Consequently, based on the pre-assumed rating capacities, over-loading in each of the network's lines would result in grid congestion. In the first case study, it is considered that each MG would consider the beta parameter (β) of the CVaR index to be 0.4 in the simulation process.

Figure 4 shows the loading of line 16 at three time intervals per ADMM iteration. As can be traced in this figure, the iterative loading of line 16 has converged to its optimum value, and the TE-based mechanism has successfully limited the power flow of line 16 to its permissible loading value.

Based on the suggested approach, the DGAs calculate the TE coordinator signals corresponding to each MG within the ADMM iterations, which aims to address the congestion and power loss in the main grid. The value of TE signal of each MG at hour 13:00 per ADMM iteration is presented in Fig. 5. The obtained results illustrate the strong performance of the ADMM-based method, which has enabled the distributed operation of the system without modeling a central coordinator. Furthermore, the converged results of the TE signal associated with each MG over the operational time horizon is shown in Fig. 6. Note that the over-power production/consumption by RESs/demands could result in the grid congestion in active distribution systems. In this context, the TE signals associated with MG 16 and 21 reach high values during 21:00-23:00 in order to address the over-consumption by load demands, which has caused congestion in line 16. Moreover, during mid-day when there is over-generation by PV units, the TE signal associated with MG 16 and 21 is decreased in order to incentivize responsive resources (i.e., CDG units, ESS units, flexible loads) to decrease/increase their power generation/consumption.

The iterative values of the power supplied from transmission system at the substation node at hours 11:00, 13:00, and 23:00 are presented in Fig. 7. The obtained results demonstrate that the ADMM-based methodology converges to the optimal solution in less than 500 iterations. Furthermore, Fig. 8 depicts the power exchange between MGs and the main grid, as well as the power supplied from transmission system over the time horizon. It could be seen that during 10:00-15:00 when the power production of PV units reach their maximum values, the surplus power is sold to the transmission system.

Furthermore, sensitivity analysis is taken into account to analyze the operational scheduling of the system in case of

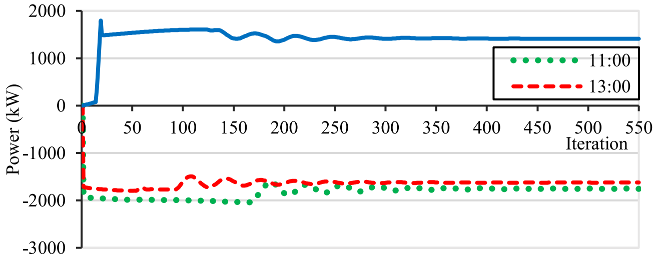

Fig. 7. Power supplied from transmission system at hours 11:00, 13:00, and 23:00 per iteration.

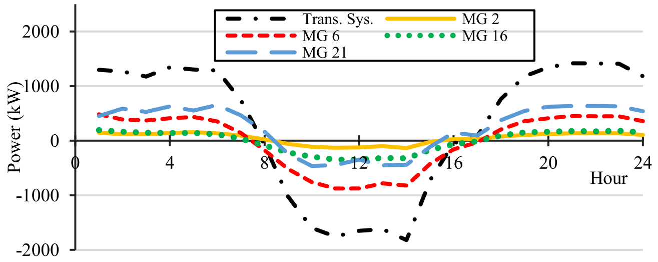

Fig. 8. Power exchanges of MGs and the main grid over the time horizon.

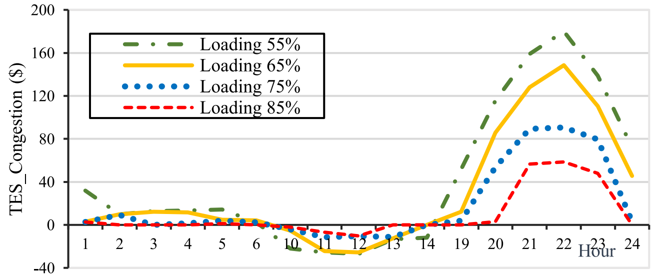

Fig. 9. Determined TE signals associated with the congestion of line 16 considering different permissible loadings for line 16 over the time horizon.

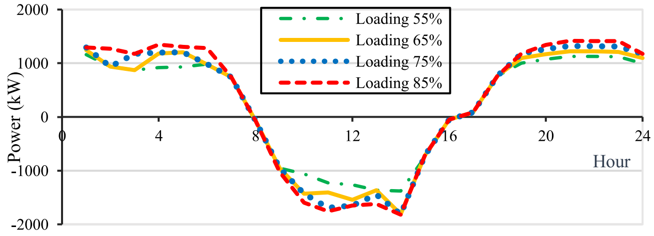

Fig. 10. Power supplied from transmission system over the time horizon.

congestion occurrences in the distribution grid. In this regard, the rated capacity of line 16 is considered to be 85%, 75%, 65%, and 55% of its maximum loading while operating the system without considering loading constraints in the distribution grid. In this respect, Figs. 9–12 present the obtained results of the sensitivity analysis from different perspectives. In this regard, Fig. 9 shows the determined TE signal associated with congestion of line 16 ($TES_{i=16,t}^{Congestion}$) considering different loadings for line 16 over the operational time horizon. As can be traced in this figure, $TES_{i=16,t}^{Congestion}$ decreases as the permissible loading of line 16 increases. Furthermore, the power supplied from transmission system over the operational time horizon is represented in Fig. 10. In this context, the power exchange is decreased by 4%, 10%, 15%, and 24% while considering the maximum permissible loading of line 16 to respectively be 85%, 75%, 65%, and 55%. Furthermore, Fig. 11 depicts the overall amount of load shedding, RESs curtailment, and the increase in the total objective cost of MGs considering different values of permissible loading for line 16. Note that the proportional increases in total objective cost are determined with respect to operating the system without considering loading constraints in the distribution grid. The obtained results show that the curtailment of RESs as well as the load shedding are increased by decreasing the rated capacity of line 16, which would led to increasing the overall objective cost. It is noteworthy that the development of the TE signal in the context of ADMM has enabled MGs to revise the scheduling of their flexible resources based on the congestion occurrences in the main grid, which would result in minimizing the operational costs of grid congestion. At last, a sensitivity analysis is conducted to analyze the effects of the CVaR parameter (β) on the operational management of the system. In this regard, the TE signals associated with the congestion occurrence in line 16 ($TES_{i=16,t}^{Congestion}$) in the case of considering β to be 0.0, 0.4, and 1.0 are shown in Fig. 12. It could be traced that the value of TE signals are higher in case that MGs are more conservative, i.e., $\beta = 1$. In other words, TE signals should be higher to incentivize conservative MGs to revise their scheduling at the current time interval.

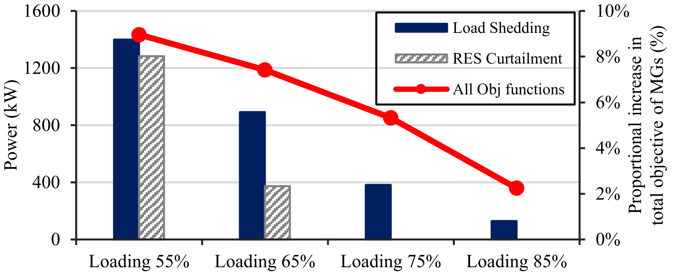

Fig. 11. Load shedding, renewable curtailment, and total objective cost considering different permissible loadings for line 16.

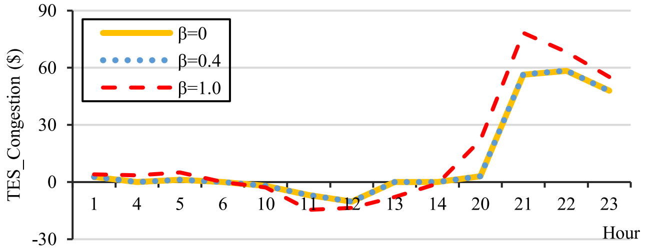

Fig. 12. Determined TE signal associated with the congestion of line 16 for different βover the time horizon.

B. 123-Bus Test Grid

In the second study, the framework is implemented on a balanced 123-bus test system which is considered in a multiple-MG structure as shown in Fig. 13. Note that the considered operational data of the test system and load demands are presented in [38]. It is noteworthy that, as shown in Fig. 13, each MG is presented based on the connecting node to the main grid of the distribution system. In this section, operation of the test system is studied in two cases; 100%-PVs

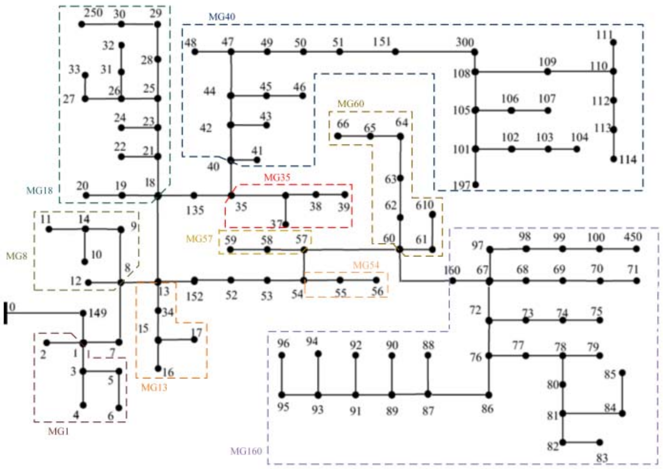

Fig. 13. The considered 123-bus multiple-MG test system.

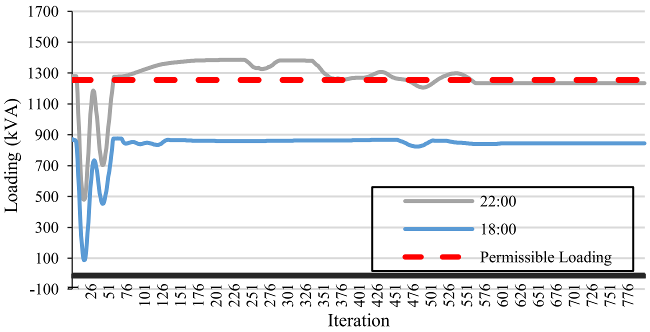

Fig. 14. Loading of Line-18 per iteration at 18:00 and 22:00 considering the 100%-PVs capacity.

and 200%-PVs. In other words, in the first case, the system is operated considered the basic capacity of PV units, while, in the second case, the capacity of the PV units is doubled in order to study the ability of the methodology in alleviating congestion issue caused by over-power generation of RESs. It is noteworthy that the capacity of the considered PV units in both cases are presented in [38]. Moreover, in both cases, it is assumed that, the rated capacity of the line connecting node 13 and node 18 (i.e., Line-18) is considered to be 85% of its maximum loading considering operating the base case without considering loading constraints in the distribution grid. In addition, it is considered that each MG would consider the beta parameter (β) of the CVaR index to be 0.4 in the simulation process. As discussed, two cases are conceived in this section to study the application of the suggested methodology in alleviating the congestion issue in both over-power generation and over-power consumption conditions.

In the first case (i.e., considering 100%-PVs), the system confronts with congestion issue in Line-18 at hours 21:00-23:00 due to over-power consumption by load demands. In this regard, in the analyzed methodology, the active power flow from line 18 at hours 21:00-23:00 is minimized by increasing the announced transactive coordinator signals to MGs 18, 35, and 40. Respectively, the loading of the Line-18 at hours 18 and 22, while running the proposed organization in an iterative manner is shown in Fig. 14. Furthermore, the TE control signals associated with MGs 18, 35, and 40 at 18:00 and 22:00 comparing with the LMP are presented in Figs. 15 and 16. Note that the MGs at 18:00 and 22:00 step are consuming power, therefore the TE control signal due to power loss in the grid is higher than LMP. Moreover, the transactive coordinator signals of MGs 18, 35 and 40 are increased at 22:00 in order to alleviate power congestion issue in Line-18.

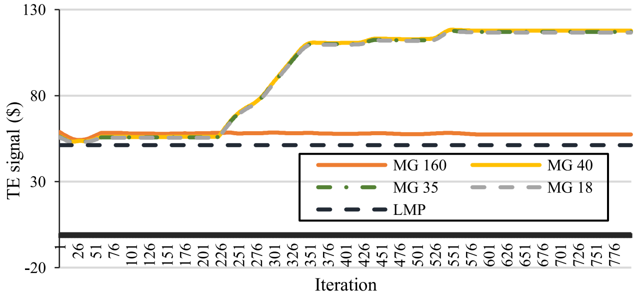

Fig. 15. TE signal of MGs at 22:00 per iteration.

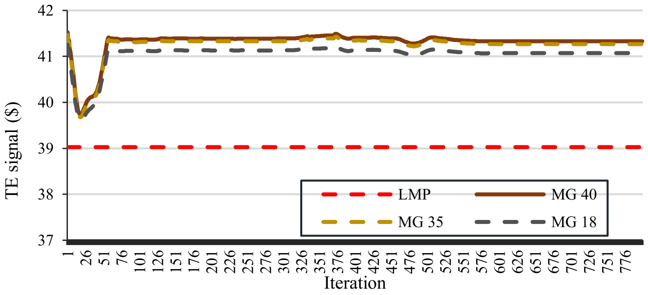

Fig. 16. TE signal of MGs at 18:00 per iteration considering the 100%-PVs capacity.

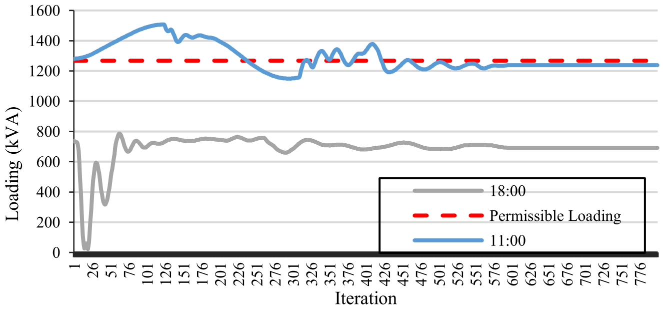

Fig. 17. Loading of Line-18 per iteration at 11:00 and 18:00.

On the other hand, in the second case (i.e., considering 200%-PVs), the system confronts with congestion issue in Line-18 at hours 11:00-12:00 due to over-power generation by PV units. In this regard, the loading of the line-18 at 11:00 and 18:00 per iteration of running the proposed organization is shown in Fig. 17. Furthermore, the transactive coordinator signals associated with MGs 18, 40, and 160 are presented in Fig. 18. Note that, in this case, the transactive coordinator signals of MGs 18, 35, and 40 are decreased at 11:00 in order to incentivize the flexible resources in these MGs to change their scheduling to alleviate the congestion issue. As a result, as shown in Fig. 19, the power generation of conventional generation units in MG 18, 35, and 40 are decreased at 11:00 to alleviate the over-power generation issue resulted in congestion issue at the respective time interval. Moreover, the TE

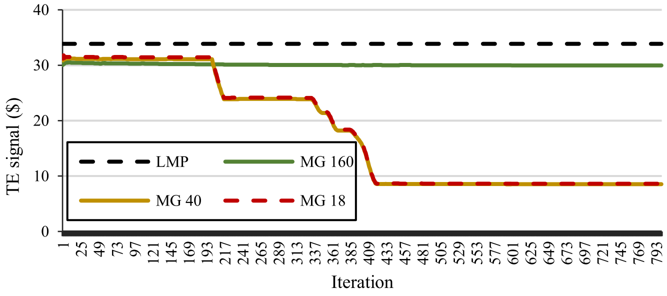

Fig. 18. TE signal of MGs at 11:00 per iteration.

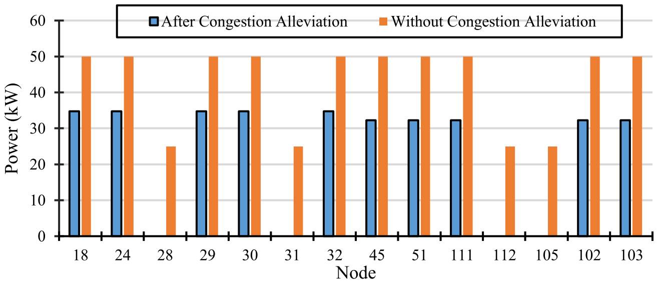

Fig. 19. Power generation by conventional generation units in MGs 18, 35, and 40 with/without congestion alleviation at hour 11:00.

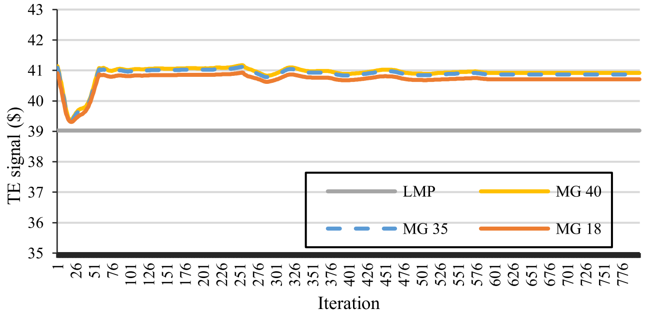

Fig. 20. TE signal of MGs at 18:00 per iteration considering the 200%-PVs capacity.

control signals associated with MGs 18, 35, and 40 at 18:00 are presented in Fig. 20. In this regard, based on the results shown in Figs. 16 and 20, by decreasing the active power flow due to higher power generation by PV units, the power loss in the grid is decreased; which would finally decrease the difference between LMP and TE control signals at different nodes. Finally, the power exchanges between the transmission and distribution grids in both case studies are represented in Fig. 21, which indicates the ability of the distribution system to sell power to the upper-level during the mid-day due to the power generation by PV units. Based upon the different studies conducted in this section, the proposed algorithm based on the TE concept and ADMM could operate the systems with the distributed structure in a decentralized manner.

IV. CONCLUSION

A distributed transactive congestion management framework for multiple-MG systems is presented in this paper. In this context, ADMM concept is employed to facilitate the independent operation of each MG without relying on a central coordinator. Moreover, a procedure is expanded in the context of ADMM to determine TE signals which are deployed to address power losses and grid congestions as well as energy costs in the system. Furthermore, stochastic programming is considered by each MG to handle uncertain parameters, while CVaR index is taken into account to model the risk of uncertainty modeling. The proposed transactive energy management methodology is implemented on two test networks, which demonstrate its efficacy in the decentralized operation of multiple-MG systems, as well as alleviating congestion issues in the main grid. Finally, sensitivity analysis is conducted to investigate the impacts of changes in modeling parameters on the operation of the main grid.

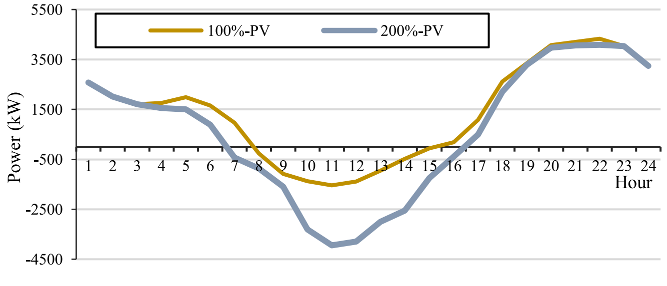

Fig. 21. Power exchange between the transmission and distribution grids considering two case studies.

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