Networked Microgrid Security and Privacy Enhancement By the Blockchain-enabled Internet of Things Approach

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***Abstract*—This paper proposes a novel framework for privacy and security enhancement of power trading in the networked microgrids (MGs) based on the blockchain-enabled Internet of Things (IoT) approach. Utilizing the blockchain-enabled IoT technology in the power trading of the network MGs can potentially lead to some significant advantages such as fewer system risks, mitigate financial fraud, and less the operational cost. A newly stochastic framework based on the unscented transform (UT) is employed to model the uncertainties of renewable energy resources and hourly load demand. Consequently, the proposed framework is tested on the network MG containing residential MG (as a non-crucial load), commercial MG (as an intermediate level load), and hospital MG (as a crucial load), to validate the effectiveness and high performance of the proposed technique.**

Keywords*— *Cybersecurity, networked microgrids, power trading, uncertainty, Blockchain technology.

NOMENCLATURE

A. Indices & Sets

k	Index of $\mathcal{RCS}$
$\mathcal{RCS}$	Remotely control switches
Ω^{D}/d	Set/index of load
Ω^{DG}/i	Set/index of DGs
Ω^{MG}/m	Set/index of networked microgrids
Ω^{T}/t	Set/index of time periods
Ω^{sw}/sw	Set/Index of RCSs switches
$\overline{(\cdot)}, \underline{(.)}$	Maximum, Minimum values for a variable

B. Constants

$\mathcal{R}^{U}/\mathcal{R}^{D}$	Ramp up/down rate
S_{im}^{U}, S_{im}^{D}	Startup/shutdown cost of DG i in microgrid m
$\lambda_{m}^{\mathcal{P}}, \lambda_{m}^{\mathcal{S}}$	Purchas/power sold cost of microgrid m
$\tau_{im}^{U}, \tau_{im}^{D}$	Minimum up/down time of DG i in microgrid m
$\lambda_{\mathcal{RCS}}$	Hourly switching operation cost

C. Variables

$\mathcal{C}, \mathcal{C}^{\mathcal{P}}$	Cost, cost of active power
I	Committed unit state
P	Active power
$P_{mt}^{\mathcal{P}}, P_{mt}^{\mathcal{S}}$	Power purchas/sold in microgrid m at time t
$\mathcal{T}^{ON}, \mathcal{T}^{OFF}$	Number of successive ON/OFF hours
δ_{mt}	Status of the microgrid m at time : 1 if MG purchasing power, and 0 if not.
$\in_{mt}$	Status of the microgrid m at time : 1 if MG power sold, and 0 if not.
$\mu_{\mathcal{RCS},k}$	Number of switching operations for k^{th} switch

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I. INTRODUCTION

MICROGRID (MG) is the summation of the loads and distributed energy resources (DERs) which can operate in both grid-connected and islanded modes. MG has been attracted a lot of attention due to some significant advantages such as closeness to the consumers, lower operation cost, higher power quality, higher reliability and resiliency, lower power losses due to reducing the transmission lines. However, along with these advantages, there exist some important challenges in operation, energy management, and protection of MGs. The energy management of single MG is extremely investigated so far. For instance, the multi-period islanding MG is investigated in [1] where the authors used the mixed-integer linear programming (MILP) method to overcome the complexity of the problem. The economic dispatch problem associated with the single MG is studied in [2-5]. The authors considered the spinning reserve to guarantee the stable operation during both grid-connected and islanded modes. The market-based MG is investigated in [6] in which the MG is in correlation with the Distribution System Operator (DSO) market. The renewable based MG is explored in [7] and [8]. The authors employed storage units to address uncertainties in renewable energy generation units. The energy management of single MG considering the dynamic thermal line rating, storage unit, and demand response are investigated in [9]. The optimal scheduling of MG considering the wind-hydro and pumped storage in generation units is studied in [10] and [11].

In the traditional grids, DSO is responsible for scheduling of the entire network. However, in the modern power grids, the DSO and MGs may have different roles and policies because of different owners. In addition, because of the interconnectivity feature of the whole grid, any change in an individual MG can potentially influence the whole network. On the other hand, based on the IEEE 1547.4 standard, decomposition of the grid into the networked MGs can enhance the total network reliability, resilience, and suitability. However, the energy management along with the security and privacy of the network would be more challenging and complicated. Despite the single MG, the energy management of the networked MG is studied in few literatures. The power mismatch control of networked MGs in explored in [12] and [13]. The networked MGs scheduling considering load uncertainty is investigated in [14]. Bi-level optimization framework is developed in [15] for the energy management of networked MGs where the upper-level is a central generation unit, and the lower-level is DERs the compensate the upper-level unit. The optimal operation of a networked microgrid is studied in [16] considering both generation and load demand uncertainties. In [17], an effective energy management framework for networked MG is explored based on the robust optimization method is developed. A decentralized framework based on the Direction Method of Multipliers (ADMM) method is proposed in [18] for optimal scheduling of network MGs. The authors modeled the uncertainty associated with the problem utilizing Monto Carlo Simulation (MCS) as well as the scenario reduction technique.

Above researches have been addressed a specified part of the network MG energy management. However, the privacy and security of the entire network are not well discussed. This paper addressed these concern by using the blockchain-enabled IoT technology. IoT includes many smart sensors that are distributed with the whole network to collect the huge data. These data may be used to effortlessly detect the faults, malicious behaviors, and violations within the whole grid [19]. Despite many advantages associated with the IoT, there exist some concerns that must be solved before the formal adoption of the IoT in the power utilities. Among them, security and efficiency of the IoT data are one of the most concerns [20]. In order to address this issues, in this paper, a novel stochastic framework is developed based on the blockchain-enabled technology. Blockchain technology can potentially convert industries into a decentralized and trustless environment. Therefore, a combination of the blockchain and IoT can reduce system risks, mitigate financial fraud and cut down operational cost. To model the uncertainty, the unscented transform (UT) method is used based on [9] and [10]. Hence, the main contributions of this paper can be summarized as

- Develop the blockchain-enabled IoT approach for the networked MG energy management. The main objective is to minimize the total operation cost of the network so that all the security and operational constraints associated with the problem are satisfied.
- Develop a stochastic framework based on the UT method to model uncertain parameters like hourly load demand and renewable energy output power.

I. Optimal Scheduling Problem of Interconnected Reconfigurable Microgrids

The proposed optimization problem includes an objective function and some constraints as

A. Objective Function

The main objective is to minimize the costs of switching, power generation by dispatchable generations (DGs), and power purchased from as

$$\min Cost = \sum_{k\in\Omega^{sw}} \mu_{\mathcal{RCS},k}\lambda_{\mathcal{RCS}} + \sum_{t\in\Omega^{\mathcal{T}}}\sum_{m\in\Omega^{\mathcal{MG}}}\sum_{i\in\Omega^{\mathcal{DG}}} \mathcal{C}_{im}(P_{imt})I_{imt} + S^{U}_{im}, S^{D}_{im} + \sum_{m\in\Omega^{\mathcal{MG}}}(\lambda^{\mathcal{P}}_{m}P^{\mathcal{P}}_{mt}\delta_{imt});\ \forall t\in\Omega^{\mathcal{T}}, \forall k\in\Omega^{sw} - \sum_{m\in\Omega^{\mathcal{MG}}}\left(\lambda^{\mathcal{S}}_{m}P^{\mathcal{S}}_{mt}\mathfrak{S}_{mt}\right) \tag{1}$$

where $\mu_{\mathcal{RCS}} = \sum_t \left|\mathcal{RCS}_{k,t} - \mathcal{RCS}_{k,(t-1)}\right|$.

B. Constraints

In any time interval, the total power generation should be equal to demand as (2). The purchased and sold powers are limited for each MG as (3) and (4). The output power of DGs within the MGs are constrained as (5). Moreover, (6) and (7) assure the ramp up and down constraints of each generation unit. Furthermore, each generation unit is limited to a minimum and maximum up and downtime as (8) and (9).

$$P^{\mathcal{P}}_{mt} - P^{\mathcal{S}}_{mt} + \sum_{m}\sum_{t} P_{imt} = \sum_{m}\sum_{d} D_{dmt} \tag{2}$$
$$\forall t\in\Omega^{\mathcal{T}}, \forall m\in\Omega^{\mathcal{MG}}, \forall d\in\Omega^{\mathcal{D}}$$

$$\underline{P^{\mathcal{P}}_{m}}\delta_{mt} \le P^{\mathcal{P}}_{mt} \le \overline{P^{\mathcal{P}}_{m}}\delta_{mt};\ \forall m\in\Omega^{\mathcal{MG}}, \forall t\in\Omega^{\mathcal{T}} \tag{3}$$

$$\underline{P^{\mathcal{S}}_{m}}\mathfrak{S}_{mt} \le P^{\mathcal{S}}_{mt} \le \overline{P^{\mathcal{S}}_{m}}\mathfrak{S}_{mt};\ \forall m\in\Omega^{\mathcal{MG}}, \forall t\in\Omega^{\mathcal{T}} \tag{4}$$

$$\underline{P_{im}}I_{imt} \le P_{imt} \le \overline{P_{im}}I_{imt} \tag{5}$$
$$\forall m\in\Omega^{\mathcal{MG}}, \forall t\in\Omega^{\mathcal{T}}, \forall i\in\Omega^{\mathcal{DG}}.$$

$$P_{imt} - P_{im(t-1)} \le \mathcal{R}^{\mathcal{U}}_{im} \tag{6}$$
$$\forall m\in\Omega^{\mathcal{MG}}, \forall t\in\Omega^{\mathcal{T}}, \forall i\in\Omega^{\mathcal{DG}}$$

$$P_{im(t-1)} - P_{imt} \le \mathcal{R}^{\mathcal{D}}_{im} \tag{7}$$
$$\forall m\in\Omega^{\mathcal{MG}}, \forall t\in\Omega^{\mathcal{T}}, \forall i\in\Omega^{\mathcal{DG}}$$

$$\tau^{U}_{im}\left(I_{imt} - I_{im(t-1)}\right) \le \mathcal{T}^{ON}_{imt} \tag{8}$$
$$\forall m\in\Omega^{\mathcal{MG}}, \forall t\in\Omega^{\mathcal{T}}, \forall i\in\Omega^{\mathcal{DG}}$$

$$\tau^{D}_{im}\left(I_{im(t-1)} - I_{imt}\right) \le \mathcal{T}^{OFF}_{imt} \tag{9}$$
$$\forall m\in\Omega^{\mathcal{MG}}, \forall t\in\Omega^{\mathcal{T}}, \forall i\in\Omega^{\mathcal{DG}}$$

II. Blockchain-Enabled Internet Of Things Approach

A. Internet of Things

Utilizing the IoT in the networked MG require the smart sensors, controllable switches, smart meters, and communication line installation. The distributed smart sensors within the network are responsible for collecting the data in physical layers and then sent to the microgrid central control (MGCC) which is located in the IoT central node as shown in Fig. 1. The IoT MGCC is answerable for processing the data and decide for the best power dispatch and assure a stable operation within the network. To this end, three steps are defined to control the active power between the networked MGs based on the IoT technology as [21]:*1) Primary step:* In this step, the smart devices are connecting with several communication protocols. This paper offered the Common Industrial Protocol (CIP) to send/receive data in the energy management of networked MGs. CIP is established in many industrial networks such as Ethernet/IP, DeviceNet, CompoNet and ControlNet that is sustained by the Open DeviceNet Vendors Association (ODVA).

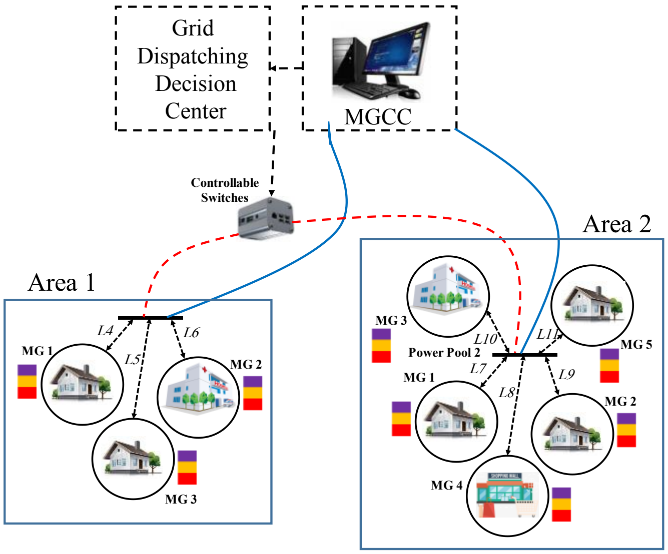

Fig. 1. The proposed networked MG

Table I
Features of the DGs

Area	MGs	Type	Min-Max Capacity (kW)	Cost ($/kWh)	Min Up/Down Time (h)	Priority
AREA 1	MG1	DG1	500-1400	2.34	3/3	P3
		DG2	400-2300	2.53	2/2	
		DG3	700-1800	2.63	2/2	
		DG4	300-2200	3.18	1/1	
	MG2	DG1	700-1600	2.17	2/2	P1
		DG2	800-2000	2.5	1/1	
		DG3	600-1800	2.8	3/3	
		DG4	500-2500	2.98	2/2	
	MG3	DG1	400-2300	2.12	1/1	P3
		DG2	700-1900	2.21	3/3	
		DG3	400-2800	2.5	3/3	
		DG4	500-2100	2.62	2/2	
AREA 2	MG1	DG1	400-1500	2.3	2/2	P3
		DG2	500-2500	2.5	3/3	
		DG3	600-2000	2.6	3/3	
		DG4	500-2000	3.1	1/1	
	MG2	DG1	600-1500	2.1	3/3	P3
		DG2	700-1800	2.5	3/3	
		DG3	400-1500	2.7	2/2	
		DG4	400-1500	2.9	2/2	
	MG3	DG1	500-2500	2.1	3/3	P1
		DG2	600-2000	2.2	3/3	
		DG3	400-3000	2.5	2/2	
		DG4	400-2000	2.6	1/1	
	MG4	DG1	800-1500	2.3	3/3	P2
		DG2	400-1800	2.5	2/2	
		DG3	800-2500	2.6	2/2	
	MG5	DG1	800-3000	2.3	2/2	P3
		DG2	700-2500	2.4	1/1	
		DG3	400-2500	2.6	3/3	
		DG4	800-1800	2.8	4/4	

2) Secondary step: In this step, the IoT first provides the required energy of the crucial loads, and then satisfies the intermediate and non-crucial loads within the network. This includes the original MGCC and the total power generation of the succeeding hour. *3) Tertiary step:* The MGCC controls the active power within the network based on the collected data from the up-step dispatching center. It should be noted that in the IoT renewable-based scheduling, a robust forecasted method is essential to predict the hourly load demand and the output power of renewable energy to gain the optimal solution.

B. Blockchain

In the networked MG energy management, each power trading within the network stands as a block, where the blocks are adding together as a list of records (ledger) by utilizing the hash address (HA). This list of records is available for all of the active participation within the whole network; while it is inaccessible for uncommitted networks. This paper develops the blockchain technology in the networked MGs energy management to offer a decentralized, trustable, and transparent environment. The proposed method can significantly enhance network security and privacy.

B.2. Priority list

In the proposed problem, a priority list is defined to fulfill the demand according to their level of significance. This list ranks the MGs based on the nature of their loads, where the higher priority belongs to the critical loads (hospital). The intermediate priority is belonging to commercial loads, and the lowest priority belongs to residential loads.

III. Simulation Results

In order to demonstrate the performance and efficiency of the proposed method, a networked MG contains eigh MGs in two area are selected as shown in Fig.1. The first area includes two residential (MG1 and MG3), and one hospital as a crucial load (MG2), where the second area includes three residential (MG1, MG2, and MG5), one hospital (MG3), and one commercial (MG4). The features of the DGs within each MG is provided in Table I. The hourly load demands of each area are presented in Figs. 2 and 3.

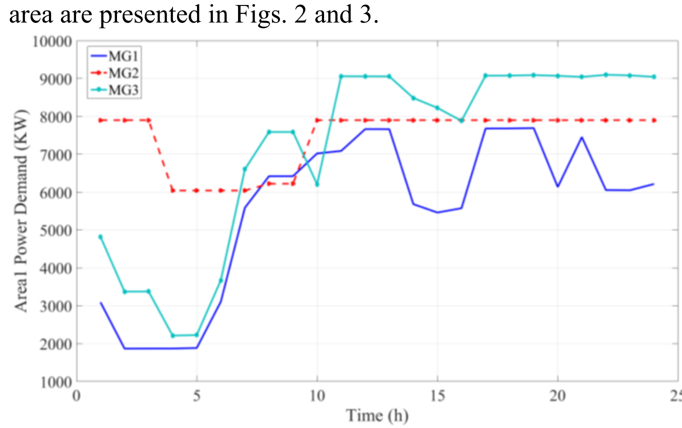

Fig. 2. Hourly load demand of area 1.

According to the simulation the simulation results, there is no feasible solution due to the shortage power in MG 2 of area 1; that means the DGs within the MG2 of area 1 are not able to satisfy the load demand. The blockchain within the area first tries to address this power shortage by the MGs of area1. In many hours MGs within the area1 can satisfy the load demand of MG2 in area 1; however, in some hours such as 12 and 13, other MGs within the area 1 are not able to satisfy

the load demand of MG2. Hence, the blockchain enabled the IoT
to provide this shortage power by the area 2. Table II and III are related to the blockchain transactions for area 1 and 2 respectively.

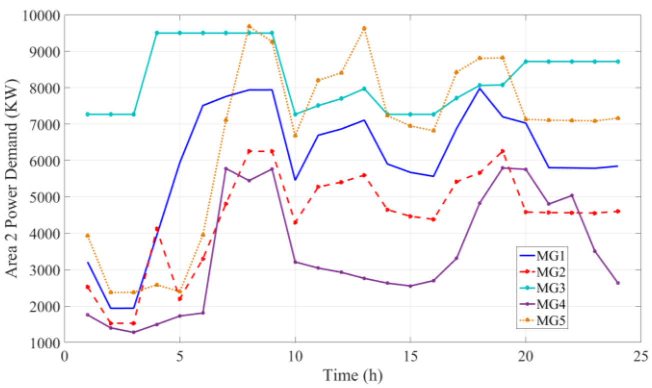

Fig. 3. Hourly load demand of area 2.

Table II
Blockchain Transactions of Area 1

Time (h)	From	To	DG	Power (kW)	Previous HA	New HA
1	MG3	MG2	DG 3	1166.41	244c2	f81b7
2	MG3	MG2	DG 3	1166.41	f81b7	16a81
3	MG3	MG2	DG 3	1166.41	16a81	21cd2
10	MG1	MG2	DG 4	1771.36	21cd2	cdfeb
	MG1	MG2	DG 4	644.60		
11	MG3	MG2	DG 4	1446.79	cdfeb	7f917
	MG1	MG2	DG 4	1057.24		
12	MG3	MG2	DG 4	1249.46	7f917	eef6a
12	IoT	MG2	------	40.04	eef6a	e56f4
	MG1	MG2	DG 4	821.11		
13	MG3	MG2	DG 4	970.40	e56f4	743bc
13	IoT	MG2	------	919.72	743bc	225ab
14	MG3	MG2	DG 4	1771.36	225ab	28f63
15	MG3	MG2	DG 4	1771.36	28f63	b22f8
	MG1	MG2	DG 3	143.50		
16	MG1	MG2	DG 4	75.39	b22f8	21a52
	MG3	MG2	DG 4	1552.46		
	MG1	MG2	DG 4	1059.25		
17	MG3	MG2	DG 4	1251.84	21a52	da8f7
17	IoT	MG2	------	55.16	da8f7	ceab7
	MG1	MG2	DG 4	761.24		
18	MG3	MG2	DG 4	899.65	ceab7	68598
18	IoT	MG2	------	1171.06	68598	fa82b
	MG1	MG2	DG 4	762.30		
19	MG3	MG2	DG 4	900.90	fa82b	5da63
19	IoT	MG2	------	2527.98	5da63	8cd21
	MG1	MG2	DG 3	196.75		
20	MG1	MG2	DG 4	334.37	8cd21	7699c
	MG3	MG2	DG 3	377.98		
	MG3	MG2	DG 4	2072.15		
	MG1	MG2	DG 3	215.03		
21	MG1	MG2	DG 4	324.09	7699c	0dd47
	MG3	MG2	DG 3	399.58		
	MG3	MG2	DG 4	2042.56		
	MG1	MG2	DG 4	475.92		
22	MG3	MG2	DG 3	406.96	0dd47	0a0ea
	MG3	MG2	DG 4	2098.38		
	MG1	MG2	DG 4	479.96		
23	MG3	MG2	DG 3	417.58	0a0ea	00015
	MG3	MG2	DG 4	2083.72		
	MG1	MG2	DG 3	172.58		
24	MG1	MG2	DG 4	414.48	00015	2cac7
	MG3	MG2	DG 3	349.41		
	MG3	MG2	DG 4	2044.79		

Also, the IoT central node decrees are presented in Table IV. It is worth noting that the IoT data are not accessible for MG1 and MG2; that means the privacy of the information within two areas. However, the data in tables II is only accessible for the committed MGs in area 1 where by placing any transaction within the area, the list of records will be updated for all the committed MGs; that means decentralization, transparency, and security within the area.

Table V
Blockchain Transactions of Area 2

Time (h)	From	To	DG	Power (kW)	Previous HA	New HA
	MG1	MG3	DG3	2000		
	MG2	MG3	DG3	1100		
4	MG2	MG3	DG4	1490.62	244c2	a302f
	MG4	MG3	DG1	243.48		
	MG5	MG3	DG2	205.92		
	MG1	MG3	DG2	2000		
	MG1	MG3	DG4	1984.61		
5	MG2	MG3	DG1	658.85	a302f	6d227
	MG4	MG3	DG1	166.01		
	MG4	MG3	DG3	230.55		
	MG1	MG3	DG2	1371.90		
	MG1	MG3	DG3	936.86		
6	MG1	MG3	DG4	1973.38	6d227	e0759
	MG2	MG3	DG2	757.87		
	MG1	MG3	DG4	1953.47		
	MG2	MG3	DG4	239.56		
7	MG4	MG3	DG2	364.94	e0759	3867c
	MG4	MG3	DG3	2482.05		
	MG1	MG3	DG4	1267.46		
	MG2	MG3	DG4	998.13	3867c	8157a
8	MG4	MG3	DG3	1688.95		
	MG5	MG3	DG3	628.15		
	MG5	MG3	DG4	885.93		
	MG1	MG3	DG4	1267.72		
	MG2	MG3	DG4	998.33		
	MG4	MG3	DG2	449.57		
9	MG4	MG3	DG3	1667.67	8157a	7660b
	MG5	MG3	DG3	626.48		
	MG5	MG3	DG4	461.90		

Here is an example to clarify the performance of the proposed method: According to the simulation results, in hour 13, MG2 which is the most crucial load has a shortage of power (see Fig. 1 and Table II). At first, the blockchain within the area informs other MGs to provide the required power. As it can see in Table II, MG1 and MG3 tried to provide this power. However, the total required power is not met yet. Hence, the blockchain enabled the IoT to provide this power from other areas. Based on the second transactions block in hour 13 of Table I, a portion of the shortage power is provided by the IoT. However, the source of power is unknown for the blockchain of area 1. This information is accessible in IoT list of records (see Table IV) wherein hour 13, the shortage power is provided by the DG3 of the MG4 in area 2 with the amount of 919.725 (kW). Figures 4-11 demonstrate the output power of DGs for area 1 and 2 respectively.

Table IV
IoT MGCC Transactions

Time (h)	Area	MG #	DG #	Provided Power (kW)
13	2	MG4	DG3	919.725
18	2	MG4	DG4	790.9046
	2	MG4	DG3	380.1651
	2	MG1	DG4	587.587
19	2	MG4	DG3	574.2
20	2	MG2	DG4	1206.2705
	2	MG4	DG3	570.5409
21	2	MG2	DG4	1330.3413

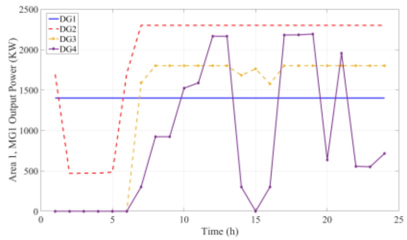

Fig. 4. The output power of MG1 of area 1

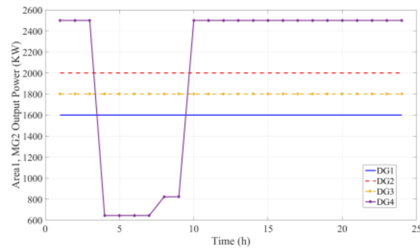

Fig. 5. The output power of MG2 of area 1

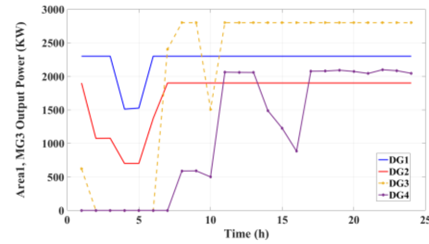

Fig. 6. The output power of MG3 of area 1

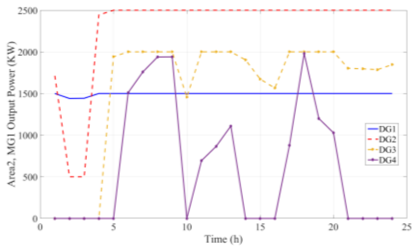

Fig. 7. The output power of MG1 of area 2

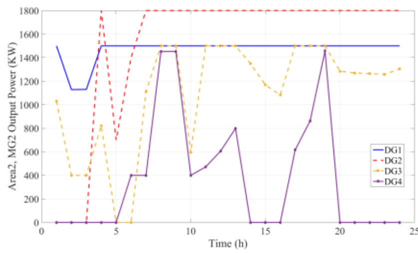

Fig. 8. The output power of MG2 of area 2

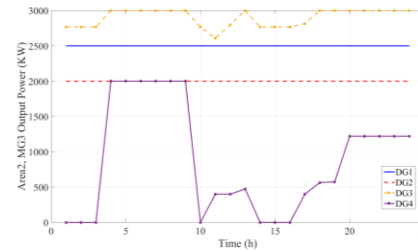

Fig. 9. The output power of MG3 of area 2

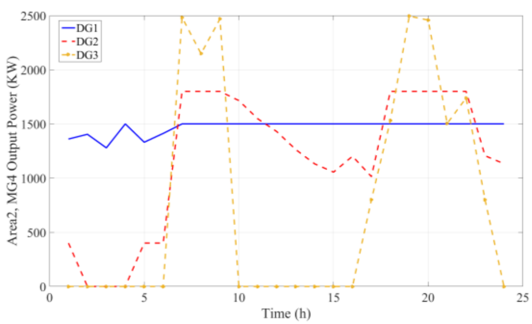

Fig. 10. The output power of MG4 of area 2

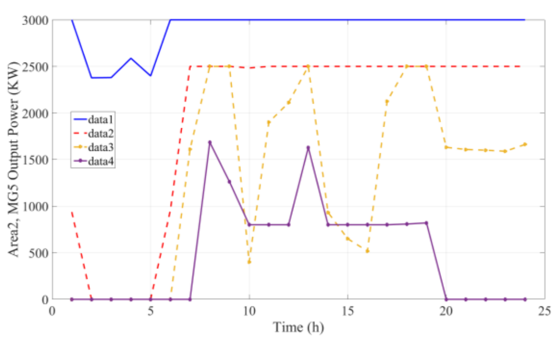

Fig. 11. The output power of MG5 of area 2

IV. CONCLUSION

In this paper, a novel framework is developed for the energy management of the networked MGs based on the blockchain-enabled IoT. Compare to the existing methods; the proposed method can lead to higher security, privacy, and transparency within the network. To have a more truthful model, a stochastic structure based on the UT is used to model the uncertainty parameters of the hourly load demand and the renewable energy output power.

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