A Novel Transactive Energy Model for Reliable Operation of Resilient Multi-Microgrids Cluster

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A Novel Transactive Energy Model for Reliable Operation of Resilient Multi-Microgrids Cluster

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***Abstract*—Nowadays, as energy networks are mixed to form a hybrid structure, resiliency is found as a vital factor for the sustainability of the energy network infrastructure. In this regard, microgrids are recognized as a potential solution in post-disaster energy network recovery efforts. However, exposure to various natural disasters, as well as uncertainties associated with renewables, have introduced the resiliency challenge as a critical issue in the optimal operation of multi-microgrids. To tackle such challenge, this paper advances the state-of-art microgrid energy sharing technique by developing an innovative transactive energy trading model for the optimal resilient operation of the renewable-based multi-microgrids cluster. The proposed transactive energy-based model is intended to improve the resiliency of microgrids in the sustainable energy supply chain after affecting the system by natural disasters. Due to the operation of microgrids with a high contribution of renewable energy sources (RESs), uncertainty quantification is performed using autoregressive integrated moving average and fast forward selection methods to produce and reduce scenarios, respectively. The effectiveness and feasibility of the proposed model are examined using a modified IEEE-10 bus test system. The results indicate a 6.18% reduction in the operation cost of the multi-microgrids under the proposed transactive energy-based model.**

Keywords— Resiliency, multi-microgrids cluster, transactive energy, renewable energy sources, sustainable power grid, optimal operation

I. INTRODUCTION

A. Motivation and Background

Today, the electric power system has experienced evolutions in transiting from a centralized bulk grid to a decentralized modern hybrid network [1]. One of the main missions of this grid modernization is to develop and pursue practical solutions to effectively dealing with the energy crisis and continuously serving the consumers' energy demand [2]. In the last decades, the socio-economic losses caused by electricity outages are considered as the evident evidence to develop a set of monolithic efforts for rapid restoration of the power system functionality that is named power system resiliency [3]. Indeed, resiliency refers to the system's ability in preserving its normal operation or rapidly recover after occurring disruptive events using the capability of anticipation, absorption, and adoption [4]. As the power system is exposing to the destructive effects of weather-related incidents, a need for the appropriate structure of the power system has attracted substantial attention for the resilient operation of the energy grid. In this respect, microgrids allow the operation of the local grid in both grid-connected and islanding modes that enable the electric power system to be sustainable and resilient in serving energy demand after the system is threatened by a natural disaster [5]. However, microgrids are typically empowered by various types of distributed energy resources (DERs) that require capable technologies to manage and control the energy supply chain in the network's different conditions [6]. Hence, a great need is felt for state-of-art technologies that not only enable the system to meet time-to-time energy load in the presence of numerous renewable energy sources (RESs) but also support the system to be sustainable and resilient when it faces diverse natural disasters. This is why we have been motivated to offer a novel transactive energy model for maintaining the resiliency and sustainability of multi-microgrids by designing a local electricity sharing market (LESM) that allows microgrids' operation in the cluster mode.

B. Relevant Literature

Threatened by man-made attacks and natural disasters, the operation of the resilient power grid has drawn significant attention in recent literature. In this respect, several studies have extended their research scope towards the development of novel techniques to make the power system more resilient and sustainable than ever before. For instance, the authors in [7] advanced the state-of-art method for energy management of the microgrid by developing the economic dispatch using a single time interval optimal power flow aiming to make the system resilient and sustainable as well as achieve a flexible time frame. In [8], the authors proposed an innovative load restoration optimization model to coordinate microgrid formation and topology reconfiguration. The proposed technique used the potential of grid modernization to exploit the benefits of operational flexibility for allowing more indispensable load pickup. A distributed bi-level cooperation control program was presented in [9] for resilient control of heterogeneous microgrid clusters with the aim of realizing load exchanging in the system. In another work [10], the impact of discrepancies in the energy management systems was explored to realize the resilient microgrid by focusing on the system's reliability as a crucial issue, particularly in the islanding mode. Moreover, the authors proposed a new optimal scheduling framework in [11] that was developed based on the average consensus-based algorithm for the resilient operation of intelligent microgrids in the industrial internet of things environment.

The ongoing plans for the electric power system highlight this undeniable fact that the highly equipped renewable systems form the foundation of the future modern energy network [12]. Given the vital role of electrical energy in daily life, modeling uncertainties in such a deregulated environment properly has taken growing attention in recent studies to improve the power grid resiliency, control power outages, and avoid serious consequences. For example, the authors in [13] presented a novel risk-constrained stochastic framework for optimal joint reserve and energy scheduling of the resilient microgrid considering the prevailing uncertainties in both grid-connected and islanding states as well as demand-side energy management. A fuzzy-robust method was proposed in [14] to capture the uncertainties in designing a sustainable and resilient power supply chain grid under the multi-objective optimization model for a real-world case study. In [15], the authors proposed a data-driven technique to estimate the maximum deviations of uncertain parameters utilizing historical data. The same research proposed a resilience index to quantify the applicability of the suggested technique for the microgrids' resilience-oriented operation. This is while the authors proposed a risk-constrained adaptive robust optimization method in [16] for adopting proactive resilient scheduling decisions in the multiple networked microgrids. Also, the risk-averse strategy is applied in [17] for uncertainty quantification in the techno-economic scheduling of the industrial microgrid.

C. Contributions and Organization

The recent literature in the context of the resilient operation of multi-microgrids has more focused on using varieties of techniques for improving the power grid resiliency in the presence of different uncertain parameters. In spite of the crucial role of microgrids in developing the power system towards the modern carbon-free infrastructure, proposing a holistic model for the resilient operation of renewable-based microgrids is a significant challenge, which has remained unfilled yet. In other words, microgrids with a large number of RESs require a comprehensive model that not only enables the system for a high operation of clean electricity production devices but also supports the system in maintaining its resiliency using a reliable and sustainable manner when the system is threatened by extreme weather hazards that are ignored in recent studies. To tackle this challenge, this paper suggests a transactive energy model to avoid severe power outages created by weather-related incidents by forming the LESM for the electricity exchanging of the multi-microgrids. Transactive energy is one of the environmentally friendly technologies that is taken into account as the key contender for orchestrating the coordinated operation of energy systems, which enables the power grid for reliably energy supply when it is integrated with the numerous RESs [18]. The proposed model is developed to not only keep the resiliency and sustainability of microgrids in the presence of RESs but also to allow the high operation of pollutant-free electricity generation units. The fluctuations in the electricity production sector of such a deregulated system need to be effectively modeled with the aim of reaching accurate results. Hence, several scenarios are generated using the autoregressive integrated moving average (ARIMA) method that are reduced to plausible numbers by exerting the fast forward selection (FFS) technique.

The remainder of this paper is structured as follows. The problem formulation, including uncertainty quantification, objective function, operational constraints, and problem analysis, are described in Section II. The numerical results and the related discussions are provided in Section III. Finally, a conclusion of this work is explained in Section IV.

II. Problem Formulation

A. Uncertainty Quantification

Generally, uncertainties are recognized as the characteristic of renewable-based systems that are enclosed as an unbounded gap for controlling the undesirable impact, which their intermittences may impose on the optimization problem [19]. In this work, five microgrids are assessed in the resilient operation process that are equipped with a great level of wind and solar systems for carbon-free electricity production. This issue has exposed the system to uncertainties originated in RESs, which need to be posed in the problem-solving process. In this regard, scenario generation techniques have gotten plausible results in considering the most of volatilities in uncertain parameters under the stochastic programming procedure. Herein, numerous scenarios are procreated by deploying the ARIMA method [20]. In the early 1970s, ARIMA was proposed by Box and Jenkins as a time series forecasting technique that enables the system to create scenarios for various types of uncertain parameters [21]. Given three parameters (x, y, z), an ARIMA time series can be modeled as follows [22].

$$\left(1-\sum_{\ell=1}^{x}\Theta_{\ell}\nabla^{\ell}\right)(1-\nabla)^{y}\,\xi_t=\left(1-\sum_{\ell=1}^{z}\Phi_{\ell}\nabla^{\ell}\right)\gamma_t \tag{1}$$

where, x and z indicate the number of autoregressive and moving average parameters. y is the differentiating order. γ_t presents the error term. ∇ represents the backshift operator. Θ_ℓ and Φ_ℓ are respectively related to autoregressive and moving average parts. To eschew the computational burden and complexity of the problem, the scenario reduction process is done by applying the FFS approach [22]. Therefore, the number of scenarios is decreased to a suitable level.

B. Objective Function

This research is aimed to suggest a transactive energy model for the resilient operation of multi-microgrids with wide penetration of renewables. The objective function for this problem is given as:

$$\begin{aligned}Z_m=&\sum_{\varpi=1}^{N_\varpi}\phi^{\varpi}.[\sum_{\tau=1}^{N_\tau}[(\alpha_{DG}^{m}.\chi_{DG}^{m,\tau,\varpi})+(\beta_{DG}^{m}.P_{DG}^{m,\tau,\varpi})+\\&(SUC_{DG}^{m,\tau}.\chi_{SU,DG}^{m,\tau,\varpi})+(SDC_{DG}^{m,\tau}.\chi_{SD,DG}^{m,\tau,\varpi})]+\sum_{\tau=1}^{N_\tau}\text{Cost}_{CL}^{\tau}\\&-\sum_{\tau=1}^{N_\tau}\pi_{ET}^{\tau}.P_{ET}^{m,\tau,\varpi}.\Delta\tau-\sum_{\tau=1}^{N_\tau}\sum_{j=1}^{N_j}\pi_{ES}^{\tau}.(L_E^{j,\tau}-P_{CL}^{j,\tau,\varpi}).\Delta\tau]\end{aligned} \tag{2}$$

where, Z_m presents the objective function. α_{DG}^{m} and β_{DG}^{m} are the coefficients for modeling the operation cost of diesel generators (DGs). $P_{DG}^{m,\tau,\varpi}$ and $\chi_{DG}^{m,\tau,\varpi}$ are the output of the DG unit and its ON/OFF status for microgrid m at time τ and scenario ϖ. $SUC_{DG}^{m,\tau}$ and $SDC_{DG}^{m,\tau}$ ($\chi_{SU,DG}^{m,\tau,\varpi}$ and $\chi_{SD,DG}^{m,\tau,\varpi}$) are the start-up and shut-down costs (ON/OFF status) of the DG unit, respectively. $P_{CL}^{j,\tau,\varpi}$ and $\text{Cost}_{CL}^{\tau,\varpi}$ present the amount of curtailable load (CL) and its cost at time τ and scenario ϖ. $P_{ET}^{m,\tau,\varpi}$ and π_{ET}^{τ} represent the amount of electricity trading with the power grid and its price at time τ. $L_E^{j,\tau}$ is the amount of electricity consumption at time τ and bus j. π_{ES}^{τ} is the electricity selling price to the consumers. ϕ^{ϖ} states the probability of the scenario ϖ. In (2), the first term models the operation cost of the DG unit. The second term indicates the cost of CL. The third term indicates the revenue (cost) of selling (purchasing) electrical energy to (from) the power system. The last term formulates the revenue of selling electricity to consumers.

C. Constraints

1) Electricity balance

In the power grid, creating electricity balance is essential to preserve the system from instabilities that can be established using the following constraint.

$$\sum_{m=1}^{N_m}(P_{DG}^{m,\tau}+P_{Wind}^{m,\tau}+P_{PV}^{m,\tau}+P_{BESU}^{m,\tau}+P_{EI}^{m,\tau}-P_{ET}^{m,\tau}-P_{EO}^{m,\tau}) = \sum_{j=1}^{N_j}(L_E^{j,\tau}-P_{CL}^{j,\tau}) \quad \forall\tau \tag{3}$$

where, electricity outputs of the wind and solar units are presented by $P_{Wind}^{m,\tau}$ and $P_{PV}^{m,\tau}$. The output of the battery electricity storage unit (BESU) is represented by $P_{BESU}^{m,\tau}$, in which its positive sign refers to the discharging state of BESU and the negative sign indicates the charging mode. The amounts of power received from the LESM and injected into this market are respectively indicated by $P_{EI}^{m,\tau}$ and $P_{EO}^{m,\tau}$.

2) Renewable energy sources (RESs)

$$P_{PV}^{m,\tau}\le S_{PV}^{m}.SR^{\tau}.\eta_{PV}^{m} \quad \forall m\ ,\ \forall\tau \tag{4}$$

$$P_{Wind}^{m,\tau}=\begin{cases}0 & \upsilon_W^{\tau}<\upsilon_{CI}^{\tau}\ ,\ \upsilon_W^{\tau}>\upsilon_{CO}^{\tau}\\ \bar{P}_{Wind}^{m}\times\left(\dfrac{\upsilon_W^{\tau}-\upsilon_{CI}^{\tau}}{\upsilon_R^{\tau}-\upsilon_{CI}^{\tau}}\right)^3 & \upsilon_{CI}^{\tau}\le\upsilon_W^{\tau}\le\upsilon_R^{\tau}\\ \bar{P}_{Wind}^{m} & \upsilon_R^{\tau}\le\upsilon_W^{\tau}\le\upsilon_{CO}^{\tau}\end{cases} \tag{5}$$

where, the size and efficiency of the solar panel are stated by S_{PV}^{m} and η_{PV}^{m}, respectively. The solar radiation is indicated by SR^{τ}. The maximum amount of wind power is denoted by $\bar{P}_{Wind}^{m}$. The wind speed is presented by υ_W^{τ} while υ_{CI}^{τ}, υ_{CO}^{τ}, and υ_R^{τ} state the cut-in, cut-out, and rated wind speed.

3) DG system

In this study, DG systems are operated as backup devices to support high-equipped renewable microgrids for ensuring a continuous power supply. The operational constraints for DG units are given as:

$$\chi_{DG}^{m,\tau}.\underline{P}_{DG}^{m}\le P_{DG}^{m,\tau}\le\chi_{DG}^{m,\tau}.\bar{P}_{DG}^{m} \quad \forall m,\ \forall\tau \tag{6}$$

$$(\chi_{DG}^{m,\tau-1}-\chi_{DG}^{m,\tau}).(T_{On,DG}^{m,\tau-1}-MUT_{DG}^{m})\ge 0 \quad \forall m,\ \forall\tau \tag{7}$$

$$(\chi_{DG}^{m,\tau-1}-\chi_{DG}^{m,\tau}).(T_{Off,DG}^{m,\tau-1}-MDT_{DG}^{m})\ge 0 \quad \forall m,\ \forall\tau \tag{8}$$

$$P_{DG}^{m,\tau}-P_{DG}^{m,\tau-1}\le Rup_{DG}^{m},\ \text{if}\ P_{DG}^{m,\tau}\ge P_{DG}^{m,\tau-1} \quad \forall m,\ \forall\tau \tag{9}$$

$$P_{DG}^{m,\tau-1}-P_{DG}^{m,\tau}\le Rdown_{DG}^{m},\ \text{if}\ P_{DG}^{m,\tau-1}\ge P_{DG}^{m,\tau} \quad \forall m,\ \forall\tau \tag{10}$$

$$\bar{P}_{DG}^{m}\le P_{GL,DG}^{m,\tau}.G_{HR}^{DG}.\Delta\tau \quad \forall m,\ \forall\tau \tag{11}$$

$$\chi_{DG}^{m,\tau}-\chi_{DG}^{m,\tau-1}\le\chi_{SU,DG}^{m,\tau} \quad \forall m,\ \forall\tau \tag{12}$$

$$\chi_{DG}^{m,\tau-1}-\chi_{DG}^{m,\tau}\le\chi_{SD,DG}^{m,\tau} \quad \forall m,\ \forall\tau \tag{13}$$

$$\chi_{DG}^{m,\tau}-\chi_{DG}^{m,\tau-1}\le\chi_{SU,DG}^{m,\tau}-\chi_{SD,DG}^{m,\tau} \quad \forall m,\ \forall\tau \tag{14}$$

where, the upper and lower bounds for power production of the DG unit are indicated by $\bar{P}_{DG}^{m}$ and $\underline{P}_{DG}^{m}$, respectively. The number of hours that the DG is ON and OFF are presented by $T_{On,DG}^{m,\tau}$ and $T_{Off,DG}^{m,\tau}$, respectively. The minimum up and down times for the DG are represented by MUT_{DG}^{m} and MDT_{DG}^{m}. The ramp up and down power for the DG are stated by Rup_{DG}^{m} and $Rdown_{DG}^{m}$. The amount of DG's gas demand and heat rate gas are respectively denoted by $P_{GL,DG}^{m,\tau}$ and G_{HR}^{DG}. Equation (6) limits the DG unit's output at the permissible range. Equations (7) and (8) model the minimum up and down times of the DG unit. Equations (9) and (10) formulate the ramp up and down constraints for the DG unit. Equation (11) limits the gas consumption for the DG unit.

4) Battery electricity storage unit (BESU)

Ensuring the continuity in the electricity supply of the system with a great share of RESs requires storage systems that allow for storing clean electricity at electrical energy generation rich times and inject it back to the grid in hours with more electricity consumption. In this work, each microgrid is empowered by BESU to realize this goal using the following constraints.

$$\chi_{Ch,B}^{m,\tau}+\chi_{Dis,B}^{m,\tau}\le 1 \quad \forall m\ ,\ \forall\tau \tag{15}$$

$$S_B^{m}.\underline{\varsigma}_B^{m}\le E_B^{m,\tau}\le S_B^{m} \quad \forall m\ ,\ \forall\tau \tag{16}$$

$$E_B^{m,\tau}=E_{I,B}^{m}+(E_{Ch,B}^{m,\tau}-E_{Dis,B}^{m,\tau}).\Delta\tau \quad \forall m\ ,\ \tau=1 \tag{17}$$

$$E_B^{m,\tau}-E_B^{m,\tau-1}=(E_{Ch,B}^{m,\tau}-E_{Dis,B}^{m,\tau}).\Delta\tau \quad \forall m\ ,\ \forall\tau\ge 2 \tag{18}$$

$$\underline{\varsigma}_{Ch,B}^{m}S_B^{m}.\chi_{Ch,B}^{m,\tau}\le E_{Ch,B}^{m,\tau}\le\bar{\varsigma}_{Ch,B}^{m}S_B^{m}.\chi_{Ch,B}^{m,\tau} \quad \forall m\ ,\ \forall\tau \tag{19}$$

$$\underline{\varsigma}_{Dis,B}^{m}S_B^{m}.\chi_{Dis,B}^{m,\tau}\le E_{Dis,B}^{m,\tau}\le\bar{\varsigma}_{Dis,B}^{m}S_B^{m}.\chi_{Dis,B}^{m,\tau} \quad \forall m\ ,\ \forall\tau \tag{20}$$

where, $E_{Ch,B}^{m,\tau}$ and $E_{Dis,B}^{m,\tau}$ ($\chi_{Ch,B}^{m,\tau}$ and $\chi_{Dis,B}^{m,\tau}$) are the charging and discharging power (ON and OFF status) by BESU. The size of BESU and electricity stored in it are respectively presented by S_B^{m} and $E_B^{m,\tau}$. The coefficient for minimum electricity stored in BESU is indicated by $\underline{\varsigma}_B^{m}$. $E_{I,B}^{m}$ is the initial electricity stored in BESU. The coefficients for upper and lower bounds of BESU's charging (discharging) are denoted by $\bar{\varsigma}_{Ch,B}^{m}$ and $\underline{\varsigma}_{Ch,B}^{m}$ ($\bar{\varsigma}_{Dis,B}^{m}$ and $\underline{\varsigma}_{Dis,B}^{m}$). Equation (15) indicates BESU can only be ON or OFF at any time. Equation (16) models the allowable range of power storing in BESU. Equations (17) and (18) formulates the electricity balance constraints in BESU that the amounts of power charging and discharging are respectively limited by (19) and (20).

5) Curtailable load (CL)

In this research, the curtailable load is intended for demand-side energy management at the necessary times. The cost of CL and its constraints are given as:

$$\text{Cost}_{CL}^{\tau}=\sum_{j=1}^{N_j}[\sigma_1^{CL}.(P_{CL}^{j,\tau})^2+\sigma_2^{CL}.P_{CL}^{j,\tau}] \tag{21}$$

$$0 \le P_{CL}^{j,\tau} \le \bar{P}_{CL}^{j} \tag{22}$$

$$\underline{P}_{CL}^{j} \le L_{E}^{j,\tau} - P_{CL}^{j,\tau} \le \bar{P}_{CL}^{j} \tag{23}$$

where, σ_1^{CL} and σ_2^{CL} are the coefficients for the CL cost. $\bar{P}_{CL}^{j}$ is the maximum amount of the curtailed load in bus *j*.

6) Power grid

$$P_{j,\tau}^{Fl}(V^{j,\tau},\theta^{j,\tau}) + L_{E}^{j,\tau} = P_{j,\tau}^{Gen} \quad \forall j \;,\; \forall \tau \tag{24}$$

$$Q_{j,\tau}^{Fl}(V^{j,\tau},\theta^{j,\tau}) + Q_{E}^{j,\tau} = Q_{j,\tau}^{Gen} \quad \forall j \;,\; \forall \tau \tag{25}$$

$$\underline{V}^{j} \le V^{j,\tau} \le \bar{V}^{j} \tag{26}$$

$$\underline{\theta}^{j} \le \theta^{j,\tau} \le \bar{\theta}^{j} \tag{27}$$

$$\underline{S}^{i,j} \le S^{i,j,\tau} \le \bar{S}^{i,j} \tag{28}$$

where, the active and reactive power flows (production) are denoted by $P_{j,\tau}^{Fl}$ and $Q_{j,\tau}^{Fl}$ ($P_{j,\tau}^{Gen}$ and $Q_{j,\tau}^{Gen}$). The voltage magnitude and phase angle are stated by $V^{j,\tau}$ and $\theta^{j,\tau}$. The complex power is indicated by $S^{i,j,\tau}$. Equations (24) and (25) model the AC power flow. Equations (26) to (28) keep the amounts of voltage, phase angle, and complex power in the standard range.

7) Local electricity sharing market (LESM)

In this paper, the LESM is developed under the transactive energy architecture to make electricity sharing among the microgrids possible. This local grid provides the possibility of electricity trading in the cluster mode and supports the system to maintain its sustainability and resilience in continuous energy serving when it is exposed to natural disasters. The LESM is subject to the following constraints.

$$\chi_{EO}^{m,\tau} + \chi_{EI}^{m,\tau} \le 1 \quad \forall m \;,\; \forall \tau \tag{29}$$

$$P_{EI}^{m,\tau} \le M \cdot \chi_{EI}^{m,\tau} \quad \forall m \;,\; \forall \tau \tag{30}$$

$$P_{EO}^{m,\tau} \le M \cdot \chi_{EO}^{m,\tau} \quad \forall m \;,\; \forall \tau \tag{31}$$

$$\sum_{m} P_{EI}^{m,\tau} = \sum_{m} P_{EO}^{m,\tau} \quad \forall \tau \tag{32}$$

$$\sum_{\tau} P_{EI}^{m,\tau} = \sum_{\tau} P_{EO}^{m,\tau} \quad \forall m \tag{33}$$

where, $\chi_{EO}^{m,\tau}$ and $\chi_{EI}^{m,\tau}$ are the respective indicators for electricity transmitting and receiving states between microgrids in LESM. M is a big number.

8) Electricity trading with the power grid

The amount of electricity exchanged between the power grid and microgrid *m* is limited using the following constraint.

$$\underline{P}_{ET}^{m} \le P_{ET}^{m,\tau} \le \bar{P}_{ET}^{m} \quad \forall m \;,\; \forall \tau \tag{34}$$

where, $\bar{P}_{ET}^{m}$ and $\underline{P}_{ET}^{m}$ are the upper and lower bounds for the electricity sharing with the main grid.

D. Problem Analysis

This article is structured to develop a novel transactive energy model for the resilient operation of multi-microgrids in the network with a high percentage of RESs contribution. Due to this, two cases are considered for examining the microgrid's operation problem. In Case I, it is assumed that the operation of microgrids is done without considering the LESM. However, Case II includes the possibility of electricity sharing for microgrids in the LESM. In both cases, it is assumed that an event occurred in the system and is led to the interruption between the power system and microgrids in the starting hour of the mid-peak period (11 am). Indeed, following this event, the connection between the power system and microgrids is interrupted and all microgrids are operated in the islanded mode at the time period 11 am to 9 pm. The time of the occurring event in the system is illustrated in Fig. 1.

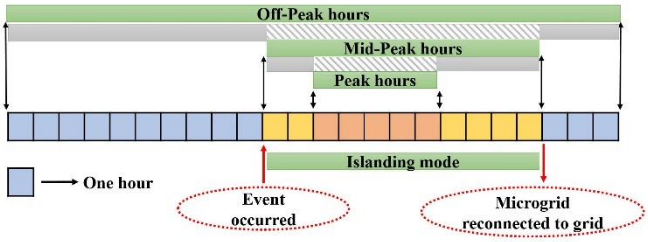

Fig. 1. The time of the occurring event in the power network

1) Case I

This case assesses the optimal resilient operation of multi-microgrids without considering their participation in the LESM. Therefore, the problem formulation for Case I is as:

Min Z_m

subject to:

$$\underline{P}_{ET}^{m} \le P_{ET}^{m,\tau} \le \bar{P}_{ET}^{m} \quad \forall m \;,\; \forall \tau = 1,\cdots 10 \text{ and } 22,\cdots,24$$

Constraints (3) – (28)

2) Case II

This case investigates the operation of microgrids considering their participation in the LESM for freely electricity sharing among themselves based on the proposed model. Thereby, constraints of the LESM are considered for this case and its problem formulation is given as:

Min Z_m

subject to:

$$\underline{P}_{ET}^{m} \le P_{ET}^{m,\tau} \le \bar{P}_{ET}^{m} \quad \forall m \;,\; \forall \tau = 1,\cdots 10 \text{ and } 22,\cdots,24$$

Constraints (3) – (33)

III. Simulation Results

In this research, a new model is offered for the resilient operation of multi-microgrids based on the transactive energy architecture. The five microgrids are considered for examining the problem in the modified IEEE 10-bus test system that its schematic is demonstrated in Fig. 2. The wind and solar systems are used for cost-effective electricity supplying in each microgrid [23]. Moreover, DG units and BESU are operated for mitigating the uncontrollable features of stochastic generators [24]. The electricity price and load information can be found in [25]. The problem is the mixed-integer nonlinear program (MINLP) due to nonlinear AC power flow equations and binary variables. This is why the DICOPT [26] and SBB [27] solvers are exerted in the general algebraic modeling system (GAMS) for simulating the problem. Two cases are assessed for assessing the problem, in which Case I models the operation of the microgrid without considering LESM constraints while Case II advantages the electricity sharing in the LESM for microgrids. The operation costs of microgrids are tabulated in Table I.

TABLE I. Operation Cost of Microgrids

Microgrid index	Case I ($)	Case II ($)
M1	42783.56	37298.774
M2	14598.569	33608.791
M3	54597.252	31155.889
M4	11058.495	20234.363
M5	43862.808	34296.542
Total cost	166900.684	156594.360

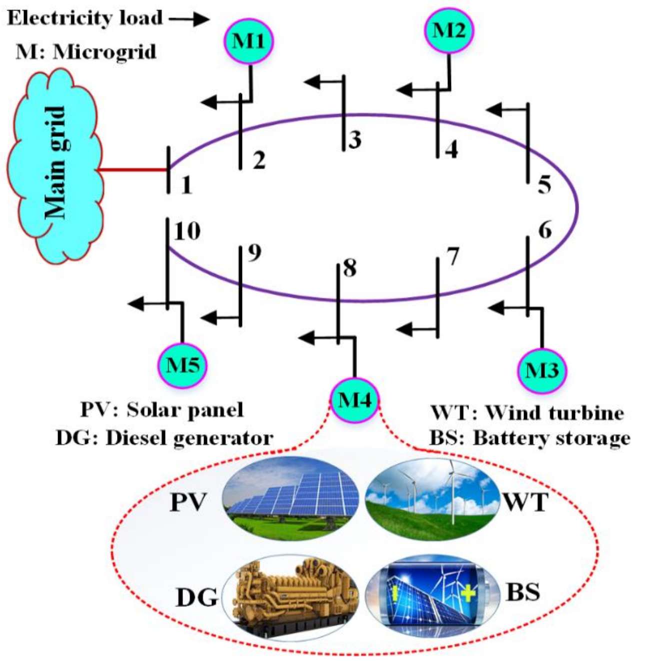

Fig. 2. Schematic of the modified IEEE 10-bus case study

According to Table I, the system witnesses a 6.18% reduction in the operation cost of microgrids in Case II than Case I. Indeed, the resilient operation of multi-microgrids under the proposed transactive energy-based model has been led to a reduction in their operation cost. In this regard, the amount of clean power generation in microgrids is depicted in Fig. 3.

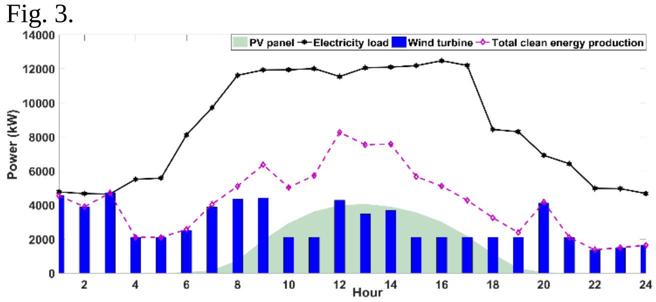

Fig. 3. The amount of RESs in microgrids

As seen in Fig. 3, desirable wind velocity in the early morning has led to more wind power production in these times than other hours of the day. This is while solar panels are dominant systems at noon in generating pollutant-free electricity. The total amount of RESs outputs indicates a great portion of the electricity load is served using environmentally friendly electricity generation systems during 24-hours. In this regard, DG systems and BESU are operated as supportive units for mitigating the negative impact of uncontrollable properties of RESs production, which their outputs in Case I and II are shown in Fig. 4.

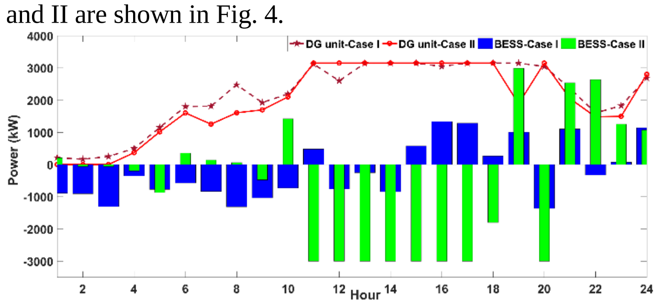

Fig. 4. The outputs of DG units and BESU in Case I and II

Given Fig. 4, the DG unit's electricity generation in Case II is lower than Case I. This is because in Case II, the resilient operation of microgrids under the proposed model benefits the transactive electricity sharing in the LESM that enables them for free electricity trading between themselves. Indeed, freely electricity exchanging has reduced the need for the high-level operation of controllable units. In Case II, BESU as another controllable system has used the electricity exchanging opportunity among microgrids for charging at noon hours to support the power network in meeting electricity at the end of the day. This is while the islanding operation during mid and peak hours has been led to the charge of BESU in the early morning with the aim of serving a portion of the load at peak and night hours. In this regard, electricity exchanging is used as one of the helpful ways for time-to-time electricity balancing in microgrids. The amounts of electricity sharing among microgrids in the LESM and with the power network are portrayed in Fig. 5.

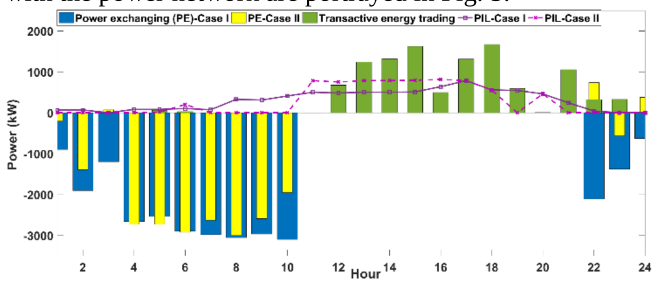

Fig. 5. The amounts of electricity trading in the LESM and the power grid

As obvious from Fig. 5, in both Case I and II, the electricity transactions between microgrids and the power network are carried out only at off-peak hours due to the islanding operation of microgrids in the mid and peak times after occurring the hypothetical event in the system at 11 am. In off-peak hours, microgrids have received more electricity in Case I from the power network in comparison with Case II. Indeed, electricity trading among microgrids in the cluster mode has caused the decreasing dependency of microgrids to the main grid in Case II. On the other hand, the amount of CL is also decreased in Case II than Case I during a day, which indicates the effectiveness of the suggested model in supporting the sustainability of the system in different conditions. In other words, microgrids have used the opportunity of free electricity sharing at noon hours to compensate for electricity shortages in Case II that not only has reduced the amount of operation cost but also has declined the amount of CL during 24-hours.

IV. Conclusion

This article proposed a novel resilient operation model for multi-microgrids using transactive energy technology. In this respect, the LESM was designed aiming to provide electricity exchanging among microgrids for maintaining the sustainability and resiliency of the system. Transactive energy sharing was applied for time-to-time electricity balancing in the power network with a great contribution of RESs. The modified IEEE 10-bus test system with five renewable-based microgrids was used for validating the proposed model. In order to quantify the fluctuations of unpredictable electricity systems, scenario generation and decrement processes were performed using ARIMA and FFS techniques, respectively. Cases I and II were intended for scrutinizing the operation problem, in which more energy cost was imposed for Case I without considering the LESM in comparison with Case II with LESM. The results proved the effectiveness of the offered model in alleviating the amount of CL and operation cost in the presence of numerous RESs. From the whole energy system viewpoint, the proposed model can effectively support the microgrids to reliably meet their energy load when an event occurred in the main grid and the local multi-microgrids separated from the power grid for islanding operation. As severe volatilities are an undeniable part of the systems with a wide penetration of renewables, the system requires robust-based models to consider the worst state of fluctuations aiming to appropriately deal with the intermittences. Developing such models can be considered as the future trends for this study.

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